UNIVERSIDADE D COIMBRA

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Sustainable Management of Contaminated Land - Examples of Portugal and Australia

Dissertação de Mestrado Integrado em Engenharia do Ambiente, na área de Especialização em Território e Gestão do ambiente, orientada pela Professora Doutora Maria Isabel Moita Pinto e pelo Professor Doutor António Alberto Santos Correia e apresentada ao Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Outubro de 2021

Faculdade de Ciências e Tecnologia da Universidade de Coimbra
Departamento de Engenharia Civil

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Acknowledgments

To begin, I would like to offer my greatest recognitions to my family for all the education and invaluable opportunities given to me and for allowing me to be the person that I am today.

To my girlfriend Tatiana, I want to show her my appreciation for being there when I needed the most.

I would also like to express my appreciation to all my professors that have accompanied me throughout my academic journey. A special thanks to Professor Maria Isabel Moita Pinto and Professor António Alberto Santos Correia, for providing me guidance throughout this journey so patiently.

I would also like to express my very great appreciation to all my colleagues of the university, especially for the ones who fought beside me in this journey and showed me the exact meaning of having a second family.

I would also like to express my very great appreciation to EI Australia company for providing me valuable information to complete my thesis work.

To finish with, I want to thank myself because I believe that even when we have all the love and support in the world, we couldn´t make it without our interior strength.

ABSTRACT

A constant battle is being fought to protect our environment. In fact, nowadays, the environmental problems are becoming an urgent matter to our society. The contamination of the soils represents one of the currently major environmental issues. Indeed, soil is an integral element of the biosphere and are at the base of socio-economic activities, with its contamination holding significant impacts to our society. Besides, several contaminants associated with soil contamination have been demonstrated to be critical to the human health. It is of top priority to understand the impact of a specific contaminant, as well as to develop and optimize soil remediation techniques to mitigate this problem. However, too frequently, the appropriate environmental care is not provided to the soils, even though that, now more than ever, the sustainable management of the land is crucial.

The main purpose of remediation is to reduce the risks associated with contamination at a specific location. Indeed, the hazards to human health and the environment are significantly reduced when contaminated sites are remediated. However, there has been a recent shift in the remediation field towards more sustainable approaches, that goes beyond this single focus of reducing the contamination associated risks. The aim of this work was to further explore the sustainable management of the land, by characterizing the associated contaminants and the appropriate remediation techniques to be applied in each case.

For that, a bibliographic review was conducted, in which the most current known contaminants were analysed, as well as the various existent strategies to remediate the contaminated soils. Besides, some case studies from Portugal and Australia were also presented in this work to contribute to a better understanding of this topic. Based on both the review and the case studies, it can be concluded that through the years the remediation techniques have been improved in order to be more sustainable. However, society is still far from an ideal situation in this field and there is still a lot of necessary changes to reach a more effective sustainable management of the land.

Keywords: Sustainable; Management; Environment; Contamination; Soils.

RESUMO

Estamos constantemente numa batalha para proteger o nosso meio ambiente. Hoje em dia, os problemas ambientais estão se a tornar, cada vez mais, uma questão urgente para nossa sociedade. A contaminação dos solos representa um dos maiores problemas ambientais. O solo é um elemento integrante da biosfera estando na base das atividades socioeconômicas, causando impactos significativos para a sociedade com a sua contaminação. Além disso, vários contaminantes associados à contaminação do solo têm demonstrado ser críticos para a saúde humana. É importante entender o impacto que um contaminante específico tem no solo, assim como desenvolver e otimizar técnicas de remediação para mitigar esse problema. No entanto, os cuidados ambientais adequados não são prestados aos solos, embora, agora mais do que nunca, seja fundamental aplicar uma gestão sustentável do solo.

O principal objetivo da remediação é reduzir os riscos associados a um local específico contaminado. De facto, os riscos para a saúde humana e para o meio ambiente são significativamente reduzidos quando estes locais contaminados são remediados. No entanto, houve uma mudança recente na área da remediação para abordagens mais sustentáveis, que vai para além da redução dos riscos associados à contaminação. O objetivo deste trabalho consistiu em explorar a gestão sustentável do solo, caracterizando os contaminantes e as técnicas de remediação adequadas a ser aplicadas.

Para isso, foi realizada uma revisão bibliográfica, na qual foram analisados alguns dos atuais contaminantes, bem como as diversas estratégias existentes para os remediar. Além disso, foram apresentados alguns casos de estudos de Portugal e Austrália, contribuindo para um melhor conhecimento deste tema. Com base na revisão e nos casos de estudo, conclui-se que ao longo dos anos as técnicas de remediação foram sendo aperfeiçoadas para as tornar mais sustentáveis. No entanto, ainda estamos longe de uma situação ideal neste campo, havendo ainda algumas mudanças necessárias para se chegar a uma gestão sustentável do solo eficaz.

Palavras-chave: Sustentável; Gestão; Ambiente; Contaminação; Solos.

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ABBREVIATIONS

ABG - Air Base Group

APA- Portuguese Environment Agency (Agência Portuguesa do Ambiente)

BHP - Broken Hill Propriety

BIP - Botany Industrial Park

BOS – Bottom Outlet Sediment

BTEX - Benzene, Toluene, Ethylbenzene, xylenes

CHC - Chlorinated hydrocarbons

CLM - Contaminated Land Management Act of 1997 of Australia

CT - Contaminant threshold

DDT - Dichlorodiphenyltrichloroethane

EPA -Environmental Protection Agency of Australia

EU - European Union

FB - Water holes

FCAP -Former ChlorAlkali Plant

FP – Piezometers

HRRP - Hunter River Remediation Project

JP4 - Jet Fuel 4

MDN - Ministry of National Defence

MW - Monitoring wells

LNEC – Portuguese National Laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil)

NGSA – National Geochemical Survey of Australia

NSW - New South Wales

PAH - Polycyclic aromatic hydrocarbons

PCB - Polychlorinated Biphenyls

PCE – Tetrachlorethylene

S – Survey/piezometers LNEC

SCC - Specific Contamination Concentration

SGV- Soil Guideline Values

S-P-T - Source-Path-Target

TCLP - Toxicity Characteristics Leaching Procedure

TOS – Top Outlet Sediment

TPH - Total petroleum hydrocarbons

VOC – Volatile Organic Compounds

SYMBOLOGY

As – Arsenic

Al – Aluminium

Ca – Calcium

Cd – Cadmium

Cl – Chlorine

CN – Copernicium

Cu – Copper

Cr – Chromium

Fe – Iron

Hg – Mercury

Mn – Manganese

Ni – Nickel

NO_3^- – Nitrate

OH – Hydroxide

Pb – Lead

PO_4^- – Phosphate

Sb – Antimony

Se – Selenium

Zn – Zinc

1 INTRODUCTION

1.1 Work Context

Environmental contamination is becoming an urgent matter to take into consideration. Indeed, nowadays several sources of contamination are affecting the air, the soil and/or the water. The soil in an essential element of the biosphere, required for diverse socio-economic activities. Nevertheless that, appropriate environmental care is not given to the soil. It is of top-priority to recognise that, when comparing to other environmental contaminations such as the air and the water, soil contamination is not only harder to identify but the remediation process is also more difficult to perform (Jones et al., 2012). Moreover, land contamination can be even more present in countries where industrialization is taking place, with the degree of social development being directly linked to the ability of effectively respond to this problem. Altogether, it is essential to preserve the soil as it is a finite and non-renewable resource.

In order to treat/remediate contaminated soils, several remediation procedures have been established. Although old remediation techniques are still effectively used nowadays, the current challenges of modern civilization have resulted in the development of novel approaches. Currently, the knowledge in this field is increasing, as the development of new technology makes it easier to detect and approach contaminated soils, as well as to understand its characteristics. There are several publications that indicate that this is an increasingly delicate topic which continues to be explored daily.

In order to execute a sustainable management of the land, the remediation of contaminated areas must follow several conditions. The main goal of the treatment is the decrease of the danger of contamination in a certain site. Indeed, when a contaminated soil is remediated, the hazards to human health and environment are reduced. However, the remediation sector has recently shifted to sustainable techniques that go beyond this single focus. Sustainable remediation must now cover also stratification of the risks, the overall advantages and possible effects associated to the remediation techniques. This decreases the overall environmental, social, and economic impact of the remediation process by removing and/or managing unacceptable hazards in a safe and timely way. Furthermore, including sustainability into decision making is critical in order to integrate a number of components in land management (i.e., renewable energy, carbon footprint, water footprint, public participation, e. g.).

The aim of the work presented here is to reveal the different approaches applied to contaminated land and its sustainable recovery. A bibliographical review was conducted to attend this objective, where the sustainable management of the land is presented, namely regarding the various strategies for remediate diverse types of contaminated soils. Besides, some case studies from Portugal and Australia are described in this work, two of them more developed then the others. The outcomes of the case studies are analysed.

1.2 Work Structure

This dissertation is divided into 4 chapters, among which the current chapter is included (Chapter 1). The current chapter is focused on a brief work introduction, where the objectives of this work are presented. Following, a literature review is presented, in which relevant ideas regarding the sustainable management of land are described, namely an overview of the types of soil contamination, the most suitable remediation techniques and the characterization of land (Portugal and Australia) (Chapter 2). In order to further characterize this work in more detail, some case studies from Portugal and Australia are described and two of them are presented with more detail than the others. The main characteristics of the studies are presented, such as: soil type, techniques applied to collect the soil and the area of study. A respective analysis of the case studies also follows (Chapter 3). Finally, the most important conclusions regarding the analysis made on chapter 3 and the answers to the questions raised in the beginning are presented (Chapter 4).

2 LITERATURE REVIEW

In this chapter the context of the work is provided, based on a literature review. This review encompasses for: soil and contamination, sustainable management, Portuguese and Australian legislation, types of contamination, existent techniques to remediate contaminated land and characterization of land.

2.1 Soil and Contamination

As part of the ecosystem, soil is an important environmental element. Soil is the source for plants and for the growth of animals, being crucial for sustaining life on earth (Wang et al., 2011). Since the beginning of humanity, we have resorted to the soil capabilities, by taking advantage of its unique characteristics. In the ancient times, soil exploration was limited to the growth of food. However, over time, new ground dependent activities have been emerging and contributing to an increased pollution. In fact, different human activities, such as industrial activities, mining, waste disposal and agricultural practices involving pesticides and herbicides, have been identified as potential sources of soil contamination(De Almeida Andrade et al., 2010; Jones et al., 2012).

Land contamination is strongly present in countries where industrialization is taking place. It is crucial to remediate these contaminated sites in order to achieve sustainable development. The main purpose of remediation is the reduction of the risk associated with contamination at a specific location. Indeed, the hazards to human health and the environment are significantly reduced when contaminated sites are remediated (Hou & Al-Tabbaa, 2014). However, there has been a recent shift in the remediation field towards more sustainable approaches, that goes beyond this single focus of reducing the contamination associated risks. Sustainable remediation must include the total benefits and implications of soil treatment, in addition to risk control. This process minimizes the overall environmental, social, and economic impacts of the remediation process by eliminating and/or controlling unacceptable hazards in a safe and timely manner. Furthermore, incorporating sustainability into decision making allows for the integration of a wide range of factors in the management of the land, such as risk management, renewable energy, carbon footprint, water footprint, public participation, e.g. (Hou & Al-Tabbaa, 2014).

The relevance of the soil for human activities makes it increasingly vulnerable to harmful effects and often results in over-exploration. Contaminants inherent to these activities can be found in a variety of physical states, selectively affecting the environment (Egwurugwu, 2007).

Degradative processes can be physical, chemical or biological. These processes reduce the soil ability to provide quantitative and qualitative products and services, referred to as soil degradation (Sims, 1990). The physical properties of the soil are deteriorated by wind and/or water, through compaction and hardening, laterization, and erosion/desertification. Biological soil degradation is manifested by a decrease in organic matter and a reduction in the soil biological life. Chemical soil degradation is linked to nutrient/fertility loss and the formation of chemical composition imbalances. Toxic chemical contamination is one of several hazards to the quality of the soil (Horta et al., 2015).

Local contamination occurs when waste/contaminant is improperly handled or when human activities result in the administration of excessive contaminants into the soil. When the relationship between the contaminated source and the quantity and spatial extent of soil contamination is ambiguous, it is referred to as diffuse contamination (Jones et al., 2012). In more detail, before the contaminants ended up in the soil over a certain region, they may have come from dispersed sources, undergone transformation and dilution in other environmental sites (Panagos et al., 2013).

The number of contaminated and possibly contaminated sites in the globe is estimated to be between 10 and 20 million (Carré et al., 2017). About 60% of contaminated soils in Europe is caused by metals (34.8%) and mineral oil (23.8%). Another 30% are due to Chlorinated hydrocarbons (CHC) (8.3%), Benzene, Toluene, Ethylbenzene, Xylenes (BTEX) (10.2%), and Polycyclic aromatic hydrocarbons (PAH) (10.9%), as represented in Figure 2.1 (Panagos et al., 2013).

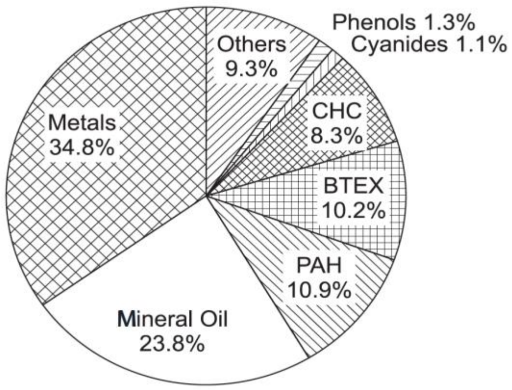

Figure 2.1 - Distribution of contaminants in contaminated sites in Europe. (Panagos et al., 2013)

Although several countries have intervened on their most urgent contaminated sites, overall remediation progresses have been slow. In 2013, only 5% of all recognized locations in the European Union (EU) were remediated. In Australia, remediation processes are accelerating at a pace of 5% each year. However, during the same time roughly 5% of new contaminated sites have been discovered. On the other hand, even with the acceleration of the discovery of contaminated soils, a more careful and quick assessment of the contaminated discovered areas is necessary (Horta et al., 2015;Carré et al., 2017).

2.2 Sustainable Management: Portuguese and Australian Legislation

Several organizations have produced reference values, known as Soil Guideline Values (SVG), in order to overcome the difficulty in recognizing health and environmental concerns associated with contaminated soils. Different organizations have different reference values Currently, the legislation in Portugal can be classified as insufficient, as it is recurrently necessary to rely on international laws to detect and classify sites at risk (APA, 2019).

The SGV refers to the presence and concentration of pollutants in the soil and defines the correspondent threshold values. These guidelines can be implemented during soil assessment, certifying the remediation process. Thus, objective values are set for remediation processes, considering the risks for human health and/or the environment. According to the Portuguese Environment Agency (APA), the Ontario or Netherlands legislation should be used to define the quality of the soil (APA, 2019).

In fact, the necessity for soil remediation prompted the creation of reference values for contaminated locations in Ontario in 1980. The document "Rationale for development of soil and groundwater standard for use at contaminated sites in Ontario" (published on April 15, 2011), establishes maximum allowed concentrations for soils, groundwater, and other substances (Ontario Ministry of the Environment, 2011).

The EU includes several countries, but there is an enormous legal disparity regarding soil protection between them. The Netherlands was the first European country to create policies and regulations that contribute to the rehabilitation of contaminated soils. Intervention values are set in the legislation of this country as concentrations that, when exceeded, require repair regardless of the type of soil (Rijkswaterstaat, 2007).

Several activities might lead to land contamination. Even though the impacts of some activities are only temporary, some others account for the risk of leaving an unwanted legacy. This legacy can be harmful to people and/or the environment, and it can have a significant impact on the utilities of the land. For instance, when soil contamination occurs in Australia, namely in New South Wales (NSW), the soil can no longer be used for productive reasons (i.e., industrial, commercial, agricultural and residential) (Environment Protection Authority, 2015). To evaluate whether the regulation is suitable to protect the environment, the Environmental Protection Agency of Australia (EPA-Australia) must consider all variables that may contribute to the significance of land contamination. Thus, it follows The Contaminated Land Management Act of 1997 of Australia (CLM Act-Australia) which creates a legislative framework that allows the EPA-Australia to coordinate the investigation and remediation of sites (Environment Protection Authority, 2015).

The CLM Act-Australia overall goal is to provide a procedure for reviewing and remediating land that the EPA-Australia believes to be severely contaminated, meeting the requirements to regulation under the CLM Act-Australia. The objectives of the CLM Act-Australia are to:

- Set responsibility for contamination management when the EPA-Australia considers that the contamination is particularly severe, requiring remediation.
- Establish the EPA-Australia role in contamination assessment, and in the monitorization of investigation, rehabilitation and management of contaminated sites.
- Provide for accreditation of contaminated land site auditors in order to guarantee adequate audit standards for contaminated land management
- Ensure the management of contaminated land, follows environmentally sustainable development principles.

The responsibility to report contamination sites to EPA-Australia emerges when the soil is contaminated with a certain substance at a level above the thresholds value specified in the guidelines of CLM Act-Australia. These guidelines provide details of the circumstances that can trigger the requirement to notify EPA-Australia (Environment Protection Authority, 2015).

2.3 Types of Contamination

Soil is a complex element that is in constant interaction with two other key natural environment elements: water and air. When the soil becomes contaminated, pollutants may spread quickly to the other elements as a result of this interaction. Thus, soil contamination creates a threat to ecosystems and human health (Muñoz-Morales et al., 2021). Depending on their properties, different pollutants have varying consequences on human health and on the environment. The effect of a contaminant is determined by its dispersibility, solubility, bioavailability, carcinogenicity, and other factors (Panagos et al., 2013).

2.3.1 Heavy Metals

Heavy metal contamination is one of the most import threat to humanity and a global problem. Aside from natural processes like volcanic eruptions and rock weathering, anthropogenic causes like rapid industrialisation, extensive use of agrochemicals (pesticides and fertilizers), and urbanization all contribute to soil heavy metal pollution (Figure 2.2). Due to its non-biodegradable nature, soil heavy metal contamination can last for many years, given that cannot decay in soil, even though they can change their oxidation states (Shah & Daverey, 2020).

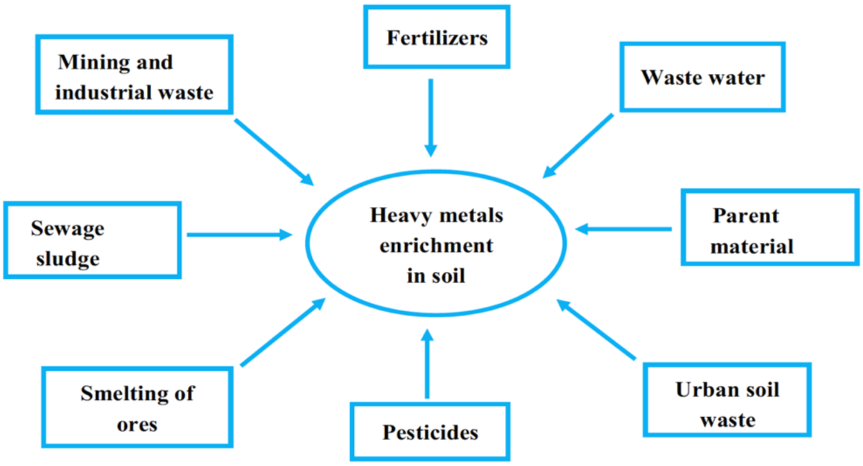

Figure 2.2 Major source of heavy metals in soil. (Mahar et al., 2016)

Heavy metals such as lead (Pb), mercury (Hg), chromium (Cr), and several metalloids such as arsenic (As), selenium (Se), and antimony (Sb), are known to be very toxic to human beings even in small doses. As a result, some of them are classified as the most hazardous substances (Mahar et al., 2016). Besides, they are considered priority pollutants in prevention and treatment regulations because they are inorganic compounds with high toxicity and reactivity, which can quickly contaminate many ecosystems and affect human health, wildlife, and flora (Candeias et al., 2014). Table 2.1 describes the sources of some heavy metal contaminants.

Table 2.1 List of selected heavy metals (and metalloids) contaminants along with their source. (Shah and Daverey, 2020)

Heavy Metals	Source
Arsenic (As)	Timber treatment, paints, pesticides, geothermal, smelting operations, thermal power plants, fuel burning etc.
Lead (Pb)	Batteries, metal products, petrol additives, paints, Smelting operations, coal-based thermal power plants, ceramics, e-waste, bangle industry
Cadmium (Cd)	Batteries, fertilizers, Zinc smelting, waste batteries, e-waste, paint sludge, incinerations & fuel combustion
Copper (Cu)	Fungicides, electrical, paints, pigments, timber treatment, fertilizers, mine tailings, electroplating, smelting operations
Chromium (Cr)	Timber treatment, leather tanning, pesticides, dyes, Mining, industrial coolants, chromium salts manufacturing
Manganese (Mn)	Fertilizer, Municipal wastewater discharges, steel production
Mercury (Hg)	Instruments, fumigants, geothermal, thermal power plants, fluorescent lamps, hospital waste (damaged thermometers, barometers, sphygmomanometers), electrical appliances.
Nickel (Ni)	Alloys, battery industry, mine tailings, smelting operations, thermal power plants
Zinc (Zn)	Dyes, paints, timber treatment, fertilizers, mine tailings, smelting, electroplating

2.3.2 Mineral Oils

Crude oil needs to be refined to produce a variety of oil products, including fuel and mineral oils (Kimber & Carrillo, 2016). Annually, massive amounts of mineral oil and its products are generated, refined, and transported around the world by land and water. As a result, there is a substantial risk of mineral oil contamination of both soil and water, accounting for significant ecotoxicological impacts (Lee et al., 2018). Pipeline blowouts, waste deposition after drilling oil and gas wells, traffic accidents, leaking from underground storage tanks, land farming and uncontrolled landfill are examples that can result in contamination (Kisic et al., 2009).

When there is mineral oil leak on the ground, it coats the soil's surface, making it impermeable. The impermeable coating on the soil surface not only prevents water from flowing freely through the soil, but it also prevents gas exchange between the air and the soil, making it anaerobic. The amount of bacteria and their metabolic activities diminish in anaerobic soil, and plant roots suffocate, resulting in ecological imbalances. Furthermore, soil contamination can affect groundwater, and some volatile hydrocarbons can evaporate and be discharged into the atmosphere, posing as a health risk to humans (Kim et al., 2019).

Moreover, mineral oils refer to a class of petroleum products known as base oils, which includes lubrification base oils and highly refined base oils (i.e. white oils). To achieve the required criteria for food and pharma purposes, the latter undergoes rigorous hydrotreatment to eliminate aromatics. Mineral oils that have been highly refined consist in complex mixtures of hydrocarbon components that include normal, iso, and cycle alkanes (also designated as normal, iso paraffins and naphthenic, respectively) (Kimber & Carrillo, 2016).

2.3.3 Polycyclic Aromatic Hydrocarbons (PAH)

PAH characterize a group of semi-volatile organic pollutants that are widespread in the environment, through natural and human sources, including multiple industrial and agricultural activities (Wick et al., 2011). They are mostly generated when hydrocarbon containing fuels are burned inefficiently. Besides, open fires, automobile exhaust emissions and residential heating systems are the most common anthropogenic sources of PAH (Von Lau et al., 2014). PAH compounds spreads across various resources, such as leaching of PAH from a soil resource into groundwater, or atmospheric transport of particulate soil PAH, as described in Figure 2.3 (Sojinu et al., 2011; Tsibart & Gennadiev, 2013;Alegbeleye et al., 2017).

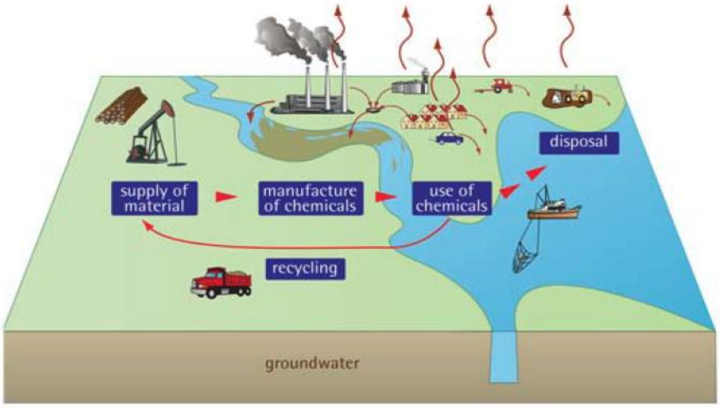

Figure 2.3 Diagram of the transfer of PAHs in the environment. (Wick et al., 2011)

PAH are constituted by a system of hydrophobic and lipophilic double bonds all over their hydrocarbon rings and formed by two or more fused aromatics (benzene rings). They have been found in high quantities in both terrestrial and aquatic environments, as well as in the air and on food (Sojinu et al., 2011; Tsibart & Gennadiev, 2013;Alegbeleye et al., 2017). Additionally, PAH can move directly or indirectly from the soil into harvesting food chains, exposing humans and other living species to high risks (Von Lau et al., 2014). Indeed, since many of these chemicals have been found to be carcinogenic, teratogenic, and mutagenic, they have the potential to affect ecosystems as well as human health (Alegbeleye et al., 2017).

2.3.4 Benzene, Toluene, Ethylbenzene and Xylene (BTEX)

Aromatic compounds entail for the second most common family of organic components that can be found in the nature. In fact, anthropogenic activity has introduced a broad array of aromatic compounds into the environment since the beginning of the industrial revolution. With such large volumes of these chemicals being manufactured, transported, and consumed, a substantial percentage will inevitably disperse to the environment (Weelink et al., 2010).

The major components of oil include BTEX (Figure 2.4). Accidental oil spills, leaking of petroleum fuels from underground storage tanks, poor oil-related waste disposal procedures, and deposition from polluted air, are all common causes of the presence of these chemicals in soils. The presence of BTEX in soils may have significant health consequences on individuals who breath or come into touch with them. Indeed, BTEX display a high volatility and it is strongly associated with the responsibility for cancer, skin irritations, respiratory difficulties, and central nervous system depression (Zhou et al., 2013).

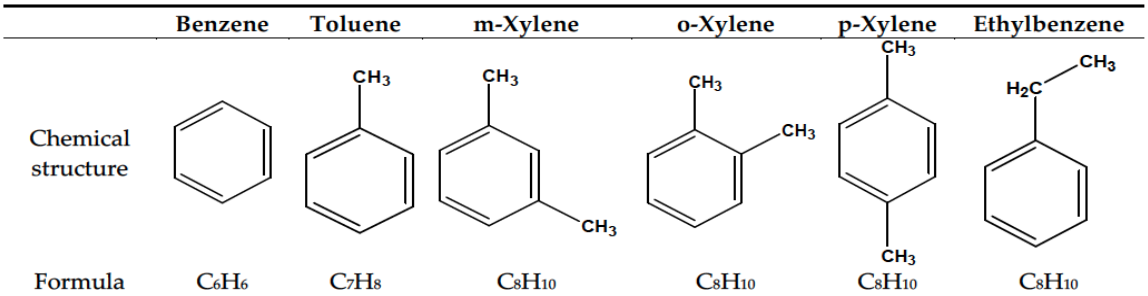

Figure 2.4 Composition of BTEX. (Weelink et al., 2010)

2.3.5 Chlorinated Hydrocarbon (CHC)

CHC refers to any chemical that contains chlorine (Cl), carbon, and hydrogen. Organochlorine pesticides (i.e., lindane and dichlorodiphenyltrichloroethane (DDT)), industrial chemicals (i.e., polychlorinated biphenyls (PCB), Cl waste products like dioxins and furans) are all included in this category. These chemicals remain in the environment, and most of them bioaccumulate in the food chain. The hazards of chlorinated hydrocarbons to human health and to the environment may vary depending on the type of contamination. For instance, exposure to chlorinated hydrocarbons has been linked to immune system suppression and cancer (EEA Glossary).

When carbon and hydrogen bond they form the ‘hydrocarbon' component of the molecule, which bonds with Cl atoms replacing the hydrogen that usually bounds to a carbon atom, forming CHC. This compounds contain a broad variety of molecular weights (size-related) and complexity (i.e., different configurations or arrangements of component atoms) (Farrington, 2019).

CHC chemicals are found in a variety of industrial products, including insecticides, solvents, thermal fluids, metal degreasers, and chemical industry raw materials. Because of their anthropogenic character and unfavourable characteristics, such as high volatility and high resistance to degradation, the impact on the environment is quite significant. Their toxicity is usually linked to the presence of Cl atoms, which promotes the formation of many chlorinated intermediates that are significantly more harmful than the original molecule (Muñoz-Morales et al., 2021).

2.4 Remediation Techniques for Contaminated Land

2.4.1 Structural Approach

The aim of remediation techniques is to disclose a permanent solution or one solution that has the highest probability of providing long term protection. The remediation procedures must be effective not only at the time of implementation, but also in the long term or at least to be able to restore over certain time periods (Tack & Bardos, 2020).

Analysis approaches based on the Source–Path–Target (S–P–T) paradigm may be a good place to start when choosing remediation procedures. The goal is to link an event (the source) to a chain of subevents (the path) to its impact at a sensitive location (the target) in the environment, as shown in Figure 2.5 (Tack & Bardos, 2020).

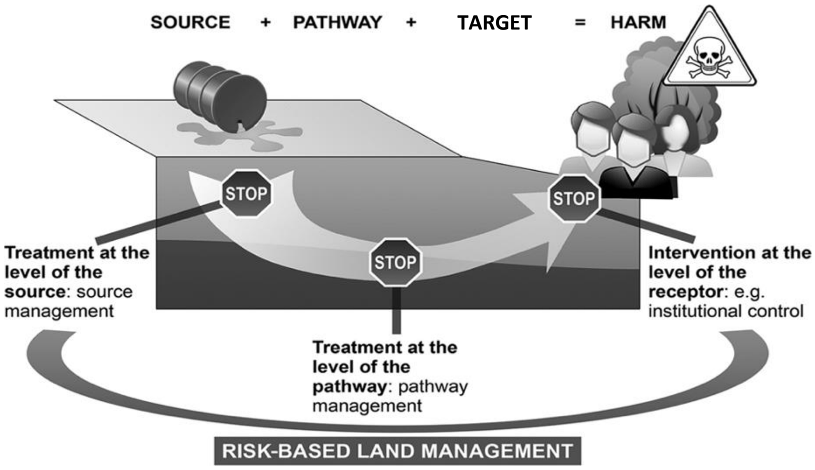

Figure 2.5 Risk management along a contaminant (S-P-T) Linkage. (Adapted from Tack and Bardos, 2020)

The three elements of the contaminated chain (S-P-T) can be targeted for remediation. The aim of the remediation intervention at the source level is to reduce the pollutant emission capacity. For that, excavation and off-site disposal, as well as on-site encapsulation, are commonly used. The action at the pathway level is designed to break the direct channel of communication between the source and the target. Moreover, the most difficult and perhaps least gratifying type of remediation treatment is the one that involves the target. It entails either a restriction on the target position or a protection of the target (Sarsby, 2013). For that, *in-situ* and *ex-situ* (on-site or off-site) processes are the two major types of treatment. As shown in Figure 2.6 (Tack & Bardos, 2020): the techniques for soil remediation are classified according to whether the soil is treated in place (*in-situ*) or is excavated for treatment *ex-situ*. Soil that is being excavated typically returns to the original location (on-site), after the respective treatment.

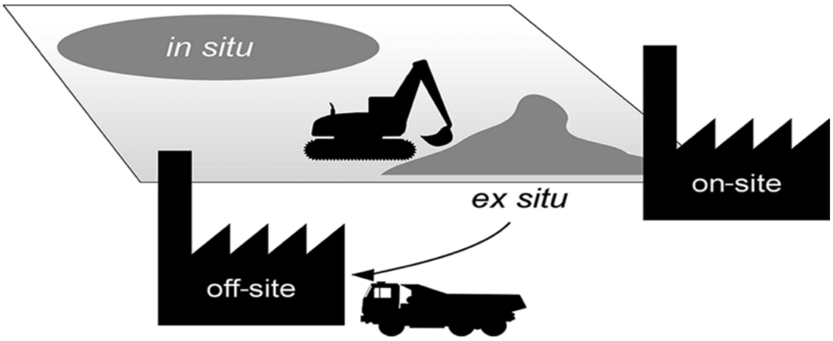

Figure 2.6 Soil remediation approaches. (Tack and Bardos 2020).

The operating concept of soil remediation techniques may also be categorised. Biological, physical, chemical, thermal, or stabilization treatment are the five categories that can be distinguished. The dividing line is not always clear and different techniques may incorporate more than one of these categories (Tack & Bardos, 2020).

2.4.2 Biological Treatment

Bioremediation is the process of transforming or degrading pollutants into non-toxic by-products using microorganisms, most often bacteria or fungi. To improve this process, it is necessary to add reagents that release oxygen, establishing aerobic conditions. On other way, the removal of oxygen and the production of hydrogen promote anaerobic conditions. In aerobic conditions, the microorganisms have the capacity to biodegrade organic pollutants into carbon dioxide, water, and microbial cell mass (DEFRA, 2010). *Bioremediation* can be classified in a number of ways (Table 2.2). Different methods to execute *ex-situ* procedures are all correlated with stimulating biological organic pollutant degradation. Controlling aeration and moisture, as well as adding nutrients and/or microbial, creates ideal conditions for microbial activity (Tack & Bardos, 2020).

Moreover, in *landfarming*, soil is spread across a certain area and controlled by traditional agricultural plowing, tiling, and other methods. *Windrow turning* is based on composting processes, in which soil is placed in windrows and moved frequently to improve aeration. *Biopile* represents other technological application which has the goal of saving space. Soil is placed in layers making high embankments with tubes in between the layers for aeration by air extraction or air injection, as well as water, nutrients, and/or injection. *Bioreactors,* used in an industrial implementation, resorts to technology from industrial fermentation processes to enable rapid and precise conversion of pollutants to innocuous molecules (Tack & Bardos, 2020).

Table 2.2 Biological Remediation Techniques (Adapted from Tack and Bardos 2020).

Ex-situ	*In-situ*
• Landfarming • Windrow turning • Biopile • Bioreactor	• Natural attenuation • Bioventing • Biosparging / Bioslurping • Phytoremediation

Other biological treatments are applied *in-situ*. *Natural attenuation* depends on the pollutants natural propensity to break down or become progressively sequestered over time. The method requires that the current pollution does not represent a threat to the environment. If the local surroundings natural buffering capability is insufficient, temporary isolation methods such as hydraulic control or the construction of physical barriers may be necessary. Besides, other treatments as pump and treat methods include *bioventing, biosparging,* and *bioslurping*. Pumps are used to increase the circulation of air and oxygen (*bioventing* and *biosparging*) or groundwater (*bioslurping*) through a system of tubes and wells placed on the site (Tack & Bardos, 2020).

Bioventing consists in a process that increases air flow in the unsaturated zone, whereas *biosparging* is the process of injecting air or other gases beneath the groundwater level. The groundwater and soil are cleaned from volatile and semi-volatile organic substances as air is sprayed into the saturated zone. The air and organic compound bubbles are attracted to the air-extraction line once they have moved to the groundwater surface. Indigenous microorganisms capture and biodegrade organic molecules as they move through the oxygen-rich and moisture-laden unsaturated zone. The organic content in the vacuum-extracted gas decreases as the indigenous microbial population grows, and more organic compounds are absorbed and digested (Figure 2.7) (Tack & Bardos, 2020)

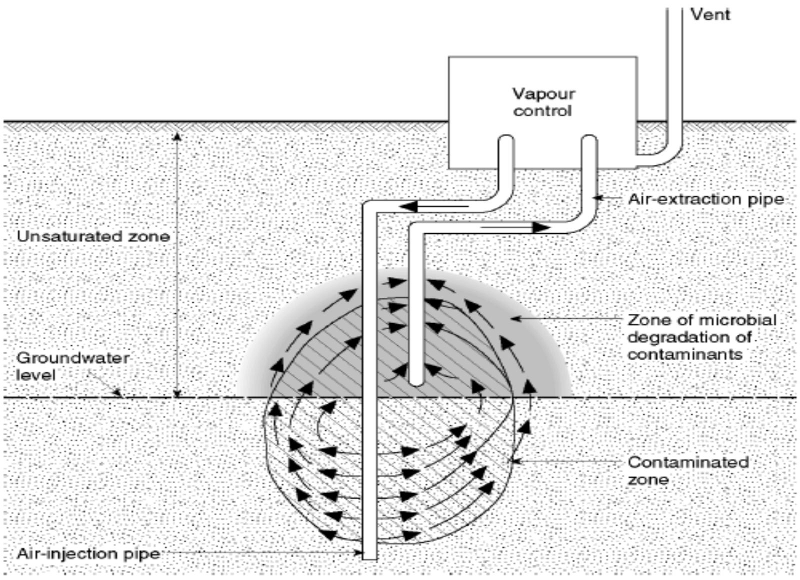

Figure 2.7 Bioventing process. (Sarsby, 2013)

"The use of green plants to eliminate contaminants from the environment or to reduce their harmfulness" is how *phytoremediation* is defined. *Phytoremediation* of metal-contaminated soils are made by the transportation of metals to the plants, then harvesting the biomass to remove the metals from the site (Tack & Meers, 2010). Hyper-accumulators (i.e., Jatropha curcas L. (Purging nut) and Lactuca sativa L. (Lettuce)) are plant species that have demonstrated the potential to collect large amounts of heavy metals. Indeed, these plants can handle higher metal concentrations (Dhaliwal et al., 2020).

2.4.3 Physical Treatment

To achieve separation of pollutants from contaminated land, physical methods rely on alterations in the physical characteristics of contaminants, soil fractions and particles. Differences in size, density, surface characteristics, magnetic properties, and/or charge can be used to distinguish contaminated particles. Volatility, density, charge, and solubility are all designated characteristics of contaminants (Tack & Bardos, 2020).

Soil vapour extraction and *steam stripping* (both of which can be classified as thermal soil remediation procedures) are examples of soil venting, a set of *in-situ* physical remediation techniques. Because many semi-volatile and volatile organic contaminants have a relatively high vapour pressure, volatilization of the contaminant from the soil is easy (Tack & Bardos, 2020). This treatment is widely recognised as the most effective *in-situ* treatment for volatile and semi-volatile contaminants including hydrocarbons and chlorinated solvents. A network of air-withdrawal or vacuum wells is built across the contaminated soil region as part of the system (Figure 2.8). The wells are linked to a vacuum pump system that maintains a constant flow of air through the contaminated ground. The extracted air is either released directly to the environment, processed via an activated carbon filter unit, or incinerated. To guarantee that airflow paths are almost horizontal, a low-permeability cover layer is usually placed (Sarsby, 2013).

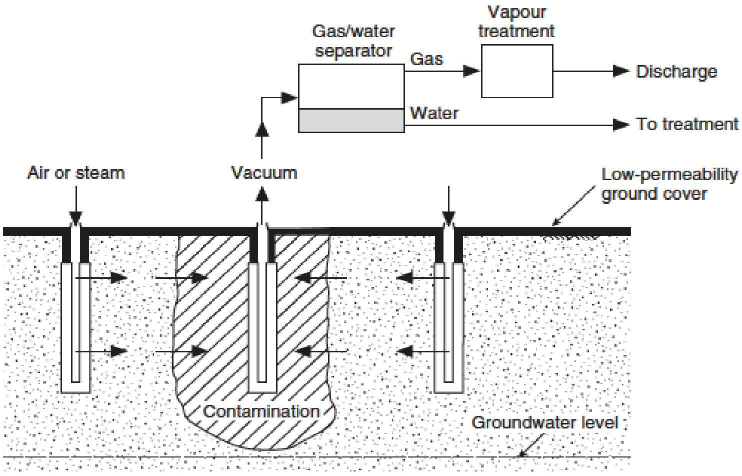

Figure 2.8 Representation of soil vapour extraction. (Sarsby, 2013)

Ex-situ physical soil remediation uses *soil washing* systems to separate pollutants from contaminated fractions based on variations in size, density, surface characteristics, and magnetic properties (Tack & Bardos, 2020). The washing process involves two cleaning steps: removing pollutants from the surface of particles (for coarse grains) and removing fines (and their related impurities) from the soil. This is generally done on-site with mobile equipment that is suited to the contaminants and soil types. Feed preparation, washing stage, and dewatering represent the three steps of the soil washing process (Figure 2.9) (Sarsby, 2013).

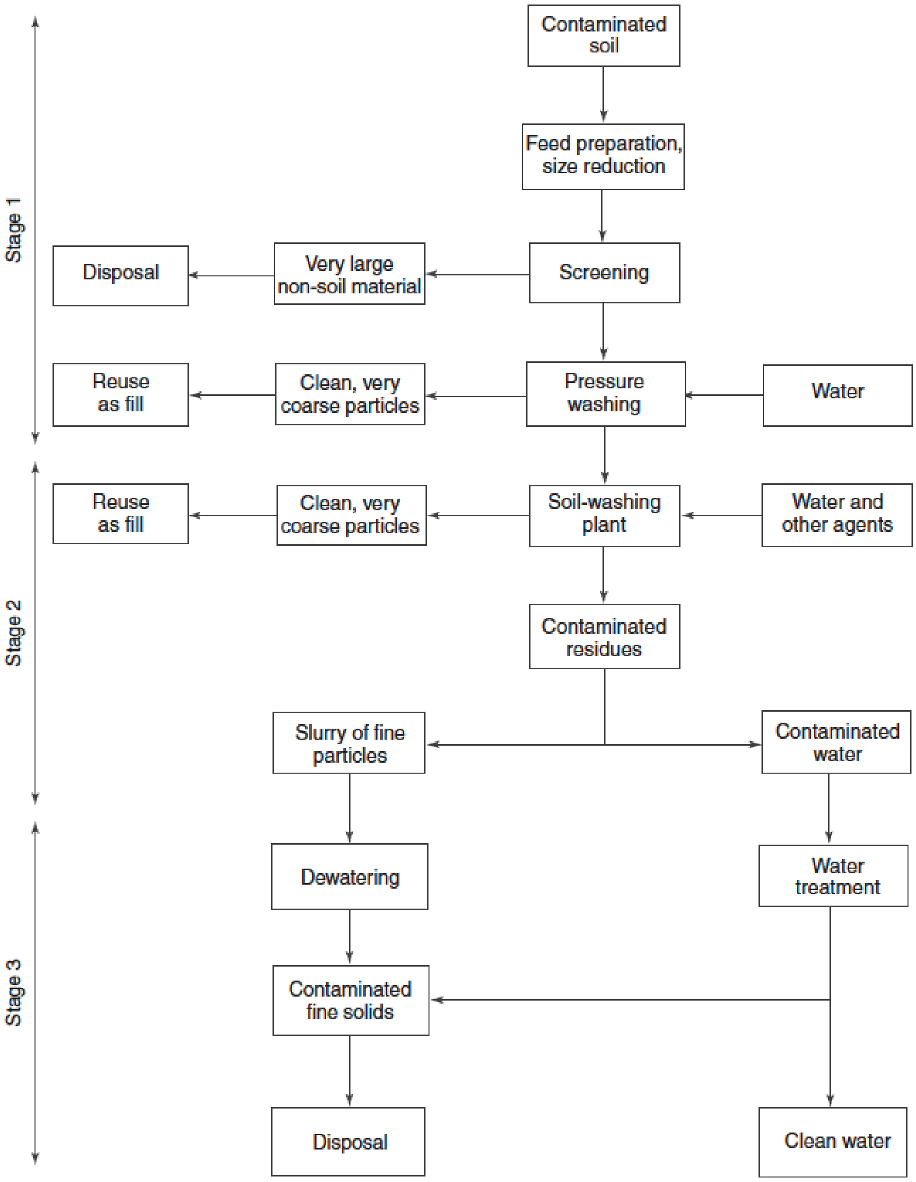

Figure 2.9 The soil washing process. (Sarsby, 2013)

At the first stage of soil washing (Feed preparation) large clods of soil are disintegrated. Screening removes large pieces of non-soil material (such as wood and metal) and high-pressure washing on screens cleans the very coarse particles (usually just superficially contaminated), which are then collected when they are clean (Sarsby, 2013).

At the second stage (Washing) the soil is submitted to a multistage attrition scrubber, where it is thoroughly combined with an extracting agent (usually water). By combining mechanical dispersal and shear stress from vigorous spinning impellers with help of addition chemical aids, contaminated silts and clays particles are separated from coarser particles and transported into the wash water. Finally scrubbed granular material goes to hydrocyclone separators which select the fine particles (Sarsby, 2013).

The third stage (Dewatering) is used to remove fine solid particles from the resulting sludge and reduce its volume. To separate the particles and any precipitation products, a combination of gravity sedimentation and dissolved air flotation is usually employed. To improve these separation processes, coagulants and flocculants can be used. The resultant sludge contains most of the residual contamination. Nevertheless, these methods are not capable of eliminating the pollutant. As a result, the contaminant must be further processed or properly disposed (Sarsby, 2013).

2.4.4 Chemical Treatment

Chemical soil remediation techniques are characterized by chemical processes that either eliminate the contaminant, modify its solubility, or reduce its toxicity (Tack & Bardos, 2020).

Electroremediation is the application of direct currents across electrodes implanted *ex-situ* in the soil to produce an electrical field for the mobilisation and extraction of pollutants (Figure 2.10). Transport under electrical fields, in combination with electrolysis and other processes, are the driving mechanisms. Furthermore, the electrical field will promote soil-water flow via the electroosmosis process. As a result, *electroremediation* is a technique for moving contaminants across treatment zones in soils where low hydraulic conductivity makes dificult the use of wells and pumps to circulate water in the soil (Tack & Bardos, 2020).

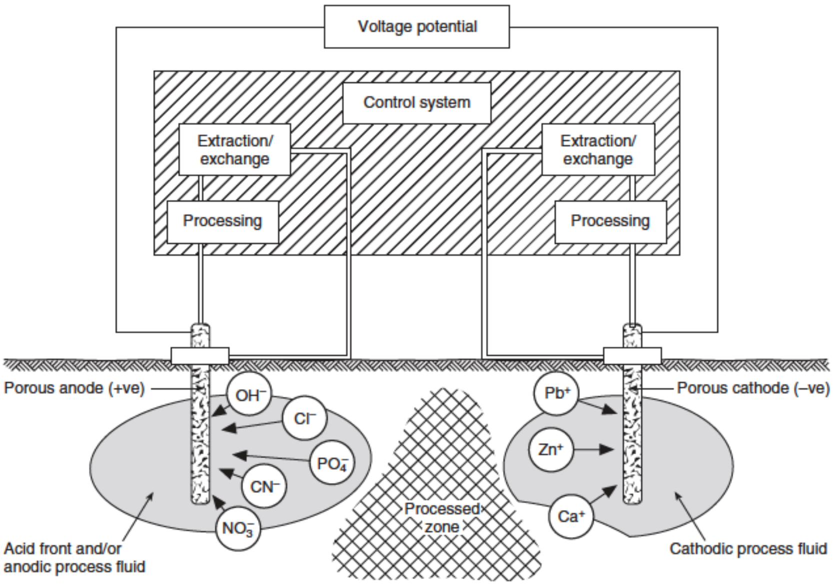

Figure 2.10 Electroremediation process. (Sarsby, 2013)

Treatments like *solidification and stabilisation* procedures intends to reduce the dispersion of soil pollutants in the environment (Tack & Bardos, 2020). *Solidification* is the process of combining materials to produce a dense, inert mass, whereas *stabilisation* is the process of chemically converting or combining wastes to a stable, inert state. Both techniques result in a solid matrix that is firmly constructed and resistant to deterioration and leaching. Most on-site stabilisation procedures employ very basic processes for mixing contaminated soil with appropriate chemicals or other additives, such as placing the contaminated soil in thin layers, spreading each layer with chemicals, and afterwards rotovating or ploughing the soil and chemicals together. Another procedure might be using spinning mixers or screw conveyors, where the additive and the soil (typically in slurry form) are mixed together. The processed soil is then poured into a mould to solidify on-site or moved to the final destination (Sarsby, 2013)

Chemical oxidation consists in an *in-situ* technique aimed for elimination of organic contaminants (i.e., BTEX, PAHs, PCBs and TPH) by converting them into water, carbon dioxide and Cl. This technique uses, in saturated zones, oxidation agents (i.e., hydrogen peroxide, Fenton's reagents, and potassium permanganate) to decompose the contaminants presented on site. On the other hand, in unsaturated zones, this technique resorts to hydrogen peroxide and ozone in gaseous form. The way that this technique operates is using an injection/withdrawal system implemented on the contaminated zone. When the oxidant is injected into the ground through the implemented wells, it extends across the soil and groundwater where interacts with the contaminants presented on site (Figure 2.11). This method is particularly suitable for soils with good or reasonable permeability. Besides, *chemical* *oxidation* can be combined with other techniques, such as *bioremediation* (Seol et al., 2003;del Reino et al., 2015).

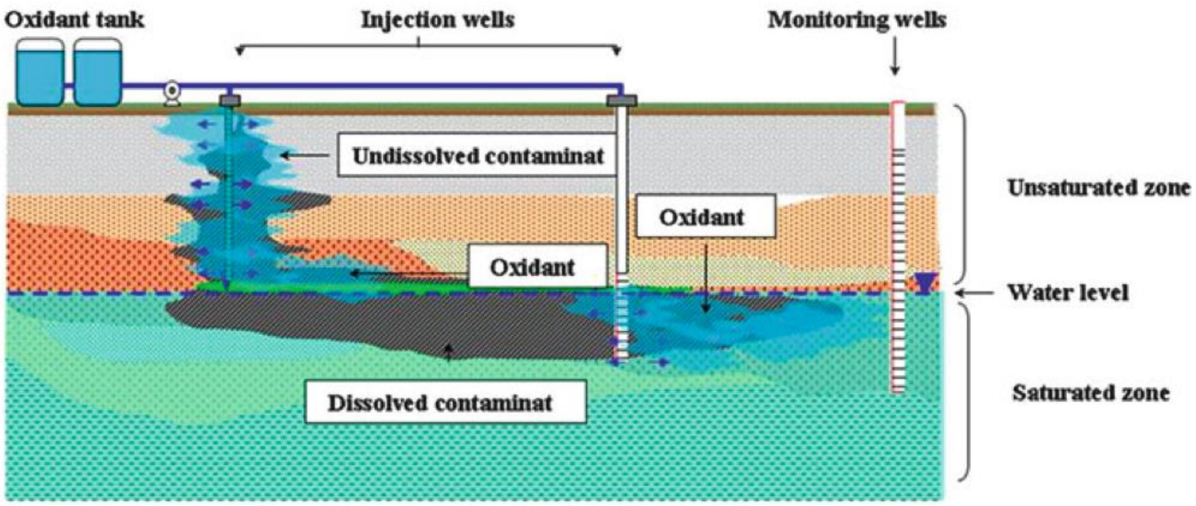

Figure 2.11 - Treatment scheme of chemical oxidation technique. (del Reino et al., 2015.)

In-situ chemical soil washing requires a stringent leachate collection control to prevent pollutants and reagents from dispersing, which is a difficult and expensive process to perform in the field. As a result, chemical soil treatment will most likely be done *ex-situ* in soil washing facilities (Tack & Bardos, 2020).

2.4.5 Stabilization Treatment

Stabilization methods work by preventing pollutants from dispersing into the environment, eliminating their harmful effects. Contaminants are not eliminated, instead, they are contained, immobilised or solidified (Figure 2.12) (Tack & Bardos, 2020).

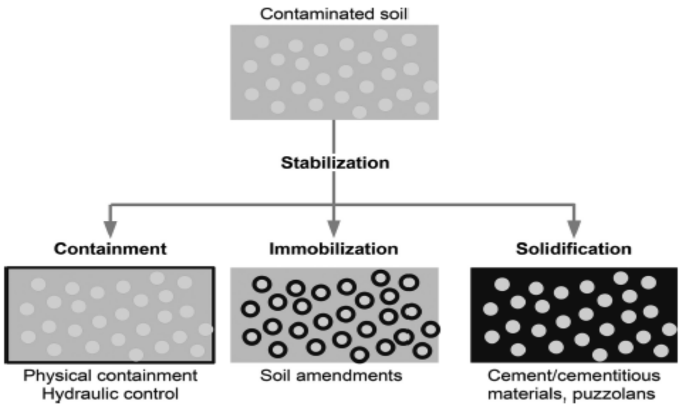

Figure 2.12 Conceptual approaches in stabilization techniques. (Tack and Bardos, 2020).

Containment can be used for many functions in contaminated sites. To prevent pollutants from migrating out of the polluted region, physical screens or hydraulic control of the groundwater table might be used to isolate it from the surrounding environment (*containment*) (Tack & Bardos, 2020). As a result, horizontal cover layers (above the pollution mass), vertical barriers (around the pollution mass), and horizontal bases (beneath the pollution mass) are all components of containment systems. When treating a specific location, it may not be required to use all of these components (Guo et al., 2006; Tack & Bardos, 2020).

Immobilization involves changing the physical/chemical environment of the soil in order to reduce the contaminants solubility. Metals in soils are stabilised by soil adjustments (organic and inorganic amendments) that improve cation exchange, adsorption, surface complexation, and precipitation. Sewage sludge, organic waste, manure compost, and bagasse are examples of organic additions, and inorganic additions are lime, phosphate salts, and fly ashes, among others (Guo et al., 2006; Tack & Bardos, 2020).

Solidification converts the polluted environment into a solid, durable matrix, where pollutants are encapsulated, and it reduces the capacity of water to solubilize and leach contaminants present in the soil. In order to create a solid substance with a low leachability of pollutants, binders like Portland cement and other cementitious materials (i.e., Fly Ash, Rice Husk Ash, Furnace Slag) are mixed with the soil (Voglar & Leštan, 2011;Hunce et al., 2012).

2.4.6 Thermal Treatment

Thermal treatment makes use of the heat. This method makes pollutants more mobile, allowing them to be removed more easily and then volatilize and separate from the contaminant area. Besides, the pollutants can be oxidise or pyrolyze in order to break them down (Vidonish et al., 2016; Zhao et al., 2019). *Thermal desorption* (TD), *radio frequency/microwave heating*, *hot air injection*, s*team injection*, *incineration*, *pyrolysis*, and *vitrification* entail some of the techniques that can be used (Table 2.3) (Tack & Bardos, 2020).

Table 2.3 Thermal Remediation Techniques (Adapted from Tack and Bardos, 2020).

Technique	Main Mechanism
Thermal desorption	Desorption
Hot air injection	Increase mobility by decreasing viscosity and increasing vapor pressure
Steam injection	Increase mobility by decreasing viscosity and increasing vapor pressure
Incineration	Oxidation
Pyrolysis	Pyrolysis (thermal cracking), desorption
Vitrification	Entrapment in solid amorphous matrix, desorption, pyrolysis, oxidation

TD can treat most of volatile or semi-volatile contaminants in soil, such as PAH, PCB, DDT, total petroleum hydrocarbon (TPH), and Hg (Zhao et al., 2019). The *TD* is the unit operation in *ex-situ* treatment systems that raises the soil temperature up to a value high enough to volatilize organic pollutants. A gaseous exhaust stream removes the pollutant for further treatment. Desorption devices generally work between 150 and 350 degrees Celsius, however, some systems can reach to 650 degrees Celsius (Tack & Bardos, 2020).

As shown in Figure 2.13 there are two stages for the *TD* system: the stage of thermal desorption and the stage of off-gas treatment. The TD phase involves the volatilization of pollutants in prepared soil by heating and other processes, such pyrolysis, degradation and oxidation. The gas created in the TD phase is released into the second stage and the waste solids are treated.

The off-gas treatment processes the gaseous pollutants produced in the TD phase, which are treated by different processes such as adsorption, condensation or incineration. To a safely discharge from the off-gas treatment stage, existent contaminated soil particles return to the previous stage in order to prevent/minimise secondary contamination. Wastewater and carbon activated waste must be carefully handled (Zhao et al., 2019).

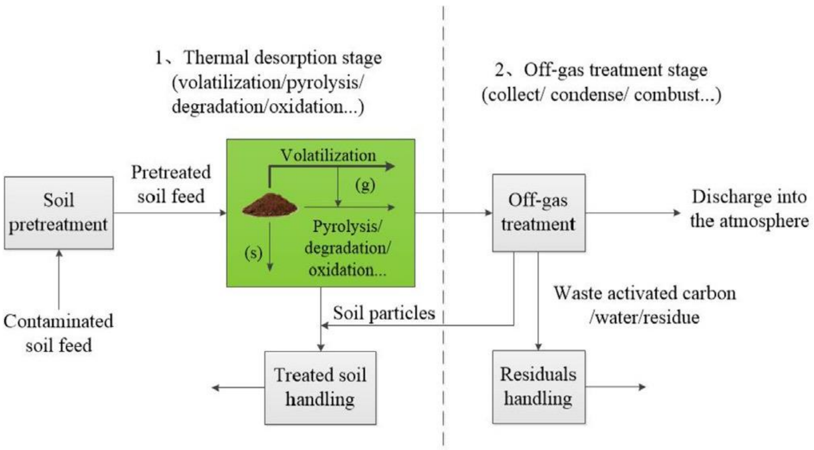

Figure 2.13 Basic process of Thermal Desorption system. (Zhao et al., 2019)

Incineration, on the other hand, entails the elimination of contaminants by using very high-temperature (600ºC–1600ºC) in order to burn the contaminated soils. In most cases, incinerators are used off-site (Vidonish et al., 2016). One-stage and two-stage systems are the two basic kinds of incineration processes. One-stage processes is where toxic organic compounds are destroyed immediately inside the contaminated soil. Bottom ash (typically return to the original site for backfilling or are sent to landfill) and gaseous emissions (generally treated to a scrubbing process to remove fly ash, residual organic compounds and acidic gases) are the end products of this incineration. To transform hazardous chemicals into the gaseous phase, two-stage methods are employed. Then volatilisation and/or pyrolysis, followed by thermal combustion of the gaseous products or condensation of the gaseous inorganic compounds are applied. The incineration can take place at a permitted facility or on-site using a mobile incinerator, with this last one being less frequent (Sarsby, 2013).

When pollutants are subjected to high temperatures and oxygen-low conditions, known as *pyrolysis* (400ºC–500ºC), the contaminants can be breakdown as effective as in the incineration process, with pyrolysis being able of maintaining the nutrient and soil characteristics. However, this treatment method is still at an experimental phase (Vidonish et al., 2016).

Different techniques are used in *in-situ* thermal treatments, such as: electrical currents (electrical resistance heating), peripheral heat sources (conductive heating), steam injection, radiofrequency, or *in-situ* soil mixing with steam and hot air injection. The higher temperature produces a decrease in the viscosity and a rise in the vapour pressure, turning liquid pumping or gas phase extraction more efficient (Triplett Kingston et al., 2010).

Vitrification is the process of digging contaminated soil, melting it in an oven, and then cooling it to make a range of glass items. To regulate the quality of the output product, it may be essential to mix contaminated soil with regular glass-making ingredients, depending on the final product. *Vitrification* does not eliminate contaminants (although high temperatures may cause many organic compounds to volatilize or burn), but rather seals them into the glass structure, making them essentially immobile and leaching proof. Emission controls for both the gases and vapours generated by the oven and the boiling water, which may be polluted, are necessary with this approach, as well as with incineration (Sarsby, 2013).

2.4.7 Selection of Techniques According with Site Contamination

The currently available remediation approaches are selected accordingly with the contaminated target. The contamination site geography, its characteristics, the remediation goal, cost-effectiveness, financial budget, implementation readiness, time requirement, and public acceptability, all contribute to determine the applicability of individual techniques in a specific soil remediation project. To choose the optimal procedures for a given soil remediation project, all of these aspects must be addressed and thoroughly analysed (Liu et al., 2018). Table 2.4 presents the current best technology associated with a certain type of soil contamination. It is important to emphasize that, at this moment, a more careful environmental analysis should be carried out.

Table 2.4 Treatment technologies screening matrix (Adapted from Sarsby, 2013)

	CONTAMINANT TYPE			
	VOC´s	HYDROCARBONS	METALS	NON-METALS
***Ex-situ* treatments**				
Biopiles	Y	Y	N	N
Incineration	Y	Y	N	Y
Pyrolysis	Y	Y	L	N
Soil washing	Y	Y	Y	Y
Solidification/Stabilisation	Y	Y	Y	Y
Thermal desorption	Y	Y	Y	N
Vitrification	Y	Y	Y	Y
Containment treatment				
Stabilization	Y	Y	Y	Y
***In-situ* treatment**				
Bioventing	Y	Y	N	N
Chemical Oxidation	Y	Y	Y	L
Electroremediation	L	N	Y	Y
Phytoremediation	Y	Y	Y	L
Soil Flushing	Y	Y	Y	Y
Soil Vapour Extraction	Y	Y	N	N
Biosparging	Y	Y	N	N
Solidification/stabilisation	Y	Y	Y	Y
Other				
Excavation and off-site Disposal	Y	Y	Y	Y

Y- Demonstrated applicability; N- No applicability; L- Limited applicability

2.5 Characterization of Land

2.5.1 Introduction

The collection of soil samples and their processing are the first steps to evaluate the impact of certain soil contamination situation. The sampling pattern will be determined by several criteria, including the history of the land contamination, the type of pollutants, and the purpose of sample collection. The sampling pattern has an impact on the cost, duration and error the sample. There are several approaches for collecting samples. Systematic, random and stratified sampling are the most common sampling grid used (Saha et al., 2017).

Sampling from sites at regular intervals is referred to as systematic sampling. The site is split into rectangular or triangular grids, with numbers assigned to each grid point (Figure 2.14-a). This sampling approach guarantees that the whole site is covered and that the samples are equally distributed (Saha et al., 2017).

Random sampling is performed by dividing the site into rectangular or triangular grids and numbering each grid point. Sampling locations are chosen at random, not arbitrarily (Figure 2.14-b). To establish sample point coordinates, a genuine "random number generator" should be employed. Given the randomization procedure, every place within the sample region has an equal chance of being chosen as a sampling point (Saha et al., 2017).

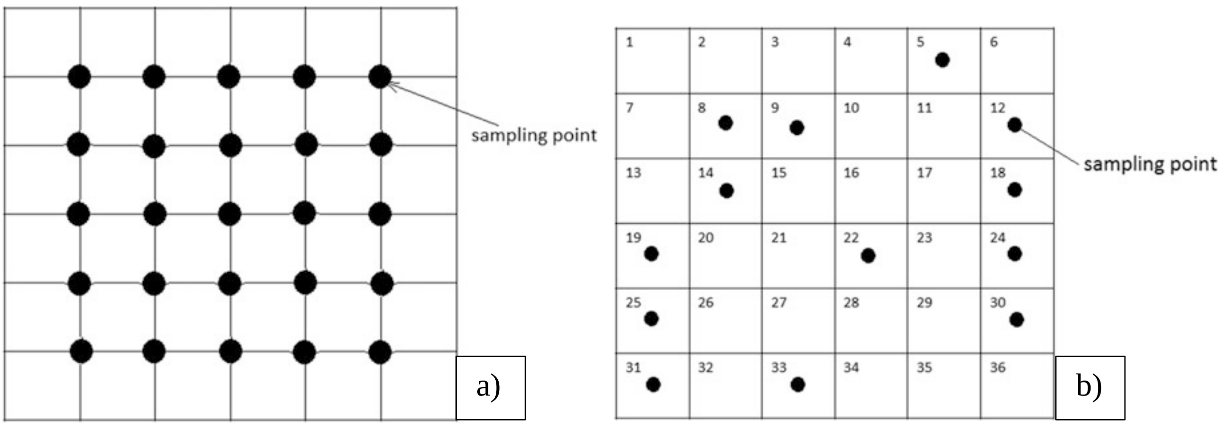

Figure 2.14 (a) Schematic systematic sampling layout. (b) Schematic random sampling layout. (Saha et al., 2017)

Representing other sampling procedure, schematic stratified layout follows the same sampling method as mentioned above. However, the grids split the polluted site into multiple blocks, and then specific sample sites inside each block are selected randomly (Figure 2.15-a). If there is a need to reduce the number of sample points due to technological constraints, the blocks for sampling can be chosen statistically using random numbers, and then sampling sites can be randomly chosen again (Figure 2.15-b) (Saha et al., 2017).

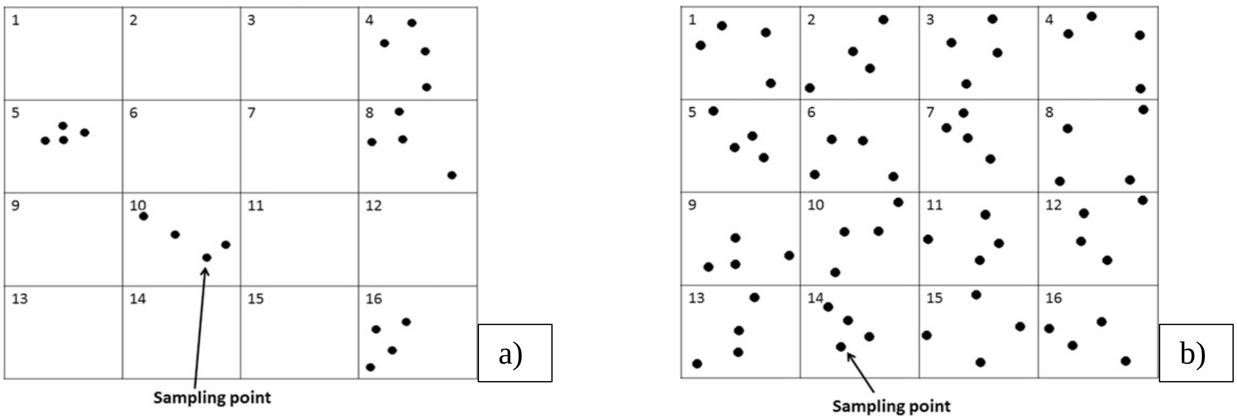

Figure 2.15 (a) Schematic stratified sampling layout is done for few bolcks selected randomly. (b) Schematic stratified sampling layout is done for each block. (Saha et al., 2017)

Different sampling methods and equipment are used for soil sample collection depending on the type of samples and the soil type. Soil samples are taken with scoops, diggers, augers, and drills (Saha et al., 2017).

Using the techniques mentioned above, it was possible with hard work and dedication to achieve, through strategic points, the creation of the national geochemical survey of Portugal and Australia.

2.5.2 Portugal Land

Portugal is positioned between latitudes 37ºN and 42ºN on the western border of Europe. Latitude, the orography, and the closeness to the Atlantic Ocean, are seen as the major climatic variables. The North is hilly, with 90% of the land above 400m, while the South prevails on undulating plains with 60% less than 400m of ground. The Mediterranean climate is moderate. A simplified soil map of Portugal is presented in Figure 2.16 (Inácio et al., 2008).

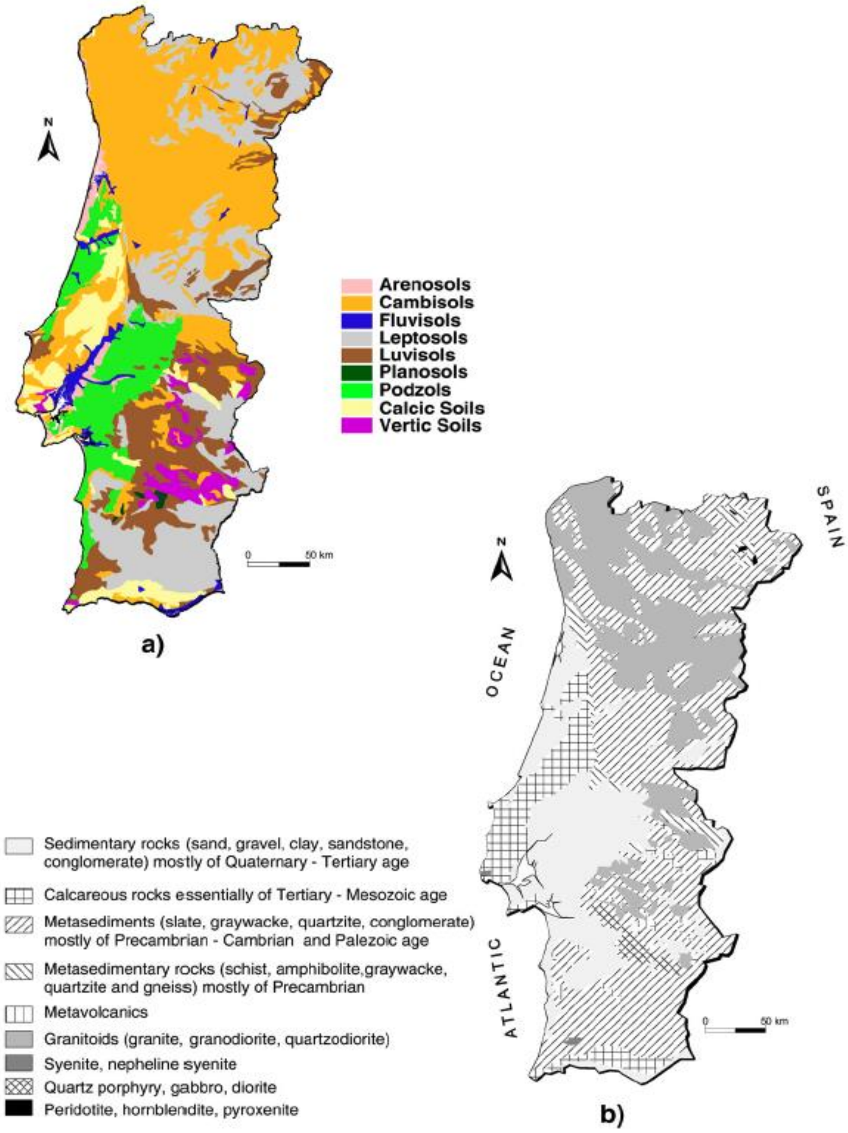

Figure 2.16 (a) Major Soil Types in Portugal (b) Lithology map of Portugal. (Inácio et al., 2008)

To obtain the information shown in Figure 2.16, sampling of the A horizon was performed at 652 sites, following a density of one site/135 km2. Besides, humus samples, mainly located in north and central forest areas of the O horizon, were collected at 195 sites, across an area of 100m2. The test sites have been selected to reflect soils that are "natural", therefore contaminated areas in proximity to industry, busy highways, mines and arable soils were excluded. Then, the chemical analysis of samples was carried by ACME Analytical Laboratories, Ltd, Vancouver, Canada (Inácio et al., 2008).

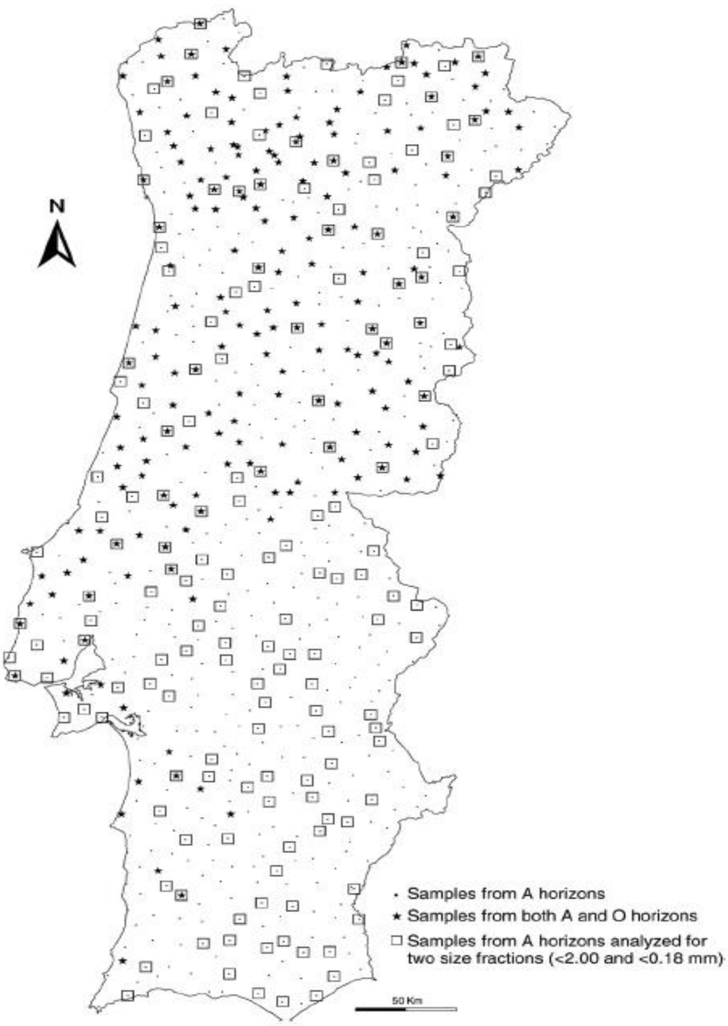

Figure 2.17 Map of Portugal Showing soil sampling sites. (Inácio et al., 2008)

Although places clearly affected by contamination were avoided in the atlas in order to represent the natural soil, it was possible to detect very high concentrations of contaminants in certain areas. This finding allowed the identification of areas that were being affected by anthropogenic factors, as shown in Figure 2.18 (Inácio et al., 2008).

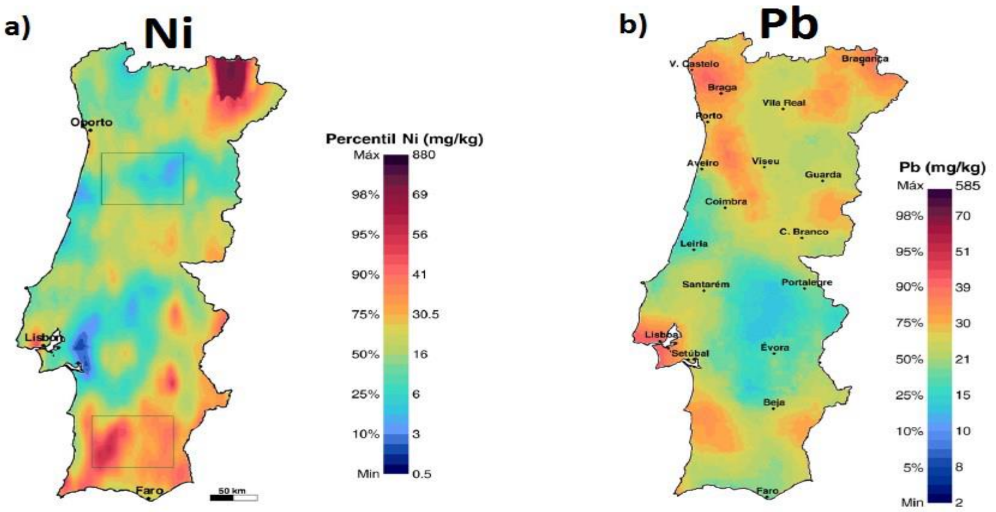

Figure 2.18 Concentration of chemical elements in Portuguese soils: (a) Nickel (b) Lead (Inácio et al., 2008)

In Portugal, soil contaminated with heavy metals is present in various situations. Figure 2.18 provides an illustration of this. This map shows how low and high Ni concentrations are found in Portugal. These major concentration discrepancies are correlated, according to Ribeiro, 2013, with large mining activities that took place in the Southern part of the country. Some mines were left inactive, and no measures were taken to protect the site from further contamination. Thus, with the contribution of some dispersing agents such as wind and rain, the surrounding areas ended up also contaminated. On the other map, the geographical distribution of concentrations of Pb is presented. By analysing the map, it is possible to notice that high concentrations of Pb are located around two large cities, Lisboa and Setúbal, namely in the littoral region south of Setúbal. This reinforces the knowledge on the important contribution of anthropogenic factors, like industry and urban development, to the environmental contamination. Traffic and industry emissions are linked to the high contamination values surrounding this two big cities, whereas the contribution of the local mineralogy to the soil contamination are unknown (Inácio et al., 2008)

2.5.3 Australia Land

Australia is the sixth biggest island continent in the world (7,682,300 km^2). The nation is extended roughly 4 000 km from east to west and 3 200 km from north to south, lying between the Indian and Pacific seas and having a coastline of 36,735 km (*Australia Government*, n.d.). A simplified soil map of Australia is shown in Figure 2.19 and Figure 2.20 (Caritat & Cooper, 2011).

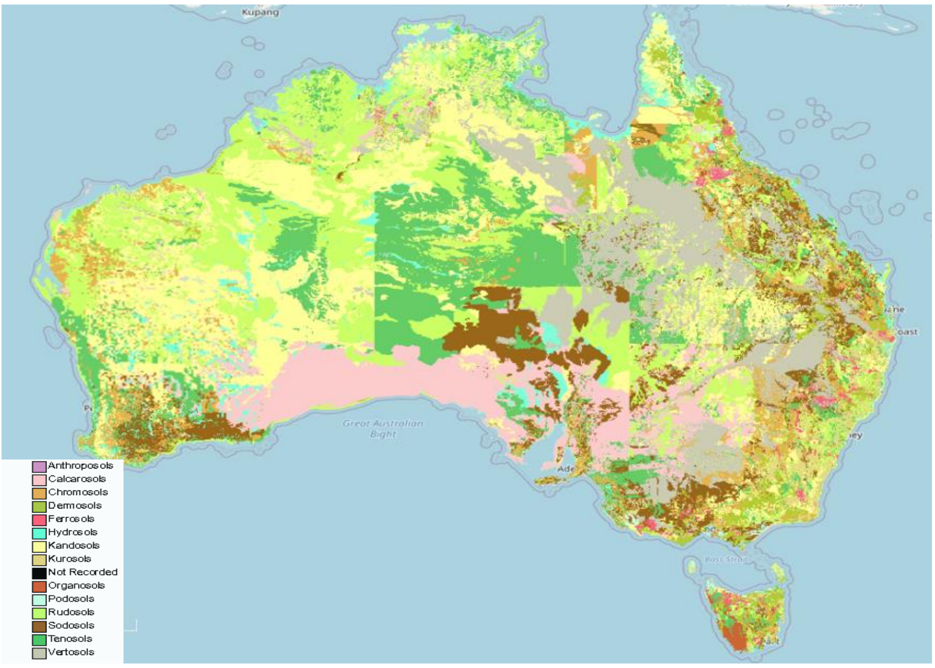

Figure 2.19 Major soils type in Australia. (Australia Geoscience)

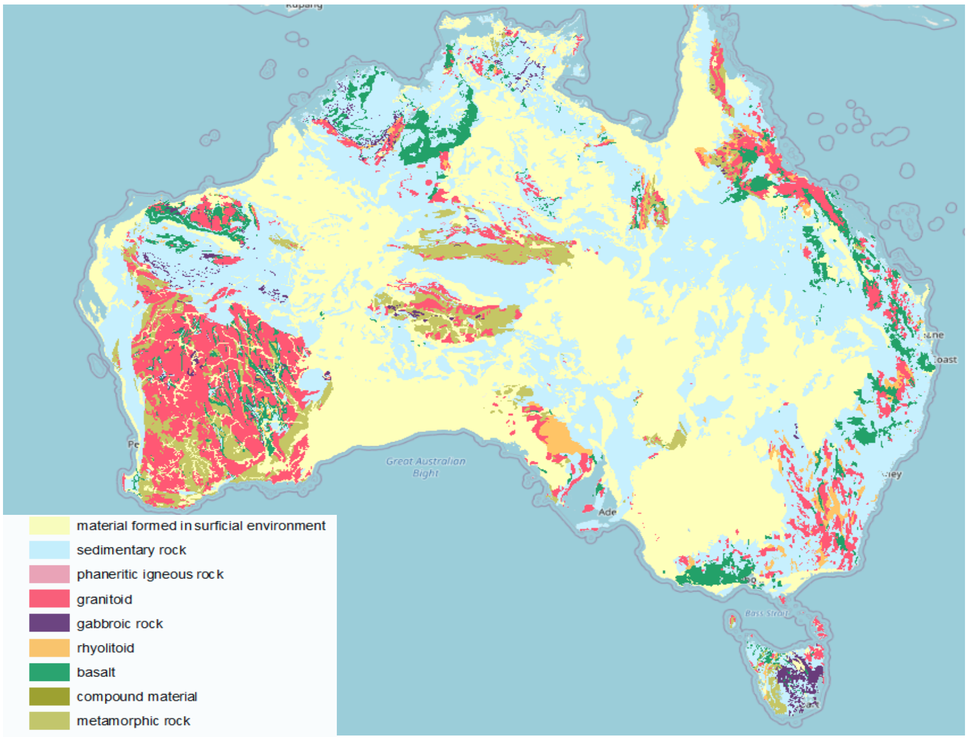

Figure 2.20 Lithology map of Australia. (Australia Geoscience)

To achieve the information shown in figures above, composite samples were collected from different sites across Australia. With the best afforts to get access to all sites defined for collecting samples, only 1186 samples were collected. Of these 1186 samples, 123 were duplicated in order to have a quality control. Furthermore, 6 samples were collected at two different sites 69 km (average distance) wide apart. Overall, a total of 1315 sample were collected (Figure 2.21). At each site two types of samples were collected; one was Top Outlet Sediment (TOS) and the other was Bottom Outlet Sediment (BOS). The first one was collected at 0-10cm depth or below the root zone (if applicable) and the second one was collected at 60 to 80 cm average depth (Caritat & Cooper, 2011).

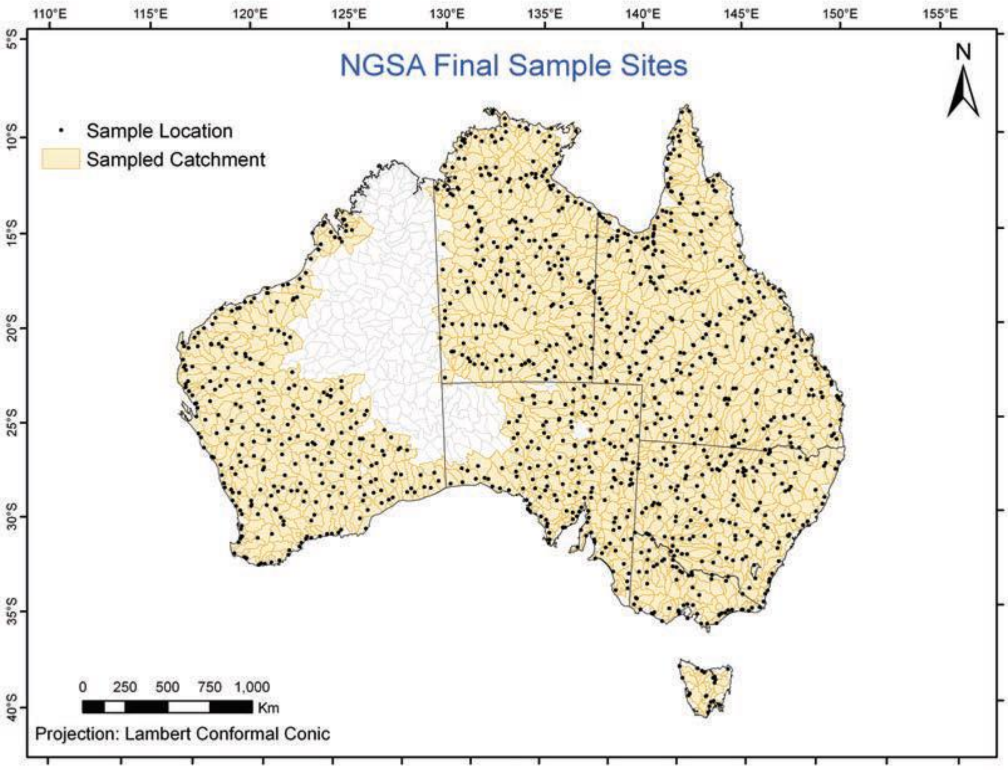

Figure 2.21 Final Distribution of soil samples for the National Geochemical Survey of Australia NGSA. (Caritat and Cooper, 2011)

3 CASE STUDIES

In this chapter some case studies from Portugal and Australia are presented, followed by a brief analysis.

3.1 Case Study of Portugal: Base das Lajes

The region understudy is in Terceira Island on east side (Figure 3.1). Base das Lajes is in the northeast band exhibiting an area of about 8.5 to 10 km in length and between 3.5 and 4 km wide from Cabo da Praia to Vila Nova located in the north. In the south, it extends from Praia da Vitória to Cabo da Praia. In Figure 3.1 there are identified three sites associated with the higher environmental risk: Main Gate Area (3001), South Tank Farm (5001) and Cinder Pit Farm (5002) (Paulo et al., 2012).

This Base das Lajes is owned and administered by the Portuguese Air Force. The Base is often referred to as the "Crossroads of the Atlantic" due to its geopolitical position. The major objective of Lajes is to help U.S. and allies in the Atlantic. The main use of Base das Lajes is as an aeroplane refuelling station. The Base das Lajes was established by the British Royal Air Force on the basis of an Interim Agreement (December 1943) between the United States and Portugal, in 1943 (CH2MHILL, 2005).

Figure 3.1 Localization of the 3 sites and the basal aquifer of Juncal. (Adapted from Ferraz Pinheiro, 2018)

In this case study, the Main Gate area (Figure 3.2) was analysed. The Main Gate Area was subdivided into areas designated by Apron A and 5 and sometimes into a third area known as 5 hydrant species, all of which accounted for the presence of contaminants. This case of study was considered for analysis and discussion of environmental contamination in the Lajes Graben area, which were performed over time by different stakeholders. Most monitoring wells (MW) are situated at the surface and intermediate suspended aquifers inside and outside the site to monitor pollution (Ferraz Pinheiro, 2018).

The presence of hydrocarbons appears to have been recognised in the soils and groundwater at Site 3001, since 1950. There were reports from employees of the facilities that the gasoline leaks occurred from tanks located at the east of Porta de Armas and on the pipeline system establishing links to other tanks (the south tank farm and Cinder Pit fuel tanks) and to the 5 Hydrants region. In this field, for example, several gasoline leaks were reported in 1982, when the tank was destroyed by a terrible earthquake, with 136,274 L of Jet Fuel 4 (JP-4) being spilled (Ferraz Pinheiro, 2018).

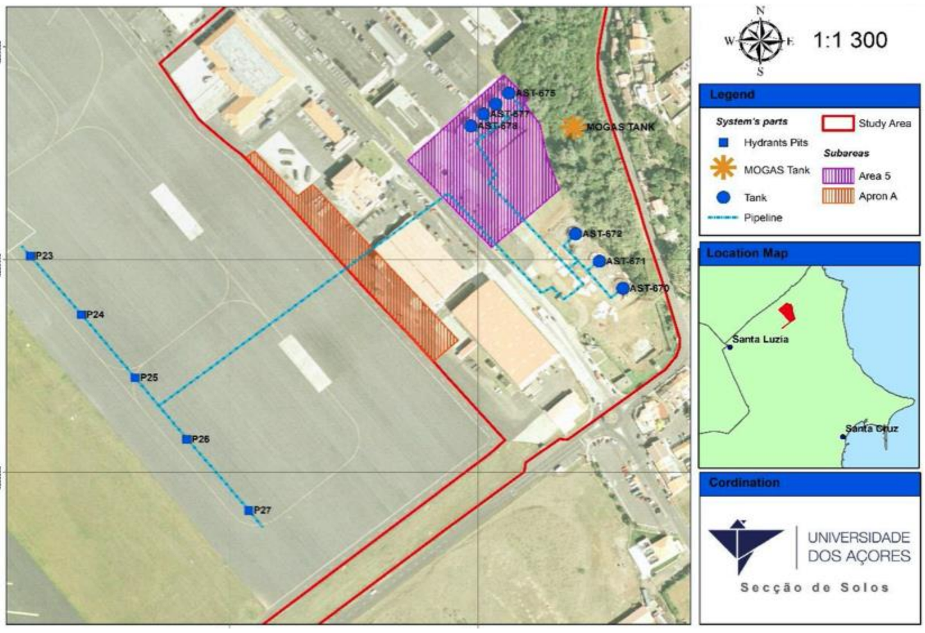

Figure 3.2 Location of the main infrastructures of the Main Gate Area, namely, 5 Hydrants (P23, P24, P25, P26 and P27), Apron A and Area 5 with pre-existing tanks (currently removed). (Ferraz Pinheiro, 2018)

Figure 3.3 shows the locations of 2020 chemical analysis groundwater sampling campaigns. Since 2013, these locations remained the same and included piezometers at the surface and in intermediate hydrogeologic formations (Leitão & Henriques, 2020).

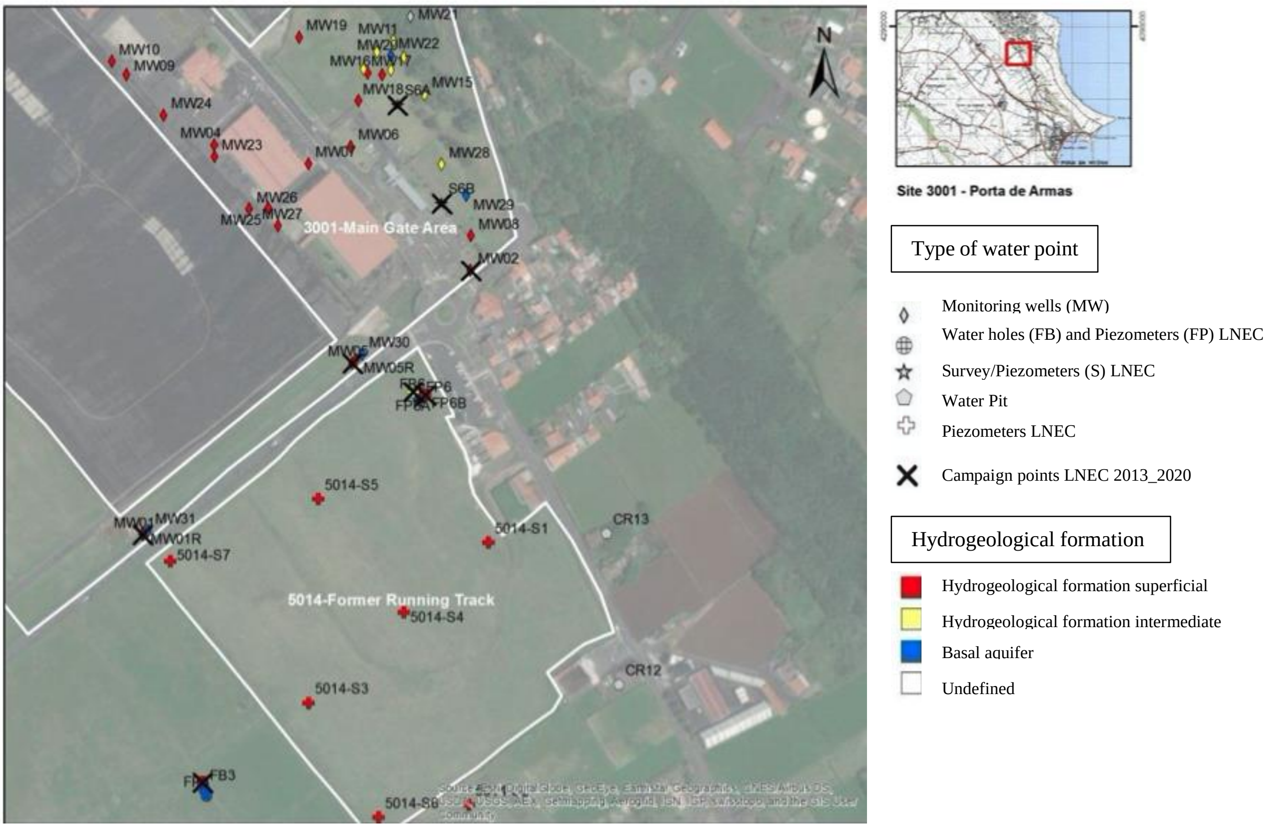

Figure 3.3 Map of groundwater sampling points inside and outside of the site 3001. (Leitão and Henriques, 2020.)

Previous studies intended to supplement the analysis conducted within this Site by 65 ABG and therefore assessed the consequences of the restoration operations on piezometers situated on the periphery of the Site 3001. The goal was to identify in time the existence of possible contaminants which could migrate into the southwest, to the Basal aquifer of Juncal (Figure 3.1), by selecting piezometers downstream of underground flow. For that, piezometers placed at the surface and in intermediate hydrogeologic formations were used for early identification of potential contamination. The Ministry of National Defense (MDN) hired National Laboratory for Civil Engineering (LNEC) to execute part of the control in the absence of the surveillance that was exercised by 65 ABG since 2018 (Leitão & Henriques, 2020).

The results from previous campaigns (Figure 3.4) showed the presence of BTEX in the same magnitude concentrations which were observed in last campaigns conducted with piezometers at same site (MW01, MW02, S6A). In recent years, contrary to what happened in previous years, it was not possible to detect this contaminant above the standards. This shows that the BTEX only exceeded requirements recorded for toluene on the S6B piezometer in September 2017. In the campaign of March 2016 (FP6B) and of September 2019 (FP6A and FP6B), the

BTEX presence were compared with piezometers outside Site 3001, but this evidence was discussed in reports for further information (Leitão & Henriques, 2020).

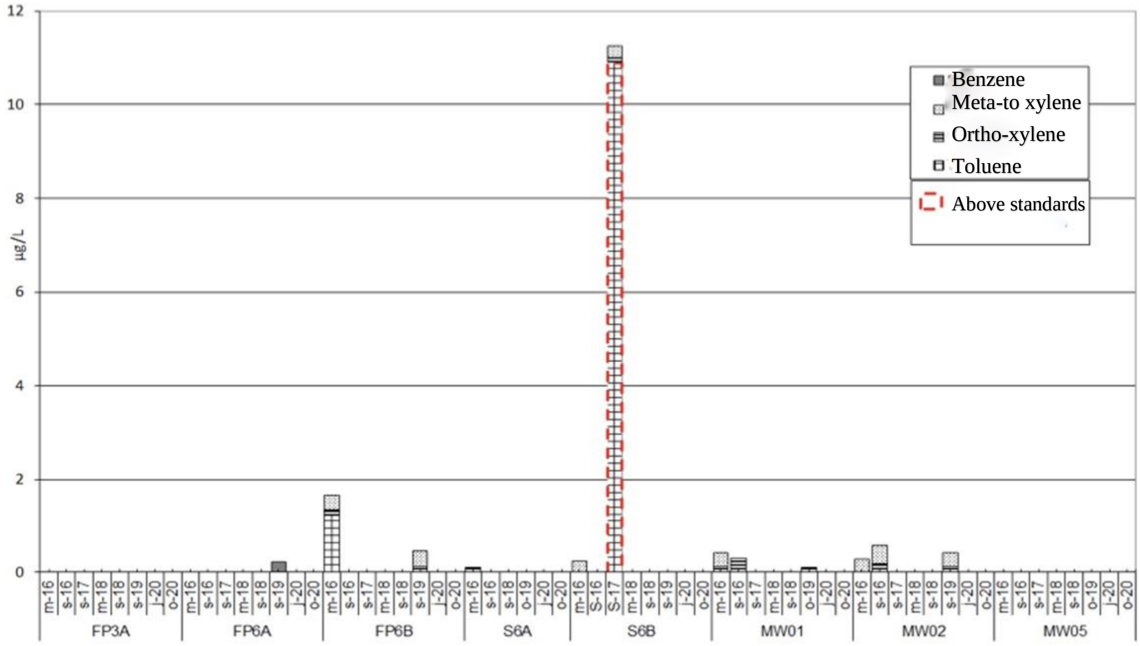

Figure 3.4 Concentration of BTEX in piezometers located inside and outside of the Site 3001 between 2016 and 2020. (Adapted from Leitão and Henriques, 2020)

Volatile organic compounds (VOC) are less present in groundwater as these compounds escape into the atmosphere, being more common near to emission sources. There are only two VOC recordings in 2020, namely the S6A piezometer, which detected the presence of tert-butyl alcohol (a chemical without a defined standard) in June (Figure 3.3). Besides, tetrachlorethylene (PCE) was detected in October using the FP6A piezometer (Figure 3.5). The presence of tert-butyl alcohol in S6A had already been observed in September 2018. Chloroform, which may be a reaction product of tert-butyl alcohol, was discovered in October 2019. The presence of tert-butyl alcohol in the groundwater of the S6A piezometer should be related to its proximity to leaks near the old fuel tanks that existed at that location (Leitão & Henriques, 2020).

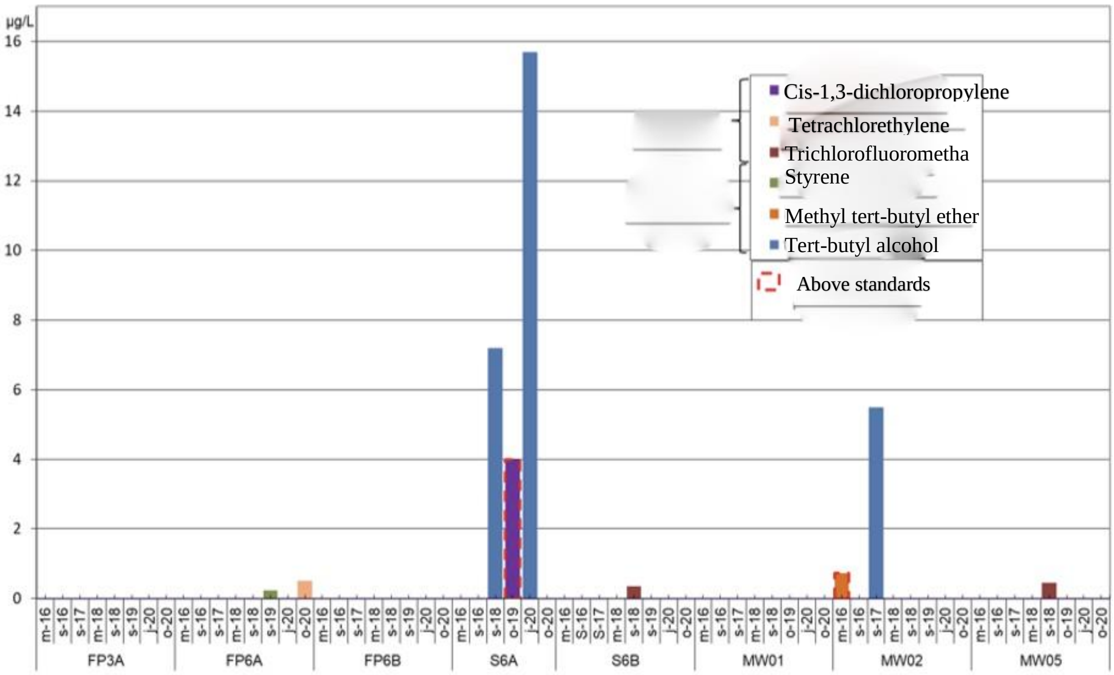

Figure 3.5 Concentration of VOCs in piezometers located inside and outside of the Site 3001 between 2016 and 2020. (Adapted from Leitão and Henriques, 2020)

Concentrations over the quantification limit in relation to TPH were observed at different locations in 2020, such as in previous campaigns (Figure 3.6). The piezometer MW05 is the only one in which concentrations over the standard are present. Since 2019, the development of TPH in the S6A piezometer appears to show an increase. The oscillations between camps are due to the leaching of soil pollutants to deeper layers, during rainfall periods (Leitão & Henriques, 2020).

In terms of PAH (Figure 3.7), the 2020 campaigns generally exhibit lower values than before. Only the FP3A piezometer has multiple parameters with values over quantification limits in the piezometers downstream of site 3001 (Leitão & Henriques, 2020).

Heavy metals (i.e., Al, Fe, Mn) were associated with concentrations above the standards, as reported in previous years, likely reflecting the fact of the site being located in a volcanic island (Leitão & Henriques, 2020).

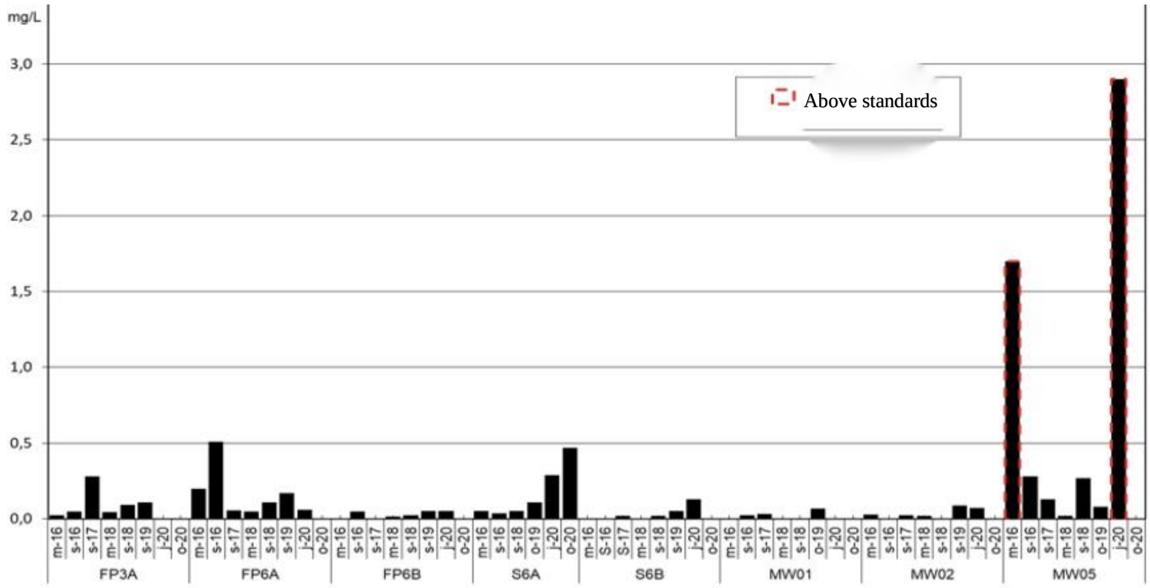

Figure 3.6 Concentration of TPH in piezometers located inside and outside of the Site 3001 between 2016 and 2020. (Adapted from Leitão and Henriques, 2020)

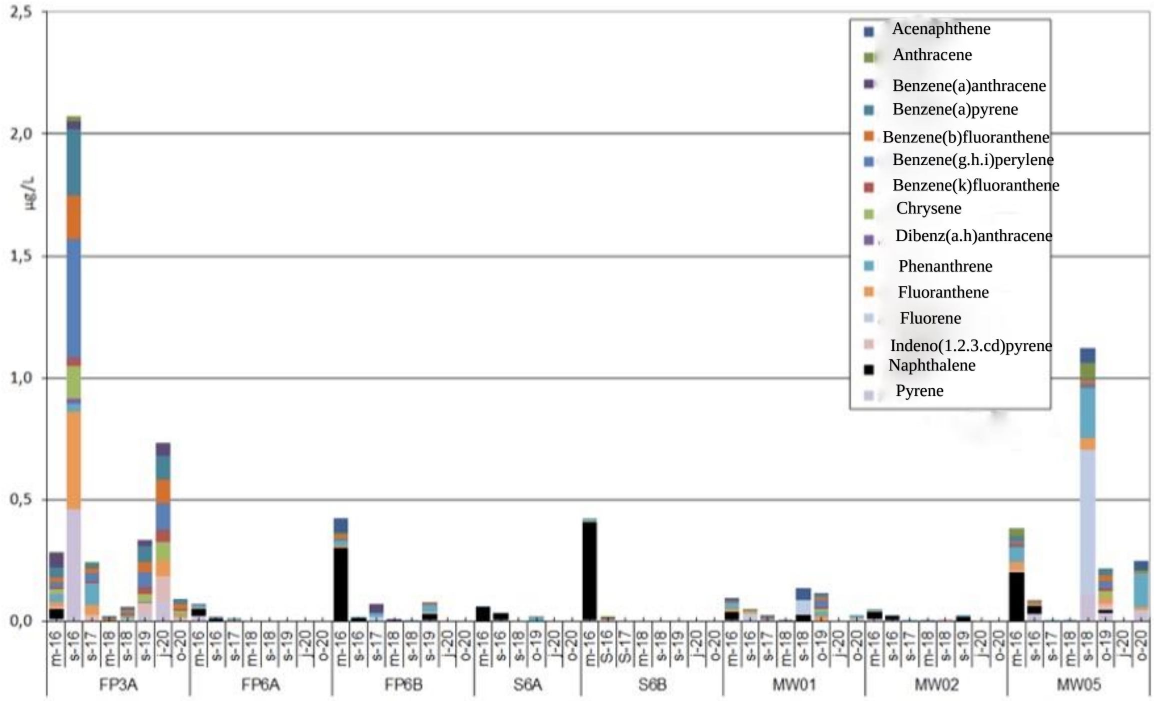

Figure 3.7 Concentration of PAH in piezometers located inside and outside of the Site 3001 between 2016 and 2020. (Adapted from Leitão and Henriques, 2020)

Although the results from 2020 reveal no additional downstream site decay, there are indicators that the inside site is still in a process of degradation. This indicates a reversal in the setback process at Site 3001. The oscillations in the observed concentrations are caused by diverse mechanisms of infiltration, by dragging of soil pollutants, as well as by chemical and biological processes of volatilization, adsorption, solubility and biological degradation (which allows gradual natural decay of hydrocarbons) (Leitão & Henriques, 2020).

The necessity of remediation of the contaminated soil should also be evaluated, taking into consideration the pollutants present at the site. Some variables, such as the adaptability to contaminants (based on analyses carried out), as well as adaptation to geological and hydrogeological context and efficacy, must be taken into consideration to select technologies that permit integrated treatment of soils, with 4 technologies being selected (Table 3.1) (Ferraz Pinheiro, 2018).

Table 3.1 Technology Analysis for Site 3001 (Adapted from Ferraz Pinheiro, 2018)

Site 3001 Soil Contaminants: TPH, VOC, PAH, BTEX, Metal Lithology: Fine Sands and Clays				
Remediation zone	Tecnology	Adaptability to contaminants	Adaptation to geological and hydrogeological	Efficacy
Soil	Bioventing	Y(except PAH and metals)	L	L
	Soil Vapour Extraction	Y (except PAH and metals)	L	Y
	Chemical Oxidation	Y	L	L
	Bioremediation	Y (except metals)	Y	Y
L (high applicability) y (Applicability)				

3.1.1 Analysis of Case Study: Base das Lajes

By analyzing the results presented on the case study related with site 3001, a variable of results from the analytical groundwater monitoring could be accounted. The results from this case study showed variable values of contamination, which could either be below or above the threshold allowed on the legislation. Besides, the values of contamination were demonstrated to be highly variable through the years. On that premise, this matter cannot be disregarded and it is important to continue with close monitoring of the site, in order to prevent contamination of areas surrounding the contaminated site. In fact, through the monitoring of the S6A, an increase in some contaminants, like VOCs and TPH, was reported, indicating a higher contamination of the interior of the site, which may result in higher degradation. Consequently, monitoring of other piezometers (i.e., FP3A, FP6A, FP6B) is also crucial since the contaminants may be spreading to off-site areas. This spreading may be happening mainly through the aquifers, but inevitably the contaminant is first filtrated by the soil, resulting in soil contamination.

Having that in mind, it is crucial to apply appropriate remediation techniques in the soil of the site 3001. Thus, based on the background provided, it is next suggested the most suitable technique to apply on site taking into consideration several criteria. For this specific case of remediation, according to Pinheiro, 2018 four remediation techniques were proposed (Table 3.1), with the chemical oxidation emerging as the most suitable one. Indeed, this technique has advantages when compared to the others that are presented, being more suitable due to the adaptability to the contaminants presented on the site.

3.2 Others Case Studies of Portugal

3.2.1 ERASE Project, Estarreja

An example of a case of remediation in Portugal was the ERASE Project, carried out by the Estarreja Contaminated Water and Soil Regeneration Company. It consisted in an environmental impact study of the stock of waste and sediments (pyrites residues with As and Pb and sludges containing Hg). With this study it was possible to characterise the natural location of the region and the environmental impact associated with decades of industrial activity. On the site where industrial activity is taking place the soil is composed majority by sandstone, shale, and marlstone. The ERASE project was planned in 1994 and initiated in 2003(Costa & Jesus-Rydin, 2001; Ribeiro, 2013).

Consequently, ERASE major aim was to minimize the risk of soil and groundwater contamination. This contamination was mainly associated to the leaching process connected with past industrial residuals at the Estarreja chemical complex. The main goal was to recover the adjacent areas used for stockpile the waste. The project was based on excavation and off-site disposal of pyrit waste and sludge from previous Quimigal and UNITECA facilities, and then insert the contaminated soil in a waterproof site of around 300,000 m^3. This whole procedure was finished in 2005. The ERASE project actual site is located in a region near to Quimigal sludge park. The confinement in waterproof sites was designed to avoid or decrease pollution, via lixiviation of stored waste, and to reduce pollutant loads to groundwater, which happened over 50 years of industrial operation. This treatment allowed to minimise leachate penetration (Costa & Jesus-Rydin, 2001; Ribeiro, 2013).

3.2.2 EXPO 98 Project, Lisbon

Another project of soil remediation in Portugal was the study case carried out for EXPO 98 which resulted in the first significant remediation activity, in 1994. This remediation was executed on polluted sites to convert the whole region in which the World Exhibition of 1998 would take place. A further investigation was carried out in Portugal on that site, revealing that at the beginning exist there a oil refinery, as well as fuel storage parks, a sulfuric acid facility, and a cracking plant, all of them had a significant contribution to the site contamination (Ferguson, 1999; Ribeiro, 2013).

The accepted solution for site remediation was based on the excavation and disposal of contaminated soil in Beirolas sanitary landfill (Portal das Nações, 2014). The principal issue with this remediation procedure was the lack of criteria for determining the level of contamination. At that time, national standards were not available for soil application. Thus, to solve the problem, the criteria and standards used relied on Ontario (Canada) legislation (Ferguson, 1999; Ribeiro, 2013).

3.2.3 CUF Hospital, Lisbon

The present study was conducted during the investigation of actions carried out in the process of construction of the new annex of the CUF Hospital, located in the intermediate zones of Parque das Nações, Lisbon. In July of 2016, during the excavation process, contaminated soils were identified. The contamination of the soils occurred during an operation of oil refinery, which was leaching with TPH, PAH and BTEX to the soil. This event is linked with the study case carried in 1994 (EXPO 98) , where the remediation process was carried out (Tomás, 2017; Dias, 2019).

During the excavation, the contaminated soils were deposited on quarries and other inappropriate places without first being analyzed by licensed companies (SISAV and EcoDeal). Then EcoDeal alerted the APA, to denounce an illegal attempt to move contaminated soil without treatment. This was possible because of the intense odor of hydrocarbons that came from the site. After that, EcoDeal started to receive the contaminated soils and proceeded with its treatment without harming the environment (Tomás, 2017;Dias, 2019).

3.2.4 Business Park Project, Barreiro

In order to investigate the contamination at the location of Barreiro Business Park a site investigation was conducted at two different times, the first one in October 2003 and the second one in July 2005. The contaminated area was the former industrial location on the left margin of the Tejo river, near Lisbon (Barreiro). In the last ten decades, the main area, which cover approximately 30 hectares, composed majority by sandstones and silty-clay, was considered a high-risk area in terms of potential contamination. Several studies were carried out through the years by several companies, such as Volda-Engineering and Industrial Management, Lda., eGiAmb and Weber Portugal (Vendas et al., 2008;Ribeiro, 2013;Gonçalves, 2016).

Further studies allowed to determine the source and the pollutants on the site during the activity of the Quimiparque. The main contaminants found were heavy metals (i.e., As, Cu and Pb), organic compounds, pyrite ash and slag. Therefore, the Quimiparque developed a plan denominated MASTERPLAN, which had the goal to requalify the territory and enhance the requalification of the area to provide Barreiro a new centrality. The solution for the site, implemented between 2008 and 2010, consisted in the removal of the old deposits of ash and Pyrite slags and were deposited on CIRVER (Vendas et al., 2008;Ribeiro, 2013;Gonçalves, 2016)

3.2.5 Analysis of The Presented Portugal Case Studies

By performing an analysis of the Portugal case studies, it was not possible to find some particularities regarding the soil type, namely in the study case of EXPO 98 and of the CUF hospital. Regarding the remediation technique, it was possible to verify that all of the cases were remediated with the same technique: excavation and off-site disposal. Some case studies, such as the EXPO 98, were misguided given the lack of knowledge and licensed companies at that time, which reflected on the use of an inappropriate remediation technique. A clear example of that is the fact that the contaminants, from the contaminated site, were disposed on a quarry with no protection to avoid further contamination. The other Portugal cases, as CUF Hospital, ERASE Project and Barreiro project, used different approaches since when the contaminated soil was removed, licensed companies were available to analyse and perform soil remediation. Indeed, in these projects, the contaminated soil was disposed in impermeabilized landfills, to prevent further contamination. However, it was not possible to find any reports of further monitoring of the sites, to guarantee that the soil left there was indeed not contaminated.

The technique of excavation and off-site disposal is used in most of the situations, since it is an easy and quick process. However, it is likely that it does not entail for a sustainable management of the land. On that premise, different techniques could be more suitable, according to the type of contamination. Based on the contaminants presented in each of the previous cases and considering the available techniques for their remediation, different remediation choices could possibly have been applied, according to chapter 2 of this dissertation. For example, the projects of EXPO 98 and CUF Hospital (contaminated with PAH, TPH and BTEX) could have been remediated by resorting to chemical oxidation, bioremediation or thermal desorption. Regarding the ERASE and Barreiro (contaminated with heavy metals), soil washing, electroremediation or soil flushing, would likely entail for the most suitable remediation processes.

3.3 Case Study of Australia: North Sydney Council

Mainland Australia accounts for six states (New South Wales, Queensland, South Australia, Tasmania, Victoria, and Western Australia). New South Wales (NSW) is a state on the east coast of Australia, with Sydney as state capital, which is also the most populous city in Australia. The study case of Australia was located on the North Sydney Council. The site used to be a school, and was being prepared for constructing a new road (EI Australia, 2020).

The collection of soil samples and their processing was performed by a suitably qualified, trained and experienced environmental engineer. To collect the soil samples, the site was split in one rectangle and the sampling points were divided equally. Manual grab samples were collected from six test pits (all the reports from the six test pits are available for consultation in the Attachment A) managed by an excavator supplied by the client and by a trained and qualified staff member (Figure 3.8). The six samples were distributed evenly across the south-western portion of the site (Figure 3.9) (EI Australia, 2020).

Figure 3.8 North Sydney Council (a) View of site conditions. (b) View of sub-surface conditions. (EI Australia, 2020)

Soil samples were collected using sterile, single-use/dedicated nitrile gloves and placed into 250g laboratory-prepared glass jars, which were capped using Teflon-sealed, screw caps and immediately refrigerated prior to being delivered to the laboratory (Authority, 2014).The collected material is mostly composed by gravelly sand (medium to coarse grained, dark brown, no odour) and by silty sand (fine to medium grained, orange with trace gravels, no odour). This is only applicable to *in-situ* fill soil material located within the south-western portion of the site (EI Australia, 2020).

Figure 3.9 Sampling points of the site. (EI Australia, 2020)

To categorise the contaminants on site, it was necessary to ensure that the levels of the highest potential contaminant did not exceed the test values for that classification of the specific contaminant concentration (SCC) and/or the toxicity characteristics leaching procedure (TCLP). These are the two measure properties of chemical contaminants that are used to classify wastes. The SCC test is the first test to be used for chemical evaluation of waste, consisting in a first waste categorization screening test. The test results of each contaminant (yellow part) based on SCC alone must be below or equal to the contaminant threshold (CT) values set out in Table 3.2 (white part). If that happens, this shall fall under one of the following classes: General solid Waste ≤ CT1 or restricted solid waste ≤ CT2. If the value of the SCC waste exceeds the CT for general solid waste, further assessments may be carried out using the TCLP test (EI Australia, 2020).

In Table 3.2 at the yellow part it is possible to analyse the concentration results present in each pit test that was collected from the site. By analysing the results presented above, it was possible to detect the presence of some contaminants such as heavy metals, PAHs, BTEX PCBs. These pollutants are harmful to the soil and the environment, so it was necessary to intervene for their remediation. As previously described, there are a series of steps to follow to classify the contaminants and proceed with their remediation, which are outlined in the NSW EPA 2014. By analysing the values in Table 3.2, it was possible to notice that all the values were below the maximum allowed by the applied legislation. So, it was possible to deduce that these contaminants were considered general solid waste. Having done their classification, it was possible to proceed with its remediation. The suitable remediation process was excavation and disposal to a facility licenced to accept this type of waste for treatment, in accordance with the protection of the Environmental Operations (waste) Regulation 2014.

Table 3.2 Summary of laboratory analytical results. (EI Australia, 2020)

Sample ID		Sampling date	Heavy Metals						PAHs		BTEX				TRHs		OCPs	OPPs	Total PCBs	Asbestos
			As	Cd	Cr#	Pb	Ni	Hg	Benzo(α)pyrene	Total PAHs	Benzene	Toluene	Ethylbenzene	Total Xylenes	C_6 - C_9	C_{10} - C_{36}				
Waste Classification Assessment Criteria	NSW EPA 2014 General Solid Waste	CT1 (mg/kg) [1]	100	20	100 [5]	100	40	4	0.8	200	10	288	600	1,000	650	10,000	<50	250	<50	NR
		TCLP1 (mg/L)	5	1	5	5	2	0.2	0.04	NR	0.5	14.4	30	50	NR	NR	NR	NR	NR	NR
		SCC1 (mg/kg) [2]	500	100	1,900	1,500	1,050	50	10	200	18	518	1,080	1,800	650	10,000	<50	250	<50	NR
	NSW EPA 2014 Restricted Solid Waste	CT2 (mg/kg) [3]	400	80	400 [5]	400	160	16	3.2	800	40	1,152	2,400	4,000	2,600	40,000	<50	1000	<50	NR
		TCLP2 (mg/L)	20	4	20	20	8	0.8	0.16	NR	2	58	120	200	NR	NR	NR	NR	NR	NR
		SCC2 (mg/kg) [4]	2,000	400	7,600	6,000	4,200	200	23	800	72	2,073	4,320	7,200	2,600	40,000	<50	1000	<50	NR
	Special Waste / Scheduled Waste																> 2 mg/kg - Scheduled Waste [5]		> 2 mg/kg - PCB Waste [6]	Where detected classification is Special Waste (Asbestos Waste)
TP1_0.1-0.2		4/12/2020	1	<0.3	25	8	1.5	0.19	<0.1	<0.8	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
TP2_0.1-0.2			2	<0.3	25	30	1.5	0.05	0.6	7.3	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
TP3_0.1-0.2			1	<0.3	27	6	1	<0.05	<0.1	<0.8	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
TP4_0.1-0.2			1	<0.3	20	14	1.1	<0.05	0.1	<0.8	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
TP5_0-0.1			<1	<0.3	18	20	0.9	<0.05	0.2	1.5	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
TP6_0-0.1			<1	<0.3	17	3	0.6	<0.05	<0.1	<0.8	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
Maximum Concentration			2	<0.3	27	30	1.5	0.19	0.6	7.3	<0.1	<0.1	<0.1	<0.3	<20	<110	<1	<1.7	<1	No
Waste Classification			*GENERAL SOLID WASTE (NON-PUTRESCIBLE)*																	

Note:

NA	Not Analysed
NC	Not Calculated
NR	No reference criteria available in current regulatory tools.
#	Scheduled Chemicals: Where none detected the LOR has been used to sum
**	Moderately Harmful Pesticides
1	NSW EPA 2014 CT1 General Solid Waste Thresholds (without leachate test), in Waste Classification Guidelines, Table 1
2	NSW EPA 2014 CT2 Maximum values for Leachable concentration and specific contaminant concentration for Restricted Solid Waste Thresholds, Waste Classification Guidelines Table 1
3	NSW EPA 2014 TCLP1/SCC1 General Solid Waste Thresholds (leachable concentration and total concentration when used together), in Waste Classification Guidelines Table 2
4	NSW EPA 2014 CT1 Maximum values for Leachable concentration and specific contaminant concentration for Restricted Solid Waste Thresholds, Waste Classification Guidelines Table 2
5	NSW EPA Scheduled Chemical Wastes Chemical Control Order 2004. Section 4.14
6	NSW EPA Polychlorinated Biphenyl (PCB) Chemical Control Order 1997. Where PCBs are reported at concentrations >2 mg/kg and <50 mg/kg, material is *non-scheduled PCB waste*. Where PCBs are reported at concentrations >50 mg/kg, material is *scheduled PCB waste*.
7	95% UCL only performed for analyte where soil concentrations exceed waste classification criteria in samples
(yellow shading)	General Solid Waste

3.3.1 Analysis of Case Study: North Sydney Council

In the case study of North Sydney Council, which was performed by EI Australia company, the technique chosen to remediate the site consisted in excavation and off-disposal of the contaminated soil in a licensed facility. However, this technique may raise questions regarding being the most suitable, the reason underlying the company choice is correlated with the legislation applicable on the country. In fact, according to that, the contaminated soil was classified as general solid waste, due to the fact that the concentration of the contaminants was below to the threshold presented on the legislation presented on CLM Act.

3.4 Others Case Studies of Australia

3.4.1 Allied Feeds and Lednez Remediation Project

One case of remediation was located on the old site of Allied Feeds and Lednez who is placed on the Rhodes Peninsula next to Homebush Bay, Sydney, NSW, Australia. This site is composed by clay, shale and sandstone. Historically, the adjacent Lednez site has been used to produce several chemicals, such as, asphalt, explosives, and chlorinated compounds. This resulted in the contamination of the site with chlorobenzenes, chlorophenols, dioxins, and organochlorine pesticides. For several decades, the necessity of remediating the sites has been clear, however, due to lack of proven successful remediation technology, the remediation of the site was not executed. The “Green” Olympics in 2000 Greenpeace elevated the necessity to remediate the site. Thus, the NSW government required to use a “non-incineration technology”, with the thermal desorption (TD) technique being chosen to remediate the soil. In fact, all sites have been remediated using TD, given about 175,000 tons of contaminated soil. The project involved a variety of regulatory, technical and logistical obstacles, including the establishment of standard regulatory best-practice, the monitoring of emissions and compliance with environmental requirements (Troxler et al., 2010).

3.4.2 Former ChlorAlkali Plant Remediation Project (FCAP)

Remediation of Hg contaminated soil was executed by Orica at the Botany Industrial Park (BIP) in NSW, namely at the site of the Former ChlorAlkali Plant (FCAP). Between 1944 and 2001 FCAP used Hg to manufacture Cl, caustic soda and hydrogen. These operations resulted in soil and groundwater contamination at FACP by Hg. Since the FCAP at BIP no longer uses Hg, an assessment of remediation for the site was carried by an expert, which identified that containment and excavation was the best remediation option. Therefore, to start the process of remediation the FCAP site was divided in three blocks A, M and G. The Block G was the local where the former operations were executed and where the contamination with Hg was most presented. At block A and M, the best remediation technique consisted in excavating contaminated soil with mercury, and backfilling with uncontaminated soil, according with the criteria of NSW EPA. At block G the same technique as in the block A and M was applied. Besides, when they removed the contaminated soil, a wall for containment was constructed to cut-off and isolate any residual leach of Hg to the groundwater. This Remediation project was conducted between 2013 and 2017 (Orica, 2016; Orica Australia, 2016).

3.4.3 Hunter River Remediation Project (HRRP)

The former Broken Hill Propriety (BHP) owned Newcastle steelworks company, which operated from 1915 to 1999. The facilities of this factory were located on the south of Hunter River, at Newcastle port, NSW. During its operation, contamination with PAH occurred in the riverbed sediments adjacent to the steelworks site. When the factory was closing the business, BHP detected that during the operation of the company, some contamination in the riverbed sediments, as previously reported, occurred and needed remediation. So, they notified the NSW EPA, and they provide support under CLM Act for the Hunter River Remediation Project (HRRP). This project was, at the time, the biggest remediation project undertaken is Australia. To remediate this contaminated site, several drags were placed in the hunter river to drag the sediment from the bottom and then a stabilisation process with cement were executed. When the stabilization process was performed, the sediments from the bottom of the river were transported by road to a facility that was constructed for that purpose. The facility was located at Kooragang Island which was previously used for waste disposal of steelworks by-products and adapted for the HRRP. This project was completed in 2012 (Marten & Bagnall, 2019).

3.4.4 Analysis of The Presented Australia Case Studies

On the Allied Feeds and Lednez situation, the technique for remediation was based on thermal desorption. This technique is likely considered the most suitable option, given the contaminants on site and the location of the facility. With this technique it was possible to remediate the soil *in-situ* and have the advantage to separate the contaminants from the solid matrix, which can then be re-inserted in the site "uncontaminated", ensuring a sustainable management of the land.

Regarding the HRRP and the FCAP projects, reports of the particularities of the soil and also of its further monitoring were not found. On the FCAP the technique for remediation was containment and excavation, followed by off-site disposal. On the HRRP, excavation was performed, followed by stabilization and off-disposal. It is likely that the remediation process which was applicable in the FCAP project was suitable based on the contaminants present on site, as well as based on the fact that the study area was located in an industrial zone and that the site for remediation was inside a facility. Thus, the use of other techniques, such as soil flushing or electroremediation, was not appropriate in this case. Accordingly, the HRRP project was based on a report of contaminants made by EPA, which analysed the suitable remediation for the site under the CLM Act, ensuring the choice of a suitable remediation technique for the type of contaminant present on site and its location.

4 CONCLUSION AND SUGGESTIONS FOR FURTHER STUDIES

Worrying situations of soil degradation and contamination have been identified in different parts of the world as a result of extractive, industrial and urban activities. Besides, soil contamination is at the origin of potential risks to public health and to the ecosystem, reinforcing the need of a rapid and effective intervention. Thus, it is urgent to optimize the current most suitable remediation techniques for soil contamination, as well as to further explore potential new solutions, in order to contribute for a sustainable management of the land.

This study aimed to characterize the contaminants that are most present in the soils, as well as the best remediation techniques, to ensure a sustainable management of the land. In order to further characterize this field, case studies from Portugal and Australia were presented throughout the thesis. The case studies from Portugal raised several issues, reinforcing the urgent need to prioritize this matter. For instance, the currently legislation applied in Portugal is notoriously insufficient, and it is recurrently necessary to rely on international law, such as that from Ontario or from the Netherlands. It is expected that the establishment of a legislation specifically for Portugal can contribute to a sustainable management of the land, given that it would be directed to contaminants and associated problems existent in Portugal.

From the Australian case studies, it is clear that they have different approaches when choosing the remediation techniques. This is likely justified by the size of the country and the fact that they have its own legislation and methods to follow when analysing a contaminated site. If a comparison is made between Portugal and Australia it is clear that Portugal needs to further develop this field, namely through the establishment of a proper legislation, to ensure a sustainable management of contaminated land. In fact, in all of the presented cases, Portugal only relies in the excavation and off-site disposal of the land, on opposite to Australia which have different and more sustainable approaches when remediating the soil.

Finally, based on all of the data gathered on this work, it is possible to conclude that advances have been made in order to disclose more sustainable techniques for soil remediation. However, the sustainable management of the land still remains poorly established in our society. Further exploration of this subject, in order to reach a more effective sustainable management of the land, should be of vital importance to protect, not only the environment but, ultimately, ourselves. To complement the work developed around this theme, it would be important to further explore the case studies, namely regarding the monitoring carried out on the contaminated soils. Furthermore, the legislation applied to contaminated soils represents other issue of urgent discussion given its global variability. More accurate strategies should be developed, by analysing and comparing the legislation of each country, as well as its efficacy.

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