Estimation of the Aftercare Period of Danish Landfills

An Interactive Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science

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Abstract

The purpose for the aftercare period, the time period a landfill undergoes after it can no longer accept waste, is to monitor the landfill for any potential problems. Danish landfills are unique because they are left uncapped which allows water to flow through the landfill. This accelerates the dilution of chemicals in leachate and thus the emissions potential of the landfill is reduced. Danish legislation requires that the aftercare period be 30 years, or however long it takes for the surrounding groundwater to fall below set substance concentration limits. This legislation is based on the concept that each generation should deal with their own problems. Our goal was to investigate current aftercare period practices, evaluate the amount of time needed for the aftercare period, and make recommendations to better address the problems associated with the aftercare period. While landfilling is relatively simple in concept, the chemistry of a landfill is a highly complex and dynamic process. A thorough understanding of landfill chemistry is necessary to model landfill behavior and determine an appropriate length for the aftercare period. Although this project does not define an appropriate length for this period, it does address several issues surrounding the length and demonstrates preliminary analysis.

1 Introduction

Denmark has a reputation as one of the most environmentally progressive countries whose philosophies and ideals can be observed today in its waste management practices. Specifically, waste management in Denmark primarily consists of recycling, incineration and landfilling. Denmark has reduced the total amount of landfilling to roughly 7% of all waste generated- a value that is significantly lower than all other EU countries, and Denmark continues to make progress in reducing the amount of waste that is landfilled [1].

The aftercare period is the phase of a landfill's life after all waste is added and closure is established. As rainwater flows through the waste, it picks up a variety to chemical compounds, creating what is known as percolate or leachate. Monitoring of the landfill percolate in addition to groundwater quality is mandated for 30 years after each landfill cell is closed, or until the levels of chemicals in the percolate have fallen to acceptable levels[1]. This time period was arbitrarily chose because 30 years is an accepted length of one generation, and the EU decided that each generation should have to deal with their waste problems. Many different aspects of the landfilling process affect the length of the aftercare period, such as waste composition, landfill structure, quantity and quality of percolate and gas. Danish landfills are classified by waste type, which often plays a large role in what type of substances and their concentrations are observed in percolate. Because landfills leach a wide variety of potentially harmful chemical compounds in the form of both dissolved solids and gases, the principal environmental concern of landfilling is groundwater contamination, which has a direct negative impact on the environment, particularly to communities whose wells draw directly from groundwater sources in the area. The aftercare period is the focus of this project, as a more appropriate aftercare period length is needed to address the post-closure environmental concerns created by landfills [2].

The Technical Adaption Committee (TAC) appointed by the EU council, has created standards for acceptable criteria for waste, which if met can be landfilled. If not the waste has to undergo further treatment before landfilling in order to meet the criteria. Current Danish legislation is stricter and has standards with respect to acceptable chemical concentrations in the groundwater. In addition, the Danish government has established a set of "acceptable criteria" for waste entering landfills to determine whether or not waste is suitable for landfilling. Unfortunately, the legislation does not seem to reflect the reality of the necessary length for the aftercare period. A less arbitrary aftercare length and a more scientifically based set of standards are needed to reduce the potential for negative environmental impact. Fortunately, research has been conducted on multiple factors that influence rates of decay of the chemicals in landfill percolate. For example, research suggests that leaving a landfill uncapped allows the landfill to expel emissions over a shorter period of time and become less toxic in the long run as opposed to remaining

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"for as long as the competent authority considers that a landfill is likely to cause a hazard to the environment an without prejudice to any Community or national legislation as regards liability of the waste holder, the operator of the site shall be responsible for monitoring and analyzing landfill gas and leachate from the site and the groundwater regime in the vicinity of the site in accordance with Annex III."

– Article 13 of Council Directive 1999/31/EC hazardous for hundreds of years. Denmark's landfills are unique in that an impermeable cap is not installed upon closure [3]. Instead, a thin soil layer is used which allows rainfall to percolate through the landfill. Research has also shown that running water or percolate through the landfill increases the rate of decay of the chemical components in the leachate. It is thought that, as a result, the environmental risk for groundwater contamination is reduced in the long term. Techniques to aerate the landfill and increase air flow through the waste body have had similar results [4]. Methods to pre-treat waste or immobilize components that would otherwise end up in percolate also exist.

While research exists with respect to reducing the "emission potentials" of landfills, there has been minimal effort to use this research in the context of the legislation in Denmark. A thorough analysis and interpretation of all factors that affect the aftercare period length has not been made. Some evidence suggests the aftercare period may need to be extended to centuries, and a definite standard has not been set to determine an appropriate aftercare period based on scientific evidence [5]. More investigation needs to be conducted encompassing all possible resources to create a complete picture and recommendation for the aftercare period.

The goal of this project was to perform an evaluation of the aftercare practices in Danish landfills and to determine the best criteria and length for aftercare. We compared compare current aftercare techniques, defined what factors influence the aftercare period, and analyzed and interpreted our findings to develop an educated estimate. By considering all available scientific data, finding data correlations, evaluating legislation and developing a better understanding of the landfill's behavior during aftercare, one can make an informed recommendation about the aftercare period. RenoSam, the sponsor of this project, serves as a consultant for its 43 municipal waste management members. Members with landfills have a vested interest in the length of the aftercare period not only because they care about the environment, but also because remediation actions to mitigate landfill contamination are expensive.

In Denmark, there is a general understanding that completely isolating the landfill body from the rest of the environment does not solve the problem of contamination potential, it simply delays the inevitable. By taking an active stance and engaging the body of the landfill in the aftercare process, the landfill can be converted to a state that is safer in the long run, taking the burden of environmentally unsafe landfills off of future generations [6].

2 Background

2.1 Introduction

Our world is characterized by mass production, industrialization, and consumerism on a scale that in constantly increasing. With a rise in first world standards and population come bigger economy, production and consumption, all amplified by increases in global population. As a result, there is a natural increase in waste generation. As a byproduct of consumption, waste must be properly managed, and effective, sustainable methods of managing waste that won't present an immediate danger to future generations are essential. Global annual waste production is on a scale so large that exact figures are not known, with an estimated 1 billion tons of waste produced in Europe alone in 2008[7].

This background provides a general overview of the waste management process, focusing on landfilling. Emphasis is placed on the methods of implementation in Denmark. A description of the structure, operation and management of landfills and their different stages of development frames how the aftercare problem fits into the overall picture. Finally, aftercare and its impacts on the Danish environment are discussed. These topics will provide a foundation for further research and investigation described in the Results and Recommendations sections.

Stakeholders in the aftercare period of Danish landfills are those who are directly tied to and impacted by the practice of aftercare. RenoSam and its' Municipal partners are the most direct stakeholders as they play a strong role in determining the exact actions taken before and during this period. The Danish government and the Danish Environmental Protection Agency (EPA) plays a large role in the governing of landfills and also has a vested interest in making sure environmentally friendly practices are used for the good of the people, future generations, and the environment. Municipalities whose drinking water comes from groundwater are stakeholders, and finally the environment is a stakeholder in a very important way, and taking proper care of it will ensure that land is clean and viable to live on for our successors.

2.2 RenoSam

RenoSam is the larger of two Danish organizations dedicated solely to consulting and advocating for Danish waste management companies. René Møller Rosendal, a consultant from RenoSam described his organization in the following way:

> "RenoSam is an organization of members (waste companies and municipalities that have waste facilities) that work to protect our member's interests relating to optimization, development, and operation of tasks associated with recycling of waste, incineration of waste, landfill of waste, and treatment of hazardous waste.
>
> Our goal is to affect the national regulations and to influence and recommend to Danish politicians the best practices in the waste management area. The 7 board members (managing Committee) of RenoSam are politicians elected by Danish citizens onto the boards of different waste management companies. RenoSam collaborates with the Danish EPA, consultants, research institutions, and others to make new waste policy."

RenoSam's members are all from the public sector (municipalities). A director, four consultants, and a secretary run RenoSam on a daily basis; this group of employees is called "RenoSam Secretariat" in Figure 1. There is a 7-memberboard, or the "Management Committee" as described by René Møller Rosendal above.

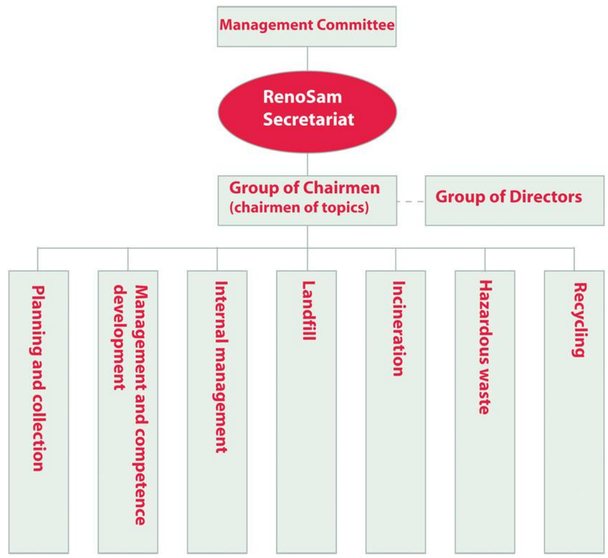


Figure 1 : Organizational Structure of RenoSam

2.3 Waste Management

Waste management is a vital part of any functional society, a system designed to discard byproducts and unneeded materials of individuals, companies, and industry. The concept of waste management is perhaps as old as civilization itself, and today can be seen in action in every modern society. Even today, some countries lack basic waste management facilities and live in conditions where health and daily life are affected by waste. First world societies are still experimenting not only with newer and more environmentally friendly waste management techniques, but also the challenge of encouraging individuals and groups to participate in the best waste reduction and recycling solutions [4].

Waste comes from homes, offices, commercial operations, industry, construction, and a variety of other sources. Waste management is the practice of actively collecting, handling, and treating generated waste using a variety of techniques such as recycling, incineration and landfilling. In order to function properly, a good waste management system must have appropriate transportation and collection infrastructure. Waste must be stored in appropriate collection systems, and then transported to locations for processing and sorting, with many such techniques designed to extract energy or transform waste to a more useful state. Some waste streams, such as Municipal Solid Waste (MSW) and Recyclables may need to be sorted. Recycling is an example of a waste stream with specific sorting designations such as glass plastic, metal, and others. Biodegradable materials, food wastes and farming byproducts can be composted and re-used as fertilizer. Municipal wastes can be incinerated to produce energy in the form of heat and electricity generation. Unusual waste streams may be shredded or crushed and landfilled or used in construction. Finally, special wastes such as batteries, electronic waste and tires have specific techniques to extract valuable or toxic materials and are subsequently recycled or disposed of. There are also specific guidelines for handling and processing medical waste which is either incinerated or processed in a manner that kills all pathogens and tissues before landfilling. Many of these specialty wastes require appropriate treatment by law [4].

In general, legislation for waste management in developed countries mandates that practices be safe and environmentally sound. There are global efforts to make recycling more readily accessible, however recycling will not completely replace disposal in the foreseeable future, thus the practice of landfilling and its associated environmental cost are still necessary.

2.4 Integrated Waste Management

Although there is no simple answer to the waste problem, technology and innovation have led to more efficient systems and waste management models, such as Integrated Waste Management (IWM). IWM techniques look at the entire waste stream and focuses on minimizing the impact of waste and maximizing the use of eco-friendly techniques such as recycling and composting. Incineration is an IWM component that is increasingly popular among developed countries because the heat output can be harvested and used for heating buildings and producing electricity [8]. Although landfilling is not the most desirable IWM component and has the potential for significant negative environmental impacts, it is still prevalent because certain waste cannot be processed by recycling, incineration, or other techniques.

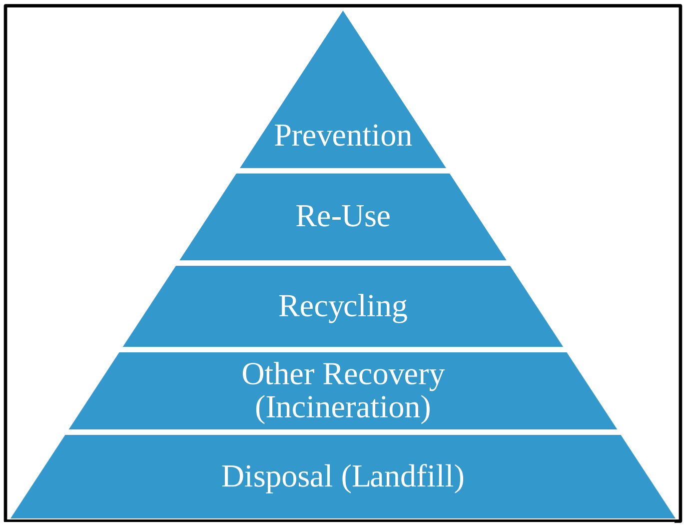


Figure 2: Waste hierarchy of IMW

IWM classifies waste by the method of treatment. The waste is separated and treated with the method of choice, regardless of the waste's origin. There is an order of preference with respect to waste management techniques that should be followed; Figure 2 shows the hierarchy of waste management techniques.

IWM places heavy emphasis on waste prevention, "minimization of waste at its source to minimize the quantity required to be treated and disposed of, achieved usually through better product design and/or process management"[9].When waste prevention practices are implemented on a large scale they can have a significant impact on the amount of waste generated, thus reduce the environmental impact of the waste stream. When waste prevention is not possible, communities are encouraged to practice recycling and composting of MSW. Incineration is used to convert MSW into energy and reduce required landfill volume. When MSW is burned into flue gas, air stack emissions from incineration plants are scrubbed and neutralized to mitigate harmful emissions.

While landfilling is an undesirable waste management technique due to the permanent nature and environmental hazards created by landfilled bodies, it is a crucial endpoint in any well designed IWM [8]. Therefore, there is a need to regularly review and reconsider the best landfill practices. Scientific advances in the understanding of landfill processes can reduce environmental impact, but only if current legislation adequately reflects the latest knowledge.

While not discussed in depth, some alternative IWM practices are presented here to give a scope of waste management around the world. Co-incineration is a thermal treatment technique which completely combusts two organic streams of high calorie content as a fuel alternative to generate heat, power, or combination of the two. Pyrolysis is another thermal treatment which anaerobically and thermally degrades organic matter to useful chemicals [10]. In some countries, leading-edge processes are being researched and implemented on a smaller experimental scale. One example is Plasma Arc Waste Disposal which utilizes an electric arc gasifier to break down waste to elemental gases and sludge. Another such process is Mechanical Biological Treatment (MBT) which can treat both household and industrial waste by a combination of waste sorting, anaerobic digestion and composting. MBT is now attracting attention as a promising alternative to landfilling in some countries [11]. Denmark chooses to use incineration and co-incineration to produce energy locally and reduce the need for waste transportation.

2.5 Waste Management in Denmark

Denmark produced 15.6 million metric tons of waste in 2008, a figure that is increasing today [12]. Denmark takes a very active stance in reducing impacts on the environment and pays special attention to solid waste management techniques in order to limit pollution from all activities [13]. Danish philosophy on waste management also recognizes the potential material and energy value of waste streams and aims to minimize health and environmental impacts of waste management.

Limited land and space in Denmark make landfilling a very unattractive solution to the waste disposal problem. Furthermore, Denmark uses groundwater extensively as a drinking water source, and prioritizes the prevention of groundwater contamination due to landfills. Figure 3 shows the waste management techniques used in European countries, by percent of waste produced [7]. According to this figure, Denmark utilizes landfilling the least compared to the rest of the European Union (EU), with a mere 7% of waste generated being landfilled in Denmark, compared to over 40% of waste generated in the European Union (EU) being landfilled[2].This is an even more impressive figure when compared to the 99% and 100% of waste that is landfilled in Romania and Bulgaria, respectively[14]. Denmark makes every effort to use recovery, recycling, and incineration, instead of the more environmentally damaging practice of landfilling. All waste has to be fully exploited for recyclable and combustible materials in Denmark as a result of Danish law passed in 1997. All waste that cannot be recycled must be incinerated to provide electricity and energy for district heating [15]. Most of the resulting residue or bottom ash from incineration is used in road construction. The remaining inorganic waste that cannot be incinerated is landfilled; this inorganic material produces significantly less methane gas than organic waste. The small amount of methane production from inorganic materials explains why only 8 of Denmark’s 45 landfills harvest methane gas for energy [1, 16, 17].

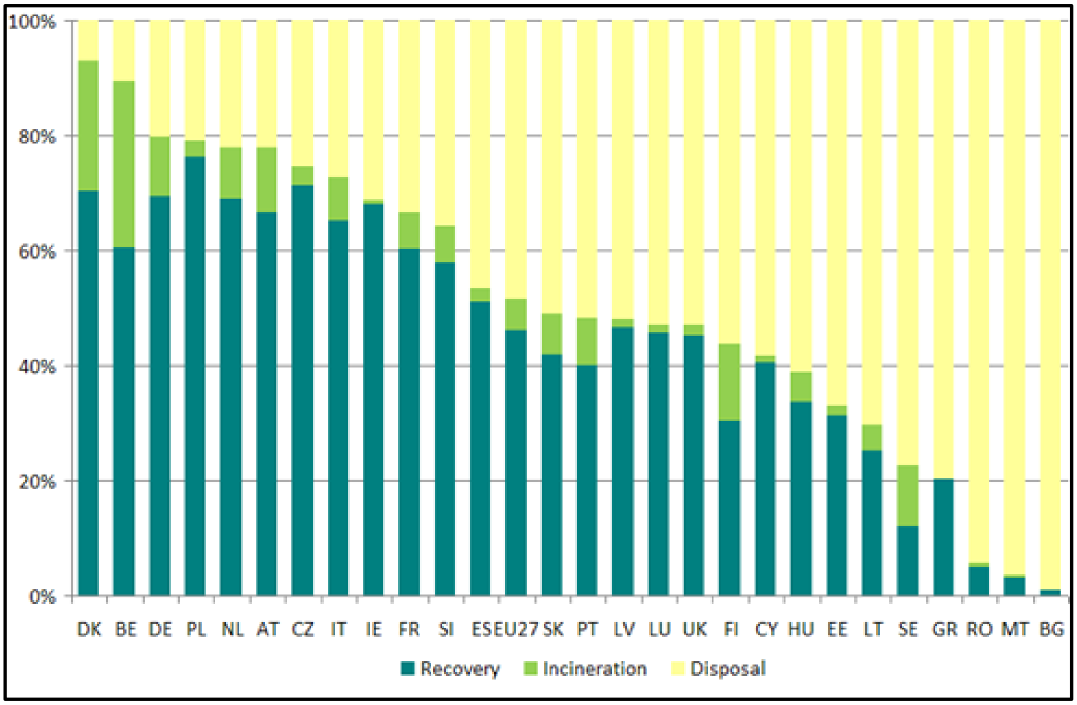


Figure 3: Waste management techniques for European countries, by percent.

Denmark takes the IWM concept to an unprecedented level compared to the rest of Europe. The Danish rate of recycling has increased steadily over time and represented 69% of total waste management in 2008 [12]. The Danish recycling rate is high relative to the EU's average of 21% [14]. In Denmark, only 7% of waste produced was landfilled in 2005, a 62% decrease from 1994[1].This shift in waste management techniques is demonstrated by Figure 4, which presents Denmark's distribution of waste management techniques, by volume, between 1994 and 2008.

The IMW concept used in Denmark, highlighted in Figure 2 is supported by Denmark's waste management taxing system. There are economic disincentives for disposing waste with incineration and landfilling in Denmark, and conversely, there are no taxes on recycling waste. Higher taxes are associated with landfilling, rather than incineration, because it is the least environmentally friendly waste management technique used in Denmark [16].

The responsibility of waste management in Denmark is placed on the waste producer, or polluter, a concept often referred to as "the polluter pays". All waste produced in Denmark must be managed by the municipality it is produced in, including commercial and industrial waste. This means each municipality (or inter-municipality cooperative entity) has its own recycling station, incinerator, and landfill. Not only does this give each municipality a sense of ownership and responsibility, but it also reduces the amount of energy and funding required for waste transportation. This location dispersed waste management method helps limit the odor, unattractive appearance and concentrated environmental impacts created by larger landfills that receive waste from a wide area [15].

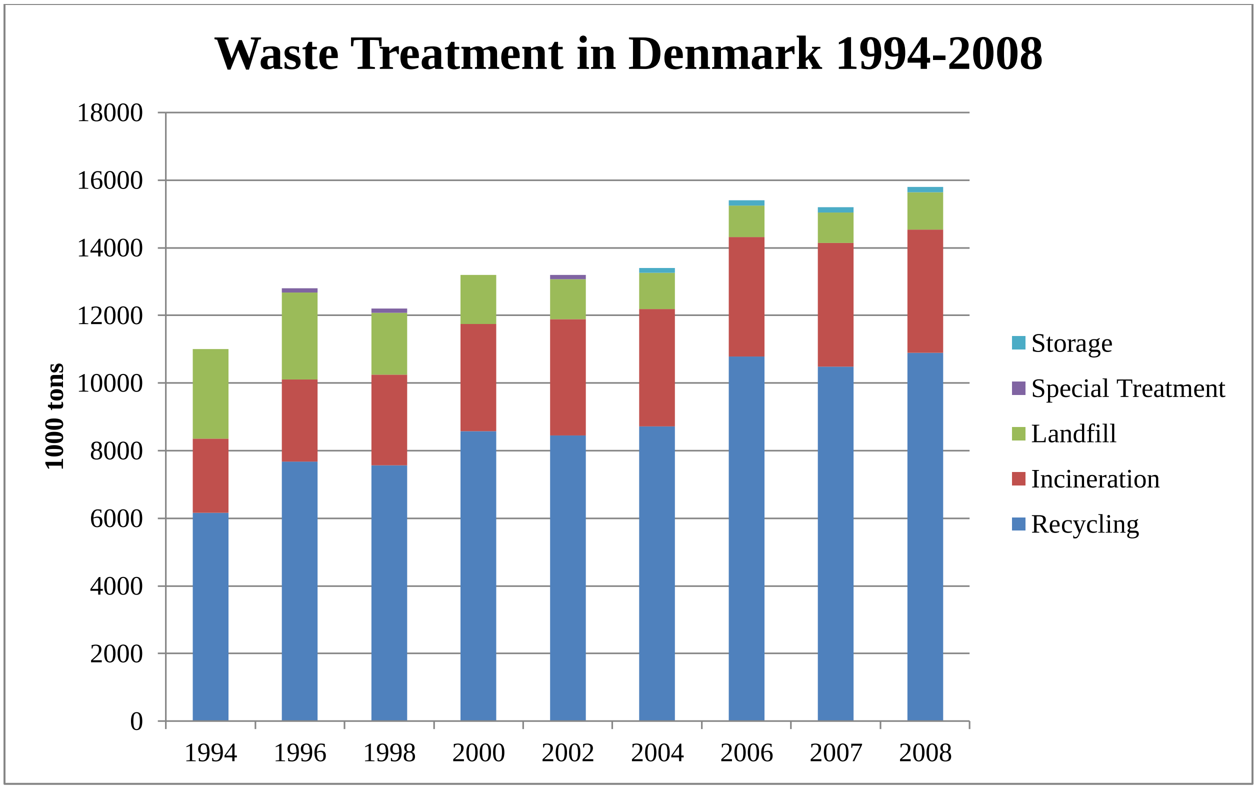


Figure 4: Denmark's waste management technique distribution between 1994 and 2008 [18]

2.6 Landfills in Denmark

There are 6 sources of waste landfilled in Denmark, as shown in Figure 5 It is important to know waste's type in order to treat it properly. Waste sources often correlate to waste types which are disposed of in specific landfills. For example, construction and building waste is usually landfilled in inert waste landfills and incineration byproducts are typically landfilled in mineral waste landfills. The classification of waste types will be discussed in greater detail in the following section.

2.6.1 Classification of Landfills

Danish regions and municipalities create different landfills based on waste materials and grades. This separation results in landfills with different infrastructures specifically tuned to the needs of each waste type in order to best address the possible environmental consequences.

Denmark's categorization of landfills is based on the European Landfill Directive (LFD) which defines three major types of landfills "based on the degree of hazardousness": landfills for hazardous, non-hazardous and inert waste. While each state reserves the right to sub-categorize their landfills, the LFD defines general guidelines to be followed, as shown in Table 1[19].

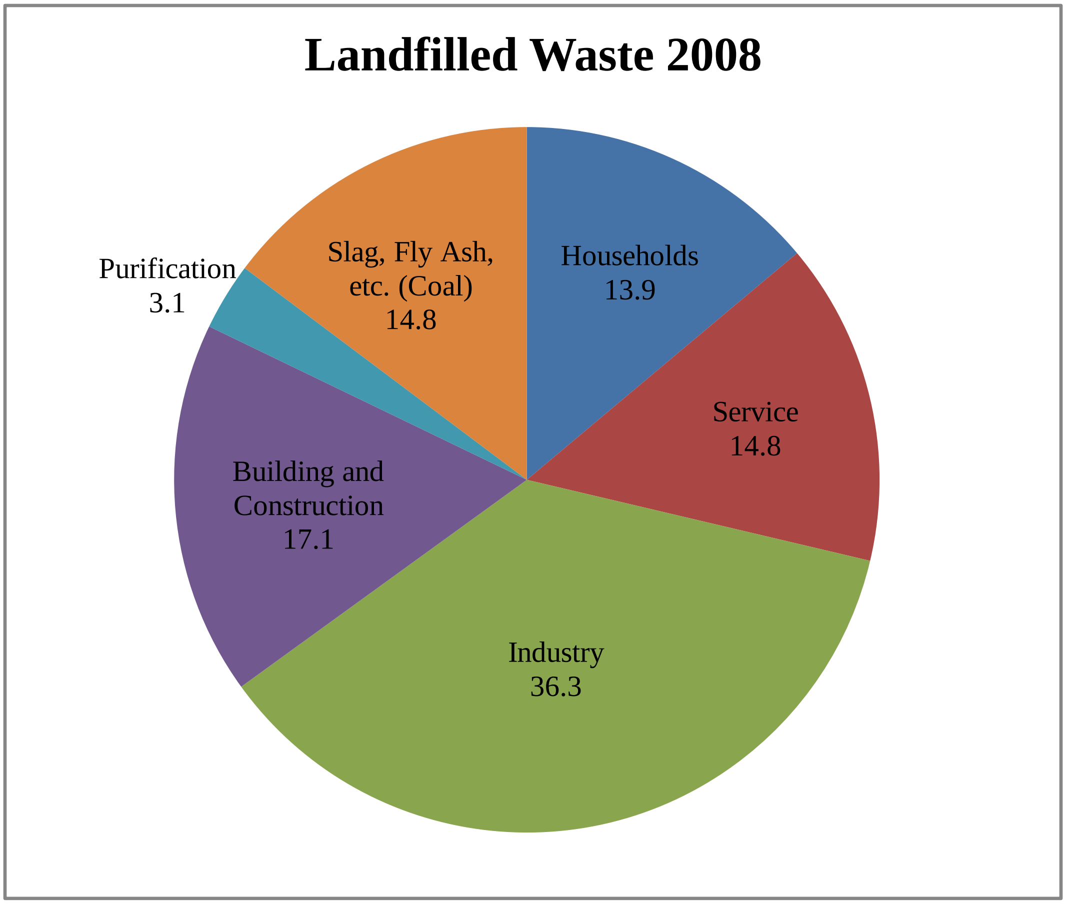


Figure 5: Landfilled Waste in Denmark 2008{{64 Danish Environmental Protection Agency 2008}}

Landfill Class	Major Sub-Category	ID
Landfill for inert waste	Landfill accepting inert waste	A
Landfill for nonhazardous waste	Landfill for inorganic nonhazardous waste with a low content of organic/biodegradable matter (inorganic non-hazardous wastes that may be landfilled together with stable, non-reactive hazardous waste)	B1a
	Landfill for inorganic nonhazardous waste with a low content of organic/biodegradable matter	B1b
	Landfill for organic nonhazardous waste	B2
	Landfill for mixed nonhazardous waste with substantial contents of both organic/biodegradable waste and inorganic waste	B3
Landfill for hazardous waste	Surface landfill for hazardous waste	C
	Underground storage site	D_{HAZ}

Table 1: European Landfill Directive Classifications {{23 Anonymous 1999}}

Denmark modifies these definitions slightly by using four waste categories instead of the LFD's three categories. Denmark divides non-hazardous waste into two subcategories: mixed Municipal Solid Waste (MSW) and mineral waste. A screening method must be used to distinguish waste types and determine if waste meets the criteria for its respective landfill classification, as shown in Figure 6.

The first step is determining if the waste is hazardous, as hazardous waste must be landfilled in a specially designed landfill. Non-hazardous waste is landfilled in a mineral waste, inert waste, or a municipal solid waste landfill.

Many precautions need to be taken to create a landfill with limited environmental consequences, with the highest priority being prevention of groundwater contamination. Proper design of environmental protection systems and desired waste-stabilization processes within the landfill are important to avoid contamination. The landfilling acceptance criteria for various types of waste is dependent on chemical concentrations and defined in Annex 2 of LFD (See Section 7.1- Appendix A)[19].

Some of the gaps in EU regulations are filled by a proposal by the Committee for the Adaptation to Scientific and Technical Progress of EC-Legislation on Waste (or Technical Adaptation Committee, TAC). The TAC creates sub-categories of Landfill Directive sections to help aid LFD in reaching its long-term goals. The TAC also sets leachate acceptance criteria for the leaching and compliance tests within the context of LFD; these tests will be discussed further in Section 2.6.3. These acceptance criteria are not normalized across the EU because the LFD does not prescribe design and operation of landfills. The acceptance criterion themselves are not normalized across landfill types; hazardous waste landfills have more lenient leachate acceptance criteria (See Table 9) than inert waste landfills (See Table 7).While this may seem counterintuitive, the design codes for hazardous waste landfills are significantly stricter than those for inert waste landfills[3].

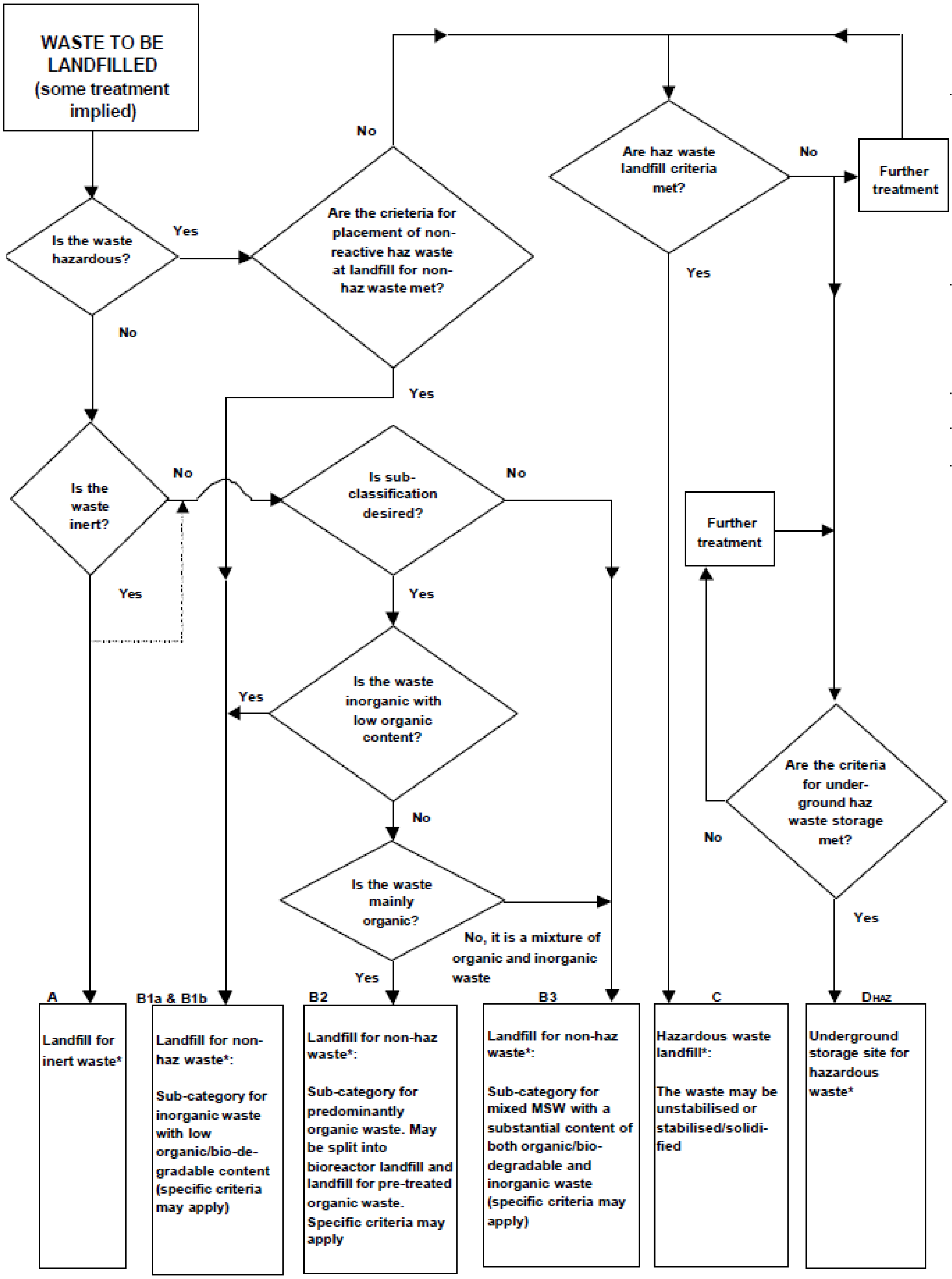


Figure 6: Waste Sorting Algorithm

2.6.2 Landfill Design

The goal of landfill design is to optimize waste disposal capacity while minimizing environmental impacts on the community. It is the responsibility of the design engineers to consider all potential environmental impacts, future use of the space after remediation, and economic feasibility.

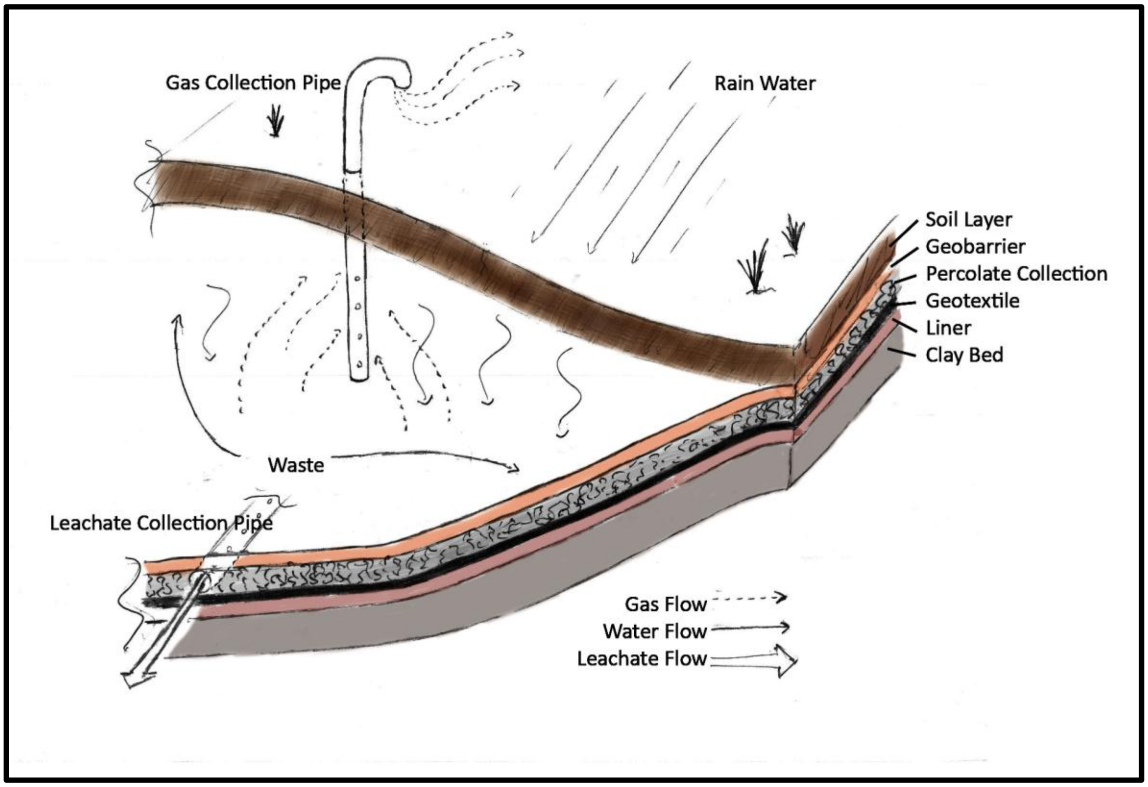


Figure 7: Landfill Structure in Denmark

Each landfills' unique characteristics, such as climate, clay, bedrock quality, and location relative to groundwater and ocean, must be considered during the design process. The landfills must adhere to best design practices as well as all legal requirements. Every landfill uses several methods to protect the surrounding environment: liner, leachate and gas collection, and groundwater testing. The design of the liner system is often considered the most critical aspect of sustainable landfilling because it is the primary protection for the environment.

The bottom liner has a projected lifespan of 80 years in Denmark; therefore it is beneficial to mitigate the potential impacts of contamination while the liner is still effective. Denmark's active approach of leaving landfills "uncapped" does just this and benefits the environment in the long run. Danish landfills allow rainwater to percolate through the waste and actively dilute the leachate, thus reducing future environmental impacts and avoiding environmental and economic catastrophe when the liner eventually breaks. When the bottom liner finally breaks, the natural degradation of the surrounding clay should protect the groundwater from contamination.

Figure 8: The bottom lining system of a new landfill cell can be seen off in the distance

Complex liner and barrier systems have many layers, each with a specific purpose. The bottom liner of a Danish landfill must include a geological barrier, leachate collection system (gravel and piping network), geotextile, impermeable polymer, and clay as shown in [20].

Each layer within the liner has a specific function to prevent seepage of percolate into groundwater. The geological barrier prevents contamination of the surrounding soil and surface water. There are strict requirements for permeability and film thickness of geological barriers, which vary by landfill type, as shown in Table 2. A thinner, less permeable liner is allowed for inert waste versus hazardous waste. These requirements for thickness are adjustable if a synthetic liner is used rather than a clay liner, but an equivalent amount of protection must be maintained- a minimum thickness of 0.5 meters of synthetic liner is required[20]. With artificial barriers, the stability of the underlying layer must be verified to prevent damage to the geological barrier.

Table 2: Requirements for the geological barrier permeability and thickness [20]

	Inert waste	Mineral Waste	Mixed waste	Hazardous waste
Permeability coefficient [m/s]	$K \le 1.0 \times 10^{-7}$	$K \le 1.0 \times 10^{-9}$	$K \le 1.0 \times 10^{-9}$	$K \le 1.0 \times 10^{-9}$
Film thickness, minimum [m] (In-situ clay)	2.0	2.0	2.0	5.0

The most commonly used geological barriers include: bedrock "with low permeability and without voids", natural clay, and artificial barriers [21]. With the development of new technologies in the past few decades, artificial barriers have improved significantly and are currently well accepted in the waste management industry, with high density polyethylene (HDPE) liners being the current industry standard. The negative side of HDPE liners is that they are susceptible to heat generated from the exothermic processes of waste, corrosion caused by leachate, and cracking in cold conditions [22].

A leachate collection system is necessary to properly remove leachate produced by the landfill. This drainage system includes a series of pipes and pumps to evacuate leachate collected by the pipe network and a layer of gravel which allows leachate to flow under the waste. The bottom of the landfill is graded so that leachate flows naturally to the pipes due to gravity.

Figure 9: Leachate Collection System Valves

Engineers must consider many factors to design an effective leachate collection system. The system must be able to handle anticipated amounts of leachate without accumulation at the bottom of the landfill over time. All components need to withstand the pressures and aggressive chemical nature of leachate. Piping and pumps should be capable of functioning properly even in a reduced capacity as the hydraulic conductivity of the system decreases over time. Leachate will inevitably deposit materials on the insides of piping systems which will build up over time and impede the flow of fluid [23]. Systems are typically installed to clean these pipes but this process is rather expensive.

Below the leachate collection system is the geotextile layer; its purpose is to prevent sharp-edged gravel from puncturing the impermeable polymer layer below due to high pressure. This pressure is created by the weight of the above waste and the compaction process. The geotextile also filters suspended solid particles in the percolate that can erode the polymer layer.

The impermeable polymer layer is considered the most important element of the seepage prevention defense line because of its leachate resistant nature. The layer is mainly synthetic bituminous polymers that carpet the landfill bed, with a strong seal between separately installed sections. The hydrophobic nature of these polymers prevents wetting and permeation by percolate.

Clay defines the bed of a landfill and it is used as a barrier between the rest of the liner and the surrounding soil and groundwater table. The clay should have an appropriate water content and be installed with proper compaction techniques in optimum weather conditions. If these factors are taken into consideration, many long term problems, such as reactions with any leaking percolate, can be avoided [22].The attenuation properties of this clay are very important to prevent groundwater contamination upon breakage of the liner.

2.6.3 Operation and Cell Construction

In Denmark there is a very specific protocol for sending waste to landfills. Both the waste producer and the landfill owner hold responsibilities in this process and must comply with Danish waste management regulations. The waste producer must create a fundamental characterization which is a document that outlines all information regarding specific waste, such as information regarding the waste's classification and special precautions necessary at the landfill. Table 3 shows all factors outlined in the fundamental characterization; this analysis is essential to determine if the waste should be accepted at a given landfill [20].

The fundamental characterization includes the results of the leaching test designed to identify any potentially environmentally harmful substances. The leaching test is used for the first year waste is deposited by a waste producer while the compliance test is used for each following consecutive year. The initial leaching test is a more in depth test than the subsequent annual compliance tests.

In Denmark, the LFD's non-hazardous category is further divided into "mineral waste" and "municipal solid waste" [17]. Municipal Solid Waste (MSW) is unique in that testing is not required for landfilling because of the high variability and high heterogeneity of its composition [24]. The other three categories of waste (inert, mineral, and hazardous) must be tested before being approved for landfilling. To test the waste, waste is sampled in a manner such that it is the best representation of the entire waste streams. The samples are placed in a testing column and water is run through it over a long period of time. The percolate values from this test sample are compared to acceptance criteria (See Section 7.1- Appendix A). The fundamental characterization test results are sent to the landfill where they are compared to the acceptance parameters set upon initial characterization results (determined on site by the landfill staff). The landfill staff then determines if the waste is appropriate for the specific site. The staff's decision is relayed back to the waste producer and the waste is dealt with accordingly. If the waste is not accepted by the landfill, pre-treatment may be required. The landfill must keep characterization information on file for a minimum of 10 years [20].

Upon arrival of waste at a landfill, the weight (in tons) is determined and a visual inspection may be performed by a trained professional. The purpose of this inspection is to ensure that the waste is sorted and does not contain combustible or recyclable material. If the waste passes inspection, a written receipt is sent to the waste producer. However, if the waste does not pass this inspection, the landfill must issue a written rejection notice with a reason for denial to the waste producer and home municipality of the waste [20].

Figure 10: A front end loader compacting trash in a cell

Once waste is approved for landfilling, it is compacted into cells which are the volume occupied by the compacted waste over a short period of time, typically every few days. Cells are arranged in rows and layers and are efficiently compacted by tractors and bulldozers to minimize the volume occupied by the waste (See Figure 10). They are then covered by soil (the daily cover) and further compacted. Waste is usually screened for bulky material like mattresses and upholstery to ensure maximum compaction. Unfortunately, firmly packed layers of waste can pose a significant obstacle for leachate flow, which can inhibit the decomposition process. Air space, the volume of space on an entire landfill site which is permitted for waste disposal, is one of the most important factors in defining the capacity and lifetime of a landfill.

2.6.4 Landfill Economics

There is strict legislation pertaining to the financial security of Danish landfill owners (as well as EU landfill owners). Owners must provide collateral to prevent abandonment of landfills, which would represent a serious environmental concern. This collateral must be in the form of either a "bank guarantee from a bank, surety insurance policy, or deposit of cash in an escrow account in a bank" to obtain approval for a new landfill [20]. These forms of insurance should be proportional to the potential costs of landfill operation and monitoring throughout its entire lifetime, including the aftercare period. The Danish Environmental Protection Agency (DEPA) prepared a spreadsheet that helps determine how much it costs to deposit waste, by tons of waste and dependent on waste type[25]. This needs to be adjusted every year according to the waste flow and available capacity.

Danish landfills are prohibited from making any profit, with the cost of landfill operation and monitoring during the active phase and aftercare period covered by waste producers. This cost is paid in the form of a landfill fee (per ton); a simple formula is used to determine this landfill fee:

Equation 1 : Landfill Fee Equation

$$\text{Cost} = \text{Government Waste Tax} + \text{Landfill Operation Cost} + \text{Security Collateral}$$

The government waste tax is a fixed 475DKK fee per ton for all Danish landfills regardless of waste type, size, etc. (exception: hazardous waste, for which there is currently no government fee). The landfill operation cost includes the cost of all elements required to successfully operate the landfill, such as equipment, employee wages, and construction. The purpose of the security collateral is to set money aside for the closure and aftercare of the landfill. A complex process is used to calculate the security collateral for landfills. The calculations take many factors into account, such as residual capacity, annual volume of waste, waste type, and inflation. The landfill operation cost and security collateral vary by site. Both are calculated for the entire landfill and then divided by the predicted capacity (in tons) which gives the price in cost per ton [5].Although there should not be a major profit, any extra funds contribute to the following year's expenses and are accounted for when the following year's cost per ton is determined.

The cost to landfill waste (per ton) varies by landfill and there is a wide distribution of costs between landfill sites, as shown in Figure 11 (does not include government waste tax). Danish legislation prohibits waste producers from transporting their waste to less expensive landfills outside their respective municipality or inter-municipality, even though the operational efficiency tends to be greater at larger landfills resulting in lower cost per ton, compared to smaller landfills [26].

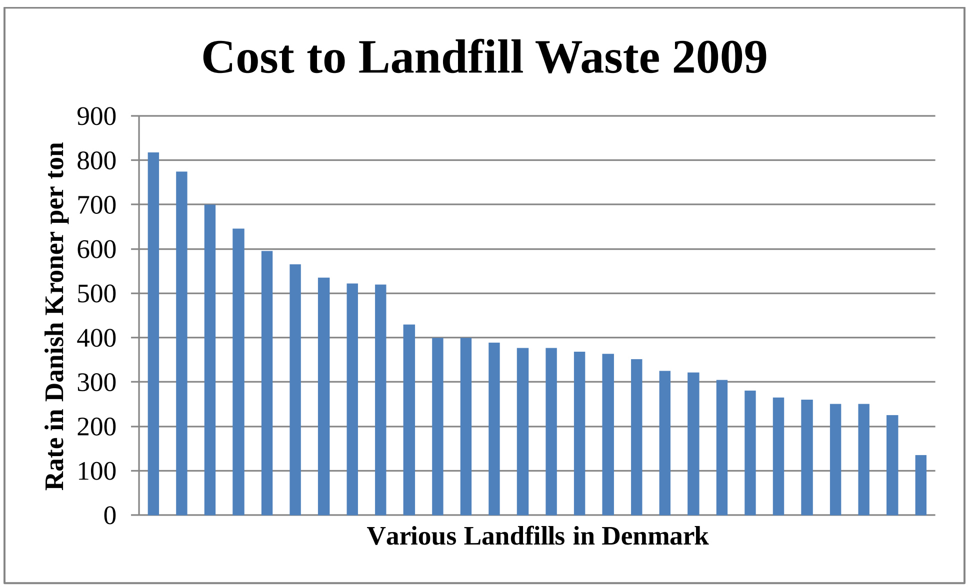


Figure 11: Cost to Landfill Waste in Denmark 2009 (excluding government waste tax)

2.6.5 Timeline of Landfill Life

Landfill life in Denmark begins with thorough planning. The Danish Government must approve the operational plans and the plans to mitigate potential environmental impacts of each landfill. An in depth assessment of these impacts is performed to determine the required monitoring frequency. Testing may be required on a monthly basis to assure impacts are minimal, specifically contamination of the water table. Many factors influence the monitoring requirements, such as topography of the land, surface and groundwater flow, locations of drinking water supplies, and proximity to bodies of water. Based on data, ground water wells must be drilled to monitor chemical concentrations. There is a set minimum of three wells, one installed in the upstream region and two downstream based on the hydrology of the groundwater table [20]

There are specific practices pertaining to landfill daily operations. Waste is added to specified cells on a daily basis (for a MSW landfill). The MSW is then compacted and covered with a thin layer of soil to reduce the odor and prevent animals and insects from getting into the landfill. This operation continues until the landfill meets its waste capacity. Regular monitoring is necessary as material is added to each different cell during the active stage of the landfill's life.

Table 3: Mandatory elements of the basic characterization [20]

Information on the generating source and origin. I
Information about the process by which waste is generated including the description and characterization of raw materials and products.
Description of the pretreatment used or a description of why a treatment is not deemed necessary.
Information on waste composition and leaching characteristics of wastes for which there is demand for testing. By requiring testing, the guidelines for characterization testing in Appendix 7 are followed. (Can be found in cited source)
Information on waste odor, color and physical form.
Information on waste EWC code in the list of wastes of the Ordinance on Waste see Appendix 2 (Can be found in cited source)
In the case of mirror entries for hazardous waste, there must be information about the particular waste hazardous properties.
Information demonstrating that the waste is not covered by the ban on landfill in accordance with § 56 of the Ordinance on waste.
Which waste class waste belongs.
Description of specific precautions to be taken at the landfill if necessary.
Assessment of the waste or its parts can be recycled or recovered in some way.
Information about the physical, stability and strength with respect to hazardous waste.

As the landfill's useful life comes to a close, a second planning stage for the aftercare period begins. Plans must be made for the closure of facilities and aftercare operation, which includes leachate processing, gas venting, and monitoring, as well as demolition of temporary roads and maintenance buildings. In most other European and US landfills, a sealed cap would be installed on top of the landfill to prevent precipitate from percolating through the body of the landfill. Denmark does not cap their landfills. Denmark covers landfills with a thin, permeable soil layer which allows as much percolate to flow through as possible. This will be discussed in greater detail later in this paper [3].

2.6.6 Environmental Impact of Landfills

Landfills can have a wide range of environmental impacts ranging from groundwater contamination to odor and noise pollution. During landfill operation, heavy machinery is used to place waste in each landfilling cell, and noise produced by this machinery may be heard by nearby establishments. When waste is exposed to air, there is a natural tendency for the odors it produces to travel to surrounding areas and subject those nearby to unpleasant smells [4]. These factors and the general unsightly nature of landfilling may lower nearby land value and desirability, especially with MSW landfills.

A major cause for concern is the possibility of groundwater contamination. As water percolates through the landfill, it draws chemicals into solution, which may then contaminate the surrounding environment when leaks form in the lining system of the landfills. Some landfills that are classified as inert landfills may possess no liner at all, relying on low chemical concentrations and natural groundwater attenuation, but with this system comes the risk of major consequences should improper material enter the landfill. When contaminates enter the groundwater system, they pose a threat to anything downstream that is fed by the groundwater. This can include wells, springs, and regions of upwelling of groundwater, rivers and shorelines. Danish regulations set thresholds to the allowable concentrations of pollutants in groundwater due to landfilling. Landfill owners must monitor these substances throughout the life of the landfill, which includes the aftercare period. This monitoring is based largely on the contents of the landfill [20].

Groundwater monitoring is important to assure a landfill is not contaminating the water table. The natural groundwater and hydrology near a landfill is an integral factor during the design and construction and placement of monitoring wells. This is to assure that the landfill does not contaminate sources of drinking water and sensitive environmental areas, and that this contamination can be measured if present. The criteria for concentrations of chemicals in groundwater are stricter in Denmark that the EU requirements because Denmark uses its groundwater extensively for drinking water. Maximum allowable values of pollutants and chemicals are specified by each landfills permit and if these values are exceeded, remediation action must be taken. These acceptable limits must be reached at a distance within 100m downstream of the landfill, or the Point of Compliance (POC) [24].

Landfills can also become home to rodents and various species of birds such as gulls and vultures, which can in turn harbor and spread disease [22]. These issues are mitigated by covering the area with a thin soil layer after each daily waste addition. Waste that has not yet been covered may also blow around under windy conditions. Landfills use fencing systems to address this issue.

2.6.7 Aftercare Period

When a landfill comes to the end of its useful life, the owner must take appropriate actions to ensure it will remain safe and stable. Minimization of the potential for environmental contamination during the aftercare period is of the utmost importance. During the aftercare period, landfill owners are responsible for regular monitoring and treatment of the landfill percolate. The length of the aftercare period has been arbitrarily set to 30 years by legislation [2]. To ensure that the landfill does not contaminate the surrounding environment in any manner, this period needs to have an appropriate length, which should address the actual window of time during which a landfill may incur such impacts to its surroundings.

There are three key behaviors that a landfill exhibits during the aftercare period. First, the different waste materials inside the landfill will exhibit a wide variety of decomposition paths and break down over time. These materials can produce byproducts in the form of gases, solids or dissolved solids. Second, any water or “percolate” flowing through the landfill will act as a medium by which dissolved solids and small concentrations of gases will move through the landfill. Finally gas byproducts, most commonly methane from organic decomposition, will rise through the structure of the landfill to special aeration wells that bring the gas to the surface [27].

Decomposition of organic waste takes place via different mechanisms and rates depending on the conditions of the landfill. Microorganisms usually assist decomposition; therefore landfill conditions are critical to the rate of decomposition. Factors which influence the rate of decomposition include whether the landfill is aerated and hospitability factors to the decomposing organisms, such as level of humidity and toxicity of waste. Decomposition mechanisms, rates and products are also highly dependent on the presence and the amount of a medium, which is primarily the water percolating through the landfill. Decomposition is typically an exothermic reaction that is accompanied with the emission of gases which can be harvested on-site. Unpleasant odors also emanate from the decomposing matter, a common phenomenon of many household waste landfills. Inert waste like construction waste is usually free of organic matter, so less methane and odor are produced. Other in-organic chemical reactions may also occur depending on the composition of waste, and these reactions are also responsible for products which may become dissolved in percolate [27].

As organic matter inside a landfill decomposes, the major gas byproducts produced are methane and carbon dioxide [6]. These gas byproducts slowly permeate through the landfill material, eventually finding their way to vent pipes that allow the gases to escape. In some landfills with high organic components, collection systems are in place to collect these emissions to be used as fuel. In 1997, Denmark mandated that all material appropriate for incineration must be incinerated, thus the organic components of current landfills are minimal. Because of this low organic content, most modern Danish landfills no longer produce large gas byproducts, therefore few harvest this gas [2].

In most of Europe and the United States, landfills are capped with an impermeable plastic membrane layer, clay layer, and topsoil covering at the end of their life. Much effort and engineering is put into designing these caps that divert precipitate away from the interior of the landfill body [28]. Barely any water trickles into the waste to leach chemicals out of the solid waste. Theoretically, the waste chemicals stay buried forever, and the only change in concentration of chemicals is due to reactions within the waste itself. But this poses a major problem to future generations when the liner eventually breaks, something Denmark hopes to avoid [25].

Denmark takes a different approach to landfill management during the aftercare period. Instead of capping the landfill with an impermeable layer, only a thin soil layer, usually 1 – 1.5 m thick is placed on top of the landfill upon closure. This soil cover consists of composted waste and dirt, which is spread out by a bulldozer; the resulting cover will never be perfectly uniform (see Figure 12).

Grass and trees are then planted on top to prevent erosion of this layer. This permeable soil cover allows rainwater to permeate freely into the landfilled mass, increasing the rate of decomposition, leaching away chemicals and decreasing their concentration in the waste layer [25].

The dilution of hazardous substances is a continuous process whose rate is directly affected by factors such as waste type, fluid flow, and liquid to solid ratio. Evaporation of rainwater, compaction of waste, waste pre-treatment, and mass transfer (of chemicals from solid waste to liquid phase) also affect the rate of dilution. The rates of leaching and hydrology inside landfills are highly variable due to the heterogeneous nature of landfill waste. The density of waste increases with increased depth due to pressure caused by compaction and the weight of above layers. The uneven nature of waste distribution causes some regions to develop higher liquid to solid ratios than other areas. This randomly distributed

Figure 12: Bulldozer spreading and compacting soil layer to landfill in aftercare

build-up of water within the waste layers results in non-uniform rates of leaching and decomposition [27].

Water that trickles down the waste layer and leaches chemicals out of the solid waste permeates into the leachate collection layer. The pipe network directs the percolate into central collection depots. These depots are used as sampling collection points for percolate testing. Independent companies (laboratories) collect samples from the depots and bring them back to their labs where they are tested. Percolate from the depots are then sent to waste water treatment facilities. There, a variety of methods are used to treat the percolate such as separation of metals, oxidization, and filtration, so it can be released to the environment [25].

The ability of a landfill to produce emissions in the form of leachate and gas is referred to as the "emissions potential" of a landfill. In order for a landfill to become environmentally neutral, this potential must be reduced to a safe level. This safe level is defined by testing of landfill leachate. Once leachate characteristics fall within acceptable levels, the landfill is considered safe and can be released from aftercare [27]. There are two primary ways that the rate of decay of the emissions potential of a landfill can be decreased. The first is by allowing rainwater or recirculating leachate to flow through the landfill, thus increasing rates of both chemical decay and the rate of dissolution of landfill components. The second is to aerate the landfill with piping networks to increase the decay of organic reactions inside the landfill. Both of these methods have large impacts on rates of decay, and thus emission potentials [29].

Denmark is considering recirculation of percolate as a more economic option than allowing rainwater to flow through only once. By allowing rainfall to trickle through the landfill and then pumping the collected percolate back into the top layer until the water is saturated with contaminants, less treatment will be required and the dilution rate is enhanced[25].

Aftercare is a complex process with many different processes and engineering components that contribute to its nature. In addition to physical aspects, legislation and regulation also play a large role in the actions taken by landfill operators. Every aspect of aftercare needs to be taken into consideration to develop the best aftercare solution.

2.7 Conclusion

While landfilling is a conceptually simple process, the reality of how a landfill operations and how it behaves after it is capped is quite complicated. The sections presented in this background highlight important concepts that represent the foundation of the knowledge for our project. There is much legal framework regulating current Danish landfill practices for the planning, use, and closure stages, but there are there are still many questions surrounding the aftercare process. Landfills present a true engineering challenge that involves careful planning and consideration because of the environmental threats that landfills create. Subjects such as law, structure, finance, impact, and operation will be important concepts in assessing the aftercare period.

3 Methodology

The purpose of our project was to consider all areas of the landfill aftercare process and evaluate current practices. Based on our background research, our goal was to make recommendations to RenoSam with respect to the aftercare period practices. Recommendations aimed to minimize the environmental impacts of landfills during the aftercare period, while taking impacts on stakeholders into account.

Our specific project objectives are as follows:

- Collect and assess background information on Danish aftercare techniques
- Investigate and assess Danish legislation surrounding the landfill aftercare period.
- Collect and analyze percolate data and rainfall data.
- Based on investigation, assessments and data analysis make recommendations for improvements to current aftercare practices.

Below, we will review each of our objectives, explain what methods we used, and how these methods address the objectives.

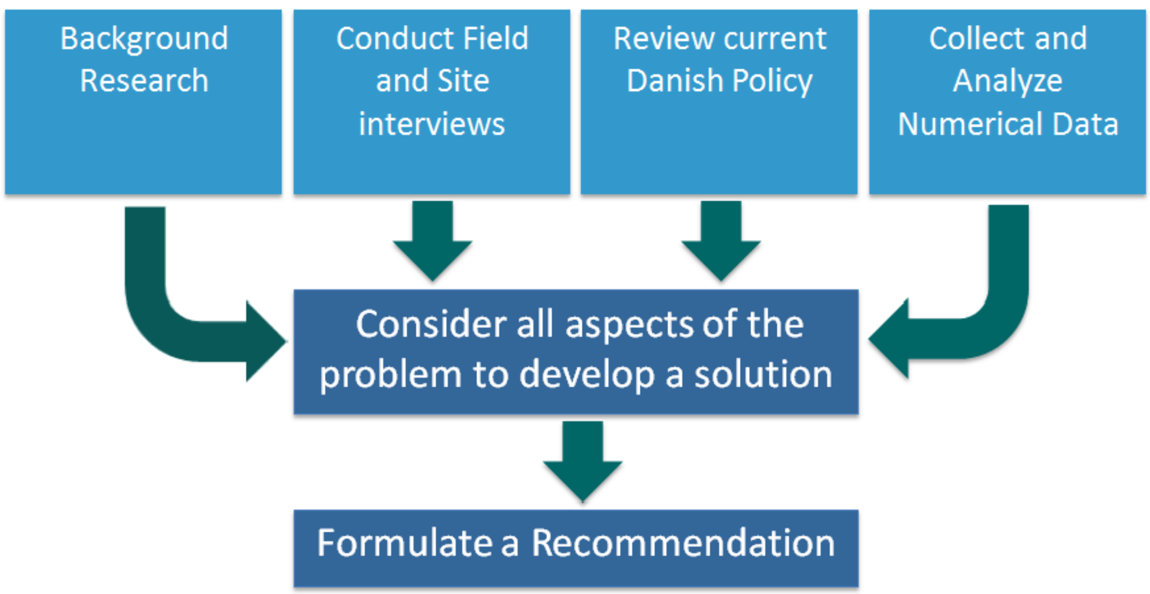


Figure 13: Phases of Methodology

3.1 Collect and assess background information on Danish aftercare techniques

In addition to background research conducted on campus, we collected landfill structural and operational information pertaining to aftercare. This complemented our work and provided a sound foundation for analyses and conclusions.

3.1.1 Review of Background Research

A solid understanding of current practices of Danish landfills was essential before analysis of the aftercare period could be performed. Many factors contribute to the aftercare period; most of these factors were researched but only the most significant factors were considered in our analysis. The methods for analysis of these factors are discussed in further detail in the following sections.

Many resources were available us during our research. The most significant resources were provided by Danish organizations listed below. This information was in the form of interviews, databases, reports, laws, and landfill visits.

- RenoSam
- Danish Environmental Protection Agency
- Danish Hydraulics Institute
- Landfill Visits in Denmark
  - Fakse Landfill
  - Odense Landfill
- Danish Meteorological Institute
- Odense Vandværk Weather Station

Background knowledge about how Danish landfills function during their lifetime and aftercare period was necessary before we could effectively use waste and percolate data to make conclusions regarding the aftercare period. Comprehension of how the liner and percolate collection systems operate was essential as they are in essence responsible for the actual percolate data, and their integrity affect both percolate collection and groundwater quality. Research of the daily operations and construction of cells was performed to understand how the structure integrity of a landfill progresses through time. These practices are key factors of landfills' performance both in terms of internal function and external impact on surroundings. When necessary, additional information was obtained from books and web sources to provide a solid foundation during the research process.

3.1.2 Interviews and Site Visits

The purpose of field and site interviews was to collect information directly from stakeholders and experts. Interviews were an essential source of information for our analysis and were performed with contacts from the resource organizations mentioned in Section 3.1.1. A general synopsis and interview agenda were created for each interviewee to explain our project and goals for the interview (See Section 7.4- Appendix D for examples).

Interviews gave insight into how to best use the data available to us. Precautions were taken to avoid bias and define each stakeholder's perspective with facts and opinions. While general questions were important and often created a starting point for each interview, interview questions often became more specific and tailored as the interview progressed. An example of questions posed is shown in Table 4. A WPI Internal Review Board (IRB) form was created and signed by interviewees when appropriate (See Section 7.5- Appendix D)

Table 4: Sample Interview Questions

Person(s) being interviewed: Interviewer (s): Location: Date:
What goes into constructing a landfill by your company? (with emphasis on infrastructure and contamination prevention measures- more in the next question) How does your company construct its lining systems for various types of waste of landfills? Percolate collection systems? What methods do you use for cell construction? What are your main concerns constructing and managing landfills? What are the costs of constructing, operating, and maintaining different landfills types? What measures are taken to close various types of landfills? (the interviewee will most probably be a manager or operator of a one type of landfill, he/she may not know about other types) What monitoring techniques and frequency are used during the active life of your landfills? During aftercare? How does leachate treatment work? Is the leachate sent directly to the waste water treatment plant? Do you feel that the aftercare period length for landfills is sufficient? (have to take financial bias into consideration) Is your company interested in changing the legislation for aftercare period length? Why? Do you feel Danish legislation on landfills is strict enough, too strict, or just right? Why?

Landfill visits were important to gain a sense of the flow of the landfilling process and magnitudes involved in those processes. We had the opportunity to observe various types of landfills and their respective operations. Field observations took the form of notes and photographs of operations.

3.1.3 Policy Research

Information collected from interviews with stakeholders helped determine whether the current aftercare legislation appropriately addressed the reality and need of the situation. A thorough understanding of Danish and European regulations pertaining to landfills was critical in order to understand the obligations of a landfill operator. These regulations must be understood to accurately assess the elements that contribute towards an environmentally safe aftercare period. Interviewing a representative from the Danish EPA contributed to our understanding of how Danish landfills are kept under governmental control and how regulations are drafted and passed.

3.2 Percolate Data Collection

Data recorded by landfill operators and rainfall data were key elements of this project. These data include the size, volume, mass, and waste composition of the landfill, rainfall data, percolate volume, and chemical analysis of percolate. Our estimations and recommendations were derived from analyses of this data. Numerical data containing collected volumes of percolate, concentrations of various substances in percolate over time, and rainfall amount was organized into Excel sheets. We focused our effort on percolate data from Municipal Solid Waste landfills because it is the most common type of waste landfilled in Denmark. Our goal was to analyze a small number of landfills which best represented MSW Danish landfills in general (listed below).

- Fladså
- Fakse
- Skårup
- Ganløse
- Gerringe

Percolate data from these landfills was plotted and compared to groundwater limit values and annual rainfall.

Descriptions of each landfill formed an important part of our analyses and can be found in the Results section and Appendices. The waste type, size of landfill, age of the landfill, volume and mass off the landfill are examples of some of the factors considered, as well as for use in L/S ratio and rainfall comparisons, which will discussed later in this report.

3.3 Data Analysis

Information on the factors that affect aftercare period length and the leaching characteristics of different types of waste exists, and provided good background for the project. However, many of these reports do not detail specific techniques and methods for calculating aftercare length. After understanding this type of background literature, our approach to aftercare estimation was to collect, organize, and graph percolate data from landfills and study the decay rates and correlations between factors to develop a rough estimate of the aftercare timeline.

To begin our analysis of the percolate data, it was essential to compile the data from each landfill into well-organized spreadsheets using Microsoft Excel. These spreadsheets were used to graph the percolate data and compare the values to acceptance criteria and rainfall data. Outliers that were more than two times the standard deviation were ignored in our analysis. A best fitting model was chosen (exponential or linear) by maximizing the R^2 value. The acceptance criteria for substance concentrations in groundwater were plotted on each respective substance plot. This allowed us to predict when the substance's concentrations would converge to these limits and when the landfill would "be ready to exit the aftercare period."

Percolate production is a product of rainfall and the concentrations of chemicals can vary non-linearly with rainfall due changes in water infiltration and solubility of chemicals. The volume of water collected in depots or other collecting stations was compared to rainfall levels. It was expected that these values be similar within a certain degree of error. A large discrepancy would indicate leakage of percolate. Annual percolate amount and annual rainfall were plotted on the same graph to draw this comparison. Figure 14 illustrates the transport phenomena of percolate in a landfill.

3.4 Formulate a Recommendation

After performing an investigation and analysis of each of the discrete parts of the methodology, all information gathered was used to formulate a recommendation.

Our ultimate goal was to make a recommendation to RenoSam which included a method to determine the aftercare period length and recommendations for further study. Although we were not able to conclude as to whether or not the length is sufficient, we were able to make recommendations relating to the aftercare period. These recommendations may be used in the preliminary steps of creating new landfill legislation or modifying the existing legislation, with RenoSam's involvement. In addition, further research may be conducted to better understand the complexity of the processes that landfills undergo.

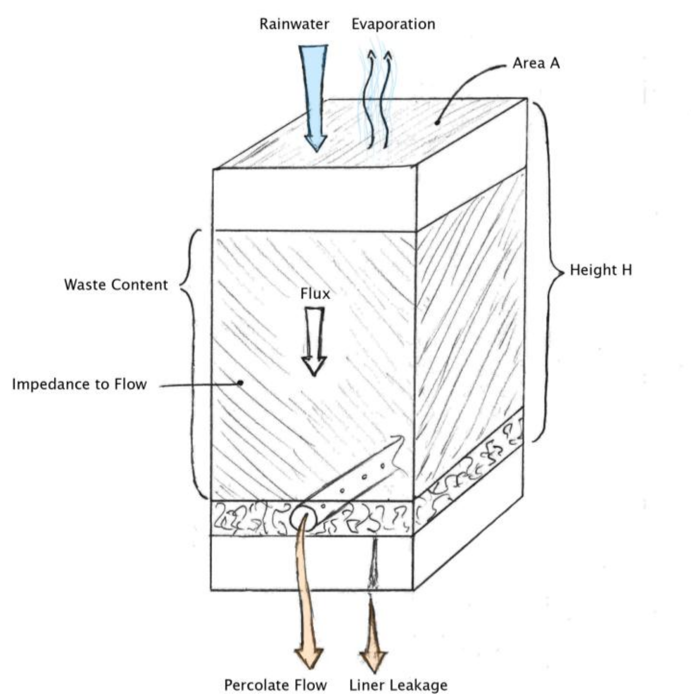


Figure 14: Rainwater percolation through a section of landfill

3.5 Summary

Our methodology changed significantly as the complexity of the project became clearer. Significant effort was necessary to organize and to the extent possible, analyze the data. Similarly, because of the complexity of the data and data analysis, interviews with experts became one of the key elements of the project. Eventually, the data, data analysis results, and the interviews were crucial to the development of our recommendations, as well as the new ideas new understanding we developed about the complexity of defining an aftercare period.

4 Results

Computing the aftercare period is a complex problem because there are many elements that contribute to the calculation of its length. RenoSam was able to provide us a significant amount of percolate data from landfills, and our original plan was to plot this data and use trends to determine when landfills could exit aftercare. However, as our research progressed, we came to realize there are many aspects to the problem that were not originally anticipated. As a result, the primary purpose of this results section is to explain the various intricacies of the problem and to give examples of where there are likely to be difficulties with specifying a single aftercare period length.

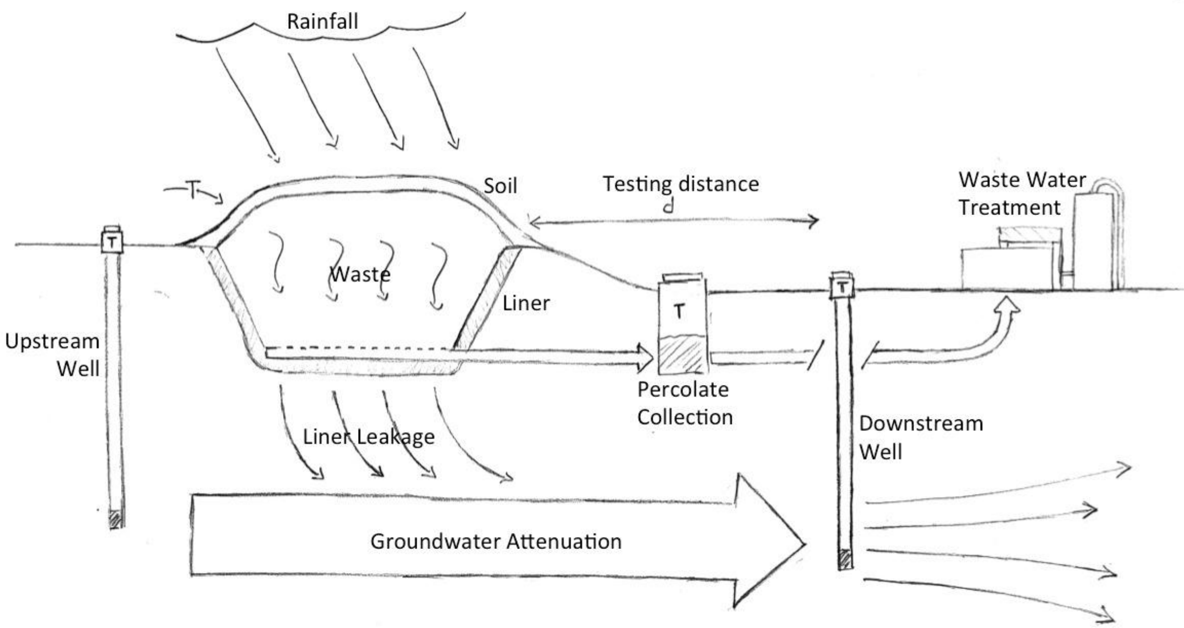


Figure 15: Flow of rainfall as it peroclates through a landfilling system

Figure 15 illustrates the key points of a landfilling system that contribute to the overall complexity of the problem. Our attempt to estimate this period length is based primarily on percolate data collected from the leachate collection systems of various landfills. In subsequent sections we also explore and report on the impacts of rainfall on the concentrations of substances and amount of leachate. In particular, precipitation that impacts a landfill may run off the surface, evaporate, or be absorbed by the landfill. Calculating the effective rainfall for each landfill location was difficult because of variation on a daily and annual basis, and evaporation and runoff rates can also vary depending on various factors. Once rainfall begins percolating through the landfill, the path of water through the landfill is heterogeneous and unpredictable. For example, the ratio of liquid to solid (L/S) and the flow rates vary depending on the permeability, size, and density of materials. The internal chemistry of a landfill is very complicated, with various substances interacting with each other based on factors such as solubility, pH, and the liquid to solid ratio. The liner and groundwater table add another level of complexity to the problem. Most liners are made of synthetic plastics and/or a clay bed depending on the landfill, and no liner will last indefinitely. As the liner degrades, the landfill will begin to release percolate into the environment.

All of these dynamic and complex components create an interconnected system that can be daunting to understand and interpret. While we were able to gain insight through data from specific landfills, further research is necessary. The following sections will discuss the processes of leachate in a landfill by following the same path which water percolates through the landfill.

Before reading the results section, it is important to understand the scope of this required third year project and, specifically how it relates to this particular project. The third year project is designed to help students explore the interaction between society and technology and the impact of technology on society. As such, the technical scope of this project was at times both outside the scope of our abilities as well as outside the scope of the required project work. Regardless, we have made our best efforts to be as technically accurate as possible given original intent of this project.

4.1 Rainfall

A comparison of the amount of percolate to the effective rainfall, the amount of rain actually entering the landfill known as effective rainfall, gives insight to the permeability of the waste (See Section 4.9 for graphs). More importantly, plots of the effective rainfall can help explain certain trends in the data- since rainfall is one of the most important driving factors in terms of volume of percolate and rainfall rates can directly influence the rate at which substances are diluted from a landfill. In addition, increased effective rainfall can create new channels in the waste for water to flow which can cause percolation in previously dry areas due to the heterogeneous nature of landfilled waste. This can, in turn, cause sudden increases in concentrations of certain substances.

Rainfall data, let alone effective rainfall data, is not easily accessible; some landfills have weather stations but most landfills are new (approximately ten years old) and do not have weather data dating back to the start of landfilling. We were not able to obtain rainfall data from any landfill dating back to the beginning of landfilling at any site. To best approximate the rainfall at each landfill site, we obtained data from a meteorological weather station, Odense Vandværk, from January 1980 through April 2011. A technical report from the Danish Meteorological Institute provided a contour map of Denmark with annual rainfall values (See Appendix B-7.3.1) [30]. This map was used to scale the rainfall data from Odense Vandværk to the locations of each landfill.

This rainfall data does not account for evaporation. We calculated the effective rainfall using Equation 2 with the assumption that runoff is zero because runoff is insignificant when compared to the effective rainfall determined solely from rainfall and evaporation.

Equation 2: General Effective Rainfall Equation

$$Effective\ Rainfall = Rainfall - (Evaporation + Runoff)$$

Effective rainfall is the annual rainfall minus annual evaporation for a specific location. We used a technical report from the Danish Meteorological Institute which displayed two different mathematical methods to approximate evaporation in Denmark, the results from which were displayed in individual contour maps (See Section 7.3- Appendix B) [31]. We averaged the values from both maps to best approximate annual evaporation for each landfill. Unfortunately, the tests that support these approximations were pan evaporation tests which do not accurately model the soil cover evaporation phenomena of landfills. Pan evaporation tests involve filling a pool with a known volume of water and monitoring the amount of water that evaporates over time. This test is inappropriate for landfills because rain is not continuous and is absorbed into the soil at landfills; evaporation is dependent on humidity, soil porosity, temperature, slope, and other factors. The general rule of thumb to compute soil surface evaporation is to use 1/3 of the evaporation found in a pan evaporation test [32]. For the purpose of this study, we divided the evaporation from the Danish Meteorological Institute's report by 3 and subtracted it from rainfall to determine the effective rainfall for each landfill location.

Equation 3: Applied Effective Rainfall Equation

$$\boldsymbol{Effective\ Rainfall = Rainfall - 1/3(Pan\ Evaporation)}$$

4.2 Liquid to Solid Ratio and Solubility

Percolate data can be expressed in two forms: a plot of concentration versus time or a plot of concentration versus the "Liquid-to-Solid Ratio" (L/S). The L/S ratio is a comparison of the volume of percolate in a landfill to the amount of waste in the landfill (See Equation 4). . This ratio is a means of normalizing data from different tests and landfills. By showing substance concentrations and other leachate testing measurements in terms of L/S ratio, we can make comparisons between different landfills and avoid inconsistency from factors such as annual rainfall.

Equation 4: Liquid-to-Solid Ratio

$$\boldsymbol{L/S = \frac{Volume\ of\ Accumulated\ Percolate\ (m3)}{Weight\ of\ Accumulated\ Waste\ (tons)}}$$

Recall that leaching is the process by which chemicals present in the waste are dissolved into the rainwater running through the landfill. The leaching behavior of chemicals represents a complex, dynamic system which is difficult to predict. For any substance, there is a limit to the amount of a substance that can become dissolved in liquid (*the solubility constant*) that depends on the temperature, pH, and other substances present in the liquid. The resulting equilibriums between chemicals remaining in waste and substances that dissolve in the leachate are complicated, and certain substances control the leaching of others. Each substance also has a range of pH values over which is able and unable to go into solution. All these interactions plus others not mentioned result with a very complicated system.

4.3 Substances and Measures

Landfill percolate is a complex mixture of dissolved substances. The substances present are mostly ionic compounds dissolved in water in varying concentrations. There are many measurements, both general and specific, that help to quantify the composition of percolate. General measurements such as pH and conductivity provide information about the overall quality of the leachate solution. pH is a measurement of the acidity of a substance and a rough measurement of the inverse log of hydronium ions in a solution. Highly acidic or basic substances are more likely to react with other substances. A pH of 7.0 is neutral, with 0 being most acidic and 14 being most basic. In landfills, pH can be a factor for the ability of a substance or chemical to dissolve into water and leach out of the landfill. Conductivity is measurement of a solutions ability to conduct electricity, and is an effective way of determining the total ionic content of a solution. These are the most general measures that can be made about a leachate solution. When paired with specific substance measures, a more complete picture can be drawn to address the aftercare problem.

There are many substances present in landfills that have oxidation potential. COD or “Chemical Oxygen Demand” is a measurement commonly used to determine the organic pollutant content of water, but the measure also includes inorganic substances. BOD, or Biochemical Oxygen Demand, is a measurement of biological substance present only. BI5 is essentially the same as BOD, but instead of being measured immediately, the measurement is performed five days later. The ratio between organic and inorganic substances depends on the type of landfill and the material being landfilled. Wastes that have been incinerated or are inert will have very low BOD values, whereas wastes with high organic waste content such as mixed municipal waste will produce higher values.

There are many specific substances that can be measured in the leachate solution. These include, but are not limited to, Sodium, Potassium, Magnesium, Calcium, Chloride, Fluoride, Ammonium, Nitrate, Sulfate, and others. Many of these substances form salts, such a Sodium Chloride or Potassium chloride. Concentrations of nitrogen or phosphorous based substances are often measured as a whole in measurements called “Total Nitrogen” or “Total Phosphorous”.

Additional trace substances are commonly present in the solution. These can include Strontium, Barium, Iron, Chromium, Cadmium, Mercury, Zinc, Lead, Copper, Nickel, and many others. Some substances such as heavy metals like Lead, Cadmium, Chromium and Mercury can have adverse health effects when present in drinking water. These substances are generally regarded as dangerous in any concentrations in water and can cause a variety of health consequences, often relating to the nervous system. Other substances such as copper and iron are actually necessary to plant and animal life in lower concentrations. However, this does not mean that these substances cannot become dangerous in higher concentrations.

A complex interplay forms between these different groups of chemicals in a landfill. In landfills with higher organic content, organic substance will often absorb any traces of heavy metals, and the landfill will produce high levels of organic pollutants and low levels of chloride and sulfate. On the other hand, landfills with incineration waste slag will produce very few organic pollutants, but are capable of producing much higher levels of toxic trace elements and dissolved salts [4].

4.4 Natural Groundwater Attenuation

Testing the groundwater is a useful technique to determine if a landfill has had negative impacts on the surrounding environment. Groundwater criteria testing are measured at the Point of Compliance (POC), typically 100 meters downstream from the landfill. There is also a control measurement taken upstream of the landfill to identify if the landfill affects the groundwater or if contamination is caused by an independent source. We compared the limit values from the groundwater criteria to the percolate data for several landfills. Although these comparisons give insight to the dilution of waste materials, the relationship between these points of measurement is not well defined. The leachate data represents the concentrations and measurements of the leachate as it exits the landfill, and does not account for the natural attenuation of groundwater. In contrast the groundwater criteria measures the influence leaked leachate has on the surrounding groundwater. It is assumed that 1% of total leachate produced in a landfill leaks though the liner during a landfill’s active life [33]. However, this value may not be accurate, depending on the effectiveness of the landfill’s liner. As the liner degrades over time, leachate will enter the groundwater system in increasing amounts. We do not know the amount of natural attenuation in the groundwater between the landfill collection depot and the POC. We can speculate that the concentrations of most substances will be higher at the leachate collection depots than at the POC, and that this will change significantly as the liner breaks down. At this point, we do not have enough information or experience to quantify the behavior of natural attenuation.

4.5 Sampling and Testing

There are no set of standards to regulate which leachate substances are tested or at what interval. These requirements are currently determined on a site specific basis which causes inconsistencies between data recorded at each landfill. This has posed challenges with comparing landfills in our analysis. More importantly, non-normalized regulations can cause varying environmental impacts from different landfills. The following table shows substances and measures taken at each landfill site studied in this report and which of these are regulated by the Groundwater Limit values. An "X" indicates the substance is recorded. It is easy to see how much variance exists between substances and measurements tester for between landfills.

Table 5: Measurements Recorded for Various Landfills Compared to Available Groundwater Criteria

	GWC	Fakse	Fladså	Gerringe	Ganløse	Skårup	
Chromium	X	X	X	X	X	X	Tested at all landfills
Nickel	X	X	X	X	X	X	
Zinc	X	X	X	X	X	X	
Cadmium	X	X	X	X	X	X	
Mercury	X	X	X	X	X	X	
Chlorine	X	X	X	X	X	X	
Ammonium	X	X	X		X	X	Tested at all but 1 landfill
pH		X	X	X	X	X	
COD		X	X	X	X	X	
Sodium		X	X	X	X	X	
Calcium		X	X	X	X	X	
Phenol	X	X	X	X			Tested at 4 landfills
Copper	X			X	X	X	
Sulfate		X	X		X	X	
Mineral Oil		X	X	X		X	
Lead	X			X		X	Tested at 3 landfills
Total Nitrogen		X	X	X			
Total Phosphorous		X	X	X			
BLY		X	X		X		
Conductivity		X	X			X	
PAH			X	X		X	
Potassium			X	X		X	
Manganese			X		X	X	
Benzene	X	X					Tested at 2 landfills
Toluene	X	X					
Xylene	X	X					
Flourine	X		X				
Mobalt	X					X	
Selenium	X					X	
Arsenic	X					X	
BI5		X	X				
Sulfide		X	X				
Tørstof		X	X				
Manganese			X			X	
Iron					X	X	
Cobalt					X	X	
Nitrate					X	X	

	GWC	Fakse	Fladså	Gerringe	Ganløse	Skårup	
Barium	X						Tested at a single landfill
Antimony	X						
2Chlorophenol	X						
Flouroethane	X						
Decane	X						
Pentadecane	X						
PCB	X						
NVOC		X					
Napthalene		X					
Ethyl-Benzene		X					
Ammonium Nitrate			X				
AOX			X				
Nitrfi Haemn			X				
SS				X			
Bicarbonate					X		
Gold						X	

4.6 Groundwater Limits Values

We compared the groundwater acceptance criteria from the Danish Statutory Order 252 for Landfills to the EU groundwater criteria (from TAC). The stricter limit for each substance was used in our analysis- a compiled version of these tables is shown in Table 6 [34, 34].

Table 6: Groundwater Criteria used for Analysis

Substance	Groundwater Criteria (mg/l)	Substance	Groundwater Criteria (mg/l)	Substance	Groundwater Criteria (mg/l)
Arsenic	0.008	Antimony	0.002	Toulene	0.005
Barium	0.7	Selen	0.01	Xylene	0.005
Cadmium	0.0005	Zinc	0.1	Napthalene	0.001
Chromium-Total	0.02	Chlorine	150	Flouranthene	0.0001
Chromium III	0.019	Flourine	1.5	Decane	0.005
Chromium IV	0.001	Sulfate	250	Pentadecane	0.005
Copper	0.1	Phenol	0.0005	PCB	0.00001
Mercury	0.0001	2-chlorphenol	0.0001	BTEX-Total	5
Mobalt	0.02	Pentachlorph	0.00001	Hydrocarbons (C6-C40)	9
Nickel	0.01	DOC/NVOC	0.003	PAH-Total	0.2
Lead	0.001	Benzene	0.001		

We superimposed the groundwater acceptance criteria for each substance on its respective graph. This allowed us to determine the substance's convergence to the criteria and predict the amount of time necessary. Figure 16 shows the exponential release of cadmium versus L/S from the Fakse landfill. The horizontal, red line represents the groundwater criteria limit value for cadmium (0.5 mg/l). As can be seen in this graph, an exponential fit is appropriate for this data set which infers that cadmium is converging to the groundwater limit value- an ideal situation.

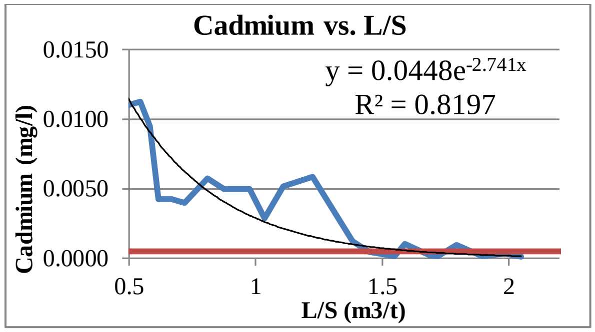


Figure 16: Exponential Release of Cadmium versus L/S from Fakse Landfill

4.7 Organization and Compilation of Data

The percolate data used in our analysis was from five landfills managed by four waste management companies. We obtained most of percolate and waste data from employees of the waste management company via RenoSam. Most of this data was available in Excel spreadsheets, although some data was manually entered into Excel from hardcopies. There were many inconsistencies in the formatting of each cell's data within a given landfill and no two landfills had identical formatting. There were also many inconsistencies in the frequency of tests performed which caused wide statistical variation. For example, there were 11 samples taken in 1987 and only 2 samples taken in 2005 from the Fakse Landfill. It was appropriate to average the percolate tests on an annual basis due to this irregular frequency of testing and the large period of time being examined, from 15 to 30 years, depending on the landfill. It was also appropriate to represent effective rainfall on an annual basis to encompass all seasons in a single data point and to be consistent with the percolate data.

Values from the individual monitoring cells were averaged by substance/measurement to represent the percolate data for the entire landfill, not specific monitoring wells. The annual averages of percolate data for all wells of each landfill were compiled into a single spreadsheet. We created scatterplots over time and over L/S with the respective measurement on the y-axis, such as concentration or pH. We used our judgment to identify outliers but only removed data points that were greater than two times the standard deviation away from the average of the data set. We used the R^2-Value to determine best fit lines for each data set when appropriate, but used only linear and exponential trends to simplify our analysis. `

4.8 Graphs and Estimation

There is valuable information embedded in the percolate data. To analyze the data, each substance's concentration versus time and/or L/S ratio was plotted.

In the analysis of percolate data, certain data trends are more desirable for predicting rates of release, specifically exponential release and linear release. These trends suggest the concentration of a substance decreases with time, which could mean the chemicals in the leachate are diluted by rainfall percolating through the landfill, thus decreasing the emission potential. Some examples of exponential and linear release are shown in Figure 17 to Figure 19.

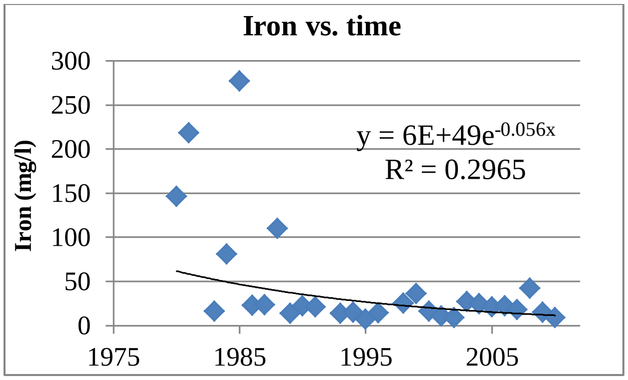


Figure 17: Exponential Release of Iron for Skårup Landfill

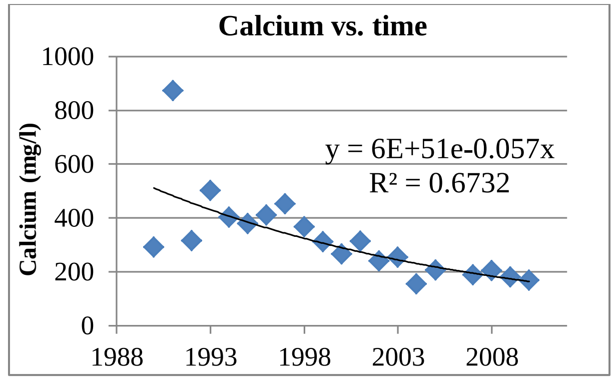


Figure 18: Exponential Release of Calcium from Fladså Landfill

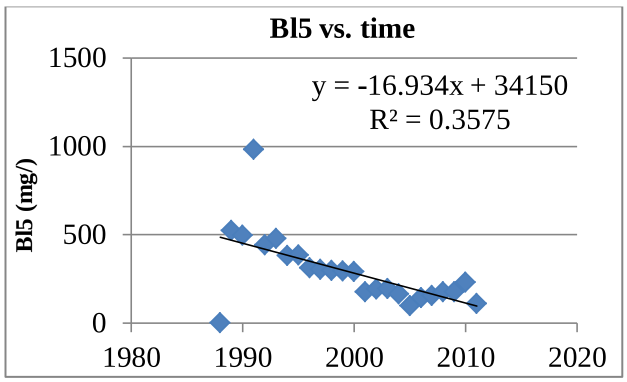


Figure 19: Linear Release of BI5 from Fladså Landfill

Graphs with exponential and linear trends are easy to interpret compared to more complicated trends with the exponential trend being the simplest and most common trend to analyze. By fitting an exponential curve to a data set in Excel, it is possible to obtain the exponential coefficient ($\mathbf{1}/\propto$); the value of this coefficient is called the time constant (see Equation 5: Exponential Equation). This time constant gives the number of years it takes for the substance's concentration to decrease by 2/3 of its initial concentration for each time constant period. For example, the graph of the concentration of manganese versus time from the Skårup landfill (Figure 20) shows exponential release which takes 12.8 years for 2/3 of its initial concentration to be released.

Equation 6 shows the calculations which support this analysis.

Equation 5: Exponential Equation

$$\boldsymbol{y = c * e^{-x*\alpha}}$$

Equation 6: Example of Time Series Analysis

$$y = (3 * 10^{67}) * e^{-0.078*x}$$

$$\propto = 0.078$$

$$t = \frac{1}{\propto} = 12.8\ years$$

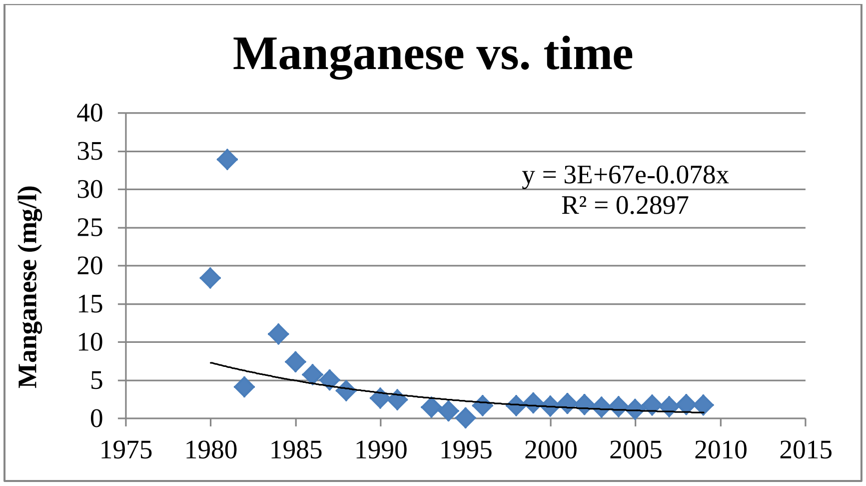


Figure 20: Exponential Release of Manganese from Skårup Landfill

Further analysis of Figure 20 can give insight into the details of exponential release. By splitting the graph into two separate graphs, dependent on the rate of release, we are able to show that exponential graphs have quick initial and then slower decreases as time moves forward, which is an important point in the scope of our project. Figure 21 shows the first 15 years of the landfill's lifetime while Figure 22 shows the past 14 years of its lifetime. The first time period Figure 21 has a time constant of k = 0.351 with a 2/3 release after 2.8 years and the second time period Figure 22 has a time constant of k = 0.006 with a 2/3 release after 167 years. This large difference in rates over time suggests manganese is diluted a large amount after initial deposition, and continues to be diluted over time, but at a much slower rate.

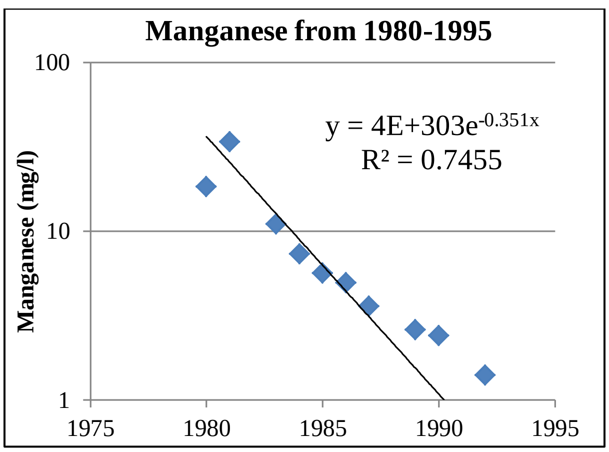


Figure 21: Concentration of Manganese between 1980 and 1995

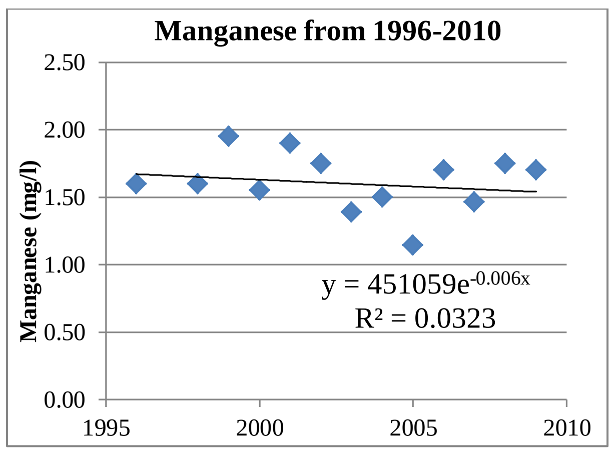


Figure 22: Concentration of Manganese between 1996 and 2010

The graphs presented to this point show ideal cases of exponential and linear release. More commonly, substances demonstrate the high complexity of landfills with irregular trends or no trends at all. These irregularities are caused by numerous factors, such as chemical interactions, precipitates in samples, new channels of rainfall through the waste, and solubility factors. We will demonstrate some of these irregularities with graphs with clear trends.

Many substances have increasing trends of concentrations during the period of percolate collection. It can be assumed that these concentrations will eventually decrease once the substance is depleted, but we do not have enough information to project this change.

There are similar trends for general measurements performed during leachate tests, such as pH, COD, and BI5. Trends like the linear increase of pH in Figure 24 give hints about the science occurring inside the each landfill.

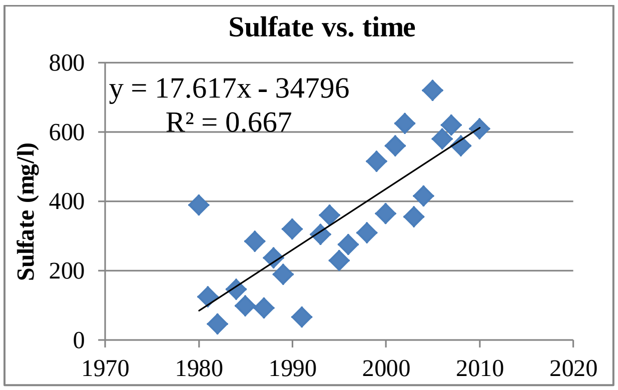


Figure 23: Linear Increase of Concentration of Sulfate from Skårup Landfill

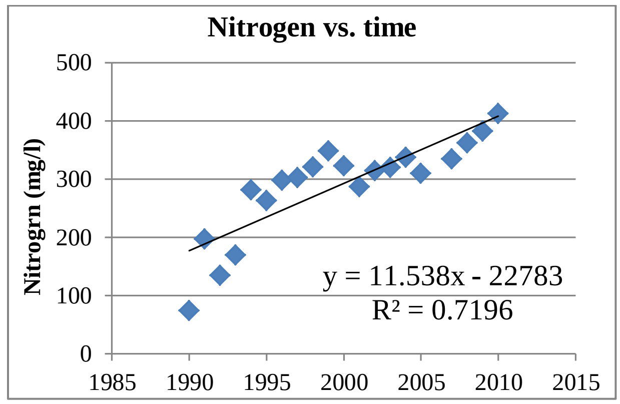


Figure 25: Linear Increase of Nitrogen from Fladså Landfill

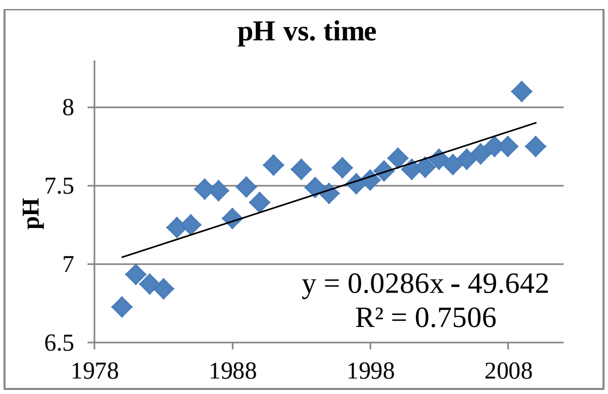


Figure 24: Linear Increase of pH from Skårup Landfill

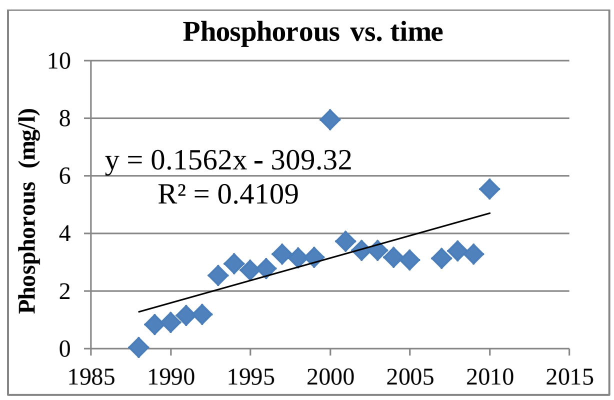


Figure 26: Linear Increase of Phosphorous from Fladså Landfill

Figure 27 shows sulfate versus L/S ratio for the Fladså landfill. This trend may be explained by some of the factors mentioned previously regarding linear increases or others factors not mentioned.

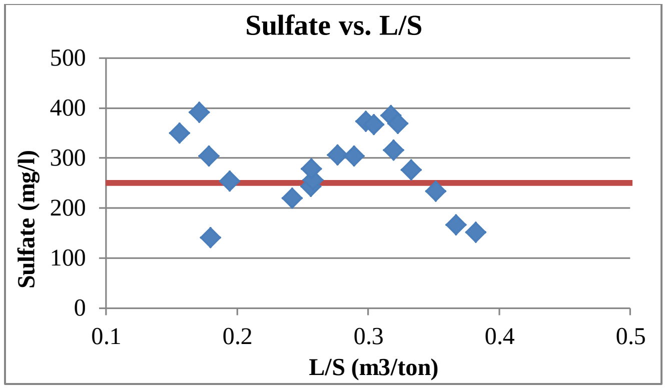


Figure 27: Concentration of Sulfate versus L/S from the Fladså landfill

It is valuable to note similarities between different substances and measurements from the same landfill. For example, chlorine, potassium, and sodium were directly proportional to each other at the Skårup landfill. Figure 28 through Figure 30 show strong correlations with each other, with R^2-Values above 0.94.

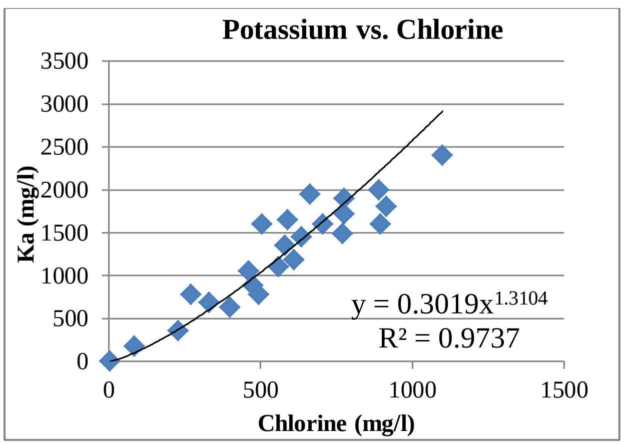


Figure 28: Correlation between Potassium and Chlorine from Skårup landfill

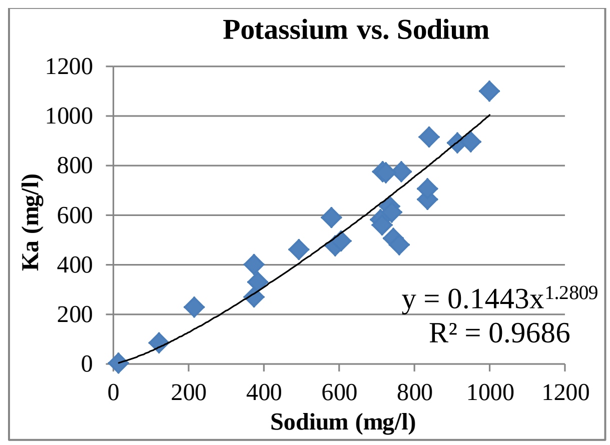


Figure 29: Correlation between Potassium and Sodium from Skårup landfill

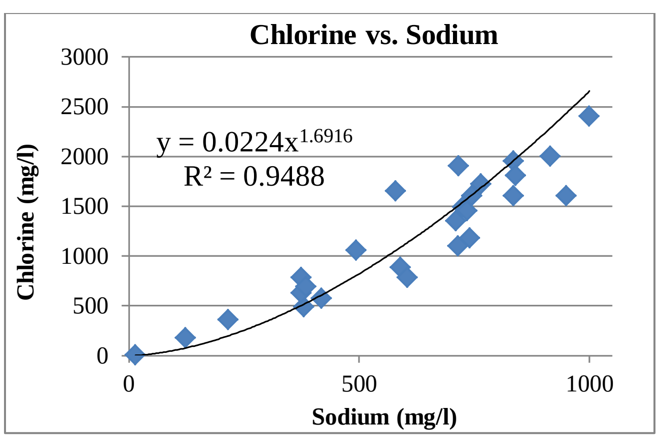


Figure 30: Correlation between Chlorine and Sodium from Skårup Landfill

Figure 31 through Figure 33 show the relationship between COD and BI5. This demonstrates the relationship between inorganic and organic oxidizable substances in the leachate.

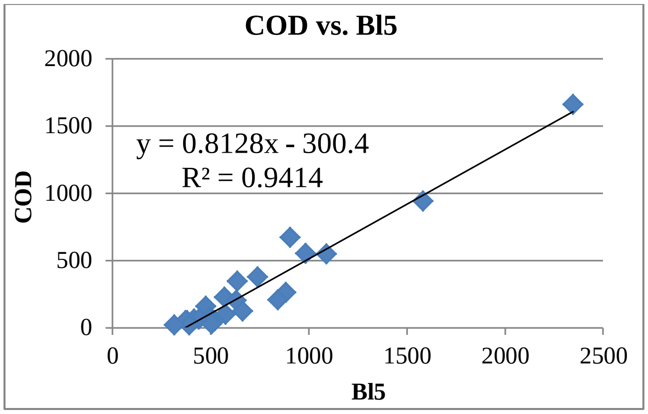


Figure 31: Correlation between COD and BI5 from Fakse Landfill

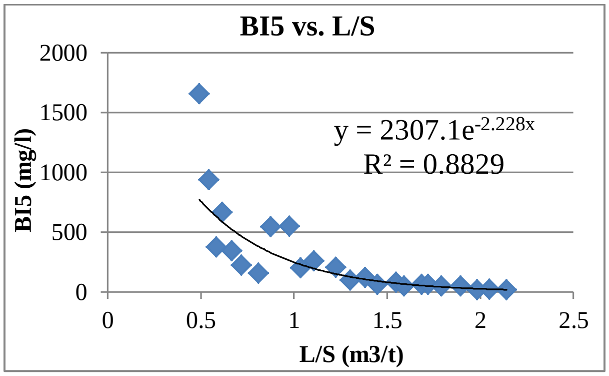


Figure 32: Exponential decrease of COD versus L/S from Fakse Landfill

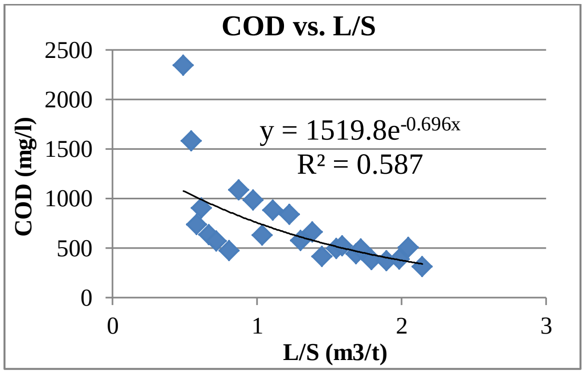


Figure 33: Exponential decrease of BI5 versus L/S from Fakse Landfill

4.9 Landfill Case Studies

The original goal of this project was to determine an appropriate amount of time for the aftercare period. Through much research of the topic and data analysis, we have determined that it is not possible to make an approximation of this length with the resources available to us. Yet we have been able to draw correlations between certain substance concentrations and the time necessary for the concentration to reach the groundwater criteria mentioned earlier in this report.

Equation 7: Length of Landfill's Life in terms of L/S

$$t = \left(\frac{L}{S}\right) * d * \left(\frac{H}{I}\right)$$

$$where\ d = density\ of\ waste\ \left(assume\ 1.5\,\frac{t}{m^3}\right)$$

$$H = average\ height\ of\ landfill(m)$$

$$I = Infiltration\ (aka\ effective\ rainfall)\left(\frac{m}{yr}\right)$$

Equation 7 was used to determine the L/S ratio by inputting a value for the number of years – typically 30 years from the year that the aftercare period began [35]. The purpose of which was to solve for the y value, concentration.

In some cases, data necessary to calculate L/S was not available; therefore data was plotted on a concentration versus time graph. By using the best fit curve equation we were able to solve for the concentration 30 years from the beginning of the aftercare period.

We calculated the magnitude of the concentrations in comparison to the groundwater limit values to express how many times greater the concentrations were at this point in time. Although this analysis does not account for natural attenuation, it does give a rough estimate as to whether 30 years is an appropriate aftercare period length for that substance. An example of this process is shown using exponential release of cadmium from the Fakse landfill:

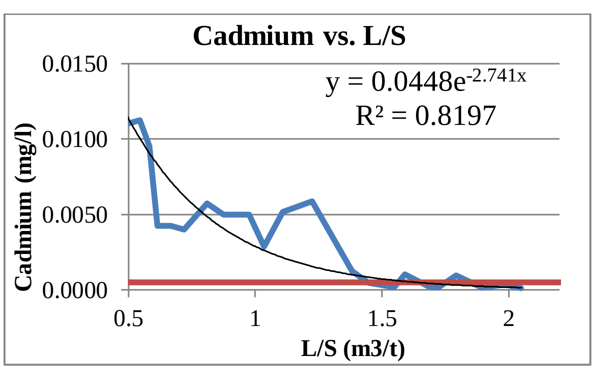


Figure 34: Exponential Release of Cadmium versus L/S from the Fakse Landfill

Step 1: Solve for L/S using Equation 7

- t = 40

- Accounts for the 30 year aftercare period and the amount of time between the initial measurement of cadmium and the beginning of aftercare

- H = 6m
- I = 0.1705 mm/year
  - Averaged effective rainfall at Fakse for operational period

Step 2: Solve for y

- $y = 0.0448 * e^{-2.741*x}$ where x = L/S ratio calculated in "Step 1"

Step 3: Calculate the magnitude of the groundwater criteria limit values

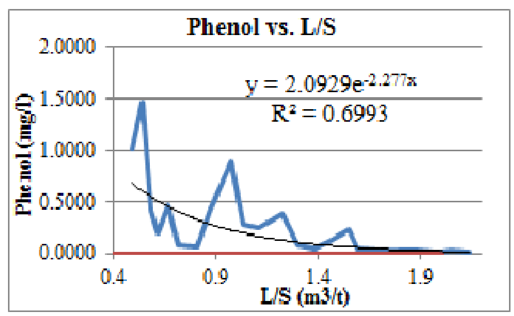
- $Magnitude = \frac{y}{Groundwater\ Criteria\ Limit\ Value}$

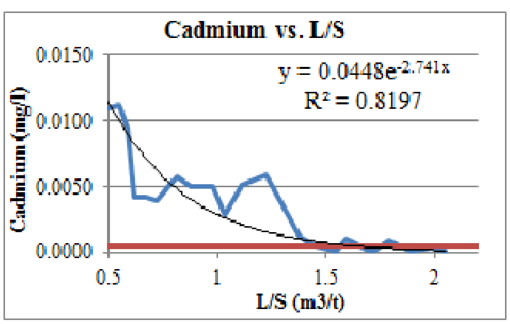
We created profiles for each landfill studied during this project. These profiles list landfill characteristics, such as height, area, and waste type. The profiles also include an aerial map of each landfill and a map of Denmark that shows the landfill locations. A graph of effective rainfall versus amount of percolate is included for most of the profiles. The correlation between these variables is quite clear just from a quick glance- an assumption that we have made throughout this project. Most profiles also include graphs of substance concentration versus L/S or time, depending on what data was available. These graphs have been analyzed by the methods described above to determine the magnitude of the limit values 30 years after the beginning of aftercare. The calculated magnitudes are included in tabular form. It should be noted that these graphs are not representative of all the data from each landfill. These graphs were chosen because they demonstrate the analysis performed on graphs with ideal cases. It would be irresponsible of us to draw conclusions based on this data alone. All data used in our analysis is available upon request.[2] One landfill profile is included in below and the rest of the profiles can be found in Section 7.2- Appendix B.

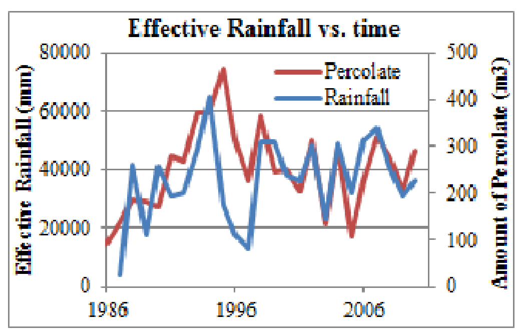
This section displayed our results regarding landfills, specifically the aftercare period. After much research and analysis, we have been able to evaluate current practices and draw correlations pertaining to landfill science. We have developed critiques and recommendations based on our observations, included in the following section.

[2] Please contact Renè Møller Rosendal from RenoSam to obtain the data that supports this report. His email address is rmr@renosam.dk and his telephone number is + 45 2251 6664

Landfill Name	Fakse
Waste Management Company	Affaldsplus
Location	Fakse, Denmark
Operational Period	1981-1997
Cost to Landfill Waste	571 DKK per ton (2008)
Height	6 m
Area	12.1 ha
Type of Waste Landfilled	Mixed Waste
Total Amount of Waste	770,000 tons
Infiltration	170.5 mm/yr
Percolate Data Available	1987-2010
Percolate Amount Data Available	1982-2010
Waste Amount Data Available	1981-1996







Substance	Groundwater Criteria Limit Values (mg/l)	Magnitude of Limit Values @ 30 years
Phenol	0.0005	745.8
Cadmium	0.1	11.2

5 Recommendations

Analysis of landfill data was challenging due to the high diversity of recorded parameters between landfills and within each landfill over time. It would be valuable to researchers, landfills operators and the environment to investigate the possibility of a more standardized set of tests. Our first recommendation is that while testing should still reflect the uniqueness of specific landfill types and landfill sites, a core set of testing requirements would be beneficial. This core set should specify which substances should be tested at every landfill (Danish Statutory Order 252 on Landfills may serve as a guide); other measures should also be taken, such as pH, BOD, and COD, as they give much insight into the science occurring in a landfill.

We have noted strong correlations between several substances tested for in the leachate (See comparison of Potassium, Sodium, and chlorine in Section 4.8). Certain substances are used as indicators during testing which suggests testing substances with strong correlations to others may not be necessary. Our second recommendation is to consider the strong correlation between certain types of lechate substances and to consider that it may be sufficient to test one substance with a strong correlation to another on a regular basis and test the other(s) less frequently. This could save landfill companies (aka the municipalities) money which could be allotted to test different substances or test other substances more frequently.

The inconsistent frequency of leachate testing is another major problem with the current testing practices in Denmark. The testing frequency varies both between landfills and at different stages within the same landfill. Proper analysis of percolate data depends on this frequency and inconsistencies create a road block. Our third recommendation is to consider proposing and supporting regulations for frequency of testing. Such regulations would provide many benefits to future research since wiht regular sampling and a normalized set of substances tested at every landfill, direct comparisons between landfills can be established and modeling efforts can be enhanced.. While we do not make a recommendation for a specific sampling period, it may be appropriate to sample leachate more frequently during the opening of a landfill cell versus the end of aftercare of the same landfill cell. If the certain substance results show clear trends, it may be possible to decrease the frequency of testing for these substances- a set of recommendations for testing frequency could be developed based on stages of the landfills life. For example: monthly testing may be appropriate during the operational phase, and bi-annual testing may be appropriate during the aftercare period.

Site specific rainfall data is another crucial aspect of landfills' analyses. We obtained rain data from a Danish weather station and related it to landfill sites by location. Although this is sufficient for the purpose of the study, the effective rainfall values used in this report do not necessarily reflect reality of rainfall and infiltration of Danish landfills. We are skeptical of the "Rule of Thumb" for which we divided the values from the pan evaporation tests by three to correlate the values to evaporation on a soil surface. As a result of these considerations, our fourth recommendation is that it would be beneficial for landfills to invest in weather stations to obtain more accurate rainfall, humidity and other weather related data that has a direct impact on percolate generation.

5.1 Data Organization

Formatting each data set into a standard format that was readable and workable was an obstacle during this project. Each landfill's data was organized in an Excel spreadsheet with different formats. For our fifth recommendation, we note that it would be valuable to researchers and landfill operators, among others, if data were available in a standardized form. The parameters for this data include percolate data (composition and amount), site specific rainfall data and other related weather data, well data, and waste data (composition and amount). For example, some landfills recorded annual data on separate Excel worksheets, while others recorded all years of the landfill's lifetime on one Excel worksheet. There is also no standardized organization of data within each worksheet- in other words, the order of the data may be very different between landfill data. To standardize this data, it may be helpful if the Danish EPA creates an Excel template for every landfill to use. This template could incorporate the core substances (refer to Section 6.1), among others and become the interface of testing standards in Denmark.

5.2 Recommendations for Modeling

This section notes our observations and details recommendations for future researchers approaching the aftercare problem from a modeling perspective. Our seventh recommendation is that a computer model of landfill dynamics be developed. This model would be very complex due to the many dynamic nature of landfills and the magnitude of factors which affect them. Validations, or comparisons of the simulations to real-life landfill tests (such as lysimeter tests), would be necessary to assure the simulator accurately predicts the reality of landfills. We believe the knowledge gained from this project has given us sufficient background understanding of the complexity of the problem. We recommend the model account for the following factors:

- Depth of landfill cells
- Geometry and area of landfill cells
- Effective rainfall entering the landfill
- Type of waste with parameters such as
    - Material composition of waste
    - Leaching behavior of waste
    - Chemical interactions of waste
    - Permeability of waste
- Liner degradation behavior
- Approximate flow rate and hydraulic conductivity of groundwater system
- Attenuation of percolate in groundwater
- Substance concentrations as measured at the point of compliance (POC)

All of these components were very investigated in our study of the aftercare period, however not all were addressed. Such a computer model would likely require significant resources and scientific knowledge, but could potentially provide an accurate prediction of landfill behavior over long periods of time.

5.3 Recommendations for Leachate Limit Value

The current European Union legislation states that aftercare should be 30 years long or the amount of time it takes for the percolate concentrations to pass the groundwater criteria (See Section 5.6). Measurements of chemicals in solution take place at three different points in the landfilling processes:

1) Leaching tests of waste before they enter the landfill
2) Percolate directly from the landfills collection system
3) Groundwater wells downstream from the landfill
4) Groundwater wells upstream from the landfill

This presents an interesting point of contention because there are no standardized limit values for actual percolate that define when the landfill may exit aftercare – instead it is expected that the values of groundwater should be within acceptable limits. Studies have shown that the liner's lifetime is approximately 80 years [17]. This means the landfill could exit aftercare and be far from environmentally stable at a point in the future (when the liner eventually breaks). Percolate exiting the landfill could exceed the ability of natural groundwater to attenuate percolate to safe values, which could cause environmental danger. The attenuation factors are unknown. Therefore, our eighth recommendation is that work be performed on developing a better understanding of the relationship between measurements taken from the percolate and measurements taken at wells, and in particular how groundwater hydrology affects this relationship.

5.4 Academic and Scientific Study

Based on the complexity of the problem and the clear need for experts in the areas of chemistry, fluid dynamic and hydraulics, we believe that involving those from these scientific and academic fields would be beneficial to creating a more precise solution to this problem. RenoSam could be at the forefront of this project in collaboration with scientists, professors and students to further the understanding of the aftercare problem to the benefit of all stakeholders involved. As with any complex system or engineering challenge, research, practice, experimentation and perseverance can make incredible things possible.

6 Conclusion

Landfills are one of the many necessary components of a modern society, and billions of tons of waste are landfilled every year around the world. As a waste disposal method, landfilling in Denmark is used as conservatively as possible in a manner that respects the environment. Aftercare still remains a critical issue that needs research and investigation in order to be better understood. While landfills may seem a safe and viable waste disposal method today, there is the possibility that many landfills may pose significant problems to future generations, both in Denmark and around the world. By investing the time and energy necessary to understand more about the aftercare problem, society would be on step closer to reducing the possibility of these impacts. It is our hope that efforts to understand this complex problem will continue in directions that will revel in the future.

Landfilling and the appropriate landfill aftercare length are a complex issue. Waste chemistry inside a landfill is a multifaceted process driven by rainfall infiltration and when added to the unknowns of liner degradation and groundwater attenuation, these issues becomes a daunting technical challenge.

Based on this study, we do not believe there is enough information to adequately estimate an appropriate length for the aftercare period at this point, either for a specific landfill or a type of landfill in general. More information and research are needed, and it is likely and the length of an aftercare period could vary between landfills, waste type, and many other factors. Given that current legislation states that the current aftercare period must be 30 years or until the landfill can safely be released from aftercare, operators of landfills should be able to prevent environmental damage so long as they continue to observe their landfills with due diligence.

7 Appendices

7.1 Appendix A – Limit Values an Acceptance Criteria

The landfilling acceptance criterion for various types of waste, dependent on chemical concentrations, is defined in Appendix A. Leaching and compliance tests must meet these criteria to be accepted by a landfill. However, the LFD does not give specifics pertaining to the design and operation of landfills, thus the acceptance criteria are not normalized across the EU.

Table 7: Leaching Limit Values for Inert Waste Landfills[3]

	L/S = 2 l/kg	L/S = 10 l/kg	C0 (percolation test)
	mg/kg dry substance	mg/kg dry substance	mg/l
As	0.1	0.5	0.06
Ba	7	20	4
Cd	0.03	0.04	0.02
Cr	0.2	0.5	0.1
Cu	0.9	2	0.6
Hg	0.003	0.01	0.002
Mo	0.3	0.5	0.2
Ni	0.2	0.4	0.12
Pb	0.2	0.5	0.15
Sb	0.02	0.06	0.01
Se	0.06	0.1	0.04
Zn	2	4	1.2
Chloride	550	800	450
Fluoride	4	10	2.5
Sulphate	560	1000	1500
Phenol index	0.47	1	0.3
DOC**	240	500	160
TDS***	2500	4000	

Table 8: Leaching limit values for non-hazardous waste and stable, non-reactive hazardous waste to be co-disposed together at landfills or cells for non-hazardous waste.[3]

	L/S = 2 l/kg	L/S = 10 l/kg	C0 (percolation test)
	mg/kg dry substance	mg/kg dry substance	mg/l
As	0.4	2	0.3
Ba	30	100	20
Cd	0.6	1	0.3
Cr total	4	10	2.5
Cu	25	50	30
Hg	0.05	0.2	0.03
Mo	5	10	3.5
Ni	5	10	3
Pb	5	10	3
Sb	0.2	0.7	0.15
Se	0.3	0.5	0.2
Zn	25	50	15
Chloride	10000	15000	8500
Fluoride	60	150	40
Sulphate	10000	20000	7000
DOC**	380	800	250
TDS***	40000	60000	

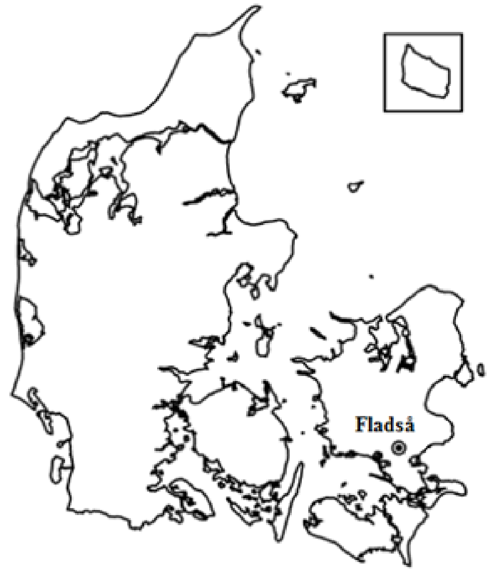
Table 9: Leaching limit values for hazardous waste landfills.[3]

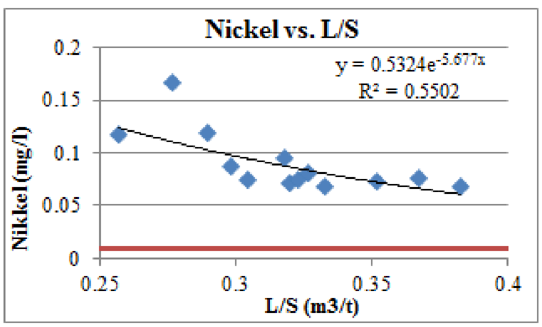
	L/S = 2 l/kg	L/S = 10 l/kg	C0 (percolation test)
	mg/kg dry substance	mg/kg dry substance	mg/l
As	6	25	3
Ba	100	300	60
Cd	3	5	1,7*
Cr total	25	70	15
Cu	50	100	60
Hg	0.5	2	0,3*
Mo	20	30	10
Ni	20	40	12
Pb	25	50	15
Sb	2	5	1
Se	4	7	3
Zn	90	50	60
Chloride	17000	25000	15000
Fluoride	200	500	120
Sulphate	25000	50000	17000
DOC**	480	1000	320
TDS***	70000	100000	

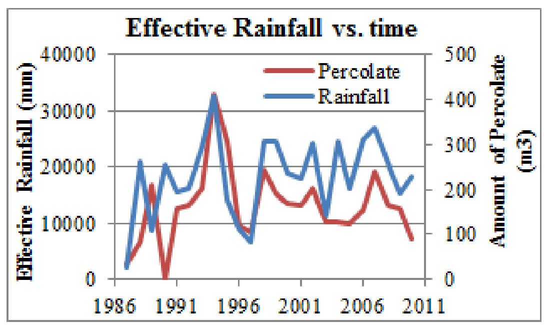
7.2 Appendix B- Landfill Profiles

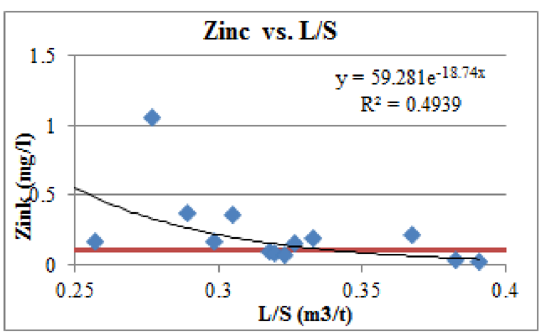
7.2.1 Fladså Landfill Profile

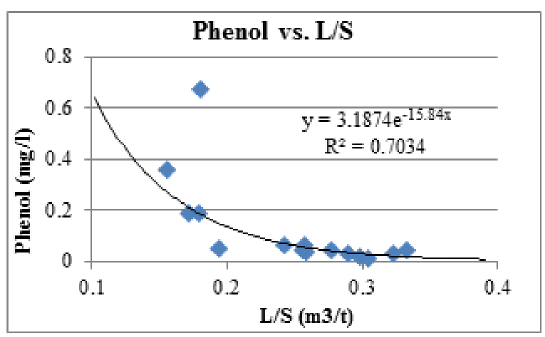
Landfill Name	Fladså
Waste Management Company	Affaldsplus
Location	Fladså, Denmark
Operational Period	1987-2008
Cost to Landfill Waste	400 DKK per ton (2005)
Height	15 m
Area	4.5 ha
Type of Waste Landfilled	Mixed Waste
Total Amount of Waste	846,480 tons
Infiltration	228.6 mm/yr
Percolate Data Available	1988-2010
Percolate Amount Data Available	1987-2010
Waste Amount Data Available	1987-2008

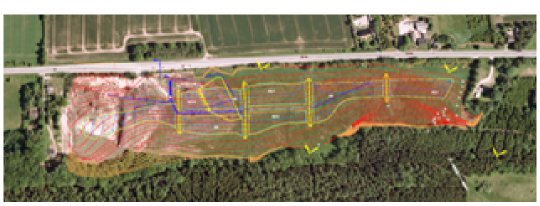








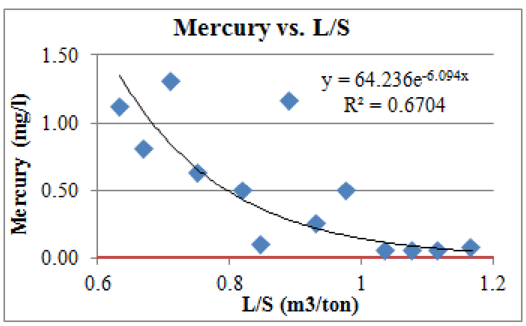


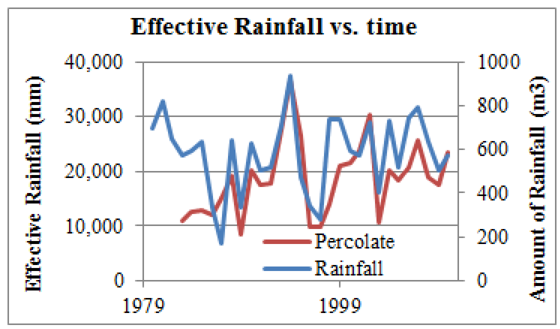


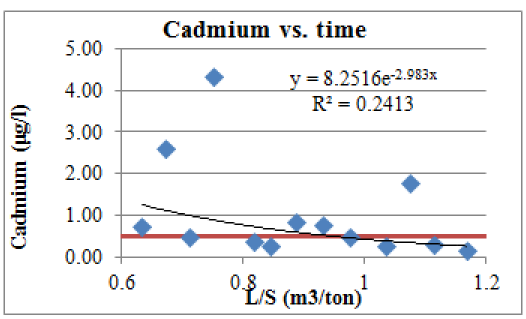
Substance	Groundwater Criteria Limit Values (mg/l)	Magnitude of Limit Values @ 30 years
Phenol	0.0005	2.8
Zinc	0.1	0.1
Nickel	0.01	0.3

7.2.2 Skårup Landfill Profile

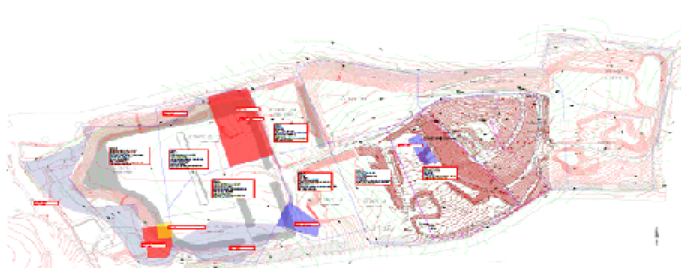
Landfill Name	Skårup
Waste Management Company	RenoSyd
Location	Skanderborg, Denmark
Operational Period	1980-2001
Cost to Landfill Waste	225 DKK per ton (2009)
Height	20 m
Area	8.1 ha
Type of Waste Landfilled	Mixed Waste
Total Amount of Waste	447,606 tons
Infiltration	583.9 mm/yr
Percolate Data Available	1980-2010
Percolate Amount Data Available	1983-2010
Waste Amount Data Available	1985-1997





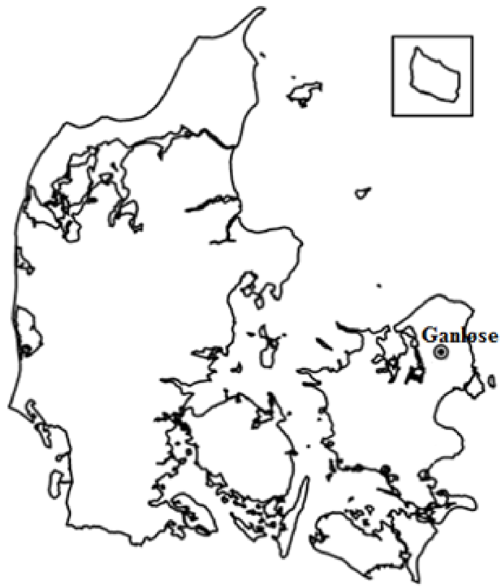


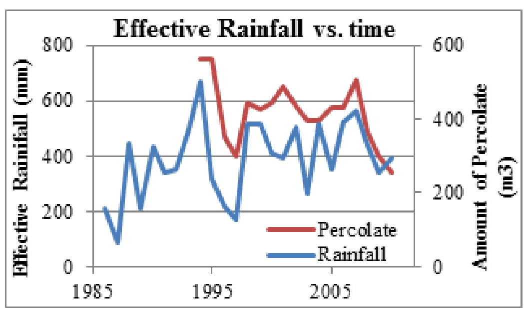
Substance	Groundwater Criteria Limit Values (mg/l)	Magnitude of Limit Values @ 30 years
Mercury	0.0001	10724.5
Cadmium	0.5	2.8

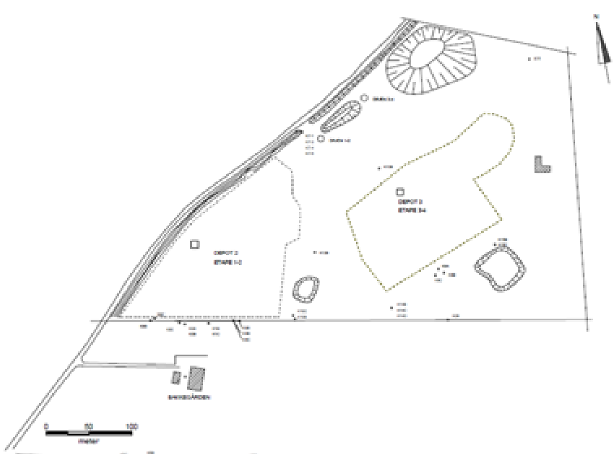


7.2.3 Ganløse Landfill Profile

Landfill Name	Ganløse
Waste Management Company	Verstforbrænding
Location	Ganløse, Denmark
Operational Period	1986-1989
Cost to Landfill Waste	Values are out of date
Height	15 m
Area	1.725 ha
Type of Waste Landfilled	Incineration Waste
Total Amount of Waste	187,500 tons
Infiltration	290.0 mm/yr
Percolate Data Available	1988-2010
Percolate Amount Data Available	1989-2010
Waste Amount Data Available	1983-1966

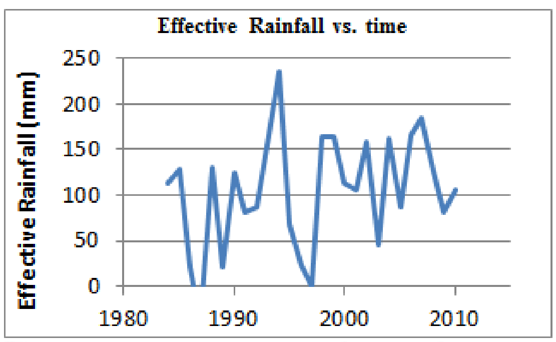






7.2.4 Gerringe Landfill Profile

Landfill Name	Gerringe
Waste Management Company	Refa
Location	Gerringe, Denmark
Operational Period	1984-present
Cost to Landfill Waste	377 DKK per ton (2009)
Height	11 m
Area	12 ha
Type of Waste Landfilled	Mixed Waste
Total Amount of Waste	770,000 tons
Infiltration	104.3 mm/yr
Percolate Data Available	1996-2010
Percolate Amount Data Available	1996-2003
Waste Amount Data Available	1984-2010



7.3 Appendix C- Tools for Data Analysis

7.3.1 Annual Rainfall by location in Denmark

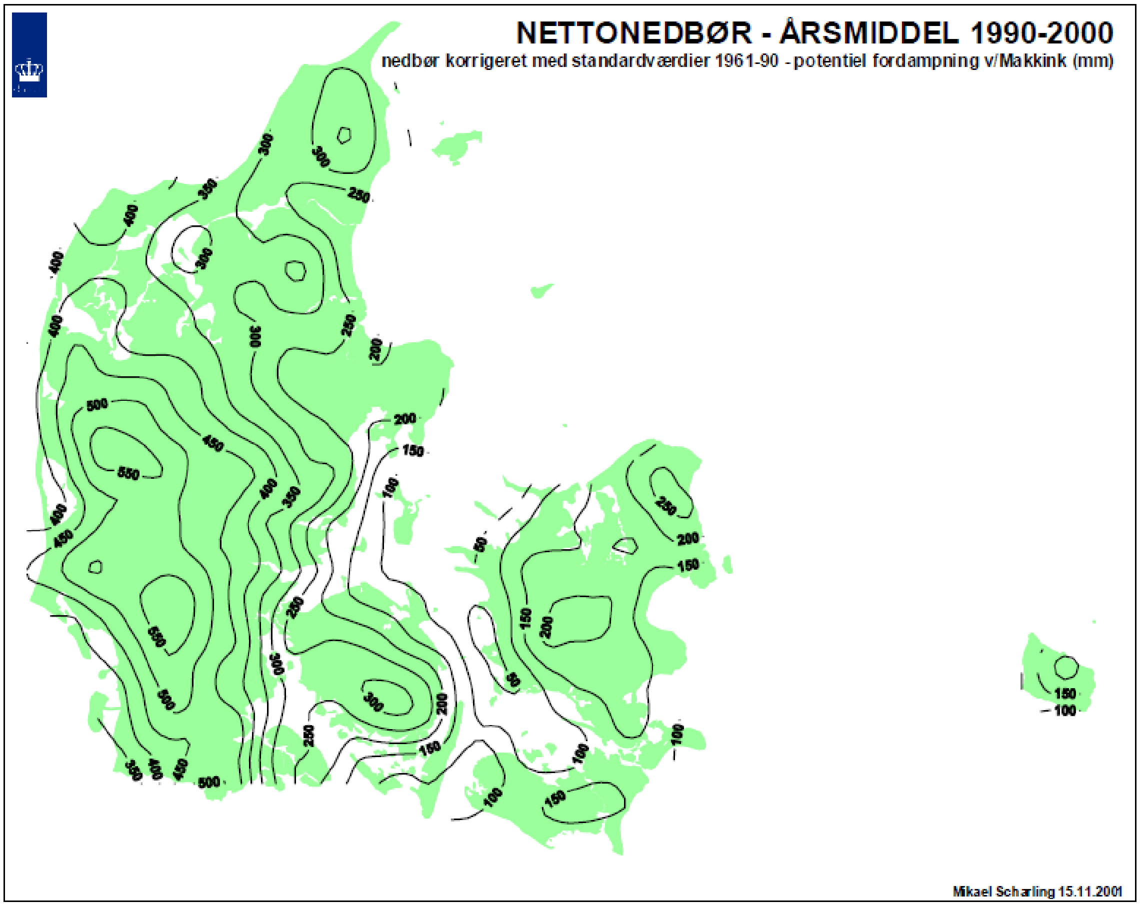


Figure 35: Annual Rainfall in Denmark [30]

Figure 36: Annual Evaporation in Denmark based on Makkinks Formula [31]

Figure 37: Annual Evaporation in Denmark based on the Penman Formula [31]

7.4 Appendix D – Visit and Interview Summaries

7.4.1 Fakse Landfill Visit Summary (Tour)

Fakse landfill is a medium sized landfill in Naestved province that accepts a variety of waste including municipal waste that is too large for incineration, asbestos and insulation waste, construction waste, treated wood for future processing, sludge waste, and composting waste. The landfill consists of 21 cells, 14cells in an old landfilling region and 7cells in a new landfilling region. The old landfill contained municipal solid waste; much of this waste would be incinerated if produced in current times because of new Danish regulations. The landfill site was split into these new and old regions, each with a separate leachate collection system. The landfilling process was observed: front end loaders (equipped with special attachments for moving waste) added material to the pile and drove over the waste to compact it down. Fakse landfill is a smaller landfill that does not include as many of the technologies and processes as larger landfills. Stray waste such as trash and bags can be seen around the landfill caught in bushes and in the surface water drainage system. The leachate collection system is located downstream from the landfill in a concrete structure buried underground. This system contains many valves from different parts of the landfill and pumps to remove the collected leachate and send it to a waste water treatment facility.

7.4.2 Ole Hjelmar, DHI (Key Informant Interview)

- Chemical reactions occur when water is present; almost all countries cap landfills to avoid these reactions. But encapsulation is "storing the problem for later generations because nothing happens for a long time because there is no water"
- Sweden: requirement to cap landfills
    - Hazardous waste: maximum of 5ml of percolate per year
    - Non-hazardous waste: maximum of 50 ml percolate per year
- Legislation for landfills in Denmark was not passed until 2001, only guidelines were present previously
- Data analysis
    - Ignore organic material in analysis
    - Complicated models are not good representations of reality because the waste is very heterogeneous
    - $L/S = \frac{\text{amount of leachate}}{\text{Total amount of solids}}$
        - Inorganic waste
        - One point in time
        - Proportional to time?
        - If more waste is added than leachate collected, it will be represented in a graph of [ ] vs. L/S with an "S" shape

    - Relate rainfall to surface area of landfill and amount of leachate collected
    - Detailed descriptions to supplement data
  - Q: "Where did the 30 year period for aftercare come from?"
    A: The thought was that each generation should take care of their own waste. The EU Directive uses 30 years as the amount of time that the landfill owners are economically responsible.
  - Regulations are soft terms (very practical) in their enforcement. Not all sites are equally vulnerable therefore uniform regulations are not present. Various enforcers have different expectations.
  - t = (L/S)*d*H/I

where t= time; L/S= liquid to solid ratio; d=depth; H= height; I= infiltration

- When choosing landfills to analyze, make sure there is a large amount of percolate
- Problems with models
  - Dry spots- no uniform flow of water
- Wastewater Treatment
  - Mixed with sewage
  - Adds a hydraulic load to the wastewater plant and it isn't very effective because the heavy metals come out in waste water and are landfilled (loop); the waste water is discharged into the ocean
- Some landfills do not have bottom liner, but use natural attenuation
  - Controlled release/seepage with only salts and trace elements

7.4.3 Odense Landfill Visit Summary (Presentation, Tour)

Description

The Odense landfill consists of two main landfilled areas on either side of a channel. The older part is artificially created land from waste that was dumped directly into the ocean during the 70s and 80s, and contains mostly municipal solid waste. Odense take a very active stance in reducing waste impact, and has outreach programs to educate others about the landfilling process and the importance of conservation and waste reduction.

Old Landfill Description:

The old landfill presents and interesting environmental issue today as the landfill has no bottom liner, and groundwater in the area travels upwards and into landfilled bodies. The old landfill has many special systems to address this unique situation, including a leachate collection system around the perimeter of the landfill, and a system to collect surface water in the event that it becomes contaminated. All of the systems are computer controlled and connected via piping buried underneath the channel.

Old Landfill Statistics:

- Up to 30m deep in some areas, variable geography with many hills.
- 10M m^3 of waste
- Currently used as a recreation area
- A landfill gas collection system collects methane from the waste.
    - 11MW of heat energy
    - 14MW of electrical energy
    - Gas sent to a local energy plant
- Vertical liners may be incorporated in the future to prevent leachate from escaping

New Landfill Description:

The new landfill serves a variety of different purposes, and has older cells containing mixed municipal solid waste, and many newer cells for incineration ash, shredder residue, composting, contaminated soil reclamation, and inert mineral waste. Each cell has its own leachate collection system and an impermeable bottom layer. The expected lifetime of the entire new landfill is 120 years. The landfill uses an advance computer system to control pumps, monitor levels in storage tanks, and determine flow rates of leachate. The control system serves a wide variety of other purposes, including monitoring of weather, gas collection systems, database storage for analysis of landfill percolate, and many other functions. Odense is a very modern landfill that employs many of the latest technologies and techniques for reducing the impact of landfilling.

New Landfill Statistics:

- Opened in 1994
- Receives waste from 4 different communities
- Pretreats leachate on site
- Currently contains
    - 70,000 Tons of Shredder waste
    - 20,000 Tons of MSW
- Active collaboration with waste sorting facilities to maximize material recovery
- Uses 1m topsoil cover on closed cells, often from recovered contaminated soil
- Due to hydrology and water table, cells are only 2-3m deep
- Evacuation of groundwater beneath liner during early stages of landfilling is necessary to prevent upheaval of liner due to pressure of upwelling groundwater
- Cells are up to 30m high

7.4.4 Meeting with Jorgen Hansen (Danish Environmental Protection Agency)

- Legislation is continuously changing
  - Ministry of Environment can pass laws if within a certain scope (Environmental Protection Act)
- European Union: Chairman from one country (rotates) decided which topics should be discussed
  - Commission
    - Proposes regulations
    - Created EU Landfill Directive & recommended it to Parliament
  - Parliament
    - Political
    - Passed EU Landfill Directive (Adopted and Sent to Member States)
  - Council
    - Technical Adaption Committee
      - Limits for leaching and compliance tests?
    - Determined leachate/waste acceptance criteria
  - Goat-Plate = member states can over implement the EU Directives
  - Denmark "goat-plates" with the EU Landfill Directive to better protect the environment, specifically the water table because Danish drinking water is not treated
- 1999: EU Landfill Directive
  - Focus was on landfill site and design requirements
  - 2001: Implementation deadline
  - 2002: EU Landfill Decision
    - Detailed annexes
    - Required unanimous decision in EU which it eventually received
- It is possible to obtain a landfill permit without a bottom liner if you can prove that the leachate will not exceed National Limit Values (used for harbor sludge). The Danish Statutory Order describes the criteria that must be met to have a landfill without a bottom liner.
- The legislation should not be site-specific but be based on leaching curves organized by waste type. A study that investigates how each type of waste leaches over time would be helpful to determine the amount financial security that is necessary per ton of waste. A more accurate estimate of this cost would benefit the municipalities who own the landfills. The polluter pays security collateral upfront; it is very important that the landfill charges an appropriate amount for this collateral to offset the costs of closure and aftercare down the road. This is important because the municipalities must pay for any unexpected extension of the aftercare period. The municipality can only make the

polluter pay when they deposit waste, not a second time when the landfill is in need of more funds for aftercare.

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7.5 Appendix E – Release Forms

7.5.1 IRB Release Form- Ole Hjelmar

2

Nathaniel VerLee; E-mail: nverlee@wpi.edu
Danielle Antonellis; Email: daniellis@wpi.edu; Tel: 781-264-8014

Professor Kent Rissmiller; Email: kjr@wpi.edu; Tel. 508-831-5019, and the University Compliance Officer (Michael J. Curley; Email: mjcurley@wpi.edu; Tel. 508-831-6919,).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time.

By signing here you acknowledge that you have been informed about and consent to be a participant in our interview. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____________________ Date: 20/4/2011
Study Participant Signature

Ole Hjelmar
Study Participant Name (Please print)

____
Email (so we may contact you)

By singing here you agree that your name may be used in our research and we may cite you as a research source. Your agreement is voluntary and optional.

____________________ Date: 20/4/2011
Study Participant Signature

____________________ Date: 20/4/2011
Signature of Person who explained this study

7.5.2 IRB Release Form – Jorgen Hansen

Nathaniel VerLee; E-mail: nverlee@wpi.edu
Danielle Antonellis; Email: daniellis@wpi.edu; Tel: 781-264-8014

Professor Kent Rissmiller; Email: kjr@wpi.edu; Tel. 508-831-5019, and the University Compliance Officer (Michael J. Curley; Email: mjcurley@wpi.edu; Tel. 508-831-6919,).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time.

By signing here you acknowledge that you have been informed about and consent to be a participant in our interview. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Jørgen Hansen
Study Participant Signature

Date: 02.05.2011

Jørgen G. Hansen
Study Participant Name (Please print)

JOGHA@MST.DK
Email (so we may contact you)

By singing here you agree that your name may be used in our research and we may cite you as a research source. Your agreement is voluntary and optional.

Jørgen Hansen
Study Participant Signature

Date: 02.05.2011

Danielle Antonellis
Signature of Person who explained this study

Date: **02.05.2011**

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