CHAPTER 6

EXAMPLES OF RISK-RELATED STUDIES: LANDFILLING OF MUNICIPAL SLUDGE

This chapter includes two examples of risk-based studies associated with the landfilling of municipal wastewater treatment plant sludges. The first example is focused on chemical risks (Dawson, English, and Fradkin, 1988), and the second addresses microbiological risks (Scarpino, et al., 1988).

CHEMICAL RISKS FROM SLUDGE LANDFILLING

Dawson, English, and Fradkin (1988) have described a risk-based approach for developing contaminant criteria for the regulation of sludge disposal. Separate methodologies have been developed for each of the five municipal sludge disposal or resource recovery alternatives: landfill; land application; distribution and marketing; incineration; and ocean disposal. In the development of each methodology, all possible contaminant migration pathways were considered. Pathways that were eliminated or rendered insignificant by management practices will be regulated through requirements for those practices as illustrated in Figure 35. All other pathways are addressed through application of the methodology. To serve as an illustration, the landfill disposal of sludge will be described.

In the case of landfilling, EPA has chosen to consider seven inorganic and ten organic contaminants as shown in Table 68 (Dawson, English, and Fradkin, 1988). Selection of these contaminants was based on their reported prevalence in sludges, relative hazard indices, and

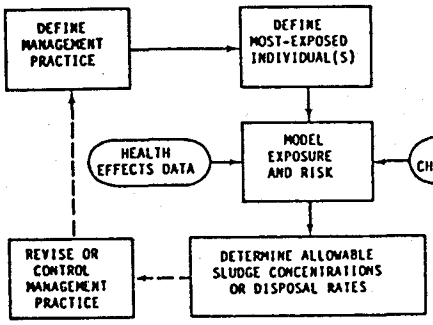


Figure 35: Criteria Derivation Procedure (Dawson, English, and Fradkin, 1988)

Table 68: Contaminants Considered in Risk Assessment of Sludge Landfilling (Dawson, English, and Fadkin, 1988)

Inorganics

Arsenic
Cadmium
Lead
Mercury
Nickel
Nitrate

Organics

Benzene
Benzo(a)pyrene
Bis-2-ethylhexylphthalate
Chlordane
DDT and metabolites
Dimethylnitrosamine
Lindane
Polychlorinated biphenyls
Trichloroethylene
Toxaphene

the availability of health-based exposure criteria. As part of the landfill methodology development, default values for distribution coefficients and decay rate constants were obtained from the literature for each of the 16 contaminants in Table 68. It should be noted that the methodology addresses only risk associated with the migration of toxic contaminants contained in the sludge. The risk associated with pathogens is not addressed.

Four potential pathways may lead to the migration of contaminants from landfills at levels of concern; these pathways shown in Figure 36 are (Dawson, English, and Fradkin, 1988):

(a) suspension of contaminated particulates in surface runoff,

(b) suspension and dispersion of contaminated particulates in air,

(c) volatilization of contaminants and dispersion in the atmosphere, and

(d) dissolution of contaminants in leachate with subsequent percolation through the unsaturated zone to ground water.

The first two pathways were deemed insignificant when landfills were required to apply adequate daily covers. As a consequence, these pathways were not addressed in the methodology, but daily cover and related practices will be required by regulation.

A three-tier conceptual approach was used in the methodology. Tier 1 uses extremely conservative assumptions (errs on the side of overpredicting potential contaminant concentrations) and makes a rapid estimate of maximum possible contaminant levels in environmental media. If criteria are not exceeded under these conditions, the approach is considered acceptable and no further analysis is required. If criteria

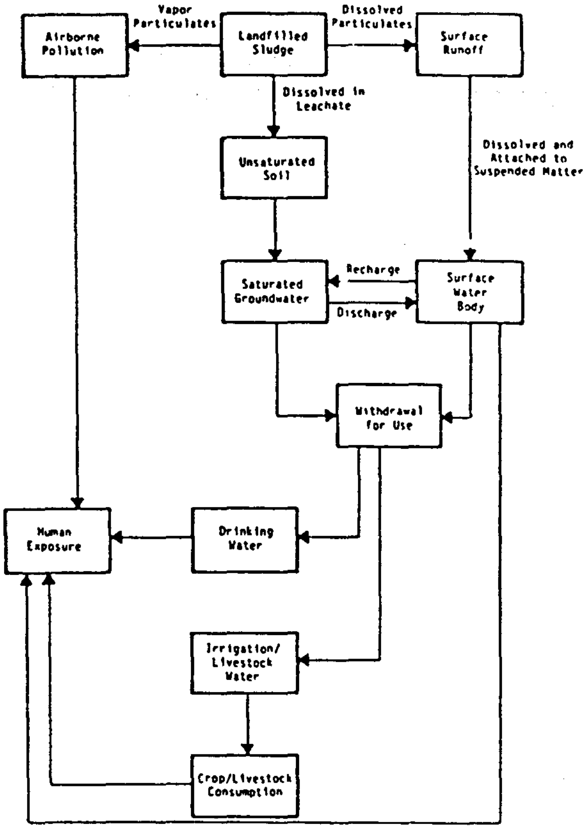
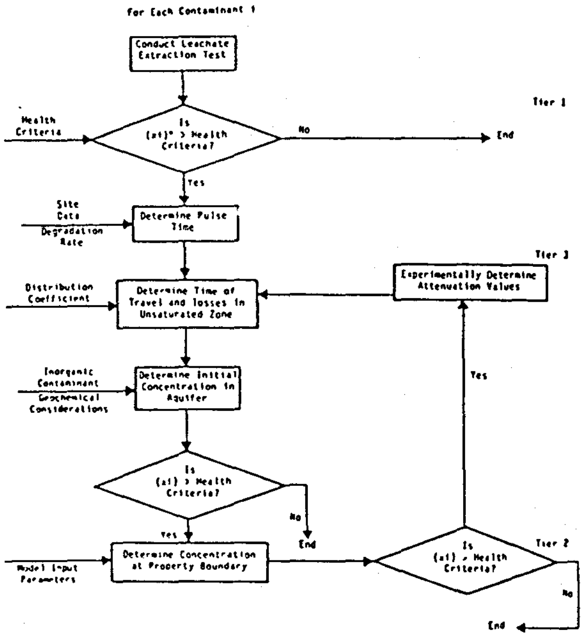


Figure 36: Possible Routes to Human Exposure from Landfilling Sludge (Dawson, English, and Fradkin, 1988)

are exceeded in this preliminary round, the applicant may choose to proceed to Tier 2 or 3, where more effort is required to produce site-specific input data for a more accurate prediction of contaminant levels. In Tier 2, literature values can be employed for some inputs such as distribution coefficients, degradation rates, and porosity. In Tier 3, the applicant applies empirical values derived at the site. For example, samples of aquifer media and leachate may be used in laboratory column tests to develop site-specific distribution coefficients (Dawson, English, and Fradkin, 1988).

To serve as an illustration, Figure 37 displays the logic flow the evaluation of the ground water pathway from landfilled sludge (Dawson, English, and Fradkin, 1988). The first level of analysis involves comparison of projected leachate concentrations with health-based criteria. Leachate concentrations are predicted by applying the EPA's Toxicity Characteristic Leachate Procedure (TCLP) to the sludge. For the vapor pathway, maximum possible vapor concentrations are compared with health-based criteria. In this case, the vapor concentration is predicted through application of Henry's law to the sludge as if it were a solution. In both cases, any contaminant with a leachate or vapor concentration below the relevant health-based criteria can be eliminated from further consideration. Those exceeding criteria are carried forward to a Tier 2 and possibly a Tier 3 analysis.

For the ground water pathway the Tier 2 analysis begins at the same point as Tier 1--use of the TCLP to define the source-term strength of the leachate. However, Tier 2 allows for site-specific inputs to predict dilution and attenuation effects that reduce resultant exposure



*(xi) = concentration of contaminant i

Figure 37: Logic Flow for Ground Water Pathway Evaluation of Landfilled Sludge (Dawson, English, and Fradkin, 1988)

levels. First, the product of recharge and leachate contaminant concentration are divided into the product of a sludge mass and total sludge concentration to determine how long a leachate pulse the sludge could produce at the predicted concentration:

$$\text{pulse time} = \frac{\text{sludge contaminant level} \times \text{sludge mass in a unit area}}{\text{annual recharge per unit area} \times \text{leachate contaminant level}}$$

Next, migration through the unsaturated zone is considered. Recharge levels and soil hydraulic properties (saturated conductivity, effective porosity, slope of the water retention curve, and bulk density) are input to a time-of-travel algorithm to estimate the average velocity of leachate through the unsaturated zone. The unsaturated zone velocity and contaminant-specific distribution and degradation rate constants are input to the CHAIN unsaturated zone transport code to determine the concentration, timing, and size of the leachate pulse as it enters the saturated zone.

In Tier 2, data on hydraulic conductivity, recharge, depth to ground water, and soil type should be determined empirically from samples. Other soil-related properties can be selected on the basis of soil type (for example, porosity estimated from textural description), while degradation rate constants and distribution coefficients can be taken from the literature. For Tier 3, the latter properties should be determined empirically with samples from the site.

Geochemical effects on inorganic contaminants are accounted for at the unsaturated zone/saturated zone interface. The geochemical predictions were developed by using the MINTEQ geochemical code, which determines equilibrium solubility for a combination of salts using catalogued thermodynamic data.

The predicted pulse time and concentrations (adjusted for geochemical effects) exiting from the unsaturated zone define the contaminant flux input to the saturated zone. This flux and parameters characterizing the aquifer are applied to the AT123D saturated zone transport code to determine the concentration, timing, and duration of the plume at the nearest point of exposure, for example, at an off-site well. The predicted peak concentration at the point of exposure is compared with health-based criteria. If criteria are exceeded, the proposed disposal alternative is deemed unacceptable. Applicants have the option of developing site-specific data for a Tier 3 analysis, implementing pretreatment to reduce contaminant levels in sludge, or exploring other means of disposal.

The second and third tiers for the vapor pathway begin through application of Henry's law to the total sludge concentration of the contaminant. In this case, however, the effects of soil cover and dispersion in the atmosphere are considered to provide a more realistic prediction of concentrations at the landfill's boundary. Two vapor loss mechanisms are considered in the analysis: volatilization of contaminants directly from sludge in an open cell during active disposal, and diffusion of contaminants through cover soil following closure of a disposal cell. Contaminant flux rates into the atmosphere are calculated using analytical constructs for the two mechanisms. Contaminant flux from active cells is calculated as a function of wind speed, temperature, vapor concentration, and contaminant molecular weight. Contaminant flux from closed cells is calculated as a function of cover soil porosity, vapor concentration, temperature, cover thickness, and contaminant molecular weight. A simplified Gaussian plume atmospheric transport model is then used with the above flux rates, wind speed, and site geometry to predict downwind vapor concentrations. These concentrations are then compared to health-based criteria.

If criteria are exceeded, the proposed disposal alternative is deemed unacceptable. Applicants have the option of developing site-specific data for a Tier 3 analysis (for example, measuring actual vapor concentrations instead of calculating them from Henry's law) or modifying disposal practices (for example, using a less permeable cover soil or thicker cover).

MICROBIOLOGICAL RISKS FROM SLUDGE LANDFILLING

Pathogenic microorganisms in municipal sludge include bacteria, viruses, protozoa, helminths, and fungi. Scarpino, et al. (1988), have described a microbiological risk assessment for the land application of municipal sludge. The risk assessment methodology involves the selection of representative pathogens, consideration of sludge use pathways, and determination of human exposure routes and the minimal infective dose.

A risk assessment for pathogens in municipal sludges requires the following input data (Scarpino, et al., 1988):

(1) numbers present in raw sludge,
(2) the type and efficiency of the sludge treatment process used initially to effect pathogen reductions,
(3) the survival capability, numbers (that is, level or concentrations), and types of the microbial pathogens

present in the applied sludge, along with the knowledge of their infective dose (minimal infective dose or MID),

(4) the reuse/disposal option used (land application or distribution and marketing (D&M), and the conditions of sludge application (that is, quantities of sludge, frequencies of application, site conditions and the application method used),
(5) the pathway, time, and distance of pathogen travel from the applied sludge through intermediate steps (that is, via air, water, or soil media, vectors, or the food chain) to human populations,
(6) the host susceptibility, socioeconoic factors, such as the host's physical status, sex, race, economic class, occupation, personal habits and the probability of contact of human populations with the pathogen, and finally,
(7) the clinical consequences (infection and disease) of exposure to the pathogen risk.

The criteria used to select representative pathogens for consideration in the risk assessment model were (Scarpino, et al., 1988):

(1) the pathogen is known to be present in municipal sludge,
(2) the pathogen is known to cause human disease,
(3) more data is available for one pathogen than for others in the same microbial group, and the pathogen has survivability similar to other members of the group,
(4) minimal infective doses (MIDs) are known,
(5) the pathogen selected survives outside the human host, and
(6) the infective routes, that is, ingestion, inhalation, or skin contact, are known.

The pathogenic organisms that were selected and used as representative of those pathogens present in municipal sludges were (Scarpino, et al., 1988):

(1) Salmonella spp. as examples of pathogenic enteric bacteria,
(2) Enteroviruses as examples of enteric viruses, and
(3) Ascaris lumbricoides and A. lumbricoides var. suum as examples of the helminths.

A total of eight sludge use pathways were included in the present model and numbered I to VIII. Three of the pathways involve the use of dewatered sludge for commercial applications, that is:

I. Fertilizer for Crops Destined for Human Consumption,
II. Fertilizer for Pasture Crops, Golf Courses, Recreational Fields, and Related Uses, and
III. Fertilizer for Horticultural Purposes and for Crops that are Processed Before Animal Consumption.

Two of the pathways involve use of dewatered sludge for residential purposes, that is:

IV. Fertilizer for Vegetable and Flower Gardens, Shrubbery, and Related Uses in the Residential Environment, and
V. Fertilizer for Residential Lawn Soil and Related Uses.

Three of the pathways involve use of liquid sludge also for commercial applications:

VI. Fertilizer for Crops Destined for Consumption,
VII. Fertilizer for Pasture Crops, and
VIII. Fertilizer for Crops that are Processed Before Animal Consumption.

The eight pathways are composed of compartments and pathogen transfers between compartments. The compartments, as shown for example in Figure 38, are the various locations where sludge or sludge-associated pathogens exist in particular pathways. Figure 38 shows Pathway IV, where dewatered sludge is used as fertilizer for vegetable and flower gardens, shrubbery, and related uses in the residential environment. The arrows indicate the transfer of pathogens to and between compartments.

In each compartment, pathogens either increase, decrease, or remain at similar levels with time, depending upon microbial growth, die-off, or no population change. Movement between compartments will affect the population in each compartment. Within each compartment, first-order, linear, differential equations have been derived to compute the rate and direction of change in the pathogen population and the effect that any

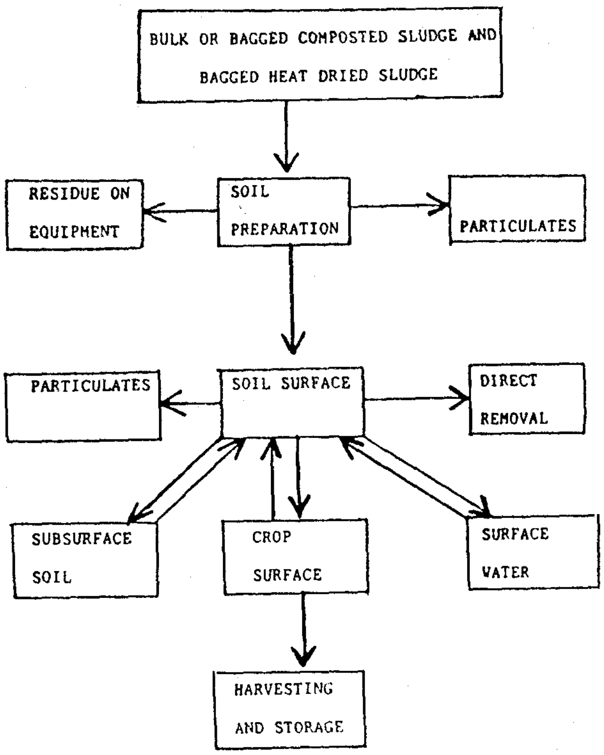


Figure 38: Pathway IV, Dewatered Sludge Use As Fertilizer for Vegetable and Flower Gardens, Shrubbery, and Related Uses in the Residential Environment (arrows indicate transfer of pathogens to and between compartments) (Scarpino, et al., 1988)

subprocesses in a compartment may have on that population. The population changes in a compartment are assessed on the basis of time, temperature, moisture content, the presence of nutrients, and other physical and chemical factors. The transfer of pathogens between compartments is described by a set of ordinary differential equations that were derived using conservative principles and known environmental parameters and relationships, and that were developed from data obtained in the literature. These equations were then integrated to determine the pathogen populations in each compartment.

The exposure to sludge pathogens was determined in five types of human exposures, including on-site persons (for example, workers, gardeners, and observers), food consumers, ground water drinkers, and offsite-pond swimmers and offsite-pond drinkers. Each exposure level was accumulated over a 24 hour period. The amount of exposure was determined by the number of sludge pathogens consumed or inhaled during that 24 hour time period. This pathogen number, in turn, was determined by the concentration of pathogens in the consumed materials (determined in each exposure pathway) multiplied by the volume or mass of material consumed. Numerous studies have been conducted to determine the infectious doeses of all classes of enteric pathogens, including viruses, bacteria, and parasites. The results of these studies have been presented in various ways. For example, viral infectivity has been based on the dose required to infect 50% (HID_{50}), 10% (HID_{10}) or 1% (HID_{01}) of an exposed population. To be conservative, the infectious dose used in this study was the minimum dose that has been reported in the literature to cause infection.

A computer model was developed to systematically integrate the information on dose-response with the information on the number of pathogens that are likely to be present. As an example, using Pathway I, Fertilizer for Crops Destined for Human Consumption, typical and reasonable worst case scenarios for the land application of sludge and D&M were performed with this computer model, producing daily probabilities of ingestion of a single Salmonella organism for each of the five types of exposure previously mentioned. Table 69 shows the sludge application rate, the pathogen fraction transferred from subsurface soil to ground water, the fraction of irrigation water from ground water, and the type of crop involved when using Pathway I (Figure 39).

For the on-site person, the ingestion probability using Pathway I was greatest (1.0) on day 1 and zero thereafter, in both scenarios. The health risk exists only on the day of sludge application. For the food consumer, the ingestion probability was zero in both scenarios for the 100 days of computer simulation. For the ground water drinker, there was an increased risk of pathogen ingestion and infection in the reasonable worst case scenario, particularly during the first 10 days or so. The risk to the ground water drinker in the typical scenario was fairly low.

For the offsite pond swimmer, the ingestion probabilities and offsite pond compartment pathogen levels for each scenario at selected days are presented in Table 70. From the data presented in Table 70, it is evident that one should stay away from the offsite pond for at least a month in either the typical or reasonable worst case scenario. The

Table 69: Best Judgment Parameter Values in Pathway I Used for Estimated Typical and Reasonable Worst Case Scenarios (Scarpino, et al., 1988)

Parameter	Typical Value	Worst Value
Sludge application rate, kg/ha	5,000	50,000
Fraction of pathogens transferred from subsurface soil to ground water	0.01	0.1
Fraction of irrigation water from ground water	0.0	0.5
Type of crop	1 (above-ground)	0 (on-ground)

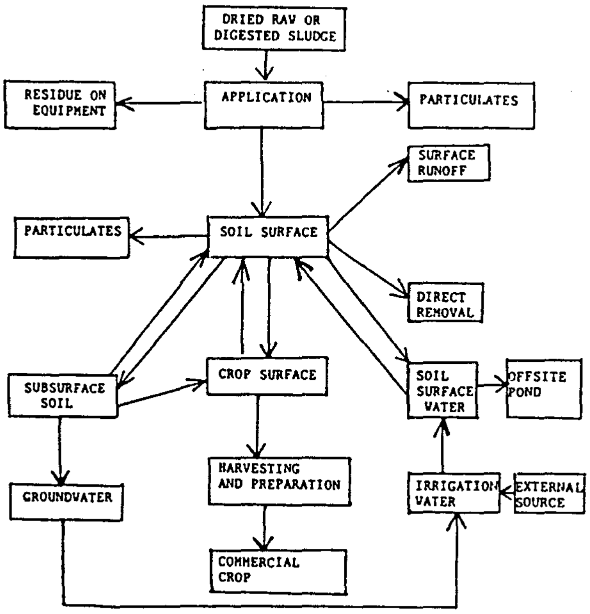


Figure 39: Pathway I, Dewatered Sludge Use as Fertilizer for Crops Destined for Human Consumption (arrows indicate transfer of pathogens to and between compartments) (Scarpino, et al., 1988)

Table 70: Salmonella Ingestion Probabilities Using Pathway I for Offsite Pond Swimmer, and Pathogen Levels in Offsite Pond Compartment (Scarpino, et al., 1988)

Scenario	Day	Ingestion Probability Per Day	Offsite Pond Total Pathogen Level[a]
Typical	1	6.882E-02	6.845E+06
Worst	1	0.510	6.853E+07
Typical	2	0.991	1.654E+07
Worst	2	1.000	1.656E+08
Typical	3	0.972	1.238E+07
Worst	3	1.000	1.240E+08
Typical	4	0.931	9.269E+06
Worst	4	1.000	9.279E+07
Typical	5	0.865	6.939E+06
Worst	5	1.000	6.947E+07
Typical	10	0.375	1.631E+06
Worst	10	0.991	1.633E+07
Typical	20	2.565E-02	9.015E+04
Worst	20	0.229	9.025E+05
Typical	30	1.435E-03	4.982E+03
Worst	30	1.427E-02	4.988E+04
Typical	60	9.920E-08	0.000E-01
Worst	60	2.426E-06	8.418E-00

[a] Pond size was assumed to be 20 m wide x 20 m long x 1 m deep, and contained 400,000 L of water.

ingestion probabilities for the off-site pond drinker are not presented, but are much higher than those for the swimmer.