Universidade de Aveiro Departamento de Ambiente e Ordenamento

2020

Patrícia Alexandra Machado Henriques

Impacte dos fogos florestais em antigas lixeiras portuguesas

Impact of wildfires on Portuguese closed waste dumps

Universidade de Aveiro Departamento de Ambiente e Ordenamento
2020

Patrícia Alexandra Machado Henriques

Impacte dos fogos florestais em antigas lixeiras portuguesas

Impact of wildfires on portuguese closed waste dumps

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia do Ambiente, realizada sob a orientação científica da Professora Doutora Maria Isabel da Silva Nunes, Professora Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, e da Doutora Bruna Raquel Figueiredo Oliveira, Investigadora do Departamento de Ambiente e Ordenamento, CESAM, Universidade de Aveiro.

Dedico este trabalho aos meus pais, avós e irmã.

o júri

presidente

Professor Doutor Mário Miguel Azevedo Cerqueira
Professor Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

Professora Doutora Maria Isabel da Silva Nunes (Orientadora)
Professora Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

Professora Doutora Nídia de Sá Caetano
Professora Coordenadora do Instituto Superior de Engenharia do Porto

agradecimentos

Este trabalho é o culminar de um longo percurso, com muitas horas de esforço e dedicação. Agradeço a todos que percorreram este longo percurso ao meu lado e me apoiaram sempre, nunca me deixando desistir. Quero agradecer em particular:

- À minha orientadora, Professora Isabel Nunes, e coorientadora Bruna Oliveira, pelo o vosso constante apoio, paciência, ajuda e incentivo, bem como, todo o tempo disponibilizado e conhecimento partilhado. Nunca em momento algum me senti abandonada ou à deriva durante todo este processo. Vocês foram imprescindíveis. Agradeço-vos do fundo do coração por tudo;

- Aos meus pais e à minha irmã, pelo incondicional apoio e força, em todas as fases deste percurso e pela a oportunidade que me deram de viver esta experiência de vida;

- À minha melhor amiga, por sempre estar do meu lado e me fazer rir e sorrir nos momentos de maior ansiedade;

- Às Giras, que caminharam ao meu lado durante estes 5 anos e me apoiaram sempre. Vocês foram uma peça fulcral e esta viagem louca não teria sido a mesma sem vocês. Obrigada por todos o momentos, por todos os risos e por toda a vossa ajuda;

- Aos meus avós e família que sempre me apoiaram.

palavras-chave

Alterações climáticas, aterros, contaminação, eventos naturais, fogos florestais, lixeiras, resíduos urbanos

resumo

Portugal é um país extremamente propenso a fogos florestais, uma combinação de fatores como o clima mediterrânico, a falta de gestão florestal e a ignição humana, combinados com as mudanças climáticas, levam à formação de incêndios florestais de dimensão pequena a catastrófica. Até ao início dos anos 2000, Portugal tinha 341 lixeiras espalhadas em todo o país, sobretudo em áreas florestais, onde os resíduos eram depositados sem controlo, diretamente no solo, usando métodos como a queima a céu aberto para reduzir o volume de resíduos.

Esta dissertação teve como objetivo a identificação dos impactes dos incêndios florestais em antigas lixeiras encerradas. Para isso, foram selecionados dois casos de estudo de antigas lixeiras afetadas por incêndios florestais em 2017 (município de Nelas) e 2019 (município de A-a-Velha). No entanto, apenas o caso de estudo da lixeira afetada por um incêndio florestal em 2019 foi um pouco mais explorado. Os resultados do trabalho de campo revelaram que o incêndio florestal foi de baixa severidade, não tendo penetrado até camadas mais profundas no solo que atingisse os resíduos. Contudo, a antiga lixeira ainda possui resíduos orgânicos que são combustíveis, e que podem, por isso, representar um perigo num eventual próximo incêndio florestal. O poder calorifico inferior dos resíduos da lixeira foi estimado em aproximadamente 9.62 MJ/kg de resíduo (base tal e qual). O *stock* de carbono orgânico presente nestes resíduos foi estimado em cerca de 4400 a 4900 toneladas que, em caso de combustão completa, resultaria numa emissão 16 a 18 mil toneladas de CO_2.

Da revisão da literatura realizada acerca dos impactes de eventos naturais em aterros e lixeiras (em operação e encerrados) verificou-se que os eventos mais retratados são a erosão costeira, as inundações e os incêndios (naturais e antropogénicos). Porém, o número de estudos reportados é diminuto, sobretudo no que concerne aos impactes dos incêndios florestais em aterros controlados ou lixeiras.

keywords

Climate change, contamination, landfills, municipal waste, natural events, waste dump, wildfires

abstract

Portugal is a country extremely prone to forest fires, a combination of factors such as the Mediterranean climate, the lack of forest management and human ignition, combined with climate change, lead to the formation of small to catastrophic wildfires. Until the early 2000s, Portugal had 341 waste dumps scattered across the country, especially in forest areas, where waste was deposited without control, directly on the ground, using methods such as open combustion to reduce the volume of waste.

This dissertation aimed to identify the impacts of wildfires in old closed waste dumps. For this purpose, two case studies of closed waste dumps affected by wildfires in 2017 (municipality of Nelas) and 2019 (municipality of A-a-Velha) were selected. However, only the case study of the closed waste dump affected by a wildfire in 2019 was a little more explored. The results of the field campaign revealed that the wildfire was of low severity, having not penetrated the deeper layers in the soil that reached the residues. However, the closed waste dump still contains organic residues that are combustible, and that can therefore represent a danger in an upcoming wildfire. The lower heating value of the waste from the waste dump was estimated at approximately 9.62 MJ/kg of waste (wet base). The stock of organic carbon present in these residues was estimated at between 4400 to 4900 ton, which, in case of complete combustion, would result in an emission of 16 to 18 thousand ton of CO_2.

From the literature overview carried out on the impacts of natural events in landfills and dumps (in operation and closed) it was found that the most portrayed events are coastal erosion, floods and fires (natural and anthropogenic). However, the number of studies reported is small, especially with regard to the impacts of wildfires in controlled landfills or dumps.

Contents

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ATSDR	Agency for Toxic Substances and Disease Registry
BOD	Biochemical Oxygen Demand
BPA	Bisphenol A
C	Carbon
C_{total}	Total carbon, % or kg/ton
CCDR	Comissões de Coordenação e Desenvolvimento Regional
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
db	Dry basis
DDT	Dichlorodiphenyltrichloroethane
ESP	Earth Surface Processes
EU	European Union
H	Component
H	Hydrogen
H_u	Low heating value, MJ/kg
HCH	Hexachlorocyclohexane
IPCC	Intergovernmental Panel on Climate Change
ISQG	Interim Sediment Quality Guidelines
m_i	Mass of each waste component, ton
m_t	Total mass of solid waste, ton
NOAA	National Oceanic and Atmospheric Administration
O	Oxygen
PAH	Polycyclic Aromatic Hydrocarbons
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PCDD	Polychlorinated dibenzodioxins
PCDF	Polychlorinated dibenzofurans
PCB	Polychlorinated biphenyls

PERSU	Plano Estratégico para os Resíduos Urbanos
PFOS	Perfluorooctane sulfonic acid
pg	Picogram
POP	Persistent Organic Pollutant
TEQ	Toxic Equivalency
TOC	Total Organic Carbon
Ton	Tonne
UK	United Kingdom
USA	Unites States of America
wb	Wet basis
wt	Weight
w_{wH}	Moisture content, kg/kg

1 INTRODUCTION

1.1 MOTIVATION AND RELEVANCE

The Portuguese strategic plan for solid waste (Plano Estratégico para os Resíduos Urbanos – PERSU), launched in 1997, introduced management goals for the short and long term, starting with the closure and recovery of all inventoried open waste dumps through the design of fundamental infrastructures for the management of waste and promoting and encouraging selective collection and recycling (GEOTA, 2015). Before PERSU came into force, more than half of the municipal waste produced in Portugal was dumped indiscriminately on non-waterproofed open waste dumps, without any environmental protection. These dumps were often unattended and with no fences, allowing for illegal depositions to occur. Also, open combustion was used to reduce the volume of waste and thus allowing more waste to be dumped (cited by - Anacleto, 2008). In total there were 341 open waste dumps in continental Portugal, most of which were located in remote forest areas, far from populations (MAOTDR, 2007).

After the closure of all waste dumps until 2001, their monitoring and maintenance was transferred to regional waste management entities. The European Directive 97/C/156/08 of 24/05/1997 (Comission of the European Communities, 1997), lists the parameters to evaluate and control, and the frequency of maintenance and environmental monitoring (Silva *et al.*, 2013). This Directive was implemented in Portugal through the Decree-Law nr. 152/2002 of May 23rd, updated in Decree-Law nr. 183/2009 of August 10th. Despite establishing the mandatory monitoring and maintenance of closed dumps, it was not always possible to do so, as many were occupied by facilities (e.g. industrial complex, workshops) and others covered with very dense vegetation, not allowing monitoring (personal communication from CCDR-Norte).

Global warming is estimated to have increased around 1.0 ºC from pre-industrial levels due to anthropogenic emissions. Continually increasing at the ongoing rate of 0.2 ºC per decade it may reach 1.5 ºC between 2030-2052. A changing trend in intensity and frequency of certain climate and weather events has been noticed since 1950. If global warming reaches 1.5 ºC, several climate changes are foreseen that include increasing frequency of heatwaves specially in Asia, Australia and Europe; increasing frequency, intensity and load of heavy rainfall, with associated flood events; increasing frequency of cyclones; and increasing frequency and intensity of droughts and precipitation deficits mainly in central and southern Europe, the Mediterranean regions, Central America and Mexico, northeast Brazil and southern Africa (IPCC, 2018).

The climate and weather play an important part for the ignition and propagation of wildfires. Climate influences the duration and severity of the wildfire season and the available amount of vegetation for combustion, while weather conditions control the water content of soils and vegetation, influencing the flammability potential (Carvalho *et al.*, 2011).

The increasing frequency of heatwaves and extreme droughts during summer, may induce a major stress in vegetation due to exposure to unfavourable conditions, that interfere with the plants development, growth or metabolism (Lichtenthaler, 2006), potentially leading to death, which increases the available biomass susceptible to burn, at greater intensity than living vegetation (Beighley e Hyde, 2018). Heatwaves together with long-term drought and low humidity, contribute to the increasing risk of wildfires. A study carried out by Parente *et al.* (2018) showed that 97 % of the total number of extreme wildfires in Portugal between 1981-2010 occurred during heatwaves.

A changing climate and extreme weather events are not the only factors contributing to the frequency and severity of wildfires. Portugal is extremely prone to wildfires due to a combination of factors such as the Mediterranean climate and abandonment of rural areas, with people moving into urban areas. Consequently, former agricultural and forest areas have no maintenance, with aboveground biomass accumulating and invasion of highly flammable vegetation (Beighley e Hyde, 2018). Another factor to consider is the high percentage of fires were originated from human ignition, i.e., 98% of all fires in Portugal were man-induced (ICNF, 2019).

The total burnt area has been increasing through the years (Figure 1). Between 1980 and 1999, burnt areas per year above 100,000 ha only occurred 6 times, a frequency of 30 %. However, from 2000 to 2017, the frequency of wildfires consuming an area of 100,000 ha or more, doubled to 60%. With 3 occurrences of wildfires consuming more than 300,000 ha, if no long-term intervention plans are put in action, the probability of extreme fires consuming 500,000 ha or more, like in 2017, is expected to increase (Beighley e Hyde, 2018).

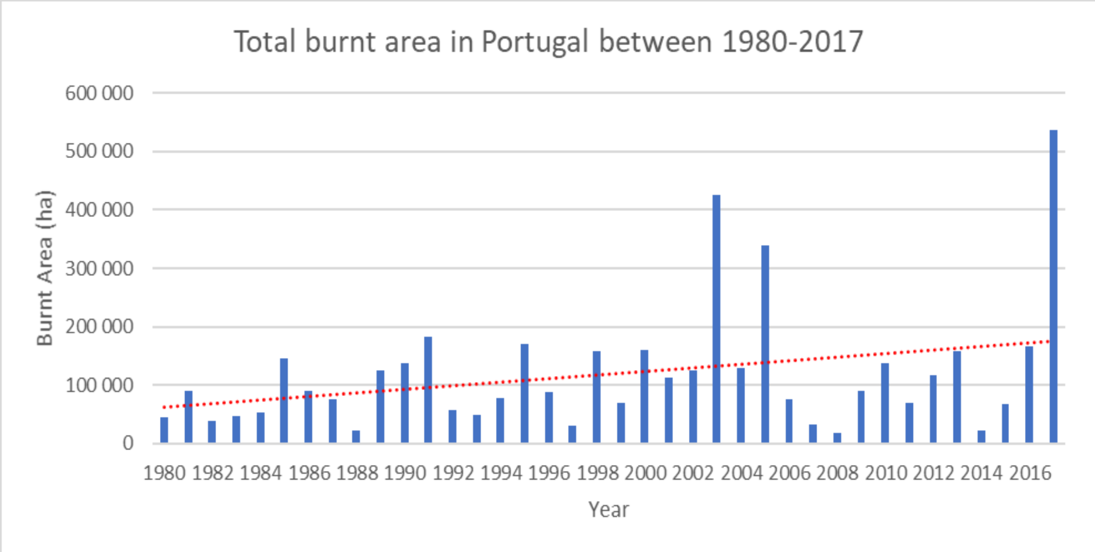


Figure 1 - Annual burnt area in Portugal from 1980 to 2017 (Data source: ICNF).

This increasing frequency together with the fact that several closed waste dumps are located in areas prone to wildfires, it's likely that some have been affected at some point. The degree of impact will depend on the severity of the wildfire and the current conditions of the closed waste dump. It's possible that some did not have an appropriate closure, lacking top lining and containment, as well as the growth of dense vegetation and woody species with roots that can potentially reach the waste material. Thus, a question arises: What are the potential environmental impacts of a wildfire that reaches old closed waste dumps?

1.2 OBJECTIVES AND STRUCTURE OF DISSERTATION

The main purpose of this dissertation is to identify the potential environmental impacts of wildfires on closed waste dumps. For that, the closed waste dumps impacted by wildfires in the last 5 years in Portugal were identified, and two case studies were selected to perform field campaign. In parallel, a literature overview was carried out to elaborate the state of the art in this research field. It was found that there are few published studies on the impacts of wildfires in waste dumps. So, an expanded literature overview, covering, in addition to wildfires, other natural phenomena with impacts in dumps and landfills was performed, in order to identify knowledge gaps in this field and to point out future research directions.

This dissertation is organized in 4 chapters. The first chapter corresponds to the introduction, where it is established the relevance and contextualization of the dissertation theme, as well as the aim. The second chapter is the literature overview, structured as a scientific article, presenting research relative to the potential environmental impacts caused by natural events affecting landfills and waste dumps. The third chapter presents the Portuguese case studies in detail, including the methodology used in the practical component of the dissertation, the obtained results and discussion, and conclusions. The fourth and last chapter presents the main conclusions and future work suggestions.

2 IMPACTS OF NATURAL (WEATHER-RELATED) EVENTS ON CLOSED AND OPERATING LANDFILLS AND WASTE DUMPS: LITERATURE OVERVIEW

Abstract

Natural events are natural phenomena capable of significantly damage human life and the environment. Anthropogenic emissions will continue warming the globe for centuries, causing changes to the climate patterns. The ongoing changing climate, consequently, affects the frequency and intensity of some events, mainly weather-related events. The number of natural events per year has been increasing exponentially over the last 30 years. Landfills and waste dumps are structures built on the ground for disposal of waste. They are the most used methods for disposal of waste, however the location of some of landfills and waste are in or within areas prone to natural severe events. The emissions of contaminants from landfills and waste dumps when impacted by a natural event, depending on the location of the landfills, may adversely affect soil/sediments and water quality, potentially putting at risk ecosystems and human health. This literature overview focuses on the threat that natural events may be to landfills and waste dumps and the potential environmental impact.

2.1 INTRODUCTION

The global climate is changing with increasing speed indicating a warming of the Earth surface, atmosphere and ocean regions. There is evidence that this is happening and that at least part of the global warming observed in recent years is attributable to human activities that emit greenhouse gases. Global warming caused by anthropogenic emissions will persist for centuries, if not millions of years, continually causing changes to the climate system (IPCC, 2018), affecting the frequency, intensity, duration, and timing of extreme weather and climate events. A global temperature increase of 1.5 ºC may increase the frequency and intensity of heavy precipitation and drought in some areas. With global mean sea level rise projected to range between 0.26-0.77 m by 2100, coastal areas susceptible to erosion and flooding will be at increasing risk (IPCC, 2018).

Landfills and waste dumps are structures built on the ground for disposal of waste, usually located away from areas used by the population (Cabeças e Levy, 2008). They are the most common methods used worldwide for managing solid waste (Idowu *et al.*, 2019).

Landfill regulations started to appear in the latter half of the 20th Century in United States of America (USA) and Europe. These regulations required leachate/gas collection and monitoring systems during operation and after closure, confinement lining to protect underlying soil and groundwater from leachate, and top lining when closing. Moreover, requirements were also stablished for the location of landfills, taking into consideration the distance of landfills from residential/recreation areas, waterways and agricultural sites, the existence of groundwater, and the risk of flooding and landslides (Council Directive, 1999; US-EPA, 1993).

However, prior to such regulations (closed) landfills operated with no protection and control, some located in risk zones, where the type and amount of waste dumped was rarely registered. Relying on surrounding soils and sediments to disperse and dilute the contaminants and minimize the pollution impact (Brand et al., 2018). In undeveloped countries that is still a common practice, with waste being dumped in uncontrolled and poorly managed sites, such as waste dumps. A study in Nigeria reported that in 2013, 68 % of waste was dumped on road sides and open spaces, 21 % disposed in proper landfill sites and 11 % was burnt (Adeniran, Adewole e Olofa, 2014).

Landfills and waste dumps represent a potentially long-lasting risk for humans and the environment. There are numerous studies relative to emissions from landfills and waste dumps during normal operations, such as the long-term production of leachates and methane (e.g. Belevi e Baccini, 1989; Chakraborty *et al.*, 2011; Kjeldsen *et al.*, 2002). However, studies relatively to emissions from landfills and waste dumps during natural events such as floods, coastal erosion, landslides, wildfires, and others, and the corresponding environmental impact are not so well known. With closed and/or operating landfills and waste dumps potentially lacking the necessary protection to sustain these events, it is important to better understand this subject. This literature overview is focused on potential environmental impacts during and after natural events, inside and in the surrounding environment of landfills and waste dumps.

2.2 METHODOLOGY

To find the relevant scientific literature regarding the impact of natural events on closed dumps and landfills, the keywords summarized in Table 1 were searched in online platforms such as Scopus, Web of Science, ScienceDirect, B-ON and Google Scholar. An analysis of the literature cited in relevant publications was also done. The search was centred on the environmental impact of different types of natural events both in operating and closed landfills and waste dumps.

Table 1 - Combination of keywords used for literature search.

Natural events	Keywords
Coastal erosion	• "landfill"; "waste dump"; "closed landfill"; "historic coastal landfill"; "closed waste dump" • "coastal erosion"; "flooding"; "erosion"; "contamination"
Earthquakes	• "landfill"; "waste dump"; "closed landfill"; "historic landfill"; "closed waste dump" • "earthquake"; "seism"; "contamination"; "leachate leakage"
Flooding	• "landfill"; "waste dump"; "historic landfill"; "closed landfill"; "closed waste dump" • "flood"; "flooding"; "inundation"; "contamination"
Landslides	• "landfill"; "waste dump"; "closed landfill"; "historic landfill"; "closed waste dump" • "landslide"; "waste slide"; "mass movement"; "soil contamination"; "contamination"
Wildfires	• "landfill"; "waste dump"; "closed landfill"; "historic landfill"; "closed waste dump" • "forest fire", "bushfire", "wildfire"; "fire"; "soil contamination"; "contamination"
Open combustion and spontaneous fires	• "landfill"; "waste dump"; "closed landfill"; "historic landfill"; "closed waste dump" • "landfill fire"; "open burning"; "dioxin contamination"; "contamination"

Results and all the research process can be found beneath in Figure *2*.

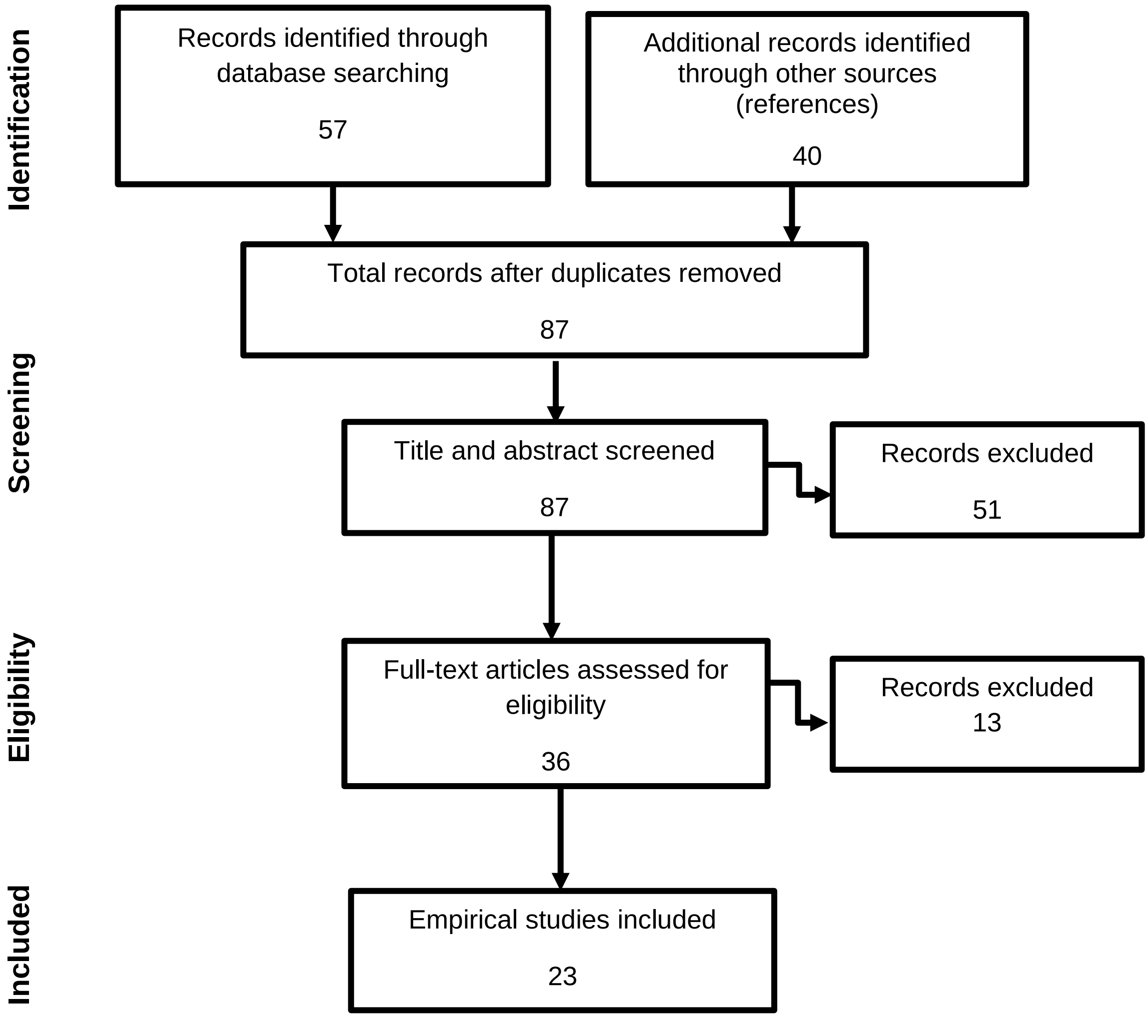


Figure 2 - Schematic representation of the literature overview research process based on Moher et al. (2009).

The total number of scientific studies found only covered 4 events (
Table *2*). The excluded scientific studies were studies that did not included municipal waste landfills/waste dumps and that did not assessed the impacts on the environment resulting from the natural events (e.g. landslides and earthquakes). Coastal erosion had the highest number of studies and more recent publications. However, coastal erosion much like the other natural events, were found studies concerning only one or two countries, and there

are other countries with the same issues (e.g. Rnz.co.nz, 2019; Stuff.co.nz, 2019) though no reported studies were found in other locations.

Table 2 - List of scientific studies per event.

Location	Natural event	Reference
England	Costal erosion	Njue (2010), Pope et al. (2011), Njue et al. (2012), O'Shea (2016), Brand (2017), O'Shea et al. (2018), Brand and Spencer (2019), Beavan et al. (2020)
Austria, England	Flooding	Laner et al.(2008; 2009),Neuhold and Nachtnebel (2011), Neuhold (2013), Brand (2017),
Greece	Spontaneous fire	Chrysikou et al. (2008), Vassiliadou et al.(2009), Vosniakos et al. (2011)
Cambodia, Croatia, Finland Greece, India, Indonesia, Jordan, Philippines, Vietnam	Open combustion	Ruokojärvi et al.(1995; 1995), Martens et al.(1998), Minh et al.(2003), Wichmann et al.(2006), Bastian et al. (2013), Fajkovic et al. (2018).

Moreover, no studies were found relatively to wildfires, only studies were found relatively to spontaneous fires and man-induced open combustion on landfills/waste dumps. However, the amount of studies found was small (10) and majority of them was not very recently published.

2.3 NATURAL EVENTS

Natural events are natural occurring phenomena that can be climatological (extreme temperatures, drought, wildfires), biological (disease epidemics and insect/animal plagues), geophysical (earthquakes, tsunami, volcanic activity), hydrological (floods, landslides), meteorological (cyclones, storms, tidal surges). Due to their severity, the phenomena have the capacity to negatively affect human life and/or the environment (Xu *et al.*, 2016).

Information on natural events worldwide since 1980 is available from NatCatSERVICE. Hydrological and meteorological events show an increasing frequency through the years, corresponding to 39 and 41 %, respectively, of the total number of natural events, while geophysical events did not significantly increase compared with the other events (Figure 3).

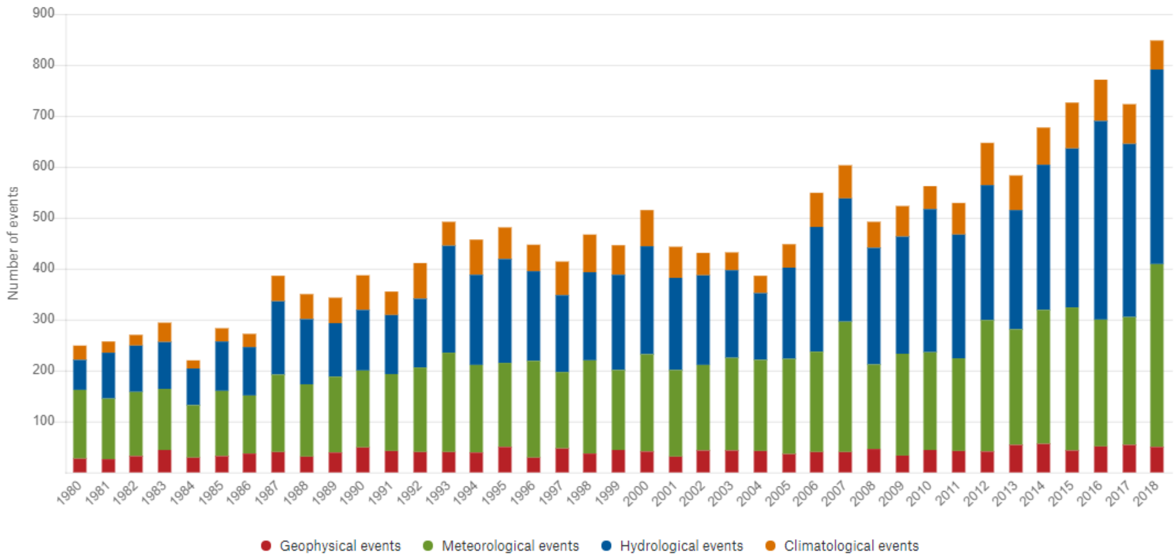


Figure 3 - Number of natural events worldwide between 1980 – 2018. Note: Accounted events have caused at least one fatality and/or produced normalised losses ≥ US$ 100k, 300k, 1m, or 3m. (Source: © 2018 Münchener Rückversicherungs-Gesellschaft, NatCatSERVICE – Consulted in April 2020).

The most impacted continent by natural events though 1980-2018 was Asia followed by North America and Europe (Figure 4).

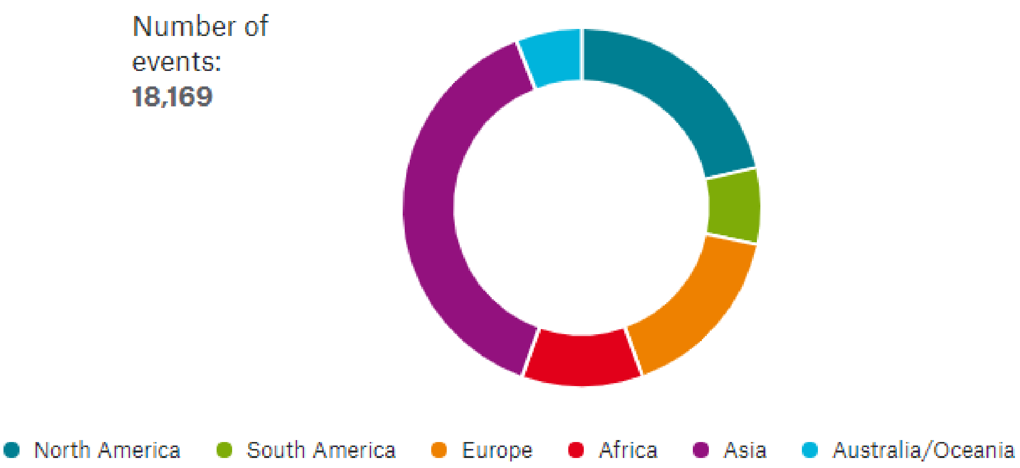


Figure 4 - Continents affected by natural events worldwide between 1980-2018. (Source: © 2018 Münchener Rückversicherungs-Gesellschaft, NatCatSERVICE – accessed in April 2020).

Some Asian countries have dificulties with waste collection and disposal, as well as lack of landfill infrastructure (Development Asia, 2017). The same is observed in Latin America and the Caribbean countries and Mexico, where waste collection and recycling rates are low, though higher then South Asia, the Middle East and Africa collection rates (Grau *et al.*, 2015). Moreover, in these undeveloped countries due to overpopulation, large amounts of waste are produced, with sometimes waste ending up discarded in illegal waste dumps, with no control (Emelie, 2019; Galicia, Páez e Padilla, 2019). Although waste management is not a concern in Europe and USA (Cogut, 2016), old closed landfills can be of concern when monitoring is absent and degradation of waste confinement is occurring, leaving these closed landfills vulnerable to the effects of natural events.

The scientific overview in the following sub-sections focuses on environmental consequences of natural weather-related events affecting closed and operating landfills and waste dumps.

2.3.1 Coastal erosion

Coastal erosion refers to the loss of coastal lands through long-term weathering, such as removal of sediments and undercutting of cliffs, due to the action of ocean waves and currents and extreme weather events. As an example, high intensity rainfall events increase the soil saturation which increases the likelihood of slope failure, resulting in landslides (Geoscience Australia, 2019a).

In the United Kingdom (UK), landfills have been located near the coast without foreseeing the increasing coastal erosion and sea level rise. Consequently, landfills that were previously protected by the shoreline are now at increasing risk of rupture, flooding, and salt-water intrusion, releasing waste material and contaminants to the marine environment (Brand, 2017).

If no confinement measures are applied in the landfills, it is likely that contaminants reach coastal waters through a leachate pollution plume (Christensen *et al.*, 2001; Njue, 2010). Where salt marshes, mudflats, and aquatic plants are present, these have the ability to capture and/or trap heavy metals and organic compounds (Akhter e Al-Jowder, 1997; Cundy e Croudace, 1995; Lenssen *et al.*, 1999). Still, the ongoing coastal erosion leads to disturbances that can induce changes in the mobilization and bioavailability of heavy metals (Acosta *et al.*, 2011; Chapman e Wang, 2001; Eggleton e Thomas, 2004; Speelmans *et al.*, 2007),

In England, there are more than 1,200 coastal landfills that closed between 1970 and mid 1990's, located on low-lying coastal plains, with a 0.5 % annual probability of coastal flooding, meaning a 1 in 200-year chance of flood (Brand, 2017). According to Brand (2017;

2019) if no interventions are performed, it is expected 1 in 10 closed coastal landfills to start eroding by 2055.

Njue *et al*. (2012; 2010) investigated the contamination of coastal wetlands, two saltmarshes and a mudflat, near three closed landfills, and if there was a connection of the contamination to the landfills. The authors found that heavy metals concentration was higher than background and pre-industrial concentration values. Those concentrations were above the limits established by the Interim Sediment Quality Guidelines (ISQG) from the Canadian Sediment Quality Guidelines for the Protection of Aquatic Life, indicating possible adverse toxicity effects on benthonic species (CCME, 1999). Radiometric dating analysis indicated that for two landfills the concentration of heavy metals came out from their activity. Furthermore, the vertical variation of heavy metals at some sediment cores suggested ongoing anthropogenic inputs, possibly a leachate plume from the landfill given the absence of any industrial sources nearby the site. However, in one study case the concentration of heavy metals suggested that the marsh received contamination from the landfill and possibly from other sources.

O'Shea *et al*. (2018; 2016) also studied the contamination of coastal wetlands, an saltmarsh adjacent to a closed landfill and found that maximum and median concentrations of heavy metals were above the National Oceanic and Atmospheric Administration (NOAA) marine sediment guidelines threshold effect level, which has be shown to cause adverse effects on benthic communities. Moreover, maximum concentrations from core samples were also compared with industry contaminated estuaries, showing a close relationship (O'Shea, Cundy e Spencer, 2018; O'Shea, 2016). The horizontal and vertical distribution of the contamination suggested that the landfill was unlikely the source of contamination and the vertical peak of heavy metals concentrations observed could be traced back to 19th century industrial activity in UK (O'Shea, 2016). For depths of approximately 100 cm, the concentration of heavy metals corresponded to the local geochemical background levels. However, it was observed that the concentrations of lead (Pb) and zinc (Zn) were higher than background concentrations, suggesting that pre-industrial sediments close to the edge of the landfill may have received anthropogenic contamination, possibly by landfill leachates (O'Shea, Cundy e Spencer, 2018; O'Shea, 2016).

Both Njue *et al*. (2012; 2010) and O'Shea *et al*. (2018; 2016) found possible ecological threats for similar heavy metal pollutants in the coastal areas analysed. Both studies found high pH values at all sites which may decrease the mobility of heavy metals due to the adsorption by clays (Bilinski *et al.*, 1991). When seawater enters contaminated sediments, salinity may decrease the pH in sediments, increasing the mobility of heavy metals (Brand, 2017). Moreover, physical disturbances, like bioturbation or erosion, can cause oxidation of anoxic estuarine sediments (Simpson, Apte e Batley, 1998; Spencer, 2002). Oxidation of sulphides to sulphates reduces sediment pH, leading to the release of precipitated metals (Laing, Du *et al.*, 2009). Any sediment disturbance, even the smallest one, has the capacity to oxidise sediments and remobilize contaminants into marine environment (Yao *et al.*, 2015), making them more available to plants and benthic species, possibly leading to bioaccumulation (Njue, 2010; O'Shea, 2016).

O'Shea *et al*. (2018; 2016) estimated the load of copper (Cu), Pb and Zn that could be released from the sediments to the Thames Estuary, if sediments of the area surrounding the landfill were disturbed. The load of Cu and Zn would be equivalent to approximately 2 and 6 % of the annual input of Cu (25,820 kg/yr) and Zn (128,425 kg/yr) from known sources into the Thames Estuary (Stevenson and Ng, 1999). O'Shea (2016) went further as to investigate whether these findings could stand for other closed landfills with the same features. Eight landfills were selected, five with hazard waste and two with inert. Results showed spatial distribution was similar, implying closed landfills, with close physical and chemical characteristics, have most likely released heavy metal rich leachates to adjacent sediments. Given the load of contaminants that could be released and the fact the salt marsh belongs to a flood prone area, coastal sediments within the Thames estuary are within the Environment Agency flood alert area, and are at risk of erosion, leading to the remobilization and bioavailability of metals into the surrounding marine environment (O'Shea, 2016).

Brand (2017; 2019) studied the potential impact of eroded waste from two closed landfills. The authors found that Cu, Pb, Zn and polycyclic aromatic hydrocarbons (PAH) concentrations from solid waste (paper, textiles and wood) and waste matrix material (particulate materials similar to soil) were above threshold levels of the Canadian Sediment Quality Guidelines (Canadian Council of Ministers of the Environment, 2001), indicating that adverse toxicity effects on benthonic species can take place (CCME, 1999). The authors also compared the heavy metals concentrations from the solid waste with the heavy metals concentrations found in adjacent sediments to Thames Estuary studied by O'Shea *et al.* (2018; 2016), and some of the concentrations of Pb and Zn from wood and textiles were higher than the concentrations of those metals in the sediments.

Moreover, Brand (2017) assessed the load of contaminants that could be released in case of total rupture (worst case scenario) of one of the two studied landfills. The load of Cu and Zn would be equivalent to approximately 638 and 327 %, respectively, of the annual input of Cu (25,820 kg/yr) and Zn (128,425 kg/yr) from known sources into the Thames Estuary (Stevenson and Ng, 1999). However, it is unlikely a landfill will rupture all at once, Brand (2017) assessed for the other studied landfill the load of contaminants that could be released assuming only the failure of one waste cell of the landfill; the load of Cu and Zn would only be equivalent to approximately 3 and 5 % respectively, of the annual input of Cu and Zn from known sources into the Thames Estuary.

The release of contaminated waste from the landfills, due to coastal erosion, means another possible load of contaminants entering the water system, increasing suspended particulate matter and nutrient loads, reducing dissolved oxygen. Impacting even more the quality of the sediments, adjacent saltmarshes, as well as the surrounding flora and fauna (Brand e Spencer, 2019).

The investigation performed by Pope *et al.* (2011), to assess the impact on intertidal sediments and biota of an already eroded landfill, found an heterogeneous spatial distribution of heavy metals and higher concentrations were found near the landslide. At some points, the concentration of heavy metals exceeded the threshold levels of the Canadian Sediment Quality Guidelines (Canadian Council of Ministers of the Environment, 2001), indicating potential for adverse toxicity effects on benthonic species (CCME, 1999). However, the results were not strong enough to link the higher concentrations to the landfill (Pope *et al.*, 2011). According to Beaven *et al*. (2020), who studied the reports of the landfill studies performed by external consultants, ordered by the district council, found that, four years after the landslide, concentrations of Pb persisted above the values of the area close to the landfill (Beaven *et al.*, 2020). Since there are no guidelines to assess the impact of landfill debris in coastal waters, Beaven *et al.* (2020) compared the results with The London Convention and Protocol guidelines (MMO, 2015) for the disposal of solid matter to the sea. All maximum heavy metal concentrations were above the guidelines and not considered acceptable for disposal without special handling and containment.

The previously listed studies were performed either in or within saltmarshes/ mudflats/low-lying marshes, typically composed of fine-grained sediments (clay and silt), where domestic and commercial waste was deposited directly on top, with no base or wall containment. This type of sediments plays a major role in the mobilization and attenuation of pollutants. Moreover, sites that showed concentrations of contaminants able of causing adverse toxicity effects on benthonic species are categorized as Special Site of Scientific Interest, local nature reserves, Special Protection Area and/or Ramsar sites ((Staffordshire Ecological Record, 2015)).

The total amount of pollutants that could be released from complete erosion of one landfill is higher than the amount that could be released from erosion of wetland sediments contaminated by landfills. However, the complete erosion of a landfill will take years until such occurs and will most likely not rupture all at once. Moreover, the increasing erosion and sea level-rise will pose a risk to coastal wetlands. For that reason, there is a need for more information relatively to the quantity of contaminants trapped in coastal wetlands, at what rate are the contaminants being released and if those pose a risk or not to the surrounding environment when released.

There has not been developed methods to assess the direct impact of landfill waste exposure and erosion of polluted sediments into marine environments (Brand, 2017). If it is possible to predict the waste erosion rate that would allow the full assessment of the impact of eroded waste and if such deterioration would take place. But such tool has not been developed yet, due to complex mechanical properties of waste erosion and waste behaviour (Brand, 2017; Dixon e Jones, 2005). However, given the difficulty of such prediction, a first step to assess the direct impact of landfill waste could be, extend the guidelines for disposal of solids to the sea (London Protocol) to include waste (Beaven *et al.*, 2020).

2.3.2 Floods

A flood occurs when an excess of water immerses land that is typically dry. The most common floods occur when watercourses overflow due to heavy rainfall or dams discharge or rupture, and when storms influence sea tides and waves (Geoscience Australia, 2019b; NOAA National Severe Storms Laboratory, [s.d.]).

When water enters landfills, physico-chemical changes may occur inside, such as modifications on the biodegradation conditions, adsorption, redox and dissolution/precipitation processes, that may cause the remobilization of contaminants (Eggleton e Thomas, 2004). Flooding can increase the volume of leachate produced, leaking to the surrounding areas (Bagchi, 1994) and decrease the mechanical stability of the landfill due to water saturation (Laner *et al.*, 2008; Laner, Fellner e Brunner, 2009).

Laner *et al*. (2008; 2009) and Neuhold (2013; 2011) assessed potential emission scenarios during a flood event affecting landfills in Austria. The list of landfills in Austria includes 103

(56 active and 48 closed) controlled landfills (operated after 1989), and 961 closed landfills (operated before 1989). One third of the total landfills were in or within areas with a 1:200 years chance of flooding, with only 60 % of active controlled landfills having flood protection and 70 % of closed controlled landfills unprotected. Closed landfills (operated before 1989) were operated without documentation and the authors assumed these sites were not protected, giving an overall of only 5% of the total landfills prepared with flood protection (Laner *et al.*, 2008; Neuhold, 2013). Laner *et al*. (2008; 2009) established two emission scenarios: 1) assuming the loss of stability due to complete erosion of landfill releasing waste, and 2) assuming contaminants leaching from landfill due to water saturation. Neuhold (2018; 2016) further explored scenario 2, considering: (I) low, (II) medium, (III) high release of soluble substances with water saturation, and (IV) stability loss of the landfill. Both authors found that contaminants emissions during a flood event could increase up to six orders of magnitude for the scenario of stability loss of the landfill and four orders of magnitude for the scenarios of leaching, compared to emissions under conventional landfill conditions. The difference between closed landfills and controlled landfills was approximately of one order of magnitude. Since most of the reported closed landfills were located in the drier eastern part of Austria, the estimated infiltration rates were low (Laner *et al.*, 2008; Neuhold, 2013). Despite the receiving water body during the flood event could increase the dilution factor by 10 up to 100, the results from Laner *et al*. (2008; 2009) and Neuhold (2013; 2011) showed that emission load would still result in a significant increase of the water pollution levels, exceeding Austrian water quality standards for discharge into rivers. However, the calculated emission potentials did not say whether or not flooded landfills might be a hazard to the environment; there was not enough information concerning to the metabolism, geotechnical characteristics and long- and short-term emission of flooded landfills, to make that assessment (Laner *et al.*, 2008). Laner *et al*. (2008; 2009) and Neuhold (2013; 2011) pointed out that the environmental impact of flooded landfills depends of several factors that influence the release of contaminants and need to be assessed separately for each landfill and flood occurrence, such as, dilution potential, availability of the contaminants and the exposure of the impacted environment.

In the course of a flood event, it is most likely that other sources of contaminants were affected as well, like wastewater treatment plants and industrial facilities. As a single source of pollution, in most instances, it is unlikely to be a significant environmental problem during flooding. However, the cumulative effect of multiple releases/discharges may be more of a concern (Laner, Fellner e Brunner, 2009).

While Laner *et al*. (2008; 2009) and Neuhold (2013; 2011) estimated the potential emission from fluvial flooding of landfills through calculations, Brand (2017) performed leaching tests with fresh and saline water, on matrix material to simulate flooding of the landfills studied. Matrix material released higher amounts of heavy metals with saline water than with fresh water. One of the heavy metals, Pb, increased up to 5.4 % of the initial concentration in the sample before leaching (Brand, 2017). The mobility of certain heavy metals increases with salinity as a result of the formation of soluble complexes with salt derived anions and competition with salt derived cations for sorption sites on the solid phase (Acosta *et al.*, 2011). This means that flooding of seawater could increase the mobility of heavy metals into leachate, leading to an increased heavy metal leachate. Though, even if some of the heavy metals concentrations in a leachate could be of environmental concern, in reality the leachate would most likely dilute and have little or no impact on the surface water quality of a water body. However, this could be more of particular concern in smaller water bodies or smaller water bodies adjacent to vast ones. Moreover, landfills have large volumes of waste materials and, therefore, there is a possibility that the total mass of heavy metals is released and may be environmentally harmful. Such would depend on the rate of waste erosion and the capacity of the receiving water body to dilute the heavy metals as they are released (Brand, 2017).

Further research is required to determine how the proportions of heavy metals released differ with the salinity gradient. As the legislation in European Union (EU) only demands waste materials to be analysed though fresh water leaching tests, and considering the results obtained from the saline leaching tests above, there could be a possibility of waste being landfilled into sensitive coastal areas that would not be considered appropriate, if legislation required waste intended to be dumped in coastal landfills, to be tested using saline water. Moreover, assess whether the proportions of organic contaminants, released during flooding, could adversely affect surface water quality (Brand, 2017).

2.3.3 Fires

2.3.3.1 Natural fires

A wildfire is a fire that burns uncontrollably in a vegetation area. Wildfires are more frequent and intense in areas with significant dry biomass and in prolonged dry season (Becker, 2014).

No scientific studies, so far, were found relative to wildfires affecting open or closed waste dumps and landfills. Still, spontaneous landfill fires and open combustion in landfills/waste dumps caused by humans are reported in the literature, to better understand the potential impact that burning of waste material may have on the surrounding environment.

For a fire to start in a landfill/waste dump, all that is required is the presence of fuel, i.e. solid waste, heat generation and intrusion of oxygen (Moqbel, Reinhart e Chen, 2010). According to Chavan *et al*. (2019) waste with low moisture content requires less ignition temperature to ignite. Those authors observed that older waste with low values of moisture, ignited at a temperature much lower than fresh waste.

The main concern with these fires is the contaminants released since the combustion conditions are not controlled and usually incomplete. Sub-surface fires generate carbon monoxide as well as incomplete combustion products, such as dioxins and furans. It can also smolder from weeks to months, meaning constant low burning of waste and release of contaminants (Bates, 2004; Chavan *et al.*, 2019).

High temperatures and dry seasons, as well as landfill gas emissions, often promote spontaneous fires in landfills (Wichmann et al., 2006). Landfill fires are a source of pollutants such as, certain persistent organic pollutants (POP) like polychlorinated dibenzo-p-dioxins (PCDD), dibenzofurans (PCDF), polychlorinated biphenyls (PCB), PAH and heavy metals (Capuano *et al.*, 2005; Chrysikou *et al.*, 2008; Ruokojärvi, Ruuskanen, *et al.*, 1995). Once these contaminants are emitted to the atmosphere, they reach ground trough dry and wet deposition, contaminating the soil, plants, water and eventually entering the food chain (Vosniakos *et al.*, 2011). POPs are persistent in the environment and are not easily degraded, having the capacity to bioaccumulate in the food chain, due to their lipophilic properties, adversely affecting human health (Chrysikou *et al.*, 2008; Wania e MacKay, 1996).

Chrysikou *et al.* (2008) studied soil samples from a spontaneous landfill fire of high proportion, and found that concentration of PAH, PCB and heavy metals were higher in the landfill that in the surrounding soils, with concentrations decreasing with distance to the landfill. However, concentrations of hexachlorocyclohexane (HCH), dichlorodiphenyltrichloroethane (DDT) and certain heavy metals in surrounding soils were equal or even higher than the landfill, indicating possible inputs from other sources such as, track vehicles and application of insecticides, given the main activity of the area was agriculture. All pollutants concentrations were below Dutch Intervention values for soil remediation, i.e., the soil quality was not threatened and therefore it was not needed intervention actions to reduce the contamination, (VROM, 2000). Moreover, according to the authors the concentrations of the soil samples from the surroundings of the landfill were similar to soils from other Greek areas (Nadal, Schuhmacher e Domingo, 2007; Samara, 2005). Overall the impact of the landfill fire was not evident as result of other inputs (Chrysikou *et al.*, 2008).

The same spontaneous landfill fire was also studied by Vassiliadou *et al*.(2009), who analysed soil and food samples from various distances near the site, for PCDD/F and PCB. Concentration of PCDD/F decreased with distance from the landfill. The soil sample taken from the landfill had the highest PCDD/F concentration. Comparing with the Netherlands and Germany guidelines for agricultural soil (Fiedler, 2003), the concentration was above the guidelines, suggesting potential human health risk. The food samples, mainly lipid containing food, showed concentrations of PCDD/F above the normal levels compared to products from the local produce. Some were even above the maximum dioxin levels allowed in EU regulation (1881/2006/EC) and had to be destroyed. PCB concentrations were normal in all analysed samples (Vassiliadou *et al.*, 2009). One year after the fire Vosniakos *et al.* (2011) found that the food produced in the area affected was no longer contaminated and free of any dioxin contamination. However, soil samples were not reanalysed, thus it is unknown whether the soil quality has improved or remained highly contaminated.

The risk of spontaneous fires should be minimized by constant monitoring of temperature and wetting the soil cover to cool it down during seasons of higher temperatures and dryness, especially if landfills are close to populated areas or agriculture and pastures areas. The type of pollutants emitted during the fire are dangerous to humans and to the environment above certain quantities.

2.3.3.2 Man-induced fires

Open combustion in landfills and/or waste dumps often occurs as a way to reduce the volume of waste (Fajkovic *et al.*, 2018).This is a common practice in countries with poor waste management and poor waste collection (Cogut, 2016). In undeveloped countries, large amounts of waste are dumped and open combusted at low temperatures, that support the formation of toxic compounds, like PCDD/F and PCB (Alawi *et al.*, 1996; Wichmann *et al.*, 2006). Waste pickers are also common in those countries, collecting recyclable materials and sometimes induce fires by scavenging through the waste (Ferronato e Torretta, 2019). Moreover, much of these open dump areas are located near populations exposing them to toxic contaminants with subsequent effects on human health and environmental quality (Minh *et al.*, 2003).

Martens *et al.* (1998) analysed the surrounding soil of a landfill in Greece from various distances, where waste was open combusted and had been uncontrollably burning, at low temperature, for 10 years at the time. The authors found that all concentrations of PAH and PCB were below the Dutch values for soil remediation (VROM, 2000), but concentration of heavy metals on the samples closest to the landfill and inside were above the remediation limit, i.e., the soil quality was threatened and therefore it needed intervention actions to reduce the contamination. Concentrations of PCDD/F were also high close to the landfill compared to control samples. The majority of the concentrations of analysed contaminants decreased with distance from the landfill (Martens et al., 1998).

Soil samples from waste dumps of various Asian countries were analysed by Minh *et al*. (2003), where waste was open combusted at low temperatures. Concentrations of PCDD/F and PCB in the soils from the waste dumps were higher than the soils from urban and agriculture areas used as control sites, meaning the waste dumps were the possible source of PCDD/F and PCB contamination, as there were no industrial or incineration activities in those areas. The soil samples from Philippines and Cambodia waste dumps showed the highest concentrations of PCDD/F and PCB, indicating substantial formation of dioxins in these sites. Moreover, soil samples from all sites contained Toxic Equivalency (TEQ) concentrations of PCDD/F, above the Agency for Toxic Substances and Disease Registry (ATSDR) guidelines, of 50 pg (picogram) TEQ/g. Concentrations above such level should be considered for potential public health actions, such as health studies, exposure investigations, surveillance, among others (Rosa, De *et al.*, 1999). Furthermore, some soil samples from Cambodia and Vietnam exceeded the Japanese standards for dioxins in soils, of 1,000 pg TEQ/g, potentially posing risk to human health (Fiedler, 2003; Minh *et al.*, 2003)

An unsanitary landfill in Croatia suffered open combustion from time to time, to reduce the volume of waste. Fajkovic *et al*. (2018) analysed the soil from a landfill shortly after an open combustion fire in 2007, and the sediments (sandy silt) from the nearby lake, one year and three years after the fire. The authors found that the lake sediments concentration of PCDD/F increased with time. Most likely due to the fact, that after three years, during that period, the sediments were continually being exposed to dry and wet depositions of those contaminants, from subsequent open combustion fires. Fajkovic *et al*. (2018) did not compare the concentrations in sediments with any guidelines, however comparing with threshold levels of the Canadian Sediment Quality Guidelines (Canadian Council of Ministers of the Environment, 2001), the concentrations were below and not harmful to aquatic environment. Concentration of PCDD/F in soil samples were higher than TEQ limit of 5 pg/g recommended for agricultural soils in Germany (Fiedler, 2003), therefore not suitable for agricultural purposes (Fajkovic *et al.*, 2018). The presence of PCDD/F in both soil and sediment samples, pointed out to the recurring open combustion happening on the investigated landfill, as a source of PCDD/F. The soil samples from the landfill showed concentrations of PCDD/F six times higher, than the concentrations of PCDD/F found in Vassiliadou *et al.* (2009) study site, where the Greek spontaneous landfill fire contaminated the soil and food from the surrounding area . However, no following research was performed at this study area (Fajkovic *et al.*, 2018). Given agriculture activity was common at that area, a study to the food produce should have been performed.

Two waste sites in Indonesia were investigated for PCDD/F and PCB soil contamination caused by open combustion and evaluated the difference between them. One was a controlled landfill where waste was compacted every day and then covered with soil every 6 months; and the other one was a waste dump where no compacting and soil layering occurred (Bastian *et al.*, 2013).The PCDD/F and PCB concentrations from the waste dump soil samples were higher than at the landfill, where soil layering occurred. The subsequent soil layering prevents a significant contamination of PCDD/F and PCB that result from the open combustion. Moreover, the concentrations of PCDD/F from both sites were above the control soils, meaning the landfill and waste dump were likely the source of dioxins. Thus, in countries where open combustion of waste or even spontaneous fires is a common occurrence, could add to their disposal process the compacting of waste and a layer of soil on top (Bastian *et al.*, 2013); this procedure does not hinder the soil contaminations, but further reduces the contamination.

2.3.3.3 Natural vs man-induced fires

Ruokojärvi *et al*.(1995; 1995) analysed waste samples from an experimental landfill fire, which was field built with waste and purposefully ignited. The other from a real spontaneous landfill fire in Finland, the landfill had solid domestic waste and a small industrial input. The authors found that the concentrations of PCDD/F and PCB in the waste samples from the spontaneous landfill fire were higher than the experimental landfill fire (Ruokojärvi et al., 1995b). Moreover, none of the samples from both sites exceeded the Finnish limit value for contaminated soil (DTSC, 2017). The slightly different waste material and conditions during the fire were most likely the reasons for the obtained results (Ruokojärvi et al., 1995a).

Wichmann *et al*. (2006) assessed the difference of soil contamination between a closed landfill that was open combusted, still smouldering 25 years after closure, and an open landfill where spontaneous fire frequently happened, both located in Jordan. The reason pointed out for the continuous smouldering after 25 years was attributed to the location, an arid area, where production of leachate was most likely small and not enough to extinguish the fire. Results demonstrated that some heavy metals, PAH and PCDD/F concentration were much higher in the samples from the closed landfill than in the open landfill. This observation indicated that the combustion and smouldering processes influenced more significantly the contamination situation on the closed landfill than on the open landfill. Moreover, the closed landfill showed similar PAH and PCDD/F concentrations with the Greek landfill (Martens et al., 1998), that operated with open combustion as well for a long time. All contaminants concentrations decreased with distance from the landfills. Soil samples from the closed landfill were also analysed ten years earlier by Alawi *et al.* (1996) for PCDD/F, during the 10 year interval the change on concentration of dioxins on soil was very small, probably due to the persistency of the contaminants and the ongoing smouldering process. Furthermore, the concentrations were compared with values from the German law on soil protection, for soil of industrial and residential areas (BBodSchV, 1999). Concentrations above these values indicate that the soil is most likely harmful and additional investigations should had been performed (Wichmann et al., 2006), as well as remediation actions, e.g. decontamination or exchange of soil (Fiedler, 2003).The samples taken closest to the closed landfill were the only ones with concentrations of PAH, Pb, and PCDD/F above the German law for residential areas. Overall the contamination in the landfills was considered sub-critical (Wichmann et al., 2006). The results were opposite to what was found by Ruokojärvi *et al*.(1995), supporting the thought that fire conditions have an influence on contaminants load released.

2.4 GENERAL DISCUSSION

An average of 2 billion ton of solid waste are produced annually and expected to grow to 3.40 billion ton by 2050. Concerning numbers, given 33 % of the 2 billion ton of waste are not being disposed of in an environmentally safe way. Only 12 % of the generated waste worldwide goes to proper controlled landfills and 33 % goes to waste dumps. In undeveloped countries, the money invested in waste management is very low, with 90 % of the waste mostly going to waste dumps (Kaza *et al.*, 2018).

The trend of natural events through the years demonstrates a rise, as well as predictions for their increasing frequency and intensity. Existing landfills and waste dumps either closed or operating, will suffer from such events, some already have, as stated in Section 2.3.

However, the attention given to this issue is rather small. There are several known affected locations such as, New Zealand (Department of Conservation, 2019), where coastal landfills are being exposed; landfills severely damage by wildfires in USA (Waste 360, 2018) and Portugal (DN, 2017), but no scientific studies were found that assessed the consequences of the events on the environment. A portion of closed waste dumps in Portugal are in forest areas and/or remote areas, with some having trees and dense vegetation on top. In case of a wildfire, the roots of the vegetation could be a channel/path for intrusion of oxygen and even sparks, as the length most likely reaches the buried waste, allowing for a sub-surface fire to possibly occur. Given the type of contaminants that are released during waste combustion, it could adversely affect soil and potentially watercourses/groundwater if those are close by.

The same goes for occurrence of landslides and earthquakes affecting landfills and waste dumps. When landslides occur ton of contaminated soil and waste are released, easily contaminating the surrounding soil and water, potentially affecting human health. This often occurs in undeveloped countries that lack of waste management and structural facilities to sustain the amount of waste that is disposed, most likely containing hazardous waste. Earthquakes, although not so frequent, if they impact landfills or waste dumps with no base protection, there may be a chance the soil base could crack allowing leachate to leak, posing a risk to groundwater quality. However, only studies concerning to the reasons behind the stability loss of landfills (e.g. Feng *et al.*, 2019) and the behaviour of landfills during seismic activity have been widely investigated (e.g. Naveem, Sitharam e Sivapullaiah, 2015).

The knowledge relatively to the impact of released waste either from breaching landfills/waste dumps or landslides, on soil/sediments, water and consequently ecosystems, is very small. Solid waste contains certain concentrations of contaminants, but it is very hard to say whether those concentrations would be bioavailable and pose a risk or stay bound to the material, once waste is released. Brand (2017) demonstrated that saline water could increase the amount of heavy metals released from waste matrix material (particulate materials similar to soil), concentrations of contaminants in solid waste might be high enough to pose a threat, if the proper conditions are found that allow major amounts of contaminants to be released.

Asia is the continent most affected by natural events, with undeveloped countries depending mostly on waste dumps for disposal of waste. Where the environment of these locations is probably already slightly contaminated, considering the lack of wall and base containment, as well as, the constant open combustion occurring on waste dumps and landfills. The consequences of a natural event in those areas could affect the resources from which the populations depend upon for survival, such as unpolluted water for consumption, which is already slim, and soil and watercourses for food. The capacity for these countries to recover from events is probably slow, given the lack of resources, compared with developed countries. Considering the potential environmental impact of these events along with the limited knowledge and tools to assess them, an analysis/research of these situations should be urgent in the near future, as trends indicate that natural events will increase over time, putting landfills and waste dumps at risk. Measures will need to be applied in order to prevent and/or mitigate potential problems and protect the environment and ecosystems, as well as human lives.

2.5 CONCLUSION AND RECOMMENDATIONS

Landfills and waste dumps are built to sustain a large amount of waste, however much of those have not been built to sustain natural events. This literature overview gathered scientific studies with the aim of identifying the potential environmental impacts from natural events affecting landfills and waste dumps. Coastal erosion and flooding showed that such disturbance could cause the remobilization of contaminants into the water column and cause the disrupt of landfills, potentially affecting the water quality and marine life. Combustion either spontaneous or man-induced, depending on waste and fire conditions, produces dangerous contaminants, the most common, dioxins, which above certain levels can cause issues to human health and the environmental quality.

The overviewed studies relatively to coastal erosion and flooding only analysed heavy metals and PAH contamination. However, there are other dangerous contaminants such as, bisphenol A (BPA), POPs (e.g. PCBs, PCDD/PCDFs, polybrominated diphenyl ethers (PBDEs), perfluorooctane sulfonic acid (PFOS), polybrominated biphenyls (PBB)), microplastics and emerging contaminants, which have already been found in landfill leachates. These are contaminants commonly found in landfills with several decades of disposal waste, such as food packaging, metal products, plastics, pesticides, electronics, furniture, flame retardants, textiles, pharmaceuticals, personal care products, between others (Pedro-Cedillo *et al.*, 2019; Ramakrishnan *et al.*, 2015; Su *et al.*, 2019; Weber *et al.*, 2011). When these contaminants are released to the environment they have the ability to negatively impact marine life, for example, BPA causes reproduction and metamorphosis issues in aquatic species (Canesi e Fabbri, 2015).

Some suggested measures to prevent the coastal erosion and floods of landfills and waste dumps are:

- Installation of sea defences (Brand, 2017);
- Relocate the landfills/waste dumps to a safer place, however it is an operation that requires a lot of money (Brand, 2017);
- Landfill mining to remove any hazard waste material that would pose a risk to the marine environment (Beaven, R. P. *et al.*, 2020);
- Nourishment of sediments and/or sand in locations where erosion is stronger to slow the removal (National Research Council, 2007);
- Creation of more wetlands, roots of saltmarsh vegetation anchor the soil/sand, helping to remain stable and resistant to erosion, as well as reduce wave energy (National Research Council, 2007);
- Installation of breakwaters, barriers built offshore to reduce wave energy reaching shore (National Research Council, 2007);
- Construction of dams and floodwalls to prevent floodwater and storm surges from entering areas at risk (National Research Council, 2013).

Overall this literature overview made notice that there is still very little knowledge relatively to the potential of natural events adversely impact landfills and waste dumps, either open or closed, and consequently affect the surrounding environment and ecosystems. Further research is required to better understand if landfills and waste dumps may be at risk from natural events.

3 THE PORTUGUESE CASE STUDIES

3.1 METHODOLOGY

The practical component of this work comprised four main steps shown in Figure 5. Firstly, wildfires (year of occurrence, location and extent of burnt area) and the location of the old (closed) dumps were inventoried in Continental Portugal. The selection of potential case studies of closed waste dumps affected by wildfires was also done in the first step. Then, the regions where the selected dumps are sited were characterized in terms of climate, soil type, etc., and a preliminary field visits were also made. These visits allowed to design the field campaign, carried out in the 3rd step, aiming to assess the degree of impact of the wildfires on the closed waste dumps. Finally, estimated the energy potential and carbon stock on the remaining waste of the closed waste dumps and the emissions of CO_2 that would occur in case of complete combustion of the waste (organic fraction) on the closed waste dumps.

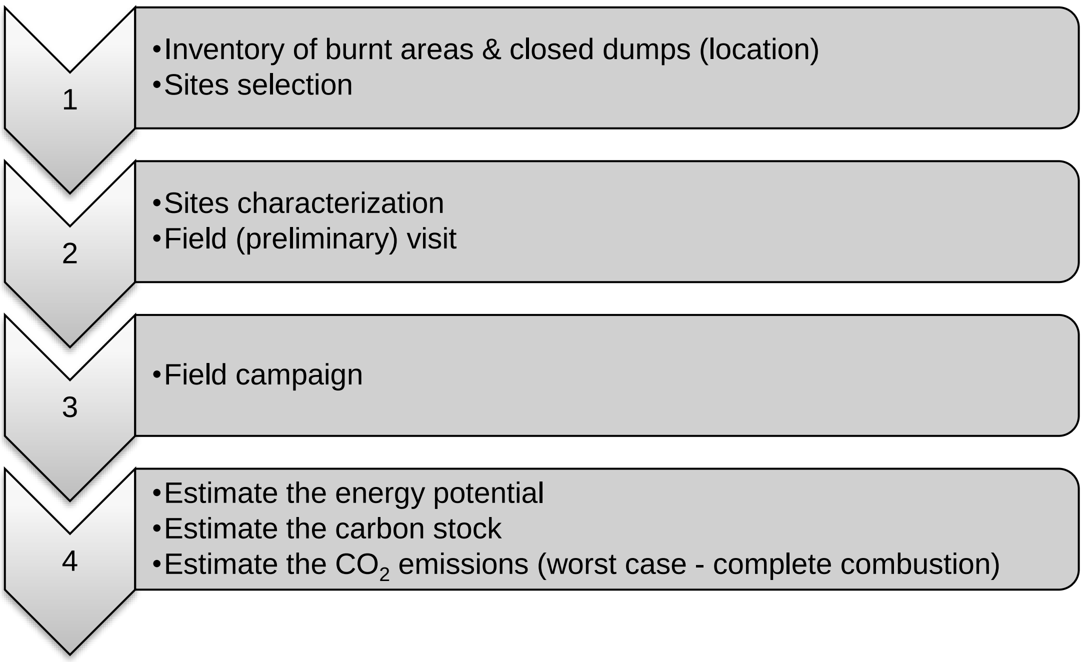


Figure 5 – Main steps of the practical work.

The main steps shown on the above figure will be describe in detail on the following sections.

3.1.1 Inventory and sites selection

In order to identify potential case studies of closed waste dumps affected recently by wildfires, it was required a map with the burnt areas in Continental Portugal between 2014 and 2019, which was provided by the research team, Earth Surface Processes (ESP) Team, from the University of Aveiro (Figure 6).

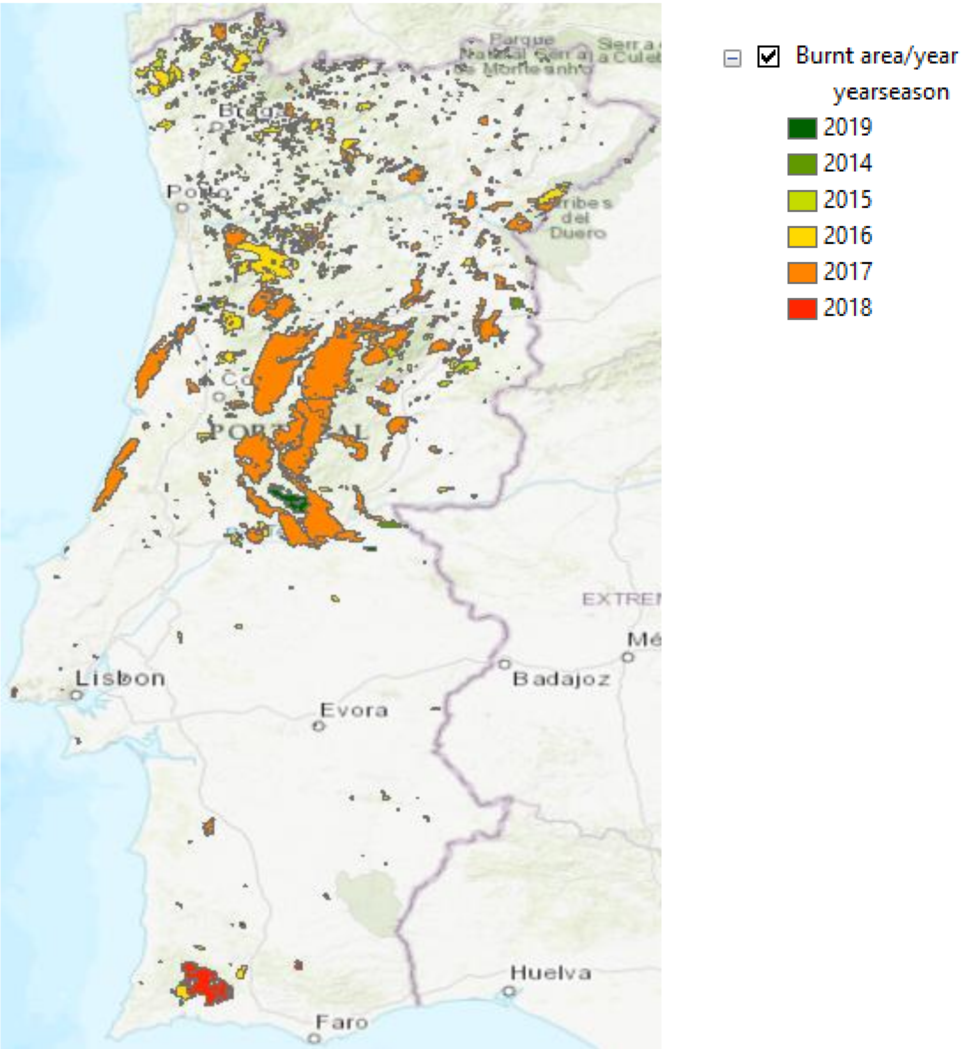


Figure 6 - Burnt area (and respective location) of wildfires between 2014-2019 in Continental Portugal (Source: ESP Team, CESAM, University of Aveiro).

Several entities were contacted mainly Comissões de Coordenação e Desenvolvimento Regional (CCDR) and waste management entities, requiring the provision of information regarding the location of closed (old) dumps. Among 341 dumps that exist in Continental Portugal, 239 dumps were identified (Figure 7). Using the Google Earth tool and the coordinates of the identified dumps, visual images demonstrated that these dumps are predominately located in forest or remote areas.

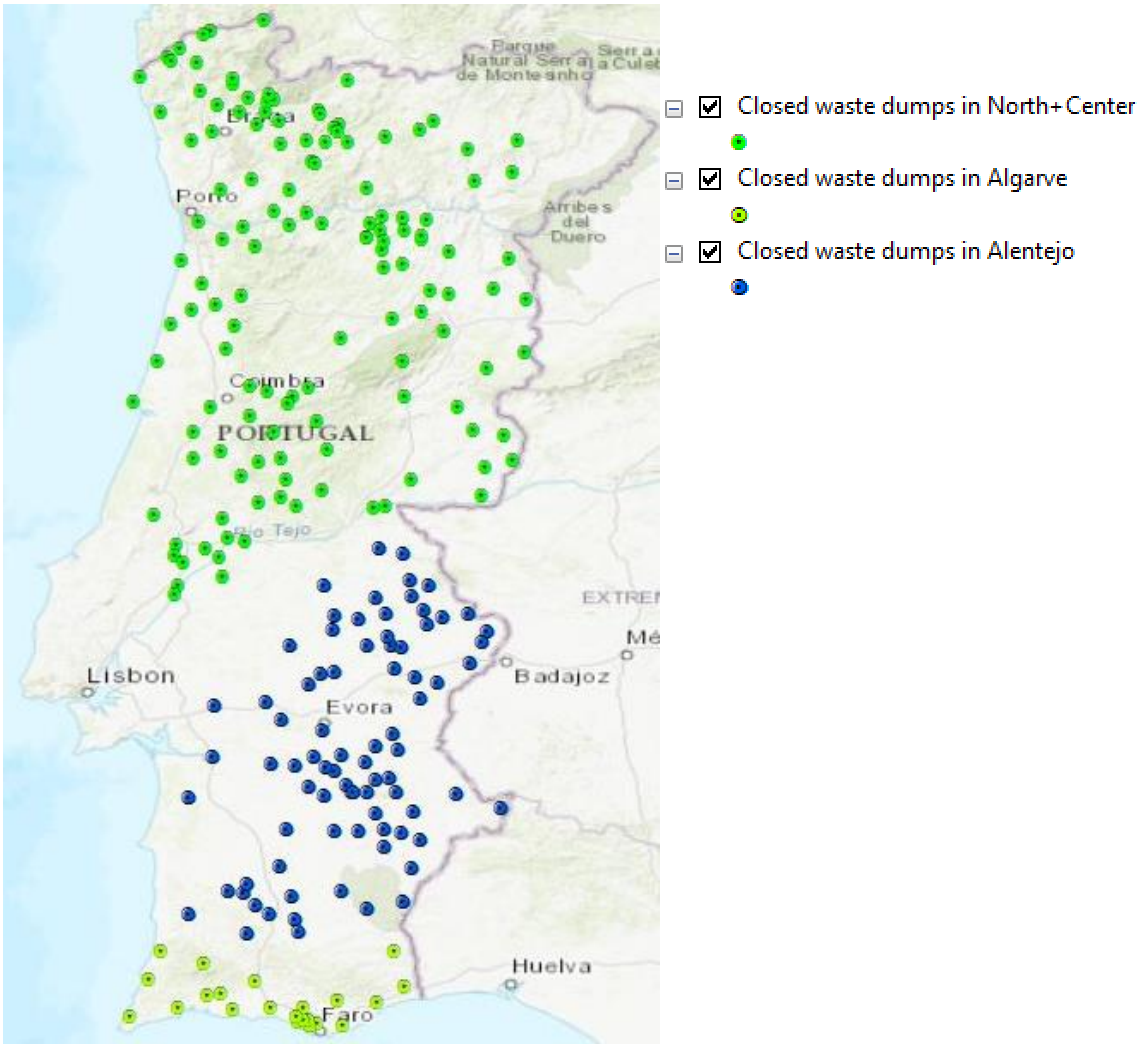
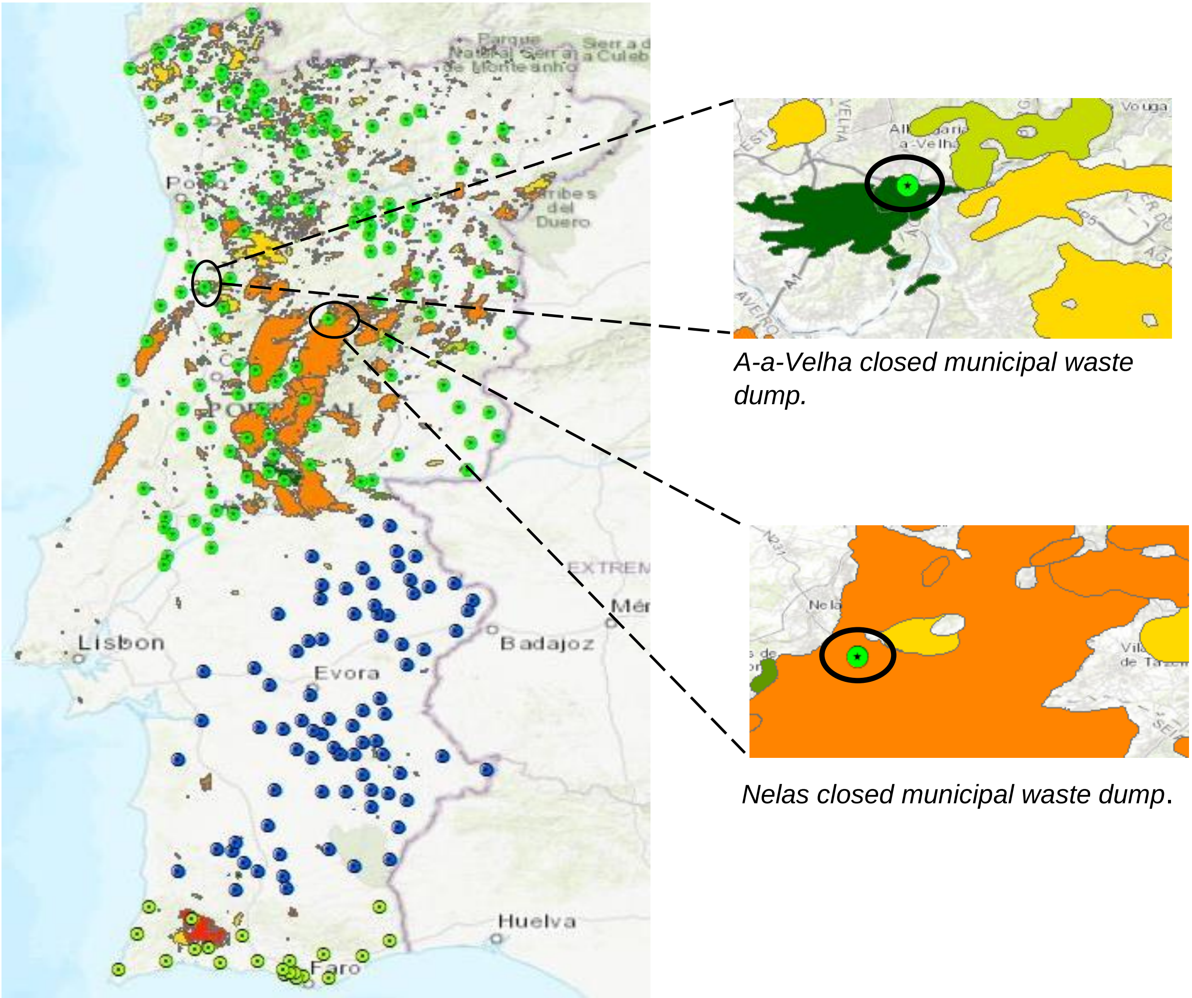


Figure 7- Location of the closed waste dumps in Continental Portugal.

The data in Figure 6 and Figure 7 were overlapped on the same map using ArcMap®, aiming to identify potential dumps impacted by wildfires and the result is in shown in Figure 8. Two closed dumps were selected as potential case studies, one sited in Albergaria-a-Velha and another one in Nelas municipality, affected by the wildfires of 2019 and 2017, respectively. Both case studies were selected given the proximety to University of Aveiro and the confirmation, by the municipalties, that the areas in which those dumps are located, were affected by wildfires.



A-a-Velha closed municipal waste dump.

Nelas closed municipal waste dump.

Figure 8 - Location of wildfires and closed municipal waste dumps, in Continental Portugal.

After selecting the case studies, the next step was to gather information relatively to each area of study, as well as to perform a preliminary field visit to the closed waste dumps. This visit aimed to visually assess the sites and find sampling points of soil/waste were the closed waste dumps might have been affected by the wildfires, and also sampling points of runoff water.

3.1.2 Sites characterization and preliminary field visit

3.1.2.1 Nelas closed waste dump

The closed waste dump (Figure 9) is located in Senhorim, in a forested area, away from population, 4.4 km from Nelas, Viseu.

Figure 9 - Google earth image of Nelas closed waste dump from 2019.

The soils typical of the region of Nelas are Humic Cambisols. These soils are poorly developed, showing very little degree of chemical and physical alteration, derive from granite, have sandy or slightly sandy texture, and are permeable. The municipality of Nelas has a forest area of approximately 8100 ha, containing mainly maritime pine (the most dominant), eucalyptus, stone pine and patches of various leafy areas. Uncultivated forest spaces resulting mainly from previous fires, also occupy an area of approximately 1300 ha. The weather in Nelas is temperate, characterized by hot and dry summers, and cold and wet winters, typical weather of Portugal. The annual mean temperature is around 12.5 and 15ºC and the average annual precipitation is 1100 mm (Município de Nelas, 2013).

The Nelas closed waste dump was visited on December 5th 2019. Once on site it was possible to observe that it was an open space (Figure 10a) with small vegetation and patches of grass (Figure 10b) on the surface of the closed waste dump. It also had vegetation damaged by tire marks (Figure 10c, Figure 10d and Figure 10e), including places where tire marks reached the dump lining (Figure 10f). There was no longer evidences that a wildfire occurred, neither the surrounding vegetation showed any signs of burnt parts. Two years had passed since the wildfire and the above ground vegetation had recovered. Since there were only underbrush on the site, it was seen that the wildfire did not significantly affect the dump and therefore it was not justifiable to proceed to the sampling stage.


(a) (b)


(c) (d)


(e) (f)

Figure 10 - Photos of Nela's closed waste dump and its surroundings: (a) no signs of recent wildfire, (b) patches of small vegetation, (c), (d) and (e) damaged areas from tire-marks, (f) damaged area with pieces of lining showing.

In addition, the lack of available information relatively to the closed waste dump, until the writing of this dissertation, such as the closure and maintenance plan, it was not possible to carried out the 3rd step of Figure 5 for this closed dump.

3.1.2.2 A-a-Velha closed waste dump

The closed waste dump is located in Assilhó, 1.2 km from A-a-Velha, Aveiro, inserted in a plantation of *Eucalyptus globulus* away from populations residence, adjacent to a train track (Figure 11).

The type of soils found in the region of A-a-Velha are Litholic soils and Slightly Unsaturated Argiluviated Soils. Both soil types are undeveloped (DRAP Centro, 2009). The municipality of A-a-Velha has a forest area of 9,744 ha, with eucalyptus occupying dominantly 83 % of the area, followed by pines with 14 %, and 3 % by oak and acacia (Município Albergaria-a-Velha, 2015). The weather in A-a-Velha, just like Nelas, is temperate with cold and rainy winters, and dry and hot summers. The mean temperature varies through the year, from 10 to 20 ºC and the average annual precipitation is around 70 mm (Município de Aveiro, 2019).

Figure 11 - Google earth images of A-a-Velha closed waste dump from 2018 (rectangle in blue corresponds to the older area of the waste dump and the red the most recent area of the waste dump).

After the implementation of PERSU in 1997, a plan for closure, environmental recovery and monitoring plan was developed by Ersuc, the local waste management entity, in 1998 for the A-a-Velha dump site.

According to Ersuc closure plan, the waste dump started operations in 1975 (the date of closure was not mentioned), pointing to a total of 42,000 ton of mostly domestic waste disposed and a total area of approximately 20,800 m^2, at the time the plan was developed. The most recent part of the dump (in red on Figure 11), an additional area to the dump used, after closure of the older area (in blue on Figure 11), has 9,500 m^2. No dates where mentioned relatively to when it was started operations or when the older area closed. Moreover, these most recent area, was not fenced during operation and illegal depositions might have occurred (Ersuc, 1998).

The plan for closure of the landfill included the compacting and adjustments/shaping, in order to have appropriate slopes to allow surface runoff of rainwater and slope stability, as well as to give a more homogeneous form to the dump site. A rainwater drainage system and leaching drainage and collection system connected to a wastewater treatment plant, were installed to minimize the risks of soil and groundwater pollution. Also, a biogas control system was installed through the implementation of a vertical drainage system (Ersuc, 1998).

A cover layer was installed to minimize the production of leachates through percolation of rainwater through the waste. The final layering was planned to consist of (Ersuc, 1998):

- a waterproof layer composed of 0.20 m of soil with silt-clay characteristics, to complement waterproofing and the protection of the synthetic materials placed on top of this layer;
- a waterproof and drainage layer composed of a geocomposite of polypropylene laminated with a polyethylene membrane;
- a drainage layer with a three-dimensional structure consisting of intertwined polypropylene filaments;
- a 200 g/m^2 geotextile on top of the drainage layer to prevent clogging by fine particles from the final covering layer;
- and a final covering layer on top of all surface with 1.0 m of local soil.

Due to stability issues and to allow an easier construction of the coverage at the level of the embankments/slopes, the thickness of the waterproof layers and final cover layer were reduced to 0.10 m and 0.20 m, respectively, without compromising the functions of each layer. This recommended waterproofing system was only used in the most recent area of the waste dump (area in red in Figure 11). The older area of the waste dump (in blue in Figure 11) was fully covered with soil and eucalyptus and, according to Ersuc, the state of degradation of the waste did not justify the implementation of waterproofing layer. It was also suggested the implementation of a gate of 5 m high and 2 m width and a fence of 1 m high with barbed wire to prevent the entering of animals in the area and the illegal deposition of waste (Ersuc, 1998).

The aesthetic and environmental recovery of a waste dump, allows for a more homogenous view, as well as, protect against water and wind erosion. Reducing potential environmental and structural problems, thus reducing unnecessary costs. Given the small thickness of soil covering the dump it was not advisable the plantation of tree species since the roots could damage the cover lining. The flat areas of the waste dump suffer less erosion than slopes, so the recommended vegetation cover was an herbaceous mixture of grasses and shrubs to bring visual and ecological value. The proposed vegetation for slope areas was the plantation of herbaceous and shrub species to prevent erosion and slope failure (Ersuc, 1998).

The foreseen maintenance activities were (Ersuc, 1998):

- preservation of the vegetation cover of the slopes;
- cleaning the rain gutters;
- control, maintenance and preservation of the leachate collection and drainage system;
- control, maintenance and preservation of the biogas collection system;
- bi-annual reporting of the status of the lining and landscaping.

The recommended time to carry out these activities was 5 years after closure. The developed monitoring plan for biogas, groundwater; leachate, surface water and structural behaviour-facility topography was developed according to guidelines giving by Directive 97/C/156/08, for disposal of waste in landfills (Ersuc, 1998).

The leachate monitoring plan involved the measurement every 6 months of the volume and composition of the leachate, including pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and conductivity. The biogas monitoring plan established the measurement of gas emissions of methane, oxygen and carbon dioxide, the temperature, pressure and velocity, every 6 months. For groundwater quality monitoring it should be measured every 6 months the chemical composition, namely pH, Total Organic Carbon (TOC), phenols, heavy metals, fluorides, arsenic and hydrocarbons, as well determine groundwater levels through installation of piezometers. Surface waters monitoring involved the analysis of water samples, collected upstream and downstream of the waste dump, according to the norms of Decree-Law nr 236/98 for water quality, for the same parameters as groundwater. For the structural behaviour, it should be carried out every 6 months a topographic checking for settlements using surface control marks, and monthly visual inspection for landslides (Ersuc, 1998).

The preliminary field visit, carried out on 6th of November of 2019, confirmed that the closed waste dump had an eucalyptus plantation on top (Figure 12). The site was open, with partial walls around but without fences or gates. There were small amounts of waste illegally dumped at the entrance. The slopes were in a sinusoidal shape, and the vertical biogas drains and a runoff gutter/ditch were visible. There were signs of the wildfire on the tree trunks and leaves (Figure 13), and stumps (Figure 14). The top of the trees were not burnt, suggesting a low severity wildfire (EFFIS, [s.d.]; Hayes e Robeson, 2009).

Figure 12 - Eucalyptus plantation in A-a-Velha closed waste dump.

Figure 13 - Burnt tree trunks in A-a-Velha closed waste dump.

Figure 14 - Burnt stump in A-a-Velha closed waste dump.

After that observation, there was a suspicion, that maybe the deepest layers of the soil, hadn't been affected by the wildfire. However, during the visit, it was possible to notice various burnt stumps, like in Figure 14. These burnt stumps were only found in the older area of the dump, where it was located the eucalyptus plantation, although the most recent area was also affected by the wildfire, it did not have trees or stumps, just small vegetation and no extensive damaged was observed. The finding of the burnt stumps left a possibility, that maybe the wildfire could have penetrated through the roots of the stumps and eventually reach deeper soil layers, or even waste material, in these points. Given no lining was used after the closure of the older area of the waste dump, only covered with 1 m of local soil, the roots could have reached the deep waste. The roots of large trees, may be long enough to reach the depths at which the waste materials are, and act as path for spreading fire in depth. All that is required is oxygen and an ignition (i.e sparks/fire). Moreover, spots of accumulation of runoff water were not found, therefore the sampling of water was opted out of the field campaign. Thus, the field campaign was aimed at collecting soil samples, whose methodology is described below.

3.1.3 Field campaign

To assess the impact of wildfire on soil and waste in deeper layers, one chose the burnt stumps in the area of rectangle in blue in Figure 11. For soil/waste sampling in each point, firstly the stump was removed (burnt top roots), when possible, and the top soil was collected with a shovel. The sampling at deeper depths was performed using an auger (Figure 15). During this procedure, if some pieces of waste were found, they were identified, packaged in a plastic bag and labelled; the same was done for soil samples. Along with the registration of the depth at which the samples were taken, using a measuring tape or an auger with measurement marks, and the description of the waste materials found mixed on the soil. These procedures would be repeated to all selected sampling points.

Figure 15 – Auger used for soil collection.

The samples of soil would be transported to lab and dried at air for characterization in terms of: ash content, BOD, conductivity, COD, heavy metals, PAH (as indicator of wildfire), pH and TOC.

Indeed, this last stage of characterization of soil samples was not carried out. Details on this will be presented in the Section 3.2.1.

The energy potential and carbon stock on the waste in A-a-Velha closed waste dump, as well as the total amount of CO_2 that would be released in case of complete combustion of the remaining waste in the closed waste dump, will be estimated. The adopted methodology to achieve such, is described on the following subsection.

3.1.4 Estimates of energy potential, carbon stock and CO_2 emissions

Based on the amount of waste deposited in the dump of A-a-Velha (Section 3.1.2.2) and in some data found in a literature review, the energy potential, the (organic) carbon stock and the carbon dioxide (CO_2) emissions were estimated. The physical composition of the waste landfilled in the dump was unknown and also out of scope of this work. Thus, it was needed to find this information in reported studies in similar dumps.

3.1.4.1 Characterization of the waste composition

Anacleto (2008) determined the physical composition of a Portuguese closed waste dump sited at Moita, with similar age as the A-a-Velha closed waste dump. The average composition of 6 samples (wet basis, wb), found by that author, and respective standard deviations, are summarized in Table 3.

T*able 3 - Physical composition of waste samples of the Moita close municipal waste dump* (*Adapted from*: Anacleto (2008)).

Component	**Fraction** [% wt, wb]
Paper & cardboard	2.34 ± 2.38
Cartons for food and beverages	1.57 ± 0.75
Plastic film	8.97 ± 3.19
Hard plastic packages	2.13 ± 1.05
Other plastics	1.76 ± 0.52
Glass	2.97 ± 1.75
Metals	1.77 ± 0.75
Textiles	3.33 ± 1.69
Wood	4.00 ± 2.96
Fine fraction (< 20 mm)	54.41 ± 13.75
Stones & inerts	6.22 ± 4.15
Others (e.g. diapers, sanitary textiles, shoes)	3.17 ± 1.56
Rest waste	7.38 ± 4.35

A majority of the values of standard deviation are very high, showing the heterogeneity of the waste among the 6 samples. To simplify calculations, instead of considering two fractions the “paper & cardboard” and “cartoons for food and beverage”, it was considered only a combined fraction of these two (so-called “paper & cardboard”), with corresponding composition of 3.81 % (wt, wb). The same strategy was applied to plastics, i.e., only one component was considered "plastics" whose fraction corresponds to the sum of the various plastic components characterized by Anacleto (2008); in this case the corresponding weight fraction is 12.51 % (wt, wb).

Some components of T*able 3* were characterized by Anacleto (2008) in terms of moisture content and the values are shown in Table 4. The number of samples used in this characterization ranged between 1 (wood component) and 12 (e.g. textile, plastic film).

Table 4 - Moisture content of some components of the waste deposited in Moita waste dump (*Adapted from*: Anacleto (2008))

Component	$\boldsymbol{w_{wH}}$ [kg H_2O/kg H]*
Paper & carboard	52.36 ± 9.00
Hard plastic packaging	10.24 ± 6.17
Plastic film	24.29 ± 6.70
Textile	38.06 ± 6.19
Fine fraction	16.29 ± 4.48
Wood	46.76
Rest waste	29.09

*$\boldsymbol{w_{wH}}$ – moisture content (wb); H – component (wb)

In this work, the moisture content of "plastics" component used corresponds to the average moisture content of the "hard plastic packaging" and "plastic film" components, i.e., 17.3 %.

The carbon stock of the total waste in a closed waste dump can be estimated using only 4 of the components, "paper & cardboard", "plastics", "textiles" and "wood", given these are the only that have organic carbon. Moreover, from the pictures on Anacleto (2008) work, the type of waste included on "others" (e.g. diapers, sanitary textiles) and "rest waste" (very small pieces of plastics) components, mostly belong to the category of plastics. Thus, in this work these components were considered as plastics.

3.1.4.2 Energy potential

The organic fraction of solid waste has energy potential, which can be estimated knowing the lower heating value of each component of the organic fraction (wood, paper & cardboard, etc.) and the mass. One approach to determine that potential is calculating the the (average) lower heating value of the waste disposed in the dump, H_u, as following:

$$H_u \left[\frac{\text{MJ}}{\text{kg,wb}}\right] = \sum_i \left[H_{u_i} \times \frac{\text{Fraction of component } i \text{ (\% wt,wb)}}{100}\right] \qquad (1)$$

where H_{u_i} is the lower heating value of the waste component i (MJ/kg, wb) (Table 5) and $\text{Fraction of component } i$ is the weight fraction of component i in the total solid waste (Table 5).

Finally, the total energy potential of the solid waste of the dump was estimated using the equation:

$$\text{Total energy potential [GJ]} = m_t \times H_u \qquad (2)$$

where m_t is the total mass (wb) of solid waste disposed in the dump (ton).

Table 5 – Fraction of waste materials and corresponding lower heating value used in this work.

Component	**Fraction** [%wt, wb]*	$\boldsymbol{H_u}$ [MJ/kg, wb]#
Paper & cardboard	3.91	15.70
Plastics	12.85	32.7
Glass	2.97	0.2
Metals	1.77	0.7
Textiles	3.33	18.3
Wood	4.00	15.4
Fine fraction (< 20 mm)	54.41	0.2**
Stones & inerts	6.22	0
Others	3.17	32.7***
Rest waste	7.38	32.7***

Source: *Anacleto (2008), # Kiely (1998); ** Considered glass; *** Considered a mixture of plastics.

In short, the steps described above for the energy potential estimation are shown in Figure 16.

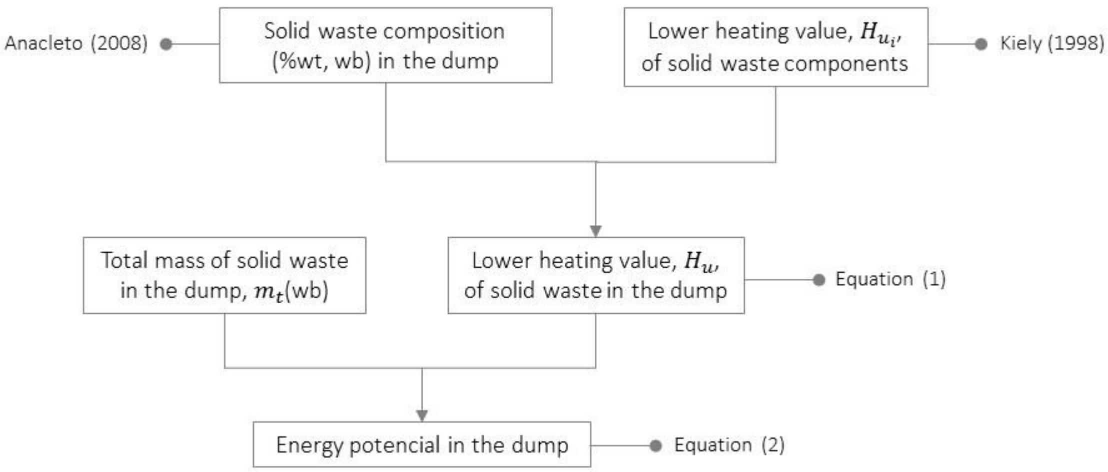


Figure 16 - The steps for calculation of the energy potential in the waste dump.

The (organic) carbon stock in the organic fraction of the solid waste is described in the next section.

3.1.4.3 Carbon stock

The estimation of carbon stock was based on 3 approaches, according to information found in literature. The 1st approach was based on the average chemical composition of waste materials using the following equation:

$$\text{Carbon stock [ton C]} = \sum_{\text{i}} \left[\frac{12 \times C}{12 \times C + H + 16 \times O} \times m_i(db)\right] \quad (3)$$

where, C, H and O are the number of carbon, hydrogen and oxygen atoms in the chemical formula.

Note: The mass in dry basis of each waste component, $m_i(db)$, was calculated using the following equation:

$$m_i(db) = m_i(wb) \times (1 - w_{wH}) \quad (4)$$

The chemical composition for "paper & cardboard" was used the simplified chemical formula of cellulose, $(C_6H_{10}O_5)_n$, one of the major components of cardboard and paper (Ma *et al.*, 2016); for "plastics" was used the simplified chemical formula of polyethylene $(C_2H_4)_n$, one of the most used polymers (Patel, 2016); for textiles one used the simplified chemical formula of cellulose, natural fibres are mainly composed of cellulose (Komuraiah, Kumar e Prasad, 2014) and wood main elemental composition is 50 % carbon, 42 % oxygen, 6 % hydrogen, 1 % nitrogen and 1 % other elements (Pettersen, 1984).

The 2nd approach for estimating the carbon stock was based on data supplied by the 2006 IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories (Pipatti, Sharma e Yamada, 2006), knowing the total carbon content (% wt, db) in each component of municipal solid waste (Table 6). The following equation was used to estimate the carbon stock:

$$\text{Carbon stock [ton C]} = \sum_{\text{i}} \left[\frac{\% \, C_{total}}{100} \times m_i(db)\right] \quad (5)$$

where the $\% \, C_{total}$ is the percentage of total carbon (wt, db).

Table 6 - Total carbon content for different waste components.

Component	% C_{total} (wt,db)#	C_{total} [kg/ton, wb]
Paper and cardboard	46	345*
Plastics	75	672*
Textiles	50	170**
Wood	50	438*

#Source: IPCC Guidelines for National Greenhouse Gas Inventories (Pipatti, Sharma e Yamada, 2006)
*Source: Larsen et al. (2013), **Source: Fellner and Rechberger (2009)

The 3rd approach used to estimate the carbon stock was based on data supplied by Larsen et al. (2013) and Fellner and Rechberger (2009), regarding the carbon content of various waste components (Table 6), and the carbon stock was estimated by:

$$\text{Carbon stock [ton C]} = \sum_{\text{i}}[C_{total} \times m_i(wb)] \quad (6)$$

where C_{total} is the mass of carbon per mass of waste (wb) (see *Table 6*).

.

3.1.4.4 CO₂ emissions

CO_2 emissions were estimated in a hypothetical scenario in which the wildfire reached the deep dump layers and, consequently, the waste disposed is burned. The worst scenario was considered, i.e., the complete combustion of all organic waste, according to the equation:

$$\text{C (s)} + \text{O}_2\text{ (g)} \rightarrow \text{CO}_2\text{ (g)} \quad (7)$$

Thus, 44 ton of CO_2 are emitted for every 12 ton of carbon burned.

The results obtained applying the methodology described above are shown and discussed in the next section.

3.2 RESULTS AND DISCUSSION

This section entitles firstly the results from the field campaign on A-a-Velha closed waste dump, described in Section 3.1.3. Followed by the results from the estimates of the energy potential, carbon stock and CO_2 emissions, in Section 3.1.4.

3.2.1 Field observations

The field campaign was done on January 22th 2020, starting from south to north. As was mentioned above in Section 3.1.3, the burnt stumps were the chosen sampling points, given the wildfire was of low severity and no other area of the waste dump showed signs of deep wildfire penetration like in the burnt stumps. The amount of burnt stumps was only 9 and all of them were sampled. Some photos from soil sampling are shown in Figure 17.

(a) (b) (c) (d)

Figure 17- Photos from soil sampling: (a) burnt stump, (b) hole after stump removal, (c) removal of top soil, and (d) Measuring the depth of sampling point.

While exploring the burnt stumps, it was noticeable that the burnt soil was greasy, probably rich in organic matter. The wildfire reached depths between approximately 20 and 70 cm (*Table 7*), but waste material was only found at approximately 80 cm, meaning the wildfire did not reach waste. The type of waste material found were pieces of glass, plastic (Figure 18a) and what looked like a piece of a diaper (Figure 18b).

This demonstrated that our suspicion was wrong. The wildfire did not reached the deepest soil layers trough the roots of the stumps. Perhaps, due to the fact, that the wildfire was of low severity, given that, in some sampling points, the wildfire reached depths between 60-70 cm, which were not very far from the depth at which waste materials were found. Moreover, A-a-Velha case study showed the influence that, woody species with high content of lignin and large vegetation with long roots may have on the surface of closed waste dumps, during a wildfire. Lignin is a polymer with a complex aromatic structure, the carbon chain contains an high amount of energy, which provides fuel for a long period during a fire (Ngole-Jeme, 2019).

Table 7- Maximum soil depths reached by the wildfire.

Sampling points	**Depth the wildfire reached soil** [cm]
1	± 60
2	± 40
3	± 40
4	± 30
5	± 50
6	± 20
7	± 50
8	± 70
9	± 60

(a)

(b)

Figure 18 - Photos of some materials found during field campaign: (a) pieces of glass and plastic and a piece of what looked like a diaper (b).

Although the date of closure of this area of the waste dump is not known, surely occurred until 2001. It's safe to assume that a long time has passed given the waste dump was opened in 1975. It is interesting to see that after all that time there is still waste present, demonstrating their long-term persistence on the environment and that they could still pose a risk if the next wildfire that comes, is able to reach these waste materials.

3.2.2 Estimates of energy potential, carbon stock and CO_2 emissions

3.2.2.1 Energy potential

The current mass of waste at A-a-Velha waste dump is not known, however it was estimated assuming the initial waste (42,000 ton) had a percentage of 40% of biowaste, based on the report "Relatório Anual de Resíduos Urbanos" (APA, 2011), where it is stated 40 % for biowaste fraction the municipal solid waste. Thus, one estimated that 25,200 ton of solid waste are currently in the old dump.

The results from Total energy potential and H_u of the waste are shown in Table 8. The obtained H_u of the waste in A-a-Velha closed waste dump was 9.62 MJ/kg (wb).

Table 8 - Results of the total energy potential and H_u of the waste.

Component	**Mass** [ton,wb]	**Total Energy** [GJ]
Paper & cardboard	986	15483
Plastics	3238	105875
Glass	748	150
Metals	446	312
Textiles	839	15357
Wood	1008	15523
Fine fraction	13711	2742
Stones & inerts	1567	0
Others	799	26122
Rest waste	1860	60814
Total	25203	242378
	$\boldsymbol{H_u}$ **total** [MJ/kg, wb] =	9.62

Considering the H_u of fuel derived from waste for production of energy may range between 10-15 MJ/kg (wb) (Caracol, 2016), the obtained estimation was not very far from it.

3.2.2.2 Carbon stock

The weight in dry basis of waste in A-a-Velha closed waste dump, was calculated and results are presented in the Table 9.

Table 9 – Weight in dry basis of some of the waste materials from A-a-Velha closed waste dump.

Component	$\mathbf{W_{wH}}$ [kg H_2O/kg H]	**Mass** [ton,db]
Paper and cardboard	0.52	470
Plastics	0.17*	2679
Textiles	0.38	520
Wood	0.47	537
Others	0.17*	661
Rest waste	0.17*	1539

*Mean value of W_{wH} of Thin plastics and Rigid plastic packaging

The carbon stock of the waste was estimated based on 3 approaches described in Section 3.1.4.3. The results based on the chemical composition of the waste are shown in the Table 10.

Table 10 - Carbon stock estimation based on the average chemical composition.

Components	**Mass** [ton, db]	**C**	**H**	**O**	**N**	**Carbon content** [ton]
Paper & cardboard	470	6	10	5		209
Plastics	4878*	2	4			4181
Textiles	520	6	10	5		231
Wood	537	58	84	37	1	269
Carbon stock [ton]						4891

*Sum of Plastics, Others and Rest waste

The results from the 2nd approach using data from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Pipatti, Sharma e Yamada, 2006), and the 3rd approach using data from Larsen et al. (2013) and Fellner and Rechberger (2009) work, are shown in the Table 11.

Table 11 - Carbon stock estimation from the 2nd and 3rd approach.

	Carbon content [ton]	
Components	**2nd approach** [ton]	**3rd approach** [ton]
Paper & cardboard	216	340
Plastics	3659	3962
Textiles	260	143
Wood	268	442
Carbon stock [ton]	4403	4887

The waste component with higher carbon content in all estimates was “Plastics”, given its weight was the highest of all waste components. For the 1st and 2nd approach, the waste component with the lowest carbon content were “Paper & cardboard”, while for the 3rd approach it was “Textiles”. Fellner and Rechberger (2009) found that “Textiles” had the lowest carbon content per weight of waste (see Table 6). The difference of results of total carbon stock between each method was small. The 1st (Table 10) and 3rd (Table 11) approach estimated carbon stock very close to each other, the 1st approach was only 0.08% higher than the 3rd approach. Moreover, the 1st and 3rd approach were only 10% and 9.9%, respectively, higher than the 2nd approach.

3.2.2.3 CO_2 emissions

Assuming the worst case scenario of complete combustion of the remaining waste on the closed waste dump, i.e. total consumption of the carbon stock on the remaining waste of the closed waste dump, the emissions of CO_2 were estimated for the resulting carbon stock of the 3 approaches described above, and the results are shown in the Table 12.

Table 12 – Estimated CO_2 emissions of the three approaches.

	Emission of CO_2 [ton]		
Component	**1st approach**	**2nd approach**	**3rd approach**
Paper & cardboard	766	792	1247
Plastics	15332	13416	14529
Textiles	847	953	523
Wood	988	984	1619
Total	**17933**	**16145**	**17918**

The obtained results from all approaches, as expected from the estimation of the carbon stock, “Plastics" were the waste component with the highest CO_2 emissions in all approaches. “Paper & carboard” were the lowest on the 1st and 2nd approach and “Textiles” on the 3rd approach. The 1st and 3rd approach had the closest results of total CO_2 emissions. In case of complete combustion of the A-a-Velha closed waste dump, CO_2 emissions could range from 16,145 to 17,933 ton, which corresponds to 0.64 and 0.71 ton of CO_2, respectively, per 1 tonne of waste burnt. Incineration of 1 tonne of municipal waste by waste incinerators in the EU has emissions around 0.7 to 1.7 ton of CO_2. (Zero Waste Europe, 2019). Thus, the emissions of CO_2 per tonne of waste from the A-a-Velha closed waste dump, would potentially be very close to the approximate interval of CO_2 emissions from waste incinerators in EU.

However, the complete combustion of the remaining waste material is unlikely during a wildfire. The incomplete combustion is most plausible scenario, due to the lack of control of the combustion conditions. This leads to the formation of worse contaminants than CO_2, such as dioxins and furans. Fires under the surface can burn at low temperatures for a long time, days to weeks, maybe even more, which leads to the constant formation of contaminants. Potentially contaminating the soil, maybe even water courses, with levels that could be dangerous to humans and the ecosystem.

3.3 CONCLUSIONS

The selected case studies were very different from each to other, both were impacted by wildfires in different years. A-a-Velha waste dump has a much larger area than Nelas waste dump, with a eucalyptus plantation on the surface, in a large portion of the total area of the waste dump, while Nelas waste dump had just small vegetation on the surface. The results from the case studies demonstrated that the wildfires most likely affected those areas in different ways. Fires with shrubs and small (roots) vegetation, usually burn only the first few centimetres of soil, due to the lack of fuel, the fires do not burn for a long time. Moreover, with dense vegetation (and deep roots) on top like the A-a-Velha closed waste dump, woody species burn for a longer time than grasses and shrubs, as they have a high content of lignin. Moreover, the fact that sampled area (the older area) did not have any kind of final cover, possibly allowed for the roots to easily reach material, putting at risk of combustion (most likely incomplete) the waste that still remains in these dumps and has significant amount of energy.

A-a-Velha waste dump is not the only one with dense vegetation on top, there are more closed waste dumps in a similar situation. Out of the identified 239 national dumps, approximately 28 dumps have some dense vegetation on top, though that number might not be accurate, since some visual images, from Google Earth, have 5 years old. Still, given there is a total of 341 closed waste dumps in Portugal, there most certainly exist various closed waste dumps with vegetation on top, exposed to wildfires hazards.

4 FINAL REMARKS AND FUTURE WORK SUGGESTIONS

The aim of this dissertation was to identify the impacts of wildfires on Portuguese closed waste dumps. In order to achieve that, firstly it was performed a literature overview concerning the environmental impacts of natural events affecting landfills and waste dumps. The continuous changing climate has been affecting the frequency and intensity of some natural events. Landfills and waste dumps are the two most used methods worldwide for disposal of waste and some of them are located within areas prone to natural events and with no protection to sustain those events. The majority of the research found was relatively to the effects of coastal erosion and flooding, showing that landfills/waste dumps impacted by those events, release contaminants that may adversely impact the surrounding environment and ecosystem. Moreover, no scientific studies were found (so far) either in Portugal or in other countries, concerning the impacts of wildfires in landfills or waste dumps. Only, about spontaneous and man-induced combustion of waste, which showed the type of contaminants that are release when waste is burnt in uncontrolled conditions, like in a wildfire.

The next step of this dissertation was the practical component, which entitled the selection of case studies to perform field campaign. Two closed waste dumps were selected, A-a-Velha and Nelas closed waste dumps, however just one was possible to proceed with field campaign. In the Nelas case study the effects of a wildfire that occurred 3 years ago were not noticeable in an area with small vegetation cover; therefore this case did not proceed for future field campaign. The A-a-Velha case study showed that no impacts (on waste disposed) were found, since the wildfire did not reach the waste material. However, the results from one case study do not stand for the rest of the existing closed waste dumps in Portugal. The A-a-Velha case study also showed the influence that large vegetation of woody species with deep roots, such as an eucalyptus plantation, may have on top of a closed waste dump during a wildfire, by increasing the probability of fire reaching waste material through the roots, as tree roots may be deep enough to reach the waste material and act as path for oxygen and sparks/fire, igniting the waste material. The low severity wildfire reached deeper than just a few centimetres in the stumps. A more severe wildfire may be able to affect deeper soil layers than that, and given older waste material has low water content, it requires much lower temperatures than fresh waste material to ignite. Moreover, waste materials were found during the sampling, showing that waste persists in the closed waste dump and potentially at risk for the next wildfire that comes. Assuming a worst case scenario of complete combustion of all the remaining waste in the closed waste dump, an estimated emission of CO_2 would be around 16,145 and 17,933 ton of CO_2. Moreover, the total lower heating value of the waste dump was also estimated, approximately 9.62 MJ/kg of burnt waste.

Portugal is extremely prone to wildfires due to the Mediterranean climate and, on the other hand, there is a lack of forest management that allows the uncontrollable growth of flammable vegetation. Depending on the escalation of the circumstances of the wildfire, it can turn to very dangerous uncontrollable wildfires. The total area burnt in Portugal has been increasing through the years with wildfires consuming more than 100,000 in more than 50 % of the cases.

Given there are more closed waste dumps in the same situation as the A-a-Velha closed waste dump, it is therefore, necessary to identify all closed waste dumps with large vegetation of deep roots on top, as well as the type of the woody species present, to assess if they are potentially at risk of wildfires; assess at what depth is the waste material currently and the its degradation status; characterize the reference state, as well as, the state of the waste dump and the environment post-fire (soil characteristics and water resources in the environment). In laboratory, through simulations and/or modelling, estimate the depth at which the waste material might be; the effect of the type of vegetation, namely the roots depth, and the type of soil during a wildfire; what would be the necessary severity/intensity of the wildfire, namely soil temperature and residence time for fire to be able to reach waste material through the roots and what would be the degree of impact on soil if fire reached waste material and burnt it, for a determinate amount of time and temperature.

Moreover, the literature overview relatively to the impact of natural events on landfills and waste dumps, demonstrated there is an overall lack of information and knowledge about this subject. The ability/capability or not for a natural event to adversely affect a landfill/waste dump, either open or closed, consequently impacting the surrounding environment, might be fundamental knowledge for the future, especially for countries where waste management is an issue. Therefore, at global scale, one suggests to identify vulnerable zones to natural events, the state of waste degradation and the state of confinement of waste dumps/landfills; study what would be the rate of contaminants being released from landfill/waste dump to surrounding environment, when impacted by a natural event, and if those contaminants would be a threat to the surrounding environment and ecosystem. Also, to study the conditions in which contaminants, bounded to solid waste materials, may become bioavailable in case of waste material releasing from landfill/ waste dump upon a natural event. Furthermore, the scientific studies concerning coastal erosion and flooding, only analysed for heavy metals and PAH contamination. Given the different types of material landfilled, other dangerous contaminants should be assessed that have the ability to negatively impact ecosystems, such as, BPA, POP, microplastics and emerging contaminants.

At last, it is suggested to reshape the literature overview chapter in a literature review article.

Wildfires in Portugal are not going to stop occurring and the closed waste dumps are not going to disappear from the forest areas. It is crucial to acquire more information to better understand if wildfires can or not adversely impact closed waste dumps and consequently the surrounding environment.

REFERENCES

ACOSTA, J. A. *et al.* - Salinity increases mobility of heavy metals in soils. **Chemosphere**. . ISSN 00456535. 85:8 (2011) 1318–1324. doi: 10.1016/j.chemosphere.2011.07.046.

ADENIRAN, A. A.; ADEWOLE, A. A.; OLOFA, S. A. - Impact of Solid Waste Management on Ado Ekiti Property Values. **Civil and Environmental Research**. . ISSN 2225-0514. 6:9 (2014) 28–35.

AKHTER, M. Salim; AL-JOWDER, Osama - Heavy metal concentrations in sediments from the coast of Bahrain. **International Journal of Environmental Health Research**. . ISSN 09603123. 7:1 (1997) 85–93. doi: 10.1080/09603129774039.

ALAWI, M. A. *et al.* - Dioxins and furans in the Jordanian environment: Part 1: Preliminary study on a municipal landfill site with open combustion nearby Amman - Jordan. **Chemosphere**. . ISSN 00456535. 32:5 (1996) 907–912. doi: 10.1016/0045-6535(95)00355-X.

ANACLETO, Sofia - **Técnicas para Recuperação de Resíduos Depositados em Antigas Lixeiras**. [S.l.] : Universidade Nova de Lisboa, 2008

APA - Resíduos Urbanos em 2010. 2011).

BAGCHI, A. - **Design, construction, and monitoring of landfills** [Em linha]. United States : John Wiley and Sons, New York, NY (United States), 1994 Disponível em WWW:<URL:https://www.osti.gov/servlets/purl/128792>.

BASTIAN, Lawin *et al.* - Behavior of PCDD/Fs during open burning of municipal solid waste in open dumping sites. **Journal of Material Cycles and Waste Management**. . ISSN 1436378X. 15:2 (2013) 229–241. doi: 10.1007/s10163-012-0114-5.

BATES, Margaret - Managing Landfill Site Fires in Northamptonshire. 2004).

BBODSCHV - Bundes-Bodenschutz-und Altlastenverordnung vom 12. **Bundesgesetzblatt (Teil I)**. 1999).

BEAVEN *et al.* - Future challenges of coastal landfills exacerbated by sea level rise. **Waste Management**. . ISSN 18792456. 105:2020) 92–101. doi: 10.1016/j.wasman.2020.01.027.

BEAVEN, R. P. *et al.* - Future challenges of coastal landfills exacerbated by sea level rise. **Waste Management**. . ISSN 18792456. 105:2020) 92–101. doi: 10.1016/j.wasman.2020.01.027.

BECKER, Per - **Our Disturbances, Disruptions and Disasters in a Dynamic World**. ISBN 9780444627094.

BEIGHLEY, Mark; HYDE, Albert - Gestão dos Incêndios Florestais em Portugal numa Nova Era: Avaliação dos Riscos de Incêndio, Recursos e Reformas. 2018) 59.

BELEVI, H.; BACCINI, P. .. - Long-term behavior of municipal solid waste landfills. **Waste Management & Research**. . ISSN 0734242X. 7:1 (1989) 43–56. doi: 10.1016/0734-242x(89)90007-4.

BILINSKI, H. *et al.* - Trace metal adsorption on inorganic solid phases under estuarine conditions. **Marine Chemistry**. . ISSN 03044203. 32:2–4 (1991) 225–233. doi: 10.1016/0304-4203(91)90040-4.

BRAND, J. H. - Assessing the risk of pollution from historic coastal landfills. **School of Geography**. PhD:2017) 1–385.

BRAND, James H. *et al.* - Potential pollution risks of historic landfills on low-lying coasts and estuaries. **Wiley Interdisciplinary Reviews: Water**. . ISSN 2049-1948. 5:1 (2018) e1264. doi: 10.1002/wat2.1264.

BRAND; SPENCER, Kate L. - Potential contamination of the coastal zone by eroding historic landfills. **Marine Pollution Bulletin**. . ISSN 18793363. 146:June 2018 (2019) 282–291. doi: 10.1016/j.marpolbul.2019.06.017.

CABEÇAS, Artur João; LEVY, João - **Resíduos Sólidos Urbanos, Princípios e Processos**. Lisboa : [s.n.]. ISBN 9799899505901.

CANADIAN COUNCIL OF MINISTERS OF THE ENVIRONMENT - Canadian Sediment Quality Guidelines for the Protection of Aquatic Life: Summary tables. 2001) 5.

CANESI, Laura; FABBRI, Elena - Environmental effects of BPA: Focus on aquatic species. **Dose-Response**. . ISSN 15593258. 13:3 (2015). doi: 10.1177/1559325815598304.

CAPUANO, F. *et al.* - Environmental prospection for PCDD/PCDF, PAH, PCB and heavy metals around the incinerator power plant of Reggio Emilia town (Northern Italy) and surrounding main roads. **Chemosphere**. . ISSN 00456535. 58:11 (2005) 1563–1569. doi: 10.1016/j.chemosphere.2004.11.065.

CARACOL, Pedro Miguel De Oliveira - Avaliação da viabilidade dos combustíveis derivados de resíduos Caso de estudo da indústria cimenteira. 2016).

CARVALHO, A. C. *et al.* - Fire weather risk assessment under climate change using a dynamical downscaling approach. **Environmental Modelling and Software**. . ISSN 13648152. 26:9 (2011) 1123–1133. doi: 10.1016/j.envsoft.2011.03.012.

CCME - Protocol for the Derivation of Canadian Sediment Quality Guidelines for the Protection of Aquatic Life. **Canadian Council of Ministers of the Environment**. 1999) 35.

CHAKRABORTY, Monojit *et al.* - Methane emission estimation from landfills in Delhi: A comparative assessment of different methodologies. **Atmospheric Environment**. . ISSN 13522310. 45:39 (2011) 7135–7142. doi: 10.1016/j.atmosenv.2011.09.015.

CHAPMAN, P. M.; WANG, F. - Assessing sediment contamination in estuaries. **Environmental Toxicology and Chemistry**. . ISSN 07307268. 20:1 (2001) 3–22. doi: 10.1002/etc.5620200102.

CHAVAN, Digambar *et al.* - Determination of ignition temperature of municipal solid waste for understanding surface and sub-surface landfill fire. **Waste Management**. . ISSN 18792456. 97:2019) 123–130. doi: 10.1016/j.wasman.2019.08.002.

CHRISTENSEN, Thomas H. *et al.* - Biogeochemistry of landfill leachate plumes. **Applied Geochemistry**. . ISSN 08832927. 16:7–8 (2001) 659–718. doi: 10.1016/S0883-2927(00)00082-2.

CHRYSIKOU, Loukia *et al.* - Distribution of persistent organic pollutants, polycyclic aromatic hydrocarbons and trace elements in soil and vegetation following a large scale landfill fire in northern Greece. **Environment International**. . ISSN 18736750. 34:2 (2008) 210–225. doi: 10.1016/j.envint.2007.08.007.

COGUT - OPEN BURNING OF WASTE: A GLOBAL HEALTH DISASTER. **R20 Regions of climate action**. October (2016).

COMISSION OF THE EUROPEAN COMMUNITIES - Proposal for a Council Directive on the landfill of waste. 1997).

COUNCIL DIRECTIVE - Council Directive 1999/31/EC on the landfill. **Official Journal of the European Communities**. . ISSN 0144-557X. 10 (1999) L182/1-19. doi: 10.1039/ap9842100196.

CUNDY, Andrew B.; CROUDACE, Ian W. - Physical and chemical associations of radionuclides and trace metals in estuarine sediments: an example from Poole Harbour, Southern England. **Journal of Environmental Radioactivity**. . ISSN 0265931X. 29:3 (1995) 191–211. doi: 10.1016/0265-931X(95)00031-5.

DEPARTMENT OF CONSERVATION - **End in sight for Fox riverbed cleanup** [Em linha], atual. 2019. [Consult. 28 abr. 2020]. Disponível em WWW:<URL:https://www.doc.govt.nz/news/media-releases/2019/end-in-sight-for-fox-riverbed-clean-up/>.

DEVELOPMENT ASIA - **Improving Waste Management: Solutions from Five Asian Cities** [Em linha], atual. 2017. [Consult. 11 abr. 2020]. Disponível em WWW:<URL:https://development.asia/summary/improving-waste-management-solutions-five-asian-cities>.

DIXON, Neil; JONES, D. Russell V. - Engineering properties of municipal solid waste. **Geotextiles and Geomembranes**. . ISSN 02661144. 23:3 (2005) 205–233. doi: 10.1016/j.geotexmem.2004.11.002.

DN - **Incêndios: Recuperação do aterro sanitário do Planalto Beirão custa 4,1 M** [Em linha], atual. 2017. [Consult. 28 abr. 2020]. Disponível em WWW:<URL:https://www.dn.pt/lusa/incendios-recuperacao-do-aterro-sanitario-do-planalto-beirao-custa-41-me----governo-8903745.html>.

DRAP CENTRO - **CARTA DE SOLOS DA REGIÃO DE AVEIRO** [Em linha], atual. 2009. [Consult. 7 mai. 2020]. Disponível em WWW:<URL:http://www.drapc.min-agricultura.pt/base/documentos/carta_solos_aveiro.htm>.

DTSC - Soil Remedial Goals for Dioxins and Dioxin-like Compounds for Consideration at California Hazardous Waste Sites. 2 (2017).

EFFIS - Field Assessment of Forest Fire Severity. [s.d.]).

EGGLETON, Jacqueline; THOMAS, Kevin V. - A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. **Environment International**. . ISSN 18736750. 30:7 (2004) 973–980. doi: 10.1016/j.envint.2004.03.001.

EMELIE, C. I. N. - ILLEGAL WASTE MANAGEMENT AND OTHER CHALLENGES FACE IN THE ENFORCEMENT OF ENVIRONMENTAL LAWS IN NIGERIA. 12:1 (2019) 1–15.

ERSUC - Recuperação Ambiental e Selagem da Lixeira de Albergaria-a-Velha. 1998).

FAJKOVIC, Hana *et al.* - Unsanitary Landfill Fires as a Source of a PCDD/Fs Contamination. **Croatica Chemica Acta**. . ISSN 1334417X. 91:1 (2018) 71–79. doi: 10.5562/cca3145.

FELLNER, Johann; RECHBERGER, Helmut - Abundance of 14C in biomass fractions of wastes and solid recovered fuels. **Waste Management**. . ISSN 0956053X. 29:5 (2009)

1495–1503. doi: 10.1016/j.wasman.2008.11.023.

FENG, Shi Jin *et al.* - Failure of an unfilled landfill cell due to an adjacent steep slope and a high groundwater level: A case study. **Engineering Geology**. . ISSN 00137952. 262:April (2019). doi: 10.1016/j.enggeo.2019.105320.

FERRONATO, Navarro; TORRETTA, Vincenzo - Waste mismanagement in developing countries: A review of global issues. **International Journal of Environmental Research and Public Health**. . ISSN 16604601. 16:6 (2019). doi: 10.3390/ijerph16061060.

FIEDLER, Heidelore - Dioxins and Furans (PCDD/PCDF). Em **The Handbook of Environmental Chemistry Vol. 3, Part O Persistent Organic Pollutants**. [S.l.] : Springer-Verlag Berlin Heidelberg, 2003v. 3. p. 123–201.

GALICIA, Francisco Gutiérrez; PÁEZ, Ana Lilia Coria; PADILLA, Ricardo Tejeida - A study and factor identification of municipal solid waste management in Mexico City. **Sustainability (Switzerland)**. . ISSN 20711050. 11:22 (2019). doi: 10.3390/su11226305.

GEOSCIENCE AUSTRALIA - **Coastal Erosion | Autralian Government Geoscience Australia** [Em linha], atual. 2019. a. [Consult. 26 abr. 2020]. Disponível em WWW:<URL:https://www.ga.gov.au/scientific-topics/community-safety/coastalerosion>.

GEOSCIENCE AUSTRALIA - **Flood | Autralian Government Geoscience Australia** [Em linha], atual. 2019. b. [Consult. 26 abr. 2020]. Disponível em WWW:<URL:https://www.ga.gov.au/scientific-topics/community-safety/flood>.

GEOTA - **A situação da gestão dos resíduos em Portugal** [Em linha], atual. 2015. [Consult. 29 abr. 2020]. Disponível em WWW:<URL:http://www.geota.pt/scid/geotaWebPage/defaultArticleViewOne.asp?categoryID=720&articleID=2454>.

GRAU, Javier *et al.* - Solid Waste Management in Latin America and the Caribbean. **Inter-American Development Bank**. 2015) 3.

HAYES, James; ROBESON, Scott - Spatial variability of landscape pattern change following a ponderosa pine wildfire in northeastern New Mexico, USA. **Physical Geography**. . ISSN 02723646. 30:5 (2009) 410–429. doi: 10.2747/0272-3646.30.5.410.

ICNF - 8º Relatório provisório de incêndios rurais. **Instituto da Conservação da Natureza e das Florestas**. 2019) 14.

IDOWU, Ibijoke Adeola *et al.* - An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences. **Waste Management**. . ISSN 18792456. 87:April (2019) 761–771. doi: 10.1016/j.wasman.2019.03.011.

IPCC - Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to. World Meteorological Organization, Geneva, Switzerland. . ISSN 1098-6596. 2018). doi: 10.1017/CBO9781107415324.004.

KAZA, Silpa *et al.* - What a Waste 2.0 - A Global Snapshot of Solid Waste Management to 2050. **World Bank Group**. . ISSN 13697021. 2018). doi: 10.1596/978-1-4648- 1329-0.

KJELDSEN, Peter *et al.* - Present and long-term composition of MSW landfill leachate: A review. **Critical Reviews in Environmental Science and Technology**. . ISSN 10643389. 32:4 (2002) 297–336. doi: 10.1080/10643380290813462.

KOMURAIAH, A.; KUMAR, N. Shyam; PRASAD, B. Durga - Chemical Composition of Natural Fibers and its Influence on their Mechanical Properties. **Mechanics of Composite Materials**. . ISSN 01915665. 50:3 (2014) 359–376. doi: 10.1007/s11029-014-9422-2.

LAING, G. DU *et al.* - Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. **Science of the Total Environment**. . ISSN 00489697. 407:13 (2009) 3972–3985. doi: 10.1016/j.scitotenv.2008.07.025.

LANER, David *et al.* - Environmental Relevance of Flooded MSW Landfills in Austria. 423:24 (2008) 1–10.

LANER, David; FELLNER, Johann; BRUNNER, Paul H. - Flooding of municipal solid waste landfills - An environmental hazard? **Science of the Total Environment**. . ISSN 00489697. 407:12 (2009) 3674–3680. doi: 10.1016/j.scitotenv.2009.03.006.

LARSEN, Anna W. *et al.* - Biogenic carbon in combustible waste: Waste composition, variability and measurement uncertainty. **Waste Management and Research**. . ISSN 0734242X. 31:10 SUPPL. (2013) 56–66. doi: 10.1177/0734242X13502387.

LENSSEN, John *et al.* - Control of Plant Species Richness and Zonation of Functional Groups along a Freshwater Flooding Gradient. **Oikos**. . ISSN 00301299. 86:3 (1999) 523. doi: 10.2307/3546656.

LICHTENTHALER, Harmut K. - The Stress Concept in Plants: An Introduction. . ISSN 1369-1481. 2006). doi: 10.1111/j.1467-856X.2004.00161.x.

MA, Y. *et al.* - Upcycling of waste paper and cardboard to textiles. **Green Chemistry**. . ISSN 14639270. 18:3 (2016) 858–866. doi: 10.1039/c5gc01679g.

MAOTDR - Plano Estratégico para os Resíduos Sólidos Urbanos (PERSU II). **Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional**. 2007) 1–196.

MARTENS, D. *et al.* - Chemical impact of uncontrolled solid waste combustion to the vicinity of the Kouroupitos Ravine, Crete, Greece. **Chemosphere**. . ISSN 00456535. 36:14 (1998) 2855–2866. doi: 10.1016/S0045-6535(97)10242-9.

MINH, Nguyen Hung *et al.* - Open dumping site in Asian developing countries: A potential source of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans. **Environmental Science and Technology**. . ISSN 0013936X. 37:8 (2003) 1493–1502. doi: 10.1021/es026078s.

MMO - High Level Review of Current UK Action Level Guidance. A report produced for the Marine Management Organisation. 2015).

MOHER, David *et al.* - Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. **PLoS Medicine**. . ISSN 15491277. 6:7 (2009). doi: 10.1371/journal.pmed.1000097.

MOQBEL, Shadi; REINHART, Debra; CHEN, Ruey Hung - Factors influencing spontaneous combustion of solid waste. **Waste Management**. . ISSN 0956053X. 30:8–9 (2010) 1600–1607. doi: 10.1016/j.wasman.2010.01.006.

MUNICÍPIO ALBERGARIA-A-VELHA - **Plano Municipal de Defesa da Floresta Contra Incêndios de Albergaria-a-Velha (2016-2020)**

MUNICÍPIO DE AVEIRO - Plano Diretor Municipal - Estudos de caracterização, Sistema

Ambiental. 2019).

MUNICÍPIO DE NELAS - Caracterização Física - Plano Diretor Municipal de Nelas. 2013) 1–42.

NADAL, Martí; SCHUHMACHER, Marta; DOMINGO, José L. - Levels of metals, PCBs, PCNs and PAHs in soils of a highly industrialized chemical/petrochemical area: Temporal trend. **Chemosphere**. . ISSN 00456535. 66:2 (2007) 267–276. doi: 10.1016/j.chemosphere.2006.05.020.

NATIONAL RESEARCH COUNCIL - **Mitigating Shore Erosion Along Sheltered Coasts** [Em linha]. Washington, DC : The National Academies Press, 2007 Disponível em WWW:<URL:https://www.nap.edu/catalog/11764/mitigating-shore-erosion-along-sheltered-coasts>. ISBN 978-0-309-10346-6.

NATIONAL RESEARCH COUNCIL - **Levees and the national flood insurance program: Improving policies and practices**. [S.l.] : Washington, DC: The National Academies Press, 2013. ISBN 030928290X.

NAVEEM, B. P.; SITHARAM, T. G.; SIVAPULLAIAH, P. V. - Seismic analysis of municipal solid waste landfill in India. **International Journal of Geotechnical Earthquake Engineering**. . ISSN 19478496. 6:2 (2015) 35–55. doi: 10.4018/IJGEE.2015070103.

NEUHOLD - Identifying flood-prone landfills at different spatial scales. **Natural Hazards**. . ISSN 0921030X. 68:3 (2013) 1425–1440. doi: 10.1007/s11069-013-0562-9.

NEUHOLD, C.; NACHTNEBEL, H. P. - Assessing flood risk associated with waste disposals: Methodology, application and uncertainties. **Natural Hazards**. . ISSN 0921030X. 56:1 (2011) 359–370. doi: 10.1007/s11069-010-9575-9.

NGOLE-JEME, Veronica M. - Fire-induced changes in soil and implications on soil sorption capacity and remediation methods. **Applied Sciences (Switzerland)**. . ISSN 20763417. 9:17 (2019). doi: 10.3390/app9173447.

NJUE *et al.* - Assessing the impact of historical coastal landfill sites on sensitive ecosystems: A case study from Dorset, Southern England. **Estuarine, Coastal and Shelf Science**. . ISSN 02727714. 114:2012) 166–174. doi: 10.1016/j.ecss.2012.08.022.

NJUE, Cyprian Njeru - Metal Migration from Coastal and Estuarine Landfills: An Integrated Geological Study from Southern England. PhD Thesis:2010) 273.

NOAA NATIONAL SEVERE STORMS LABORATORY - **Severe Weather 101 - Flood Basics** [Em linha] [Consult. 31 mar. 2020]. Disponível em WWW:<URL:https://www.nssl.noaa.gov/education/svrwx101/floods/>.

O'SHEA; CUNDY, Andrew B.; SPENCER, Kate L. - The contaminant legacy from historic coastal landfills and their potential as sources of diffuse pollution. **Marine Pollution Bulletin**. . ISSN 18793363. 128:May 2017 (2018) 446–455. doi: 10.1016/j.marpolbul.2017.12.047.

O'SHEA, Francis - **Assessment of diffuse pollution originating from estuarine historical landfills** [Em linha]. [S.l.] : School of Geography,Queen Mary, University of London, 2016 Disponível em WWW:<URL:https://qmro.qmul.ac.uk/xmlui/handle/123456789/12995>.

PARENTE, J. *et al.* - Heat waves in Portugal: Current regime, changes in future climate and impacts on extreme wildfires. **Science of the Total Environment**. . ISSN 18791026. 631–632:2018) 534–549. doi: 10.1016/j.scitotenv.2018.03.044.

PATEL, Rajen M. - Polyethylene. **Multilayer Flexible Packaging: Second Edition**. 2016) 17–34. doi: 10.1016/B978-0-323-37100-1.00002-8.

PEDRO-CEDILLO, Liliana San *et al.* - Removal of BPA from landfill leachates using fenton-adsorption process. **Quimica Nova**. . ISSN 16787064. 42:4 (2019) 418–424. doi: 10.21577/0100-4042.20170354.

PETTERSEN, Roger C. - The Chemical Composition of Wood. **Nature**. . ISSN 00280836. 116:2921 (1984) 610–613. doi: 10.1038/116610a0.

PIPATTI, Riitta; SHARMA, Chhemendra; YAMADA, Masato - Chapter 2: Waste generation and compositon. **IPCC Guidelines for National Greenhouse Gas Inventories**. 5:2 (2006) 23.

POPE *et al.* - Influence of a collapsed coastal landfill on metal levels in sediments and biota - A portent for the future? **Journal of Environmental Monitoring**. . ISSN 14640325. 13:7 (2011) 1961–1974. doi: 10.1039/c0em00741b.

RAMAKRISHNAN, Anushuya *et al.* - Emerging contaminants in landfill leachate and their sustainable management. **Environmental Earth Sciences**. . ISSN 18666299. 73:3 (2015) 1357–1368. doi: 10.1007/s12665-014-3489-x.

RNZ.CO.NZ - **«We need to make plans»: Auckland landfills at risk from sea level rise** [Em linha], atual. 2019. [Consult. 15 mai. 2020]. Disponível em WWW:<URL:https://www.rnz.co.nz/news/national/386757/we-need-to-make-plans-auckland-landfills-at-risk-from-sea-level-rise>.

ROSA, Christopher T. DE *et al.* - Dioxin and dioxin-like compounds in soil, Part II: Technical support document for ATSDR policy guideline. **Toxicology and Industrial Health**. . ISSN 07482337. 15:6 (1999) 558–576. doi: 10.1177/074823379901500604.

RUOKOJÄRVI, P.; ETTALA, M.; *et al.* - Polychlorinated dibenzo-p-dioxins and -furans (PCDDs AND PCDFs) in municipal waste landfill fires. **Chemosphere**. . ISSN 00456535. 30:9 (1995) 1697–1708. doi: 10.1016/0045-6535(95)00055-D.

RUOKOJÄRVI, P.; RUUSKANEN, J.; *et al.* - Formation of polyaromatic hydrocarbons and polychlorinated organic compounds in municipal waste landfill fires. **Chemosphere**. . ISSN 00456535. 31:8 (1995) 3899–3908. doi: 10.1016/0045-6535(95)00264-9.

SAMARA, Constantini - Chemical mass balance source apportionment of TSP in a lignite-burning area of Western Macedonia, Greece. **Atmospheric Environment**. . ISSN 13522310. 39:34 (2005) 6430–6443. doi: 10.1016/j.atmosenv.2005.07.027.

SILVA *et al.* - **Resíduos Urbanos – Relatório Anual, 2011**

SIMPSON, Stuart L.; APTE, Simon C.; BATLEY, Graeme E. - Effect of short-term resuspension events on trace metal speciation in polluted anoxic sediments. **Environmental Science and Technology**. . ISSN 0013936X. 32:5 (1998) 620–625. doi: 10.1021/es970568g.

SPEELMANS, M. *et al.* - Influence of flooding, salinity and inundation time on the bioavailability of metals in wetlands. **Science of the Total Environment**. . ISSN 00489697. 380:1–3 (2007) 144–153. doi: 10.1016/j.scitotenv.2006.07.041.

SPENCER, Kate L. - Spatial variability of metals in the inter-tidal sediments of the Medway Estuary, Kent, UK. **Marine Pollution Bulletin**. . ISSN 0025326X. 44:9 (2002) 933–944. doi: 10.1016/S0025-326X(02)00129-7.

STAFFORDSHIRE ECOLOGICAL RECORD - **SACs, SPAs & RAMSAR Sites - Staffordshire Ecological Record** [Em linha], atual. 2015. [Consult. 21 abr. 2020]. Disponível em WWW:<URL:http://www.staffs-ecology.org.uk/html2015/index.php?title=Special_Areas_of_Conservation,_Special_Protection_Areas_%26_RAMSAR_Sites>.

STUFF.CO.NZ - **Erosion continues to expose West Coast landfill** [Em linha], atual. 2019. [Consult. 15 mai. 2020]. Disponível em WWW:<URL:https://www.stuff.co.nz/environment/114750318/erosion-continues-to-expose-west-coast-landfill>.

SU, Yinglong *et al.* - Occurrence of microplastics in landfill systems and their fate with landfill age. **Water Research**. . ISSN 18792448. 164:2019). doi: 10.1016/j.watres.2019.114968.

US-EPA - **Municipal Solid Waste Landfill Criteria - Technical Manual: Chapter 6, Subpart F - Closure and Post-Closure**

VASSILIADOU, Irene *et al.* - Dioxin contamination after an accidental fire in the municipal landfill of Tagarades, Thessaloniki, Greece. **Chemosphere**. . ISSN 00456535. 74:7 (2009) 879–884. doi: 10.1016/j.chemosphere.2008.11.016.

VOSNIAKOS, F. K. *et al.* - Emission of dioxins and related compounds from the burning of solid waste in the landfill of tagarades, thessaloniki (greece) - Control of dairy products and olive oil. **Journal of Environmental Protection and Ecology**. . ISSN 13115065. 12:3 A (2011) 1255–1261.

VROM - **Circular on target values and intervention values for soil remediation**

WANIA, Frank; MACKAY, Donald - Tracking the Distribution of Persistent Organic Pollutants. **Environmental Science & Technology**. . ISSN 0013-936X. 30:9 (1996) 390A-396A. doi: 10.1021/es962399q.

WASTE 360 - **Calabasas Landfill on Rebound After California Wildfires** [Em linha], atual. 2018. [Consult. 28 abr. 2020]. Disponível em WWW:<URL:https://www.waste360.com/landfill-operations/calabasas-landfill-rebound-after-california-wildfires>.

WEBER, Roland *et al.* - Persistent organic pollutants and landfills - A review of past experiences and future challenges. **Waste Management and Research**. . ISSN 0734242X. 29:1 (2011) 107–121. doi: 10.1177/0734242X10390730.

WICHMANN, H. *et al.* - Assessment of the environmental impact of landfill sites with open combustion located in arid regions by combined chemical and ecotoxicological studies. **Chemosphere**. . ISSN 00456535. 65:10 (2006) 1778–1783. doi: 10.1016/j.chemosphere.2006.04.058.

XU, Jiuping *et al.* - Natural disasters and social conflict: A systematic literature review. **International Journal of Disaster Risk Reduction**. . ISSN 22124209. 17:2016) 38–48. doi: 10.1016/j.ijdrr.2016.04.001.

YAO, Xinying *et al.* - Distribution and contamination assessment of heavy metals in soils from tidal flat, oil exploitation zone and restored wetland in the Yellow River Estuary. **Wetlands**. . ISSN 19436246. 36:February (2015) 153–165. doi: 10.1007/s13157-015-0637-3.

ZERO WASTE EUROPE - The impact of Waste-to-Energy incineration on climate Policy

Briefing. September (2019).