A DECISION SUPPORT TOOL FOR CONCEPTUAL SITE MODEL DEVELOPMENT AT CONTAMINATED SITES

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A DECISION SUPPORT TOOL FOR CONCEPTUAL SITE MODEL DEVELOPMENT AT CONTAMINATED SITES

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ABSTRACT

A DECISION SUPPORT TOOL FOR CONCEPTUAL SITE MODEL DEVELOPMENT AT CONTAMINATED SITES

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A conceptual site model (CSM) is simply a description of the environmental conditions at a contaminated site and surrounding area, which provides all interested parties with a vision of the site. CSM mainly identifies the source-pathway-receptor linkage to guide for effective site characterization, risk assessment and remedial investigations.

Development of CSM is complicated because it is 'case specific' and there is no single route to follow during decision making concerning the contaminated site. Moreover, type and extent of information needed varies according to size and level of contamination and site heterogeneity.

The objective of this study is to develop a decision support tool that guides the site assessors during identification of possible decision routes that can be encountered; the procedure to be followed; and the information and data to be collected at each stage. This tool also introduces interactions between CSM and sampling strategies designed for various purposes. Developed decision support tool adapts to each specific contaminated site. Furthermore, a detailed review of sampling strategies is presented as a guidance for site assessors.

The decision support tool is equipped with standardized tools used for CSM development, i.e. information/data collection forms, illustrative tools and exposure pathway diagram. Information on site, geology, hydrogeology, contamination source, contaminants and receptors is collected via CSM form. Illustrative tools may vary from very simple site sketches to very complex 3D drawings depending on the needs of the specific contamination cases. Exposure pathway diagram (EPD) is used to identify all transport mechanisms and potential exposure pathways. EPD is embedded into a user-friendly decision assistance tool based on Microsoft Excel and Visual Basic for Applications. The applicability and utility of the decision support tool was tested using two case studies. Case study applications indicated that the developed methodology satisfies the objectives aimed in this study.

Keywords: Contaminated sites, Contaminated site management, Conceptual site model, Site investigation, Decision support tool

ÖZ

KİRLENMİŞ SAHALAR İÇİN KAVRAMSAL SAHA MODELİNİN GELİŞTİRİLMESİNDE KULLANILABİLİR BİR KARAR DESTEK ARACI

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Kavramsal saha modeli (KSM), basit olarak, kirlenmiş bir saha ve etrafındaki çevresel koşulları, ilgili tüm paydaşlara saha hakkında bir fikir verebilecek şekilde tanımlamakta kullanılan bir araçtır. KSM temel olarak saha karakterizasyonunu, risk değerlendirmesini ve temizleme incelemelerini yönlendirmek amacı ile sahadaki kaynak-taşınım yolu-alıcı ilişkisini gösterir. KSM'nin geliştirilmesi, sahaya özgü olması ve kirlenmiş saha hakkında karar almada takip edilecek tek bir yol olmaması nedeniyle karmaşıktır. Ayrıca, ihtiyaç duyulan bilginin çeşidi ve kapsamı, kirliliğin boyutu ve seviyesinin yanı sıra sahanın heterojenliğine de bağlıdır.

Bu çalışmanın amacı; olası kararların, takip edilmesi gereken prosedürün ve bilgi ihtiyacının belirlenmesinde ilgili araştırmacıyı yönlendirecek bir karar destek aracı geliştirmektir. Buna ek olarak, KSM geliştirilmesi ile çeşitli amaçlar için tasarlanan örnekleme stratejileri arasındaki ilişkilerin ortaya konulması da hedeflenmiştir. Geliştirilen karar destek aracının, bütün kirlenmiş saha vakalarında uygulanabilir olmasına dikkat edilmiştir. Ayrıca, örnekleme stratejileri ile ilgili olarak, saha değerlendiriciler için rehber niteliğinde detaylı bir inceleme sunulmuştur.

Karar destek aracı, KSM geliştirilirken kullanılacak olan bazı araçlar ile donatılmıştır. Bunlar; KSM bilgi/veri derleme formu, KSM şeması ve taşınım yolları çizelgesidir. KSM formu saha, sahanın jeolojik ve hidrojeolojik özellikleri, kirletici kaynağı, kirleticiler ve alıcılar hakkında bilgi toplanması amacı ile geliştirilmiştir. KSM şeması, vakanın ihtiyaçlarına bağlı olmak üzere, basit krokilerden veya üç boyutlu daha kapsamlı görüntülerden oluşabilir. Taşınım yolları çizelgesi ise, sahadaki taşınım mekanizmalarının ve potansiyel maruziyet yollarının belirlenmesi amacı ile kullanılmalıdır. Taşınım yolları çizelgesi, Microsoft Excel ve Visual Basic Uygulamaları kullanılarak geliştirilen kullanıcı dostu bir karar destek sistemine entegre edilmiştir. Geliştirilen karar destek aracının uygulanabilirliği ve yararlılığı iki örnek vaka çalışması ile test edilmiştir. Örnek vaka çalışmaları, geliştirilen metodolojinin bu çalışmada hedeflenen amaçları karşıladığını göstermiştir.

Anahtar Sözcükler: Kirlenmiş sahalar, Kirlenmiş sahaların yönetimi, Kavramsal saha modeli, Saha incelemesi, Karar destek aracı

To my family,

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ABBREVIATIONS

AB	: Air Base
ARAMS	: Adaptive Risk Assessment Modelling System
ASTDR	: Agency for Toxic Substances and Disease Registry
BTEX	: Benzene, toluene, ethylbenzene, xylene
C	: Fixed sampling cost
c_h	: Cost per population unit in the hth stratum
c_o	: Fixed overhead cost
C_w	: Concentration of chemical in water
CSM	: Conceptual site model
DDT	: Dichloro-diphenyl-trichloroethane
DEP	: Department of Environmental Protection
DMİ	: Turkish State Meteorological Service
DNAPL	: Dense non-aqueous phase liquid
d_r	: Relative error
DQA	: Data quality analysis
DRMO	: Defense reutilization and marketing office
DSİ	: General Directorate of State Hydraulic Works
EC	: European Commission
EPA	: Environmental Protection Agency
EPD	: Exposure pathway diagram
EU	: European Union
f	: Finite population correction factor
FIELDS	: Field Environmental Decision Support
f_{oc}	: Fraction of organic carbon associated with the soil
FTRT	: Federal Remediation Technologies Roundtable

G	: Grid size
GSQS	: Generic soil quality standards
K_d	: Soil-water partition coefficient
K_H	: Henry's law constant
K_{oc}	: Organic carbon partition coefficient
L	: Length of semi-major axis of the hot spot
LNAPL	: Light non-aqueous phase liquid
L_s	: Number of strata
METU	: Middle East Technical University
MoEF	: Ministry of Environment and Forestry
MSDS	: Material safety data sheet
MTA	: General Directorate of Mineral Research and Exploration
n	: Realistic sample size
N	: Target population number
NAPL	: Non-aqueous phase liquid
n_h	: Optimum number of samples
N_h	: Target population
PAH	: Polycyclic aromatic hydrocarbons
PCB	: Polychlorinated biphenyls
POM	: Particulate organic matter
R	: Radius
RAIS	: Risk Assessment Information System
S	: Expected shape of the hot spot
SADA	: Spatial Analysis and Decision Assistance
SPCR	: Soil Pollution Control Regulation
SSL	: Soil screening levels
SVOC	: Semi-volatile organic compounds
TOX	: Total organic halides
TPH	: Total petroleum hydrocarbons
TÜBİTAK	: Scientific and Technological Research Council of Turkey

TVOC	: Total volatile organic compounds
UK	: United Kingdom
US	: United States
W_h	: Relative sample size of hth stratum
WHO	: World Health Organization
V	: Prespecified value,
$Var(\bar{x})$	: Variance
VBA	: Visual Basic for Applications
VOC	: Volatile organic compound
V_p:	: Vapor pressure of the chemical
VSP	: Visual Sample Plan
VVOC	: Very volatile organic compound
β	: Consumer's risk
μ	: True mean over all N units in the population
μ_h	: True stratum mean
μ_i	: True value for ith unit.
η	: Estimate of coefficient of variation
σ^2	: True variance

CHAPTER 1

INTRODUCTION

1.1. Background

Soil is the thin layer of material covering earth's surface. It is a non-renewable natural resource, and contains mineral particles, organic matter, water, air and living organisms (EC, 2008). Soil has many important functions such as biomass production, storing, filtering and transforming nutrients and water, hosting the biodiversity pool, acting as a platform for most human activities, providing raw materials, acting as a carbon pool and storing the geological and archeological heritage. In its 2002 Communication "Towards a Thematic Strategy on Soil Protection", the European Commission (EC) identified eight main threats to which soils in the EU (European Union) countries are confronted. These are erosion, organic matter decline, contamination, salinisation, compaction, soil biodiversity loss, sealing, landslides and flooding (EC, 2006a).

As a consequence of rapid industrialization, soil pollution has become an important worldwide environmental problem since late sixties. A site where there is an anthropogenic and confirmed presence of dangerous substances of such a level that they expose a significant risk to human health or the environment is defined as a contaminated site (EC, 2006b). Main sources of soil pollution are: uncontrolled and inappropriate waste disposal, use of pesticides and chemical fertilizers in agriculture, leaks or spills during storage and transport of hazardous chemicals, and deposition of atmospheric pollutants to soil.

Soil and groundwater contamination originates from non-point (diffuse) or point sources. Non-point sources are more extensive in area. Soil pollution caused by pesticides and chemical fertilizers used in agricultural activities, deposition of atmospheric pollutants and urban runoff are potential diffuse sources of contamination. On the other hand, point sources include releases of contaminants from a discrete location such as; leaking underground storage tanks, waste disposal facilities and spills from ruptured or corroded storage tanks and transfer pipes at industrial sites (Boulding and Ginn, 2004). This study focuses on soil contamination due to point sources; thereafter contamination refers to contamination from point sources.

Soil pollution has been a public concern in Turkey in recent years because of very serious soil and groundwater contamination cases experienced in Turkey. In 1999 Körfez Earthquake, 6000 tones of acrylonitrile released from an acrylic fiber manufacturer (AKSA), located in Yalova. This release resulted in contamination of soil, surface water and groundwater. In 2004, at Batman Tüpraş Refinery, petroleum spilled to groundwater for some years caused a serious explosion at city center resulting in deaths, injuries and extensive environmental damage. In 2006, hundreds of drums containing hazardous chemicals and wastes illegally dumped in Tuzla region in İstanbul were discovered. This caused a great public reaction since content of many drums were not known and the site was very close to residential areas.

The requirements for proper management of contaminated sites in Turkey are: legal instruments, implementation of a suitable management system, political determination, expertise and technological capacity. Soil Pollution Control

Regulation (25831/2005) focuses mainly on agricultural use of sewage sludge and does not include any proper management tools or strategies for contaminated sites. In terms of political determination, initiative of the Ministry of Environment and Forestry (MoEF) of Turkey is encouraging since the beginning of 2000s. Expertise in soil contamination and remediation is limited to a few consulting companies. Moreover, there is lack of experience and technological capacity in terms of field and lab investigations and site cleanup implementations.

In order to fill the gaps in terms of legal instruments and management system, a project has been completed at Middle East Technical University (METU) Environmental Engineering Department. The project is called "Development of an Environmental Management System for Sites Contaminated by Point Sources" and funded by the Scientific and Technological Research Council of Turkey (TÜBİTAK). The information on the project presented in this section is gathered from TÜBİTAK-KAMAG (2009). The main objective of the project was to develop a sustainable management system and its associated methodologies and tools for the MoEF. The outputs of the project can be listed as: (i) Contaminated Sites Management System, including methodologies and tools for identification, registration, investigation, assessment, classification and remediation of contaminated sites in Turkey, (ii) web-based information system which is used in the preliminary site assessment and serves as a data base for contaminated site inventory, (iii) Soil Pollution Control Regulation (SPCR) as a main legal document for management of contaminated sites, consistent with the EU Soil Framework Directive. Regulation will mainly include a clear definition of 'contaminated site', soil quality guideline values for contaminants, bureaucratic mechanisms for management of contaminated sites, and Technical Guidance Documents for site characterization and sampling, risk assessment, and remedial investigation, planning and monitoring. Hereafter, newly proposed SPCR is termed as SPCR throughout the text.

Conceptual site model (CSM), which is the main focus of this study, is an important and useful tool in management of contaminated sites. In order to make the concept clearer, the proposed management system which is given in SPCR is explained briefly in the following paragraphs.

The contaminated sites management system, developed by METU team, is comprised of four main phases: (i) identification and registration (inventory), (ii) preliminary assessment, (iii) detailed assessment and (iv) remediation. The general flowchart of the management system is given in Figure 1.1.

The management system begins with identification and registration system which ensures registration of sites and development of an inventory for contaminated sites. Considering the potential polluting activities in Turkey, a list called “polluting industrial activities” is developed. The industrial facilities that are engaged with these kinds of activities are included in the list of potentially contaminated sites. Any potentially contaminated site may be classified as a “suspected site” as a result of several mechanisms: (i) assessment of the information form presented by site owner, (ii) regular or irregular inspections conducted by provincial authorities of MoEF, (iii) natural disasters, (iv) industrial accidents, and (v) personal or institutional notifications. If an industrial facility is subjected to any notification; or spill/leak occurred as a result of an accident/disaster (e.g. earthquake); or a suspicious situation is discovered at the facility, the site is included in the suspected site list. Orphan sites, for which the owner of contamination is unknown, may be included in the suspected sites list by means of notification.

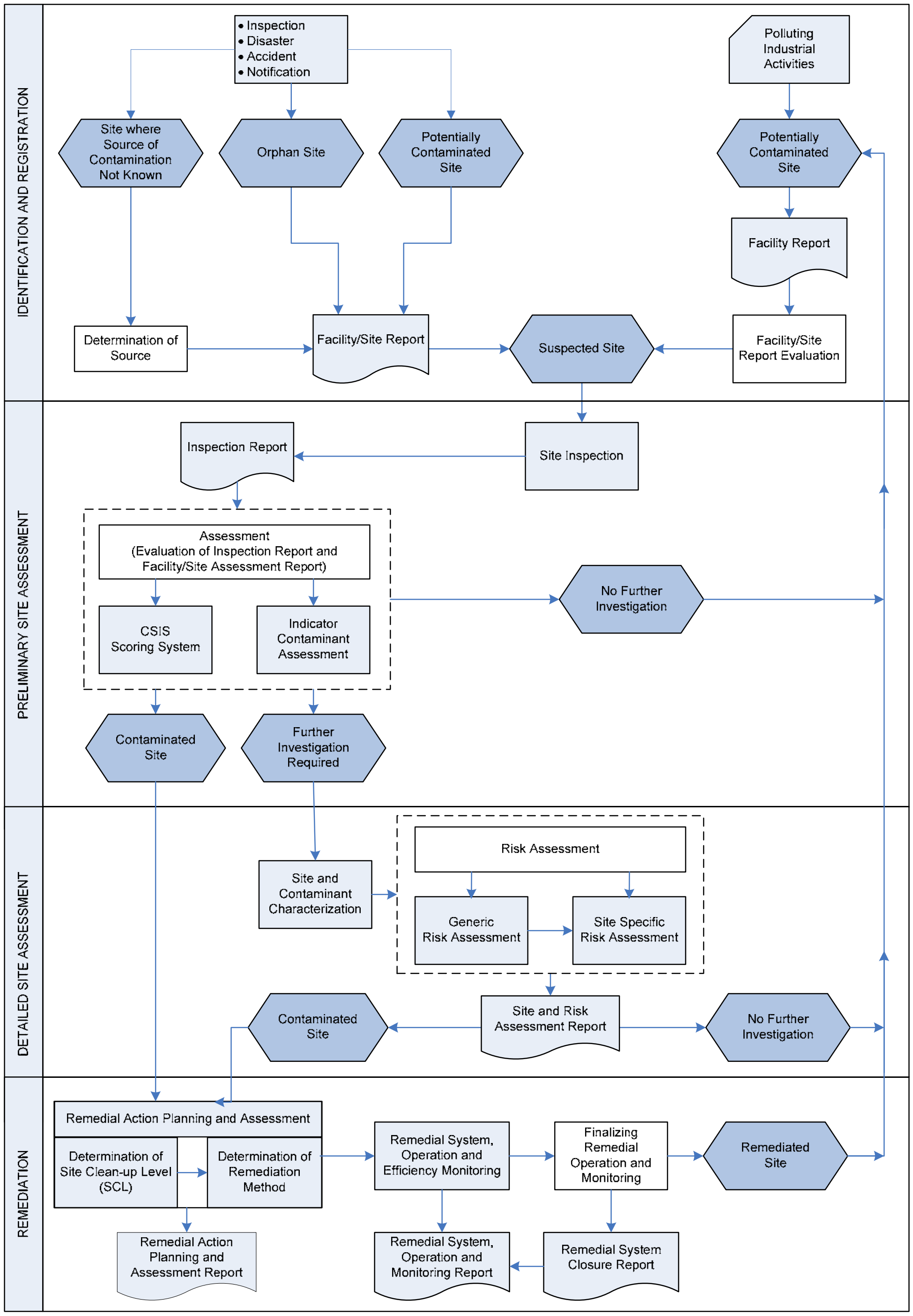


Figure 1.1 Management System for Contaminated Sites for Turkey (Adapted from TÜBİTAK-KAMAG, 2009)

All suspected sites are subject to preliminary assessment. The main aim of preliminary assessment is to determine whether the doubts of contamination is reasonably realistic or not, and to determine the need for detailed investigation. Site inspection is conducted by provincial authorities of MoEF by completing an inspection form. The inspection form is evaluated together with the information on site/facility via a web based scoring system.

If the source of contamination (e.g. chemical spilled) is not known, the scoring system is not used and indicator parameter analysis is performed. Indicator parameters are developed based on industrial sectors and used as indication of any contamination. These indicator parameters are TPH (total petroleum hydrocarbons), TOX (total organic halogens), BTEX (benzene, toluene, ethylbenzene, xylene), TVOC (total volatile organic compounds), oil and grease and heavy metals. For each industry, the corresponding indicator parameters are listed.

There are three possible results of preliminary assessment at a contaminated site:

(i) no further investigation → the site should be kept in inventory

(ii) further investigation → detailed site assessment should be performed

(iii) remediation → remedial investigations and cleanup activities should be started immediately.

Detailed site assessment has three main steps: site and contamination characterization, generic risk assessment and detailed risk assessment. In site and contamination characterization; historical data and information is collected, CSM is developed, all possible source-pathway-receptor links are identified. Contaminants of concern are identified and surface soil and subsurface sampling is carried out and contaminant concentration is determined. Groundwater sampling is performed in order to determine whether groundwater contamination exists or not.

In generic risk assessment, contaminant concentration measured at the site is compared with the Generic Soil Quality Standards (GSQSs) for pathways defined in generic scenario which includes ingestion and dermal absorption, inhalation of fugitive dusts, inhalation of volatiles, and ingestion of groundwater. If contaminant concentration exceeds GSQSs, then further assessment decision is made and site-specific risk assessment starts for all potentially open pathways. Other possible exposure pathways are also identified in this phase.

In site-specific risk assessment phase, site-specific information is collected. Site-specific risk levels are calculated based on intake of contaminants through the corresponding exposure pathways. If the risk level is greater than the target risk level, the site is classified as contaminated and it needs to be remediated.

In remediation phase, risk-based site clean-up level is determined, all applicable remedial technology alternatives are identified and the most appropriate technology satisfying the remediation goal is selected. After design and construction of the selected remedial technology, effectiveness of remediation should be monitored.

Developing a management system was a necessity in order to systematically identify, register, investigate and remediate the contaminated sites in Turkey. This management system includes many stages for which making correct decisions is very important. Especially in detailed site assessment phase, which includes identification of source, potential exposure routes, receptors and contaminant distribution, decision making is very critical for the progress of the studies. Moreover, since management of contaminated sites is a new issue in Turkey, there is a lack of experienced personnel. Therefore, the site assessors should be guided by the help of decision support tools in order to provide a sustainable management system.

Detailed site assessment is a very critical and crucial stage for management of contaminated sites. For proper management of contaminated sites; the source, type and nature of contamination should be identified and characterized accurately during detailed site assessment phase. The level and extent of site characterization may range from very simple to highly complex, depending on the contamination case under consideration.

Developing a CSM is a very useful and essential tool for detailed site assessment. CSM is basically a description of environmental conditions at a contaminated site and its surrounding area. CSM is used in all stages of detailed site assessment, mainly site characterization and sampling. Development of CSM can be complicated because it is highly ‘case specific’; there is no single route to follow; there are many questions to be answered and every single answer affects the subsequent steps to be followed. Furthermore, type and extent of information needed varies according to the size and level of contamination and site heterogeneity.

1.2. Objective and Scope

The objective of this study is to develop a decision support tool that will guide the engineers in the process of developing CSM for contaminated sites. This decision support tool is based on the relationship between the procedures followed for CSM development and stages of contaminated sites management system, especially site investigation and sampling.

One of the main objectives of this study is to form a guidance for site investigators. For this purpose, a detailed literature review on sampling design types is presented. After introducing the most common sampling design types, a decision tree is developed which helps site investigators to select the most appropriate sampling design type.

Moreover, development of various tools that can be used in a systematic manner for CSM building was also aimed. In this respect, an information collection form, illustrative tools and exposure pathway diagram (EPD), are introduced in this study. A CSM form is developed which is also suggested to be used by site assessors while collecting data and information during site characterization. Necessary information on site, geology, hydrogeology and hydrology, source of contamination, contaminants and receptors is identified with the help of CSM form. Illustrative tools basically indicate possible sources, exposure pathways, receptors and their linkages. They may vary from very simple site sketches to very complex 3D visualizations depending on the needs. Exposure pathway diagram is used to identify all possible exposure pathways that should be considered. This diagram includes all possible exposure pathways; not only the ones that are defined for generic soil quality standards but also other exposure pathways. Exposure pathway diagram which is developed within the scope of TÜBİTAK KAMAG project mentioned above, is embedded to a decision assistance tool using Microsoft Excel and Visual Basic for Applications (VBA)

Developed methodology is applied to two case studies in order to visualize the CSM tools and demonstrate the utility and applicability of the decision support tools. Methodology developed in this study for CSM building is consistent with the main concepts of contaminated sites management system developed for Turkey.

The thesis is organized into the following chapters. Chapter 2, Literature Review, presents the literature on conceptual site model, sampling for site investigation and sampling design for site investigation. Chapter 3, Development of Methodology, presents the relationship and information flow between CSM and SPCR processes, decision tree for sampling design and CSM Tools. In Chapter 4, developed methodology is applied to two case studies. Finally, Chapter 5, Conclusions and Recommendations, provides the conclusions and suggests topics for future research.

CHAPTER 2

LITERATURE REVIEW

2.1. Conceptual Site Model

A conceptual site model is a simplified description of environmental conditions at a contaminated site and the surrounding area, which provides all interested parties with a vision of the site. It depicts information about likely contaminants, pathways and receptors and highlights key areas of uncertainty (Nathanail and Bardos, 2004). In general, a CSM is prepared for the purpose of helping the site assessors to better understand what is currently known about the site conditions and where there may still be significant data gaps. The process of developing a CSM will help identifying areas within the site where significant uncertainty still exists. Areas showing significant uncertainty should be identified as data gaps that needed to be filled (Byrnes, 2009). The importance of CSM should not be underemphasised in describing initial views about the risks likely to be posed by site, and guiding any additional data collection effort (UK Environment Agency, 2000).

A CSM can be presented in a variety of ways but usually comprises pictures, diagrams, maps, tables and text. Typically, it comprises a plan and cross-section of the site together with text to amplify the information presented in the figures. It may also include block diagrams or occasionally mathematical models. The common feature is that the CSM highlights the essential issues at the site.

(Nathanail and Bardos, 2004). A CSM may be prepared in a tabular and/or graphical format that identifies the contamination sources, contaminant release mechanisms, pathways for contaminant migration, exposure routes and potential receptors (Byrnes, 2009).

According to Nathanail and Bardos (2004), CSM can be used for several purposes:

- To collect the information gathered during desk studies, site inspections and site investigations.
- To guide further investigation; in creating the model, the gaps in information quickly become apparent. These are then translated into the aims of the (next stage of) investigation.
- To aid interpretation of results.
- To assist with monitoring changes over time; the model can be amended as evidence of the spread of reduction in contamination becomes apparent.
- To provide a format for communicating the results of the investigation to all stakeholders; the CSM captures the essence of the site allowing the key issues to be explained.
- To identify the risks present at the site.
- To scope the risk assessment.
- To develop remediation strategies.
- To verify that remediation has broken all source-pathway-receptor pollutant linkages.

Table 2.1 shows the stages to be followed during developing and updating a CSM.

Table 2.1 Stages of CSM development (Nathanail and Bardos, 2004)

Stage	CSM
Desk study	Produce hand-drawn plan and cross-section and list likely sources prior to carrying walkover
Walkover	Produce a report quality conceptual site model comprising plan, cross-section, text and network diagram
Site investigation	Add details on nature of sources and pathways
Monitoring	Add information to reflect changes; may need to create additional diagrams to show change over time
Remediation	Add information to reflect changes

The type and extent of information needed changes according to condition of site and contamination. The CSM should be first prepared by searching history of activities at the site and surrounding area and performing a site visit. Desk-based search may provide a good understanding of the contamination. Table 2.2 summarizes how to benefit from certain information obtained from desk-based research such as information on historical and current uses of the site or land use.

The content of CSM should reflect the site conditions and its extent should change according to complexity of contamination. Nathanail and Bardos (2004) reports that the requirement for diagrams (plan, cross-section and network diagram) may vary according to the site. For instance, for a site where there is only one source with few pathways a network diagram may be sufficient.

Table 2.2 Examples for benefiting from desk-based research (UK Environment Agency, 2000)

Desk-based research	**Benefit**
Desk-based research on historical and current uses of the site and surrounding land	- type of hazardous substances likely to be present - their possible locations and likely physical form
Land use information (including future uses)	- key receptors that occupy or are in close contact with the site (e.g. householders, animals and plats, nearby surface waters) - associated pathways (e.g. soil ingestion, inhalation of dust)
Information on geological, hydrogeological and ecological settings	- other possible pathways and receptors that may be located some distance away from the site (e.g. migration of gases through permeable strata towards a nearby housing estate, leaching of soluble contaminants from the site soils into groundwater and towards a nature reserve)

Moreover, Nathanail and Bardos (2004) suggest using different colours for sources, pathways and receptors on plans or cross-sections. Sources should be marked in red in order to reflect danger. Pathways should be marked in orange to reflect the fact that the contaminant travels through the pathway and the concentration is usually less compared to that at the source. Different colours can be used for receptors: brown for human, blue for water, green for ecological systems, crops and livestock and grey for buildings and structures.

Development of conceptual site model is the first step of soil screening process of US (United States) EPA (Environmental Protection Agency) (US EPA, 1996b). CSM is expected to provide the information necessary to determine the applicability of Soil Screening Levels (SSLs) to the site and to calculate SSLs. Moreover, CSM identifies data gaps and helps focus data collection and evaluation on the site-specific development and application of SSLs. Attachment A of Soil Screening Guidance document (US EPA, 1996b) introduces the content of CSM in four summary forms, worksheets and CSM diagram. Table 2.3 summarizes the content of CSM used for US EPA soil screening process. Nathanail and Bardos (2004) presents the contents of CSM based on American Society for Testing and Materials (ASTM) E1689-95 as summarized in Table 2.4.

Table 2.3 Content of CSM used for US EPA soil screening process

Contents	Key information to include
General site information	• Name, location and status of the site • Past and current activities • Previous investigations
Site characteristics	• Hydrogeologic characteristics: hydrogeologic setting, aquifer parameters (hydraulic conductivity, hydraulic gradient, thickness) • Direction of groundwater flow across the site • Infiltration rate • Meteorological characteristics
Exposure Pathways and Receptors	• Land use conditions (current, surrounding and future land use) • Contaminant release mechanisms (check all that apply) • Media affected (or potentially affected) by soil contamination. • SSL exposure pathways applicable at site, basis for not including any pathway, other exposure pathways
Soil Contaminant Source Characteristics	• Name, type, location, depth and area of sources • Description of history of contamination and past/current remedial or removal actions • Contaminant types • Average soil characteristics (average water content, fraction organic carbon, dry bulk density, pH)
Worksheets	• Contaminant-specific properties necessary to calculate SSLs (chemical properties, regulatory and human health benchmarks) • Contaminant concentrations by source • Surface SSLs by exposure area (for ingestion, other (plant uptake; fugitive dust)) • Subsurface SSLs by source (inhalation of volatiles, migration to ground water)
CSM Diagram	• a product of CSM development that represents the linkages among contaminant sources, release mechanisms, exposure pathways and routes, and receptors to summarize the current understanding of the soil contamination problem.
Maps, site sketch	

Table 2.4 Content of CSM based on ASTM E1689-95

Contents	Key information to include
Site summary	• Outline of site history and current site conditions • Main sources of contamination • Potential (significant) pollutant linkages
Description of site and surrounding area	• Summary of previous site uses • Contaminative uses on or near to the site current and future operations
Geology including possible variations across site	• Geological strata and their significance in terms of source, pathway and receptor • Evaluation of likely pathways via underlying geological sequence
Hydrogeology including possible variations across site	• Aquifer classification of each geological stratum and comments on likely permeability • Position of water table(s) • Groundwater flow direction • Surface/groundwater interaction (discharge/recharge zones) • Anthropogenic alterations (e.g. buried utilities, drainage systems, pumping wells, under-ground storage tanks, former foundations)
Information source	• Stage of investigation • Amount of investigation carried out • Media investigated (soil / water / gas)
Ground conditions	• Materials encountered • Depths to and thicknesses of materials • Lateral extent of materials
Source identification	• Details of substances and properties known, likely or suspected of being present
Source characterisation	• Contamination: soil, leachable soil, groundwater, surface water, gas • Locations on site • Contaminant properties (solubility, volatility, density, tendency to sorb, toxicity) • Contaminant phases (solid, sorbed, gas, aqueous, light non-aqueous phase liquid (LNAPL), dense non-aqueous phase liquid (DNAPL)) • Summary of concentrations; and reference appropriate guideline values

Table 2.4 (continued) Content of CSM based on ASTM E1689-95

Potential pathways	• Groundwater • Surface water and sediment • Vadose (unsaturated) zone • Drains / service runs • Air (dust, inhalation of vapours) • Direct contact (ingestion, dermal) • Plant uptake • Food chain
Potential receptors	• Groundwater, surface water • People (e.g. adult, child, worker, resident, visitor, trespasser) • Ecological systems • Property - crops and livestock, pets, buildings (including ancient monuments)
Potential (significant) pollutant linkages	• Consider potential linkages to each receptor in turn and explain reasons for acceptance or rejection • This evaluation greatly aided by use of pictures / diagrams
Risk drivers	• Substances that are likely to pose the most risk • Acute toxicity; non-threshold substances; threshold substances • High solubility; low solubility; persistence
Limitations	• Assumptions, uncertainties

Considering the contents for CSM proposed by two different approaches, which are presented above, it can be seen that the contents are very similar. Although there are some differences in the level of detail, both focus on introducing the source-pathway-receptor relationship.

Triad approach is a technical and scientific initiative developed with the support of US EPA to manage decision uncertainty for characterizing and remediating contaminated sites which emphasizes the importance of CSM. The elements of Triad approach are systematic project planning, dynamic work strategies and real-time measurement technologies. Managing decision uncertainties is critical since the decisions are based on data.

Triad approach offers an increase in decision confidence in addition to a decrease in cost by the help of conceptual site model. Crumbling (2004b) claims that Triad approach provides approximately 30-50% cost savings compared to traditional strategies for site characterization, remediation, and monitoring. In Triad approach, CSM is defined as a mental picture to base the decision that enables to predict and describe the nature and extent of the contamination as well as receptor exposure. A CSM uses all available historical and current information to estimate:

- where contamination is (or might be) located and how much is there,
- how variable concentrations may be and how much spatial patterning may be present,
- what is the fate and migration of the contaminants,
- who might be exposed to contaminants or harmful degradation products,
- what might be done to manage risk by mitigating exposure.

Due to many physical and/or chemical mechanisms, contaminant distribution is rarely homogenous. Heterogeneous contaminant distribution results in sampling uncertainty and decision errors. Knowledge of the physical mechanisms of contaminant release and migration can be used to predict contaminant locations and the degree of spatial patterning. These predictions form the basis for drawing up the preliminary CSM, which are then tested as data collection confirms, rejects, or modifies the current CSM. CSM should be refined as more information is collected (Crumbling, 2004b).

Accuracy of the decisions increase as CSM represent the actual situation more correctly. However, generating “representative” data is difficult when heterogeneous environmental media are involved. Firstly, role of data in the decision-making process should be understood. The intended decision indicates the target population for data collection and analysis. CSM also guides design of sampling and analysis plans to fill data gaps that precludes confident decision-making.

2.2. Sampling for Site Investigation

In order to prepare a guidance document for site investigators, a detailed review of literature on site investigation and sampling is conducted. A methodical summary of the conducted literature review on site investigation and sampling design types is presented in Sections 2.2 and 2.3.

Site investigation is very crucial for management of contaminated sites. Adequate and accurate data should be collected through sampling to meet the requirements of each specific contamination case. Objectives of sampling should be set clearly. Some examples to sampling objectives are to:

- determine the site characteristics
- determine the source of contamination
- determine the nature and extent of contamination (e.g. average or maximum contaminant concentration; or contaminant plume)
- monitor trends in environmental conditions or indicators of health
- identify potential migration routes and exposure pathways
- determine if there are any receptors that are or/may be exposed to contaminant of concern (Nathanail and Bardos, 2004; Byrnes,2009).

The main objective of site investigation is to characterise sources, pathways, receptors and their linkages. To achieve this objective, the development of CSM is essential. The limitations and uncertainties of CSM that is developed by desk study and visual inspection should form the base for site investigation. Likelihood of possible sources, pathways and receptors that are identified in CSM should be investigated in detail (Nathanail and Bardos, 2004). Site investigation should be planned according to the site in consideration, i.e. it is site specific, because, the parameters or media to be investigated varies according to characteristics of contaminant and/or contamination.

There are two main groups of site investigations: non-intrusive and intrusive. In order to select the appropriate method, following factors should be considered: contaminants of concern, analyses to be performed on samples, type of sample being collected (i.e., grab, composite, or integrated), sampling depth, clay content of the soil, moisture content of the soil, approximate depth to groundwater and aquifer characteristics (Byrnes, 2009). Some examples of both investigation methods are listed in Table 2.5.

Table 2.5 Some examples of intrusive and non-intrusive investigations (Byrnes, 2009 and Nathanail and Bardos, 2004)

Non-intrusive investigations	**Intrusive investigations**
- Aerial photography - Surface geophysical surveying - Surface radiological surveying - Electromagnetic profiling - Resistivity - Microgravity - Seismic - Infrared thermography - Airborne gamma spectrometry - In-situ gamma spectroscopy - Ambient air sampling	- Soil gas surveying - Shallow and deep soil sampling - Sediment sampling - Surface water and deep soil sampling - Groundwater sampling - Building material sampling - Tank, drum or container sampling - Pipe surveying - Remote surveying

2.2.1. Non-intrusive Investigations

Non-intrusive techniques are non- or minimally invasive and they aid detecting variations in the ground base on contrasts in physical and chemical properties (Nathanail and Bardos, 2004) (i.e. they do not require physical penetration of the ground surface (Byrnes, 2009). Non-intrusive investigations should be considered before sampling environmental media, since it can provide an optimum positioning of the intrusive sampling points (Byrnes, 2009). By the help of non-intrusive sampling, large areas can be covered in a relatively short time (Nathanail and Bardos, 2004). Furthermore, these methods are cheaper when compared to obtaining same data by collection and analysis of individual environmental samples (Byrnes, 2009).

2.2.2. Intrusive Investigations

Intrusive methods usually require the penetration of ground or water surface. Accessibility, cost, the nature of the contamination, ground conditions and the depth to investigate are the factors to be considered when selecting the technique for obtaining the samples (Nathanail and Bardos, 2004).

Gilbert (2006) states that there are four main sample types for intrusive methods: grab samples, composite samples, swipe samples and integrated samples. Swipe samples are not covered in this study since they are used to determine the amount of removable radioactivity from a surface (Byrnes, 2009). Grab samples, composite samples and integrated samples are explained further in the following paragraphs.

<u>Grab samples</u>: A grab sample is physical collection of a media sample from a single location for analysis. Grab samples should be used when the objective of

sampling is determining the range of concentration levels (minimum and maximum) for a contaminant at a site. Grab samples are effective in collecting samples for site characterization, waste characterization, risk assessment, remedial design and post-remediation confirmation (Byrnes, 2009).

Composite samples: Composite samples are prepared either by collecting multiple grab samples from different locations or, by collecting sample from different depths from the same sampling location and homogenizing these depth intervals together for analysis. Composite sampling provides the mean concentration level at a site and it tends to dilute the analytical results. Therefore, composite sampling results cannot be interpreted as a reliable estimate of the range of concentration levels. Composite samples should be used for site characterization to reduce costs and in some cases for waste characterization. However, composite samples cannot meet the needs of sampling studies performed for risk assessment or site-closeout (Byrnes, 2009).

Integrated samples: Integrated sampling is collection of a sample from same location over an extended period of time. Integrated samples are usually performed for assessment of surface water, groundwater or air quality over time. Integrated samples should not be used for sampling volatile organic compounds (VOCs) (Byrnes, 2009).

2.2.3. Depth-wise Sampling

Determining the depths from which samples are obtained should be based on CSM and judgement of site assessors. Previous information on likely sources, exposure pathways and receptors guides the determination of sampling depths. Shallow samples are collected if likely receptor is people and likely exposure pathways are ingestion of soil or dermal contact. On the other hand, sampling deeper in the unsaturated zone may be required in order to identify the impact on groundwater (Nathanail and Bardos, 2004). Site assessor should take into account the following factors while selecting the sampling depths (UK Environment Agency, 2000):

- appearance, color and odor of the strata and other materials, and changes in these;
- presence or absence of subsurface features such as pipes, tanks and foundations;
- areas of obvious damage, e.g. to the building fabric.

According to Bardos *et al* (2004), for most scenarios, a minimum of 2-4 soil samples should be taken through the soil profile with at least one sample being in natural strata. If contamination has penetrated the natural strata, sampling should continue to depths at which contamination is suspected to be at background concentrations or it is physically impossible to sample. Moreover, in US EPA (1996b), site boundary to investigate in terms of depth is specified as 'depth of contamination or to the water table, whichever is more shallow'.

Nathanail and Bardos (2004) states that sampling depths should be considered for all three media: soil, water and gas/vapour and introduces suggested sampling depths for all. For soil, suggested sampling depths are given according to exposure scenario. Suggestions for sampling depths for soil, groundwater and gas media are given in Table 2.6. Moreover, in UK Environment Agency 2000, basis for sampling at depths 0 – 0.5 m and >0.5 m is given. According to this document, sampling depths up to 0.5 m can be applicable to assess

- human/animal intake arising from ingestion and dermal contact,
- potential for wind entrainment leading to inhalation (of contaminated soils and dusts) or deposition onto neighbouring land,
- surface water run-off (e.g. due to flash flooding),
- uptake by shallow rooting plants (e.g. crops, ornamental and wild species), and
- surface leaching to groundwater.

Table 2.6 Suggestions for sampling depths for soil, groundwater and gas media (Nathanail and Bardos, 2004)

Soil	
Direct ingestion or dermal contact	→ surface soil / top 0.15 m
Ingestion via vegetable uptake	→ 0.3 -0.5 m
Ingestion, dermal or inhalation due to activities at depth, e.g. excavations or foundations	→ to anticipated depth of penetration
Inhalation of volatile contaminants	→ to extent of gas permeable ground
Downward migration of contaminants to groundwater	→ at a range of depths (often at fixed intervals of 0.5 or 1.0 m) to prove extent of contamination; → immediately above the water table (as poorly soluble compounds tend to concentrate in the capillary zone); → usually there should be sufficient sampling to prove the depth where the material is uncontaminated
Penetration of plastic pipes;	→ at depths at which pipes are likely to be present
Deterioration of construction materials	→ ground in contact with construction materials
Contamination threatens ecosystems (a protected habitat, e.g. RAMSAR site)	→ soil supporting, or that should be supporting, feature of interest or earthworms (surrogate for ecosystem health)
Groundwater	
Based on defining the zone in which the well screen be placed (screened section should not be longer than 3 m). Factors that should be considered for screens: • in the vicinity of the water table to test for the presence of NAPL (Non-aqueous Phase Liquid) • sufficiently below the water table to ensure there is sufficient water for sampling • at depths likely to intersect contamination migration at depth • above likely base of aquifer to intercept DNAPLs	
Gas/Vapor	
Gas sampling or monitoring depths are determined by the zone in which well screen is placed. The screen should be placed: • at depths likely to intersect source • at depths likely to intersect migration pathways Exposure scenarios to be considered: • inhalation of gases/vapour by people explosion leading to death of people and damage to buildings	

Sampling soil deeper than 0.5 m is applicable;

- to assess
  - intake via ingestion/inhalation/dermal contact arising from 'abnormal' (or unpredicted) excavation (e.g. children digging dens) or for other purposes such as
  - swimming pools, ponds, house extensions
  - uptake by deep rooting shrubs and trees
  - intake by, or arising from, the activities of burrowing animals
  - intake arising from construction/maintenance of buildings and services, for example foundations (usually within 2m of final formation level); water supply pipes, telecommunications, gas & power (0.5 – 1m of final formation level) and sewers (from 0.5 – 1m of final formation level);
- to locate perched water or groundwater
- to confirm depth of made ground
- to locate possible lateral pathways for gas or vapour migration in made ground
- to establish extent of any leaching of soluble constituents from superficial soils
- to detect 'deep' contaminants (e.g. gas generating materials, leachable materials, dense
- solvents located on top of an impermeable stratum)
- to obtain information on 'background' soil properties
- to locate 'natural' lateral migration pathways.

Depth-related information presented in cross-sections is valuable for assessment of migration pathways. However, this type of information is not useful for declaring contaminant distribution or behaviour of sub-surface environment (UK Environment Agency, 2000).

2.3. Sampling Design for Site Investigation

Sampling design identifies the number, type, location and timing of samples including the explanations and justifications for all decisions. Sampling design should be based on the objectives of site investigation and on the uncertainties identified in CSM (Nathanail and Bardos, 2004). A good sampling design should be cost-effective, i.e. it should represent the actual condition of contamination with a minimum number of samples, thus with a minimum expenditure of resources.

Sampling strategy/design should include (Nathanail and Bardos, 2004):

- justification of selecting targeted or non-targeted sampling
- sampling objectives
- media to be sampled
- sampling locations
- number of samples to be collected
- sample depth
- sample storage and handling.

Although the sampling strategy is developed prior to field studies, site assessors should have some discretion on samples to be collected and sampling locations according to the overall sampling strategy and objectives of the sampling and information revealed as sampling proceeds (Nathanail and Bardos, 2004).

There are two main categories (which may also be used in combination) for sampling designs: targeted and non-targeted sampling designs. Sampling strategy should include the justification of selecting targeted or non-targeted sampling, or a combination of them, in addition to the sampling objectives. Applications, advantages and disadvantages of targeted and non-targeted sampling designs are summarized in Table 2.7. Following sections provide further explanation for targeted and non-targeted sampling designs.

In addition to targeted and non-targeted sampling designs, Gilbert (2006) introduces a third type: search sampling which is used for locating contamination sources or hot spots. Search sampling is discussed in Section 2.3.3, to locate hot spots.

2.3.1. Targeted (or judgemental) sampling

Targeted (or judgemental) sampling designs are developed based on available information and professional judgement. Targeted sampling is used when there is adequate information on the location or characteristics of contamination. Targeted sample designs are applicable for obtaining quick and effective confirmation of nature and presence of contaminants; for identifying the nature and likely direction of migration pathways and for confirming the presence or absence of contamination in a specific location (UK Environment Agency, 2000).

Judgemental sampling should not be used for collecting data in order to support site/ facility closeouts since these data does not provide statistical evaluation. Targeted sampling is usually used in combination with non-targeted sampling for site characterization because these data are often needed together for risk calculations, modelling studies, etc. (Byrnes, 2009).

Table 2.7 Applications, advantages and disadvantages of targeted and non-targeted sampling designs (US EPA, 2002a; Nathanail and Bardos, 2004 and Byrnes, 2009)

	Targeted sampling design	Non-targeted sampling design
Applications	- Based on professional knowledge - Applied for; - sites where the site assessor has reliable historical and physical knowledge, - relatively small scale features or conditions under investigation, - obtaining quick and effective confirmation of nature and presence / absence of contamination levels of concern, - sites where there is an urgency for investigation because of schedule or emergency considerations.	- Based on sampling theory - Applied for; - sites where there is insufficient information on the likely locations of the contamination - obtaining more representative data on the condition of entire site - areas where the distribution of contamination is expected to be homogenous
Advantages	- Can be very efficient with good priori information - Quick, cheap and easy to implement	- Provides ability to calculate uncertainty associated with estimates - Provides reproducible results within uncertainty limits - Provides ability to make statistical inferences - Can handle decision error criteria
Disadvantages	- Depends only on expert knowledge - Limits the statistical inference - Can not reliably evaluate precision of estimates (uncertainty can not be accurately quantified) - Depends on personal judgement to interpret data relative to study objectives	- Random locations may be difficult to locate - An optimal design depends on an accurate conceptual site model

2.3.2. Non-targeted (or probabilistic) sampling

Non-targeted (or probabilistic) sampling designs have a statistical basis and allow the site assessors to specify a confidence level. For non-targeted sampling designs, statistical theory is applied and identification of sampling units involves random selection (US EPA, 2002a). Non-targeted sampling should be used when there is not enough previous knowledge or when a site assessor aims to obtain more representative data on the condition of the entire site (UK Environment Agency, 2000).

Eliminating hot spots of given size to given confidence level, determining average concentration, standard deviation and 95th percentile upper confidence level for mean and identifying spatial distribution and confidence may be listed as some example cases where probabilistic sampling design can be used (Nathanail and Bardos, 2004).

2.3.2.1. Basic statistical concepts

In general, sampling provides an incomplete picture of the population since only a few of all possible samples are taken from the population (i.e., contaminated soil). As the data are incomplete, the population will not be represented exactly. This causes making an incorrect decision about the status of the population. Mean concentration can be used as a single number that represents the contaminant concentration although it will not give a complete picture of contaminant concentration for the site. A pattern would probably be observed, if measured concentrations from all possible samples were ordered from lowest to highest. For instance, there may be a few very low and a few very high concentrations, but the great majority of the concentrations could mass around a single value in the middle. This pattern can be represented graphically with a distribution diagram which is given in Figure 2.1 (Byrnes, 2009).

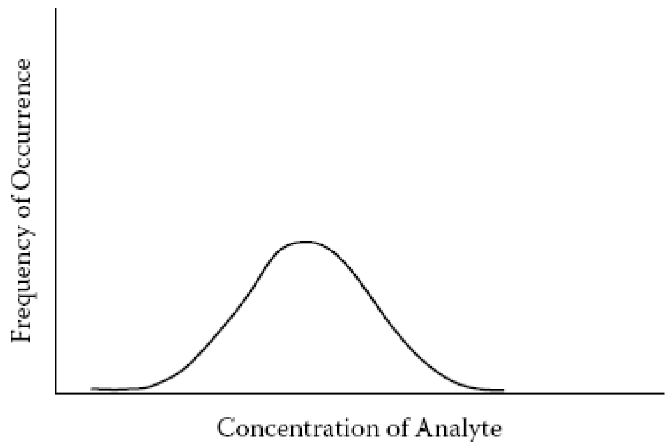


Figure 2.1 Graphical illustration of a distribution (Byrnes, 2009)

Distribution provides information that cannot be deduced from the mean alone. First, one can see the full range of measured concentrations. Second, it is often easier to define a central point around which most of the measured concentrations accumulate; i.e., roughly equivalent to the mean. Third, a distribution indicates how tightly grouped or how widely spread out the concentrations are. This is called the *level of dispersion* or *variance* in statistical terminology and can be determined by calculating the standard deviation or variance of all measured concentrations. Standard deviation has an important role in calculating the number of samples. If the variance of measured concentrations is low, then the mean of a few samples accurately represents the site. However, if the variance of measured concentrations is high, then the mean of a few samples are less likely to be representative.

In order to have a reasonable mean value, a subset of all possible samples should be selected and an estimate of the mean should be determined. There are several methods that are commonly used for selecting a subset of all possible samples and all methods have a probability of leading a decision error. Common sampling design types can be listed as:

- Simple random sampling
- Stratified sampling
- Systematic sampling
- Adaptive cluster sampling
- Two-stage sampling
- Multiple-stage sampling
- Ranked set sampling
- Double sampling
- Sequential sampling

Many different sources are reviewed and three most common design types are discussed within the context of this study: (i) simple random sampling, (ii) stratified sampling, and (iii) systematic sampling. Details are presented in the following sections. Figure 2.2 gives two-dimensional examples for some of the sampling design types mentioned above.

The most efficient sampling design type depends on the objectives, budget of the study in addition to amount of prior information. In some cases, sampling designs can be used in combination.

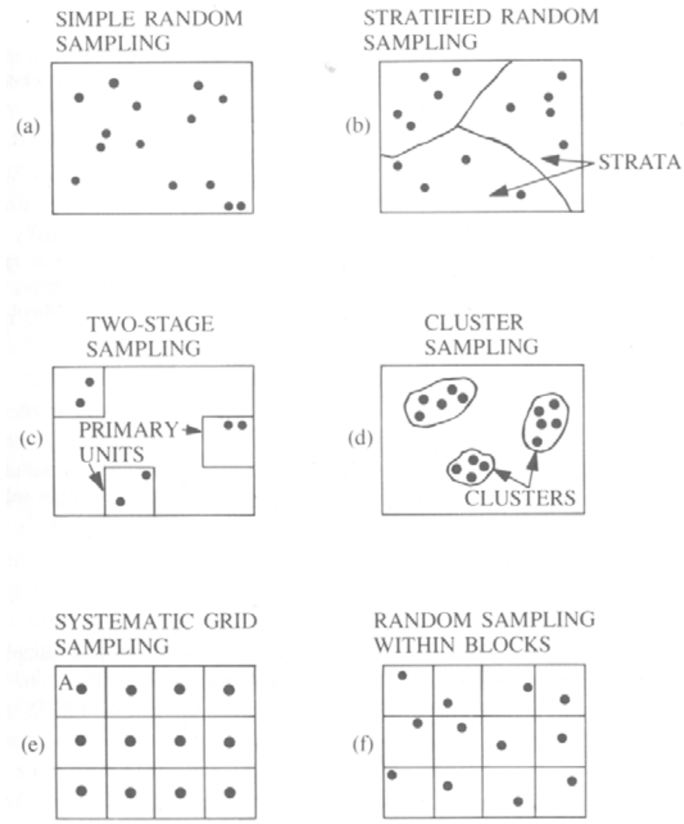


Figure 2.2 Some two-dimensional probability sampling designs (Gilbert, 2006)

2.3.2.2. Simple Random Sampling

Simple random sampling should be preferred when there is a little historical information about the site and contamination. Moreover, the population being sampled should be relatively uniform or homogenous; i.e., no major patterns of contamination or hot spots are expected. The site should be divided into areas of possible sampling units in order to implement simple random sampling. A number should be assigned to each sampling unit within the population. A subset of sampling units is then chosen randomly among the assigned numbers. Each of the sampling units assigned a number has an equal probability to be chosen for sampling. Inaccessible sampling units should not be assigned numbers (Byrnes, 2009 and US EPA, 2002a).

Advantages of simple random sampling are:

- It can be used when little or no historical data is available.
- It prevents bias by ensuring selecting of a sample that is representative of the sampling frame, provided that the sample size is extremely small.
- Procedures needed to select a simple random sample are simple.
- Statistical analysis of the data is relatively straightforward since most common statistical analysis procedures assume that the data were obtained using a simple random sampling design.
- Explicit formulae, tables and charts used for estimating minimum sample size are available.

Limitations of simple random sampling are:

- The number of samples needed may be relatively large.
- The sampling points may not be uniformly dispersed.

Assume a *target population* number of *N* and simple random sampling is used to select *n* of *N* units. If *N* is finite, the first step is to number the units from 1 to *N*. Then *n* integers between 1 and N may be selected using a *random number table*. Using a random number table ensures that every unselected integer has the same chance of being chosen. Details on using random number tables are given in Cochran (1977) and Gilbert (2006).

As discussed before, simple random sampling is advantageous when target population is homogenous and the aim is to estimate the mean and variance. The true mean of a population can be estimated from

$$\mu = \frac{1}{N}\sum_{i=1}^{N} \mu_i \tag{1}$$

where;

μ : true mean over all N units in the population,

μ_i : true value for ith unit.

The true variance, σ^2, of the N concentrations is

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(\mu_i - \mu)^2 \tag{2}$$

However, it is usually impossible or not feasible to measure all N units. For a realistic sample size, n; mean $\bar{x}$ and variance s^2 are computed from the data as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{4}$$

Random sampling error in $\bar{x}$ and $N\bar{x}$ is their variences $Var(\bar{x})$ and $Var(N\bar{x})$ which are;

$$Var(\bar{x}) = \frac{1}{n}(1-f)\sigma^2 \tag{5}$$

$$Var(N\bar{x}) = N^2 Var(\bar{x}) \tag{6}$$

$$= \frac{1}{n}N^2(1-f)\sigma^2$$

where f is finite population correction factor and it is equal to n/N.

Three approaches to determine number of samples (n) are presented in Gilbert (2006). Each approach is based on choosing n such that the estimated mean achieves a prespecified accuracy: variance, margin of error or relative error.

Prespecified Variance

Assume that $Var(\bar{x})$ must be smaller than a prespecified value, V. If $V = Var(\bar{x})$ is set in Equation 5,

$$n = \frac{\sigma^2}{V + \sigma^2/N} \tag{7}$$

If N is large relative to σ^2, Equation 7 reduces to

$$n = \frac{\sigma^2}{V} \tag{8}$$

If σ^2 is not known, it may be estimated by taking an initial set of n_1 and calculating s^2. Cox (1952) showed that enough additional samples should be taken so that the final number of measurements is

$$n = \frac{s^2}{V}\left(1 + \frac{2}{n_1}\right) \tag{9}$$

Prespecified Margin of Error

The absolute margin of error d that can be tolerated and an acceptably small probability α of exceeding that error can also be specified to estimate sample size. Sample size should be chosen such that; $Prob\ [|\bar{x} - \mu| \geq d] \leq \alpha$.

If V in Equation 8 is replaced by $(d/Z_{1-\alpha/2})^2$, where $Z_{1-\alpha/2}$ is the standard normal deviate that cuts of $(100\alpha/2)\%$ of the upper tail of a standard normal distribution; Equation 8 becomes

$$n = \left(Z_{1-\alpha/2}/d\right)^2 \quad (10)$$

Equation 9 is valid only if $\bar{x}$ is normally distributed. If the data is approximately normally distributed, but σ^2 is not known, t distribution is used. Then, $Z_{1-\alpha/2}$ should be replaced with $t_{1-\alpha/2,n-1}$, which is the value of t variable that cuts of $(100\alpha/2)\%$ of the upper tail of the t distribution with $n-1$ degrees of freedom. Since $t_{1-\alpha/2,n-1}$ depends on n, sample size should be determined by an iterative process. Details are explained in Gilbert (2006).

Prespecified Relative Error

If a reliable value for σ^2 is not available, but an estimate of coefficient of variation $\eta = \sigma/\mu$ exists; relative error $d_r = |\bar{x} - \mu|/\mu$ should be specified such that; $Prob\ [|\bar{x} - \mu| \geq d_r\mu] = \alpha$. Then Equation 10 becomes

$$n = \left(Z_{1-\alpha/2}\ \eta/d_r\right)^2 \quad (11)$$

where η is prespecified. Gilbert (2006) presents values of n calculated by Equation 11 for several values of α, d_r and η.

2.3.2.3. Stratified Sampling

Stratified sampling should be used when there is an obvious differentiation in terms of the investigated parameter (e.g. soil texture or contaminant concentration) throughout the site. Target population is divided into subgroups called strata, considering the prior information on the site. Each separate sub-group that are internally homogenous is sampled by simple random sampling (Gilbert, 2006). By forming strata that are as homogenous as possible, expected gain in efficiency will be maximized. In addition, stratified sampling can be used when the cost per sampling location varies significantly. In this case, inexpensive sub-area should be sampled more densely, or vice versa. Stratification is also a solution if separate estimates are required for sub-areas. Prior information should be analyzed carefully to make an optimal design (de Gruijter et al., 2006). Moreover, some physical factors such as topography, site boundaries, roads, rivers, etc. may also be determinent on stratification (Gilbert, 2006).

Advantages of stratified sampling are:

- Stratified sampling results in more representative sample compared to simple random sampling (US EPA, 2002a).
- This method may lead higher efficiency and lower cost if an appropriate stratification can be applied (de Gruijter et al., 2006).
- It provides a better control of accuracy for specific subareas of interest (de Gruijter et al., 2006).

Disadvantage of stratified sampling can be the fact that inappropriate stratification or allocation of sample sizes to the strata will decrease the efficiency when compared to simple random sampling (de Gruijter et al., 2006).
The overall mean μ for a population of N units in L_s strata and true stratum mean μ_h are

$$\mu = \frac{1}{N}\sum_{h=1}^{L_s} N_h\mu_h = \sum_{h=1}^{L_s} W_h\mu_h \tag{12}$$

$$\mu_h = \frac{1}{N_h}\sum_{i=1}^{N_h} \mu_{hi} \tag{13}$$

where N_h is the target population and $W_h = N_h/N = n_h/n$ is relative sample size of hth stratum.

Cochran (1997) describes a method to determine n_h, number of samples within the hth stratum, when the objective is obtaining the overall population mean μ

or population total $N\mu$. In this method, either the $Var(\bar{x}_{st})$ is minimized for a fixed sampling cost C or C is minimized for a prespecified $Var(\bar{x}_{st})$.

$$C = c_0 + \sum_{h=1}^{L_s} c_h n_h \tag{14}$$

where c_0 is the fixed overhead cost and c_h is the cost per population unit in the hth stratum. Then, the optimum number of samples n_h is obtained by

$$n_h = n \frac{W_h \, \sigma_h / \sqrt{c_h}}{\sum_{h=1}^{L_s} (W_h \, \sigma_h / \sqrt{c_h})} \tag{15}$$

where σ_h is the true population standard deviation for hth stratum. n is number of samples collected in all L_s strata and it can be calculated by prespecifying three different parameters: fixed cost, variance and margin of error in order to obtain n_h.

<u>Prespecified fixed cost</u>

If total cost C is prespecified, n can be calculated by

$$n = \frac{(C - c_0) \sum_{h=1}^{L_s} (W_h \, s_h / \sqrt{c_h})}{\sum_{h=1}^{L_s} (W_h s_h \sqrt{c_h})} \tag{16}$$

where s_h is square root of variance of the n_h measurements in stratum h, s_h^2, and it is obtained from prior studies. c_0 represents overhead costs and $C - c_0$ represents the money available for collecting and measuring samples excluding overhead costs.

<u>Prespecified variance</u>

If $Var(\bar{x}_{st})$ is fixed to V, n is obtained by

$$n = \frac{\left(\sum_{h=1}^{L_s}(W_h s_h \sqrt{c_h})\right) \sum_{h=1}^{L_s}(W_h\, s_h / \sqrt{c_h})}{V + \frac{1}{N} \sum_{i=1}^{L_s} W_h s_h^2} \tag{17}$$

Prespecified margin of error

If margin of error $d = |\bar{x}_{st} - \mu|$is prespecified to a tolerable and a small probability α of exceeding that error, n is obtained by

$$n = \frac{Z_{1-\alpha/2}^2 \sum_{h=1}^{L_s} W_h\, s_h^2 / d^2}{1 + Z_{1-\alpha/2}^2 \sum_{h=1}^{L_s} W_h\, s_h^2 / d^2\, N} \tag{18}$$

2.3.2.4. Systematic/Grid Sampling

Unlike the sampling designs discussed so far, systematic sampling does not use a random selection method for choosing sampling units; they are selected systematically in a specific pattern (Gilbert, 2006). Systematic sampling generally covers both sampling over time and over space. However, systematic sampling over time is not covered within the context of this study. According to US EPA (2002a), systematic sampling is advisable in three situations:

(i) To make an inference about a population parameter; results are more efficient if the target population are correlated,

(ii) To estimate a trend or to identify a spatial correlation; trends or correlation can be estimated efficiently since there is a constant distance interval between sampling locations,

(iii) To look for a “hot spot” or to make a statement about the maximum size object that could be missed. Details are discussed in Section 2.3.3.

According to US EPA (1989a), systematic sampling should be avoided when the pattern of contamination is likely to have a cyclic or periodic pattern across the sample area (e.g. waste placed in trenches) because, systematic sampling design may capture only high (or low) values of the contaminant resulting in biased results.

Systematic sampling is achieved by using grids over the space. There are three aspects considered for design of a systematic sampling plan: the shape of grid cells, the size of grid cells, and the direction of the grid. There are three options for grid shape; square, triangular and hexagonal (Figure 2.3). Although the precision of triangular grids is high, operational easiness of square grids prevail and makes square grids the most common grid shape. Grid size can be defined as the distance between adjacent grid nodes and it is determined according to sample size n. Direction of the grid indicates the geographical orientation of the grids (de Gruijter et al., 2006).

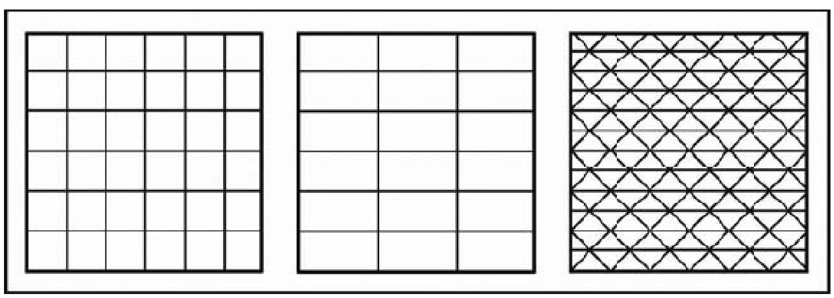


Figure 2.3 Some systematic sampling design options according to grid shapes: square, rectangular and triangular grids (Byrnes, 2009)

Grid designs:

Square grid designs are the most common systematic designs. According to Gilbert (2006), aligned and central square grids are the easiest ones to design and implement (Figure 2.4).

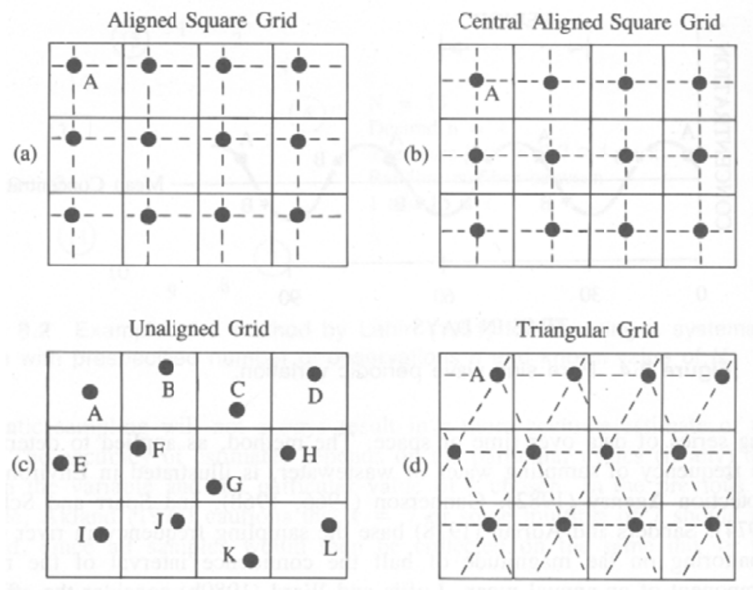


Figure 2.4 Some systematic sampling design patterns (Gilbert, 2006)

Unaligned gridding is proposed by de Gruijter et al. (2006). A random x coordinate is generated for each row of strata, and a random y coordinate for each column. The sampling location in a stratum is then found by combining the coordinates of its row and column.

Ferguson (1982) discusses the efficiency of square grid, stratified random, unaligned grid and simple random sampling designs and concludes that an efficient sampling design should be stratified; have only one sampling location in each strata; be systematic; and unaligned.

Another pattern called the herringbone pattern (Figure 2.5) was devised and after several analyses, it is argued that the herringbone grid design is the most efficient design in terms of required sample size for a specified probability of success to hit a hotspot, or vice versa (Ferguson, 1982).

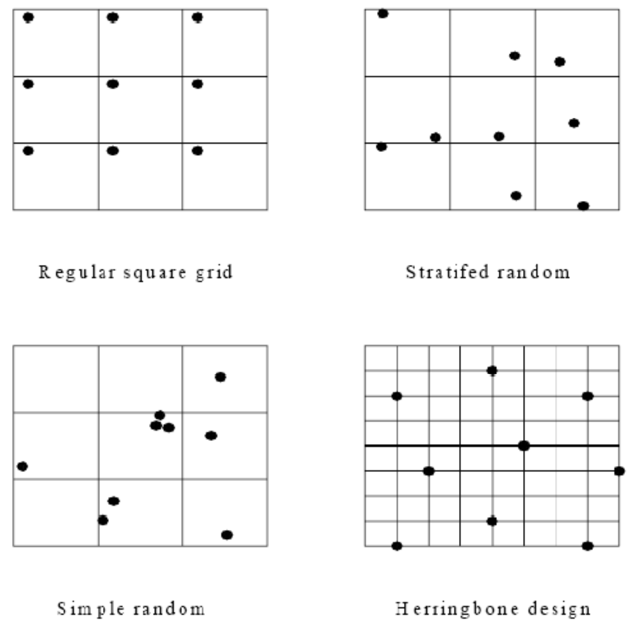


Figure 2.5 Examples of different sampling patterns (UK Environment Agency, 2000)

Advantages of systematic sampling can be listed as:

- Systematic sampling provides more complete spatial coverage, better precision and a corresponding decrease in the required sample size. (de Gruijter et al., 2006; US EPA, 2002a and US EPA, 1989a)
- Easy and straightforward to design and implement in practice (Gilbert, 2006 and US EPA, 2002a)
- Grid designs can be implemented with little or no prior information (US EPA, 2002a)
- Time required to locate consecutive locations in the field may reduce depending on the regularity of the grid depending on the scale, the accessibility of the terrain and the navigation technique used (de Gruijter et al., 2006).

Limitations are:

- Systematic sampling is not as efficient as other designs in the presence of prior information.
- Unbiased estimate of the sampling variance can not be determined (de Gruijter et al., 2006).
- Total travel distance between sampling locations may be high since they are evenly distributed (de Gruijter et al., 2006).
- The sample size is usually determined randomly and this may result in high cost (de Gruijter et al., 2006).

Gilbert (2006) states that although the same formula for estimating the mean for random sampling can be used for systematic sampling; different formulas must usually be used to estimate the variance. Four designs that use systematic sampling and allow one to estimate an unbiased variance $\mathrm{Var}(\bar{\mathrm{x}})$ is discussed: (i) Multiple systematic sampling, (ii) Systematic stratified sampling, (iii) Two-stage sampling, and (iv) complementary systematic and random sampling. Moreover, Gilbert (2006) presents some approximations for estimating $\mathrm{Var}(\bar{\mathrm{x}})$ when a single systematic sample size of n has already been collected or the foregoing designs are not feasible.

Pattern of contamination at the site and the construction of systematic sampling affect the precision of sampling. On the other hand, the standard error of a mean based on systematic sampling is usually comparable to or less than the standard error of a mean based on simple random sampling of the same size. Therefore, using the sample size formulas provided for simple random sampling for systematic sampling will be a conservative approach for human health an environment (US EPA, 1989a). If systematic sampling is used to locate hot spots, sample size should be estimated as it is given in Section 2.3.3.

2.3.3. Search Sampling - Locating Hot Spots

Search sampling is used to locate pollution sources or hot spots of contamination. Hot spots are defined as elevated concentration of contaminants (Australia DEP, 2001). Systematic grids are used to determine the location of highly contaminated local areas.

Following assumptions are valid for all discussions in this section:

1. Shape of the hot spot is circular or elliptical.
2. Square, rectangular or triangular grids are used.
3. Area sampled in grid points is only a small portion of the site.

Procedure to determine grid size is as follows (Gilbert, 2006):

- Specify the length of semi-major axis of the hot spot, L, that is intended to detect. L is equal to radius R if hot spot is circular.
- Specify the expected shape of the hot spot, S, i.e. length of short axis of the ellipse divided by length of long axis of the ellipse. S is equal to 1 for circular hot spot.
- Specify the consumer's risk β which is the acceptable probability of not finding the hot spot.

Figure 2.6 can be used to find grid size G. Detailed information on how to use Figure 2.6 can be found in Gilbert (2006). Gilbert (2006) states that these nomographs are developed by Zirschky and Gilbert (1984) by using a software (ELIPGRID) that is developed by Singer (1972, 1975). Gilbert (2006) presents two more nomographs for rectangular and triangular grids, which are not covered within this study.

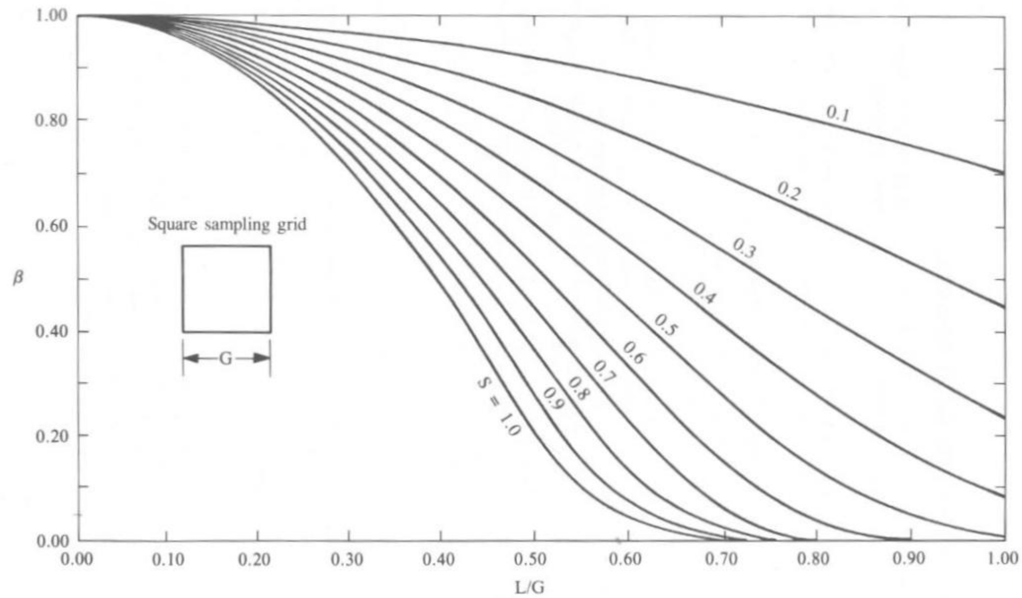


Figure 2.6 Curves relating L/G to β for different target shapes S for square grids (Gilbert, 2006)

Note that, these curves can also be used to determine (i) the maximum hot spot size that can be located for a given budget and consumer's risk and (ii) the consumer's risk β for a given size and shape when using a specified grid size.

CHAPTER 3

DEVELOPMENT OF METHODOLOGY

Contaminated site problems are highly case specific. Therefore, the procedure to be followed for site assessment may be complex and depends on many factors; such as nature of contamination, contaminant properties, site characteristics and land use. Contaminant properties determine the fate of contaminant, i.e. dispersion of contaminant in air, soil and water and thus the severity of the contamination. Volatility, mobility and toxicity are some examples to critical contaminant properties. Site characteristics, especially soil, geological and hydrogeological properties, also influence the transport of contaminants. Contaminant distribution in subsurface is usually heterogeneous due to many different mechanisms such as retardation, biodegradation etc.. Besides, type of land use determines the activities and potential receptors at the site. Different activities and receptors yield in different exposure routes of contaminants. For instance, direct ingestion of contaminated soil is a likely exposure pathway if the land use is residential or playground. However, it is usually not considered with commercial or industrial land uses.

There may be numerous combinations of above-mentioned factors for contaminated site cases. Therefore, it may be very difficult to follow a single procedure for management of each contamination case. Every single contamination problem may need a different site investigation and remediation strategy.

As it is explained in Section 2.1, CSM helps the site managers/assessors to clearly interpret the existing information that is required to develop a solution for a contaminated site problem. CSM provides the experts with knowledge of information gap and guides the following investigations. CSM should be modified in certain stages of site assessment in order to embed the collected data to the whole picture.

To reduce decision errors during site assessment and remediation studies and to make an optimal sampling design, a representative CSM is critical. CSM should reflect the exact situation in the site as well as introducing the data gap.

This study provides a standardized methodology for developing and updating CSM. It is aimed to develop a generic procedure that is comprehensive enough to be applicable to every single soil contamination problem. Developed procedure is parallel and consistent with general procedure followed by many countries, as well as by the Turkish SPCR. In this way, site and risk assessors who conduct the activities needed in the contaminated site management systems can use the outputs of this study as a technical guidance. As an example of such systems, Turkish SPCR procedure is described in Section 1.1 in detail.

A generic flowchart is produced to indicate the relationship and information flow between CSM and SPCR processes. Details of the produced flowchart are presented in Section 3.1. Moreover, a decision tree is developed in order to be used by site assessors while implementing the sampling strategy. Details of the decision tree are given in Section 3.2. Adopted approach is supported by standardized CSM tools: (i) CSM form for information collection, (ii) exposure pathway diagram for identifying possible exposure routes of contaminant, and (iii) illustrative tools to represent possible source-pathway-receptor linkages. These tools are developed to help the site assessor by identifying how to develop a CSM, which type of information is collected, how to visualize the collected data and how to interpret the outputs of CSM. Details of CSM tools are given in Section 3.3.

3.1. The Relationship and Information Flow Between CSM and SPCR Processes

Figure 3.1 summarizes the management system described by SPCR and indicates the stages where CSM is to be developed and updated. CSM is first developed during site and contamination characterization. Data collected in this step should be used to develop the initial CSM.

CSM tools are used to represent the existing and/or collected data. As it can be seen in Figure 3.1, site characteristics (e.g. land use, geological and hydrogeological properties and meteorological data), source characteristics, information on contaminant and contamination and receptors are considered to develop the CSM form. Moreover, exposure pathway diagram is developed regarding all possible exposure pathways. Collected data and information is delineated by the help of illustrative tools. CSM is updated throughout the process, whenever new data is collected. As it is shown in the Figure 3.1, it is updated after sampling and analysis, site specific risk assessment and remedial investigations.

A flowchart that indicates the relationship of SPCR procedure to CSM in terms of data flow is produced in order to be used by site assessors. It shows which type of output data of one procedure will be the input to the other procedure. For instance, existing/historical site data that is obtained from desk study and site visit is the input for developing the initial CSM. On the other hand, uncertainties and missing data concluded from CSM will guide the sampling design. Figure 3.2 introduces the relationship and information flow between CSM process and SPCR site assessment procedure.

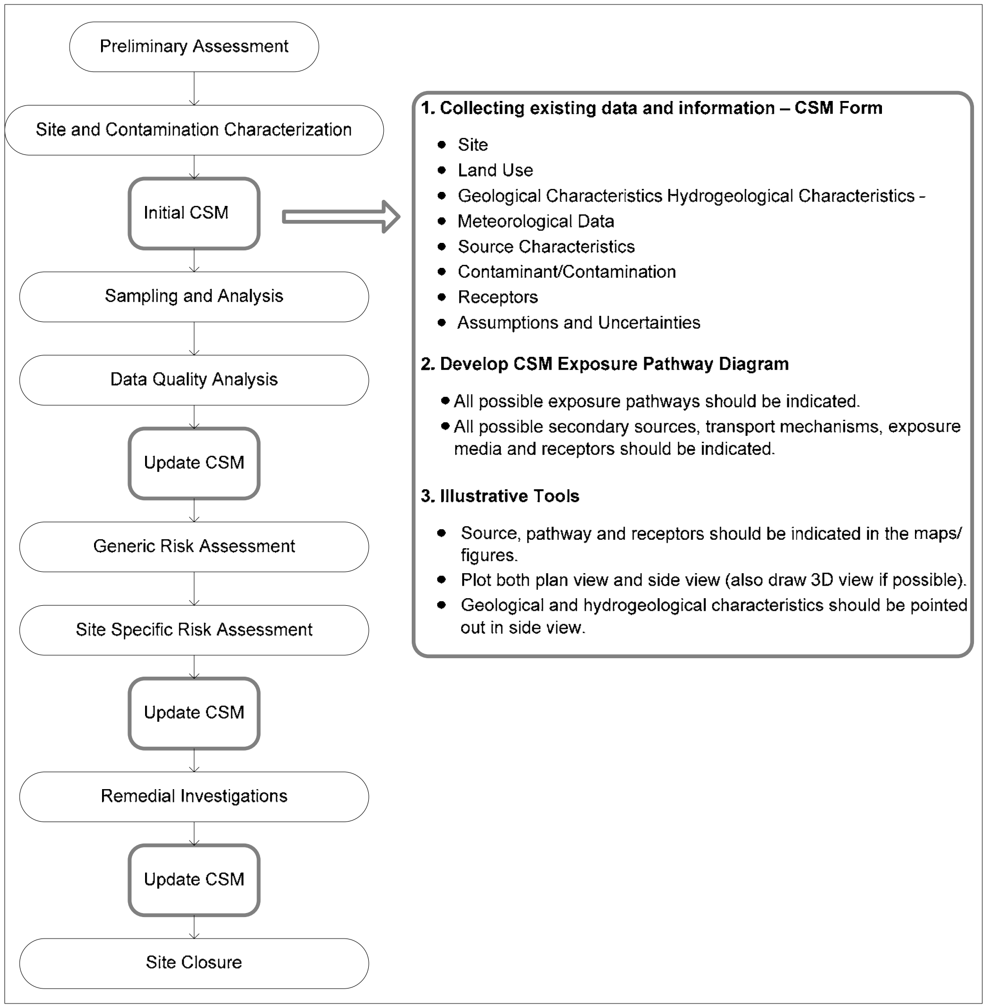


Figure 3.1 SPCR management system and CSM

Existing/historical site data should be collected to develop the initial CSM. A desk study including review of existing documents and reports should be followed by a site visit. Information included in CSM helps the site assessor to determine: possible location(s) of sources or contamination, possibly contaminated media, potential migration routes of contaminant, potential exposure routes, and likely receptors exposed to contamination.

Type of information and the sources of information is explained in Section 3.3.1. Initial CSM forms the basis for sampling design by identifying the uncertainties and data gap. The first decision made for a sampling design is to choose whether to use targeted or non-targeted sampling. Details of both sampling designs are explained in Section 2.3. Targeted sampling should be used for sites where the site assessor has reliable historical and physical knowledge. If existing data is not sufficient to make targeted sampling, non-targeted sampling should be preferred. For targeted sampling, statistical approaches or methods are not used to determine the number or location of sampling points. Instead, selection of sampling locations/depth is only based on professional judgement of the expert. CSM indicates whether existing information is sufficient to perform targeted sampling. A decision tree for selecting sampling design type is discussed in Section 3.2.

In order to perform site investigation, data gap should be identified by the help of CSM. Site assessors should identify the information needed for follow-up studies and compare it with the existing information presented in CSM. Data needed for follow-up studies depends on the objectives of site investigation. Different type and extent of data will be needed for different sampling objectives such as identifying potential exposure routes and determining average contaminant concentration. Therefore, sampling objectives should be determined carefully and set clearly. After setting the sampling objectives and indicating the data for the specific objective; CSM tools are used to identify data gap. CSM form will clearly indicate which data is missing. Exposure pathway diagram can also be used to determine the data gap in identification of exposure pathways that should be considered in generic risk assessment. According to SPCR Generic Risk Assessment Procedure, incomplete pathways will be eliminated and contaminant concentration at the site will only be compared to generic soil quality standards for complete exposure pathways.

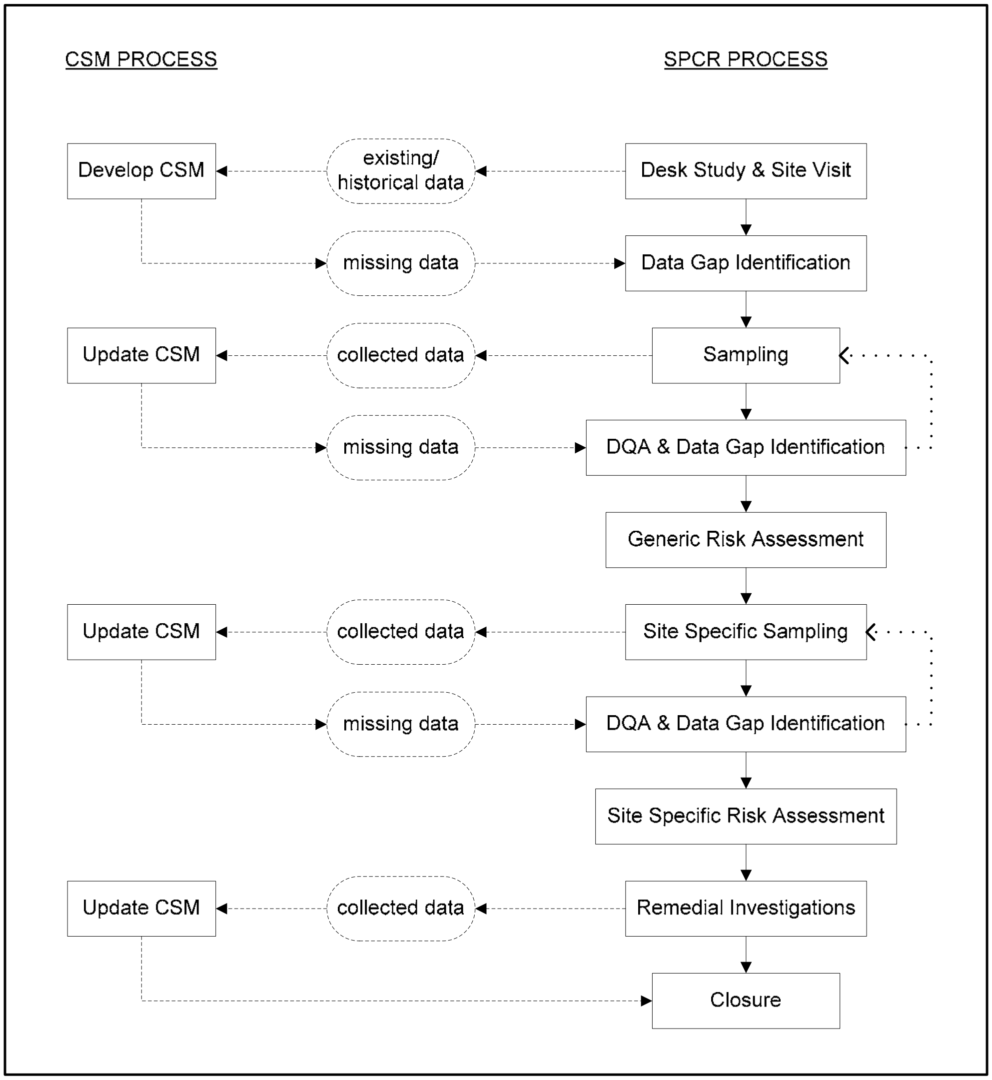


Figure 3.2 Flowchart describing the relationship and information flow between CSM and SPCR processes

Sampling should be designed such that it provides all data to determine complete exposure pathways. For instance, site assessor can decide to measure specific soil properties in order to make sure that an exposure pathway is complete or not. Sampling design, which is based on CSM, should be feasible since adequate data is to be collected with a fixed budget, in a fixed period of time. The site assessor should balance the quality and quantity of data to be collected as well as the cost and duration of sampling studies. After sampling is performed according to the proposed design, Data Quality Analysis (DQA) should be done in order to demonstrate whether collected data meets the specified data quality needs which is given in SPCR. If data quality needs are not met, additional sampling may be required. Data quality objectives are qualitative and quantitative statements established prior to data collection, which specify the quality of the data required (US EPA, 1989b). CSM is updated using data collected during sampling. For instance, if the contaminant concentration is measured; distributions of contaminant contours should be inserted into the site sketch. In addition, sampling and analysis results may give a clue in terms of fate and transport of the contamination. For example, if it is found out that groundwater is shallow enough for the contaminant in surface soil to reach (considering the mobility of the contaminant), EPD should be updated accordingly.

If contaminant concentration at the site is higher than generic soil quality standards for one or more exposure pathways or if a complete pathway which is not included in the generic scenario exists; site specific risk assessment is carried out. Before performing sampling to collect site specific data, one should clearly identify the data need for site specific risk assessment. All inputs of models or calculations to be used should be defined and they should be compared to updated CSM in order to clarify the data gap. Site specific sampling results will be used as input for remedial investigations if a remedial solution is required at the end of site specific risk assessment.

3.2. Decision Tree for Sampling Design

Types of sampling design and their advantages, limitations and statistical inferences are given in Section 2.3. Since number and locations of the sampling points need to be determined accordingly, deciding on the type of sampling design is critical. Based on the literature review summarized in Section 2.3, a decision tree that can be used as a decision support tool while selecting the type of sampling design is developed within the scope of this study. Decision tree for sampling design is given in Figure 3.3.

While selecting the type of sampling design, firstly, one should decide whether to use targeted or non-targeted sampling. Targeted (or judgemental) sampling designs are developed based on available information and professional judgement. It should be used when there is adequate information on the location or characteristics of contamination. Regarding this fact, the first question to be answered is if there is adequate information or not. For instance, if the objective of the sampling is to determine the contaminant concentration in a relatively small area, targeted sampling can be used if the exact location of a contaminant spill is known. For this case, the knowledge of exact location of the contamination is considered adequate. If the answer is 'yes', then targeted sampling design is to be selected. Having the correct answer to this question depends on the professional knowledge of the site assessor. It is important to ensure that available information/data will be sufficient to make a sampling design which can satisfy the sampling objectives. Secondly, one should decide whether the contaminant distribution is homogenous or not. If the contamination is known to be homogenous throughout the site, simple random sampling should be selected. The site is divided into areas of possible sampling units and a subset of sampling units is then chosen randomly to take samples. Since each of the sampling units have an equal probability to be chosen; a representative sampling can be performed only if there is a homogenous contaminant distribution.

If the contaminant distribution is not homogeneous, it is important to identify if there is an obvious differentiation at the site. If the prior information reflects that there is a differentiation in terms of contaminant distribution, stratified sampling should be used. Because stratified sampling suggests dividing the site into strata defined according to the presumed differentiation.

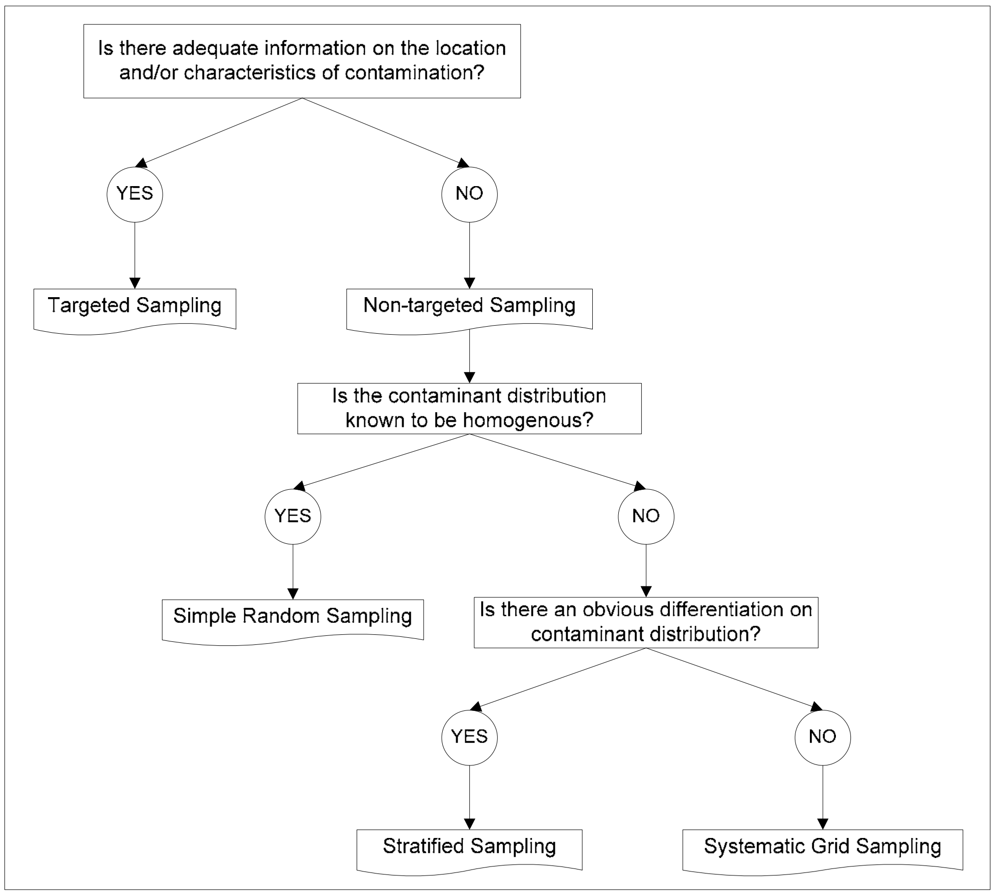


Figure 3.3 Decision tree for sampling design (adapted from de Gruijter et al., 2006)

If there is not an obvious differentiation on contaminant distribution, systematic grid sampling should be used. Because it provides more complete spatial coverage, better precision and a corresponding decrease in the required sample size when there is no or little prior information. After selecting the sampling design type according to developed decision tree, the number of samples should be determined for non-targeted sampling design types (i.e. simple random sampling, stratified sampling and systematic/grid sampling). Different approaches for calculating the number of samples are compiled from the literature and related equations are given in Section 2.3.2.

In conclusion, decision tree is implemented to select the correct sampling design. It is easy to use and applicable to any contamination case. The utility of the decision tree is tested by the help of two case studies which are presented in Chapter 4.

3.3. CSM Tools

The procedure to develop an initial CSM is given in Table 3.1. As it can be seen from Table 3.1, existing data should be collected and analyzed in order to be prepared for site visit. After site visit, information obtained from desk study and site visit will be combined to make a decision regarding if further investigation is needed. For example, sampling design, which includes determination of the number and location of samples, is based on collected data. In the same way, a correct identification of exposure routes from a source to a receptor is crucial for risk assessment studies. Therefore, data should be organized and analyzed correctly in order to make right decisions during preliminary and detailed site investigation stages.

Use of CSM tools helps site assessors to successfully collect, organize and analyze data that is important for management of contaminated sites. These tools include CSM form, illustrative tools and exposure pathway diagram which are explained in detail in the following sections. CSM form is developed to provide the scope of data to be collected. Illustrative tools are explained to see how to visualize collected information and data. Finally, exposure pathway diagram is developed to provide insight on what are the potential exposure routes in contaminated sites and how to identify valid exposure pathways for contamination cases. Step 5 given in Table 3.1 indicates the main outputs of CSM (sources, potential exposure pathways, receptors, uncertainties and assumptions) and roughly explains the use of CSM tools to obtain and demonstrate these outputs.

Table 3.1 Process for developing CSM (based on Nathanail and Bardos, 2004 and US EPA, 1996b)

Step 1: Desk study: collect existing data (historical records, maps, aerial photographs, reports etc.)
Step 2: Analyze existing data for site visit
Step 3: Perform site visit (visual inspection in the site and interviews with site owners, workers and community)
Step 4: Organize and analyze collected data
Step 5: Build initial CSM
- Identify sources of contamination
  - Mark on plan and cross-section,
  - List sources in CSM form
- Identify potential migration routes and exposure pathways
  - Mark on plan and cross-section (e.g. using arrows)
  - Develop Exposure Pathway Diagram
  - List potential migration routes and exposure pathways in CSM form
- Identify receptors
  - Mark on plan and cross-section
  - List receptors in CSM form
- Identify affected media (soil, groundwater, etc.)
- List all uncertainties and state assumptions
Step 6: Review the model as a whole

3.3.1. CSM Form

Collecting needed data and information for site characterization is important for the progress of site assessment. A form is developed to make it simpler and clearer for investigators collecting information. This form is also suggested to be used for developing CSM in the technical guidance document on risk assessment of new Turkish SPCR. CSM form is given in Appendix A.

Data to be collected can be summarized in 7 main headings: site, site geology, hydrogeology, hydrology, source, contaminant/contamination and receptors (US EPA, 1998; Nathanail and Bardos, 2004 and US EPA, 1996b).

3.3.1.1. Site

Historical information should be collected in order to identify past and current use of the site. Current and future land use should be known in order to determine possible receptors and exposure pathways. Moreover, surface or subsurface features that may affect the transport of pollution should be identified. Aerial photography, site inspection, historical photographs, operational records and interviews with owners, workers and local residents may be used to collect information.

3.3.1.2. Geology

Geology of the site should be described to anticipate its effects on fate and transport of contaminants. Geological formations and stratigraphy may be required to evaluate the subsurface conditions. Available maps and geotechnical reports may be useful for deriving this information.

3.3.1.3. Hydrogeology

Aquifer classifications of geological layers, depth to groundwater, groundwater flow direction and hydraulic gradient and conductivities of hydrogeological units are useful to clarify the possibility of contaminant to migrate to groundwater or possible receptor wells. Moreover, discharge recharge zones and anthropogenic alterations such as pumping wells and drainage systems should be included. Hydrogeological maps, geotechnical reports, previous drilling activities may be used as data source.

3.3.1.4. Meteorology

Monthly and/or annual average precipitation and temperature, and wind speed and most frequent wind direction should be known in order to characterize the fate and transport of contaminants. Meteorological information may also be important for health and safety issues. This kind of data can be obtained from meteorological databases or onsite measurements.

3.3.1.5. Source characteristics

Contamination source is commonly defined as drums, storage tanks, surface impoundments, waste piles, and landfills that contain hazardous substances. Furthermore, contaminated soil may also be considered as a source of contamination. Location, type (such as tank, contaminated soil, etc.), condition, dimension and depth of source, if it is underground, are important to understand the potential impact of releases. This type of information may be obtained from interviews with owners and workers, and facility plans and records in addition to site inspection.

3.3.1.6. Contaminant/Contamination

A preliminary estimate on type and extent of contamination may give information on the potential risks at the site. Physicochemical and fate properties such as vapor pressure, partition coefficients and persistence of contaminant point out potential exposure routes. Moreover, toxicological properties may indicate the urgency of action. Information on contamination may be derived from interviews with owners and workers. Some simple analysis, such as anticipating the location of contaminant plume considering transport properties of contaminant, source location and site characteristics like groundwater flow direction and gradient, may be conducted. For contaminant data, material safety data sheets (MSDSs) and various chemical databases (e.g., EPA chemical fact sheets) are useful sources.

3.3.1.7. Receptors

Human population around the contaminated site should be characterized in order to identify the potential exposures. Number, location and type of population (residents; adult or child, workers; construction workers and site trespassers) should be identified. Moreover, type and extent of contact of human with contamination such as usage of contaminated groundwater or surface water and direct contact with contaminated soil should be identified. Land use may also be an indicator for sensitivity of receptors. This kind of information may be obtained from census bureau in addition to interviews with local authorities and residents. Table 3.2 summarizes suggested sources and institutions to obtain such data. In addition to data sources listed in below table, environmental impact assessment reports may provide most of the needed data.

Table 3.2 Information to be collected for developing CSM Form and suggested data sources

Information on:	Including:	Suggested data sources:
Site	- Type of industry - Location - History of site - Current and future land use - Surface and/or subsurface features	Aerial photography, site inspection, historical photographs, operational records and interviews with owners, workers and local residents (Municipalities for land use plans)
Geology	- Geological layers and their thicknesses	Available geological maps and geotechnical reports (MTA)
Hydrogeology	- Aquifer classifications of geological layers - Hydraulic conductivities of geological layers - Depth to groundwater - Hydraulic gradient - Groundwater flow direction - Discharge recharge zones - Anthropogenic alterations (pumping wells, drainage systems, etc.)	Hydrogeological maps, geotechnical reports, previous drilling activities (MTA, DSİ)
Meteorology	- Precipitation rate (monthly and/or annual average) - Temperature(monthly and/or annual average) - Wind speed and direction	Interviews with owners, workers and local residents Local meteorological data (DMİ)
Source characteristics	- Location and type of source - Condition of source - Depth of source (if it is underground) - Dimensions	Facility plans, interviews with owners and workers Visual inspection
Contaminant/ Contamination	- Type of contamination (spill, leak, etc.) - Extent of contamination - Contaminated media - Toxicological, physicochemical and fate properties of contaminant	Interviews with owners and workers Visual inspection Material safety data sheets (MSDSs)
Receptors	- Number and location of population - Type of population: residents (adult or child), workers, construction workers and site trespassers	Census bureau Interviews with local authorities and residents
Assumptions, uncertainties	- Assumption - Uncertainties	

3.3.2. Exposure Pathway Diagram

Exposure is defined as "the contact of an organism, i.e., humans in the case of health risk assessment, with a chemical/physical agent". Exposure pathways are "the specific routes through which the human population may come in contact with site contaminants under a specific land use". A complete pathway should exist for exposure to occur (Soesilo and Wilson, 1997). According to US EPA (1989b), a pathway is complete if there is (i) a source or chemical release from a source, (ii) an exposure point where contact can occur, and (iii) an exposure route by which contact can occur. Otherwise, the pathway is incomplete, such as the situation where there is a source releasing contaminants to air but there are no nearby people. In identification of exposure pathways, sources, releases, types, and locations of chemicals at the site; the likely environmental fate (including persistence, partitioning, transport, and inter-media transfer) of these chemicals; and the location and activities of the potentially exposed populations should be considered (US EPA, 1998).

During human health risk assessment, the magnitude of human exposure to contaminants should be estimated. However, failure to identify an important pathway may seriously affect the results of risk assessment. Exposure pathways describe the migration of contaminants in the environmental media and they are determined using results of site characterization together with the knowledge on potential receptors (Soesilo and Wilson, 1997).

EPD is an essential CSM tool that helps to identify all potential exposure pathways, i.e. routes of a contaminant to reach from a source to a receptor. A correct identification of exposure pathways is critical for any contaminated site investigation since risk assessment studies are based on these routes. In other words, generic and site specific risk assessment are performed for complete exposure pathways, which are determined by the help of CSM. Irrelevant pathways are eliminated (e.g. inhalation of volatiles is to be eliminated for non-volatile contaminants) to save money and time during investigation and assessment. Pathway identification is crucial mainly for two reasons:

(i) Once an exposure pathway is eliminated, it is completely removed from the risk assessment procedure. If a valid pathway is eliminated, this will result in disregarding risks to human health.

(ii) If an invalid pathway is not eliminated, this will result in waste of time and money since sampling and site investigations are, to a large extent, designed according to the exposure pathways.

In this study, an exposure pathway diagram which includes all possible exposure pathways that should be considered for human health risk is developed. This diagram, given in Figure 3.4, is partly based on the approach used by US EPA. However, it is adapted to Turkish approach given in the new SPCR and EPD is mentioned in the related technical guidance document of SPCR. Since ecological risk is not considered in SPCR, EPD does not include any ecological exposure routes; it is based on human health risks. In addition to being consistent with SPCR, it is a generic tool, i.e. it is applicable to any contamination case. Details on development of EPD are given in following sections. Each of the exposure pathways taken into account during the development of EPD are explained in Section 3.3.2.2.

EPD is embedded into a user-friendly decision assistance tool based on Microsoft Excel and Visual Basic for Applications (VBA). This tool enables to develop an accurate and relevant EPD for a given site by answering relatively simple questions introduced within a query. It prevents making wrong decisions by the help of some controls and warnings. In addition, it provides a standard format for reporting EPD. Details of the decision assistance tool are given in Section 3.3.2.3.

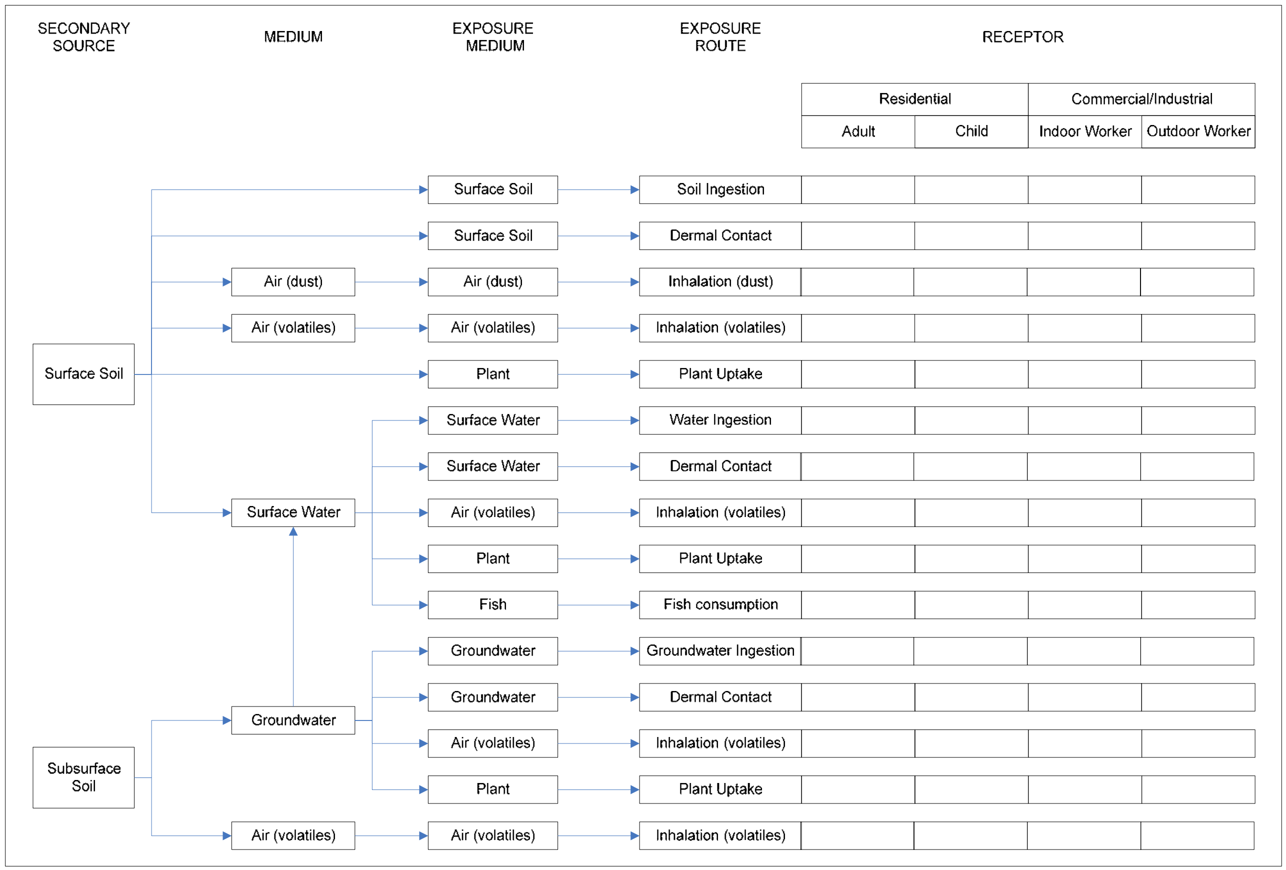


Figure 3.4 Exposure Pathway Diagram

3.3.2.1. Contaminant Fate and Transport Processes in Subsurface

In order for a better understanding of these exposure pathways, firstly a broad overview of contaminant fate and transport in the subsurface is needed. The reason for this is exposure pathways are determined according to basic transport and transformation processes that contaminants undergo. Furthermore, the site assessors should be able to comprehend the importance of subsurface and contaminant characteristics that affect the fate and transport of contaminants in the environment. Following sections provide an overview of important contaminant and subsurface properties in addition to basic transport and transformation processes.

3.3.2.1.1. Transport and Transformation Processes

According to US EPA (1989b), three questions related to fate and transport of contaminant should be answered:

(1) What chemicals occur in the sources at the site or in the environment?

(2) In what media (onsite and offsite) do they occur now?

(3) In what media and at what location may they occur in the future?

According to Sunahara et al. (2002), organisms may be exposed to soil pollutants through two different pathways: (i) direct contact with the soil (soil ingestion, dermal contact, or inhalation); (ii) after transfer of contaminants from the soil compartment to another environmental compartment such as groundwater or air. Hence, in order to identify potential exposure pathways, the site assessor should firstly identify the fate and transport of contaminant in soil and subsurface.

Soesilo and Wilson (1997) noted that the contaminant released to environment can: (i) remain unchanged in its present location, (ii) be carried elsewhere by the transport process or (iii) be transformed into other chemical species. Major contaminant transport and transformation processes in soil and subsurface environments are summarized in the following paragraphs.

When a contaminant is introduced at the ground surface, it must migrate through the unsaturated zone toward the aquifer. Hence, contaminants will move through soil, sediment, fractured rock, manmade conduits, or other routes on their way to the saturated zone. If cracks or fractures (macropores) exist, the contaminant may flow directly into the crack and move downward. Some contaminants may not readily move through the vadose zone unless some other force of liquid acts on them. In this case, transport of the contaminants are facilitated, or aided by something that enhances movement. The recharge of water through the soil profile may cause leaching, or dissolve the contaminant into water that recharge groundwater. Soil vapors from volatile contaminants can move in the subsurface away from the source. The movement may occur through natural deposits or through manmade conduits such as utility trenching, pipelines, and vents to the ground surface or basements (Palmer, 1996).

The depth of penetration of contaminants depends on the type and quantity of contaminants spilled; whether spilled on the surface or from a subsurface source, duration of leak, physical and chemical properties of contaminant as well as physical and hydraulic properties of soil (Palmer, 1996).

Some of the essential subsurface contaminant transport processes are advection, diffusion, dissolution, volatilization, and retardation which slow down the rate of contaminant migration due to adsorption, precipitation and filtration (Boulding and Ginn, 2004). Some of these processes occur within a single phase, while others occur between different phases (e.g., adsorption, volatilization and dissolution) (Soesilo and Wilson, 1997). These transport processes are briefly explained in Table 3.3.

Table 3.3 Main transport processes and their descriptions

Process	**Description**
Advection	A physical process by which a solute (contaminant dissolved in water) is transported in flowing pore-water or groundwater and moves at the same velocity with the groundwater flow.
Diffusion	The movement of a contaminant under the influence of concentration gradient. Contaminants in air or water have the affinity to physically move from areas of high concentration to areas of lower concentration.
Dissolution	The process that dissolves a solid or NAPL to form ions or molecules which are uniformly distributed in water or another solvent.
Volatilization	The transfer of an organic substance from a liquid phase to a gaseous phase. The transfer rate depends on the temperature, the vapor pressure of the chemical, and the difference in the concentrations between the liquid and gas phases. Organics may volatilize from the leachate and move to the ground surface. Emissions may come from the volatilization of dissolved chemicals in contaminated groundwater.
Adsorption	A process in which the soluble contaminants are removed from water by contact with the sorbent (solid surface). Otte et al. (2007) lists the major surfaces for adsorption as: clay, organic matter and iron, manganese and aluminum oxides and hydroxides.
Precipitation	The converse of dissolution. It occurs when a chemical reaction transfers a solute to a much less soluble form. It is particularly applicable to heavy metals such as nickel, mercury, chromium, and lead. Precipitation is dependent on pH. Most metals precipitate at high pH levels.
Filtration	The entrapment of solid particles and large dissolved molecules in the pore spaces of the soil and aquifer media. Filtration limits slow by clogging pore spaces and reducing hydraulic conductivity of the material (Boulding and Ginn, 2004).

In addition to transport processes, transformation processes also affect the fate of contaminants in the environment. Transformation processes cause a change in the chemical structure of contaminants. All or a portion of the chemical is transformed to other chemical species. These processes are biodegradation, oxidation-reduction, hydrolysis, halogenation and dehalogenation, photolysis and complexation. The major transformation processes biodegradation, oxidation-reduction and hydrolysis are briefly explained in Table 3.4.

Table 3.4 Main transformation processes and their descriptions

Process	Description
Biodegradation	Transformation of organic substances to smaller molecules through the oxidation and reduction mechanism induced by the metabolic activity of native microorganisms (Soesilo and Wilson, 1997). The simpler daughter products may be as toxic as or more toxic than the original compounds (Boulding and Ginn, 2004).
Oxidation-reduction (redox)	A chemical reaction that occurs with organic and inorganic chemicals and involves the gain or loss of oxygen (Soesilo and Wilson, 1997). Abiotic and biotic redox reactions strongly affect the solubility and mobility of heavy metals. Biologically mediated redox reactions are able to transform most organic contaminants (Boulding and Ginn, 2004).
Hydrolysis	A chemical process by which chemical substances react with water molecules. It is a significant process for chlorinated organics which normally are not readily transformed by biodegradation. (Soesilo and Wilson, 1997)

3.3.2.1.2. Contaminant and Subsurface Properties Affecting Fate and Transport

While assessing contaminant fate and transport, site physical characteristics, source characteristics, and extent of contamination should be considered together (US EPA, 1998). A chemical's nature and interaction with the soil constituents (mobility) influence its fate. Moreover, exposed organisms can affect previously non-exposed organisms through ecological linkages such as symbiotic association, food chain transfer, etc. Therefore, the impact of a contaminated soil on its environment is multi-factorial (Sunahara et al., 2002). Important chemical and physical properties of the contaminant and soil and subsurface properties influencing the fate and transport of a contaminant are summarized in the following paragraphs. Solubility, volatility, tendency to be adsorbed by solids, chemical reactivity, biodegradability and density of chemicals are important to identify the fate and transport of chemicals. These properties are briefly described in Table 3.5.

Table 3.5 Chemical and physical properties of contaminants and their descriptions

Contaminant Property	**Description**
Solubility	The degree and ease to which the chemical or compound will dissolve in water or in another solute (Palmer, 1996) at a specified temperature. It is affected by temperature (Soesilo and Wilson, 1997). Highly soluble contaminants have relatively low sorption coefficients for soils, tend to volatilize from soils and are more readily biodegraded. Contaminants that are soluble in water tend to be readily transported through the vadose zone. Conversely, contaminants that are soluble in organic solvents and poorly soluble in water tend to exhibit high retardation and low mobility (Wilson et al., 1994).
Volatility	Tendency of a chemical to volatilize (i.e., the transport of a compound from the liquid to the vapor phase at a given temperature). This is an important pathway for chemicals with high vapor pressure or low solubilities. Vapor pressure is the pressure exerted by a chemical vapor in equilibrium with its solid or liquid form at any given temperature used to calculate the rate of volatilization of a pure substance from a surface. The higher the vapor pressure, the more likely a chemical is to exist in gaseous state. A volatile organic compound is any hydrocarbon, except methane and ethane, with vapor pressure equal to or greater than 0.1 mm Hg (Palmer, 1996). Vapor pressure of a contaminant is estimated from the following relationship: $V_p = C * K_H$ where K_H: Henry's Law Constant, V_p: vapor pressure of the chemical, and C_w: concentration of chemical in water. Henry's Law Constant provides a measure of the extent of chemical partitioning between air and water at equilibrium. The higher Henry's Law Constant, the more likely a chemical to move in response to concentration gradients (US EPA, 1989b; Wilson et al., 1994).

Table 3.5 (continued) Chemical and physical properties of contaminants and their descriptions

Biodegradability	Biodegradation is an important mechanism governing the fate of contaminant in the vadose zone and is dependent on several factors. Commonly, the biodegradation or disappearance rate of a chemical is expressed in terms of its half life $t_{1/2}$, defined as the time needed for half of the concentration to react (Wilson et al., 1994).
Sorption or soil-water partition coefficient (K_d)	The primary chemical-associated parameter of interest for sorption. K_d provides a soil specific measure of the extent of chemical partitioning between soil and water, unadjusted for dependence upon organic carbon. To adjust for the fraction of organic carbon associated with the soil (f_{oc}), $K_d = f_{oc} * K_{oc}$ can be used, where K_{oc} is organic carbon partition coefficient. The higher the K_d (or K_{oc}), the more likely a chemical is to bind to soil or sediment than to remain in water (US EPA, 1989b).
Diffusivity or diffusion coefficient	Indicates the movement of a molecule in a liquid or gas medium as a result of differences in concentration (that is diffusion). The higher the diffusivity, the more likely a chemical is to move in response to concentration gradients (US EPA, 1989b).
Chemical structure	Often controls the solubility, sorption, and transformations characterizing the compound. Clearly, the transport of organic compounds is dependent on their structural properties (Wilson et al., 1994).

As it is mentioned before, contaminant behavior in the subsurface is determined by the characteristics of soil and subsurface as well as its own chemical and physical characteristics. Soil and water properties influencing contaminant behavior can be listed as: permeability, soil texture, soil structure, temperature, pH, water content, bulk density, porosity, sorptive capacity, redox potential, organic carbon content, ion exchange capacity and hydraulic conductivity (Wilson et al., 1994; Soesilo and Wilson, 1997). Major subsurface properties are briefly described in Table 3.6.

Table 3.6 Soil and subsurface environmental properties and their descriptions

Subsurface Property	**Description**
Temperature	Influences the rate of chemical reactions in the subsurface. Rate of acid-base reactions, dissolution and biodegradation often increases with increasing temperature.
Soil pH	Affects the mobility of some contaminants. For example, the mobility of most trace elements and heavy metals increases with decreasing pH (Wilson et al., 1994). Moreover, sorption, precipitation-dissolution and oxidation-reduction reactions are strongly influenced by changes in pH (Boulding and Ginn, 2004).
Porosity	The ratio of the volume of voids by the total soil volume. Retardation process is directly affected by soil porosity.
Organic carbon content	Highly influences the sorption of non-ionic organic compounds.
Groundwater velocity	Groundwater velocity is a major subsurface parameter that determines the level of advection (i.e. contaminant transport with groundwater flow). The higher the groundwater velocity, the larger the distance travelled by contaminant plume (Otte et al., 2007).
Redox potential	The tendency of a reversible redox system to be oxidized or reduced. Its influence on biotransformation processes is significant (Boulding and Ginn, 2004).
Hydraulic conductivity	The capacity of a porous medium to transmit water (Palmer, 1996).

To summarize, transport and transformation processes, that is fate of the contaminant, depend on both soil and subsurface properties and contaminant properties. Table 3.7 gives soil and subsurface properties and contaminant properties which influence abovementioned transport and transformation processes.

Table 3.7 Subsurface and contaminant properties affecting fate and transport processes (based on Sabatini and Knox, 1991)

Transport Processes	**Soil and Subsurface Properties**	**Contaminant Properties**
Advection	Groundwater velocity Porosity Hydraulic conductivity	Independent of contaminant
Diffusion	Dispersivity Pore water velocity	Diffusivity
Dissolution / Precipitation	pH Other metals	Solubility versus pH Speciation reactions
Volatilization	Degree of saturation	Vapor pressure Henry's law constant
Adsorption	Organic matter content Clay content Specific surface area	Solubility Octanol-water partition coefficient
Filtration		
Transformation Processes	**Soil and Subsurface Properties**	**Contaminant Properties**
Biodegradation		Biodegredability
Oxidation-reduction	pE pH	pK_a
Hydrolysis	pH Competing reactions	Hydrolysis half life

3.3.2.2. Development of Exposure Pathway Diagram

As mentioned before in Section 3.3.2, exposure pathway diagram is developed as a tool that enables identification of relevant exposure pathways at a contaminated site. As can be seen from Figure 3.4, the diagram has five main columns: secondary source, medium, exposure medium, exposure route and receptor. Possible exposure pathways are indicated in the diagram by connecting these five components by the help of arrows.

In fact, all exposure pathways start with a 'primary source', i.e., the starting point of contaminant release, which is not indicated in the diagram. Primary sources can be drums and storage tanks, waste dump areas, waste lagoons and piping or distribution systems. Secondary source is the medium which is contaminated due to a leak or spill of a contaminant from a primary source. Secondary source is either surface soil, subsurface soil or both. Transport mechanism and exposure route is expected to differ depending on the secondary source. Exposure routes that take place in the EPD are explained in the following paragraphs.

Surface soil as secondary source

Surface soils may become contaminated because of hazardous material spills or leaks during manufacturing, processing, storage or transfer operations as well as illegal waste dumping (US EPA, 1988). Exposure to contaminated surface soil can be directly or after the contamination is transferred to another exposure media such as air, surface water or plant. Potential exposure pathways for surface soil as secondary source are given in Figure 3.5. Explanations of these exposure pathways can be followed with their associated numbers given at the last column in Figure 3.5. Each exposure pathway is explained below. Four type of receptors grouped under two land use type is considered. These are adults and children for residential land use, and indoor and outdoor workers for commercial/industrial land use.

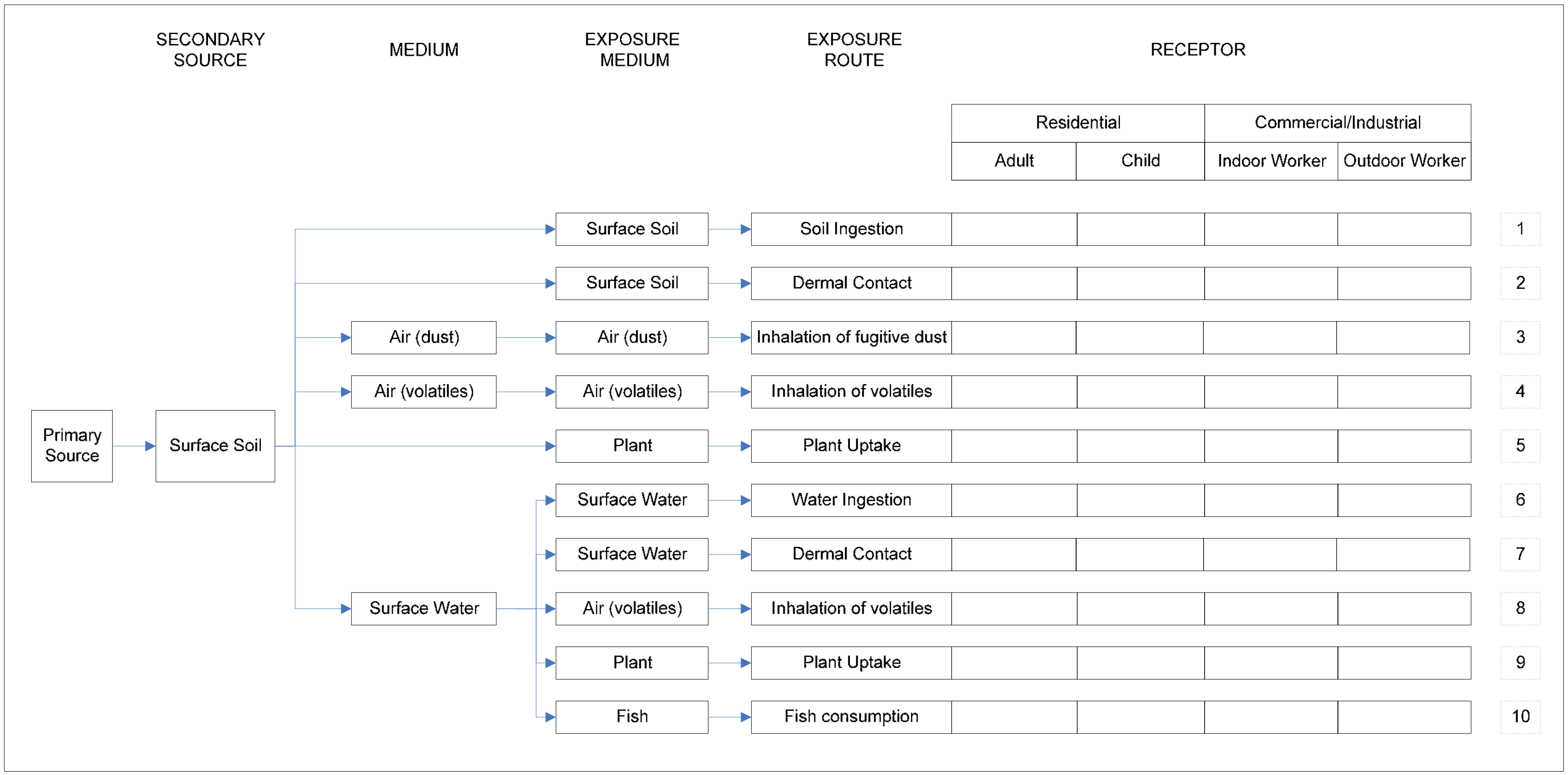


Figure 3.5 Potential exposure pathways given for surface soil as secondary source

[1] Surface Soil → Ingestion

Ingestion of soil may contribute to human health risk for residential land use. Children may have access to areas of contaminated soil, and may ingest some contaminated soil during play. Such ingestion may result from "pica" behavior (i.e., intentional eating of soil by very young children) or from normal hand to mouth contact (US EPA, 1988). For contaminated surface soil under the residential land use, direct ingestion is routinely taken into account regardless of type of the contaminant.

[2] Surface Soil → Dermal Contact

If direct access to contaminated soil is possible, dermal contact may contribute to human health risk for certain contaminants. According to US EPA (2002b), dermal contact pathway should be evaluated for both residential and non-residential soil exposure scenarios depending on the types of activities occurring at a site (e.g., landscaping) and on the contaminants of concern present. Outdoor worker in addition to adults and children may be exposed to contaminated soil. Six individual compounds (Arsenic, Cadmium, Chlordane, Dichloro-diphenyl-trichloroethane (DDT), Lindane and Pentachlorophenol) and two classes of compounds (polycyclic aromatic hydrocarbons (PAHs) and semi-volatile organic compounds) should be considered to cause health risk through dermal contact to contaminated soil (US EPA, 2002b).

[3] Surface Soil → Air (fugitive dust) → Inhalation of fugitive dust

Emissions of contaminated fugitive dusts can result from a combination of such factors as (i) wind erosion of wastes and contaminated soils, and (ii) vehicles travelling over contaminated, unpaved roads. Exposure by inhalation of fugitive dusts outdoor can occur in recreational areas as well as in residential, commercial or industrial areas (US EPA, 1988).

Inhalation of fugitive dusts is a consideration for semi-volatile organics and metals in surface soil (US EPA, 2002b). Site characteristics also determine the effectiveness of this exposure pathway. Inhalation of fugitive dusts is of high concern for dry, dusty soils; high average annual wind speeds and vegetative cover less than 50 percent (US EPA, 1996b). Therefore, inhalation of fugitive dusts may be neglected if the climate is very humid, average wind speed is low and/or vegetation cover is high, provided that these site characteristics are proved with appropriate site data.

[4] Surface Soil → Air (volatiles) → Inhalation of volatiles

If the soil is contaminated by volatile compounds, one of the potential release mechanisms is release of volatile components to the atmosphere via evaporation (US EPA, 1988). Adults, children and outdoor workers may be exposed to volatile contaminants by inhalation. VOCs and mercury are most likely to expose a risk via this pathway (US EPA, 2002b). Some of the factors affecting volatile release from soil can be listed as: temperature, ambient pressures and amount of rainfall.

[5] Surface Soil → Plant → Plant Uptake

Consumption of garden fruits and vegetables grown in contaminated soils may result in risk to human health (through food chain) for residential receptors (US EPA, 1996b). Although this pathway may be of high concern for residential settings where people obtain most of their food from their own gardens, generic soil quality standards can only be calculated for arsenic, cadmium, mercury, nickel, selenium and zinc based on empirical data on the uptake (US EPA, 1996a). Organic compounds are not addressed due to lack of empirical data. If the site assessor determines that potential receptors are exposed to high amount of contaminants via soil-plant-human pathway, further site and chemical specific investigations should be carried out to estimate actual exposure.

[6] Surface Soil → Surface Water → Ingestion

If surface water (contaminated through surface runoff) is a source of potable water by residences or commercial/institutional establishments, the population served may experience considerable exposure through ingestion. In addition, significant quantities of contaminated water may be ingested inadvertently while swimming. Thus, water ingestion through contaminated surface water should be taken into account for all compounds and all type of receptors (i.e., adult, child and worker) if it is used (or has a potential to be used) for drinking.

[7] Surface Soil → Surface Water → Dermal Contact

If surface water (contaminated through surface runoff) is a source of potable water, the dermal exposure associated with bathing or showering should be considered. In addition, swimming in contaminated waters can result in dermal exposure to contaminants over the entire body. If the waters are commercially fished, fishermen may be exposed through dermal contact with contaminated water, although such exposure will generally be overshadowed by other exposure mechanisms (US EPA, 1988). This pathway should be considered for population in residences and commercial/institutional establishments using water from contaminated surface water, as well as residential population swimming in the contaminated surface water. Six individual compounds (Arsenic, Cadmium, Chlordane, DDT, Lindane and Pentachlorophenol) and two classes of compounds (PAHs and semi-volatile organic compounds) should be considered for this pathway (US EPA, 2002b).

[8] Surface Soil → Surface Water → Air (volatiles) → Inhalation of Volatiles

If contaminated surface water is a source of potable water, the population may also be exposed to contaminants through inhalation of volatiles while showering or bathing. Furthermore, swimmers will be exposed to volatile contaminants in the water through inhalation (US EPA, 1988). This pathway should be considered for population in residences and commercial/institutional establishments using water from contaminated surface water, as well as residential population swimming in the contaminated surface water. VOCs and mercury are most likely to expose a risk via inhalation of volatiles (US EPA, 2002b).

[9] Surface Soil → Surface Water → Plant → Plant Uptake

Consumption of garden fruits and vegetables grown in soils irrigated with contaminated water may result in risk to human health (through food chain) for residential receptors (US EPA, 1996b). Although this pathway may be of high concern for residential settings where people obtain most of their food from their own gardens, generic soil quality standards can only be calculated for arsenic, cadmium, mercury, nickel, selenium and zinc based on empirical data on the uptake (US EPA, 1996a). Organic compounds are not addressed due to lack of empirical data. If the site assessor determines that potential receptors are exposed to high amount of contaminants via soil-plant-human pathway, further site and chemical specific investigations should be carried out to find out actual exposure.

[10] Surface Soil → Surface Water → Fish → Fish Consumption

Consumption of fish caught in contaminated surface waters can be an important ingestion route. This phenomenon results in tissue concentrations of contaminants in predator fish exhibiting levels that greatly exceed the ambient concentration in the water body (US EPA, 1988).

<u>Subsurface soil as secondary source</u>

Underground storage tanks, pipelines or buried barrels and deeper penetration of surface spills may result in contaminated subsurface soil. Contaminants in subsurface soil may transport to the groundwater or volatilize to the air. Groundwater contamination can occur by infiltration or direct migration. Infiltration is the most common groundwater contamination mechanism. A portion of the rainfall slowly infiltrates the soil through pore spaces in the soil matrix and it dissolves organic or inorganic contaminants forming leachate. The leachate continues to migrate until it reaches the saturated zone. In the saturated zone, contaminants move horizontally with groundwater flow and vertically due to gravity, or presence of significant vertical hydraulic gradient. In addition to infiltration, contaminants can migrate directly into groundwater from underground sources such as storage tanks and pipelines that lie in the unsaturated zone. These sources may result much greater concentrations of contaminants because of the continually saturated conditions (Boulding and Ginn, 2004).

Potential exposure routes for subsurface soil as secondary source are given in Figure 3.6. Explanations of these exposure routes can be followed with their associated numbers given at the last column in Figure 3.6.

[11] Subsurface Soil → Air (volatiles) → Inhalation of Volatiles

Volatile contaminants in subsurface soil may pose a risk to human health by inhalation both indoors and outdoors. Inhalation of volatiles volatilizing directly from subsurface soil to above ground should be taken into account for adult, child and outdoor worker. Moreover, there is also the potential for migration of volatile compounds from subsurface into basements of buildings. Indoor inhalation of volatiles should be considered for adult, child and indoor worker. Current and/or future site conditions (present or potential future existence of a building on or near source area) should be taken into account together with the contaminant of concern. VOCs and mercury are most likely to expose a risk via this pathway (US EPA, 2002b).

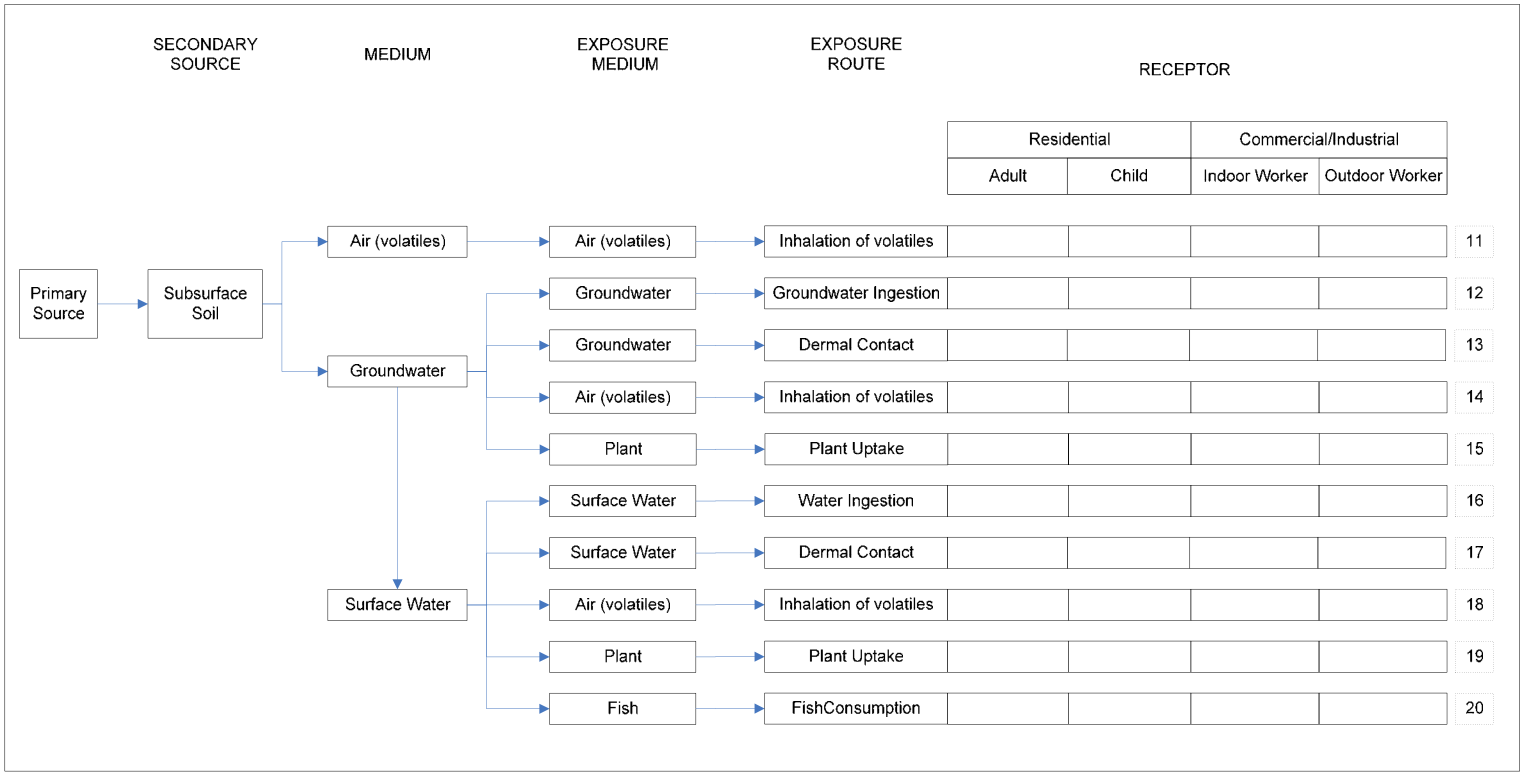


Figure 3.6 Potential exposure pathways given for subsurface soil as secondary source

[12] Subsurface Soil → Groundwater → Groundwater Ingestion

If contamination has the potential to migrate into an aquifer and if groundwater is a source of potable water by residences or commercial/institutional establishments, the population served may experience considerable exposure through ingestion. Thus, groundwater ingestion through contaminated groundwater should be taken into account for all compounds and all type of receptors (i.e., adult, child and worker) if it used (or has a potential to be used) for drinking.

[13] Subsurface Soil → Groundwater → Dermal Contact

If contamination has the potential to migrate into an aquifer and if groundwater is a source of potable water, the dermal exposure associated with bathing or showering should be considered (US EPA, 1988). This pathway should be considered for population in residences and commercial/institutional establishments using water from groundwater. Six individual compounds (Arsenic, Cadmium, Chlordane, DDT, Lindane and Pentachlorophenol) and two classes of compounds (PAHs and semi-volatile organic compounds) should be considered with dermal contact to contaminated surface water (US EPA, 2002b).

[14] Subsurface Soil → Groundwater → Air (volatiles) → Inhalation of Volatiles

Volatile contaminants migrated to groundwater from subsurface soil may pose a risk to human health by inhalation both indoors and outdoors. Inhalation of volatiles volatilizing directly from subsurface soil to ground surface should be taken into account for adult, child and outdoor worker. Moreover, there is also the potential for migration of volatile compounds from subsurface into basements of buildings. Inhalation of volatiles indoors should be considered for adult, child and indoor worker. Current and/or future site conditions (present or potential future existence of a building on or near source area) should be taken into account together with the contaminant of concern. VOCs and mercury are most likely to expose a risk via this pathway (US EPA, 2002b).

[15] Subsurface Soil → Groundwater → Plant → Plant Uptake

Consumption of garden fruits and vegetables grown in soils irrigated with contaminated groundwater may result in risk to human health (through food chain) for residential receptors (US EPA, 1996b). Although this pathway may be of high concern for residential settings where people obtain most of their food from their own gardens, generic soil quality standards can only be calculated for arsenic, cadmium, mercury, nickel, selenium and zinc based on empirical data on the uptake (US EPA, 1996a). Organic compounds are not addressed due to lack of empirical data. If the site assessor determines that potential receptors are exposed to high amount of contaminants via soil-plant-human pathway, further site and chemical specific investigations should be carried out to find out actual exposure.

[16] Subsurface Soil → Groundwater → Surface Water → Ingestion

Contamination can migrate into an aquifer and contaminated groundwater can reach to a surface water body. If surface water is a source of potable water by residences or commercial/institutional establishments, the population served may experience considerable ingestion exposure. In addition, significant quantities of contaminated water may be ingested inadvertently while swimming. Thus, water ingestion through contaminated surface water should be taken into account for all compounds and all type of receptors (i.e., adult, child and worker) if it used (or has a potential to be used) for drinking.

[17] Subsurface Soil → Groundwater → Surface Water → Dermal Contact

Contamination can migrate into an aquifer and contaminated groundwater can reach to a surface water body. If surface water is a source of potable water, the dermal exposure associated with bathing or showering should be considered. In addition, swimming in contaminated waters can experience dermal exposure to contaminants over their entire body. If the waters are commercially fished, fishermen may be exposed through dermal contact with contaminated water, although such exposure will generally be overshadowed by other exposure mechanisms (US EPA, 1988). This pathway should be considered for population in residences and commercial/institutional establishments using water from contaminated surface water. Six individual compounds (Arsenic, Cadmium, Chlordane, DDT, Lindane and Pentachlorophenol) and two classes of compounds (PAHs and semi-volatile organic compounds) should be considered with dermal contact to contaminated surface water (US EPA, 2002b).

[18] Subsurface Soil → Groundwater → Surface Water → Air (volatiles) → Inhalation of Volatiles

Contamination can migrate into an aquifer and contaminated groundwater can reach to a surface water body. If contaminated surface water is a source of potable water, the population may also be exposed to contaminants through inhalation of volatiles while showering or bathing. Furthermore, swimmers will be exposed to volatile contaminants in the water through inhalation (US EPA, 1988). This pathway should be considered for population in residences and commercial/institutional establishments using water from contaminated surface water, as well as residential population swimming in the contaminated surface water. VOCs and mercury are most likely to expose a risk via inhalation of volatiles (US EPA, 2002b).

[19] Subsurface Soil → Groundwater → Surface Water → Plant → Plant Uptake

Contamination can migrate into an aquifer and contaminated groundwater can reach to a surface water body. Consumption of garden fruits and vegetables grown in soils irrigated with contaminated water may result in risk to human health (through food chain) for residential receptors (US EPA, 1996b). Although this pathway may be of high concern for residential settings where people obtain most of their food from their own gardens, generic soil quality standards can only be calculated for arsenic, cadmium, mercury, nickel, selenium and zinc based on empirical data on the uptake (US EPA, 1996a). Organic compounds are not addressed due to lack of empirical data. If the site assessor determines that potential receptors are exposed to high amount of contaminants via soil-plant-human pathway, further site and chemical specific investigations should be carried out to find out actual exposure.

[20] Subsurface Soil → Groundwater → Surface Water → Fish → Fish Consumption

Contamination can migrate into an aquifer and contaminated groundwater can reach to surface waters. Consumption of fish caught in contaminated surface waters may be an important ingestion route. This phenomenon results in tissue concentrations of contaminants in predator fish exhibiting levels that greatly exceed the ambient concentration in the water body (US EPA, 1988).

3.3.2.3. Decision Assistance Tool for Developing a Site Specific Exposure Pathway Diagram

As it is discussed in Section 3.3.2, identification of relevant exposure pathways is critical for human health risk assessment. An exposure pathway diagram, presented in Figure 3.4, is developed in order to provide the site assessor with a vision of potential exposure routes. This diagram enables the site assessor to simply select the potential exposure pathways for relevant receptors (i.e., adult, child, indoor worker and outdoor worker). For all contaminated site problems, an EPD should be developed in the scope of CSM. However, since developing EPDs are highly case specific and can be complicated, some mistakes may occur due to complexity of the case. These mistakes can be seen more often if the site assessor is inexperienced in risk assessment.

Several models and softwares are developed by US EPA which are used for visualization, data management, sampling design, modelling, risk assessment, remedial process selection and cost/benefit analysis required for management of contaminated sites. Some of these tools are investigated in order to see the logic behind decision support tools used for contaminated site studies. Tools that are examined in detail are explained in the following paragraphs.

- VSP (Visual Sample Plan): a simple tool based on statistical and mathematical concepts that technically illustrates defensible sampling schemes using an actual map of the target area. VSP applies to surface soil investigations, building surface sampling and water body studies. Its modules are sampling design, sensitivity analysis and sampling cost analysis (US EPA, 2005).

- SADA (Spatial Analysis and Decision Assistance): incorporates tools from environmental assessment fields into an effective problem-solving environment. Its modules are geospatial analysis, statistical analysis, human health risk assessment, ecological risk assessment, cost/benefit analysis, sampling design and decision analysis (US EPA, 2005).

- FIELDS (Field Environmental Decision Support) Tools for ArcGIS: developed by a team of biologists, environmental scientists, computer programmers, and geologists. Its modules include: sample design, database query, geospatial modelling and analysis, human health and ecological risk assessment and remediation (US EPA, 2005).

- ARAMS (Adaptive Risk Assessment Modelling System): incorporates various existing databases and models for exposure, intake/update, and effects (health impacts) into an object-oriented, conceptual site modelling framework. In addition to its functions such as Statistical Analysis, Human Health Risk Assessment and Ecological Risk Assessment, it is also used to develop exposure pathway diagram. ARAMS provides an object-oriented environment where the user can “build” the EPD interactively (US EPA, 2005).

As it is noted before in Section 2.1, the Triad approach focuses on the explicit identification and management of decision uncertainty as the organizing principle for conducting environmental projects, both characterization and remediation. Although the Triad CSM, goes beyond the “box and arrow” structure of the EPD, ARAMS is a useful tool where simplified contaminant-pathway-receptor CSM serves as the unifying concept for risk analysis. ARAMS uses the contaminant-pathway-receptor CSM to provide the framework for its graphical user interface. When the user selects a CSM component (source, pathway, or receptor) from the program’s menu, the graphical user interface installs an icon representing the component in its main view and links it to the other components the user has selected (US EPA, 2005 and FTRT, 2009).

Benefits of decision support tools and importance and complexity of developing EPDs put forth the need for a tool to develop EPD for consideration. To overcome the risk of making mistakes while developing EPD, a decision assistance tool is built using Microsoft Excel 2007 and VBA. Although this idea was struck up from ARAMS, the procedure is different. ARAMS lets the user select or enter primary source, exposure medium and receptor, and it yields a report introducing exposure routes in a diagram. Developed tool helps determining the potential exposure pathways automatically by answering several simple questions. The answers to questions are stored in the Excel sheet and relevant (or potential) exposure pathways are automatically checked or not, by the help of excel functions in an output sheet. This decision assistance tool consists of three Excel worksheets: questionary, database and output.

(i) Questionary

An electronic questionary is developed to collect input data interactively. The questionary includes 17 questions which can easily be answered after a site visit following the desk-based study. First, the contaminant of concern is selected from a dropdown list, which includes 148 compounds for which generic soil quality standards are given in new Turkish SPCR. If there are more than one contaminants at the site, EPD should be developed separately for each compound. After selecting the contaminant, 16 simple questions should be answered as 'yes' or 'no'. A screenshot of questionary is given in Figure 3.7.

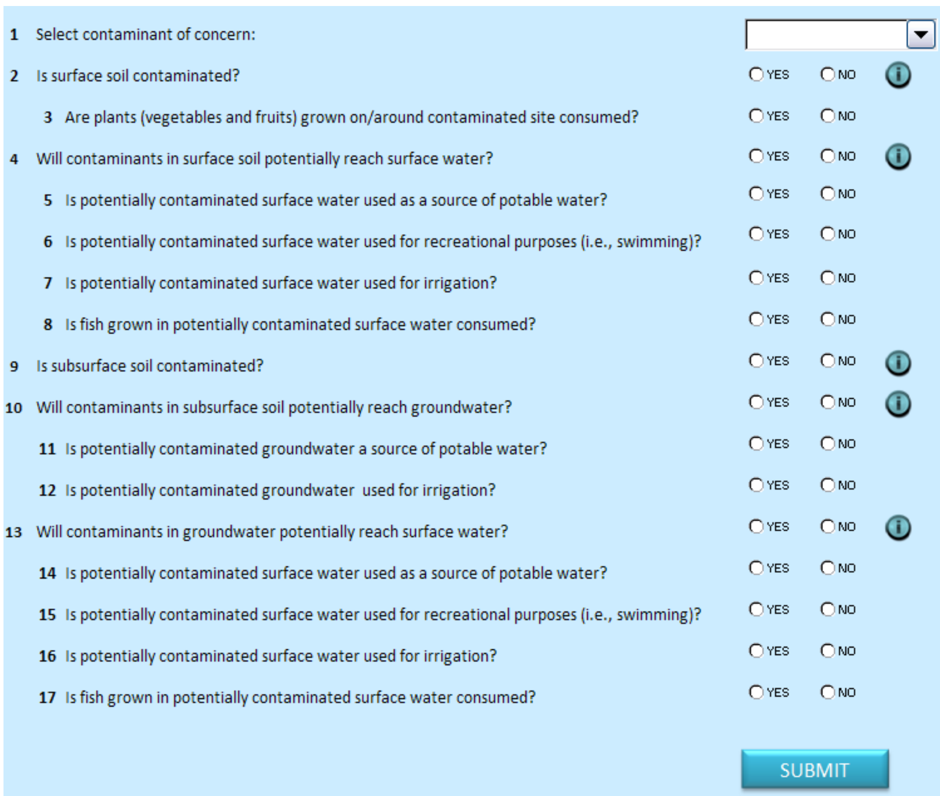


Figure 3.7 A screenshot of questionary

Some of the questions should only be answered if answer to another question is 'yes'. When the answer to that question is 'no', the user gets a warning message which guides him/her to the next question to answer. For instance, if the answer to question 'Is surface soil is contaminated?' is 'no', there is no need to answer the question 'Are plants (vegetables and fruits) grown on/around contaminated site consumed?'. The reason for this is the fact that eating plants grown in soil can only expose a risk to human health if there is contamination in surface soil. For these type of questions, a message box telling which question to answer next appears when the answer is 'no'. The questions and some points and tips that should be considered while answering the questions are included in Table 3.8. Some of the questions can not be answered directly, i.e. consideration of other factors is required. For this type of questions, there are buttons which can be used to get information on factors to be considered while answering.

Table 3.8 Questions to be answered to develop EPD and tips that should be considered while answering the questions

#	Question	Consider while answering:
1	Select Contaminant	Select the contaminant of concern.
2	Is surface soil contaminated?	Select 'yes' if there is an obvious contamination in surface soil.
3	Are plants (vegetables and fruits) grown on/around contaminated site consumed?	Select 'yes' if people are consuming the vegetables or fruits grown on the contaminated soil.
4	Will contaminants in surface soil potentially reach surface water?	Select 'yes' if there is a surface water body that is contaminated or has the potential of being contaminated. Surface water bodies in surrounding areas or areas downstream of the site, slope of the land, amount of precipitation should be taken into account.
5	Is potentially contaminated surface water used as a source of potable water?	Select 'yes' if considered surface water is used for municipal water supply purposes.
6	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	Select 'yes' if considered surface water is used for recreational purposes such as swimming.
7	Is potentially contaminated surface water used for irrigation?	Select 'yes' if considered surface water is used for irrigation of plants.

Table 3.8 (continued) Questions to be answered to develop EPD and tips that should be considered while answering the questions

#	Question	Consider while answering:
8	Is fish grown in potentially contaminated surface water consumed?	Select 'yes' if people are consuming fish caught from (potentially) contaminated surface water.
9	Is subsurface soil contaminated?	Select 'yes' if the source is underground or if contamination in the surface soil seeps (or has the potential to seep) in subsurface soil.
10	Will contaminants in subsurface soil potentially reach groundwater?	Consider soil texture in unsaturated zone, depth to aquifer, mobility of the contaminant.
11	Is potentially contaminated groundwater used as a source of potable water?	Select 'yes' if considered groundwater is used by residents and institutions for drinking or for other purposes such as bathing.
12	Is potentially contaminated groundwater used for irrigation?	Select 'yes' if considered groundwater is used for irrigation of plants.
13	Will contaminants in groundwater potentially reach surface water?	Consider surface water bodies in surrounding areas or areas downstream of the site and groundwater discharge to surface water.
14	Is potentially contaminated surface water a source of potable water?	Select 'yes' if considered surface water is used for municipal water supply purposes.
15	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	Select 'yes' if considered surface water is used for recreational purposes such as swimming.
16	Is potentially contaminated surface water used for irrigation?	Select 'yes' if considered surface water is used for irrigation of plants.
17	Is fish grown in potentially contaminated surface water consumed?	Select 'yes' if people are consuming fish caught from (potentially) contaminated surface water.

As it is mentioned before, some of the questions should only be answered depending on the answer of another related question. This situation is explained below:

- Questions from number 2 to number 8 are related to surface soil contamination. If surface soil is not contaminated, i.e. the answer to question number 2 is 'no', then there is no need to answer questions from 3 to 8.
- Questions from number 4 to 8 are related to surface water contamination resulting from contaminated surface soil. If there is no possibility that contaminants in surface soil reaches surface water, i.e. the answer to question number 4 is 'no', then there is no need to answer then questions from 5 to 8.
- Questions from number 9 to number 17 are related to subsurface soil contamination. If subsurface soil is not contaminated, i.e. the answer to question number 9 is 'no', then there is no need to answer questions from 10 to 17.
- Questions from number 10 to 17 are related to groundwater contamination resulting from contaminated subsurface soil. If there is no possibility that contaminants in subsurface soil reaches groundwater, i.e. the answer to question number 10 is 'no', then there is no need to answer questions from 11 to 17.
- Questions from number 13 to 17 are related to surface water contamination resulting from contaminated groundwater. If there is no possibility that contaminants in groundwater reaches surface water, i.e. the answer to question number 13 is 'no', then there is no need to answer questions from 13 to 17.

All these conditions and circumstances are considered while developing the decision assistance tool. The user gets a warning messages when the answer to one of the questions number 2, 4 , 9, 10 or 13 is 'no'.

When the answers to the questionary are completed, the results should be submitted to see the site specific exposure pathway diagram. A 'submit button' is put in the bottom of the form, which directs the user to complete worksheet and get the output.

While developing this questionary, several tools within Microsoft Excel are used. Dropdown list for selecting contaminant and radio buttons for answering the questions are built using *Form Controls* in *Controls* toolbox. The results of each selection are assigned to cells in the same worksheet which can not be seen by the user. For contaminant selection, the assigned cell takes one of the values from 1 to 148. For each of the 16 question, the cells assigned to that question can take the values 1 or 2. These values (or a combination of them) determine whether an exposure pathway is valid or potentially applicable for receptors of concern. Relationship between the answers of the questions and validity of exposure pathways are set by the help of some excel functions, especially *if function*. Details of these relations are given in Appendix B. User forms and VBA is used to develop information buttons, warning messages and submit button. VBA codes (macros) are also given in Appendix B.

(ii) Database

Database worksheet includes the chemical based information required to decide whether an exposure pathway is a potential concern for a certain chemical which is selected in the questionary. Occurrence of some exposure pathways depend on the type of contaminant. These pathways are direct dermal contact, inhalation of fugitive dust and inhalation of volatiles.

Human health risk via dermal contact is considered for SVOCs (Semi-volatile organic compounds), PAHs, arsenic, cadmium, chlordane, DDT and lindane. For inhalation of fugitive dust, SVOCs and metals are taken into account. On the other hand, only VOCs and mercury (the only volatile metal) are considered for inhalation of volatiles (US EPA, 2002b). The relevance of specific contaminants to these exposure pathways and the procedure used to develop the database is explained below.

For inhalation of volatiles, only volatile organic compounds and mercury are considered (US EPA, 2002b). A literature survey is conducted in order to classify organics as VOCs and SVOCs. According to WHO (World Health Organization) (1989), volatility of organic compounds can be classified with respect to their boiling points. Four classes are defined for an organic chemical: very volatile organic compound (VVOC), volatile organic compound, semi-volatile organic compound and particulate organic matter (POM). Boiling point data for all compounds is taken from Risk Assessment Information System (RAIS) of U.S. Department of Energy (RAIS, 2009). The categories and associated boiling point ranges are given in Table 3.9.

Table 3.9 Categorization of organic chemicals with respect to boiling point (WHO, 1989)

Category	Boiling Point	
	from (^oC)	**to (^oC)**
Very volatile organic compound (VVOC)	<0	50-100
Volatile organic compound (VOC)	50-100	240-260
Semi-volatile organic compound (SVOC)	240-260	380-400
Particulate organic matter (POM)	>380	

This classification is modified according to needs of this study. First, since VVOCs should also be considered for inhalation of volatiles, first two categories are combined under VOCs. Second, 260 ^oC is taken as the upper limit for VOCs. Third, in order to be conservative in selection of exposure pathways, the largest range is taken for SVOCs. Finally, POM is not considered since it is not in the context of this study. Final classification used in developed decision assistance tool is:

VOCs: boiling point < 260 ^{o}C

SVOCs: 240 ^{o}C < boiling point < 400 ^{o}C

The overlap of categories between 240 to 260 ^{o}C does not cause a problem since the aim of developing an exposure pathway diagram is to identify all potential pathways. In the excel sheet, two separate columns are formed for SVOCs and VOCs which analyzes boiling point value of the chemical and classifies it accordingly. If a compound belongs to one of these groups, “1” appears in the associated cell, otherwise “0” appears.

PAHs that take place in the contaminant list of newly proposed Turkish SPCR have “1” in the related column of the database worksheet. Chemicals which are classified as PAHs are determined based on the list given in Harvey (1991). These are acenaphthene, anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenz(a,h)anthracene, fluoranthene, fluorine, indeno(1,2,3-cd)pyrene, naphthalene, and pyrene.

According to these classifications, each chemical has a value of “1” or “0” for dermal contact, inhalation of fugitive dust and inhalation of volatiles. If the chemical is SVOC, PAH, arsenic, cadmium, chlordane, DDT or lindane; then it has “1” in the column indicating dermal contact. If the selected compound is a SVOC or a metal, its value for inhalation of fugitive dust pathway is “1”. In the same way, if the compound is a VOC or mercury, then there is “1” in the column of inhalation of volatiles. Namely, each compound in the list has a value of “1” or “0” for these three exposure pathways. When the contaminant of concern is selected in the questionary, it is automatically found in the database worksheet by the help of a *lookup function*. The values that the contaminant gets for mentioned pathways are determined and it is written in a summary table. For instance, if the contaminant of concern is benzene, only inhalation of volatiles will be considered among these three exposure pathways. On the other hand, if the contaminant selected in the questionary is lindane, dermal contact and inhalation of fugitive dust exposes potential risk to human health. In Table 3.10, the values for benzene and lindane are given as an example. These three values given in the summary table are used in the *if statements* in the output worksheet to determine whether a pathway is relevant or not.

Table 3.10 Summary table for benzene and lindane

Contaminant:	**Dermal Contact:**	**Inhalation of Fugitive Dust:**	**Inhalation of Volatiles:**
Benzene	0	0	1
γ-HCH (Lindane)	1	1	0

(iii) Output: Site Specific EPD

As noted previously, after all questions in the questionary are answered, the answers should be submitted. A button is used to automatically direct the user to worksheet including the exposure pathway diagram. In the output sheet, the potential exposure pathways are indicated with a "✓" sign in accordance with the selected contaminant and answers given to the questions. Other pathways are indicated with a "×" sign. A screenshot of the output sheet is given in Figure 3.8. Since occurrence of each pathway and receptor combination depends on certain conditions, each cell associated to a combination is defined by an *if statement.* Some examples are given below in order to explain the logic behind the relationship between the questions in the questionary and exposure pathways.

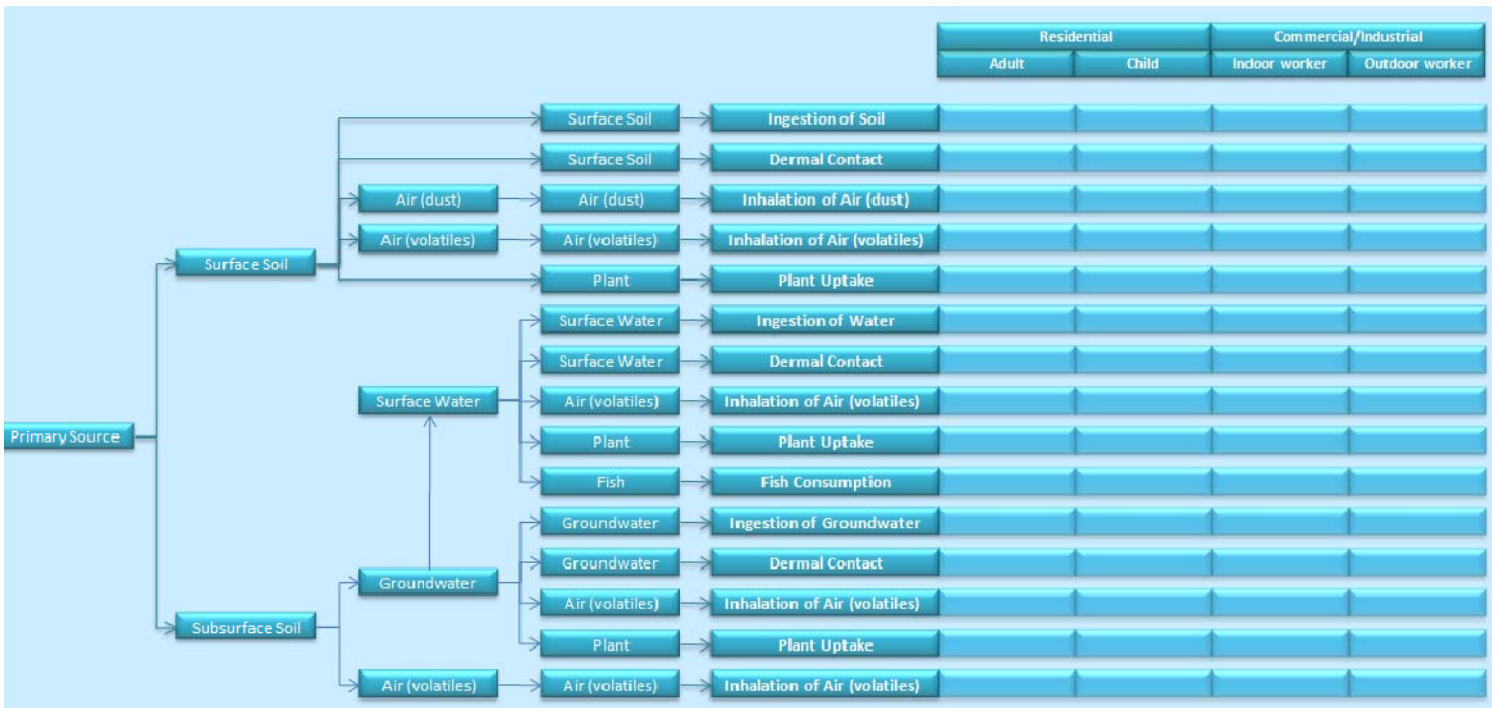


Figure 3.8 A screenshot of EPD given in output sheet before the questionary is completed

Example 1: Soil ingestion is only considerable when surface soil is contaminated and receptor is children. However, this exposure does not depend on the contaminant type. In other words, this will be an open pathway for children if surface soil is contaminated, regardless of contaminant type. Therefore, "+" sign will be seen in the associated cell if Question 2 is answered as 'yes'.

Example 2: Inhalation of dust is a valid pathway for residential receptors (adult and child) as well as outdoor workers. Surface soils contaminated with SVOCs or metals are of potential concern. Therefore, if selected contaminant is a SVOC or metal and if answer to Question 2 is 'yes', then inhalation of fugitive dust is a potential exposure pathway for adults, children and outdoor workers.

Example 3: Dermal contact to contaminated groundwater is considered for SVOCs, PAHs, arsenic, cadmium, chlordane, DDT or lindane contamination if subsurface is contaminated and if contaminants in subsurface soil potentially reach groundwater. In addition, in order for a receptor to have a dermal contact with the contaminated water there are two possible conditions. First, potentially contaminated groundwater is used as a potable water source which means dermal contact during showering exists. Second, potentially contaminated groundwater is used for recreational purposes such as swimming. However, the second possibility is only valid for residential receptors. There will be a '+' sign in the associated cells if answer to questions 14 or 15 (for residential receptors) are 'yes', in addition to questions 9, 10, 13 and selected contaminant is one of the abovementioned compounds. Conditions and *if statements* for all exposure pathway receptor combinations are given in Appendix B.

3.3.3 Illustrative Tools

Main objective of developing a CSM during contaminated site studies is to provide a clear picture of the site that is understandable by all stakeholders. This can be provided by the help of illustrative tools. On the other hand, CSM illustrative tools can be used during sampling design and sampling studies. CSM illustrative tools include all site sketches (plan view or cross-sectional) or maps on which source-pathway-receptor linkages are shown. Figure 3.9 and 3.10 are two examples for CSM illustrative tools which are drawn for a hypothetical contaminated site.

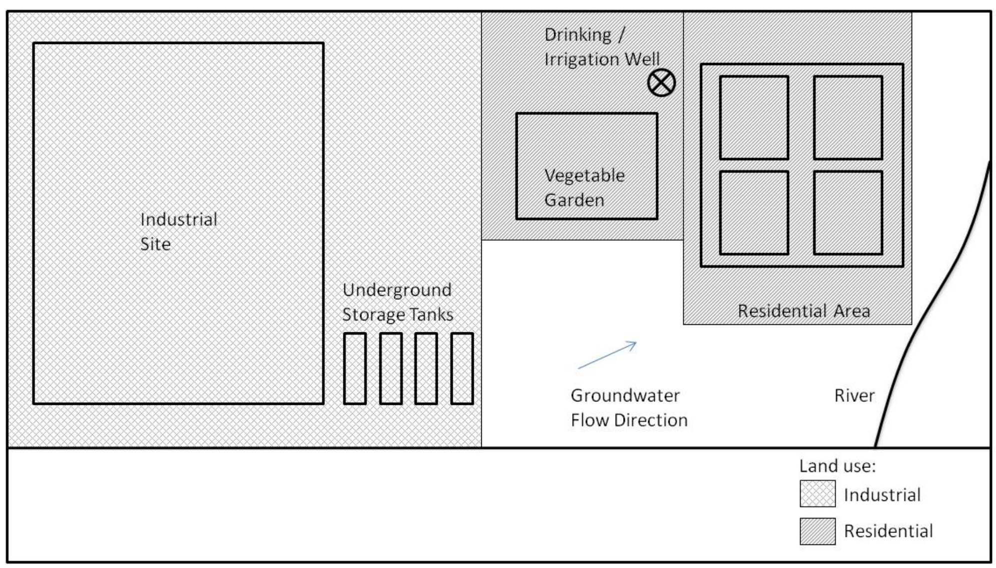


Figure 3.9 Plan view of a contaminated site

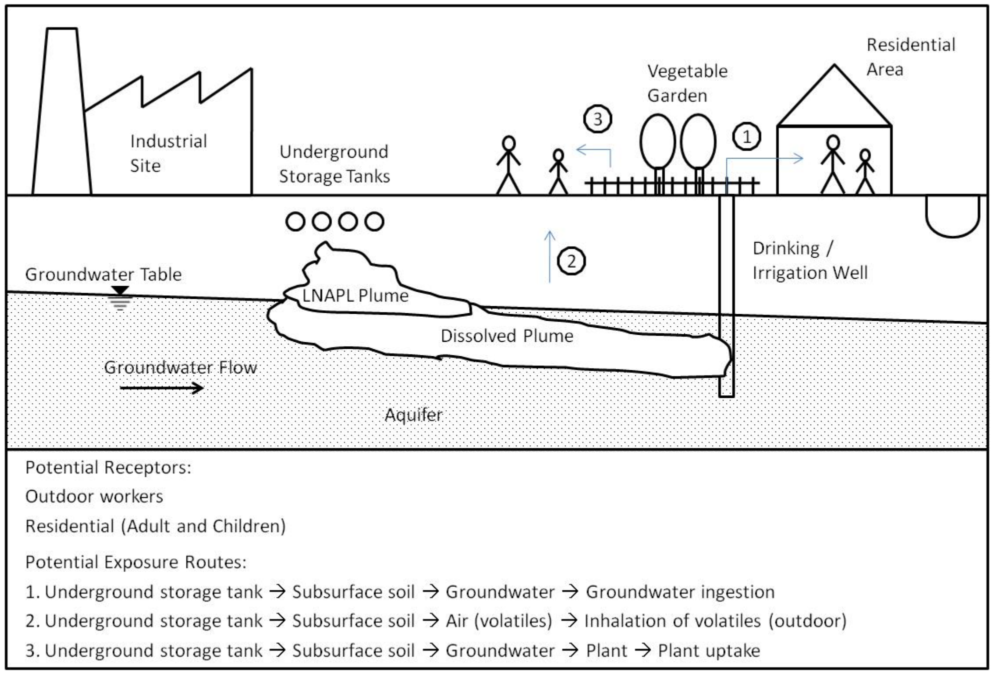


Figure 3.10 Cross-sectional view of a contaminated site

Extent of information included in illustrative tools varies according to the specific contamination case. However, it is possible to make a general list of data that can be marked on:

- Site boundaries
- Current land use
- Buildings, gardens and play grounds
- Surface water resources
- Geological layers and their thicknesses
- Hydrogeologic units
- Depth to groundwater
- Groundwater flow direction
- Source location
- Potential receptors
- Potential pathways (can be illustrated using arrows)

In CSM form given in Appendix A, some of the questions have a '*' sign, indicating that they should also be marked in maps or diagrams.

Level of complexity of illustrative tools is case specific and it depends on the extent and complexity of contamination at the site. Number of compounds, number of sources, contaminated media (e.g., surface soil, groundwater, etc.), and exposure pathway affect complexity of illustrative tools. For instance, if one compound is releasing from one single source its representation on a cross-sectional diagram will be simpler compared to multiple compounds releasing from single/multiple sources.

As it is mentioned in Section 3.1, CSM should be updated as soon as new data is collected. Therefore the level of detail of illustrative tools will increase with the progress in site assessment stages. In the initial CSM, information collected by the help of CSM form and potential pathways identified using EPD should be transferred to illustrative tools. The first illustrative tool developed for a site may be a simple site plan on which only the potential sources, pathways and receptors are marked. As the investigations carried out, exact sources, pathways and receptors will be determined rather than potential ones. Moreover, subsurface properties and contaminant distribution will be clarified with sampling studies. For instance, if the source is underground, after sampling studies, subsurface geological and hydrogeological properties should be embedded into the illustrative tools. In the same way, contaminant plumes and concentration contours may be shown on a map or site plan after soil or groundwater or both are sampled to identify the contaminant distribution. In the remediation stage, where the contaminant distribution and subsurface properties are exactly known, 3D drawings can be used for remedial investigations or remedial design.

CHAPTER 4

CASE STUDY APPLICATIONS

The methodology developed for building CSM is applied to two case studies for several reasons. First, assessing the utility and applicability of the methodology is aimed. Second, case study applications are expected to make the concepts developed in this study clear. Third, examples of reporting for CSM building and site investigations are provided. Finally, it enables us to discuss the benefits of developing a decision support tool for CSM.

Within the scope of case study applications, two real contaminated site problems are handled. Both of these cases are assessed by and remediation measures are applied for one of these cases. Thus, this enables to evaluate the effectiveness of the developed methodology. First, initial conceptual site models are built using required information given in related reports. For this purpose, CSM form is filled out, EPD is formed using the developed tool and illustrative tools are prepared. Afterwards, initial CSM is evaluated in order to guide site investigation studies. Sampling studies are designed and performed according to this evaluation. Regarding the results of sampling, CSM is updated and updated CSM tools are presented. Updated CSM is evaluated in order to decide the scope of further studies including risk assessment and remediation.

First case is polychlorinated biphenyl (PCB) contamination occurred due to storage activities in İncirlik Air Base (AB). Second case is a hydrocarbon contamination case in a refinery. The following sections in this chapter are written as if the activities including investigations and assessments were really performed.

4.1. PCB Contamination in İncirlik Air Force Base

This study is based on remedial investigation reports prepared for PCB contaminated soils study in İncirlik AB (Law Environmental Inc., 1997). It is assumed that investigations have been started after the notification of the involved institution. In other words, the contamination case is handled as if there are no previous investigations, although the reports included results of site characterization studies.

Some part of the information presented in the reports is used in a later stage of case study application. For instance, although there were contaminant concentration data prior to remedial investigation, it is not considered in the preliminary investigation while implementing the case study.

4.1.1. Initial Conceptual Site Model

A desk study including review of existing documents and reports is followed by a site visit. As it is mentioned in Section 3.1, existing or historical data collected during desk-based study and site visit is used for developing initial CSM. First, CSM form is filled out using the gathered information. The completed CSM form for İncirlik AB is given in Appendix C and the explanations for CSM form are given in Section 3.3.1. Based on the collected data, exposure pathway diagram is developed by the help of EPD decision assistance tool. Finally, source-pathway-receptor linkages are given in CSM illustrative tools.

4.1.1.1. CSM Form

Site Assessor

Conceptual site model is developed by Beril Büyüker from Middle East Technical University.

General Site Information

The old Defense Reutilization and Marketing Office (DRMO) yard at İncirlik AB in Adana was used for storage of oil drums containing PCBs between early 1970s and 1988. During storage and pick up activities, PCBs leaked from several drums into surface soil. In 1991, the soil is excavated and stored in approximately 300 drums and in pile of soil on the site. DRMO is currently not in use.

The area belongs to İncirlik AB and the land use is considered to be industrial/commercial. However, there is the possibility that the site may be used for housing or as a playground after remediation. Thus, future land use is residential, considering the worst-case scenario.

The main surface features in the old DRMO yard included: an excavation of approximately 62 meters in length, 16 meters in width and 0.5 meters in depth; the stockpile and approximately 300 drums containing approximately 500 cubic meters of soil. The area of old DRMO is generally flat with various type of vegetation cover, including the excavation and stockpile. The site is surrounded by a chain link fence and barriers.

Site characteristics

There is no information on site geology or hydrogeology. Climate of İncirlik region is semi-arid. According to data taken from website of Turkish State Meteorological Service, annual average precipitation is 670.8 mm; annual average temperature is 19.1 ^{o}C. Average wind speed is 1.4 m/s and most frequent wind direction: is North - Northeast.

Source

The sources of contamination at the site are soil stockpile and excavation pit in addition to approximately 300 drums containing PCB contaminated soil. Further information on the locations of the sources is presented in Section 4.1.1.3. The sources are unprotected.

Contaminant/contamination

Contaminant of concern is PCBs which are a group of synthetic organic chemicals that can cause a number of different harmful effects.

The following information on PCBs was gathered from ATSDR (2000). PCBs are either oily liquids or solids. They are colorless to light yellow and have no known smell or taste. PCBs are highly persistent, i.e., they do not readily break down and therefore may remain for very long periods of time. Heavy kinds of PCBs are more likely to settle into soil/sediment while lighter PCBs are more likely to evaporate to air. PCBs are taken up into the bodies of small organisms and fish in water. They are also taken up by other animals that eat these aquatic animals as food. In water, PCBs may be transported by currents, attach to bottom sediment or particles in the water, and evaporate into air. Sediments that contain PCBs can also release the PCBs into the surrounding water. PCBs adsorb strongly to soil and will not usually be carried deep into the soil with rainwater. Skin conditions, such as acne and rashes, may occur in people exposed to high levels of PCBs. Some studies in workers suggest that exposure to PCBs may also cause irritation of the nose and lungs, gastrointestinal discomfort, changes in the blood and liver, and depression and fatigue. There are not any samplings or measurements for contaminant concentration. Contamination is obvious in surface soil. Subsurface soil and groundwater should be investigated.

Receptors

The old DRMO yard is currently not in use. There are residential settings in the south of the site, south of the İstanbul drive. In the east of the site there is a playground, baseball field and school, east of D street, and houses lie to the east of these. North and west of the site are base buildings such as warehouses. The most likely receptors are future site workers, including future on-site industrial workers and utility workers and local youth that may trespass at the site. Residential receptors have also potential to be exposed to contamination, considering the residential future land use scenario. Due to the proximity of both industrial and residential areas, both future workers and local residents will be included as potential receptors during risk evaluation.

There are not any surface water bodies around the site. Drainage canals are present; however they are not used for any purpose. Since the site is flat, the climate is semi-arid, soils are very dense, run-off from the site drains to excavation pit which has neither inlet nor outlet to surface water. There are several groundwater wells used as potable water source of İncirlik AB. Some of them are located at a distance approximately 200-300 meters from the contaminated area. Depths of these wells are varying approximately between 60 to 120 meters.

Assumptions and Uncertainties

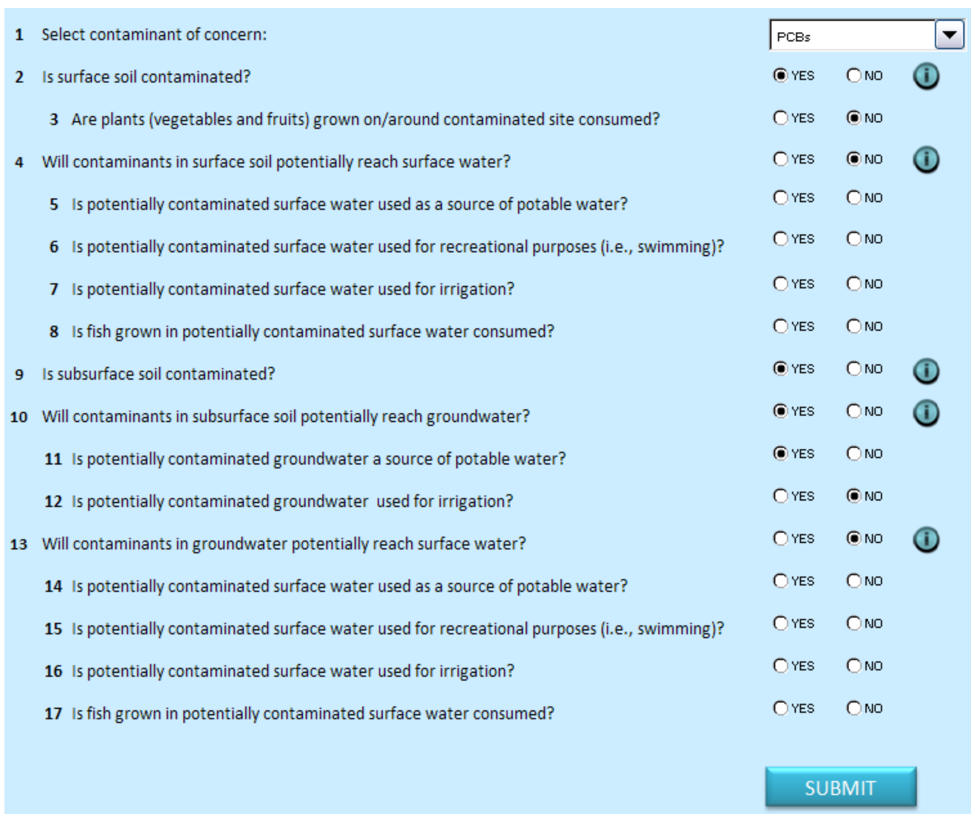
There is lack of information on geological and hydrogeological characteristics at the source area. Moreover, extent and concentration of PCB contamination in surface and subsurface soil should be identified for risk assessment studies.

Additional Information

Several photographs taken during site visit are presented in Attachment A of CSM form.

4.1.1.2. Site Specific EPD

Following the desk –based study, site visit and filling out CSM form, a site specific EPD is developed in order to see the potential exposure routes. EPD decision assistance tool is used for developing the diagram. The screenshot of the filled out questionary is given in Figure 4.1. Explanations of answers to each question are given in Table 4.1.



1	Select contaminant of concern:	PCBs
2	Is surface soil contaminated?	(•) YES ( ) NO
3	Are plants (vegetables and fruits) grown on/around contaminated site consumed?	( ) YES (•) NO
4	Will contaminants in surface soil potentially reach surface water?	( ) YES (•) NO
5	Is potentially contaminated surface water used as a source of potable water?	( ) YES ( ) NO
6	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	( ) YES ( ) NO
7	Is potentially contaminated surface water used for irrigation?	( ) YES ( ) NO
8	Is fish grown in potentially contaminated surface water consumed?	( ) YES ( ) NO
9	Is subsurface soil contaminated?	(•) YES ( ) NO
10	Will contaminants in subsurface soil potentially reach groundwater?	(•) YES ( ) NO
11	Is potentially contaminated groundwater a source of potable water?	(•) YES ( ) NO
12	Is potentially contaminated groundwater used for irrigation?	( ) YES (•) NO
13	Will contaminants in groundwater potentially reach surface water?	( ) YES (•) NO
14	Is potentially contaminated surface water used as a source of potable water?	( ) YES ( ) NO
15	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	( ) YES ( ) NO
16	Is potentially contaminated surface water used for irrigation?	( ) YES ( ) NO
17	Is fish grown in potentially contaminated surface water consumed?	( ) YES ( ) NO

SUBMIT

Figure 4.1 Questionary filled out for İncirlik Air Base

Table 4.1 Explanations of the answers given for developing EPD for İncirlik AB

Question	Explanation of the Answers
1	The contaminant of concern is PCBs.
2	There is an obvious contamination in surface soil.
3	There is no evidence that plants (vegetables or fruits) are grown on/around the site.
4	Contaminants in surface soil will not reach surface water (via surface runoff) due to several reasons. First, there is not a surface water body around the site. Secondly, the area is comparatively flat and soil is dense clay. Finally, drainage canals at the site have no inlet or outlet to a surface water body.
5 to 8	Not answered since surface runoff is not possible.
9	Contaminants in surface soil may reach (or may have reached) subsurface soil.
10	Despite the fact that depth to groundwater is expected to be around 20 meters and PCBs are highly persistent compounds, there is still the possibility that contamination in subsurface soil reaches groundwater.
11	Potentially contaminated groundwater is used as a source of potable water from several wells in the air base.
12	Groundwater is not used for irrigation.
13	The potential for surface water contamination due to groundwater contamination is negligible.
14 to 17	Not answered since there is no possibility that surface water is contaminated by contaminants in groundwater.

EPD, built following the submission of the query, is given in Figure 4.2. As can be seen from Figure 4.2, potential exposure routes are: (i) ingestion of soil by children, (ii) direct dermal contact to contamination by adults and children, (iii) inhalation of PCBs together with fugitive dusts in the air by adults, children and outdoor workers, (iv) ingestion of contaminated groundwater by adults, children, indoor workers and outdoor workers, and (v) dermal contact to contaminated groundwater by adults, children, indoor workers and outdoor workers.

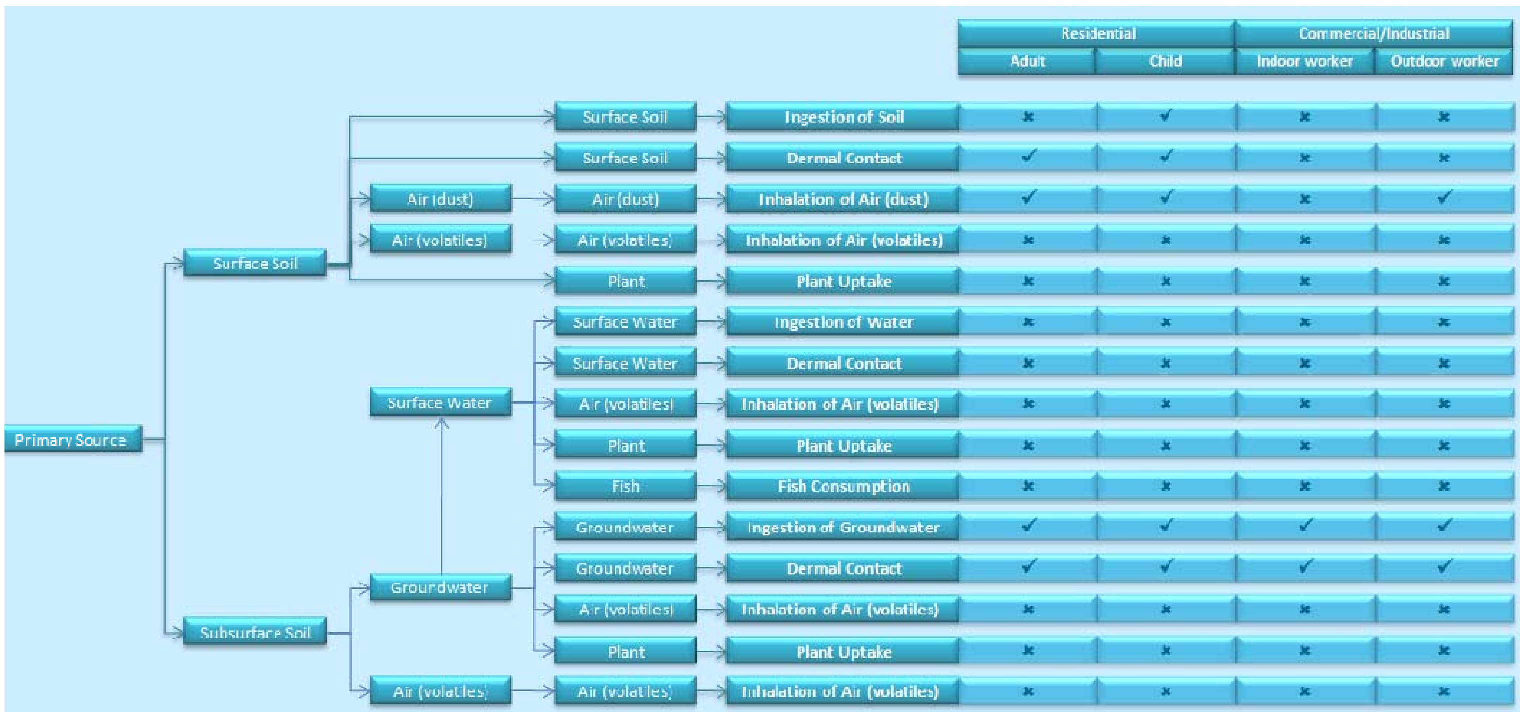


Figure 4.2 EPD developed for İncirlik Air Base

4.1.1.3. Illustrative Tools

Following the preliminary investigations, the sources and potential receptors are drawn on a site plan. The sketch is given in Figure 4.3.

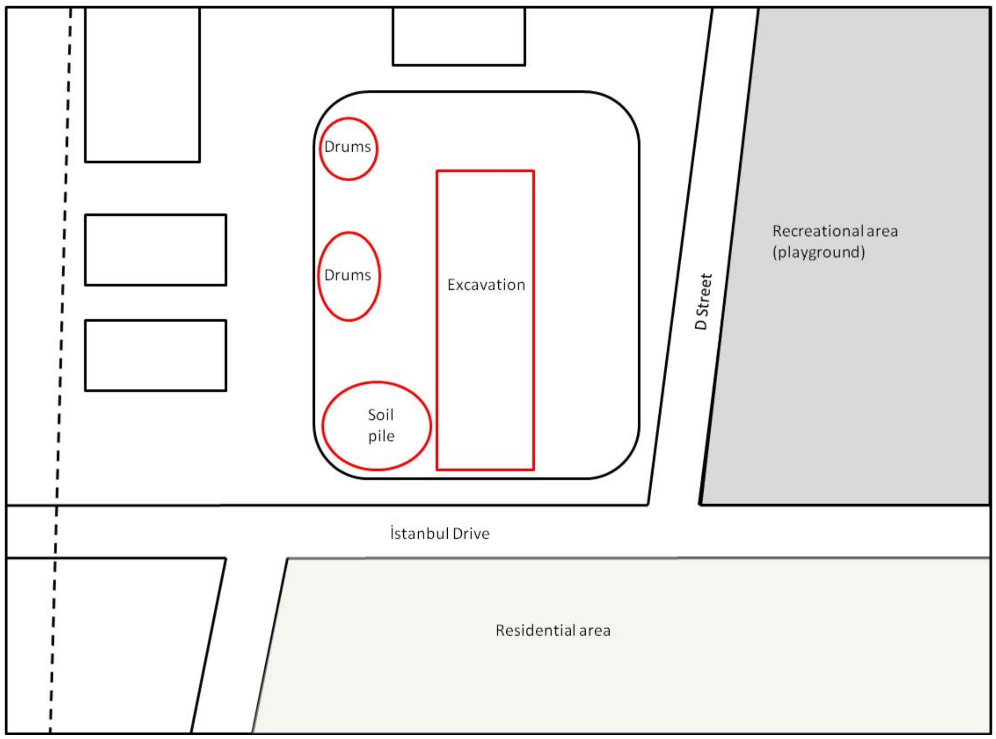


Figure 4.3 Contamination sources marked on a site sketch

4.1.1.4. Evaluation of Initial CSM and Data Gap Identification

Initial CSM provided a clear overview of the site. Existing and collected information is put together by the help of CSM form. Location of sources and land use types around the contaminated area are illustrated in a site plan. Finally, potential exposure pathways are identified by the help of EPD tool.

As it is noted before, exposure pathways should be identified prior to risk assessment studies. Therefore, uncertainties detected after initial CSM should be clarified during site investigation. Data gap and uncertainties identified by the help of CSM tools constitute the basis and scope of sampling studies.

As can be seen from CSM form for İncirlik AB, some part of data which is important for site characterization is missing. This data gap should be filled during sampling. Thus, geological and hydrogeological data should be collected at the source area. Moreover, in order to characterize the extent of contamination, PCB concentration should be measured both in source locations (excavation pit + soil pile + drums) and remaining part of the yard. The depth of PCB contamination should be determined by sampling subsurface soil.

Furthermore, uncertainties met during development of EPD should also be considered. As it is explained in Section 4.1.1.2, although it has not been justified yet, groundwater contamination is assumed to be highly likely in order to be conservative. Sampling should also aim at justifying if groundwater is contaminated. To summarize following data should be collected during site investigation:

(i) for justification of groundwater contamination: stratighraphy, hydraulic conductivity and depth to groundwater;

(ii) for identification of extent of contamination: PCB concentrations in surface and subsurface soils should be determined.

4.1.2. Sampling

Sampling activities should be performed to obtain data to meet following objectives:

- Determine horizontal and vertical extent of PCBs in the surface and subsurface soils.

- Perform field and laboratory tests for characterization of the physical and hydraulic properties of site soils.
- Collect site specific groundwater data.

4.1.2.1. Sampling Design

In order to reach the objectives listed above, sampling design should be done. For this purpose, decision tree for sampling design given in Section 3.2 is used. Targeted sampling can be performed for the stockpile since location and characteristics of contamination are known. For excavation pit and its surroundings, targeted sampling is not applicable. Contaminant distribution along the site is not known to be homogenous. Therefore, simple random sampling will not be advantageous.

On the other hand, since source locations handled separately, there is not an obvious differentiation on contaminant distribution. Thus, systematic grid sampling is suggested for this area. Figure 4.4 indicates the decision flow for sampling design both for stockpile, and within and around the excavation pit. Sampling points selected for surface soil can also be used for taking samples from subsurface soil.

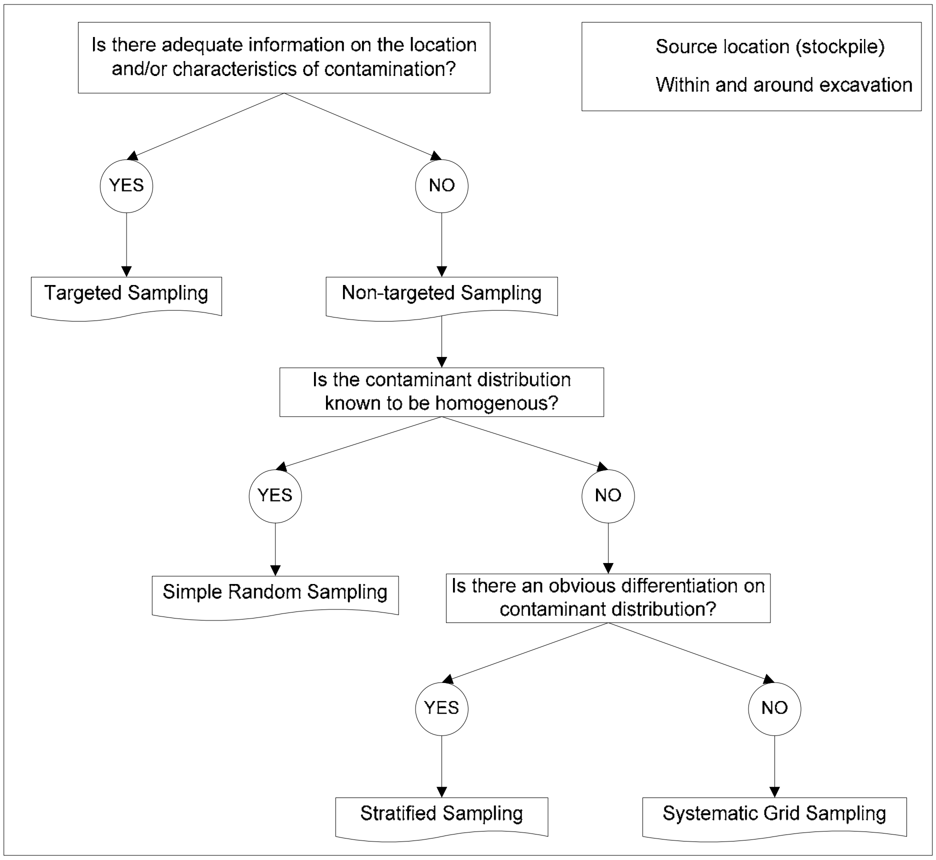


Figure 4.4 Sampling design types suggested for İncirlik AB

4.1.2.2. Sampling Activities and Results

According to the objectives listed above, site investigation aims at determining PCB concentrations and subsurface hydrogeology of the site. The horizontal and vertical extent of PCB contamination in the site soils was determined by collecting soil samples at the surface and at various depths across the site. According to the results of study, subsurface PCB concentrations are negligible. However, there is significant amount of PCBs in the stockpile and around the northeast edge of the excavation pit.

To define subsurface hydrogeology of the site, three soil borings were drilled. An aquifer was not encountered within the upper 20 meters of the site. The geotechnical data included moisture content, particle size, and Atterberg Limits. In-situ soil infiltration tests were performed. Hydraulic conductivity was measured; values ranged from 5.2×10^{-7} cm/s to 5.84×10^{-6} cm/s. Considering site stratigraphy, the boring data indicate that the site is underlain by clay and silty clay with occasional sand lenses.

The vertical extent of contamination appears to be restricted to the top 0.5 meters of soil. Soil infiltration tests, hydraulic conductivity tests, and the lithological profile of the site suggest that migration of the PCBs to depth greater than 0.5 meters has not occurred. The dense clay identified at the site does not allow infiltration of PCB components in significant depth. Depth to groundwater was determined to exceed well beyond 20 meters below the soil surface. Therefore, the potential for contaminant migration into the groundwater from the site is essentially non-existent.

4.1.3. Updated CSM

Information lacking at the beginning, which is collected during site investigation should be reflected to CSM form. Information or data that should take place in updated CSM form are: contaminant concentrations, geological layers, hydraulic conductivity and depth to groundwater table.

One of the main objectives of site investigation was to overcome the uncertainties encountered while developing EPD. For this purpose, the potential for groundwater contamination with PCBs was investigated and EPD is modified accordingly. Since groundwater is not found down to 20 meters and there is not a significant contamination in subsurface soil, site soils are dense clay and PCBs are highly sorptive chemicals, it is decided that groundwater contamination is not likely. Updated EPD is presented in Figure 4.5.

In light of the results of the sampling studies, new maps and/or drawings may be used to illustrate the site and contamination. For this purpose, PCB concentration contours can be reflected on a scaled site map. Sampling points and locations of soil borings can also be indicated on these maps. Moreover, soil and subsurface properties can be used to draw cross-sectional diagrams that will be useful in risk assessment stage.

In conclusion, potential exposure pathways that should be taken into account for risk assessment are determined as:
(i) Surface Soil → Ingestion of Soil (for children)
(ii) Surface Soil → Dermal Contact (for children and adults)
(iii) Surface Soil → Inhalation of Air (dust) (for children, adults and outdoor workers).

Risk assessment should be performed considering the identified pathways. Remedial investigations should also be conducted according to contaminant distribution and soil and subsurface properties at the site, as well as exposure pathways.

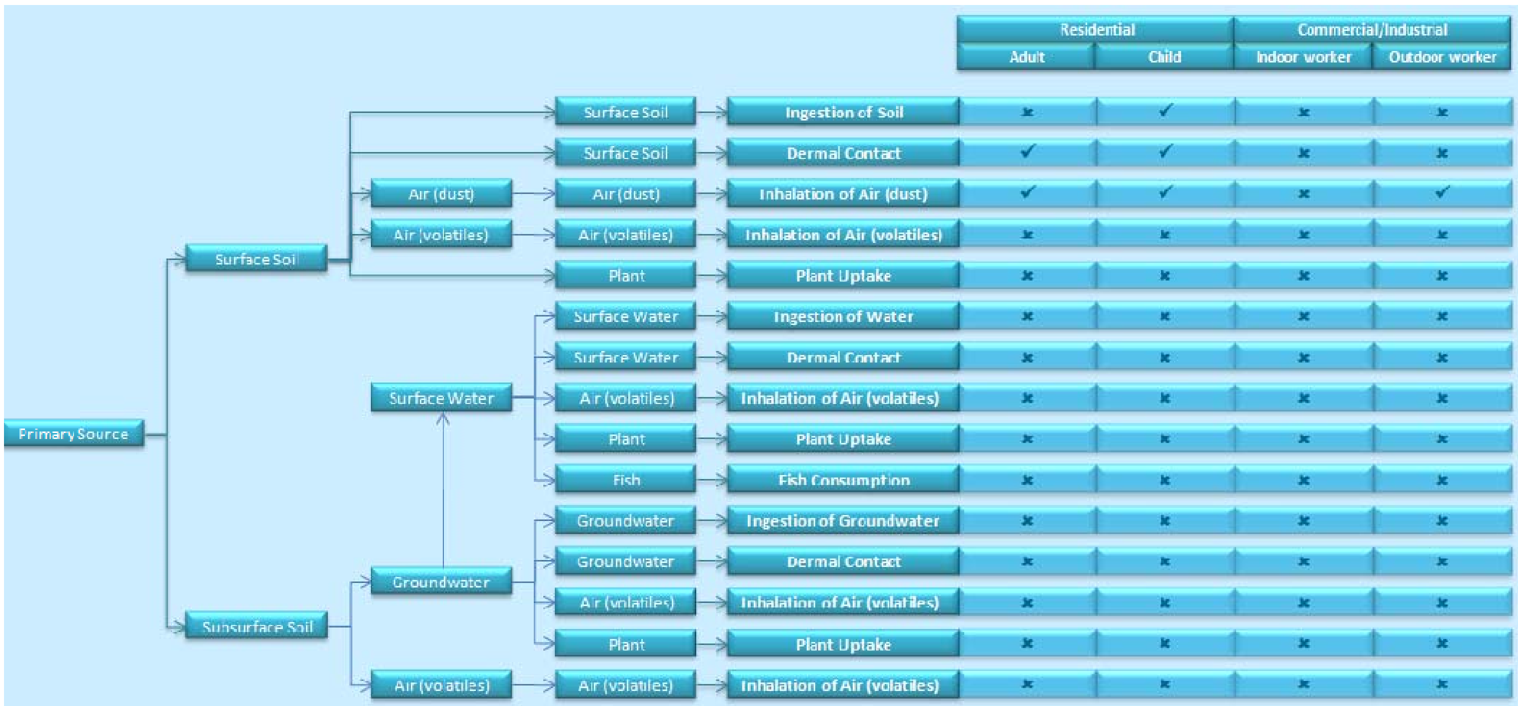


Figure 4.5 Updated EPD for İncirlik AB

4.2. Hydrocarbon Contamination in Soil and Groundwater

This case study is based on confidential report prepared by a governmental institution in order to characterize groundwater pollution in a province where a refinery is present (Confidential Report, 2005). Hydrocarbons leaking from the refinery over the years had reached the groundwater and moved through the city center. Groundwater contamination came out with a serious explosion at a commercial site in the city center resulting in deaths and injuries. Following the explosion, several groundwater and soil-gas samples were taken to determine the extent of the contamination. It is determined that groundwater was highly contaminated especially in some parts of the city around the refinery and commercial site where the explosion occurred.

The report prepared for this case aims to investigate the contamination in groundwater, to identify the geological formations, to determine the direction of groundwater flow and to find out extent and distribution of the contamination. It is assumed that no contaminant measurements had been conducted prior to development of initial CSM, although the report includes the results of several sampling studies. On the other hand, data on geology and hydrogeology of the site, which is also given in the report, is considered as if it already existed from previous investigations. Moreover, although it was not proved legally, the source of pollution is attributed to the refinery.

4.2.1. Initial Conceptual Site Model

A desk study including review of existing documents and reports is followed by a site visit. As it is mentioned in Section 3.1, existing or historical data collected during desk-based study and site visit is used for developing initial CSM. First, CSM form is filled out using the gathered information. The completed CSM form for the refinery is given in Appendix D and the explanations for CSM form are given in Section 3.3.1. Based on the collected data, exposure pathway diagram is developed by the help of EPD decision assistance tool. Finally, source-pathway-receptor linkages are given in CSM illustrative tools.

4.2.1.1. CSM Form

Site Assessor

Conceptual site model is developed by Beril Büyüker from Middle East Technical University.

General Site Information

Hydrocarbon pollution at the site first came into the picture after a fatal explosion in city center. The suspected source of contamination is the petroleum refinery, which is approximately 100 meters away from the commercial buildings where the explosion had occurred. Contamination has occurred due to leak of products during storage or transport within the facility. Contaminants moved with the groundwater flow. Volatile contaminants had accumulated in the basements of buildings resulting in an explosion.

The refinery is in the city center and surrounded by residential or commercial buildings as well as other industrial sites. The refinery is still in use.

Site characteristics

Şelmo formation which consists of clay, sandstone and gravel, is very common around the contaminated site. The major unit is clay. Thickness of this layer is approximately 50 m. Around the valley of the river, alluvial soils are common. The thickness of this layer is approximately 10-12 m. Depth the groundwater in the region varies between 5 to 10 m.

According to statistical data for the site taken from website of Turkish State Meteorological Service, annual average precipitation is 484.7 mm; annual average temperature is 16.6 ^{o}C. Average wind speed is 1.2 m/s and most frequent wind direction: is West.

Source

Although it is assumed that the contamination has originated from the petroleum refinery, specific source location where the contaminants had leaked is not identified.

Contaminant/contamination

The contaminant of concern is BTEX. The following information on BTEX was gathered from ASTDR (2004). Media contaminated with these chemicals include air, water, and soil. Contamination of groundwater can result in volatilization into indoor air when the groundwater is used as household water. In addition, contamination of groundwater and subsurface soil can result in migration of these chemicals into basements as soil gas. Each of the chemicals in the mixture of concern is volatile, well absorbed, extensively metabolized, and does not persist in the body for long periods of time. All of the BTEX chemicals can produce neurological impairment via parent chemical-induced changes in neuronal membranes. Benzene can additionally cause hematological effects, which may ultimately lead to aplastic anemia and acute myelogenous leukemia. There is evidence that ethylbenzene is carcinogenic in other tissues. No studies were located that directly examined joint toxic actions of benzene, toluene, ethylbenzene, and xylenes on the nervous system, but additive joint neurotoxic action is plausible for environmental exposures based on predictions from physiologically based pharmacokinetic (PBPK) modeling studies with BTEX and a ternary mixture of its components, and supporting data from neurotoxicity interaction studies of binary component mixtures. Toluene and xylenes have been categorized as not classifiable as to human carcinogenicity by, reflecting the lack of evidence for the carcinogenicity of these two chemicals.

There are not any samplings or measurements for contaminant concentration. Contamination is expected to be present in groundwater and soil gas.

Receptors

The site is very close to residential area. Thus, people in residential area including adults and children may be exposed to contaminants. The site is also very close to commercial site where the explosion had occurred. Moreover, both indoor and outdoor workers working at the refinery or at other facilities around it have the risk to be exposed to hydrocarbon pollution.

There is a river to the west of the contaminated area. Contamination may be transported to the river via groundwater since groundwater may be recharging the river. There is a dam built across that river that is used as a municipal water supply. Therefore, it is assumed that the river is used as a potable source of water as well as irrigation, fishing and recreational purposes. There are many groundwater wells on and around the site used for several purposes including drinking and irrigation.

Assumptions and Uncertainties

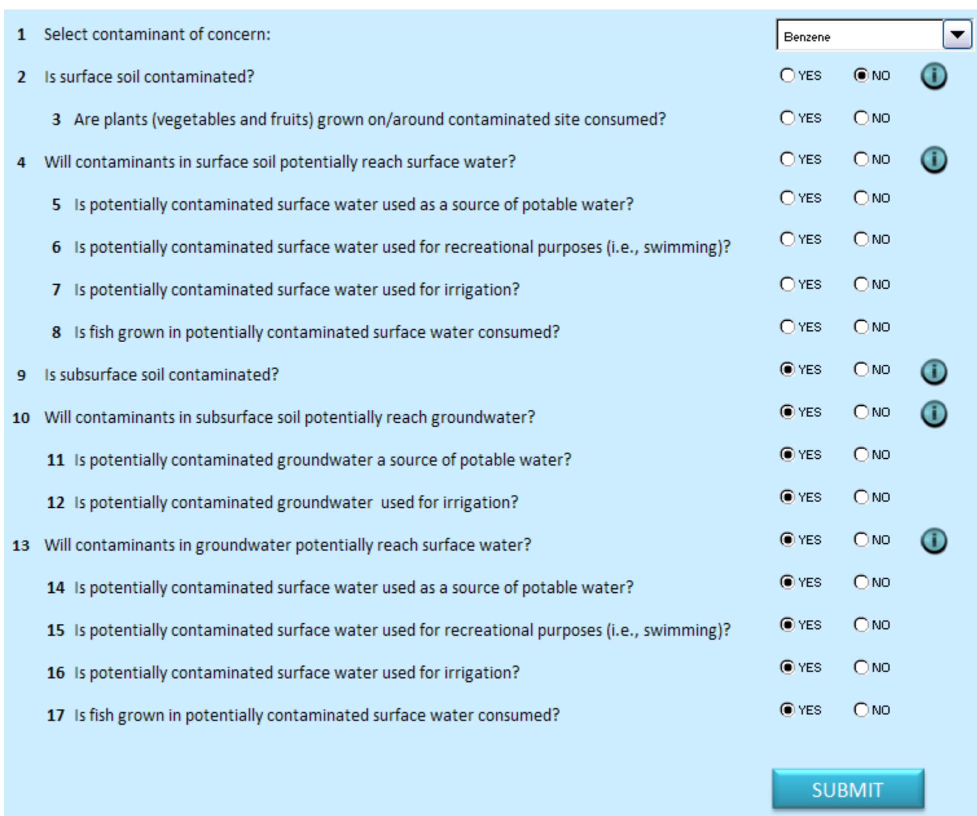
There is lack of information on some geologic and hydrogeologic characteristics at the contaminated site such as hydraulic conductivity. Moreover, distribution and plume of BTEX contamination should be identified for risk assessment studies.

Additional Information

Geological investigation report and boring logs are presented as an attachment.

4.2.1.2. Site Specific EPD

Following the desk –based study, site visit and filling out CSM form, a site specific EPD is developed using EPD decision assistance tool in order to see the potential exposure routes. The screenshot of the filled out questionary is given in Figure 4.6. Explanations of the answers given for developing EPD for hydrocarbon contamination case are given in Table 4.2. Since the decision assistance tool allows selecting individual compounds rather than contaminant groups such as BTEX, the contaminant of concern is selected as benzene because the fate and transport properties of all BTEX compounds are expected to be similar. EPDs for ethylbenzene, toluene and xylenes are also developed. However, they are not presented here since they give the same EPD as benzene.



1	Select contaminant of concern:	Benzene	
2	Is surface soil contaminated?	YES	NO (selected)
3	Are plants (vegetables and fruits) grown on/around contaminated site consumed?	YES	NO
4	Will contaminants in surface soil potentially reach surface water?	YES	NO
5	Is potentially contaminated surface water used as a source of potable water?	YES	NO
6	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	YES	NO
7	Is potentially contaminated surface water used for irrigation?	YES	NO
8	Is fish grown in potentially contaminated surface water consumed?	YES	NO
9	Is subsurface soil contaminated?	YES (selected)	NO
10	Will contaminants in subsurface soil potentially reach groundwater?	YES (selected)	NO
11	Is potentially contaminated groundwater a source of potable water?	YES (selected)	NO
12	Is potentially contaminated groundwater used for irrigation?	YES (selected)	NO
13	Will contaminants in groundwater potentially reach surface water?	YES (selected)	NO
14	Is potentially contaminated surface water used as a source of potable water?	YES (selected)	NO
15	Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?	YES (selected)	NO
16	Is potentially contaminated surface water used for irrigation?	YES (selected)	NO
17	Is fish grown in potentially contaminated surface water consumed?	YES (selected)	NO

SUBMIT

Figure 4.6 Questionary filled out for hydrocarbon contamination case

Table 4.2 Explanations of the answers given for developing EPD for hydrocarbon contamination case

Question	Explanation of the Answers
1	The contaminant of concern is BTEX. However, contaminant list does not include contaminant groups such as BTEX. Therefore benzene, ethylbenzene, toluene or xylenes can be selected.
2	Surface soil is not contaminated. The source of contamination is under the ground and contaminant is not observed above ground surface.
3 to 8	not answered since surface soil is not contaminated.
9	Subsurface soil is contaminated.
10	Contaminant had already reached groundwater.
11	Contaminated groundwater is used as a source of potable water.
12	Contaminated groundwater is used for irrigation.
13	Contamination may reach the river indicated in Figure 4.8.
14	Potentially contaminated surface water is used as a source of potable water.
15	Potentially contaminated surface water is used for swimming.
16	Potentially contaminated surface water is used for irrigation.
17	Fish grown in potentially contaminated surface water is consumed.

EPD, built following the submission of the query, is given in Figure 4.7. As can be seen from Figure 4.7, potential exposure routes are: (i) ingestion of contaminated surface water for all types of receptors, (ii) inhalation of BTEX from contaminated surface water for all types of receptors, (iii) consumption of plants irrigated with contaminated surface water for adults and children, (iv) fish consumption for adults and children, (v) ingestion of contaminated groundwater for all types of receptors, (vi) inhalation of BTEX from contaminated groundwater for all types of receptors, (vii) consumption of plants irrigated with contaminated groundwater for adults and children, and (viii) inhalation of BTEX directly from subsurface soil for all types of receptors.

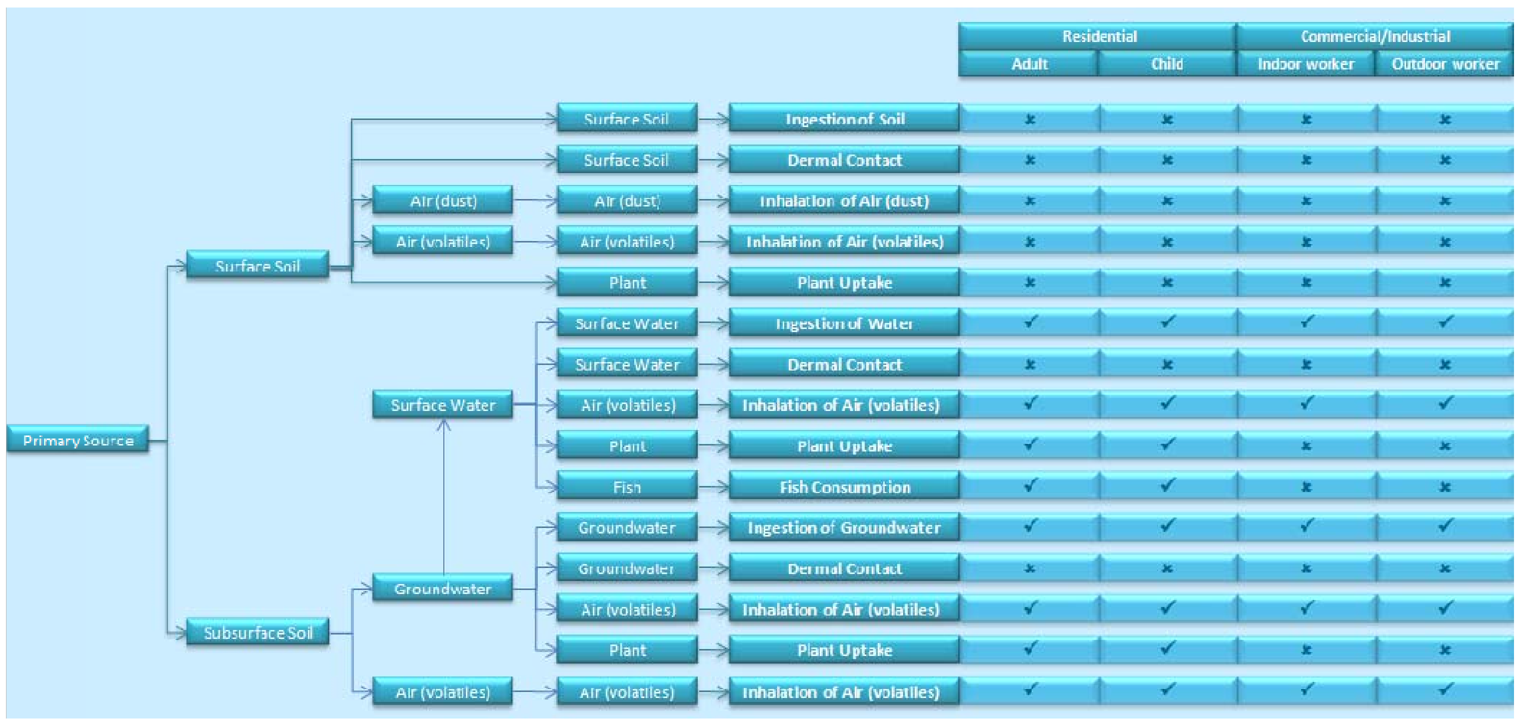


Figure 4.7 EPD developed for hydrocarbon contamination case

4.2.1.3. Illustrative Tools

Following the preliminary investigations, the sources and potential receptors are drawn on a site plan. The sketch is given in Figure 4.8.

Figure 4.8 Plan view of the site and its surroundings

4.2.1.4. Evaluation of Initial CSM and Data Gap Identification

Initial CSM provided a clear overview of the site. Existing and collected information is put together by the help of CSM form. Location of sources and land use types around the refinery are illustrated in a site plan. Finally, potential exposure pathways are identified by the help of EPD tool. As it is noted before, exposure pathways should be identified prior to risk assessment studies.

Therefore, uncertainties detected after initial CSM can be clarified during site investigation. Data gap and uncertainties identified by the help of CSM tools constitute the basis and scope of sampling studies.

As can be seen from CSM form for hydrocarbon contamination case, some part of data, which is important for site characterization is missing. This data gap should be filled during sampling. First, contaminant plume and distribution should be determined in order to characterize the extent of contamination. In addition, missing soil and subsurface properties such as hydraulic conductivity should be determined. Finally, sampling efforts should be done considering the uncertainties met during EPD development. For this purpose, the potential of contaminants to reach the river through groundwater should be determined.

4.2.2. Sampling

Sampling activities should be performed to obtain data to meet following objectives:

- Determine contaminant plume and distribution in the groundwater.
- Perform field and laboratory tests for characterization of the physical and hydraulic properties of site soils.
- Determine the presence or the potential of contamination in the river.

4.2.2.1. Sampling Design

In order to achieve the objectives listed above, an effective sampling design should be done. For this purpose, decision tree for sampling design given in Section 3.2 is used to define the strategy to determine contaminant distribution in groundwater. Targeted sampling is not applicable because the exact location of contamination is not known. Contaminant distribution along the site is not known to be homogenous. Therefore, simple random sampling will not be advantageous. On the other hand, there is not an obvious differentiation on contaminant distribution. Thus, systematic grid sampling is suggested to determine the contaminant distribution at the site. Figure 4.9 indicates the decision flow for sampling design for the contaminated site. Sampling points selected for groundwater can also be used for taking samples from subsurface soil.

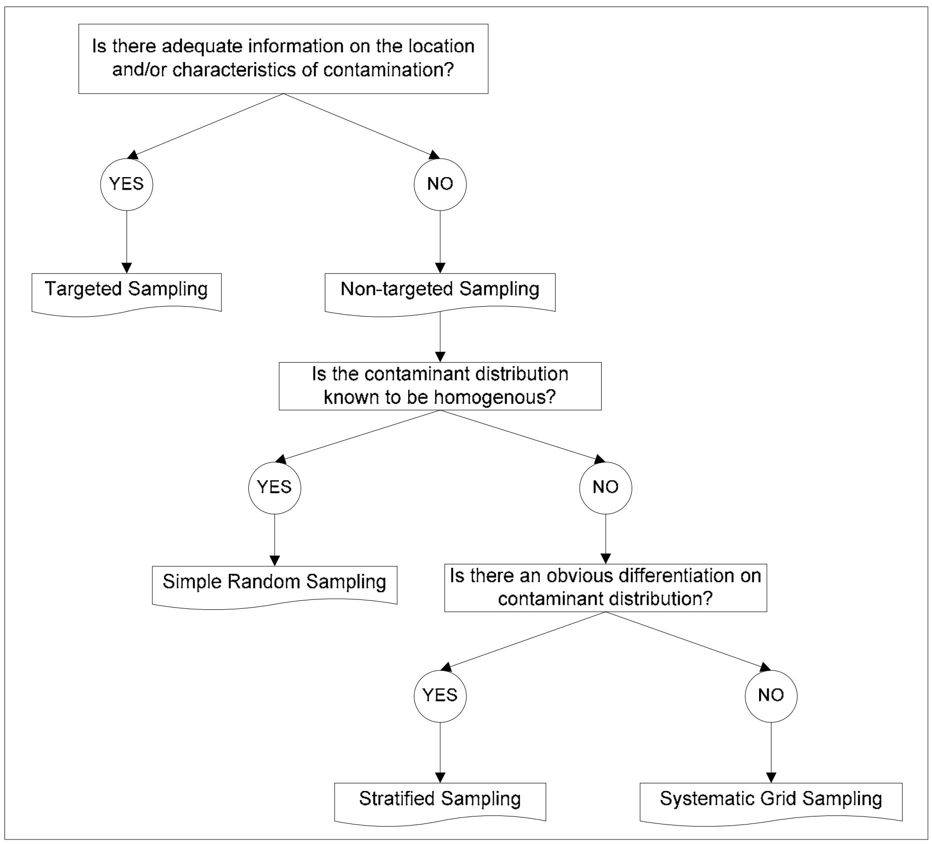


Figure 4.9 Sampling design types suggested for hydrocarbon contamination case

4.2.2.2. Sampling Activities and Results

According to the objectives listed above, site investigation aims at determining BTEX concentrations in subsurface soil and groundwater, in addition to describing subsurface hydrogeology of the site. The horizontal and vertical extent of BTEX contamination in the site was determined by collecting soil samples at the subsurface soil and at various depths through groundwater. According to the results of study, groundwater is highly contaminated with BTEX especially around the refinery and in some part of the city center. The results showed that approximately 1 km^2 area is highly contaminated. Around this high concentration zone, especially in the direction of groundwater flow, there is an approximately 2 km^2 of intermediate concentration zone and 2 km^2 of low contamination zone. Moreover, site-specific geologic and hydrogeologic data is collected in order for a better understanding of contaminant fate and transport in the subsurface.

The results showed that contaminant plume did not reach the river. However, since the river is in the direction of groundwater flow and the plume moves with the flow, there is a potential risk that contamination may reach the river.

4.2.3. Updated CSM

Information lacking at the beginning, which is collected during site investigation should be reflected to CSM form. Information or data that should take place in updated CSM form are: contaminant concentration and hydraulic conductivity.

One of the main objectives of site investigation was to overcome the uncertainties encountered while developing EPD. The only uncertainty was about contamination of surface water. As it is explained in the previous section, although contamination has not reached yet, there is a potential risk that it may happen. Therefore, there is no need to update the EPD since potential human health risks are considered in risk assessment stage as well as current risks.

In light of the results of the sampling studies, new maps and/or drawings may be used to illustrate the site and contamination. For this purpose, BTEX concentration contours can be reflected on a scaled site map. Sampling points and locations of soil borings can also indicated on these maps. Moreover, soil and subsurface properties can be used to draw cross-sectional diagrams that will be useful in risk assessment stage.

CHAPTER 5

CONCLUSIONS AND RECOMMEDATIONS

5.1. Summary and Conclusions

Management of contaminated sites is one of the most important environmental problems in Turkey. In the scope of a TÜBİTAK KAMAG project, SPCR is amended and a systematic approach is developed for management of contaminated sites. According to new SPCR, identification and registration, preliminary assessment, detailed site assessment and remediation are the main phases in management of contaminated sites. Among these stages, detailed site assessment is very critical since the site and contamination is characterized in this stage. CSM is a useful tool that should be used in detailed site assessment and remedial planning and implementation.

In this study, a decision support tool is developed to guide the site assessors in the process of developing CSM for contaminated sites. Within the scope of decision support tool, a flowchart describing the relationship and information flow between CSM and SPCR processes are produced. Furthermore, a decision tree is developed to guide the site assessors during sampling design. Developing various tools that can be used in a systematic manner for CSM building was also aimed. In this respect, an information collection form, illustrative tools are and exposure pathway diagram, are presented in this study. EPD is embedded into a user-friendly decision assistance tool based on Microsoft Excel and VBA. This tool enables to develop an accurate and relevant EPD for a given site by answering relatively simple questions introduced within a query. It guides the user by the help of some controls and warnings. In addition, it provides a standard format for reporting EPD.

Finally, developed flowchart, decision tree and CSM tools are applied to two case studies in order to visualize the CSM tools and demonstrate the utility and applicability of the decision support tool. Within the scope of case study applications, two real contaminated site problems are handled. Both of these cases are assessed and one case is remediated in the past, which enables to evaluate the effectiveness of developed methodology. First case is PCB contamination occurred due to storage activities in İncirlik Air Base. Second case is a hydrocarbon contamination case in soil and groundwater.

First, initial conceptual site models are built using required information given in related reports. For this purpose, CSM form is completed, EPD is formed using developed tool and illustrative tools are prepared. Afterwards, initial CSM is evaluated in order to guide site investigation studies. Sampling studies are designed and performed according to this evaluation. Regarding the results of sampling, CSM is updated and updated CSM tools are presented. Updated CSM is evaluated in order to decide the scope of further studies including risk assessment and remediation.

Flowchart for CSM development is utilized for following the steps in detailed site assessment and information flow between SPCR procedure and CSM. Decision tree developed for sampling design helped to determine the appropriate and beneficial design type just by answering very simple questions. CSM tools were also very practical especially in terms of collecting information. CSM form helped to collect existing information in an organized manner. CSM form and site sketches helped to identify the data gaps. In addition to data gaps, uncertainties encountered during building EPD guided the site investigations following the initial CSM. In conclusion, case study applications showed that the developed methodology meets the objectives of this study.

To conclude, developed decision support tool is believed to be very beneficial especially in countries like Turkey, where management of contaminated sites is a relatively new issue. The reason for this is management of contaminated sites is highly case and site specific and it is too hard to develop a standardized procedure that can be followed in every case. Developed methodology is parallel to the procedure for management of contaminated sites given in newly proposed SPCR. Therefore, the tools and literature review presented in this thesis can be used by experts in consultant companies or in authorized institutions such as MoEF after the newly proposed SPCR comes into force.

Since there is not a standardized procedure, the progress of the studies is highly dependent on the site assessor. Inexperienced site assessors can use the developed methodology to guide their decision, while experienced site assessors can also benefit from developed tools by justifying their decisions. It should be recognized that the methodology developed in this study is useful for initial/screening level site assessment. Site specific applications will require expert judgement and additional effort on sampling and evaluation of contamination case.

5.2. Future Recommendations

It is believed that methodology presented in this study is a useful decision support tool for building CSM which is included in the scope of the management process given in the new SPCR. However, this methodology can be improved and/or can form the basis for other studies.

Tools developed in this thesis can be integrated in a single software that stores and processes the information, and illustrates and reports the results. First, it should allow data entry for CSM building and responses to the entered data by indicating the data gap and uncertainties can be developed. Thereby, data collected for contaminated sites can be stored in an inventory. Secondly, decision assistance tool developed for building EPD can be integrated to this software. Third, the software can make sampling design according to entered data and specified data quality objectives. A software that enables to make sampling design that includes the number and location of sampling points will be very useful for designing site investigations. This tool should include visual features (e.g. indicating the sampling locations and sampling results on a site map/plan) and be consistent with the new Turkish SPCR. VSP and SADA models that are developed by US EPA can be taken as examples. It should be noted that this type of decision support tools require a multi-disciplinary effort of a team consisting geologists, software engineers, and statisticians as well as environmental engineers.

REFERENCES

Agency for Toxic Substances and Disease Registry (ASTDR). (2004). *Interaction Profile for: Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX)*. US Department of Health and Human Service, Atlanta GA: USA.

Agency for Toxic Substances and Disease Registry (ASTDR). (2000). *Public Health Statement: Polychlorinated Biphenyls (PCBs).* US Department of Health and Human Service, Atlanta GA: USA.

Australia Department of Environmental Protection (DEP). (2001). *Development of Sampling and Analysis Program*. Perth: Government of Western Australia.

Boulding J.R. and Ginn J.S. (2004). Practical Handbook of Soil, Vadose Zone, and Ground-water Contamination: Assessment, Prevention, and Remediation, Second Edition. Florida, USA: CRC Press.

Byrnes, M.E. (2009). Field Sampling Methods for Remedial Investigations, Second Edition. New York, USA: CRC Press.

Cochran, W.G. (1977). Sampling Techniques. New York, USA: John Wiley & Sons.

Confidential Report on Hydrocarbon Contamination in a Refinery. (2005). Turkey.

Crumbling, D.M. (2004a). *Summary of Triad Approach*. http://www.triadcentral.org, (Last accessed date: 29.03.2009). USA.

Crumbling, D.M. (2004b). The Triad Approach to Managing the Uncertainty in Environmental Data. US Environmental Protection Agency. Washington, DC, USA: NEMC 2004 Proceedings.

de Gruijter, J., Brus, D., Bierkens, M., and Knotters, M. (2006). Sampling for Natural Resource Monitoring. The Netherlands: Springer.

European Commission (EC). (2002). *Towards a Thematic Strategy on Soil Protection* (No. COM(2002) 179 final). Brussels.

European Commission (EC). (2006a). *Proposal for a Directive of the European Parliament and of the Council, Establishing a Framework for the Protection of Soil and Amending Directive 2004/35/EC* (No. COM(2006) 232 final). Brussels.

European Commission (EC). (2006b). *Thematic Strategy for Soil Protection* (No. COM(2006) 231 final). Brussels.

European Commission (EC). (2008). *Soil*. http://ec.europa.eu/environment/soil/index_en.htm, (Last accessed date: 29.11.2008).

Ferguson, C. C. (1992). The statistical basis for spatial sampling of contaminated land. *Ground Engineering, Volume 25*, No 5, pp. 34-38.

Federal Remediation Technologies Roundtable (FTRT). (2009). *ARAMS Overview* http://www.frtr.gov/decisionsupport/DST_Tools/arams.htm, (Last accessed date: 10.01.2009). USA.

Gilbert R.O. (2006). Statistical Methods for Environmental Pollution Monitoring. USA: John Wiley & Sons.

Harvey R.G. (1991). Polycyclic Aromatic Hydrocarbons: Chemistry and Carcinogenicity. Cambridge, UK: Cambridge University Press.

Law Environmental, Inc. (1997). Final Remedial Investigation Report: PCB Contaminated Soils Study İncirlik AB Volume I and Volume II, GA USA.

Nathanail, C.P. and Bardos, R.P. (2004). Reclamation of Contaminated Land. Chichester, UK: John Wiley & Sons.

Otte P.F., Zijp M.C., Kovar K., Lijzen J.P.A., Swartjes F.A. and Verschoor A.J. (2007). Report on A Tiered Procedure to Assess Risk Due to Contaminant Migration in Groundwater. The Netherlands: National Institute for Public Health and Environment (RIVM).

Palmer C. M. (1996). Principles of Contaminant Hydrogeology, Second Edition. USA: CRC Press.

Risk Assessment Information System (RAIS). (2009). Toxicity and Physical Properties, http://rais.ornl.gov/cgi-bin/tox/TOX_select, (Last accessed date: 11.06.2009). USA.

Sabatini D.A. and Knox R.C. (1992). Transport and Remediation of Subsurface Contaminants: Colloidal, Interfacial, and Surfactant Phenomena. USA: ACC Press.

Soesilo J.A. and Wilson S.R. (1997). Site Remediation: Planning and Management. USA: CRC Press.

Sunahara G.I., Renoux A.Y., Thellen C., Gaudet C.L., and Pilon A. (2002). Environmental Analysis of Contaminated Sites (Ecological & Environmental Toxicology Series). UK: John Wiley & Sons.

TÜBİTAK-KAMAG. (2009). *Project Final Report for 106G008 Development of an Environmental Management System for Sites Contaminated by Point Sources*. Turkey.

UK Environment Agency. (2000). *Secondary Model Procedure for the Development of Appropriate Soil Sampling Strategies for Land Contamination (No. P5-066/TR).* Bristol, UK.

US Environmental Protection Agency (EPA). (1988). *Superfund Exposure Assessment Manual*. (No. EPA/540/1-881001). Washington, DC, USA.

US Environmental Protection Agency (EPA). (1989a). *Methods for Evaluating the Attainment of Cleanup Standards, Vol. 1. Soils and Solid Media* (No. PB89-234959). Washington, DC, USA.

US Environmental Protection Agency (EPA). (1989b) *Risk Assessment Guidance for Superfund - Volume I: Human Health Evaluation Manual (Part A)* (No. EPA/540/1-89/002). Washington, DC, USA.

US Environmental Protection Agency (EPA). (1996a). *Soil Screening Guidance: Technical Background Document*. (No. EPA/540/R-95/128). Office of Solid Waste and Emergency Response, Washington, DC, USA.

US Environmental Protection Agency (EPA). (1996b). *Soil Screening Guidance: User's Guide*. (No.9355.4-23) Office of Solid Waste and Emergency Response, Washington, DC, USA.

US Environmental Protection Agency (EPA). (1998). *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA: Interim Final* (No. EPA/540/G-89/004). Washington, DC, USA.

US Environmental Protection Agency (EPA). (2002a). *Guidance on Choosing a Sampling Design for Environmental Data Collection* (No. QA/G-5S). Washington, DC, USA.

US Environmental Protection Agency (EPA). (2002b). *Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites*. (No. OSWER 9355.4-24). Washington, DC, USA: Office of Emergency and Remedial Response.

US Environmental Protection Agency (EPA). (2005). *Decision Support Tools - Development of a Screening Matrix for 20 Specific Software Tools*, Washington, DC, USA: Office of Superfund Remediation and Technology Innovation Brownfields and Land Revitalization Technology Support Center.

World Health Organization (WHO). (1989). *Indoor Air Quality: Organic Pollutants.* (No.111). Copenhagen, Denmark: EURO Reports and Studies.

Wilson L.G., Everett L.G., Cullen S.J. (1994). Handbook of Vadose Zone Characterization and Monitoring. USA: CRC Press.

APPENDIX A

CONCEPTUAL SITE MODEL FORM

CONCEPTUAL SITE MODEL FORM	Date:

1. SITE ASSESSOR	
Name-Surname:	
Institution/Company:	
Job title:	
Telephone number:	
Fax:	
e-mail :	

2. GENERAL SITE INFORMATION			
Name of the site or facility:			
Location:			
Type of activity (NACE Code):			
Status:			
History of site and surroundings:			
Land use of site:		Current land use *	Future land use
	Residential		
	Industrial/Commercial		
	Agricultural		
	Forest		
	Construction area		
	Recreation		
Surface and/or subsurface features:			

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<tr><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td colspan="6">Hydrogeology</td></tr>
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<tr><td colspan="2">Seasonal and/or average temperature values (^{o}C):</td><td colspan="4"></td></tr>
<tr><td colspan="2">Wind speed and (most frequent) direction:</td><td colspan="4"></td></tr>
</table>

4. SOURCE	
Location*:	
Type of source (eg. UST, contaminated soil) :	
Condition of source:	
Depth of source (if it is underground) (m):	
Dimensions of the source:	

5. CONTAMINANT/CONTAMINATION	
Type of contamination (spill, leak, etc.):	
Extent of contamination:	
Contaminant of concern:	
Contaminant phase (solid, sorbed, gas, aqueous, LNAPL, DNAPL)	
Toxicological, physicochemical and fate properties of contaminant:	
Contaminant concentration (if there are previous sampling studies) (mg/kg):	
Contaminated media:	

6. RECEPTORS			
Population	Approximate number	Distance to source	Explanations (exposure duration, exposure frequency, etc.)
Residential – adults			
Residential – children			
Commercial/Industrial – Indoor Workers			
Commercial/Industrial – Outdoor Workers			
Surface water sources inside or outside the site boundaries, used for drinking or other purposes (fishing, drinking, etc) *:			
Groundwater wells inside or outside the site boundaries, used for drinking or other purposes (irrigation, process, etc)*:			
Explain the activities of (potentially) exposed populations in or around contaminated site:			
Define sensitive subpopulations (children, pregnant and nursing woman, etc.)			

7. ASSUMPTIONS AND UNCERTAINITIES	
Explain assumptions about contamination:	
Explain uncertainties about contamination (that should be identified in next phase):	

8. ADDITIONAL DATA / INFORMATION	
Additional data and information that may be useful:	
List attached documents and figures:	

* Mark on CSM illustrative tools.

APPENDIX B

EXPOSURE PATHWAY DIAGRAM – DECISION ASSISTANCE TOOL

B.1 CONDITIONS USED TO IDENTIFY EXPOSURE PATHWAYS

The occurrence of an exposure pathway is determined according to contaminant of concern and answers given to the questions asked in EPD decision assistance tool.

Questions asked in decision assistance tool:

Q1. Select contaminant of concern:
Q2. Is surface soil contaminated?
Q3. Are plants (vegetables and fruits) grown on/around contaminated site consumed?
Q4. Will contaminants in surface soil potentially reach surface water?
Q5. Is potentially contaminated surface water used as a source of potable water?
Q6. Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?
Q7. Is potentially contaminated surface water used for irrigation?
Q8. Is fish grown in potentially contaminated surface water consumed?
Q9. Is subsurface soil contaminated?
Q10. Will contaminants in subsurface soil potentially reach groundwater?

Q11. Is potentially contaminated groundwater a source of potable water?

Q12. Is potentially contaminated groundwater used for irrigation?

Q13. Will contaminants in groundwater potentially reach surface water?

Q14. Is potentially contaminated surface water used as a source of potable water?

Q15. Is potentially contaminated surface water used for recreational purposes (i.e., swimming)?

Q16. Is potentially contaminated surface water used for irrigation?

Q17. Is fish grown in potentially contaminated surface water consumed?

Contaminant classification:

D: contaminants that are considered with dermal contact (SVOCs, PAHs, arsenic, cadmium, chlordane, DDT and lindane)

V: contaminants that are considered with inhalation of volatiles (VOCs and mercury)

F: contaminants that are considered with inhalation of fugitive dust SVOCs and metals

In the output sheet, the potential exposure pathways are indicated with a "✓" or a "×" sign in accordance with the selected contaminant and answers given to the questions. Conditions that are used to form if functions in the output sheet for every exposure pathway and receptor combination are given below.

[1] Surface Soil → Ingestion

Adult : -

Child : If Q2=yes

Indoor Worker : -

Outdoor Worker : -

[2] Surface Soil → Dermal Contact

Adult	: If Q2=yes and C=D
Child	: If Q2=yes and C=D
Indoor Worker	: -
Outdoor Worker	: If Q2=yes and C=D

[3] Surface Soil → Air (fugitive dust) → Inhalation of fugitive dust

Adult	: If Q2=yes and C=F
Child	: If Q2=yes and C=F
Indoor Worker	: -
Outdoor Worker	: If Q2=yes and C=F

[4] Surface Soil → Air (volatiles) → Inhalation of volatiles

Adult	: If Q2=yes and C=V
Child	: If Q2=yes and C=V
Indoor Worker	: -
Outdoor Worker	: If Q2=yes and C=V

[5] Surface Soil → Plant → Plant Uptake

Adult	: If Q2=yes and Q3=yes
Child	: If Q2=yes and Q3=yes
Indoor Worker	: -
Outdoor Worker	: -

[6] Surface Soil → Surface Water → Ingestion

Adult	: If Q2=yes; Q4=yes and Q5=yes
Child	: If Q2=yes; Q4=yes and Q5=yes
Indoor Worker	: If Q2=yes; Q4=yes and Q5=yes
Outdoor Worker	: If Q2=yes; Q4=yes and Q5=yes

[7] Surface Soil → Surface Water → Dermal Contact

Adult : If Q2=yes; Q4=yes; Q5 or Q6=yes and C=D

Child : If Q2=yes; Q4=yes; Q5 or Q6=yes and C=D

Indoor Worker : If Q2=yes; Q4=yes; Q5=yes and C=D

Outdoor Worker : If Q2=yes; Q4=yes; Q5=yes and C=D

[8] Surface Soil → Surface Water → Air (volatiles) → Inhalation of Volatiles

Adult : If Q2=yes; Q4=yes; Q5 or Q6=yes and C=V

Child : If Q2=yes; Q4=yes; Q5 or Q6=yes and C=V

Indoor Worker : If Q2=yes; Q4=yes; Q5=yes and C=V

Outdoor Worker : If Q2=yes; Q4=yes; Q5=yes and C=V

[9] Surface Soil → Surface Water → Plant → Plant Uptake

Adult : If Q2=yes; Q4=yes and Q7=yes

Child : If Q2=yes; Q4=yes and Q7=yes

Indoor Worker : -

Outdoor Worker : -

[10] Surface Soil → Surface Water → Fish → Fish Consumption

Adult : If Q2=yes; Q4=yes and Q8=yes

Child : If Q2=yes; Q4=yes and Q8=yes

Indoor Worker : -

Outdoor Worker : -

[11] Subsurface Soil → Air (volatiles) → Inhalation of Volatiles

Adult : If Q9=yes and C=V

Child : If Q9=yes and C=V

Indoor Worker : If Q9=yes and C=V

Outdoor Worker : If Q9=yes and C=V

[12] Subsurface Soil → Groundwater → Groundwater Ingestion

Adult	: If Q9=yes; Q10=yes and Q11=yes
Child	: If Q9=yes; Q10=yes and Q11=yes
Indoor Worker	: If Q9=yes; Q10=yes and Q11=yes
Outdoor Worker	: If Q9=yes; Q10=yes and Q11=yes

[13] Subsurface Soil → Groundwater → Dermal Contact

Adult	: If Q9=yes; Q10=yes; Q11=yes; C=D
Child	: If Q9=yes; Q10=yes; Q11=yes; C=D
Indoor Worker	: If Q9=yes; Q10=yes; Q11=yes; C=D
Outdoor Worker	: If Q9=yes; Q10=yes; Q11=yes; C=D

[14] Subsurface Soil → Groundwater → Air (volatiles) → Inhalation of Volatiles

Adult	: If Q9=yes; Q10=yes; Q11=yes; C=V
Child	: If Q9=yes; Q10=yes; Q11=yes; C=V
Indoor Worker	: If Q9=yes; Q10=yes; Q11=yes; C=V
Outdoor Worker	: If Q9=yes; Q10=yes; Q11=yes; C=V

[15] Subsurface Soil → Groundwater → Plant → Plant Uptake

Adult	: If Q9=yes; Q10=yes and Q12=yes
Child	: If Q9=yes; Q10=yes and Q12=yes
Indoor Worker	: -
Outdoor Worker	: -

[16] Subsurface Soil → Groundwater → Surface Water → Ingestion

Adult	: If Q9=yes; Q10=yes; Q13=yes and Q14=yes
Child	: If Q9=yes; Q10=yes; Q13=yes and Q14=yes
Indoor Worker	: If Q9=yes; Q10=yes; Q13=yes and Q14=yes
Outdoor Worker	: If Q9=yes; Q10=yes; Q13=yes and Q14=yes

[17] Subsurface Soil → Groundwater → Surface Water → Dermal Contact

Adult : If Q9=yes; Q10=yes; Q13=yes; Q14 or Q15=yes and C=D

Child : If Q9=yes; Q10=yes; Q13=yes; Q14 or Q15=yes and C=D

Indoor Worker : If Q9=yes; Q10=yes; Q13=yes; Q14=yes and C=D

Outdoor Worker : If Q9=yes; Q10=yes; Q13=yes; Q14=yes and C=D

[18] Subsurface Soil → Groundwater → Surface Water → Air (volatiles) → Inhalation of Volatiles

Adult : If Q9=yes; Q10=yes; Q13=yes; Q14 or Q15=yes and C=V

Child : If Q9=yes; Q10=yes; Q13=yes; Q14 or Q15=yes and C=V

Indoor Worker : If Q9=yes; Q10=yes; Q13=yes; Q14=yes and C=V

Outdoor Worker : If Q9=yes; Q10=yes; Q13=yes; Q14=yes and C=V

[19] Subsurface Soil → Groundwater → Surface Water → Plant → Plant Uptake

Adult : If Q9=yes; Q10=yes; Q13=yes and Q16=yes

Child : If Q9=yes; Q10=yes; Q13=yes and Q16=yes

Indoor Worker : -

Outdoor Worker : -

[20] Subsurface Soil → Groundwater → Surface Water → Fish → Fish Consumption

Adult : If Q9=yes; Q10=yes; Q13=yes and Q17=yes

Child : If Q9=yes; Q10=yes; Q13=yes and Q17=yes

Indoor Worker : -

Outdoor Worker : -

B2. VBA CODES (MACROS)

VBA codes used in EPD decision assistance tool are given in Table B.1.

Table B.1 VBA codes used in EPD decision assistance tool

Explanation	**Code**
Workbook Codes for (i) appearing welcome message at the opening of the file, (ii) providing all questions are unanswered in the beginning.	**Private Sub** Workbook_Open() welcome.Show Sheets("q").Range("K1").Value = Empty Sheets("q").Range("K2").Value = Empty Sheets("q").Range("K3").Value = Empty Sheets("q").Range("K4").Value = Empty Sheets("q").Range("K5").Value = Empty Sheets("q").Range("K6").Value = Empty Sheets("q").Range("K7").Value = Empty Sheets("q").Range("K8").Value = Empty Sheets("q").Range("K9").Value = Empty Sheets("q").Range("K10").Value = Empty Sheets("q").Range("K11").Value = Empty Sheets("q").Range("K12").Value = Empty Sheets("q").Range("K13").Value = Empty Sheets("q").Range("K14").Value = Empty Sheets("q").Range("K15").Value = Empty Sheets("q").Range("K16").Value = Empty Sheets("q").Range("K17").Value = Empty **End Sub**
Module name: INFO Codes for information messages appearing when clicked on 'info' buttons	**Sub Q2_info()** info_Q2.Show **End Sub** **Sub Q4_info()** info_Q4.Show **End Sub** **Sub Q9_info()** info_Q9.Show **End Sub** **Sub Q10_info()** info_Q10.Show **End Sub** **Sub Q13_info()** info_Q13.Show **End Sub**

Table B.1 (continued) VBA codes used in EPD decision assistance tool

Module name: NO Codes for warning messages appearing when 'no' is selected for questions 2, 4, 9, 10 and 13.	**Sub Q2_no()** NO_Q2.Show **End Sub** **Sub Q4_no()** NO_Q4.Show **End Sub** **Sub Q9_no()** NO_Q9.Show **End Sub** **Sub Q10_no()** NO_Q10.Show **End Sub** **Sub Q13_no()** NO_Q13.Show **End Sub**
Module name: RESULT Code for directing the user to output sheet when clicked on 'submit button'	**Sub** Result() ' RESULT Macro Sheets("Result").Select Range("A1").Select **End Sub**

APPENDIX C

CONCEPTUAL SITE MODEL FORM – İNCİRLİK AB

CONCEPTUAL SITE MODEL FORM	**Date:**

1. SITE ASSESSOR	
Name-Surname:	Beril Büyüker
Institution/Company:	Middle East Technical University
Job title:	Environmental Engineer
Telephone number:	+903122100000
Fax:	+903122100000
e-mail :	case@case.com

<table>
<tr><th colspan="4">2. GENERAL SITE INFORMATION</th></tr>
<tr><td>Name of the site or facility:</td><td colspan="3">Old Defense Reutilization and Marketing Office (DRMO)</td></tr>
<tr><td>Location:</td><td colspan="3">İncirlik Air Base, Adana</td></tr>
<tr><td>Type of activity (NACE Code):</td><td colspan="3">Military site</td></tr>
<tr><td>Status:</td><td colspan="3">Currently not in use</td></tr>
<tr><td>History of site and surroundings:</td><td colspan="3">- Used for storage of oil drums containing PCBs between early 1970s and 1988. PCBs leak from several drums during storage and pick up activities surface soil. Soil excavated and stored in approximately 300 drums and in pile of soil on the site (1991).</td></tr>
<tr><td rowspan="7">Land use of site:</td><td></td><td>Current land use *</td><td>Future land use</td></tr>
<tr><td>Residential</td><td></td><td>x</td></tr>
<tr><td>Industrial/Commercial</td><td>x</td><td></td></tr>
<tr><td>Agricultural</td><td></td><td></td></tr>
<tr><td>Forest</td><td></td><td></td></tr>
<tr><td>Construction area</td><td></td><td></td></tr>
<tr><td>Recreation</td><td></td><td></td></tr>
<tr><td>Surface and/or subsurface features:</td><td colspan="3"></td></tr>
</table>

3. SITE CHARACTERISTICS					
Site Geology					
Geological layers and their thicknesses* :	Geological Layer	Thickness (m)			
Hydraulic conductivities of geological layers (m/s):	Geological Layer	Typical	Min.	Max.	Measurement /Reference
Hydrogeology					
Aquifer classification of geological layers:	Geological layer	Aquifer classification			
Depth to groundwater (m)* :	Typical	Min.	Max.	Reference	
Groundwater flow direction* :					
Hydraulic gradient (m/m):	Typical	Min.	Max.	Reference	
Discharge - recharge zones:					
Anthropogenic alterations (pumping wells, drainage systems, etc.)					
Meteorology					
Annual average precipitation (mm):	670.8 mm (www.adana.dmi.gov.tr)				
Seasonal and/or average temperature values (^{o}C):	Annual average: 19.1 ^{o}C (www.adana.dmi.gov.tr)				
Wind speed and (most frequent) direction:	1.4 m/s, Most frequent wind direction: North – Northeast (www.adana.dmi.gov.tr)				

4. SOURCE	
Location*:	Source location is marked on plan view
Type of source (eg. UST, contaminated soil) :	Contaminated soil in stockpile and excavation Drums containing contaminated soil
Condition of source:	Unprotected drums and soil pile
Depth of source (if it is underground) (m):	-
Dimensions of the source:	Approximately 300 drums containing approximately 500 cubic meters of soil, soil pile and excavation

5. CONTAMINANT/CONTAMINATION	
Type of contamination (spill, leak, etc.):	Leak
Extent of contamination:	Approximately 300 drums containing, approximately 500 cubic meters of soil, soil pile and excavation
Contaminant of concern:	Polychlorinated biphenyls (PCBs)
Contaminant phase (solid, sorbed, gas, aqueous, LNAPL, DNAPL)	PCBs sorbed in soil
Toxicological, physicochemical and fate properties of contaminant:	A number of different harmful effects to human health. Persistent. Heavy kinds tend to settle in soil/sediment. Lighter PCBs likely to evaporate
Contaminant concentration (if there are previous sampling studies) (mg/kg):	-
Contaminated media:	Surface soil

6. RECEPTORS			
Population	Approximate number	Distance to source	Explanations
Residential – adults			
Residential – children			
Commercial/Industrial – Indoor Workers			
Commercial/Industrial – Outdoor Workers			
Surface water sources inside or outside the site boundaries, used for drinking or other purposes (fishing, drinking, etc) *:	Drainage canals – not used for any purpose		
Groundwater wells inside or outside the site boundaries, used for drinking or other purposes (irrigation, process, etc)*:	Groundwater wells from 200-300 meters to the site. Used as potable water source at the air base. Depth of wells approximately between 60 to 120 meters.		
Explain the activities of (potentially) exposed populations in or around contaminated site:	Housing to the south of the site Playground to the east of the site Activities of indoor and outdoor worker at the contaminated site		
Define sensitive subpopulations (children, pregnant and nursing woman, etc.)	Children in the playground. Residential receptors in housing area to the south of the site.		

7. ASSUMPTIONS AND UNCERTAINITIES	
Explain assumptions about contamination:	-
Explain uncertainties about contamination (that should be identified in next phase):	Site geological and hydrogeological characteristics. Contaminant concentration in surface and subsurface soil.

8. ADDITIONAL DATA / INFORMATION	
Additional data and information that may be useful:	-
List attached documents and figures:	Photographs Maps

* Mark on CSM illustrative tools.

APPENDIX D

CONCEPTUAL SITE MODEL FORM – HYDROCARBON CONTAMINATION IN SOIL AND GROUNDWATER

CONCEPTUAL SITE MODEL FORM	**Date:**

1. SITE ASSESSOR	
Name-Surname:	Beril Büyüker
Institution/Company:	Middle East Technical University
Job title:	Environmental Engineer
Telephone number:	+903122100000
Fax:	+903122100000
e-mail :	case@case.com

<table>
<tr><th colspan="4">2. GENERAL SITE INFORMATION</th></tr>
<tr><td>Name of the site or facility:</td><td colspan="3">Refinery</td></tr>
<tr><td>Location:</td><td colspan="3">Confidential</td></tr>
<tr><td>Type of activity (NACE Code):</td><td colspan="3">23</td></tr>
<tr><td>Status:</td><td colspan="3">In use</td></tr>
<tr><td>History of site and surroundings:</td><td colspan="3">Hydrocarbon contamination in groundwater resulting from a leak in the refinery caused an explosion.</td></tr>
<tr><td rowspan="7">Land use of site:</td><td></td><td>Current land use *</td><td>Future land use</td></tr>
<tr><td>Residential</td><td>x</td><td>x</td></tr>
<tr><td>Industrial/Commercial</td><td>x</td><td>x</td></tr>
<tr><td>Agricultural</td><td>x</td><td>x</td></tr>
<tr><td>Forest</td><td></td><td></td></tr>
<tr><td>Construction area</td><td></td><td></td></tr>
<tr><td>Recreation</td><td></td><td></td></tr>
<tr><td>Surface and/or subsurface features:</td><td colspan="3"></td></tr>
</table>

3. SITE CHARACTERISTICS		
Site Geology		
Geological layers and their thicknesses* :	Geological Layer	Thickness (m)
	Şelmo formation (very common)	approximately 50
	Alluvial (around the valley of river)	10-12

Hydrogeology		
Aquifer classification of geological layers:	Geological layer	Aquifer classification
	Gravel and sandstone layers in Şelmo formation	
	Alluvial aquifer	

Hydraulic conductivities of geological layers (m/s):	Geological Layer	Typical	Min.	Max.	Measurement /Reference

Depth to groundwater (m)* :	Typical	Min.	Max.	Reference
	5-10			
Hydraulic gradient (m/m):	Typical	Min.	Max.	Reference

Groundwater flow direction* :	Southeast to Northeast and North
Discharge - recharge zones:	
Anthropogenic alterations (pumping wells, drainage systems, etc.)	

Meteorology	
Annual average precipitation (mm):	484.7 mm (www.diyarbakir.dmi.gov.tr)
Seasonal and/or average temperature values (^{o}C):	Annual average: 16.6 ^{o}C (www.diyarbakir.dmi.gov.tr)
Wind speed and (most frequent) direction:	1.2 m/s, Most frequent wind direction: West (www.diyarbakir.dmi.gov.tr)

4. SOURCE	
Location*:	Refinery
Type of source (eg. UST, contaminated soil) :	Not defined
Condition of source:	Uncontrolled
Depth of source (if it is underground) (m):	-
Dimensions of the source:	-

5. CONTAMINANT/CONTAMINATION	
Type of contamination (spill, leak, etc.):	Leak
Extent of contamination:	-
Contaminant of concern:	BTEX
Contaminant phase (solid, sorbed, gas, aqueous, LNAPL, DNAPL)	-
Toxicological, physicochemical and fate properties of contaminant:	Highly volatile. Highly flammable
Contaminant concentration (if there are previous sampling studies) (mg/kg):	-
Contaminated media:	Subsurface soil and groundwater

6. RECEPTORS			
Population	Approximate number	Distance to source	Explanations
Residential – adults			
Residential – children			
Commercial/Industrial – Indoor Workers			
Commercial/Industrial – Outdoor Workers			
Surface water sources inside or outside the site boundaries, used for drinking or other purposes (fishing, drinking, etc) *:	A river to the west of the contaminated area and a dam built across that river. The river may be used as a potable source of water as well as irrigation, fishing and recreational purposes.		
Groundwater wells inside or outside the site boundaries, used for drinking or other purposes (irrigation, process, etc)*:	Many groundwater wells on and around the site used for several purposes including drinking and irrigation.		
Explain the activities of (potentially) exposed populations in or around contaminated site:	Housing and playgrounds Agricultural activities Activities of indoor and outdoor worker at the contaminated site and at other industrial facilities around the refinery		
Define sensitive subpopulations (children, pregnant and nursing woman, etc.)	Children in the playground. Residential receptors in housing area.		

7. ASSUMPTIONS AND UNCERTAINITIES	
Explain assumptions about contamination:	-
Explain uncertainties about contamination (that should be identified in next phase):	Contaminant plume and distribution. Site-specific properties (e.g. hydraulic conductivity)

8. ADDITIONAL DATA / INFORMATION	
Additional data and information that may be useful:	Geological investigation reports, boring logs
List attached documents and figures:	Maps

* Mark on CSM illustrative tools.