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MATHEMATICAL MODELING OF A BIOGAS RECOVERY SYSTEM AT THE İZAYDAŞ, KOCAELİ SANITARY LANDFILL

by

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MATHEMATICAL MODELING OF A BIOGAS RECOVERY SYSTEM AT THE İZAYDAŞ, KOCAELİ SANITARY LANDFILL

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ABSTRACT

Sanitary landfilling is a widely used economic and practical application for the disposal of municipal and industrial solid wastes. A key problem associated with the storage of the organic waste material in a landfill is the generation of landfill gasses and the potential hazards associated with their migration and emission into the atmosphere. At the same time, methane, which makes up about half the total gases produced, can be used for the generation of energy. Consequently, an important component of landfill design and management is evaluating the potential energy that can be recovered from these landfill gasses and, if deemed favorably, designing an appropriate gas collection system.

The purpose of this study is to asses the potential of landfill gas generation and recovery from Lot 7 of the İZAYDAŞ solid waste disposal site in Izmit, Turkey. A multi-step model is developed to evaluate the performance and aid in the operation of an active gas collection system for Lot 7, a closed lot for municipal waste disposal. The model consists of three main components: (i) a water balance model, HELP; (ii) a gas generation model, LANDGEM: and (iii) a gas flow model, MODAIR, based on the MODFLOW computer program. The model will be used also to evaluate the efficiency of the existing wells to serve as gas collection wells, and assess the sensitivity of the gas collection system to key parameters and assumptions.

The model was based on the actual landfill design for Lot 7 and the actual data on the amounts of solid waste disposed of in Lot 7. Additional laboratory tests on a number of synthetically generated samples were conducted to determine the flow properties of the solid waste. Weather data from the nearby Kocaeli meteorological station were incorporated in the model. For parameters that were not available, best estimates from the literature were used. Because of the relatively high uncertainty in the definition of some parameters, a range of values were also considered.

The results of this study indicate that the main factors influencing the efficiency of the gas collection system are: (i) decay rate of the organic component of the solid waste, (ii) the mode of operation of the active gas collection system, (iii) the air permeability of the soil cover. Specifically, the decay rate controls the duration of the most active gas generation period and the required extraction rates to capture the generated gases. Time-dependent gas extraction rates, as opposed to time-invariant extraction rates, was shown to lead to reduced gas losses into the atmosphere and higher landfill gas concentration in the collected gas. Moreover, the use of low permeability soil cover can also lead to reduced air intrusion into the collection system.

ÖZET

Düzenli depolama, evsel ve endüstriyel katı atıkların bertarafında çok yaygın olarak kullanılan ekonomik ve uygulanması kolay bir yöntemdir. Bunun yanında düzenli depolama sahasında organik atık depolanmasından kaynaklanan önemli bir sorun çöp gazı oluşumu ve bu gazın kontrolsüz yayılımı ve havaya karışmasıdır. Ancak, üretilen toplam gazın yarısı olan metan, enerji üretiminde kullanılabilmektedir. Buna bağlı olarak katı atık depolama sahalarının tasarımı ve işletilmesindeki önemli kriterlerden biri bu çöp gazlarından kazanılacak potansiyel enerjinin belirlenmesi, ve elverişli olması durumunda uygun bir gaz toplama sistemi tasarlanmasıdır.

Bu çalışmanın amacı İZAYDAŞ düzenli katı atık depolama sahasındaki Lot 7 de çöp gazı oluşumu ve toplanmasının potansiyelinin değerlendirilmesidir. İZAYDAŞ düzenli depolama sahasındaki işletimi bitip kapanmış olan Lot 7 için aktif gaz toplama sistemi performansının değerlendirilmesi ve işletilmesine yardımcı olmak amacıyla çok basamaklı bir model geliştirilmiştir. Model üç bileşenden oluşmaktadır; (i) bir su dengesi modeli: HELP, (ii) bir gaz üretim modeli: LANDGEM ve (iii) bir gaz akım modeli: MODAIR (MODFLOW bazlı bilgisayar programı). Model mevcut olan kuyuların gaz toplama kuyusu olarak kullanılmasının verimliliğini belirlemek ayrıca gaz toplama sisteminin önemli parametre ve varsayımlara hassasiyetini değerlendirmek amacı ile de kullanılacaktır.

Model Lot 7 için mevcut düzenli depolama sahası tasarımı ve Lot 7 de depolanan gerçek katı atık miktarlarını baz alınarak hazırlanmıştır. Ek olarak katı atık içindeki akım özellikleri yapay olarak hazırlanmış numuneler ile yapılan deneyler sonucunda belirlenmiştir. Düzenli depolama alanı yakınındaki Kocaeli meteoroloji istasyonunun hava durumu bilgileri modele dahil edilmiştir. Mevcut olmayan parametreler için literatür bilgilerinin en uygun olanları tahmin edilerek kullanılmıştır. Bazı parametrelerin diğerlerine nispeten büyük oranda belirsiz olmalarından dolayı ayrıca bir değer aralığı dikkate alınmıştır.

Bu çalışmanın sonuçları gaz toplama sisteminin verimini etkileyen ana faktörleri: (i) katı atık organik bölümünün bozunma hızı, (ii) aktif gaz toplama sisteminin işletilme biçimi (iii) yüzey toprak örtüsünün geçirimsizliği olarak göstermektedir. Özellikle bozunma hızı, aktif gaz üretim döneminin süresini ve üretilen gazı toplamak için gereken çekim hızını kontrol etmektedir. Zamana bağlı gaz çekim hızları zamana bağlı olmayanlara oranla havaya bırakılarak kaybedilen gaz oranını azaltmakta ve toplanan gazın içindeki çöp gazı konsantrasyonunu arttırmaktadır. Ayrıca düşük geçirimliliğe sahip yüzey toprağı kullanmak da toplama sistemine hava girişini azaltmaktadır.

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1. INTRODUCTION

1.1. Landfill Development and Significance

Land disposal of refuse has long been a key element in waste management. It has been practiced by communities for more than five thousand years as shown by evidence found on many archaeological sites (White-Hunt, 1980). In modern solid waste management, many countries still consider landfilling as the preferred method of disposing municipal solid waste (MSW) because it is generally the cheapest way of eliminating refuse compared with other methods such as incineration and composting (Lema et al., 1988). A survey carried out in 1989 on the production and disposal of MSW in 15 industrial countries suggested that 68.8 per cent of their MSW was disposed of by landfilling (Cossu, 1989).

Due to a growing awareness of the impact of landfills on the environment together with the introduction of more stringent regulations, uncontrolled open dumps commonly found two decades ago are disappearing and being replaced by well engineered sanitary landfills. With increasing research and engineering input devoted to landfill design and management, modern sanitary landfilling is fast becoming a state-of-the-art technology.

The current landfill technology is primarily based on a permanent storage and containment or "dry cell" concept (Owens et al., 1993). Most of the research activities have been concentrating on the design of liner, cover, and hydraulic system with the aim of sealing off a landfill from the external environment as much as possible. The idea is to minimize the amount of water entering the waste. With the limited moisture present within a well-encapsulated landfill cell, the waste can then be preserved in a relatively inactive state, discouraging the formation of leachate and landfill gas to reduce environmental impacts. While this landfilling technique may delay decomposition due to a lack of moisture, experience with this type of landfill has brought about a growing concern regarding to their long-term encapsulating performance. As the containment system ages and becomes less effective, there is a long-term risk that the suppressed biodegradation may turn active in the future.

With a better understanding of landfill decomposition processes and behavior, there has been a strong trend in recent years to shift the philosophy of landfill design from the permanent storage concept towards a bioreactor approach (Onay and Pohland 2001).

The bioreactor landfill concept, in contrast to the permanent storage approach, allows active landfill management based on an understanding of the biological, chemical and physical processes involved (Tchobanoglous, 1993). It focuses on enhancing the degradation processes to stabilize the waste and aims to bring forward the inert state of a landfill in a relatively short time. It basically utilizes a landfill as a bioreactor to treat and stabilize the waste rather than merely as a burial ground. It offers the potential to avoid the long-term environmental risk associated with the "dry tomb" approach as well as providing other operational benefits.

Landfilling or land disposal has been the most commonly used method for waste disposal by far (Tchobanoglous, 1993). The planning, design and operation of modern landfills involve the application of a variety of scientific, engineering, and economic principles due to their high pollution potential. The environmental impacts of landfills are associated mainly with the emission of leachate and biogas. Sanitary landfilling aims to stabilize the landfill in an efficient and controlled way, so that the environmental impacts are minimized (Tchobanoglous, 1993).

Anaerobic decomposition of organic fraction of solid waste in the landfill environment produces landfill gas (LFG) (Arigala et al., 1995). LFG mainly consists of methane and carbon dioxide, both of which are odorless. LFG can migrate through soil into structures located on or near landfills. Since methane presents a fire or explosive threat, LFG must be controlled to protect property, and public health and safety. A positive side to LFG control is energy recovery. Thus, engineered solutions are needed to efficiently and safely monitor, collect, and process landfill gas.

The modeling of gas generation and transport from a municipal solid waste landfill is a complicated task due to the complex processes taking place in the landfill. Biogas characteristics and production rate are mainly influenced by: the characteristics of the emplaced wastes, the interaction between waste and percolating moisture in the landfill, climatic conditions of the site, landfill design, hydrogeological properties of the site, microbial activities and the stage of landfill stabilization (McBean et al., 1995).

1.2. Objectives and Scope of Study

Landfilling has been the most economical and environmentally acceptable method for the disposal of solid wastes in Turkey, as in the rest of the world. However, the increased usage of this method and public awareness are driving concerns on the pollution potential and hazard of gas produced in landfills. Even the safest landfill designs have a finite life expectancy for complete biogas generation and transport through the atmosphere.

Being one of the largest sanitary landfills in Turkey, İZAYDAŞ landfill site has a high potential of generating environmental problems. By its huge potential of energy, biogas recovery is also a big financial support for operational expenses of any landfill. Therefore, this study aims to simulate numerically biogas generation and its transport for the given site. The model consists of three components; a water balance model, a gas generation model and a gas flow model.

Moisture content was determined by HELP model (Schroeder, 1994) based on local meteorological data and real landfill layer properties. The Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills.

The Landfill Gas Emissions Model (LandGEM) (EPA, 1988) was used to estimate methane emissions from landfill. Landfill gas generation rates were calculated with a first order decay model used in LandGEM.

The gas flow model is accomplished by the MODAIR (Guo, 1996) computer program, a gas flow model in porous media. MODAIR is an adaptation of air transport under transient conditions to MODFLOW (McDonald and Harbaugh, 1988) which is developed to simulate groundwater flow in porous media.

By choosing optimum parameters in every step of this study, the aim is to provide reliable predictions to the authorities regarding the investment decision process to create an active gas collection system in İZAYDAŞ Landfill Site.

2. LITERATURE REVIEW

This chapter provides a comprehensive review of the current knowledge and developments related to bioreactor approach in landfilling. The term bioreactor approach in landfilling is used here to represent any active landfill management that aims to stabilize waste in contrast to the conventional permanent storage containment landfills. The chapter starts with some background information on MSW degradation in landfills, followed by an overview of bioreactor enhancement techniques.

2.1. Municipal Solid Waste Degradation in Landfills

2.1.1. Evolution Sequence

With knowledge of the decomposition processes, it is not difficult to understand that most landfills receiving MSW proceed through a series of rather predictable events. Such a sequence has been described by, among others, Farquhar and Rovers (1973), and Christensen and Kjeldsen (1989). The sequence can be separated into five distinct phases in terms of gas composition and leachate concentrations as illustrated in Figure 2.1. (Christensen and Kjeldsen, 1989; Farquhar and Rovers, 1973)

Aerobic Degradation: Phase 1 is the short initial **aerobic** decomposition where oxygen is still present within the landfill mass. The amount of leachate generated in the aerobic process is generally not substantial.

In this degradation process, aerobic bacteria convert organic matter mainly into carbon dioxide, water, energy (heat), and biomass product.

Often a landfill is capped with a low permeability cover and the amount of oxygen that can penetrate into the waste is limited. Also the waste in most modern landfills is highly compacted with a minimum void. Hence the initial aerobic biodegradation generally lasts only a short time and the bacteria activities decline upon the depletion of oxygen.

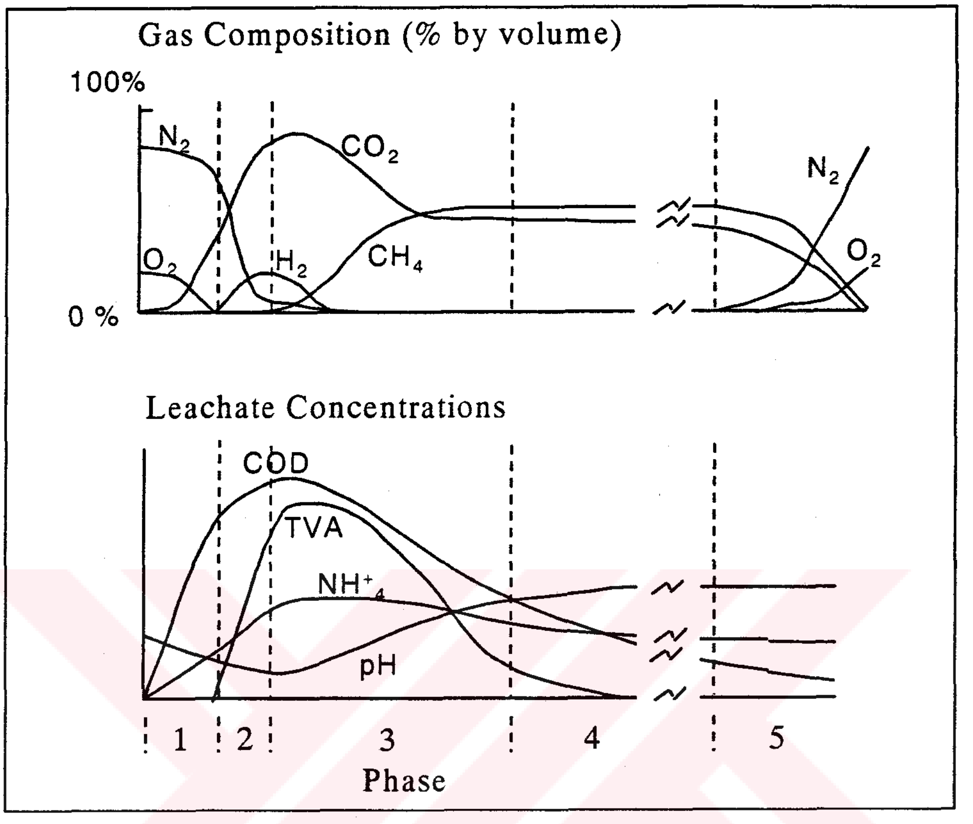


Figure 2.1. Typical landfill evolution sequence in terms of gas and leachate composition (Tchobanoglous, 1993)

After this short initial aerobic stage, the only part of the landfill body that may still involve aerobic metabolism will be the uppermost layer where oxygen may exist by means of diffusion and rainwater infiltration.

Anaerobic Degradation: Phase 2 covers the immediate anaerobic degradation processes of acid-fermentation and acetogenesis. The two processes together are generally referred to as the **acid production** phase. The concentration of volatile fatty acids rises to a peak and pH of the leachate reaches its lowest. There is a concurrent increase in inorganic ions which is due to the leaching of easily soluble material in the more acidic environment. Thus, the leachate generated at this stage is of high strength. The content of nitrogen in the landfill gas diminishes as it is displaced by hydrogen and carbon dioxide generated in the fermentative and acetogenesis processes.

There are three main groups of bacteria involved in the anaerobic landfill ecosystem:

Fermentative bacteria: These bacteria perform hydrolysis and organic acid fermentation. They are a large heterogeneous group of strictly anaerobic and facultative anaerobic bacteria (the latter prefer anaerobic conditions but can make use of oxygen on a temporary basis).

Acetogenic bacteria: They are heterogeneous bacteria that convert the products derived from the above fermentation into acetic acid.

Methane producing bacteria: These bacteria are strictly anaerobic and are very sensitive to the presence of oxygen and pH of the environment. They use only specific substrates.

The four important anaerobic degradation steps as indicated in Figure 2.2 are:

Hydrolysis: This is an important process through which the solid and complex dissolved organic matters are broken down into smaller, soluble components required for subsequent microbial conversions (e.g. carbohydrates into simple sugars, proteins into amino acids and lipids into glycerol and long chain fatty acids). Hydrolysis is promoted by the extra cellular enzymes produced by the fermentative bacteria (Christensen and Kjeldsen, 1989; Aragno, 1988).

Acid Fermentation: The dissolved organic matter from hydrolysis is fermented by the fermentative bacteria primarily into volatile fatty acids (VFAs), alcohols, hydrogen and carbon dioxide. The acid fermentation process thus results in a high concentration of volatile fatty acids.

Acetogenesis: The acetogenic group of bacteria converts the longer chain volatile fatty acids (propionate, butyrate, isobutyrate, valerate, isovalerate and caproate) and alcohols into acetate (the shortest chain fatty acid), hydrogen, and carbon dioxide.

Methanogenesis: Subsequently methane is produced by the methanogenic bacteria. The conversion is carried out either by the acidophilic group converting acetic acid to methane and carbon dioxide, or by the hydrogenophilic group converting hydrogen and carbon dioxide to methane. Both groups are strictly anaerobic and require a condition of low redox potential. They are also sensitive to pH; the range of pH tolerated by the methanogenic bacteria is limited (at a range between 6 and 8).

Phase 3 is a **transition** from the above acid phase to the next methanogenic phase with a steady growth of methanogenic bacteria. As the growth of methanogenic bacteria is initially suppressed by the acidic environment, it usually takes some time for them to develop and dominate the system. The methane concentration increases slowly with a decrease in hydrogen and carbon dioxide. With the gradual development of the methanogenic microbial population, more acetic acid is converted into methane resulting in an increase in pH. With the redox potential dropping to its lowest value, nitrates and sulphates are reduced to ammonia and sulphides respectively.

Phase 4 is the **methanogenic** phase at which the methanogenic bacteria have overcome the acidic environment and established themselves well in the system. It is distinguished by a steady methane production. The methane concentration for a typical landfill would be around 50 to 60 per cent by volume with the rest being mostly carbon dioxide. When the degradation reaches this stage, the composition of leachate is characterized by a close-to-neutral pH value, a low concentration of volatile acids, and a reduced amount of total dissolved solids. Thus, the high strength leachate generated from the preceding acid production is weakened by this methanogenesis process.

Phase 5 is the final **post-methanogenic** stage. There is a lack of long term scientific data related to this maturation stage. It is generally expected that the landfill mass will eventually evolve towards an aerobic condition as the rate of oxygen diffusion into the waste exceeds the oxygen consumption rate. Other degradation, which requires an aerobic environment, will then take place. It is believed that the rate at which such a final evolution may progress, or whether it will occur at all, depends on specific landfill conditions such as moisture content and final cover.

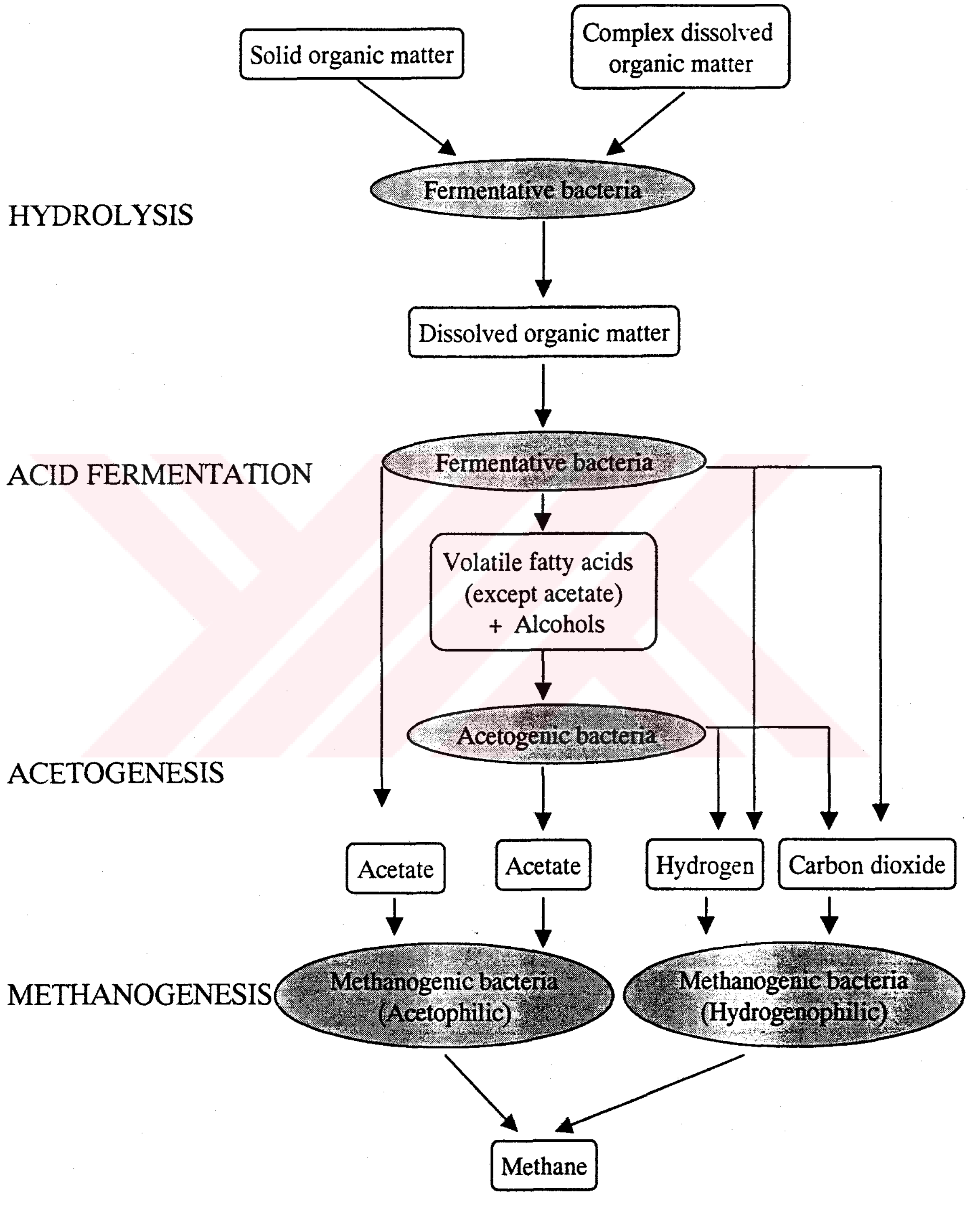


Figure 2.2. Simplified anaerobic degradation processes involving various bacteria groups in a landfill ecosystem (Based on Tchobanoglous, 1993)

This idealized evolution sequence, applies to a homogeneous landfill mass. One should recognize that as most landfills are constructed of sub-cells or pockets of waste of different ages and conditions, it is common that more than one of the above phases may take place concurrently in a full-scale landfill. Therefore, the evolution of a real landfill situation could be more complicated. Nevertheless, the overall landfill gas and leachate development patterns as described in Figure 2.1 can be useful stabilization indicators. The time scale of the evolution sequence is omitted intentionally as the duration of each phase may vary considerably depending on many influencing factors which are discussed below.

2.1.2. Factors Affecting MSW Stabilization in Landfills

The fundamental factors that affect the efficiency of MSW degradation in a landfill system are summarized in Table 2.1 and are discussed below.

Moisture: Moisture is essential for the activities of all microorganisms including the bacteria consortium in the landfill ecosystem. Many investigations have shown that the methane production rate of a landfill rises with an increase in moisture content of the waste (DeWalle and Chian, 1978; Rees, 1980; Pohland, 1986). Hartz and Ham (1983) reported that methane production would decrease as moisture level in the waste decreases and would cease completely below the 10 per cent moisture level (by wet mass).

Rees (1980) provided a summary of research findings which suggests that the landfill gas production rate rises exponentially with increase in moisture content up to 60 per cent (by wet mass). Higher moisture content does not seem to enhance nor decrease the gas production rate (Pohland, 1986).

Furthermore, moisture movement in a landfill facilitates the following: (a) the exchange of substrates, nutrient and buffer, (b) the dilution of inhibitors, and (c) the distribution of bacteria within the landfill environment. A laboratory study (Hartz and Ham, 1983) showed that the rate of methane production with free moisture movement increased ten-fold as compared with a quiescent condition.

However, if moisture is added to the waste too fast, it may produce a negative effect by over-cooling the system (Farquhar and Rovers, 1973). This is because the anaerobic decomposition is also influenced by temperature.

Oxygen: The presence of oxygen inhibits the activities of anaerobic bacteria in a landfill. As discussed earlier, the methanogenic bacteria are strictly-anaerobic and are very sensitive to the presence of oxygen. It has been reported that an optimum redox potential is between -200mV (Farquhar and Rovers, 1973) and -300mV (Christensen and Kjeldsen, 1989). However, lysimeter scale studies also showed that methanogenic phase could be developed at a redox potential of about -100mV (Mata-Alvarez and Martinez-Viturtia, 1986).

Although atmospheric oxygen may penetrate into the landfill by means of air diffusion and rain water infiltration, the presence of aerobic bacteria in the uppermost layer of the waste would consume the oxygen and if there is a well-sealed capping, it would limit the presence of oxygen to the top 1m or less of the waste mass.

pH: The pH in a landfill system can have a significant influence on the methane conversion. While the fermentative and acetogenic bacteria can tolerate a wider range of pH, the methanogenic microorganisms are only active within a narrow pH range of between 6 and 8 (Ehrig, 1983; Farquhar and Rovers, 1973).

It is not uncommon to observe a suppressed on-set of methanogenesis due to an over-stimulated acid production, where the system is said to become “sour”. Similarly, in a well established methanogenic system, if due to any reason (e.g. intrusion of oxygen) the activity of methanogenic bacteria in the landfill ecosystem is suppressed and the conversion of hydrogen, carbon dioxide and acetic acid to methane would not proceed; the pH of the system will drop as a result of the accumulation of volatile fatty acids. Any decrease in the pH will further slow down the growth of the methanogenic bacteria. In an extreme case, this may stop the whole methane conversion.

Alkalinity: Alkalinity results from the presence of hydroxides, carbonates, and bicarbonates of elements such as calcium, magnesium, sodium, potassium, or ammonia. It is expressed in terms of calcium carbonate. It acts as an effective pH buffer, which may significantly improve the efficiency of the degradation by maintaining a close to neutral pH range in the landfill ecosystem. It has been reported that an acetic acid to alkalinity ratio less than 0.8 is essential for the initiation of methane production (Ehrig, 1983). Farquhar and Rovers (1973) suggested that an alkalinity in excess of 2000 mg/L and a concentration of volatile acids less than 3000 mg/L are required for good methane production.

Temperature: Farquhar and Rovers (1973) reported that there are three groups of methanogenic bacteria operating at different temperature ranges, namely psychrophilic (<20°C), mesophilic (20°C to 44°C) and thermophilic (>44°C). Mesophilic bacteria are relevant to landfill methanogenesis.

Laboratory studies have reported that the production of methane increased significantly (up to 100 times) when temperature raised from 20°C to 40°C (Christensen and Kjeldsen, 1989, Hartz et al, 1982). The optimum temperature for methane production was at 41°C, while Mata-Alvarez and Martinez-Viturtia (1986) showed that the optimum temperature range was between 34 to 38°C in laboratory test cells with leachate recirculation.

The amount of heat energy generated by anaerobic decomposition processes is small compared to aerobic degradation. However, because landfill wastes and earth capping are good insulation materials, the heat loss to the external environment is generally minimal. Thus, the heat generated by the anaerobic processes is often enough to maintain an elevated temperature within the landfill mass. In a temperate climate, landfill temperature between 30°C and 45 °C has been reported (Rees, 1980).

Hydrogen: Since hydrogen acts as both substrate and product in the various anaerobic conversions, it plays an important role in the balance of the microbial ecosystem.

At low hydrogen pressure the fermentation process yields hydrogen, carbon dioxide and acetate. At high hydrogen pressure, the process produces volatile fatty acids (except acetate) and alcohols (refer to Figure 2.1).

For the subsequent acetogenesis, if the hydrogen pressure in the landfill system is too high, longer chain volatile fatty acids generated in the above fermentation process will not be converted into acetate (along with hydrogen and carbon dioxide) but will accumulate. Barlaz et al. (1987) suggested that this conversion requires a hydrogen pressure below 10^{-6} atmospheres.

Nutrients: If a biological system is to function properly, nutrients must be available in adequate amounts. Nutrients usually refer to nitrogen, phosphorus and other micro-nutrient including sulfur, calcium, magnesium, potassium, iron, zinc, copper and cobalt. Anaerobic assimilation requires much less nutrient than aerobic conversion processes. In most landfills, there are generally adequate supplies of these nutrients. However, heterogeneity of a landfill may create local nutrient-deficient pockets.

Sulfate: Christensen and Kjeldsen (1989) suggested that landfill methane production would reduce if sulfate is available. Sulfates are reduced to sulfides under the anaerobic conditions and may upset the biological process if the sulfide concentration exceeds 200 mg/L (Tchobanoglous et.al., 1991).

Inhibitors: While oxygen, hydrogen, pH, and sulfate all have inhibitory effects on the methanogenic bacteria as discussed above, the inhibitors that are described in this section are cations, heavy metals and organic compounds.

Effects of cations (sodium, potassium, calcium, magnesium and ammonium) on methane production have been studied by McCarty and McKinney (1961). These cations, in low concentrations, are essential as micro-nutrient. But in high concentrations, they significantly inhibit methane production. The study reported a range of concentration levels that would cause different levels of impacts. However, in landfill environment, the concentrations of these cations are usually below the moderate inhibitory levels as indicated in Table 2.1.

For heavy metals, Ehrig (1983) suggested that their concentrations commonly present in landfill wastes are not high enough to influence significantly the sensitive methanogenic bacteria.

The toxic effects caused by various organic compounds have been studied by several researchers and are summarized by Christensen and Kjeldsen (1989). They concluded that fairly high concentrations of these toxic organic compounds are required to impose a significant inhibitory effect on a methanogenic system. In MSW landfills, their concentrations would generally be too low to have any inhibitory effect.

Table 2.1. Summary of influencing factors on landfill degradation (Yuen, 1999)

Influencing factors	Criteria / Comments	References
Moisture	Optimum moisture content : 60 per cent and above (by wet mass)	Pohland (1986) and Rees (1980)
Oxygen	Optimum redox potential for methanogenesis: -200mV -300mV below -100mV	Farquhar and Rovers (1973) Christensen and Kjelden (1989) Pohland (1980)
pH	Optimum pH for methanogenesis: 6 to 8 6.4 to 7.2	Ehrig(1983)/ Farquhar and Rovers(1973)
Alkalinity	Optimum alkalinity for methanogenesis : 2000mg/l Maximum organic acids concentration for methanogenesis : 3000mg/l Maximum acetic acid/alkalinity ratio for methanogenesis : 0.8	Farquhar and Rovers (1973) Farquhar and Rovers (1973) Ehrig (1983)
Temperature	Optimum temperature for methanogenesis 40°C 41°C 34-38°C	Rees (1980) Hartz et al. (1982) Mata-Alvarez et al. (1986)
Hydrogen	Partial hydrogen pressure for acetogenesis: Below 10^{-6} atm.	Barlaz et al. (1987)
Nutrients	Generally adequate in most landfill except local systems due to heterogeneity	Christensen and Kjelden (1989)
Sulphate	Increase in sulphate decreases methanogenesis	Christensen and Kjelden (1989)
Inhibitors	Cation concentrations producing moderate inhibition (mg/ l) : Sodium 3500-5500 Potassium 2500-4500 Calcium 2500-4500 Magnesium 1000-1500 Ammonium(total) 1500-3000 Heavy metals : No significant influence Organic compounds : Inhibitory only in significant amount	McCarty and McKinney (1961) Ehrig (1983) Christensen and Kjelden (1989)

3. SITE DESCRIPTION

İZAYDAŞ Landfill Site is a part of the Izmit Integrated Environmental Management Project which consists of five parts;

- Clinical and Hazardous Waste Incineration and Power Plant
- Izmit Eastern Part Domestic and Industrial Waste Water Treatment Plant
- Industrial Waste and Domestic Solid Waste Sanitary Landfill
- Waste Water Interceptor
- River Rehabilitation

İZAYDAŞ Landfill Site is a major component of this project because waste water treatment plant sludge and incineration plant ashes are disposed in the hazardous waste lot. Aerial view of the İZAYDAŞ Landfill site is given in Figure 3.1. Because of high potential of environmental threat, the landfill site was built with an impermeable bottom layer. Leachate from the waste lots is collected for primary treatment then transferred to the waste water treatment plant.

3.1. Site History

The Sanitary Landfill area is located near Solaklar-Durbasan village road and is connected to Kandıra Highway. The site was planned to consist of seven lots as given in Figure 3.2.

A total area of 800,000 m^2 is reserved for industrial and municipal solid waste disposal. All lots accept municipal solid waste; except Lot 6 which is designed for hazardous solid waste disposal only.

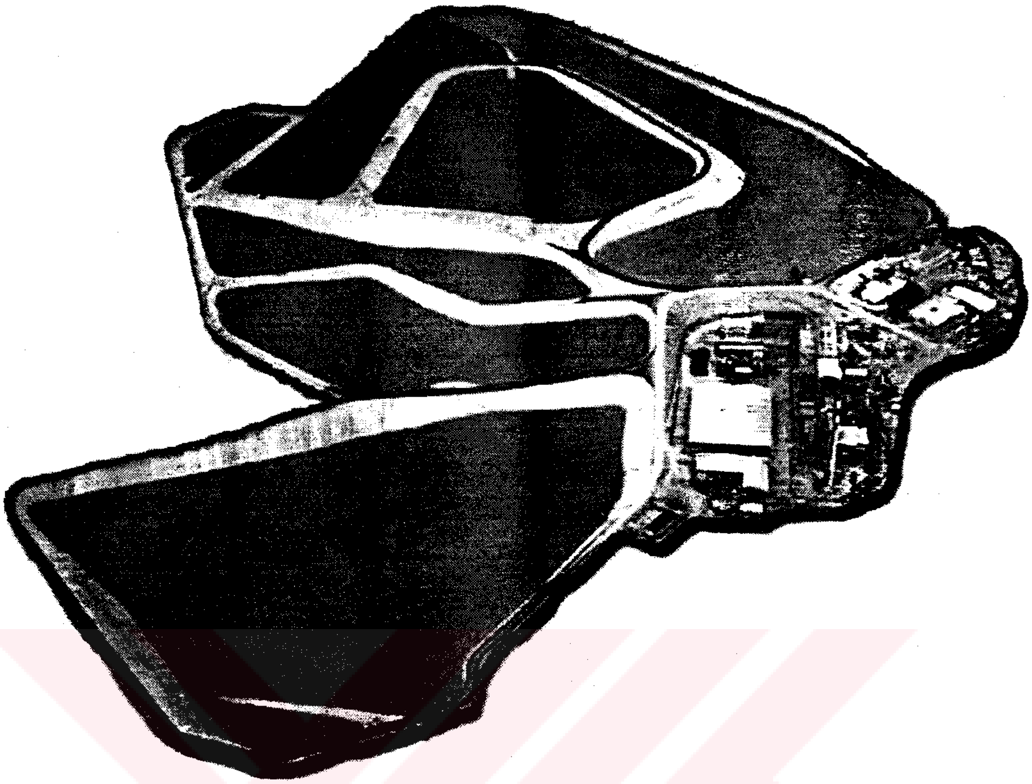


Figure 3.1. İZAYDAŞ landfill site aerial view

The storage capacity of domestic solid wastes is 3,125,000 m^3 and of industrial solid wastes is 790,000 m^3. Waste water treatment plant sludge and incineration plant ashes are also processed as industrial wastes and they are disposed into the hazardous waste lot. The landfill bottom compromises of a series of layers to prevent leachate leakage into the ground water. A cross sectional view is given in Figure 3.3.

Leachate is collected by HDPE perforated pipes then taken to the chemical primary treatment plant (DAF, Dissolved Air Floating, Unit) and from there transferred to the Izmit Domestic and Industrial Waste Water Treatment.

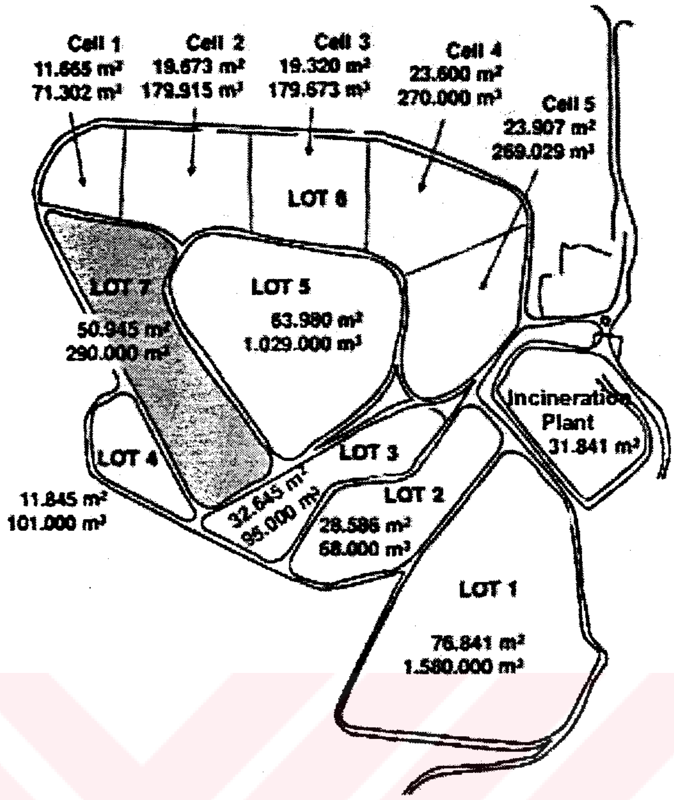


Figure 3.2. Site map of İZAYDAŞ landfill site

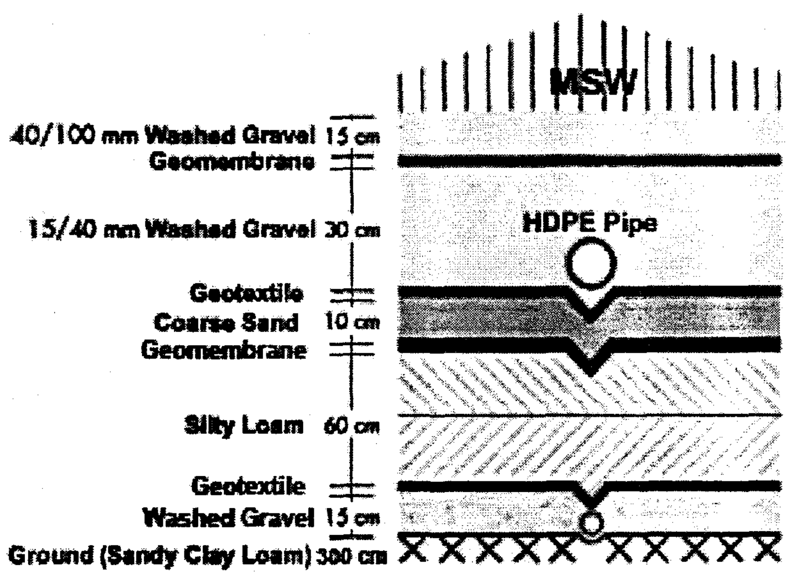


Figure 3.3. Landfill bottom cross section

Municipal solid waste disposal was started with Lot 7 which was closed in September 2000. This thesis study covers only Lot 7, which is marked by diagonal lines in Figure 3.1.

General information regarding the waste disposal at İZAYDAŞ landfill site are given in Table 3.1.

Table 3.1. General properties of solid waste lots of İZAYDAŞ landfill site.

MSW Lot#	Area (m^2)	Volume (m^3)	Queue	Start Date	Close Date	Stored Waste (t)
1	76,841	1,580,000	6			
2	28,586	68,000	4			
3	32,645	95,000	5			
4	11,845	101,000	3			
5	63,980	1,029,000	2	23.02.2000		573,645
7	50,945	290,000	1	09.06.1997	23.02.2000	393,794
Sub Total	264,842	3,163,000				
Cell# of Hazardous Lot6						
1	11,665	71,302	Daily MSW Mean = 500 tonnes/day			
2	19,673	179,915				
3	19,320	179,673	Surface slope for all lots = 25 per cent			
4	23,600	270,000				
5	23,907	269,029				
Sub Total	98,165	969,919				
TOTAL	363,007	4,132,919				

There is little information and data about solid waste composition disposed to İZAYDAŞ. Therefore, the composition of the synthetically prepared sample used for the hydraulic conductivity analysis was taken similar to the MSW composition of the city of Istanbul due to the similar geographical and economical conditions. Moreover, data from the Istanbul Region are used in the gas generation model.

3.2. Existing Gas Venting Wells

A gas collection system in İZAYDAŞ was part of the landfill design project but due to poor economic conditions, it was not taken into action. However, during operation of Lot 7, 20 wells, located 20 m apart to each other were constructed to collect and release generated landfill gases into the atmosphere. In this study the gas collection system is assumed to consist of the existing venting wells. The layout of the gas extraction system is shown in Figure 3.4. Also well numbers and their positions are given in Table 3.2.

Table 3.2. Well numbers and their positions

Well Code	Coordinates		Elevation		Waste Depth
	Y	X	Bottom	Top	
L7W01	16059.75	7357.15	144.99	150.61	5.62
L7W02	16080.09	7313.64	143.39	148.95	5.56
L7W03	16110.10	7254.02	143.22	147.35	4.13
L7W04	16135.47	7206.83	143.62	147.71	4.09
L7W05	16165.27	7155.21	145.11	151.31	6.20
L7W06	16199.83	7093.87	148.89	155.14	6.25
L7W07	16233.56	7042.43	152.47	158.99	6.52
L7W08	16.104.05	7355.48	149.70	158.11	8.41
L7W09	16117.77	7304.13	149.37	156.81	7.44
L7W10	16141.45	7258.40	149.21	155.88	6.67
L7W11	16175.15	7197.38	148.05	156.41	8.36
L7W12	16204.32	7140.63	148.91	162.12	13.21
L7W13	16246.19	7083.38	151.16	164.71	13.55
L7W14	16286.01	7077.20	155.03	163.08	8.05
L7W15	16261.19	7121.46	154.33	161.33	7.00
L7W16	16232.41	7161.41	153.18	160.38	7.20
L7W17	16176.97	7234.63	152,50	160.66	8.16
L7W18	16150.93	7281.41	153.71	160.36	6.65
L7W19	16142.46	7325.28	154,00	161.47	7.47
L7W20	16149.02	7354.07	154.43	158.59	4.16

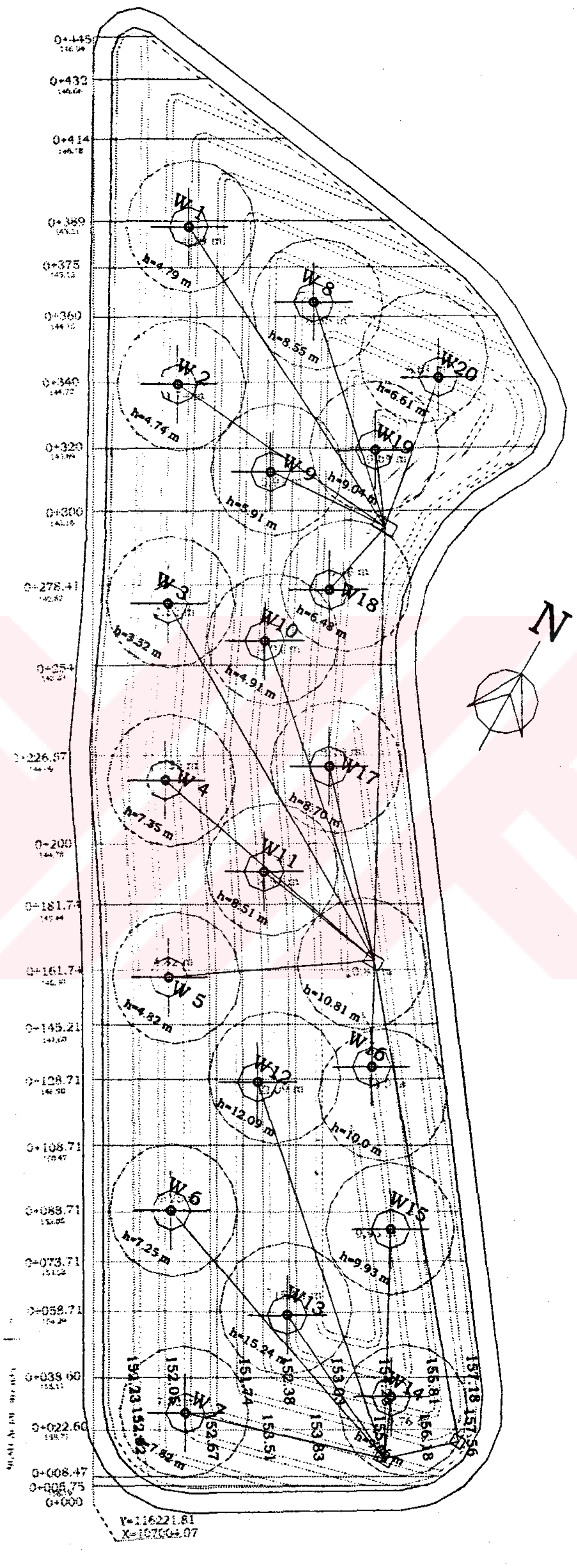


Figure 3.4. Layout of the gas extraction system in Lot 7

4. METHODOLOGY

This chapter describes the methodology used to evaluate the potential for energy recovery from Lot 7. A flow chart of the methodology is presented in Figure 4.1. First, the long term moisture distribution within the landfill waste and cover is estimated. Second, the gas production rates over a 50 year period are computed. Third, laboratory tests were conducted to evaluate the permeability of the waste material. Finally, a gas transport model was developed to design and optimize the gas collection. Each of these steps is described in the following subsections.

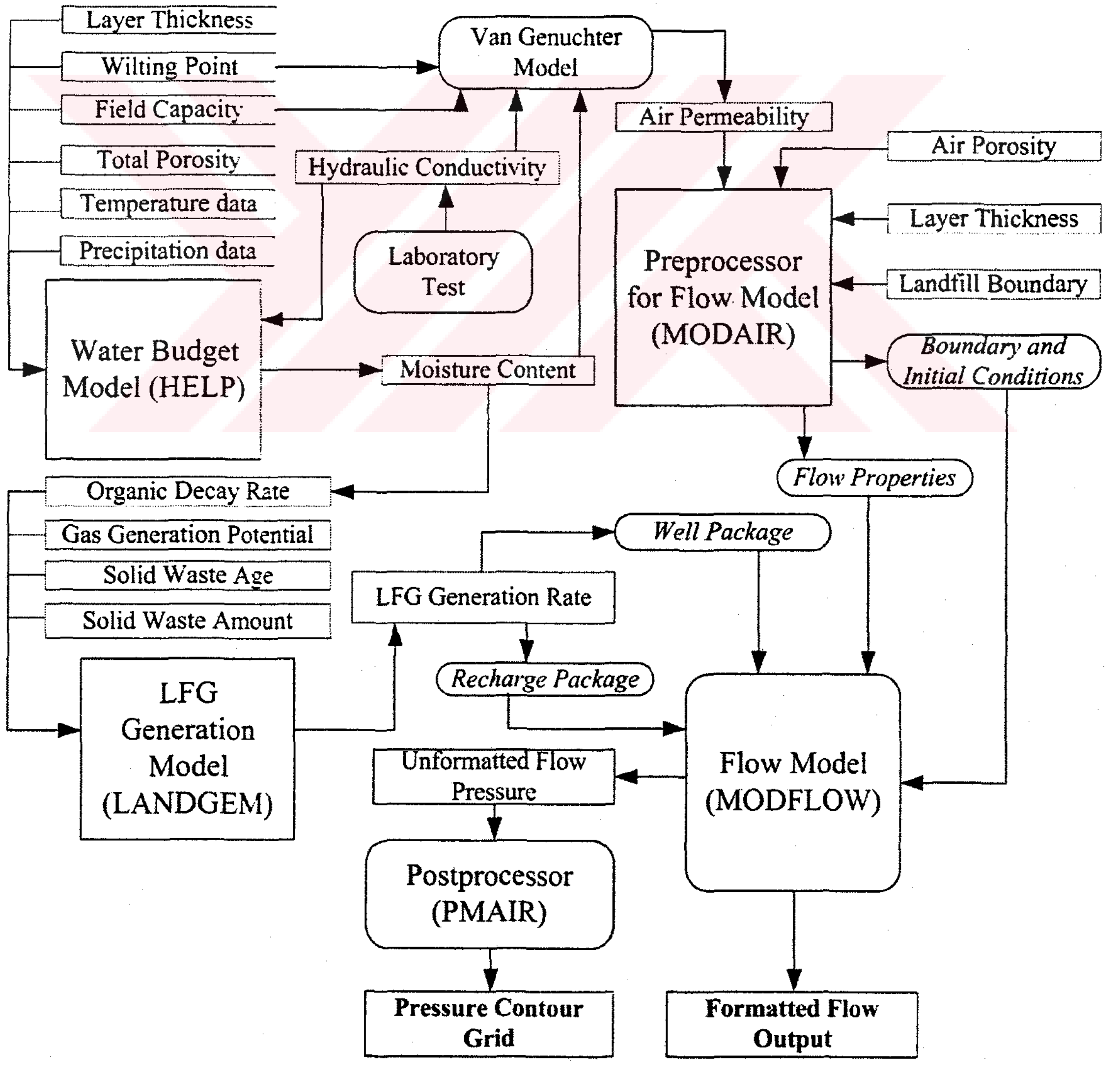


Figure 4.1. Flow chart of the modeling approach

4.1. Numerical Modeling of Moisture Content

The Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills (Schroeder, 1999). The model uses weather, soil and design data to simulate the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The program was developed to conduct water balance analysis of landfills, cover systems and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, liner leakage and landfill moisture content that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model, is applicable to open, partially closed and fully closed sites.

The necessary soil data include porosity, field capacity, wilting point, saturated hydraulic conductivity, initial moisture storage, and Soil Conservation Service (SCS) runoff curve number for antecedent moisture condition II. The model contains default soil characteristics for 42 material types for use when measurements or site-specific estimates are not available. The porosity, field capacity, wilting point and saturated hydraulic conductivity are used to estimate the soil water evaporation coefficient and Brooks-Corey soil moisture retention parameters. Design specifications include such items as the slope and maximum drainage distance for lateral drainage layers, layer thicknesses, layer description, area, leachate recirculation procedure, subsurface inflows, surface characteristics, and geomembrane characteristics.

4.1.1. Soil Moisture Retention and Hydraulic Conductivity

The HELP program requires values for the total porosity, field capacity, wilting point, and saturated hydraulic conductivity of each layer that is not a liner. The saturated hydraulic conductivity is required for all liners. Values for these parameters can be specified by the user or selected from a list of default values provided in the HELP program. The HELP default soils and their corresponding values are given in Table 4.1. The values are used to compute moisture storage. unsaturated vertical drainage, and head on liners and soil water evaporation.

Retention Parameters: Relative moisture retention or storage used in the HELP model differs from the water contents typically used. The soil water storage or content used in the HELP model is defined on a per volume basis:

$$V_t = V_s + V_w + V_a \tag{4.1}$$

where;

V_t : total volume (L^3)

V_s : soil volume (L^3)

V_w : water volume (L^3)

V_a : air volume (L^3)

Total porosity is an effective value, defined as the volumetric water content (volume of water per total volume) when the pores contributing to change in moisture storage are at saturation. Total porosity can be used to describe the volume of active pore space present in soil or waste layers. Field capacity is the volumetric water content at a soil water suction of 0.33 bars or remaining after a prolonged period of gravity drainage without additional water supply. Wilting point is the volumetric water content at a suction of 15 bars or the lowest volumetric water content that can be achieved by plant transpiration. These moisture retention parameters are used to define moisture storage and relative unsaturated hydraulic conductivity.

The HELP program requires that the wilting point be greater than zero but less than the field capacity. The field capacity must be greater than the wilting point and less than the porosity. Total porosity must be greater than the field capacity but less than 1. The general relation among moisture retention parameters and soil texture class is shown in Figure 4.2.

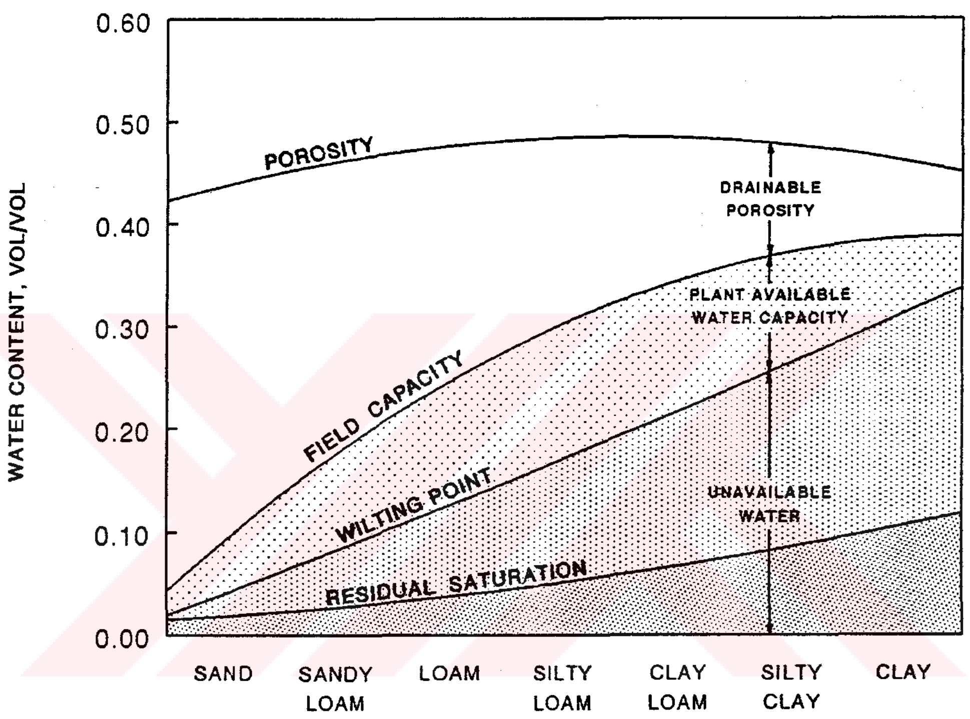


Figure 4.2. Relation among moisture retention parameters and soil texture class (Schroeder, 1994)

The HELP user can specify the initial volumetric water contents of all non-liner layers. Soil liners are assumed to remain saturated at all times. If initial water contents are not specified, the program assumes values near the steady-state values (allowing no long-term change in moisture storage) and runs a year of simulation to initialize the moisture contents closer to steady state. The soil water contents at the end of this year are substituted as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results of the volumetric water content initialization period are not reported in the output.

Unsaturated Hydraulic Conductivity: Darcy's constant of proportionality governing flow through porous media is known as hydraulic conductivity or coefficient of permeability or sometimes simply as permeability. Hydraulic conductivity is a function of media properties, such as particle size, void ratio, composition, fabric, degree of saturation, and the kinematic viscosity of the fluid moving through the media. The HELP program uses the saturated and unsaturated hydraulic conductivities of soil and waste layers to compute vertical drainage, lateral drainage and soil liner percolation. The vapor diffusivity for geomembranes is specified as a saturated hydraulic conductivity to compute leakage through geomembranes by vapor diffusion.

The saturated hydraulic conductivity is used to describe flow through porous media where the void spaces are filled with a wetting fluid (e.g., water). The saturated hydraulic conductivity of each layer is specified in the input.

The unsaturated hydraulic conductivity is used to describe flow through a layer when the void spaces are filled with both wetting and non-wetting fluid (e.g., water and air). The HELP program computes the unsaturated hydraulic conductivity of each soil and waste layer using the following equation, reported by Campbell (1974):

$$K_u = K_s \left[\frac{\theta - \theta_r}{\varphi - \theta_r} \right]^{3 - \frac{2}{\lambda}} \tag{4.2}$$

where;

K_u	: unsaturated hydraulic conductivity, (cm/s)
K_s	: saturated hydraulic conductivity, (cm/s)
Θ	: actual volumetric water content, (vol/vol)
θ_r	: residual volumetric water content, (vol/vol)
φ	: total porosity, (vol/vol)
λ	: pore-size distribution index, (dimensionless)

Residual volumetric water content is the amount of water remaining in a layer under infinite capillary suction. The HELP program uses the following regression equation, developed using mean soil texture values from Rawls et al. (1982), to calculate the residual volumetric water content:

$$\theta_r = \begin{cases} 0.014 + 0.25\ WP & for\ WP \geq 0.04 \\ 0.6\ WP\ for\ WP < 0.04 \end{cases} \tag{4.3}$$

where;

WP : volumetric wilting point, (vol/vol)

λ : pore-size distribution index, (dimensionless)

The residual volumetric water content and pore-size distribution index are constants in the Brooks-Corey equation relating volumetric water content to matrix potential (capillary pressure and adsorptive forces) (Brooks and Corey, 1964):

$$\frac{\theta - \theta_r}{\phi - \theta_r} = \left(\frac{\psi_b}{\psi} \right)^{\lambda} \tag{4.4}$$

where;

ψ : capillary pressure, (bars)

ψ_b : bubbling pressure, (bars)

Bubbling pressure is a function of the maximum pore size forming a continuous network of flow channels within the medium (Brooks and Corey, 1964). Brakensiek et al. (1981) reported that Equation 4.2 provides a reasonably accurate representation of water retention and matrix potential relationships for tensions greater than 50 cm or 0.05 bars (unsaturated conditions).

The HELP program solves Equation 4.4 for two different capillary pressures simultaneously to determine the bubbling pressure and pore-size distribution index of volumetric moisture content for use in Equation 4.3. The total porosity is known from the input data. The capillary pressure-volumetric moisture content relationship is known at two points from the input of field capacity and wilting point. Therefore, the field capacity is inserted in Equation 4.4 as the volumetric moisture content and 0.33 bar is inserted as the capillary pressure to yield one equation. Similarly, the wilting point and 15 bar are inserted in Equation 4.4 to yield a second equation. Having two equations and two unknowns (bubbling pressure and pore-size distribution index), the two equations are solved simultaneously to yield the unknowns. This process is repeated for each layer to obtain the parameters for computing moisture retention and unsaturated drainage.

Table 4.1. Default soil characteristics of HELP model (Schroeder, 1994)

Soil Texture Class			Total Porosity	Field Capacity	Wilting Point	Saturated Hydraulic Conductivity
LOW DENSITY SOILS						
HELP	USDA	USCS	vol/vol	vol/vol	vol/vol	cm/sec
1	CoS	SP	0.417	0.045	0.018	$1.0x10^{-2}$
2	S	SW	0.437	0.062	0.024	$5.8x10^{-3}$
3	FS	SW	0.457	0.083	0.033	$3.1x10^{-3}$
4	LS	SM	0.437	0.105	0.047	$1.7x10^{-3}$
5	LFS	SM	0.457	0.131	0.058	$1.0x10^{-3}$
6	SL	SM	0.453	0.190	0.085	$7.2x10^{-4}$
7	FSL	SM	0.473	0.222	0.104	$5.2x10^{-4}$
8	L	ML	0.463	0.232	0.116	$3.7x10^{-4}$
9	SiL	ML	0.501	0.284	0.135	$1.9x10^{-4}$
10	SCL	SC	0.398	0.244	0.136	$1.2x10^{-4}$
11	CL	CL	0.464	0.310	0.187	$6.4x10^{-5}$
12	SiCL	CL	0.471	0.342	0.210	$4.2x10^{-5}$
13	SC	SC	0.430	0.321	0.221	$3.3x10^{-5}$
14	SiC	CH	0.479	0.371	0.251	$2.5x10^{-5}$
15	C	CH	0.475	0.378	0.251	$2.5x10^{-5}$
21	G	GP	0.397	0.032	0.013	$3.0x10^{-1}$
MODERATE DENSITY SOILS						
22	L	ML	0.419	0.307	0.180	$1.9x10^{-5}$
23	SiL	ML	0.461	0.360	0.203	$9.0x10^{-6}$
24	SCL	SC	0.365	0.305	0.202	$2.7x10^{-6}$
25	CL	CL	0.437	0.373	0.266	$3.6x10^{-6}$
26	SiCL	CL	0.445	0.393	0.277	$1.9x10^{-6}$
27	SC	SC	0.400	0.366	0.288	$7.8x10^{-7}$
28	SiC	CH	0.452	0.411	0.311	$1.2x10^{-6}$
29	C	CH	0.451	0.419	0.332	$6.8x10^{-7}$
HIGH DENSITY SOILS						
16	Liner Soil		0.427	0.418	0.367	$1.0x10^{-7}$
17	Bentonite		0.750	0.747	0.400	$3.0x10^{-9}$

Default soil texture abbreviations in Table 4.1 are

For USDA (US Department of Agriculture);

G :Gravel

S :Sand

Si :Silt

C :Clay

L :Loam (sand, silt, clay, and humus mixture)

Co :Coarse

F :Fine

For USCS (Unified Soil Classification System);

G : Gravel

S : Sand

M : Silt

C : Clay

P : Poorly Graded

W : Well Graded

H : High Plasticity or Compressibility

L : Low Plasticity or Compressibility

4.2. Landfill Gas Generation Model

The Landfill Gas Emissions Model (LandGEM) is used to estimate methane emissions from landfills (EPA, 1998). The biodegradation of refuse in landfills produces landfill gas, mainly consisting of methane and carbon dioxide, with trace amounts (less than 1 per cent of the total landfill gas) of nonmethane organic compounds (NMOC). NMOC, when released into the atmosphere, can contribute to the formation of ozone through a series of photochemical reactions (EPA, 1998). The landfill gas also sweeps other vapors present in the landfill to the surface as it flows through the refuse. The other vapors present in the landfill can include a variety of different NMOC and compounds that are identified by state or federal air quality regulations as air pollutants. The rate of generation of landfill gas, and thus the rate of air emissions from landfills, is highly variable from landfill to landfill; models attempt to account for the variability of factors such as kind of refuse, pH, temperature, or availability of nutrients for methanogens.

LandGEM estimates emission rates based on the landfill gas generation rate and the amount of refuse in the landfill. The landfill gas generation rate in this model is based on a first order decomposition model, which estimates the landfill gas generation rate using two parameters: L_0, the potential methane generation capacity of the refuse, and k, the methane generation decay rate, which accounts for how quickly the methane generation rate decreases, once it reaches its peak rate. The methane generation rate is assumed to be at its peak upon placement of the refuse in the landfill. This model provides an opportunity to enter L_0 and k values using actual test data and landfill specific parameters, or use default L_0 and k values derived from test data.

The amount of refuse in the landfill is calculated for this model using site-specific characteristics of the landfill entered by the user, such as the years the landfill has been in operation, the amount of refuse in place in the landfill, and the design capacity.

Air emissions from landfills come from landfill gas, generated by the decomposition of refuse in the landfill. Landfill gas is assumed by this model to be roughly half methane and half carbon dioxide, with additional, relatively low concentrations of other air pollutants.

The following information is needed to estimate emissions from a landfill:

- The design capacity of the landfill,
- The amount of refuse in place, or the annual refuse acceptance rate,
- The methane generation rate (k),
- The potential methane generation capacity (L_0),
- The concentration of total nonmethane organic compounds (NMOC) and speciated NMOC found in the landfill gas,
- The years the landfill has been in operation, and
- Whether the landfill has been used for disposal of hazardous waste.

The basic first order decay model is as follows (EPA, 1998):

$$LFG = 2\ L_0\ R\ (e^{kc}-e^{-kt}) \quad (4.5)$$

where:

LFG : Total amount of landfill gas generated in current year (m^3/year)

L_0 : Total methane generation potential of the waste (m^3/kg)

R : Average annual acceptance rate during active life (kg)

k : Decay constant for the rate of methane generation (1/year)

t : Time since landfill opened (years)

c : Time since landfill closure (years)

If the methane generation potential, L_0, and the decay constant, k, were known with certainty, the first order decay model would predict landfill gas generation relatively accurately; however, the values for L_0 and k can vary widely, and are difficult to estimate accurately for a particular landfill. L_0 is not affected by climate conditions where as k does. In dry conditions k value is lower which means gas generating is slow. A range of values for L_0 and k are given in Table 4.2. Because of the difficulty in defining these parameters, a range of values is considered in this study.

Table 4.2. Suggested values for first order decay model variables (EPA, 1996)

Variables	**Range**	**Suggested Values**		
		Wet Climate	Medium Moisture Climate	Dry Climate
L_0 (m^3 CH_4/kg)	0 – 0.312	0.14 - 0.18	0.14 - 0.18	0.14 - 0.18
k (1/year)	0.003 – 0.4	0.10 – 0.35	0.05-0.15	0.02-0.10

4.3. Laboratory Analysis of the Solid Waste

The parameter controlling gas flow through the waste is the air permeability. However, because of the unavailability of the proper instrumentation to measure the air permeability, the hydraulic permeability was measured and then converted to air permeability. For this purpose, synthetic waste samples were prepared according to the composition data presented in Table 4.3 for the hydraulic conductivity testing (Arikan et al., 1997). The data in Table 4.3 are representative of municipal waste in the Istanbul region.

Table 4.3. Composition of the synthetic sample (Arikan et al., 1997)

Material	%
Organics	45
Inert	15
Paper	14.5
Plastic	9.5
Textile	5.6
Glass	3.8
Metal	2.2
Other	4.4

4.3.1. Hydraulic Conductivity Analysis

The coefficient of permeability is a constant of proportionality related to the ease with which a fluid passes through a porous medium. Two general laboratory methods are available for determining the coefficient of permeability of a soil directly. These are the constant-head method (ASTM, 1997), described below, and the falling-head method (Tavenas, 1983). Both methods use Darcy's law given as:

$$v = K.i \quad (4.6)$$

The corresponding flow rate (or quantity per unit time) is

$$q = K.i.A \tag{4.7}$$

where;

q : quantity of fluid flow in a unit time, (L^3/T)

K : coefficient of permeability, or hydraulic conductivity, in velocity units (L/T)

i : hydraulic gradient or head loss (L/L)

h : total head difference across the flow path of length, (L)

L : length of sample that produces the head difference (and in units of h).

A : cross-sectional area of soil mass through which flow q takes place in units consistent with K. (L^2)

Neither the constant-head nor the falling-head laboratory method provides a reliable value for the in-situ coefficient of permeability of a soil. One is a fortunate if the value obtained is correct within one order of magnitude. Reasons for this are varied, but the major ones are as follows:

The soil in the permeability device is never in the same state as in the field, it is always disturbed to some extent. Orientation of the in-situ stratum to the flow of water is probably not duplicated. In sands, the ratio of horizontal flow to vertical flow is on the order of

$$K_h / K_v \geq 3 \tag{4.8}$$

This ratio is impossible to duplicate in the sample, even when the void ratio may be duplicated by careful placement and compaction.

Conditions at the boundary are not the same in the laboratory. The smooth walls of the permeability mold make for better flow paths than if they were rough. If the soil is stratified vertically, the flow in the different strata will be different, and this boundary condition may be impossible to reproduce in the laboratory.

The hydraulic head, h is usually 5 to 10 times larger in the laboratory test than in the field. Field values of i= h/L are often much less than 1.5 unless there is flooding or water impoundment (reservoir or dams). The high laboratory gradient may produce turbulent flow and wash some of the fine materials out. Considerable evidence indicates that Darcy's law is nonlinear-at least at large values of hydraulic gradient i so that v equals to K_i^n.

The effect of entrapped air on the laboratory sample will be large even for small air bubbles since the sample is small.

In this study the Falling Head Method was chosen to obtain more accurate values of the permeability of the solid waste which is characterized by low density and low confining pressure. Schematic view of the falling head test equipment is given in Figure 4.3.

The equation applicable to this test is as follows;

$$K = \frac{aL}{At} \ln \frac{h_1}{h_2} \tag{4.9}$$

where;

K	: hydraulic conductivity (cm/s)
a	: cross sectional area of burette or other standpipe (cm^2)
L	: height of the sample (cm)
A	: cross sectional area of soil sample (cm^2)
t	: time (s)
h_1	: hydraulic head across sample at beginning of test (t = 0), (cm)
h_2	: hydraulic head across sample at end of test ($t = t_{test}$), (cm)

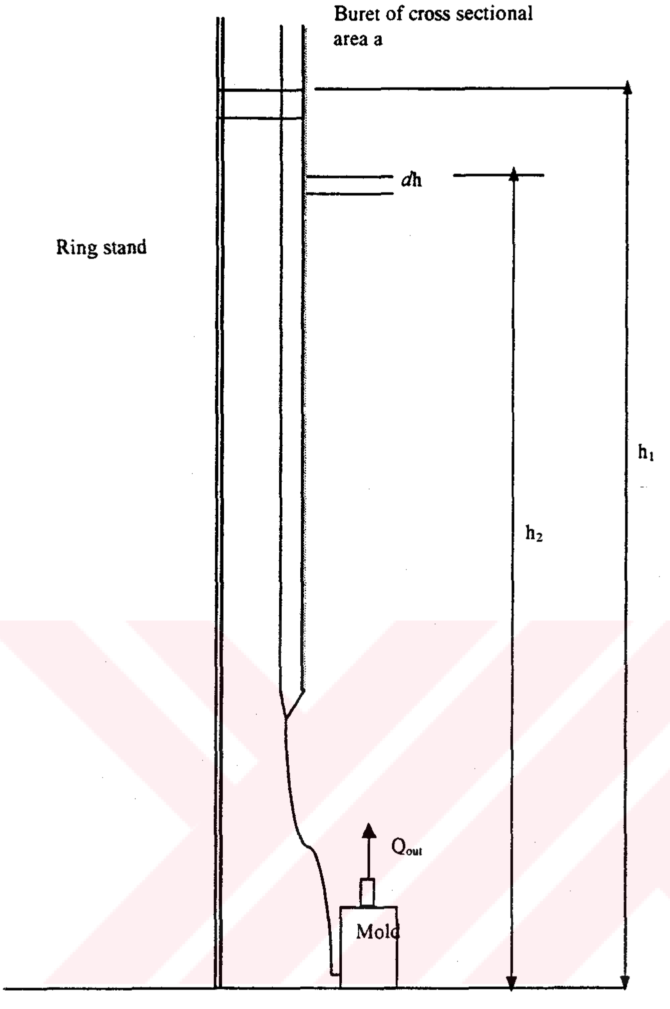


Figure 4.3. Line details of the falling head test equipment

4.3.2. Air Permeability Calculation

In the gas flow model, the air permeability of the different landfill layers is needed. The hydraulic conductivity and the air permeability are function of the intrinsic permeability of the soil, the fraction of water and gas filling the pores, and the properties of these two fluids (density, viscosity). They are related to each other according to the equations described below:

In unsaturated porous media, the permeability of water or air can be expressed in terms of a relative permeability and the intrinsic permeability of the media:

$$k_w(\theta) = k_{int} \,.\, k_{rw} \tag{4.10}$$

where;

$k_w(\theta)$: water permeability of the porous media (cm^2)

k_{int} : intrinsic permeability (cm^2)

k_{rw} : relative water permeability (cm^2)

Equation 4.10 is also applicable to air permeability of porous media:

$$k_a(\theta) = k_{int} \,.\, k_{ra} \tag{4.11}$$

where;

$k_a(\theta)$: air permeability of porous media (cm^2)

k_{ra} : relative air permeability (cm^2)

Intrinsic permeability can be defined in terms of hydraulic conductivity:

$$k_{int} = \frac{K\mu}{\rho g} \tag{4.12}$$

where;

K : hydraulic conductivity (cm/s)

μ : kinematic viscosity ($N.s/m^2$)

ρ : density of water (g/L)

g : gravity (m/s^2)

Van Genuchten (1980) defines an expression for relative air permeability

$$k_{ra} = [1 - S_e]^{1/2} \cdot [1 - S_e^{1/m}]^{2m} \tag{4.13}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4.14}$$

where;

θ : water content (vol/vol)

θ_r : residual water content (vol/vol)

θ_s : total porosity (vol/vol)

$$m=1-1/N \tag{4.15}$$

where;

N : water retention model parameter (unitless)

Therefore, to compute the air permeability the following steps were made:

1. The water saturated hydraulic conductivity K is measured in the laboratory (Section 4.3.1).
2. The intrinsic permeability is calculated using Equation 4.12.
3. The moisture content within the different landfill layers is calculated from the HELP model (Section 4.1).
4. The relative permeability is calculated using Equations 4.13 and 4.14 for the appropriate van Genuchten parameters.
5. The air permeability is computed using Equation 4.11.

4.4. Modeling of Gas Flow

MODAIR is a software package for modeling air flow in the unsaturated zone, including transient air flow to soil vapor extraction well (Guo, 1996). MODAIR is based on the U.S. Geological Survey modular finite-difference ground water flow model, which is commonly called MODFLOW, can simulate ground-water flow in a three-dimensional heterogeneous and anisotropic medium provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. A constant-density fluid is also assumed.

MODAIR provides an interface to prepare the input files of MODFLOW for use in air flow simulations. MODAIR also provides a post-processor which enables preparing 2D plan-view or cross-sectional plots of air pressure distributions.

Conventional numerical models for ground-water simulation have been suggested for use in air flow simulation. Under steady state conditions, the governing equation for air flow is linear with respect to pressure-squared (Guo, 1996); therefore, a conventional ground water simulator can be readily adapted. However, for transient conditions, which is the case in this study, the governing equation for air flow is nonlinear, and linearization is necessary if a ground-water simulator is to be applied.

The development of the linearized formulation is illustrated by considering one dimensional flow. To demonstrate the linearization approach, the one-dimensional form of the governing equation solved in MODFLOW is analyzed. However, in the model the approach was extended to three-dimensional flow.

Moreover, the MODAIR program does not include a term for the gas generation rate needed for the simulation of gas flow in a landfill. Therefore, the linearization approach was extended to include a gas generation rate spatially distributed over the landfill waste. The gas generation rates are time dependent and can be related to the recharge term in the groundwater flow equation. The detailed derivation of the linearization approach with a distributed source term (the gas generation term) is presented below:

The 1D groundwater flow equation with pumping and recharge is:

$$\frac{\delta}{\partial x}\left[A_x\rho_w K_x \frac{\partial h}{\partial x}\right]\Delta x \pm W_m^w + R_m^w = S_s\rho_w \Delta V \frac{\partial h}{\partial t} \tag{4.16}$$

where;

h	: hydraulic head (L)
A_x	: cross sectional area perpendicular to the x direction (L^2)
ρ_w	: water density (ML^{-3})
K_x	: hydraulic conductivity (LT^{-1})
W_m^w	: mass injection/extraction rate of water (MT^{-1})
R_m^w	: mass recharge rate of water (MT^{-1})
S_s	: specific storage (L^{-1})
Δx	: length of a computational cell (L)
ΔV	: volume of a computational cell (L^3)

If the following variables are substituted into the Equation 4.16;

$$Ax = \Delta y \Delta z$$

$$\Delta V = \Delta x \Delta y \Delta z$$

$$T = K\Delta z$$

$$S = Ss\Delta z$$

$$W_v^w = \frac{W_m^w}{\rho_w}$$

$$R_v^w = \frac{R_m^w}{\rho_w}$$

and ρ_w is assumed to be constant; the 1-D form of the flow equation actually solved in MODFLOW is derived as follows:

$$\frac{\delta}{\partial x}\left[\Delta y T_x \frac{\partial h}{\partial x}\right]\Delta x \pm W_v^w + R_v^w = S\Delta x \Delta y \frac{\partial h}{\partial t} \tag{4.17}$$

where;

T : transmissivity (L^2T^{-1})

S : storage coefficient (dimensionless)

W_v^w : volumetric flow rate of water (L^3T^{-1})

R_v^w : volumetric recharge rate of water (L^3T^{-1})

Δy : width of the computational cell (L)

Δz : thickness of the computational cell (L)

The analogous governing equation for one dimensional air flow through a porous medium is:

$$\frac{\delta}{\partial x}\left[A_x\rho_a\frac{k_x}{\mu}\frac{\partial P}{\partial x}\right]\Delta x \pm W_m^a + R_m^a = \varepsilon\Delta V\frac{\partial\rho_a}{\partial t} \tag{4.18}$$

where:

ρ_a : air density (ML^{-3})

k_x : permeability of the porous media (LT^{-1})

μ : air viscosity ($ML^{-1}T^{-1}$)

P : pressure ($ML^{-1}T^{-2}$)

W_m^a : the mass injection/extraction rate of air (MT^{-1})

R_m^a : the distributed air source term (MT^{-1})

ε : air-filled porosity (dimensionless)

The governing equation is linearized by considering only small deviations from the ambient pressure, P_0:

$$\frac{P}{P_0} \approx 1 \tag{4.19}$$

If it is assumed that air behaves as an ideal gas and that the system is isothermal, the linearized form of the air flow equation can be written as:

$$\frac{\delta}{\partial x}\left[\Delta y\Delta z k_x\frac{\partial P^2}{\partial x}\right]\Delta x \pm 2W_v^a\mu P_w + 2R_v^a\mu P_0 = \frac{\varepsilon\mu\Delta z}{P_0}\Delta x\Delta y\frac{\partial P^2}{\partial t} \tag{4.20}$$

where:

W_v^a : the volumetric air pumping rate of the well (L^3T^{-1})

R_v^a : gas generation rate/area of the landfill (volumetric recharge rate) (LT^{-1})

P_w : the pressure at the well ($ML^{-1}T^{-2}$)

Equations 4.18 and 4.20 can be said to be identical in form if the following relationships are considered:

$$h = P^2 \tag{4.21}$$

$$S = \frac{\varepsilon\mu\Delta z}{P_0} \tag{4.22}$$

$$T = k\Delta z \tag{4.23}$$

$$W_v^w = 2\mu P_w W_v^a \tag{4.24}$$

$$R_v^w = 2\mu P_0 R_v^a \tag{4.25}$$

These relations allow for the use of MODFLOW for the simulation of airflow in porous media. The key approximation in linearization is using constant ambient pressure, P_0 in the storage term. This approximation will always underestimate the storage term, S in Equation 4.18 for an extraction system, because of the pressure during operation of an air extraction well will always be less than or equal to P_0. However, if the pressure within the landfill is close to ambient, the approximation error is small. The benefit of using a program such as MODFLOW in this study is that it is very widely used and tested program. Moreover, the linearization of the equation makes it easier to solve numerically.

The standard recharge package of MODFLOW is used to add the time-dependent gas generation rates. Because MODAIR does not directly allow for distributed sources the input files for MODFLOW are modified to include a recharge file where the recharge term is determined by equating the distributed source terms in Equation 4.25.

The main input data needed for the simulation of gas are:

1. Time dependent landfill gas generation rates
2. Flow properties of the cover soil and solid waste (air-filled porosity, air permeability)
3. Landfill layer dimensions
4. Well extraction rates

For complex systems there is no analytical solution of Equation 4.20. MODFLOW employs finite difference method to solve this problem by replacing the continuous system with a finite set of discrete points in space and time. With this approach the partial derivatives are replaced by terms calculated from the differences in head values at these points. The resultant system of linear algebraic difference equations is solved to compute values of the head at specific points and times. Using the relationships derived above (Equation 4.21) the computed head values are converted into gas pressure.

The flow terms in MODFLOW output files formatted or unformatted are expressed in a unit of $g^2.cm/sec^4$. To obtain the desired volumetric flow rate, results must be converted by using the following equation (based on Equation 4.24).

$$q_v = \frac{Q}{2\mu P} \tag{4.26}$$

where;

Q	: flow reported in MODFLOW output files ($g^2.cm/s^4$)
q_v	: volumetric flow rate (cm^3/s)
μ	: air viscosity (g/cm.s)
P	: pressure at the cell or in the well ($g/cm.s^2$)

Figure 4.5 shows the Lot divided into 2976 cells for every layer which are located by rows, columns and layer inside the model. The cells are square with side of 5 meters. There are 32 columns and 93 rows covering the entire lot. Each well is located within one cell so

that pressure distribution can be observed in the wells as well as around them. Hence, the influence of gas extraction rates on the pressure drops can be seen in and around the wells.

The landfill cross section consists of 3 layers. The first two layers represent the soil cover, while the third one represents solid waste. The cover soil is divided into two layers: with layer 1 (thickness 10 cm) defined as a constant pressure layer to simulate the effect of atmospheric pressure just above the landfill surface. The second and third layers have time dependent pressure distributions calculated by the model. Figure 4.4 shows a cross section view of a representative cell used in the gas flow model.

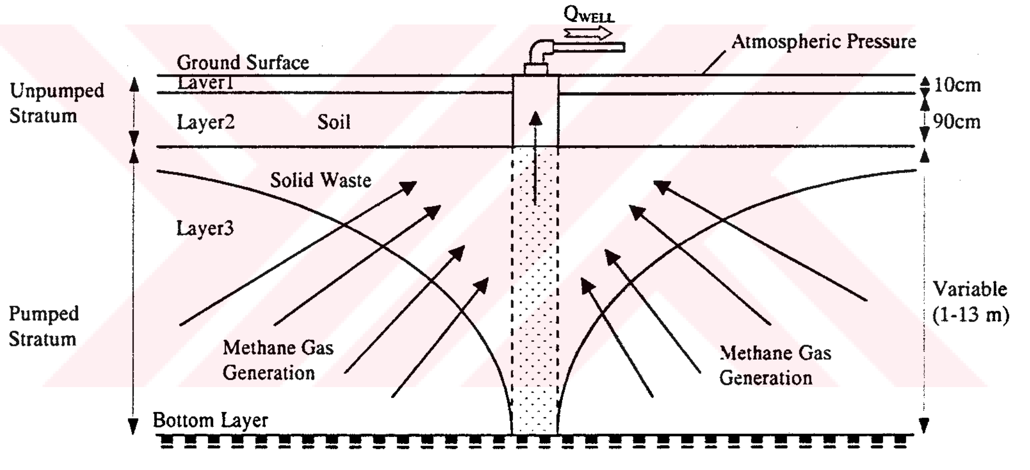


Figure 4.4. Model cross section of the extraction wells for gas flow model

In Lot7 of the İZAYDAŞ Landfill Site the waste depth varies according to topography of the site. Thus the depth of the waste is also allowed to vary in the gas flow model. From the waste depth data at the existing venting wells the depth of the waste for every cell in the model is estimated using the Kringing Interpolation method (SURFER graphics software). Figure 4.6 shows the location of the wells as well as the contours of the interpolated waste thickness that were incorporated in the gas flow model.

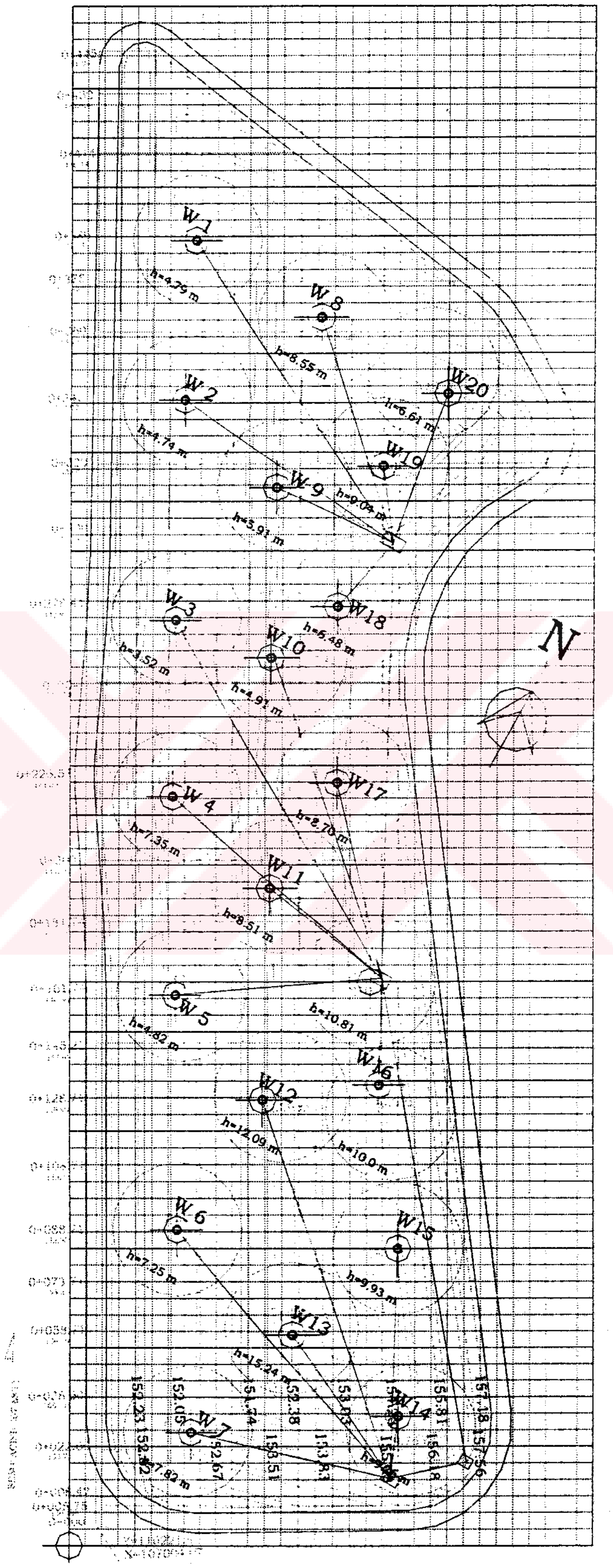


Figure 4.5. Plan view of the computational grid used in the gas flow model

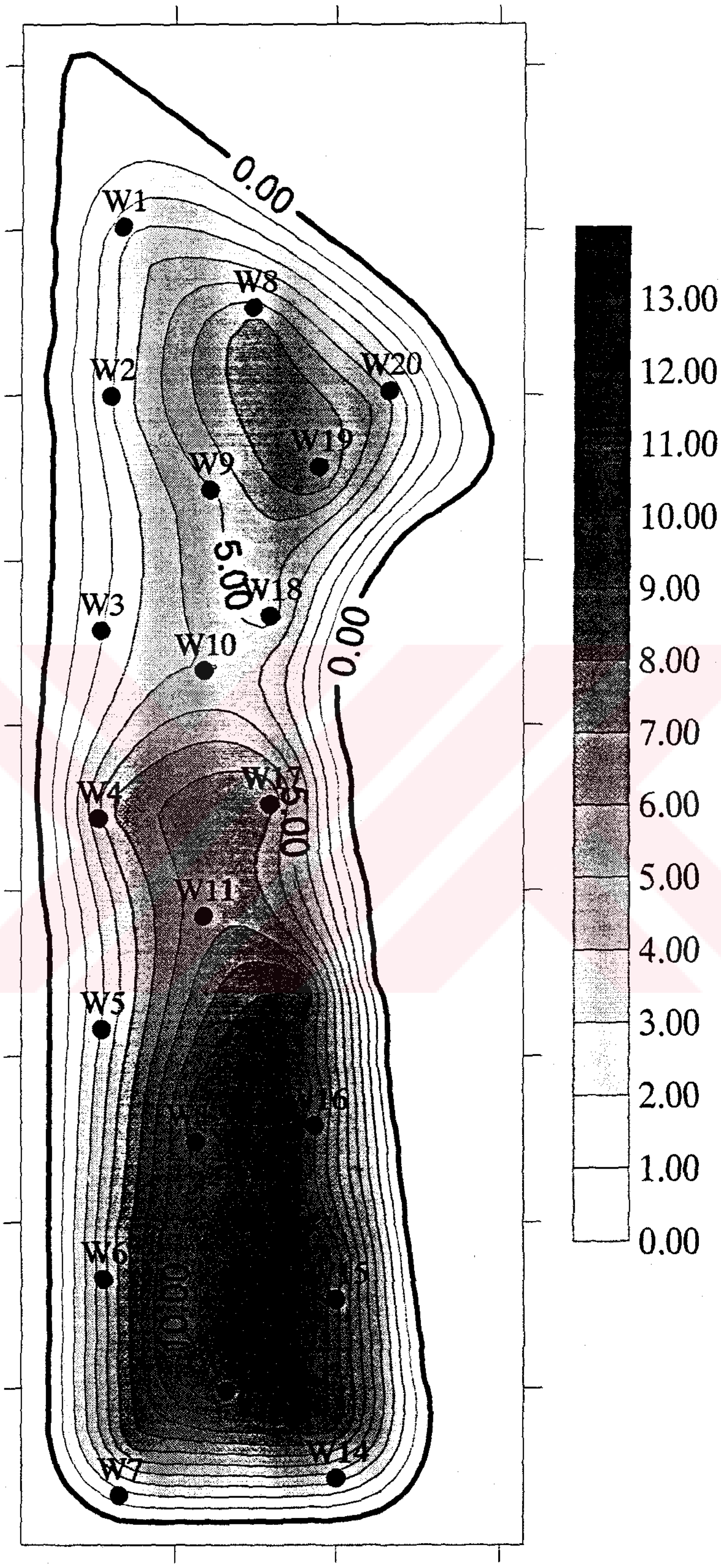


Figure 4.6. Contour plot of the waste thickness in meters used in the gas flow model

5. RESULTS

5.1. Hydraulic Conductivity

In laboratory testing for the hydraulic conductivity, sidewall leakage is a major problem. Sidewall leakage is the water bypassing the sample along the sidewalls of the tube. Sidewall leakage leads to increased flow through the sample and therefore overestimation of the hydraulic conductivity. To reduce sidewall leakage and its impact on the hydraulic conductivity measurement, the sample must be adequately compacted. However, if the sample is overcompacted, the measured permeability would be less than that of the undisturbed sample under field conditions.

Therefore, to assess the impact of compaction on the measured waste permeability, different levels of compaction were considered. Some experiments were performed with low compaction, but these samples would be expected to lead to high level of sidewall leakage. Other samples were subjected to somewhat higher compaction than the actual waste in the field. It is expected that these samples would lead to permeability measurements most resembling field conditions. To see the effect of high density on permeability, the last sample was subjected to slightly higher compaction than the others.

After compaction, additional weight on top of the sample was placed to represent the cover soil of the landfill. For this purpose it is assumed that the sample will be overlain on average with 4 meters of waste having density of 557 kg/m^3. This corresponds to the following weight being placed over the waste sample:

$\gamma.h = 557 \times 4 = 2230 \ kg/m^2 = 0.223 \ kg/cm^2$

Area = 12 cm^2

Top Weight = 12 x 0.223= 2.676 kg

In total 23 samples were prepared by compacting the waste inside the mold with a compaction hammer. The hit number by the compaction hammer was used to create the same type of compaction for the different samples. To the extent possible, the compaction value must represent the actual waste in terms of density.

An example calculation for the hydraulic conductivity K performed at 21°C for the first sample is given below. The other results are given in Table 5.1

Sample Dimensions : 6 cm
Mass Mold : 534.70 g
Mass Sample + Mold : 591.97 g
Mass Sample : 57.27 g
Area : 28.3 cm^2
Height : 2.3 cm
Volume : 65.09 cm^3
Density, ρ : 0.879 g/cm^3 (under natural drainage conditions)
*d*h : 20.1 cm (corresponding to 20 ml volume with cross-sectional area $a=0.952\ cm^2$)
h_1 : 95.0 cm
h_1 : 74.9 cm
T : 21 °C

$\alpha = \eta_T/\eta_{20} = 0.00981/0.0105 = 0.9761$

$K_T = \ln(95/74.9) \times (0.952 \times 2.3) / (28.3 \times 36.4)$

$K_T = 5.052\times10^{-4}$ cm/s

Table 5.1. Hydraulic conductivity values of synthetic solid waste samples

Sample No	Weight (g)	Q_{Out} (ml)	Time (s)	K (cm/s)	Density (kg/L)
101	591.97	20	36.43	5.05×10^{-4}	0.88
102	591.97	20	34.97	5.26×10^{-4}	0.88
103	591.97	20	35.07	5.24×10^{-4}	0.88
104	591.97	20	35.94	5.12×10^{-4}	0.88
201	585.41	20	34.37	5.35×10^{-4}	0.78
202	585.41	20	35.28	5.21×10^{-4}	0.78
203	585.41	20	36.57	5.03×10^{-4}	0.78
204	585.41	20	39.31	4.68×10^{-4}	0.78
301	581.27	20	33.72	5.45×10^{-4}	0.72
302	581.27	20	34.23	5.37×10^{-4}	0.72
303	581.27	20	36.16	5.09×10^{-4}	0.72
304	581.27	20	37.03	4.97×10^{-4}	0.72
401	587.03	20	40.5	4.54×10^{-4}	0.80
402	587.03	20	42.59	4.32×10^{-4}	0.80
403	587.03	20	43.88	4.19×10^{-4}	0.80
404	587.03	20	45.06	4.08×10^{-4}	0.80
501	603.22	20	68.09	2.70×10^{-4}	1.05
502	603.22	20	70.09	2.62×10^{-4}	1.05
503	603.22	20	71.72	2.56×10^{-4}	1.05
504	603.22	20	72.47	2.54×10^{-4}	1.05
601	581.27	20	18.09	1.02×10^{-3}	0.72
602	581.27	20	17.38	1.06×10^{-3}	0.72
603	581.27	20	17.22	1.07×10^{-3}	0.72

Note: Actual Density of the placed waste in Lot 7, ρ: 0.557 kg/L

The above laboratory results show the variability in the measured hydraulic conductivity with a general increase in the conductivity with decrease in density. The arithmetic average of all these measurements is 4.86×10^{-4} cm/s.

5.2. Moisture Content

The HELP (Hydrologic evaluation of Landfill Performance) model is used to predict the long-term average moisture content inside the landfill. Two main types of data are needed by the model for this calculation: (i) soil and design data and (ii) weather data. The soil and design data are based on the design and properties of Lot 7. The weather data are based on data collected at the Kocaeli, Turkey meteorological station. The daily long-term rainfall, temperature and solar radiation data were synthetically generated by the HELP model using the data of the Kocaeli meteorological station.

5.2.1. Soil and Design Data

İZAYDAŞ landfill site was built according to the latest solid waste regulations of Turkey (Turkish Ministry of the Environment, 2000). A typical cross section for all of the municipal solid waste lots is given in Figure 5.1.

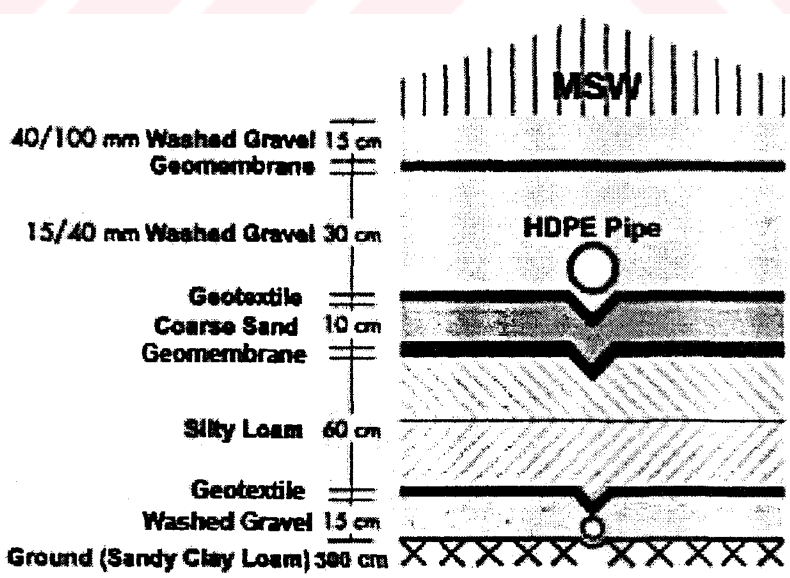


Figure 5.1. Typical MSW lot cross section for İZAYDAŞ landfill site.

The hydrological properties used in the model for the different landfill layers are given in Tables 5.2 to 5.12for Lot 7 profile without final cap. These values are based on appropriate literature values and default values from the HELP manual for similar soil types.

The SCS Runoff curve number and initial moisture settings are calculated by the HELP model. To represent the actual solid waste lot conditions, soil is assumed to be bare (i.e., no vegetation is present).

Run off method and initial moisture settings are calculated by the model itself. To represent the actual solid waste lot conditions, vegetation class is selected as bare soil.

The profile structure of Lot 7 is given in Table 5.2.

Table 5.2. Profile structure

Layer	Top (cm)	Bottom (cm)	Thickness (cm)
Fine Sandy Loam	0.0000	-100.0000	100.0
Municipal Waste	-100.0000	-670.0000	570.0
Gravel	-670.0000	-685.0000	15.0
Gravel1	-685.0000	-715.0000	30.0
Coarse Sand	-714.9995	-724.9995	10.0
Drainage Net (0.6cm)	-724.9990	-725.5990	0.6
High Density Polyethylene	-725.5990	-725.7990	0.2
Silty Loam	-725.7990	-785.7990	60.0
Gravel2	-785.7990	-800.7990	15.0
Sandy Clay Loam	-800.7985	-1100.7985	300.0

Table 5.3. Layer 1: Fine sandy loam (vertical percolation) layer parameters

Parameter	Value	Units
Top slope length	3000	(cm)
Top Slope	30.000	(degree)
Total porosity	0.4730	(vol/vol)
Field capacity	0.2220	(vol/vol)
Wilting point	0.1040	(vol/vol)
Saturated hydraulic conductivity	44.928	(cm/day)
Subsurface inflow	0	(cm/day)

Table 5.4. Layer 2: Municipal waste (vertical percolation) layer parameters

Parameter	Value	Units
Total porosity	0.6710	(vol/vol)
Field capacity	0.2920	(vol/vol)
Wilting point	0.0770	(vol/vol)
Saturated hydraulic conductivity	42.000	(cm/day)
Subsurface inflow	0	(cm/day)

Note: The saturated hydraulic conductivity is obtained from laboratory tests.

Table 5.5. Layer 3: Gravel (lateral drainage) layer parameters

Parameter	Value	Units
Total porosity	0.397	(vol/vol)
Field capacity	0.032	(vol/vol)
Wilting point	0.013	(vol/vol)
Saturated hydraulic conductivity	0.003	(cm/s)
Subsurface inflow	0	(mm/year)

Table 5.6. Layer 4: Gravel 1 (lateral drainage) layer parameters

Parameter	Value	Units
Total porosity	0.320	(vol/vol)
Field capacity	0.050	(vol/vol)
Wilting point	0.020	(vol/vol)
Saturated hydraulic conductivity	0.010	(cm/s)
Subsurface inflow	0	(mm/year)
Bottom Slope Length	9900.00	(cm)
Bottom Slope	13.00	(degree)

Table 5.7. Layer 5: Coarse sand (lateral drainage) layer parameters

Parameter	Value	Units
Top slope length	9900	(cm)
Top Slope	13.00	(degree)
Total porosity	0.437	(vol/vol)
Field capacity	0.062	(vol/vol)
Wilting point	0.024	(vol/vol)
Saturated hydraulic conductivity	$5.8x10^{-3}$	(cm/sec)
Subsurface inflow	0	(mm/year)

Table 5.8. Layer 6: Drainage net (geotextiles and geonets) parameters

Parameter	Value	Units
Total porosity	0.85	(vol/vol)
Field capacity	0.01	(vol/vol)
Wilting point	0.005	(vol/vol)
Saturated hydraulic conductivity	33	(cm/s)
Subsurface inflow	0	(mm/year)

Table 5.9. Layer 7: HDPE (geomembrane liner) parameters

Parameter	Value	Units
Saturated hydraulic conductivity	$2x10^{-13}$	(cm/s)
Pinhole density	2	(#/ha)
Installation defects	2	(#/ha)
Placement quality	4	(-)
Geotextile transmissivity	0	(cm^2/s)

Table 5.10. Layer 8: Silty loam (vertical percolation) layer parameters

Parameter	Value	Units
Total porosity	0.451	(vol/vol)
Field capacity	0.419	(vol/vol)
Wilting point	0.332	(vol/vol)
Saturated hydraulic conductivity	$1x10^{-6}$	(cm/s)
Subsurface inflow	0	(mm/year)

Table 5.11. Layer 9: Gravel 2 (lateral drainage) layer parameters

Parameter	Value	Units
Total porosity	0.320	(vol/vol)
Field capacity	0.050	(vol/vol)
Wilting point	0.020	(vol/vol)
Saturated hydraulic conductivity	$1x10^{-2}$	(cm/s)
Subsurface inflow	0	(mm/year)
Bottom Slope Length	9900.00	(cm)
Bottom Slope	13.00	(degree)

Table 5.12. Layer 10: Sandy clay loam (barrier soil liner) parameters

Parameter	Value	Units
Top slope length	9900	(cm)
Top Slope	13.00	(degree)
Total porosity	0.3705	(vol/vol)
Field capacity	0.2440	(vol/vol)
Wilting point	0.0960	(vol/vol)
Saturated hydraulic conductivity	$3.7x10^{-6}$	(cm/day)
Subsurface inflow	0	(cm/day)

5.2.2. General Design and Evaporative Zone Data

Table 5.13 lists the assumptions made regarding the surface runoff and the initial moisture content of the model layers. The SCS runoff curve number was computed from default soil data base using soil texture sandy loam with bare ground conditions, a surface slope of 13 per cent and a slope length of 99 meters. Because of the long term simulations (100 years) that were made, the impact of the initial moisture content is minimal.

Table 5.13. Evapotranspiration data

Parameter	Value	Units
SCS runoff curve number	90.90	-
Fraction of area allowing runoff	100.00	%
Area projected on horizontal plane	5.095	hectares
Evaporative zone depth	25.0	cm
Initial water in evaporative zone	4.782	cm
Upper limit of evaporative storage	11.575	cm
Lower limit of evaporative storage	2.900	cm
Initial snow water	0.000	cm
Initial water in layer materials	345.844	cm
Total initial water	345.844	cm
Total subsurface inflow	2.900	mm/year

Evapotranspiration and weather data: Evapotranspiration data were obtained from State Meteorological Institute for Kocaeli. The data are listed in Table 5.14.

Table 5.14. Evapotranspiration data

Parameter	Value	Units
Station latitude	40.75	degrees
Maximum leaf area index	3.00	-
Start of growing season	60	day
End of growing season	305	day
Evaporative zone depth	25.0	cm
Average annual wind speed	2.20	km/h
Average 1st quarter relative humidity	74.00	%
Average 2nd quarter relative humidity	68.00	%
Average 3rd quarter relative humidity	67.00	%
Average 4th quarter relative humidity	74.00	%

Precipitation and temperature data was synthetically generated by the HELP model for hundred years using coefficients for Kocaeli Turkey given in the Table 5.15.

The solar radiation data was synthetically generated by the HELP model using coefficients for New York by being the same parallel with Kocaeli (Latitude:40.75°).

Table 5.15. Meteorological observation results obtained from the State Meteorological Institute (DMI)

Months	Average Temp. (°C)	Average Precipitation (mm)	Year 1999 Precipitation (mm)	Year 2000 Precipitation (mm)	Average Evaporation (mm)	Average Wind Speed (m/s)	Average Moisture (%)
Observation Years	27	39	1	1	21	19	27
January	5.7	92.0	30.1	154.3	28.1	2.2	75
February	6.3	81.5	102.6	63.7	29.8	2.4	75
March	7.8	70.8	53.4	113.5	37.0	2.2	72
April	12.5	46.5	20.4	97.6	53.0	2.4	69
May	17.4	43.0	17.2	30.0	67.8	2.2	68
June	21.2	51.0	109.5	44.3	82.9	2.2	66
July	23.3	42.8	82.9	34.8	93.5	2.2	66
August	23.5	26.1	26.1	34.2	95.7	2.0	66
September	20.0	69.2	7.4	96.1	68.1	1.7	70
October	15.8	66.4	45	101.7	43.8	1.6	74
November	12.5	72.6	121.4	28.9	19.9	1.8	74
December	8.5	106.0	78	50.3	33.4	2.0	75
Annual	14.5	768.0	694	849.4	671.8	2.1	71

To estimate the steady state moisture content within the various landfill layers, one hundred years of simulation were done using the HELP model. The resultant Moisture content of the solid waste and soil cover as calculated by model are given in Figure 5.2.

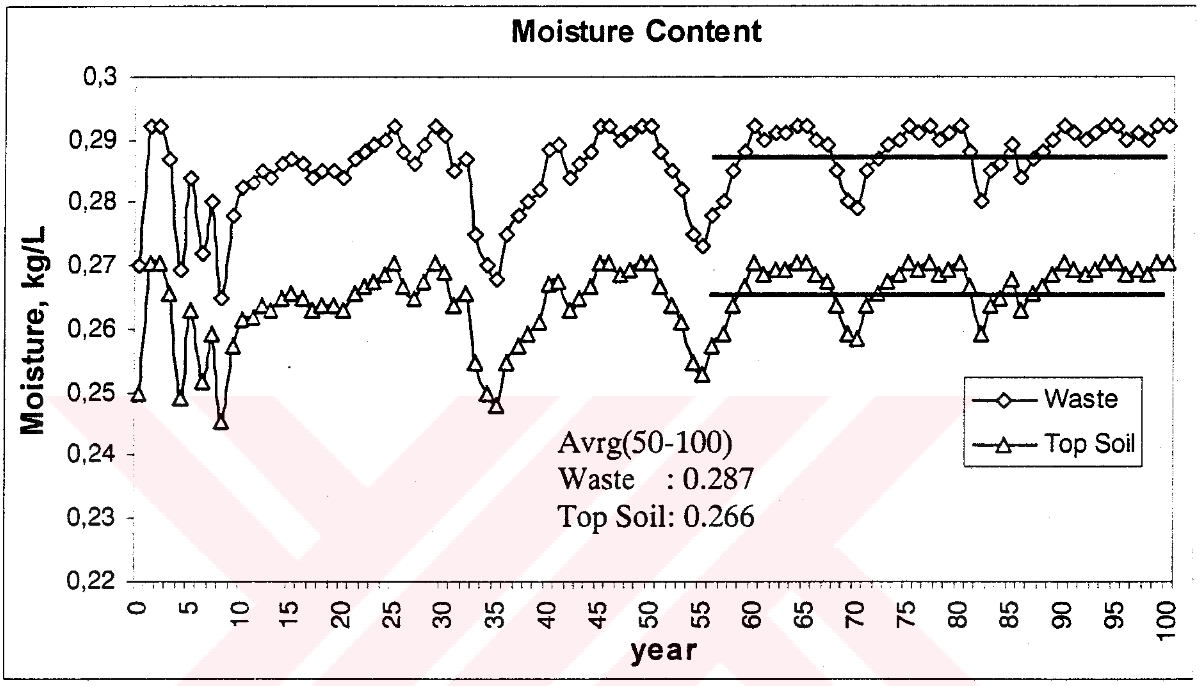


Figure 5.2. Moisture content of solid waste and cover soil

There are higher fluctuations at the beginning of the simulation while after fifty years the system is getting closer to steady state conditions. The average values reported in Figure 5.2 are based on the simulated data between years 50 and 100.

Solid Waste moisture content average = 0.287 vol/vol

Top Soil moisture content average = 0.266 vol/vol

5.3. Air Permeability of the Waste and Soil Cover

The laboratory data described in Section 5.1 are for the hydraulic conductivity (i.e., flow of water) through the waste. In order to be used in the gas flow model, these values must be converted to air permeability. For calculating air permeability of the solid waste and final cover soil, Equations 4.11, 4.13, 4.14 and 4.15 are used with the appropriate parameters taken from the HELP manual (Schroeder,1994) and a study by Carsel and Parrish (1988) respectively. Table 5.16 gives the parameters used in calculating air permeability of solid waste and final cover soil. These values were selected for media similar to the solid waste and cover soil found at İZAYDAŞ.

Table 5.16 Parameters used in air permeability calculation

Type	θ	θ_s	θ_r	N	K (cm/s)	m=1-1/N
Solid Waste	0.287	0.671	0.077	3	$4.86x10^{-4}$	0.67
Sandy Loam	0.266	0.41	0.065	1.89	$3.7x10^{-5}$	0.47

Since the air permeability is function of the moisture content, the long-term average moisture content in the waste layer and the soil cover, as calculated by the HELP model, were used. The calculation of the air permeability of the solid waste is shown below:

$$K_a(\theta) = k_{int} \cdot k_{ra} \qquad k_{int} = \frac{K\mu}{\rho g}$$

K $= 4.86x10^{-4}$ cm/s

μ $= 1.31E-02$ g/cm.s (for water)

ρ $= 1000$ g/L (for water)

g $= 9.81$ m/s^2

$$k_{ra} = [1 - S_e]^{1/2} \cdot [1 - S_e^{1/m}]^{2m}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$S_{e\ waste}$ =0.354

$k_{int\ waste}$ = 6.48x10^{-7} cm^2

$k_{ra\ waste}$ = 0.584

$K_a(\theta)_{waste}$ = 3.79x10^{-7} cm^2

The calculation of the air permeability of the soil cover is shown below:

$$k_{int} = \frac{K\mu}{\rho g}$$

K = 3.7E-05 cm/s

μ = 1.31E-02 g/cm.s (for water)

ρ = 1000 g/L (for water)

g = 9.81 m/sec^2

$$k_{ra} = [1 - S_e]^{1/2} \cdot [1 - S_e^{1/m}]^{2m} \qquad S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$S_{e\ soil}$ =0.583

$k_{int\ soil}$ = 4.94 x10^{-9} cm^2

$k_{ra\ soil}$ = 0.450

$K_a(\theta)_{soil}$ = 2.22 x10^{-9} cm^2

By comparison the air permeability values which were determined at the Kemerburgaz Landfill Site (Ergene, 2002) are 4.5x10^{-7} cm^2 for solid waste and 2.0 x10^{-9} cm^2 for cover soil. The values obtained in this study are consistent with these values.

5.4. Landfill Gas Generation Rates

The solid waste quantity and its composition are the most significant factor in gas generation rates. The most reliable data in this project is the amount of the waste because in İZAYDAŞ every solid waste truck is weighed as it enters and the landfill site.

Disposal of waste in Lot 7 started receiving waste in 1997 and was closed in February of 2000. From the beginning of 1997 to the end of 1999, only domestic waste was disposed of Lot 7. Until February 2000 the total amount collected in Lot 7 reached to 399,145,112 kg.

The annual amounts of collected solid waste up to the end of 2003 are given in the Table 5.17.

Table 5.17. Total collected solid waste amounts in the landfill

Year	Domestic (kg)	Hazardous (kg)	TOTAL (kg)
1997	$5.106x10^7$	$8.606\ x10^5$	$5.192x10^7$
1998	$1.527x10^8$	$2.026x10^6$	$1.547x10^8$
1999	$1.640x10^8$	$3.561x10^6$	$1.675x10^8$
2000	$1.885x10^8$	$1.115x10^7$	$1.997x10^8$
2001	$1.838x10^8$	$1.064\ x10^7$	$1.945x10^8$
2002	$1.842x10^8$	$1.167\ x10^7$	$1.958x10^8$
2003	$1.873x10^9$	$2.339\ x10^7$	$2.107x10^8$
Total	$1.112x10^9$	$6.329x10^7$	$1.175x10^9$

An important factor influencing the potential for energy recovery is the methane generation rate in the landfill gas. Landfill gas is usually 50 per cent methane and 49 per cent carbon dioxide and 1 per cent other organic gasses. At İZAYDAŞ, the methane percentage is measured periodically at a number of monitoring wells by hanging down methane measurement probe inside the wells. Because these measurements are influenced by the immediate conditions surrounding the monitoring wells, they may not be indicative of the entire lot. Moreover, at certain times the wells may be partially flooded by leachate water. This may be due to collection of precipitation or the local clogging of the leachate collection system.

Methane concentrations inside wells of Lot 7 are regularly measured manually. Figure 5.3 shows the methane percentage in the gas at different times.

If the wells with very low amount of methane are neglected, it can be said that methane rates are between 35 to 50 per cent of biogas generated inside Lot 7. This shows that the system is in transition from the acid phase to the next methanogenic phase with a steady growth of methanogenic bacteria. As the growth of methanogenic bacteria is initially suppressed by the acidic environment, it usually takes some time for them to develop and dominate the system. The methane concentration increases slowly with a decrease in hydrogen and carbon dioxide.

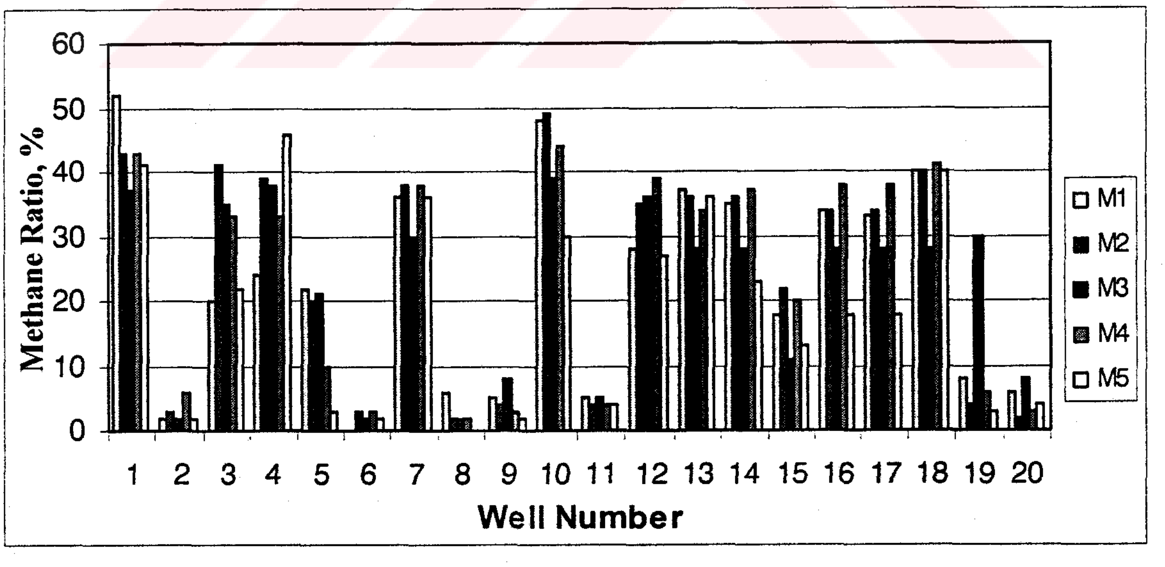


Figure 5.3. Measured methane percentage in the gas at different wells and times

M1 : 06.06.2002

M2 : 24.06.2002

M3 : 18.07.2002

M4 : 09.10.2002

M5 : 22.04.2003

Based on this data it can be assumed that the methane concentration in the LFG gas can potentially reach 50 per cent, the standardized value for municipal solid waste landfills. Therefore, the 50 per cent methane concentration will be used in the gas generation model and subsequent gas flow model.

Moisture content of the solid waste is a very important factor influencing landfill to gas generation. A saturation of about 60 per cent is ideal for decomposition of organics leading methane generation. Moisture content directly affects the decay rate, k, which defines the first order decay model used in LandGEM. For medium moisture climate, k is given between 0.05-0.15/year with site specific examinations. (EPA, 1996). It is generally difficult to define the k value for a specific site because of the needed long term observations. Therefore, the methane production is calculated for three different decay rates of 0.05, 0.10 and 0.15/year. A decay rate of 0.05/year value is appropriate for our case with near 30 per cent of moisture content. Moisture content can be increased by leachate recirculation on the site to raise the decay rate levels.

The methane generation potential, L_0, depends only on the amount of decomposable organic content amount of the solid waste. It is not affected by either moisture content or climate conditions. Because of the similarity of the municipal solid wastes collected throughout the Istanbul region, it is assumed that the İZAYDAŞ landfill site solid waste has a 170 kg/ton solid waste gas generation capacity (Arikan, 1997).

Based on all values described above, the results of methane production rates calculated using the LandGEM program are given in the Figure 5.4 below. Irrespective of the k values used, the gas generation rates are significantly lower than peak rates once the waste age is about 20 years. For this purpose the gas flow model will be simulated up to year 2020.

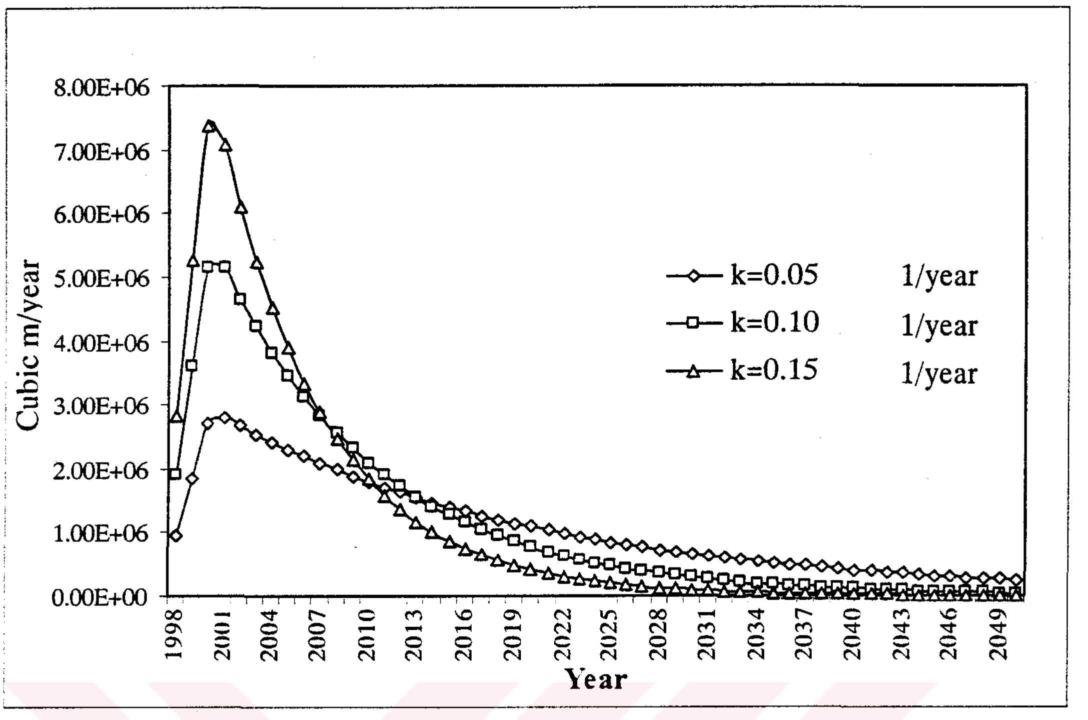


Figure 5.4. Methane generation rates for Lot 7 at different decay rates

5.5. Results of the Gas Flow Model

Gas flow within Lot 7 is simulated using the estimated air permeability of the waste and cover soil (Section 5.3), and the estimated gas generation rates (Section 5.4). Within Lot 7 there are currently 20 vents for the discharge of generated gas into the atmosphere. The gas flow model will be used to assess the potential for energy recovery from the lot and the adequacy of the existing wells to serve as gas collection wells. The model will be used also to assess the sensitivity of the gas collection system to key parameters and assumptions as described below.

The flow of gas within the landfill and to the gas collection system is simulated over years 1999 to 2020. Throughout this 22 year period, constant gas extraction rates and time-dependent extraction rates are considered to evaluate performance of the gas collection system and using two values of the values of the organic content decay rates. The first decay rate value is 0.5/year, which is more realistic value for waste of Istanbul and the other is 0.1/year which is higher by a factor of 2. Variable gas extraction rates are chosen to be 10 per cent higher than the annual gas generation rates calculated by LandGEM. This would lead to slightly higher pressure drop at the wells for increased gas collection while minimizing air intrusion into the system and loss of gas along the landfill boundaries. Because of the high variability of gas generation rates, the highest is four times more than the lowest in the simulation time period constant gas extraction rates are selected at 50 per cent higher and 50 per cent lower than the average.

An important parameter influencing the efficiency of the gas collection system is the air permeability of the soil cover. Currently there is no soil cover present on Lot 7. Therefore, simulations were made with two types of soil covers: (i) a silty loam 100 cm thick with air permeability of 2.22×10^{-9} cm^2, (ii) an air permeability reduced by a factor of 10 to 2.22×10^{-10} cm^2. These runs will provide a way to assess the sensitivity of the gas collection system to the permeability of the soil cover. A list of the runs conducted in this study is given in Table 5.18.

Table 5.18. Cases considered in the gas flow model.

Case Number	Decay rate k (1/year)	Gas Extraction Rate, (m^3/hour/well)	Cover Soil Air Permeability (cm^2)
1	0.05	Variable*: 16.96 to 48.42	2.22×10^{-9}
2	0.05	Constant: 24.75	2.22×10^{-9}
3	0.05	Constant: 44.55	2.22×10^{-9}
4	0.05	Variable*: 16.96 to 48.42	2.22×10^{-10}
5	0.10	Variable*: 33.90 to 92.37	2.22×10^{-9}
6	0.10	Constant: 29.70	2.22×10^{-9}
7	0.10	Constant:74.26	2.22×10^{-9}
8	0.10	Variable*: 33.90 to 92.37	2.22×10^{-9}
9	0.10	Variable*: 16.96 to 48.42	2.22×10^{-10}
*110 per cent of estimated annual LFG generation rates, depends on assumed decay rate.			

Figure 5.1 give the annual percentage of LFG captured, the percentage of LFG at the well and the percentage of air at the well, all for Case 1. The results show that variable pumping rates give steady results with 88 per cent of LFG captured while 20 per cent of

extra air collected by pumping. This latter ratio is high to accept for a proper landfill gas collection where air in the well should not be higher than 10 per cent. This ten per cent corresponds to $12.8x10^6$ m^3 out of $128x10^6$ m^3 collected from the wells in 22 years and is the result of air intrusion from the surroundings. In this case $26.6x10^6$ m^3 air intrudes into the system. Moreover $14.4x10^6$ m^3 of landfill gas, which is 50 per cent methane, escapes from the site to the atmosphere. This intrusion of air and loss of LFG along the boundaries of the lot is mainly a result of poor well placement. For this case, it is estimated that $51x10^6$ m^3 of methane gas will be collected over a 22 year period after processing and separation of $128x10^6$ m^3 gas by this system.

The simulation covers the first five years which have already passed to show the loss of methane gas. For Case 1, $16.9x10^6$ m^3 of methane would have been collected by 2004, if the collection system had been in operation since the beginning of waste disposal.

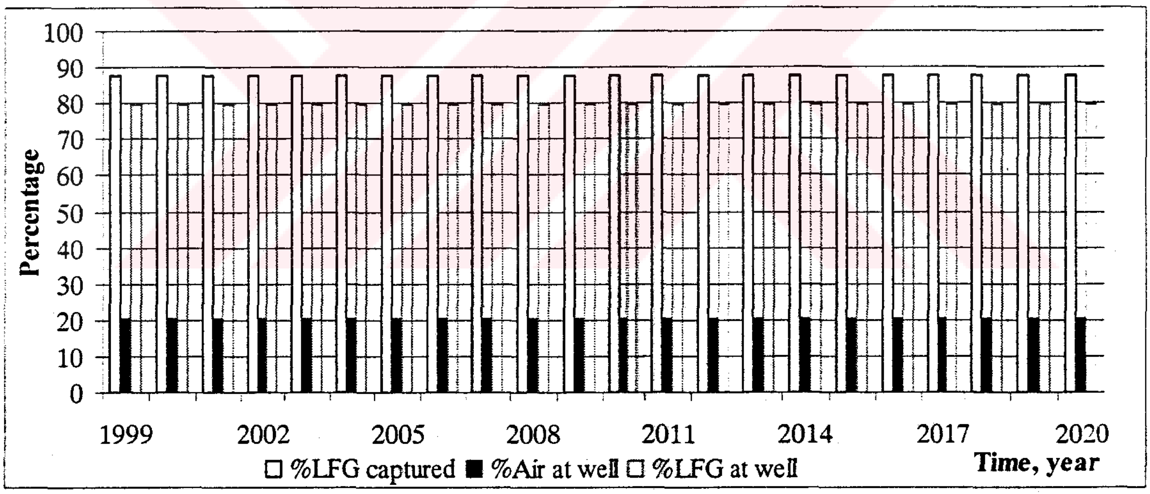


Figure 5.5. LFG and air percentages for Case 1

In Case 2, constant gas extraction rates are for each year starting from 1999 to 2020. Figure 5.2 shows the corresponding annual percentage of LFG captured and percentage of LFG in the collected gas. In early years LFG capture rates are decreasing. From year 2003 and on, LFG capture increases accompanied by an increase in air intrusion into the system. In 2002 while LFG is almost 100 per cent at the well, LFG capture rate is 53 per cent which means 47 per cent of LFG is released to the atmosphere. With these conditions it is estimated that the system acquires $41.7x10^6m^3$ of methane by processing $95.3x10^6m^3$ of collected gas. Meanwhile $33.2 \times 10^6 m^3$ LFG escapes into the atmosphere which is more than two times than Case 1.

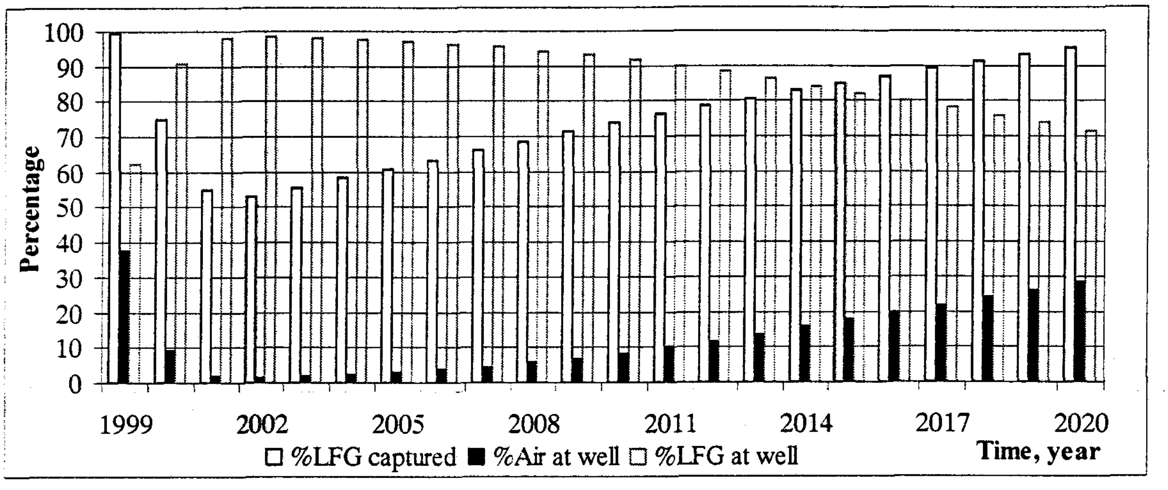


Figure 5.6. LFG and air percentages for Case 2

In Case 3, an increased but constant gas extraction rates is applied for each year. Figure 5.7 shows the corresponding annual percentage of LFG captured and percentage of LFG in the collected gas. The pumping rates in this case are nearly two times more than Case 2, but the fraction of air at the wells and air intrusion from the surrounding areas do not increase linearly with the extraction rates. At the same time, higher extraction rates lead to lower landfill gas losses, which is similar to what is predicted for Case 2 (Figure 5.6).

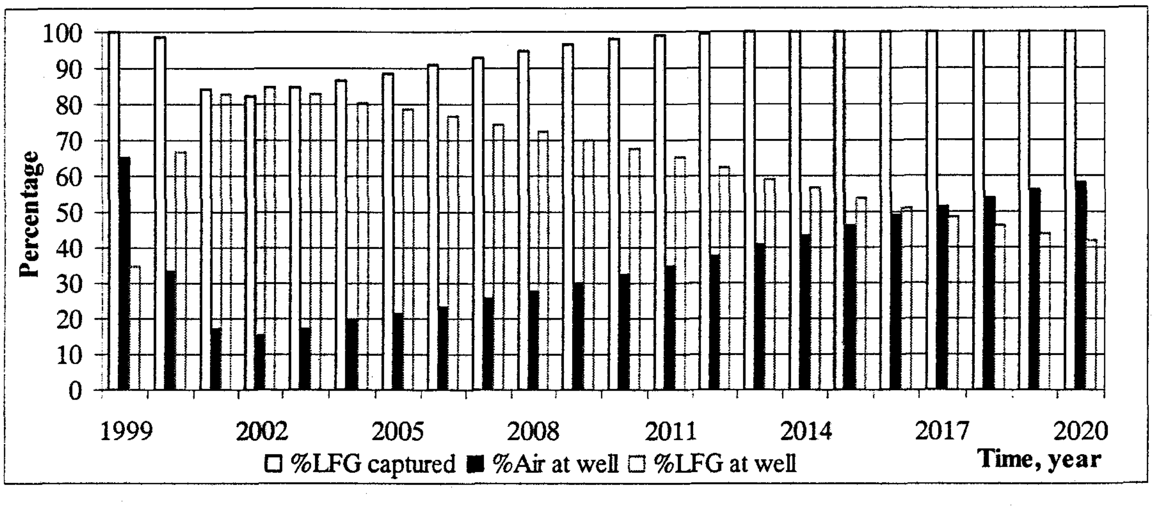
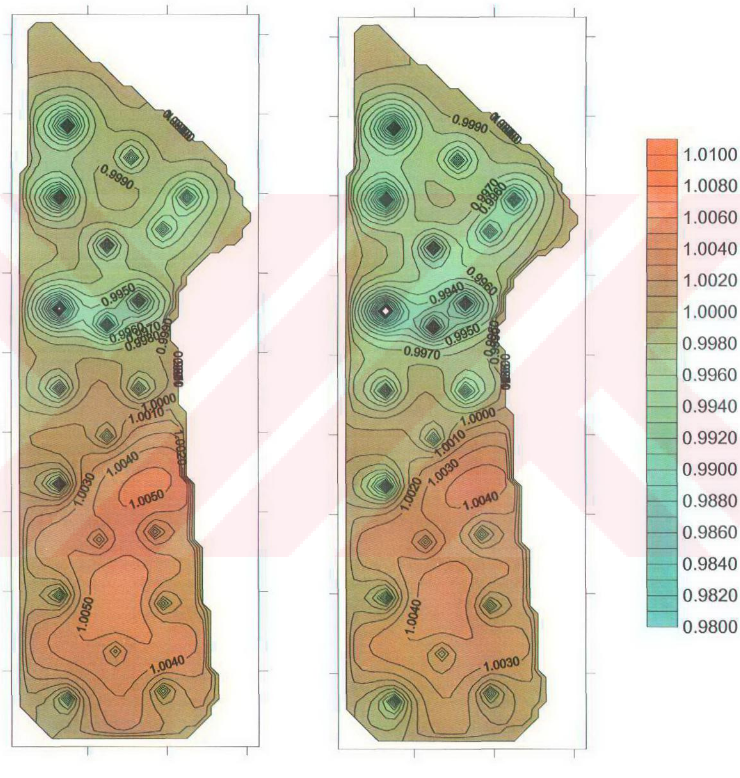


Figure 5.7. LFG and air percentages for Case 3

Figure 5.8 shows the pressure distribution within the waste for year 2002 and for constant (Case 3) and variable (Case 1) extraction rates. The figures show little difference in the pressure distribution for these two cases. The results are expected because constant extraction rates are high enough to cover early years of simulation.

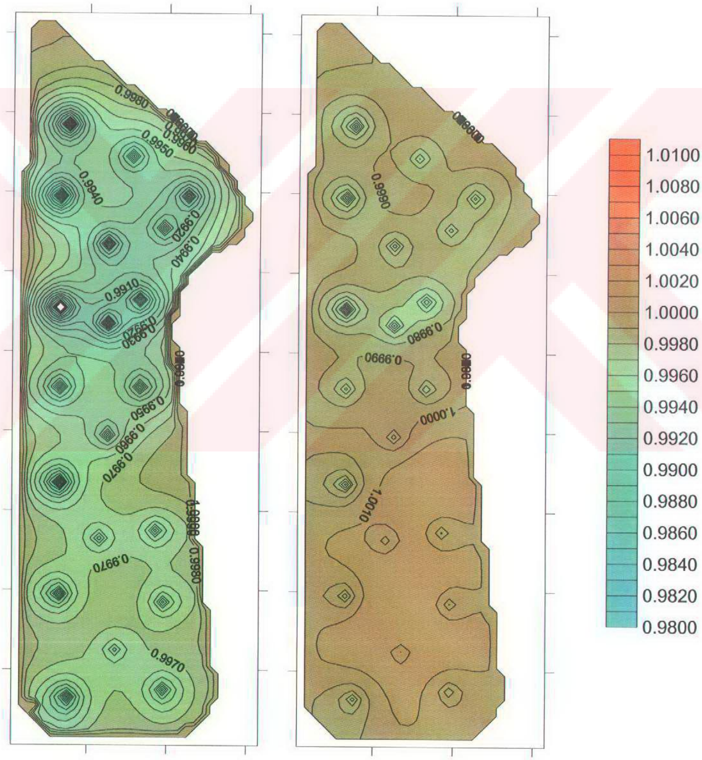


Case 3 Case 1

Figure 5.8. Pressure distribution (in atm) for year 2002 of Case 3 and Case 1

Moreover, all pressure values within the waste are close to the atmosphere pressure, 1.0 atm. Where the pressure drop below 1.0 atm, air intrusion occurs. In areas with pressure values greater than 1.0 atm, LFG losses to the atmosphere may occur. The pumping rates are same for all the wells, thus the northern side of the lot with less waste thickness shows higher pressure drop.

Figure 5.9 shows the pressure distributions for Cases 1 and 3 for year 2020, a year characterized by lower gas generation rates. Because the extraction rates used in Case 1 decrease with the decrease in gas generation rates, the pressure drop predicted at the wells remains small. On the other hand, for Case 3, large pressure drops are predicted.



Case 3 Case 1

Figure 5.9. Pressure distribution (in atm) for year 2020 of Case 3 and Case 1

Overall, it is not desirable to have a constant rate of pumping because of the time-dependent variable gas generation rates. In early years methane capture is getting higher. After few years the gradual decrease in landfill gas generation rates leads to less gas generated compared to the collected gasses. Thus, air intrusion compensates the shortage of LFG against constant rate of extraction from the wells.

To evaluate the effect of the soil cover permeability on the performance of the gas collection system, the cover soil permeability is reduced by a factor of ten. In landfilling covering of the waste as well as sealing the bottom and sides of the waste mass is important to establish the proper anaerobic degradation conditions and for enhanced gas collection.

Figure 5.10 shows the percentage of LFG capture and the percentage of LFG at the well for Case 4. Case 4 is similar to Case 1 (variable extraction rate) except that the top soil permeability is reduced by a factor of 10. In this case the LFG capture rates reach an average of 94 per cent which is about 6.8 per cent higher than that of Case 1. The LFG percentages at the wells are also increased by 6.2 per cent while air intrusion to the system decreased to 14 per cent. Hence, the decrease in the permeability of landfill cover results in a reduction of both the entrance and release of gas through the boundaries.

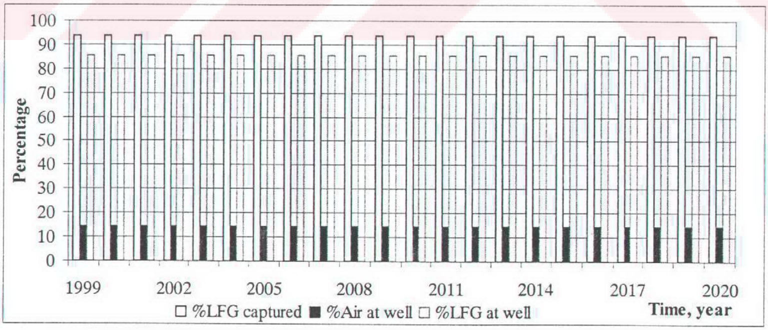


Figure 5.10. LFG and air percentages for Case 4

As a result, $3.69x10^6 m^3$ more methane would be collected until 2020 with the same system and solid waste but a reduced permeability of the soil cover. In comparison to Case 1, Case 4 shows that there is a significant improvement if less permeable soil is used for the soil cover. Periodic maintenance of the cover would be also need to maintain a tight seal of the waste volume.

Cases 5 through 8 are the same as Cases 1 through 4, respectively, except that now the organic decay rate is increased by a factor of 2 to 0.1 /year. Case 5, like Case 1, assumes that the total gas extraction rate from the twenty wells is 10 per cent greater than annual gas generation rate from the entire waste volume.

Figure 5.11 shows that the landfill gas collection system performance in Case 5 is similar to that of Case1. This suggests that while the organic waste volume is an important factor to the LFG generation, the decay rate value does not significantly influence the performance of the gas collection system. Note however that the amount of gas generated in any particular year may be different. The system can easily be adapted by increasing extraction rates and adding a second separation unit and a burner beside the old ones to handle the collected landfill gas. In Case 5 which has the higher k value, a larger portion of the gas is lost between years 1999 and 2004 due to faster decomposition of organic waste.

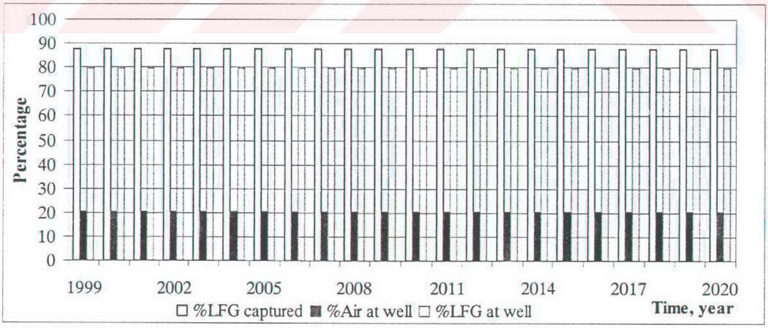


Figure 5.11. LFG and air percentages for Case 5

Figures 5.12 to 5.14 show the percent LFG captured and percent of LFG in the captured gas for Cases 6, 7 and 8 respectively, all for k = 0.1 /year. For the cases with constant extraction rates, high fluctuations in the pressure rate lower the collection performance because differences between the extraction rate and gas generations are higher than those of the first set of runs (Cases 2 and 3). This means that constant extraction rates may be adequate for very low decay rates.

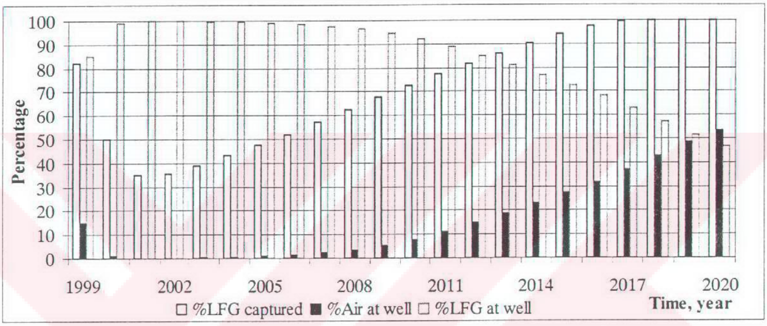


Figure 5.12. LFG and air percentages for Case 6

Decreasing permeability of cover soil for Case 8 also has the same effect as in Case 4: a decrease in LFG losses and a decrease in air intrusion are predicted.

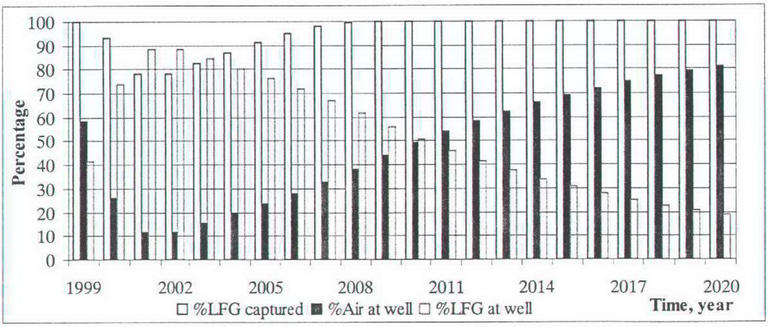


Figure 5.13. LFG and air percentages for Case 7

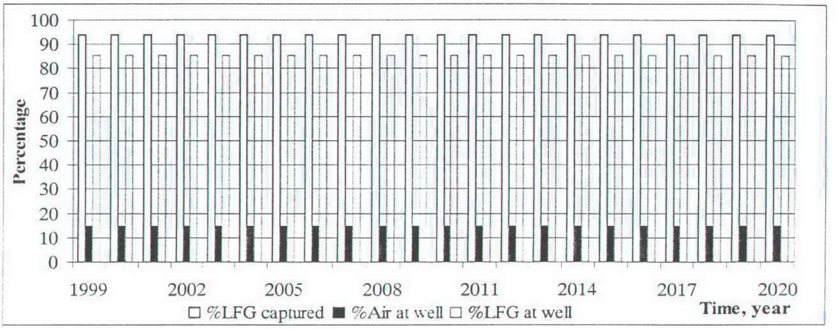


Figure 5.14. LFG and air percentages for Case 8

A major unknown which can have a significant effect on the model predictions is the organic decay rate. In reality several factors will influence the decay rate (moisture content, temperature, landfill phase etc) These factors are difficult to model in advance and as such it is quite possible that the actual decay rate may be different than what was assumed thus far in this study. Case 9 is similar to Case 4 but assumes that the decay rate is underestimated. Specifically, Case 9 is a combination of Case 4 on the one hand and Case 8. It assumes the same variable extraction rates of Case 4, but a higher decay rate of 0.1/year as in Case 5 to 8. Figure 5.15 shows that the selected extraction rates are not enough to collect the generated LFG and most of it is released to atmosphere.

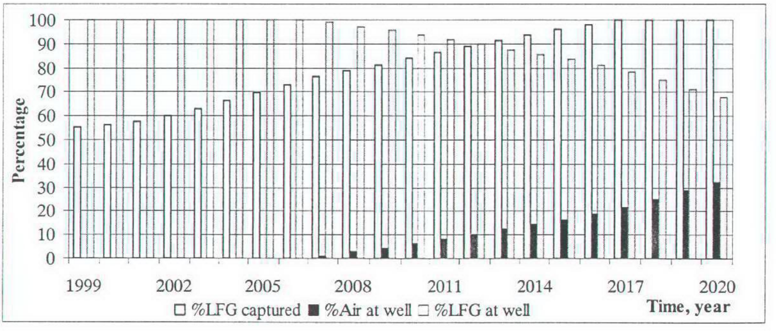
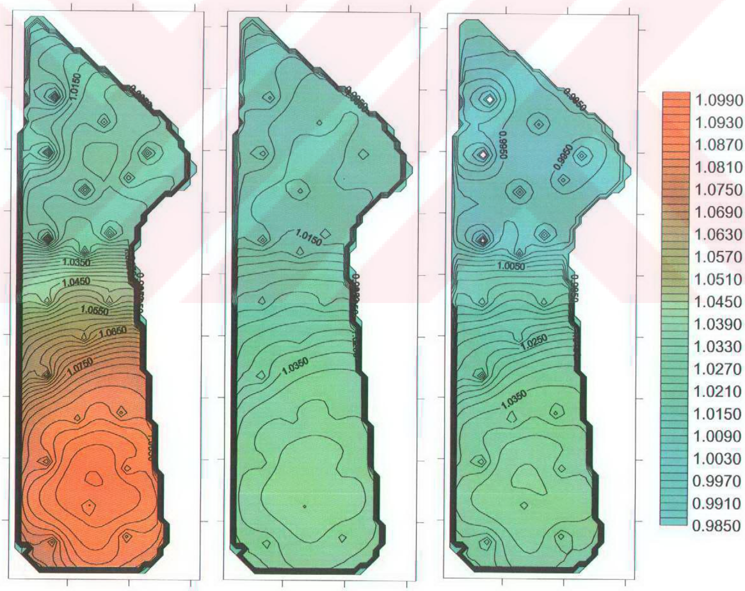


Figure 5.15. LFG and air percentages for Case 9

Performance of collection system in Case 9 is low, similar to cases with constant pumping rates. Faster degradation leads to faster consumption of organics in solid waste. Excessive air intrusion is predicted to occur after 2007. This shows that variable extraction rates of Case 4 can not compensate for the higher LFG generation rates associated with Case 9.

Figure 5.16 shows the unsteady pressure values for years 1999, 2004 and 2009 of Case 9. In 1999 high amounts of gas generation are predicted with insufficient extraction at the wells leading to high pressure inside the lot. In 2004 near uniform pressure is predicted over the entire lot. In 2009, pressure drops are getting higher causing to high air intrusion through the boundaries.



1999 2004 2009

Figure 5.16. Pressure distribution (in atm) for years 1999, 2004 and 2009 of Case 9

A summary of the comparison of the various cases is presented next. Figure 5.17 shows that LFG capture rates are high and stable for Cases 1, 4, 5 and 8 with variable gas extraction rates. On the other hand, constant pumping rates, especially low ones like Case 2 and 6, lead to large fluctuations on the LFG capture performance. Lowering the permeability of the cover soil also increases the performance of the gas collection system. Case 9 shows a linear increase with time.

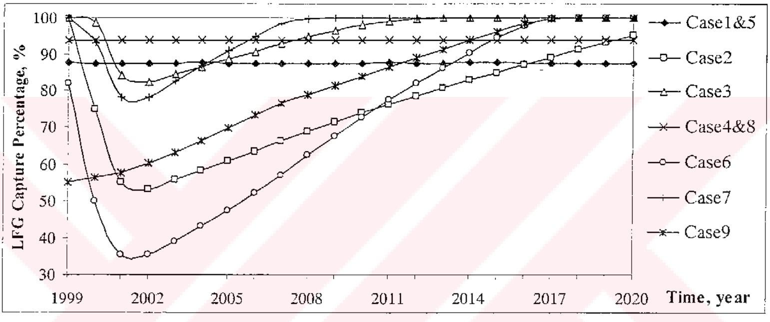


Figure 5.17. LFG capture comparison for all cases

Figure 5.18 shows the LFG percentage at the wells. For earlier years the LFG percentage at the wells is very high in Cases 2 and 6; however capture rates are very low due to low extraction rate which is not sufficient to collect whole gas. So, a big fraction of the landfill gas escapes into the atmosphere.

For Cases 3 and 7 low LFG percentages and high percentages of capture rates are associated with excessive amount of air intrusion into the collection system, particularly for the later years.

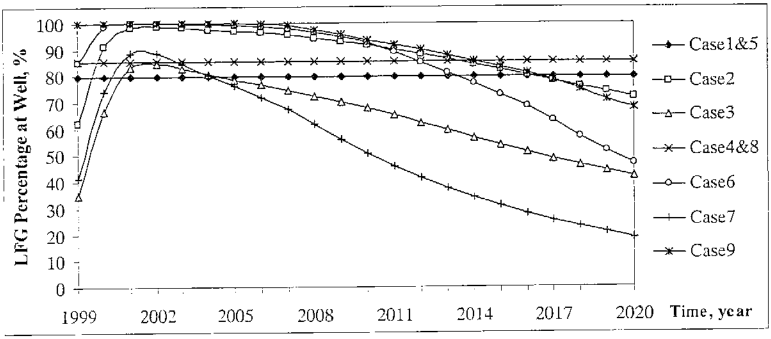


Figure 5.18. LFG percentages at wells (comparison for all cases)

Figure 5.19 shows that for Case 7 the collected gas by year 2020 is very low in methane content: 80 percent of collected gas is air and the rest is landfill gas of which methane is half. Case 4 and Case 8 give lower and more stable results in terms of air percentage at wells.

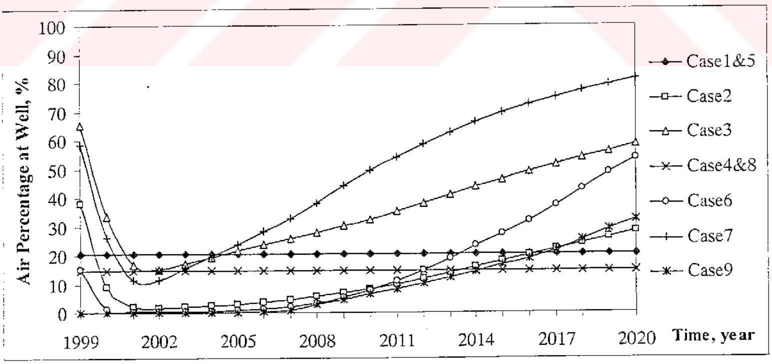


Figure 5.19. Air percentages at well (comparison for all cases)

If methane capture rate is compared rather than percentages for all cases it can be seen that, not related to different case parameters, landfill gas collection system performance stabilizes after high organic consumption occurs. Figure 5.20 shows that in all cases after 2014 methane capture rates are nearly the same. On the other hand, wide range of capture rates occurs before 2014. For example in 2002 capture rate in Case 8 is nearly 3.5 times more than capture rate in Case 2. The figure also represents that wrong decision in design of LFG collection systems can result in high amounts of methane loss in early years. Moreover, the highest rates of methane at the wells are associated with the cases with lower soil cover permeability.

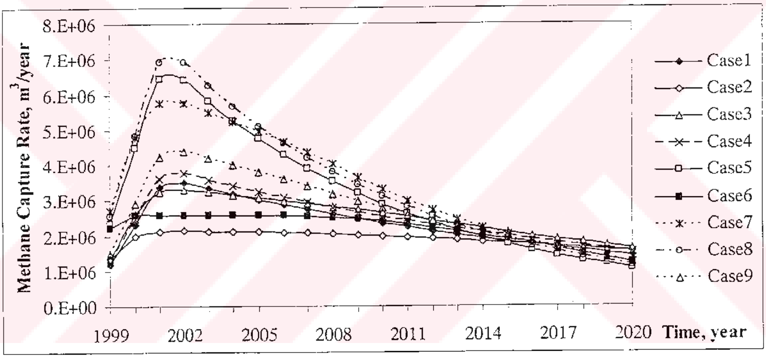


Figure 5.20. Methane capture rates (comparison for all the cases)

Figure 5.21 shows the rate of LFG not collected at the wells (i.e., released along the top and sides of the lot into the atmosphere. While methane capture rates in Case 9 are higher than Case 1 and 4, a large portion of the LFG can not be collected as given in Figure 5.21. Because of its much lower collection rates and hence higher LFG release into the atmosphere, Case 6 appears to have the poorest performance.

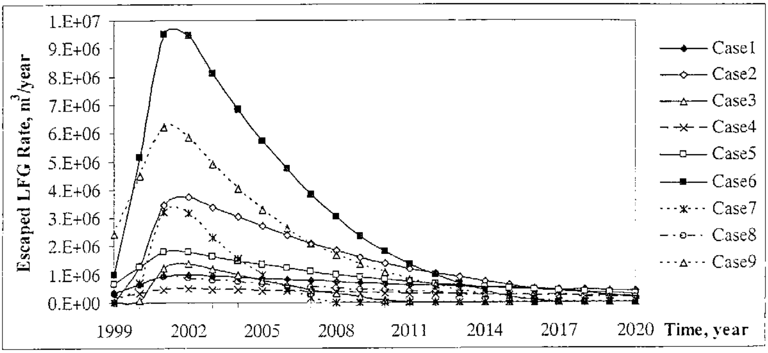


Figure 5.21. Escaped LFG rates (comparison for all the cases)

Overall, the above simulations indicate that Case 4 (low soil permeability and variable extraction rate, base case decay rate) would result in the highest system performance (defined here as high LFG capture and reduced air intrusion). The estimated annual LFG volumes that would be captured based on this scenario are listed in Table 5.19.

Table 5.19. Annual gas extraction and methane collection amounts for Case 4

Year	Extracted Gas, m^3	Methane Collected, m^3
1999	2.97×10^6	1.27×10^6
2000	5.79×10^6	2.47×10^6
2001	8.47×10^6	3.62×10^6
2002	8.82×10^6	3.77×10^6
2003	8.39×10^6	3.58×10^6
2004	7.98×10^6	3.41×10^6
2005	7.59×10^6	3.24×10^6
2006	7.22×10^6	3.09×10^6
2007	6.87×10^6	2.94×10^6
2008	6.54×10^6	2.79×10^6
2009	6.22×10^6	2.66×10^6
2010	5.91×10^6	2.53×10^6
2011	5.63×10^6	2.40×10^6
2012	5.35×10^6	2.29×10^6
2013	5.09×10^6	2.17×10^6
2014	4.84×10^6	2.07×10^6
2015	4.61×10^6	1.97×10^6
2016	4.38×10^6	1.87×10^6
2017	4.17×10^6	1.78×10^6
2018	3.96×10^6	1.69×10^6
2019	3.77×10^6	1.61×10^6
2020	3.59×10^6	1.53×10^6
TOTAL	1.28×10^8	5.47×10^7

6. CONCLUSIONS

A multi-step model is developed to evaluate the performance and aid in the operation of an active gas collection system at the İZAYDAŞ municipal solid waste site in Izmit, Turkey. This study focuses on Lot 7, a closed lot for municipal waste. The lot includes 20 gas venting wells at a spacing of about 20 m, screened within the waste to release LFG generated into the atmosphere and prevent the buildup of high pressure within the waste. The model consists of three major components: a water balance model, a gas generation model and a gas flow model.

As part of this study, the hydraulic conductivity of the solid waste was determined with a series of laboratory experiments using synthetic samples prepared based on general properties of solid waste generated within the Istanbul Region. The hydraulic conductivity was used in the HELP (water budget) model to compute the long term moisture content and for computing the air permeability of the waste volume and soil cover, both needed in the gas flow model.

Moisture content calculations were based on site specific weather data and actual landfill layer properties. For parameters for which no direct measurements were available, appropriate literature values were used. The model was simulated for hundred years to get the long-term moisture content of the solid waste and cover soil layers. Results of the HELP model indicate that the average long-term moisture contents (water volume/ total volume) in the waste and soil cover are about 0.29 and 0.27, respectively.

Landfill gas generation rates were calculated with a first order decay model using the computer program LandGEM. Actual data on the operation years, waste volumes, waste age, waste composition and climatic data were incorporated in the model. Overall, it is anticipated that between 1999 and 2020 about 50-70 million m^3 of LFG would be generated. However, some portions of that gas have already been lost since the initial placement of waste until the present time. Monitoring data collected at the site confirm that high percentages of methane are being released from the lot.

The gas flow model is based on the MODAIR computer program, a model for gas flow in porous media. MODAIR is an adaptation of MODFLOW a groundwater flow model to air transport under transient conditions. However the MODAIR program, which was primarily developed for gas flow in the vadose zone, does not allow for the inclusion of spatially distributed source terms (such as an LFG generation term). Therefore, the recharge package of MODFLOW is included to simulate the presence of distributed transient gas generation rates. The simulation length of the modified MODAIR program is assumed to be 22 years beginning with year 1999 to the end of 2020. The model was also used to assess the effectiveness of the gas collection system to key parameters, namely: (i) mode of operation. constant or variable extraction rates, (ii) air permeability of the soil cover, (iii) waste decay rate.

Since the initial placement of the waste, it is estimated that between $15x10^6$ m^3 and $33x10^6$ m^3 of methane has been generated and lost into the atmosphere. The range in the lost methane volume is primarily due to the uncertainty in the definition of the decay rate.

Extraction of gas at constant rates is expected to decrease the system performance. Under such conditions, large fractions of LFG may get released into the atmosphere in the early years, while excessive air intrusion into the collection system is predicted for the later years. Model simulations indicate that the LFG capture can be as low as $14x10^6$ m^3/year in the first five years of operations while the air intrusion after year 2010 can be as high as $32x10^6$ m^3/year. These values are in due to the assumed decay rate.

Improved performance is obtained when variable gas extraction rates are used. By setting the gas extraction rates equal to 110 per cent the annual gas generation rates, it is expected that most of the LFG generated would be captured.

A best estimate decay rate for municipal sold waste decomposition is about 0.05/year. For this value, it is expected that about $54.7x10^6$ m^3 of methane will be collected between year 1999 and 2020 (assuming variable extraction rate and $2.22x10^{-10}$ cm^2 soil cover permeability). If the decay rate decreases by a factor of 2, the total methane collected will be about $75.9x10^6$ m^3 for the same period.

Air intrusion into the gas collection system is strongly dependent on the air permeability of the soil cover. Assuming an air permeability of 2.22×10^{-9} cm^2 leads to about 20 per cent air intrusion. However if the permeability is reduced by an order of magnitude, the air intrusion into the system decreases to 15 per cent. This suggests that an air permeability not greater than 2.22×10^{-10} cm^2 and preferably lower be used to cover the waste. These values correspond to an intrinsic permeability of about 4×10^{-10} cm^2, assuming about 60 per cent water saturation.

Finally, this study shows that an integrated water budget and gas generation and flow modeling approach is a useful tool for evaluating energy recovery potential from landfills and for designing proper gas collection systems. Moreover, the model can be used for optimization purposes during the operation of the gas collection system as additional data becomes available.

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