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Project Summary

Production and Management of Leachate from Municipal Landfills: Summary and Assessment

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Production and management of leachate from municipal landfills were evaluated to identify practical information and useful techniques for design engineers and site operators. Advantages, limitations, and comparative costs were also assessed for various approaches to the problem. The study addressed public health impacts, management options, and additional research needs on the generation, control, and monitoring of landfill eration, contol, and monitoring of landfill leachates. Numerous mathematical models have been proposed for estimating leachate generation, and they are usually based on the water balance method. Several fairly successful models are proposed here for simulating the change in leachate strength with increasing landfill age of cumulative leachate volume. A program to monitor the zone of saturation is established to give a prompt indication of groundwater contamination.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

In 1990, a projected 295 to 341 million metric tons of municipal refuse will be produced in the United States. When water passes through this refuse in a sanitary landfill, it accumulates various contaminants. This percolate or leachate may then enter underlying groundwaters and seriously degrade the water quality of the aquifer. Landfill leachate may thus exert a major environmental impact.

Leachate production can be minimized or nearly eliminated by preventing water contact with the refuse by the use of surface and subsurface drainage and properly selected cover material that is graded and seeded with a high evapotranspiration (ET) crop. Various studies concerning sanitary landfill behavior have been conducted to understand, delineate, and define significant management options.

The objectives of this study were: (1) to clarify the understanding of leachate production and management options through a critical review and analysis of existing information; (2) to identify practical information and techniques that can be used by design engineers and site operators; (3) to delineate weaknesses in the available data base; and (4) to identify useful techniques for estimating and mitigating the environmental and public health impacts of leachate generation. The specific objectives were to document: (1) current methods, advantages, and limitations of various approaches; (2) comparative costs; (3) additional research needs on the generation, significances, and associated costs of controlling and monitoring leachate from municipal landfills. Presentation of the results is in terms of leachate generation, composition, and migration, available control technology, and environmental monitoring.

Leachate Generation

Leachate generation at a landfill site depends on many factors. Volume is generally determined by the availability of water, landfill surface conditions, refuse conditions, and underlying soil conditions. Factors affecting availability of water include direct precipitation, surface run-on, groundwater intrusion, irrigation, refuse decomposition, and co-disposal of liquid waste or sludge with refuse. In most cases, precipitation (including rainfall and snowfall) will be the principal source of leachate. Many methods for estimating leachate generation neglect the effects of rainfall intensity, frequency, or duration. Intensity influences the impact of raindrops on the surface soil particles, which could change infiltration rates and leachate quantity. Frequency and duration also affect infiltration and runoff. Quantitative information on the effects of such rainfall characteristics on leachate generation is lacking. Snowmelt usually occurs at rates considerably below the infiltration capacity of unpacked soils. Surface runoff from snowmelt may therefore be rare.

Surface run-on is mostly affected by surface topography and can be determined by surface measurement, empirical formulas, or graphic methods. The rational method is expressed in terms of uniform rate of rainfall intensity, landfill area, and a runoff coefficient. The key to successful estimation of surface runoff by the rational method is the correct choice of the coefficient dependent on surface characteristics, type and extent of vegetation, and surface slope. Cook's method uses an empirical relationship between drainage area and peak flow, with modifications for climate, relief, infiltration, vegetal cover, and surface storage. Other methods include the Burkli-Ziegler and McMath formulas. Groundwater intrusion occurs if the base of the landfill is below the groundwater table. This condition may be determined by a hydrologic investigation and calculations using Darcy's Law. Precise measurement of underground flow is not feasible. The extent of microbial activity and consequent water production depends mainly on the amount and pH of interstitial moisture, temperature, presence of oxygen, composition and particle size of the refuse, organisms present, and the degree of mixing. Decomposition is much faster under aerobic than anaerobic conditions. Under aerobic conditions, decomposition may reduce volatile matter and carbon concentrations by 50% in a year.

The volume of water available for leaching from disposal of sewage sludge with municipal solid waste may be affected by the type and amount of sludge, moisture content, moisture-holding capacity, and the effect of compaction and decomposition of the release of water. ET, which is the sum of water loss by evaporation and transpiration, is affected by vegetation and cover material (type, dimension, compaction, etc.), surface topography, temperature, humidity, and wind speed above the landfill. ET determination methods fall into three general categories—theoretical, analytical, and empirical. Various measurement methods are soil-moisture sampling, lysimeter measurements, and adjusted pan evaporation. Many empirical or theoretical equations have been derived for estimating ET rates. Some typical equations are the Hedke, Lowry-Johnson, Blaney-Morin, Blaney-Criddle, Thornwaite, and Fenman equations. Leachate may be channeled through the refuse and dispersed by intermediate cover layers, or it may seep through the pores of the refuse. If no channeling has occurred in the refuse, leachate will first appear when soil cover and refuse reach field capacity. The time required for the first appearance of leachate can be obtained using the moisture-routing calculation or by using a graphic technique. If channeling does occur, leachate will not be produced until at least a portion of the refuse reaches field capacity. Specific information describing the effects of management or operating practices on leachate production is not available.

Numerous mathematical methods have been used for quantitative estimates of the volume of leachate generated from landfills. The approaches are all derived from the water balance principle—a one-dimensional flow model based upon the retention and transmission characteristics of the refuse and cover soil. Although the water balance method has been widely used for estimating landfill leachate, the accuracy and sensitivity of the method for the actual landfill are less studied. More than a hundred different approaches are available for water balance calculations, but no comparisons have been made to identify which approach can achieve better results, or which is suitable for what types of landfill conditions. The applicability and accuracy of the water balance calculations can be determined by analyzing the suitability of the approaches and the closeness of the calculated results to actual measurements. Site verification of various leachate estimation techniques is largely lacking, however. Applicability and accuracy are difficult to verify for actual landfills because of the lack of accurate leachate generation data. Selection of applicable leachate volume estimation methods should thus be based on the specific site circumstances, availability of data, scientific and engineering judgments, and the experience of the designer and operator in leachate generation estimation.

Numerous methods have been proposed for determining infiltration capacity and rate. Theoretical methods are not recommended because of their highly simplified nature and their requirement for determining special watershed properties. Three general appoaches are: actual measurement, estimation from runoff, and empirical calculation. The American Society of Civil Engineers (ASCE) empirical method is based on relative minimum infiltration capacities and takes into account vegetal covers. Equations also exist for snowmelt infiltration.

Leachate Composition

Leachates are usually highly contaminated and can degrade surface water and groundwater. Viruses are only occasionally detected in leachates, though their potential presence in leachates of fresh refuse cannot be overlooked. Bacterial and viral populations decrease significantly with refuse age or time of leaching. Elevated landfill temperatures resulting from biodegradation can help to inactivate bacteria and destroy viruses. The chemical characteristics of leachate also contribute to bacterial inactivation. Little work has been done regarding fungi and parasites in leachate.

The rate of solubilization of a refuse mass is governed by specific microbial populations dependent on chemical and physical processes, including pH effects, redox effects, precipitation, ion exchange, adsorption and complexation, biological effects, physical sorption effects, and temperature. These processes create a highly complex and dynamic system and considerable variability in leachate composition.

Leachate composition is a function of numerous factors, including those inherent in the refuse mass and landfill location, and those created by designers and site operators. The chemical and microbiological character of refuse is largely uncontrollable. Ambient temperatures and rainfall are unalterable characteristics, but refuse density, permeability, depth, and water application can be regulated. Compared with unshredded refuse, shredded material yields increased landfill field capacity, a greater concentration of pollutants in leachate, and a higher rate of pollutant removal per volume of leachate. Conversely, baling produces a more dilute leachate, delays attainment of landfill field capacity, and removes less mass per volume of leachate than shredded or unbaled refuse. Higher rates of water application produce more dilute leachate and greater mass removals as a function of time. Increasing landfill depth promotes stronger leachate. Landfill temperature fluctuates with the seasonal ambient temperature variation near the landfill surface, but these amplitudes are less pronounced with increased landfill depth.

The addition of municipal wastewater treatment plant (WWTP) sludges or industrial sludges to municipal landfills provides both beneficial and adverse effects on leachates. WWTP sludge and refuse admixtures accelerate the rate of stabilization of biodegradable organic matter. The addition of industrial waste may cause more toxic elements to occur in leachates and may adversely affect the biochemical stabilization processes. Some of the specific findings are as follows:

1. Seeding municipal refuse with primary sewage sludge increases the biological stabilization rates of organic pollutants.
2. Addition of septic tank pumpings accelerates the methanogenic process.
3. Bacterial loading does not increase.
4. Leachate organics and total dissolved solids (TDS) are reduced.
5. Inorganic ion concentrations are largely unaffected.
6. Admixed WWTP sludge and refuse produces an acidic leachate with a higher BOD, but chemical composition does not differ.
7. Co-disposal accelerates leachate formation through the additional moisture.
8. Epidemiological evidence of diseases resulting from WWTP sludge co-disposal is lacking.

The leaching trends of chemically stabilized and unstabilized industrial wastes disposed with municipal solid waste (MSW) are as follows:

1. The release of major metal contaminants from treated or untreated electroplating sludge was not observed when it was disposed with MSW.
2. Untreated chlorine production brine sludge disposed with MSW releases significant quantities of aluminum, cadmium, copper, chlorine, mercury, sodium, and other dissolved solids.
3. Disposal of MSW with chemically stabilized chlorine production brine sludge significantly reduces the mass release of toxic metals.
4. Disposal of MSW with calcium fluoride and sewage sludge improves leachate quality with respect to BOD, COD, TOC, alkalinity, pH, and iron.

Two approaches can be used to model the composition of leachates as a function of time or cumulative leachate volume: (1) to describe quantitatively the physical, chemical, and biological processes that occur during leaching, and (2) to avoid mathematical expression and focus on leachate concentration histories. The models are sensitive to such factors as refuse placement and composition, hydraulic phenomena, and landfill configuration. Agreement of the various models with experimental data ranges from fair to very good. At present, leachate composition models are appropriate primarily for research purposes, since as mathematical expressions they merely interpret experimental results.

Leachate Migration

Soils are chemically sorbent bodies consisting of: (1) inert chemical compounds, (2) difficult and easily soluble substances, (3) soluble salts and acids, (4) complex insoluble compounds, and (5) a wide variety of organisms. Soil represents a medium in which a series of complex biological activities are occurring simultaneously. Soil properties most useful in predicting the mobility of leachate contaminants are: (1) texture, (2) content of hydrous oxides, (3) type of content of organic matter, (4) particle size distribution, (5) cation exchange capacity, and (6) pH. The attenuation and migration of contaminants in the soil and water system are influenced by diffusion and dispersion, dilution, straining, precipitation/dissolution, adsorption/desorption, complexation, ion exchange, redox, and microbial activity.

The most important physical properties relative to leachate migration are diffusion and dispersion, dilution, sorption, and straining. Hydrodynamic dispersion is the result of variations in pore velocities within a soil. It is effective in attenuating the maximum constituent concentration rather than the total quantity of the constituent in a pulse or slug of leachate. Complexation involves the reaction of metal ions with inorganic anions and organic liquids. Complex formation affects attenuation and migration in two ways: In solution, it greatly increases the concentration of constituents by forming soluble complexes; or, if the complex formation exists between the soluble constituents and solid surfaces, the constituents levels decrease. Most ion exchange effects orginate from exchange sites on layered silicate clays and organic matter. The exchange capacity of soils is affected by the kind of quantity of clay mineral and organic matter and the pH of the soil/water solution. Redox reactions occur when redox potential in leachates is different from that of soil solutions. Redox reactions are greatly affected by degradation of organic compounds in the soil. Through biological assimilation, the trace metals may be transformed into microbial tissue and immobilized. The migration of trace metals in the soil/water system is extremely complex. The fate of chlorinated hydrocarbons, is very difficult to predict. Volatilization, microbial degradation, chemical hydrolysis, oxidation, and sorption can be involved. The fate of pesticides in soil/water systems involves adsorption/desorption, microbial decomposition, volatilization, soil moisture, and physical properties of the soil. Adsorption /desorption is considered most important. Virus survival depends on soil moisture content, temperature, pH, nutrient availability, and antagonisms. Viruses that penetrate the soil surface are expected to survive longer than those retained near the surface.

Leachate migration models can be classified into four generic categories: descriptive, physical, analog, and mathematical models. The models can also be subcategorized by method of analysis and particular approach. Empirical models are based completely on observation and/or experimentation. Conceptual models use equations based on conservation of mass, energy, and momentum. In a deterministic model, all input variables and system parameters are assumed to have fixed mathematical relationship with each other. Stochastic models take into account intrinsic randomness associated with parameters. Static models evaluate steady-state conditions, and dynamic models evaluate changing variables. One-, two-, and three-dimensional models may also be used.

Available Control Technology

Environmental control technologies are divided into four areas: Groundwater control, leachate composition control, collection systems, and treatment methods.

Groundwater control measures are presented in terms of groundwater/leachate isolation and leachate plume control. The groundwater/leachate isolation methods can be defined as those approaches by which contaminants are contained within the fill and not permitted to migrate into the groundwater. The available control techniques include synthetic liners, bottom sealers, slurry trenches, grout curtains, and sheet piling cutoff walls. The liners may be used both as collection devices and as means for isolating leachate. Bottom sealing offers advantanges, especially in coarse soils and gravels. The seal can prevent groundwater from entering the fill and impound the leachates formed. A slurry trench prevents the horizontal subsurface movement of water. Its advantages include simple construction methods, leachate-resistant bentonites, low maintenance, and minimal liner deterioration. Slurry trenches are most effective where a shallow groundwater condition exists and an impermeable bedrock stratum is available for contact with the barrier. A grout curtain performs a function similar to that of a slurry trench. Advantages of sheet piling cutoff walls over slurry trenches and grout curtains are ease of construction, maintenence-free nature, and low construction costs.

Plume control refers to efforts to isolate a contaminated groundwater body. Methods involve drains to intercept upgradient groundwater to lower the water table, well point systems to prevent groundwater flow through the fill or leachate collection down gradient, and deep-well systems that are a deeper form of the well point systems. Surface water control measures such as contour grading, surface water diversion, surface sealing, and revegetation are used to minimize the quantity of water entering the landfill.

The purpose of leachate composition control is to reduce the strength and contaminant flux of leachate. Leachate recirculation offers advantages such as accelerated refuse stabilization, and treatment systems are not always required. Co-disposal of sewage sludge or alkaline wastes can help to accelerate stabilization. The use of limestone as an additional attenuation layer is an effective, low-cost aid in controlling the migration of heavy metals.

The approaches to leachate treatment are biological (aerobic and anaerobic) and physical/chemical (precipitation, adsorption, coagulation, oxidation, and reverse osmosis). Newly formed landfill leachate is best treated by biological processes, whereas leachate from stabilized landfills is best treated with physical/chemical methods. Aerobic treatment can effectively remove organic matter and metals from leachate. Removal of 90% to 99% of BOD and COD and some metal removal have commonly been reported. Problems with aerobic treatment include long treatment times, foaming, nutrient deficiencies, toxic inhibition, and oxygen depletion. Anaerobic treatment has been effective in reducing organic loads: Organic removals of 90% to 99% have been demonstrated. Advantages over aerobic treatment are low solids buildups and an absence of aeration requirements, which allows energy savings. Treatment times are comparable. A major product of anaerobic digestion is methane, which can be used as an energy source.

The successful treatment of high-strength leachates requires combinations of biological and physical/chemical processes. The design of a treatment system depends not only a leachate character, but on location. Landfills near a wastewater treatment plant may take advantage of the facility, but distance sites will require an aerated lagoon, land application, or a complete treatment system. Treatment costs may represent 25% or more of total landfill costs.

Environmental Monitoring

The zone of aeration is that area beneath the top soil and overlying the water table in which pore space co-exists with air, or in which the geologic materials are unsaturated. Monitoring the zone of aeration may be achieved with or without sampling. Sampling approaches include pore water extraction from soil cores and deployment of pressure/vacuum lysimeters to obtain in situ water samples. The water samples may be analyzed for major anions, trace metals, TOC, pH, specific conductance, organics, and other specific constituents. Core samples provide information on physical characteristics such as soil texture, water content, hydraulic conductivity, and bulk density. For shallow sampling of soils and vadose waters, traditional hand augers and bucket-type samplers may be used. For deeper sampling, standard drilling equipment is required.

Nonsampling approaches to monitoring require tensiometers, psychrometers, electrical resistance blocks, and neutron moisture logging. Nonsampling methods provide for the determination of water content and movement in the vadose zone. Tensiometers employ a mercury manometer to measure soil-water pressures during unsaturated flow conditions. Psychrometers use a porous bulb with a chamber to measure relative humidity in the soil. Electrical resistance blocks measure either soil-water content or pressure. The neutron thermalization method measures changes in the volumetric water content within a soil horizon and delineates perched water zones and estimates flow rates.

The zone of saturation is that portion of the groundwater system in which available pore space is occupied by water. Monitoring within the zone of aeration has traditionally been accomplished with single-screened wells. But the cluster well and the air-lift sampler allow for multiple sampling points throughout the aquifer. Multi-sampling wells provide a vertical distribution of contaminants and greater flexibility, especially in three-dimensional volume monitoring.

Selection of the optimum location for sampling and nonsampling devices is largely site-specific. In all cases, the devices are situated below the landfill to maintain contact with interstitial waters.

Monitoring frequency should be flexible, allowing for modifications at each site.

Monitoring parameters are determined largely by the purpose of the monitoring program (Table 1). Many researchers have developed lists of key indicator parameters. Their selection should be modified, as required, to meet site-specific situations.

EPA and the American Public Health Association (APHA) provide detailed descriptions of appropriate containers for various chemical species and sampling techniques. Methods are intended to retard biological activity, retard hydrolysis of chemical compounds and complexes, and reduce the volatility of constituents. Preservation techniques are generally limited to pH control, chemical addition, refrigeration, and freezing.

Conclusions and Recommendations

The quantity of leachate produced from a municipal landfill may vary considerably with management or operating practices, depending on whether leachate is viewed as a short- or long-term problem. Operational factors which affect leachate quantity may include: cover material handling, watering prior to compaction, watering following compaction, daily variation in cell construction, and variation in waste composition (e.g., municipal refuse alone or codisposal of municipal refuse and sewage sludge or industrial wastes; milled or unmilled refuse).

Numerous mathematical methods have been proposed for a quantitative

Table 1. *Monitoring Parameters and Applicable Situations*

Parameter	*Applicable situation*
Suitability of aquifer as a drinking water source	*Need exists to identify facilities that may be severely degrading present and future drinking water supplies.*
Chlorine, iron, manganese, phenols, sodium, and sulfate	*Groundwater contamination must be assessed after it is determined that a facility is leaking.*
Specific conductance, pH, total organic carbon, and total organic halogen	*A threshold assessment must be made as to whether a facility is leaking.*

estimation of the volume of leachate generated from landfills and are usually based on a mass balance approach (i.e., water balance method). Components of these models are relatively easy to obtain, but other model variables such as the surface runoff coefficients, runoff curve number, and evapotranspiration from the landfill surface are more difficult to develop. Limited field data exists for verification for many of the leachate generation models. Therefore, the applicability, accuracy, and sensitivity of leachate generation models, is largely unknown. Additional research should be conducted regarding such variables as water contribution from refuse degradation, refuse permeability, evapotranspiration, surface runoff coefficients, and runoff curve numbers.

The composition of leachate produced from a municipal landfill is highly variable, depending on factors such as refuse composition, refuse processing, landfill age, the rate of infiltration, landfill depth, and landfill temperature. The quality of leachate can be controlled to a large degree. Shredding and baling of refuse, landfill depth, and the rate of water application to the landfill surface can influence the rate at which contaminants are released from refuse, and can determine whether leachates have a long- or short-term pollution potential.

Based on empirical data garnered from a number of studies addressing landfill and leaching behavior, several models have been developed which describe leachate quality as a function of time or cumulative leachate generation. The most promising of these models attempts to simulate the physical/chemical and biological processes which occur during leaching. Presently, however, the leachate composition models are useful only in ininterpreting experimental results rather than in finding application to field-scale problems.

Leachate migration models are based upon constituent mass transport and water flow equations. Numerous models are available for predicting chemical and physical migration; biological models, however, are generally lacking. While a large number of conceptual-mathematical models exist, none are universally applicable for the simulation of all the physical, chemical, and biological processes that are operative in a typical waste disposal system. The complexity of these processes, which operate in a simultaneous and interactive manner, is probably such that the development of a generic model would be impractical because the resulting program would undoubtedly become so large and complex that the cost of operating it would be exorbitant.

Leachate control technology is a relatively well-developed methodology for the management of landfill leachates. Various groundwater and surface water control approaches are available for the control of leachate into or out of the fill. Approaches in which dewatering or counter pumping (injection) is practiced appear to be effective control measures, although the long-term energy costs for pumping are restrictive. Accelerated stabilization processes such as leachate recycling and nutrient addition are promising, but require additional study. Extensive liner technology is available; however, field verification studies have, in general, been inconclusive regarding anticipated liner lifetime.

Vadose zone monitoring has received little attention in contrast to the advanced technology for monitoring in the zone of saturation. This discrepancy reflects, to a large extent, the greater complexity of flow in the vadose zone, compared to saturated flow, and the related problem of obtaining a representative sample for analysis. Incorporation of vadose zone devices can provide an early warning of potential groundwater pollution. If remedial measures are implemented prior to the onset of extensive groundwater contamination, the associated renovation costs could be reduced significantly. Additionally, an effective vadose zone monitoring network could reduce, or largely preclude, the requirements for groundwater monitoring. The savings in costs for construction of groundwater wells could be significant, particularly in western regions where water tables are often hundreds of feet deep. Vadose zone monitoring requires additional study to better define both the dominant phenomena occurring in this zone, as well as optimum monitoring equipment.

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The complete report, entitled "Production and Management of Leachate from Municipal Landfills: Summary and Assessment," (Order No. PB 84-187 913; Cost: $34.00, subject to change) will be available only from:

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