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Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Trichloroethylene

PREFACE

This document is one of a series of preliminary assessments dealing with chemicals of potential concern in municipal sewage sludge. The purpose of these documents is to: (a) summarize the available data for the constituents of potential concern, (b) identify the key environmental pathways for each constituent related to a reuse and disposal option (based on hazard indices), and (c) evaluate the conditions under which such a pollutant may pose a hazard. Each document provides a scientific basis for making an initial determination of whether a pollutant, at levels currently observed in sludges, poses a likely hazard to human health or the environment when sludge is disposed of by any of several methods. These methods include landspreading on food chain or nonfood chain crops, distribution and marketing programs, landfilling, incineration and ocean disposal.

These documents are intended to serve as a rapid screening tool to narrow an initial list of pollutants to those of concern. If a significant hazard is indicated by this preliminary analysis, a more detailed assessment will be undertaken to better quantify the risk from this chemical and to derive criteria if warranted. If a hazard is shown to be unlikely, no further assessment will be conducted at this time; however, a reassessment will be conducted after initial regulations are finalized. In no case, however, will criteria be derived solely on the basis of information presented in this document.

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SECTION 1

INTRODUCTION

This preliminary data profile is one of a series of profiles dealing with chemical pollutants potentially of concern in municipal sewage sludges. Trichloroethylene (TCE) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing) or placed in a landfill.* This profile is a compilation of information that may be useful in determining whether TCE poses an actual hazard to human health or the environment when sludge is disposed of by these methods.

The focus of this document is the calculation of "preliminary hazard indices" for selected potential exposure pathways, as shown in Section 3. Each index illustrates the hazard that could result from movement of a pollutant by a given pathway to cause a given effect (e.g., sludge → soil → plant uptake → animal uptake → human toxicity). The values and assumptions employed in these calculations tend to represent a reasonable "worst case"; analysis of error or uncertainty has been conducted to a limited degree. The resulting value in most cases is indexed to unity; i.e., values >1 may indicate a potential hazard, depending upon the assumptions of the calculation.

The data used for index calculation have been selected or estimated based on information presented in the "preliminary data profile", Section 4. Information in the profile is based on a compilation of the recent literature. An attempt has been made to fill out the profile outline to the greatest extent possible. However, since this is a preliminary analysis, the literature has not been exhaustively perused.

The "preliminary conclusions" drawn from each index in Section 3 are summarized in Section 2. The preliminary hazard indices will be used as a screening tool to determine which pollutants and pathways may pose a hazard. Where a potential hazard is indicated by interpretation of these indices, further analysis will include a more detailed examination of potential risks as well as an examination of site-specific factors. These more rigorous evaluations may change the preliminary conclusions presented in Section 2, which are based on a reasonable "worst case" analysis.

The preliminary hazard indices for selected exposure routes pertinent to landspreading and distribution and marketing and landfilling practices are included in this profile. The calculation formulae for these indices are shown in the Appendix. The indices are rounded to two significant figures.

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* Listings were determined by a series of expert workshops convened during March-May, 1984 by the Office of Water Regulations and Standards (OWRS) to discuss landspreading, landfilling, incineration, and ocean disposal, respectively, of municipal sewage sludge.

SECTION 2

PRELIMINARY CONCLUSIONS FOR TRICHLOROETHYLENE IN MUNICIPAL SEWAGE SLUDGE

The following preliminary conclusions have been derived from the calculation of "preliminary hazard indices", which represent conservative or "worst case" analyses of hazard. The indices and their basis and interpretation are explained in Section 3. Their calculation formulae are shown in the Appendix.

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Trichloroethylene

Landspreading of sludge is expected to produce slight increases in the soil concentration of TCE. This increase may be large when sludge containing high concentrations of TCE is applied at a high rate (500 mt/ha) (see Index 1).

B. Effect on Soil Biota and Predators of Soil Biota

Conclusions were not drawn because index values could not be calculated due to lack of data.

C. Effect on Plants and Plant Tissue Concentration

Conclusions were not drawn because index values could not be calculated due to lack of data.

D. Effect on Herbivorous Animals

Conclusions were not drawn because index values could not be calculated due to lack of data.

E. Effect on Humans

Conclusions were not drawn because index values could not be calculated due to lack of data.

II. LANDFILLING

Landfilled sludge is expected to increase the concentration of TCE in groundwater; this increase may be large at a disposal site with all worst-case conditions (see Index 1). Groundwater contaminated by landfilled sludge is not expected to increase the cancer risk from TCE, except when all worst-case conditions prevail at a disposal site (see Index 2).

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

SECTION 3

PRELIMINARY HAZARD INDICES FOR TRICHLOROETHYLENE IN MUNICIPAL SEWAGE SLUDGE

I. **LANDSPREADING AND DISTRIBUTION-AND-MARKETING**

A. **Effect on Soil Concentration of Trichloroethylene**

1. **Index of Soil Concentration (Index 1)**

a. **Explanation** - Calculates concentrations in μg/g DW of pollutant in sludge-amended soil. Calculated for sludges with typical (median, if available) and worst (95 percentile, if available) pollutant concentrations, respectively, for each of four applications. Loadings (as dry matter) are chosen and explained as follows:

0 mt/ha	No sludge applied. Shown for all indices for purposes of comparison, to distinguish hazard posed by sludge from preexisting hazard posed by background levels or other sources of the pollutant.
5 mt/ha	Sustainable yearly agronomic application; i.e., loading typical of agricultural practice, supplying ~50 kg available nitrogen per hectare.
50 mt/ha	Higher single application as may be used on public lands, reclaimed areas or home gardens.
500 mt/ha	Cumulative loading after 100 years of application at 5 mt/ha/year.

b. **Assumptions/Limitations** - Assumes pollutant is incorporated into the upper 15 cm of soil (i.e., the plow layer), which has an approximate mass (dry matter) of 2 x 10^3 mt/ha and is then dissipated through first order processes which can be expressed as a soil half-life.

c. **Data Used and Rationale**

i. **Sludge concentration of pollutant (SC)**

Typical	0.46 μg/g DW
Worst	17.85 μg/g DW

The typical and worst concentrations were statistically derived from sludge concentration data for TCE (U.S. EPA, 1982) and represent the 50th and 95th percentiles of the cumulative frequency, respectively. (See Section 4, p. 4-1.)

ii. **Background concentration of pollutant in soil (BS)** = 0.00063 μg/g DW

This value is the only background concentration for TCE in soil that was immediately available (Battelle, 1977a). It is not possible to determine whether this value is representative of the concentration of TCE in soil. (See Section 4, p. 4-1.)

iii. **Soil half-life of pollutant ($t_{\frac{1}{2}}$)** - Data not immediately available.

Although data exist for the half-life of TCE in air and water (see Section 4, p. 4-8), they cannot be used to estimate the half-life in soil. The worst-case condition, that TCE does not degrade in soil, was assumed for this analysis.

d. **Index 1 Values (μg/g DW)**

Sludge Concentration	Sludge Application Rate (mt/ha)			
	0	5	50	500
Typical	0.00063	0.0018	0.012	0.093
Worst	0.00063	0.045	0.44	3.6

e. **Value Interpretation** - Value equals the expected concentration in sludge-amended soil.

f. **Preliminary Conclusion** - Landspreading of sludge is expected to produce slight increases in the soil concentration of TCE. This increase may be large when sludge containing high concentrations of TCE is applied at a high rate (500 mt/ha).

B. **Effect on Soil Biota and Predators of Soil Biota**

1. **Index of Soil Biota Toxicity (Index 2)**

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with soil concentration shown to be toxic for some soil organism.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Soil concentration toxic to soil biota (TB)** - Data not immediately available.

d. **Index 2 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds toxic concentration. Value > 1 indicates a toxic hazard may exist for soil biota.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

2. **Index of Soil Biota Predator Toxicity (Index 3)**

a. **Explanation** - Compares pollutant concentrations expected in tissues of organisms inhabiting sludge-amended soil with food concentration shown to be toxic to a predator on soil organisms.

b. **Assumptions/Limitations** - Assumes pollutant form bioconcentrated by soil biota is equivalent in toxicity to form used to demonstrate toxic effects in predator. Effect level in predator may be estimated from that in a different species.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Uptake factor of pollutant in soil biota (UB)** - Data not immediately available.

iii. **Feed concentration toxic to predator (TR)** - Data not immediately available.

d. **Index 3 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Values equals factor by which expected concentration in soil biota exceeds that which is toxic to predator. Value > 1 indicates a toxic hazard may exist for predators of soil biota.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

C. **Effect on Plants and Plant Tissue Concentration**

1. **Index of Phytotoxic Soil Concentration (Index 4)**

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with the lowest soil concentration shown to be toxic for some plants.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Soil concentration toxic to plants (TP)** - Data not immediately available.

d. **Index 4 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which soil concentration exceeds phytotoxic concentration. Value > 1 indicates a phytotoxic hazard may exist.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

2. **Index of Plant Concentration Caused by Uptake (Index 5)**

a. **Explanation** - Calculates expected tissue concentrations, in µg/g DW, in plants grown in sludge-amended soil, using uptake data for the most responsive plant species in the following categories: (1) plants included in the U.S. human diet; and (2) plants serving as animal feed. Plants used vary according to availability of data.

b. **Assumptions/Limitations** - Assumes an uptake factor that is constant over all soil concentrations. The uptake factor chosen for the human diet is assumed to be representative of all crops (except fruits) in the human diet. The uptake factor chosen for the animal diet is assumed to be representative of all crops in the animal diet. See also Index 6 for consideration of phytotoxicity.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Uptake factor of pollutant in plant tissue (UP)** - Data not immediately available.

d. **Index 5 Values (μg/g DW)** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals the expected concentration in tissues of plants grown in sludge-amended soil. However, any value exceeding the value of Index 6 for the same or a similar plant species may be unrealistically high because it would be precluded by phytoxicity.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

3. **Index of Plant Concentration Permitted by Phytotoxicity (Index 6)**

a. **Explanation** - The index value is the maximum tissue concentration, in μg/g DW, associated with phytotoxicity in the same or similar plant species used in Index 5. The purpose is to determine whether the plant tissue concentrations determined in Index 5 for high applications are realistic, or whether such concentrations would be precluded by phytotoxicity. The maximum concentration should be the highest at which some plant growth still occurs (and thus consumption of tissue by animals is possible) but above which consumption by animals is unlikely.

b. **Assumptions/Limitations** - Assumes that tissue concentration will be a consistent indicator of phytotoxicity.

c. **Data Used and Rationale**

i. **Maximum plant tissue concentration associated with phytoxicity (PP)** - Data not immediately available.

d. **Index 6 Values (µg/g DW)** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals the maximum plant tissue concentration which is permitted by phytotoxicity. Value is compared with values for the same or similar plant species given by Index 5. The lowest of the two indices indicates the maximal increase that can occur at any given application rate.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

D. **Effect on Herbivorous Animals**

1. **Index of Animal Toxicity Resulting from Plant Consumption (Index 7)**

a. **Explanation** - Compares pollutant concentrations expected in plant tissues grown in sludge-amended soil with feed concentration shown to be toxic to wild or domestic herbivorous animals. Does not consider direct contamination of forage by adhering sludge.

b. **Assumptions/Limitations** - Assumes pollutant form taken up by plants is equivalent in toxicity to form used to demonstrate toxic effects in animal. Uptake or toxicity in specific plants or animals may be estimated from other species.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)** - Values were not calculated due to lack of data.

ii. **Feed concentration toxic to herbivorous animal (TA)** - Data not immediately available.

There are some data concerning TCE animal toxicity (see Section 4, p. 4-9), but the animals studied were not herbivorous and feed concentrations were not supplied.

d. **Index 7 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which expected plant tissue concentration exceeds that which is toxic to animals. Value > 1 indicates a toxic hazard may exist for herbivorous animals.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Explanation** - Calculates the amount of pollutant in a grazing animal's diet resulting from sludge adhesion to forage or from incidental ingestion of sludge-amended soil and compares this with the dietary toxic threshold concentration for a grazing animal.

b. **Assumptions/Limitations** - Assumes that sludge is applied over and adheres to growing forage, or that sludge constitutes 5 percent of dry matter in the grazing animal's diet, and that pollutant form in sludge is equally bioavailable and toxic as form used to demonstrate toxic effects. Where no sludge is applied (i.e., 0 mt/ha), assumes diet is 5 percent soil as a basis for comparison.

c. **Data Used and Rationale**

i. **Sludge concentration of pollutant (SC)**

Typical	0.46 μg/g DW
Worst	17.85 μg/g DW

See Section 3, p. 3-1.

ii. **Fraction of animal diet assumed to be soil (GS) = 5%**

Studies of sludge adhesion to growing forage following applications of liquid or filter-cake sludge show that when 3 to 6 mt/ha of sludge solids is applied, clipped forage initially consists of up to 30 percent sludge on a dry-weight basis (Chaney and Lloyd, 1979; Boswell, 1975). However, this contamination diminishes gradually with time and growth, and generally is not detected in the following year's growth. For example, where pastures amended at 16 and 32 mt/ha were grazed throughout a growing season (168 days), average sludge content of forage was only 2.14 and 4.75 percent, respectively (Bertrand et al., 1981). It seems reasonable to assume that animals may receive long-term dietary exposure to 5 percent sludge if maintained on a forage to which sludge is regularly applied. This estimate of 5 percent sludge is used regardless of application rate, since the above studies did not show a clear relationship between application rate and initial contamination, and since adhesion is not cumulative yearly because of die-back.

Studies of grazing animals indicate that soil ingestion, ordinarily <10 percent of dry weight of diet, may reach as high as 20 percent for cattle and 30 percent for sheep during winter months when forage is reduced (Thornton and Abrams, 1983). If the soil were sludge-amended, it is conceivable that up to 5 percent sludge may be ingested in this manner as well. Therefore, this value accounts for either of these scenarios, whether forage is harvested or grazed in the field.

iii. **Feed concentration toxic to herbivorous animal (TA)** - Data not immediately available.

d. **Index 8 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals factor by which expected dietary concentration exceeds toxic concentration. Value > 1 indicates a toxic hazard may exist for grazing animals.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

E. Effect on Humans

1. **Index of Human Cancer Risk Resulting from Plant Consumption (Index 9)**

a. **Explanation** - Calculates dietary intake expected to result from consumption of crops grown on sludge-amended soil. Compares dietary intake with the cancer risk-specific intake (RSI) of the pollutant.

b. **Assumptions/Limitations** - Assumes that all crops are grown on sludge-amended soil and that all those considered to be affected take up the pollutant at the same rate. Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)** - Values were not calculated due to lack of data.

ii. **Daily human dietary intake of affected plant tissue (DT)**

Toddler	74.5 g/day
Adult	205 g/day

The intake value for adults is based on daily intake of crop foods (excluding fruit) by vegetarians (Ryan et al., 1982); vegetarians were chosen to represent the worst case. The value for toddlers is based on the FDA Revised Total Diet (Pennington, 1983) and food groupings listed by the U.S. EPA (1984a). Dry weights for individual food groups were estimated from composition data given by the U.S. Department of Agriculture (USDA) (1975). These values were composited to estimate dry-weight consumption of all non-fruit crops.

iii. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

iv. **Cancer potency** = 1.9×10^{-2} $(mg/kg/day)^{-1}$

The value given was statistically derived for human from data obtained for mice which had developed hepatocellular carcinoma when exposed to TCE. (See Section 4, p. 4-4.)

v. **Cancer risk-specific intake (RSI)** = 3.68 µg/day

The RSI is the pollutant intake value which results in an increase in cancer risk of 10^{-6} (1 per 1,000,000). The RSI is calculated from the cancer potency using the following formula:

$$RSI = \frac{10^{-6} \times 70 \text{ kg} \times 10^{3} \text{ µg/mg}}{\text{Cancer potency}}$$

d. **Index 9 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value > 1 indicates a potential increase in cancer risk of > 10^{-6} (1 per 1,000,000). Comparison with the null index value at 0 mt/ha indicates the degree to which any hazard is due to sludge application, as opposed to pre-existing dietary sources.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

2. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)**

a. **Explanation** - Calculates human dietary intake expected to result from pollutant uptake by domestic animals given feed grown on sludge-amended soil (crop or pasture land) but not directly contaminated by adhering sludge. Compares expected intake with RSI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals receiving all their feed from sludge-amended soil. Assumes that all animal products consumed take up the pollutant at the highest rate observed for muscle of any commonly consumed species or at the rate observed for beef liver or dairy products (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)** - Values were not calculated due to lack of data.

ii. **Uptake factor of pollutant in animal tissue (UA)** - Data not immediately available.

iii. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	43.7 g/day
Adult	88.5 g/day

The fat intake values presented, which comprise meat, fish, poultry, eggs and milk products, are derived from the FDA Revised Total Diet (Pennington, 1983), food groupings listed by the U.S. EPA (1984a) and food composition data given by USDA (1975). Adult intake of meats is based on males 25 to 30 years of age and that for milk products on males 14 to 16 years of age, the age-sex groups with the highest daily intake. Toddler intake of milk products is actually based on infants, since infant milk consumption is the highest among that age group (Pennington, 1983).

iv. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

v. **Cancer risk-specific intake (RSI)** = 3.68 μg/day

See Section 3, p. 3-9.

d. **Index 10 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

3. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Explanation** - Calculates human dietary intake expected to result from consumption of animal products derived from grazing animals incidentally ingesting sludge-amended soil. Compares expected intake with RSI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals grazing sludge-amended soil, and that all animal products consumed take up the pollutant at the highest rate observed for muscle of any commonly consumed species or at the rate observed for beef liver or dairy products (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Animal tissue** - Data not immediately available.

ii. **Sludge concentration of pollutant (SC)**

Typical	0.46 μg/g DW
Worst	17.85 μg/g DW

See Section 3, p. 3-1.

iii. **Background concentration of pollutant in soil (BS)** = 0.00063 μg/g DW

See Section 3, p. 3-2.

iv. **Fraction of animal diet assumed to be soil (GS)** = 5%

See Section 3, p. 3-7.

v. **Uptake factor of pollutant in animal tissue (UA)** - Data not immediately available.

vi. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	39.4 g/day
Adult	82.4 g/day

ii. **Assumed amount of soil in human diet (DS)**

Pica child	5 g/day
Adult	0.02 g/day

The value of 5 g/day for a pica child is a worst-case estimate employed by U.S. EPA's Exposure Assessment Group (U.S. EPA, 1983a). The value of 0.02 g/day for an adult is an estimate from U.S. EPA, 1984a.

iii. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

iv. **Cancer risk-specific intake (RSI)** = 3.68 μg/day

See Section 3, p. 3-9.

d. **Index 12 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

5. **Index of Aggregate Human Cancer Risk (Index 13)**

a. **Explanation** - Calculates the aggregate amount of pollutant in the human diet resulting from pathways described in Indices 9 to 12. Compares this amount with RSI.

b. **Assumptions/Limitations** - As described for Indices 9 to 12.

c. **Data Used and Rationale** - As described for Indices 9 to 12.

d. **Index 13 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

II. LANDFILLING

A. Index of Groundwater Concentration Resulting from Landfilled Sludge (Index 1)

1. **Explanation** - Calculates groundwater contamination which could occur in a potable aquifer in the landfill vicin-

ity. Uses U.S. EPA's Exposure Assessment Group (EAG) model, "Rapid Assessment of Potential Groundwater Contamination Under Emergency Response Conditions" (U.S. EPA, 1983b). Treats landfill leachate as a pulse input, i.e., the application of a constant source concentration for a short time period relative to the time frame of the analysis. In order to predict pollutant movement in soils and groundwater, parameters regarding transport and fate, and boundary or source conditions are evaluated. Transport parameters include the interstitial pore water velocity and dispersion coefficient. Pollutant fate parameters include the degradation/decay coefficient and retardation factor. Retardation is primarily a function of the adsorption process, which is characterized by a linear, equilibrium partition coefficient representing the ratio of adsorbed and solution pollutant concentrations. This partition coefficient, along with soil bulk density and volumetric water content, are used to calculate the retardation factor. A computer program (in FORTRAN) was developed to facilitate computation of the analytical solution. The program predicts pollutant concentration as a function of time and location in both the unsaturated and saturated zone. Separate computations and parameter estimates are required for each zone. The prediction requires evaluations of four dimensionless input values and subsequent evaluation of the result, through use of the computer program.

2. **Assumptions/Limitations** - Conservatively assumes that the pollutant is 100 percent mobilized in the leachate and that all leachate leaks out of the landfill in a finite period and undiluted by precipitation. Assumes that all soil and aquifer properties are homogeneous and isotropic throughout each zone; steady, uniform flow occurs only in the vertical direction throughout the unsaturated zone, and only in the horizontal (longitudinal) plane in the saturated zone; pollutant movement is considered only in direction of groundwater flow for the saturated zone; all pollutants exist in concentrations that do not significantly affect water movement; for organic chemicals, the background concentration in the soil profile or aquifer prior to release from the source is assumed to be zero; the pollutant source is a pulse input; no dilution of the plume occurs by recharge from outside the source area; the leachate is undiluted by aquifer flow within the saturated zone; concentration in the saturated zone is attenuated only by dispersion.

3. Data Used and Rationale

a. Unsaturated zone

i. Soil type and characteristics

(a) Soil type

Typical	Sandy loam
Worst	Sandy

These two soil types were used by Gerritse et al. (1982) to measure partitioning of elements between soil and a sewage sludge solution phase. They are used here since these partitioning measurements (i.e., K_d values) are considered the best available for analysis of metal transport from landfilled sludge. The same soil types are also used for nonmetals for convenience and consistency of analysis.

(b) Dry bulk density (P_{dry})

Typical	1.53 g/mL
Worst	1.925 g/mL

Bulk density is the dry mass per unit volume of the medium (soil), i.e., neglecting the mass of the water (Camp Dresser and McKee, Inc. (CDM), 1984).

(c) Volumetric water content (θ)

Typical	0.195 (unitless)
Worst	0.133 (unitless)

The volumetric water content is the volume of water in a given volume of media, usually expressed as a fraction or percent. It depends on properties of the media and the water flux estimated by infiltration or net recharge. The volumetric water content is used in calculating the water movement through the unsaturated zone (pore water velocity) and the retardation coefficient. Values obtained from CDM, 1984.

(d) Fraction of organic carbon (f_{oc})

Typical	0.005 (unitless)
Worst	0.0001 (unitless)

Organic content of soils is described in terms of percent organic carbon, which is required in the estimation of partition coefficient, K_d.

Values, obtained from R. Griffin (1984) are representative values for subsurface soils.

ii. **Site parameters**

(a) **Landfill leaching time (LT)** = 5 years

Sikora et al. (1982) monitored several sludge entrenchment sites throughout the United States and estimated time of landfill leaching to be 4 or 5 years. Other types of landfills may leach for longer periods of time; however, the use of a value for entrenchment sites is conservative because it results in a higher leachate generation rate.

(b) **Leachate generation rate (Q)**

Typical	0.8 m/year
Worst	1.6 m/year

It is conservatively assumed that sludge leachate enters the unsaturated zone undiluted by precipitation or other recharge, that the total volume of liquid in the sludge leaches out of the landfill, and that leaching is complete in 5 years. Landfilled sludge is assumed to be 20 percent solids by volume, and depth of sludge in the landfill is 5 m in the typical case and 10 m in the worst case. Thus, the initial depth of liquid is 4 and 8 m, and average yearly leachate generation is 0.8 and 1.6 m, respectively.

(c) **Depth to groundwater (h)**

Typical	5 m
Worst	0 m

Eight landfills were monitored throughout the United States and depths to groundwater below them were listed. A typical depth to groundwater of 5 m was observed (U.S. EPA, 1977). For the worst case, a value of 0 m is used to represent the situation where the bottom of the landfill is occasionally or regularly below the water table. The depth to groundwater must be estimated in order to evaluate the likelihood that pollutants moving through the unsaturated soil will reach the groundwater.

(d) **Dispersivity coefficient (α)**

Typical 0.5 m
Worst Not applicable

The dispersion process is exceedingly complex and difficult to quantify, especially for the unsaturated zone. It is sometimes ignored in the unsaturated zone, with the reasoning that pore water velocities are usually large enough so that pollutant transport by convection, i.e., water movement, is paramount. As a rule of thumb, dispersivity may be set equal to 10 percent of the distance measurement of the analysis (Gelhar and Axness, 1981). Thus, based on depth to groundwater listed above, the value for the typical case is 0.5 and that for the worst case does not apply since leachate moves directly to the unsaturated zone.

iii. **Chemical-specific parameters**

(a) **Sludge concentration of pollutant (SC)**

Typical 0.46 mg/kg DW
Worst 17.85 mg/kg DW

See Section 3, p. 3-1.

(b) **Soil half-life of pollutant ($t_{\frac{1}{2}}$)** - Data not immediately available.

See Section 3, p. 3-2.

(c) **Degradation rate (μ)** = 0 day^{-1}

The unsaturated zone can serve as an effective medium for reducing pollutant concentration through a variety of chemical and biological decay mechanisms which transform or attenuate the pollutant. While these decay processes are usually complex, they are approximated here by a first-order rate constant. The degradation rate is calculated using the following formula:

$$\mu = \frac{0.693}{t_{\frac{1}{2}}}$$

Since a soil half-life value was not immediately available, the degradation rate was assumed to be zero, which represents the worst-case condition.

(d) **Organic carbon partition coefficient (K_{oc}) = 198 mL/g**

The organic carbon partition coefficient is multiplied by the percent organic carbon content of soil (f_{oc}) to derive a partition coefficient (K_d), which represents the ratio of absorbed pollutant concentration to the dissolved (or solution) concentration. The equation (K_{oc} x f_{oc}) assumes that organic carbon in the soil is the primary means of adsorbing organic compounds onto soils. This concept serves to reduce much of the variation in K_d values for different soil types. The value of K_{oc} is from Lyman (1982).

b. Saturated zone

i. Soil type and characteristics

(a) **Soil type**

Typical	Silty sand
Worst	Sand

A silty sand having the values of aquifer porosity and hydraulic conductivity defined below represents a typical aquifer material. A more conductive medium such as sand transports the plume more readily and with less dispersion and therefore represents a reasonable worst case.

(b) **Aquifer porosity (Ø)**

Typical	0.44 (unitless)
Worst	0.389 (unitless)

Porosity is that portion of the total volume of soil that is made up of voids (air) and water. Values corresponding to the above soil types are from Pettyjohn et al. (1982) as presented in U.S. EPA (1983b).

(c) **Hydraulic conductivity of the aquifer (K)**

Typical	0.86 m/day
Worst	4.04 m/day

The hydraulic conductivity (or permeability) of the aquifer is needed to estimate flow velocity based on Darcy's Equation. It is a measure of the volume of liquid that can flow through a unit area or media with time; values can range over nine orders of magnitude depending on the nature of the media. Heterogenous conditions produce large spatial variation in hydraulic conductivity, making estimation of a single effective value extremely difficult. Values used are from Freeze and Cherry (1979) as presented in U.S. EPA (1983b).

(d) **Fraction of organic carbon (f_{oc}) =** 0.0 (unitless)

Organic carbon content, and therefore adsorption, is assumed to be 0 in the saturated zone.

ii. **Site parameters**

(a) **Average hydraulic gradient between landfill and well (i)**

Typical	0.001 (unitless)
Worst	0.02 (unitless)

The hydraulic gradient is the slope of the water table in an unconfined aquifer, or the piezometric surface for a confined aquifer. The hydraulic gradient must be known to determine the magnitude and direction of groundwater flow. As gradient increases, dispersion is reduced. Estimates of typical and high gradient values were provided by Donigian (1985).

(b) **Distance from well to landfill ($\Delta \ell$)**

Typical	100 m
Worst	50 m

This distance is the distance between a landfill and any functioning public or private water supply or livestock water supply.

(c) **Dispersivity coefficient (α)**

Typical	10 m
Worst	5 m

These values are 10 percent of the distance from well to landfill ($\Delta \ell$), which is 100 and 50 m, respectively, for typical and worst conditions.

(d) **Minimum thickness of saturated zone (B)** = 2 m

The minimum aquifer thickness represents the assumed thickness due to preexisting flow; i.e., in the absence of leachate. It is termed the minimum thickness because in the vicinity of the site it may be increased by leachate infiltration from the site. A value of 2 m represents a worst case assumption that preexisting flow is very limited and therefore dilution of the plume entering the saturated zone is negligible.

(e) **Width of landfill (W)** = 112.8 m

The landfill is arbitrarily assumed to be circular with an area of 10,000 m^2.

iii. **Chemical-specific parameters**

(a) **Degradation rate (μ)** = 0 day^{-1}

Degradation is assumed not to occur in the saturated zone.

(b) **Background concentration of pollutant in groundwater (BC)** = 0 μg/L

It is assumed that no pollutant exists in the soil profile or aquifer prior to release from the source.

4. **Index Values** - See Table 3-1.

5. **Value Interpretation** - Value equals the maximum expected groundwater concentration of pollutant, in μg/L, at the well.

6. **Preliminary Conclusion** - Landfilled sludge is expected to increase the concentration of TCE in groundwater; this increase may be large at a disposal site with all worst-case conditions.

B. **Index of Human Cancer Risk Resulting from Groundwater Contamination (Index 2)**

1. **Explanation** - Calculates human exposure which could result from groundwater contamination. Compares exposure with cancer risk-specific intake (RSI) of pollutant.

2. **Assumptions/Limitations** - Assumes long-term exposure to maximum concentration at well at a rate of 2 L/day.

3. **Data Used and Rationale**

   a. **Index of groundwater concentration resulting from landfilled sludge (Index 1)**

      See Section 3, p. 3-22.

   b. **Average human consumption of drinking water (AC)** = 2 L/day

      The value of 2 L/day is a standard value used by U.S. EPA in most risk assessment studies.

   c. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

   d. **Cancer potency** = 1.9×10^{-2} $(mg/kg/day)^{-1}$

      See Section 3, p. 3-9.

   e. **Cancer risk-specific intake (RSI)** = 3.68 µg/day

      The RSI is the pollutant intake value which results in an increase in cancer risk of 10^{-6} (1 per 1,000,000). The RSI is calculated from the cancer potency using the following formula:

$$RSI = \frac{10^{-6} \times 70 \text{ kg} \times 10^{3} \text{ µg/mg}}{\text{Cancer potency}}$$

4. **Index 2 Values** - See Table 3-1.

5. **Value Interpretation** - Value >1 indicates a potential increase in cancer risk of 10^{-6} (1 in 1,000,000) due only to groundwater contaminated by landfill. The value does not account for the possible increase in risk resulting from daily dietary intake of pollutant since DI data were not immediately available.

6. **Preliminary Conclusion** - Groundwater contaminated by landfilled sludge is not expected to increase the cancer risk from TCE, except when all worst-case conditions prevail at a disposal site.

TABLE 3-1. INDEX OF GROUNDWATER CONCENTRATION RESULTING FROM LANDFILLED SLUDGE (INDEX 1) AND INDEX OF HUMAN CANCER RISK RESULTING FROM GROUNDWATER CONTAMINATION (INDEX 2)

	Condition of Analysis[a,b,c]							
Site Characteristics	1	2	3	4	5	6	7	8
Sludge concentration	T	W	T	T	T	T	W	N
Unsaturated Zone								
Soil type and characteristics[d]	T	T	W	NA	T	T	NA	N
Site parameters[e]	T	T	T	W	T	T	W	N
Saturated Zone								
Soil type and characteristics[f]	T	T	T	T	W	T	W	N
Site parameters[g]	T	T	T	T	T	W	W	N
Index 1 Value (μg/L)	0.013	0.49	0.013	0.013	0.066	0.50	100	0
Index 2 Value	0.0068	0.26	0.0068	0.0068	0.036	0.27	56	0

[a]T = Typical values used; W = worst-case values used; N = null condition, where no landfill exists, used as basis for comparison; NA = not applicable for this condition.

[b]Index values for combinations other than those shown may be calculated using the formulae in the Appendix.

[c]See Table A-1 in Appendix for parameter values used.

[d]Dry bulk density (ρ_{dry}), volumetric water content (θ), and fraction of organic carbon (f_{oc}).

[e]Leachate generation rate (Q), depth to groundwater (h), and dispersivity coefficient (α).

[f]Aquifer porosity ($\emptyset$) and hydraulic conductivity of the aquifer (K).

[g]Hydraulic gradient (i), distance from well to landfill ($\Delta \ell$), and dispersivity coefficient (α).

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

SECTION 4

PRELIMINARY DATA PROFILE FOR TRICHLOROETHYLENE IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

Observed in 10 of 20 sludges	Naylor and Loehr, 1982 (p. 20)
Observed in 232 of 432 samples (54%) from 40 publicly-owned treatment works (POTWs)	U.S. EPA, 1982 (p. 41)
Observed in 30 of 41 samples (73%) from 10 POTWs	U.S. EPA, 1982 (p. 49)

2. Concentration

Municipal sewage sludge 50th percentile: 0.460 µg/g (DW) 95th percentile: 17.85 µg/g (DW)	Values statistically derived from sludge concentration data presented in U.S. EPA, 1982
Median 57 µg/L (WW); range 2 to 1,927 µg/L for 10 treatment plants. Median 0.98 µg/g (DW); range 0.048 to 44 µg/g (DW) for 210 treatment plants.	Naylor and Loehr, 1982 (p. 10)
1 to 32,700 µg/L from 40 POTWs	U.S. EPA, 1982 (p. 41)
2 to 299 µg/L from 10 POTWs	U.S. EPA, 1982 (p. 49)

B. Soil - Unpolluted

1. Frequency of Detection

Data not immediately available.

2. Concentration

0.63 ng/g (DW) from control site in Arkansas	Battelle, 1977a (p. 5-35)

C. Water - Unpolluted

1. Frequency of Detection

Observed in 4 of 112 drinking waters, 1976 Observed in 28 of 113 cities, 1976 Observed in 19 of 105 cities, 1977	U.S. EPA, 1980 (p. C-1)
72 of 179 surface water samples had >1 µg/L of TCE (ca 1977)	U.S. EPA, 1983c (p. 3-14)

2. Concentration

a. Freshwater

<5 µg/L mean, <1 to 29 µg/L range from major surface water systems in United States.	Battelle, 1977b (p. 2-18)
Up to 403 µg/L measured in some surface waters	U.S. EPA, 1983c (p. 3-22)

b. Seawater

Data not immediately available.

c. Drinking Water

22 µg/L in tap water from Arkansas	Battelle, 1977a (p. 5-35)
Present but not quantifiable in Miami drinking water	Battelle, 1977b (p. 2-19)
Not detected to 0.5 µg/L in drinking water from 5 U.S. cities	Battelle, 1977b (p. 2-20)
11 µg/L (1976), 4 cities 2.1 µg/L (1976), 28 cities 1.3 µg/L (1977), 19 cities	U.S. EPA, 1980 (p. C-1)
806 µg/L protective ambient water level	U.S. EPA, 1980 (p. C-32)
0.1 to 0.5 µg/L in 5 samples from 10-city survey (ca 1975)	National Academy of Sciences (NAS), 1977 (p. 777)
1 to 32 µg/L range in U.S. drinking water	U.S. EPA, 1983c (p. 1-1)

D. Air

1. Frequency of Detection

TCE observed in 290 of 480 samples (60%) for industrial and urban areas of New Jersey	Bozzelli and Kebbekus, 1982 (p. 700-704)

2. Concentration

a. Urban

1.84 to 3.29 $\mu g/m^3$ range of means, 4.8 to 14.59 $\mu g/m^3$ range of high values for urban suburban areas of New Jersey 5.13 to 15.13 $\mu g/m^3$ range of means, 32.97 to 170 $\mu g/m^3$ range of high values for industrial areas of New Jersey	Bozzelli and Kebbekus, 1982 (p. 700-704)
1.69 $\mu g/m^3$ mean, 0.13 to 9.73 $\mu g/m^3$ range for Los Angeles 1.03 $\mu g/m^3$ mean, <0.27 to 3.41 $\mu g/m^3$ for Wilmington, Ohio	Bozzelli and Kebbekus, 1982 (p. 706)
<5.4 to 1,459 $\mu g/m^3$ near chemical manufacturing plants	Battelle, 1977a (p. 5-5, 5-6, 5-11, and 5-12)

b. Rural

0.27 to 1.89 $\mu g/m^3$ in rural locations through the United States	Bozzelli and Kebbekus, 1982 (p. 706)

E. Food

1. Frequency of Detection

Data not immediately available.

2. Concentration

There is no information available on occurrence of TCE in U.S. foodstuffs. Data from England shows <10 ng/g TCE in meats, and <5 ng/g in fruits, vegetables, and beverages	U.S. EPA, 1980 (p. C-1)
TCE was used as a solvent for food extractions (e.g., caffeine). Current maximum allowable concentrations in food are 10 $\mu g/g$ in instant coffee;	U.S. EPA, 1980 (p. C-1)

25 μg/g in ground coffee, and 30 μg/g in spice extracts (21 CFR 121:1041; FDA)

Average daily human dietary intake data is not immediately available.

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity

a. Qualitative Assessment

U.S. EPA's Carcinogen Assessment Group ranks TCE as an IARC Group 2B compound but recognized scientific sentiment for ranking as Group 3, the difference depending on the view taken about mouse liver tumor response.

b. Potency

Cancer potency is 1.9×10^{-2} (mg/kg/day)$^{-1}$.	U.S. EPA, 1983c (p. 8-96)

This value was statistically derived for humans from data associated with a 1000 to 2339 mg/kg/day exposure level for mice that resulted in hepatocellular carcinoma.

However, the U.S. EPA's Science Advisory Board has recently disputed the judgment of the Carcinogen Assessment group that TCE should be regarded as a potential human carcinogen because of impurities in the test materials.

c. Effects

Heptocellular carcinoma in mice	U.S. EPA, 1983c (p. 8-96)

2. Chronic toxicity

a. ADI

Data not immediately available.

b. Effects

Rats administered TCE by gavage for 78 weeks displayed decreased body weight and survival times as well as slight to moderate degenerative and regenerative alterations of renal tubules. — U.S. EPA, 1984b (p. 5)

3. Absorption Factor

No data for humans but rats absorbed 80 to 100% of ingested TCE. — U.S. EPA, 1984b (p. 2)

4. Existing Regulations

A health advisory for TCE in drinking water has been established. One-day, ten-day, and long-term suggested levels are 2.0 mg/L, 0.20 mg/L, and 0.75 mg/L, respectively. — U.S. EPA, 1985

105 mg/L suggested 24-hour no adverse response level for humans
15 mg/L suggested seven-day no adverse response level for humans. — NAS, 1980 (p. 165)

B. Inhalation

1. Carcinogenicity

a. Qualitive Assessment

U.S. EPA's Carcinogen Assessment Group ranks TCE as an IARC Group 2B compound, but recognized scientific sentiment for ranking TCE as Group 3, the difference depending upon the view taken about mouse liver tumor response.

b. Potency

Cancer potency is 6.5×10^{-3} (mg/kg/day)$^{-1}$, based on lung tumor response in mice. However, the U.S. EPA's Science Advisory Board has recently disputed the judgment of the Carcinogen Assessment Group that TCE should be regarded as a potential human carcinogen. — U.S. EPA, 1984b (p. 18)

2. **Chronic Toxicity**

Data not evaluated since assessment based on carcinogenicity.

3. **Absorption Factor**

Absorption of TCE through the lungs is rapid and reaches equilibrium in approximately 2 hours.	U.S. EPA, 1984b (p. 2)

4. **Existing Regulations**

American Conference of Governmental Industrial Hygienists (ACGIH) has set the time weighted average (TWA)-threshold limit value (TLV) at 270 mg/m^3. The short-term exposure limit (STEL) is 560 mg/m^3.	U.S. EPA, 1984b (p. 16)

III. PLANT EFFECTS

A. Phytotoxicity

Data not immediately available.

B. Uptake

Data not immediately available.

"There is no direct evidence of bioaccumulation of TCE in the food chain. Few studies have been made of the ecological consequences of TCE in the environment."	U.S. EPA, 1983c (p. 1-1)

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

See Table 4-1.

B. Uptake

"There is no direct evidence of bioaccumulation of TCE in the food chain."	U.S. EPA, 1983c (p. 1-1)

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. Freshwater

a. Acute

Daphnia magna acute toxicity at 64,000 µg/L	U.S. EPA, 1980 (p. B-3)
Daphnia pulex acute toxicity at 45,000 µg/L	
Fathead minnow acute toxicity at 40,700 µg/L	
Bluegill acute toxicity at 66,800 µg/L	

b. Chronic

No chronic tests have been conducted with any freshwater species.	U.S. EPA, 1980 (p. B-2)

2. Saltwater

a. Acute

Grass shrimp showed signs of erratic swimming, uncontrolled movement, and loss of equilibrium after several minutes exposure to 2,000 µg/L. Same conditions displayed by sheepshead minnows at 20,000 µg/L.	U.S. EPA, 1980 (p. B-3)

b. Chronic

No chronic tests have been conducted with any saltwater species.	U.S. EPA, 1980 (p. B-2)

B. Uptake

Bioconcentration factor for bluegill was 17 with a tissue half-life of less than one day.	U.S. EPA, 1980 (p. B-3)

VI. SOIL BIOTA EFFECTS

Data not immediately available.

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT OF POLLUTANT

Chemical formula: C_2HCl_3 — Love and Eilers, 1980 (p. 414)
Molecular weight: 132 g/mol
Density: 1.46 g/mL
Boiling point: 87°C
Solubility: 1,000 to 1,100 mg/L in water
Vapor pressure: 74 mm Hg
Henry's Law constant: 0.48-0.49

Octanol/water partition coefficient: 195 — U.S. EPA, 1984b (p. 1)

Soil mobility: 1.6
(predicted as retardation factor for soil depth of 140 cm and organic carbon content of 0.087%)

Half-life in air: 3.7 days
Half-lives in water: 1 to 4 days and
3 to 90 days

Half-life in soil: Data not immediately available.

Organic carbon partition coefficient: 198 mL/g — Lyman, 1982

TABLE 4-1. TOXICITY OF TRICHLOROETHYENE TO DOMESTIC ANIMALS AND WILDLIFE

Species	Chemical Form Fed	Feed Concentration (μg/g)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration of Study	Effects	References
Rat	TCE	NR[a]	NR	4,920	NR	LD_{50}	NAS, 1977 (p. 778)
Rat	TCE	NR	NR	1,780	8 weeks	Highest no effect level	NAS, 1980 (p. 160)
Mice	TCE	NR	NR	3,160	8 weeks	Highest no effect level	NAS, 1980 (p. 160)
Mice	TCE (gavage)	NR	NR	1,000-2,339	103 weeks	Hepatocellular carcinomas	U.S. EPA, 1983c (p. 8-2)
Rat	TCE (gavage)	NR	NR	500-1,000	103 weeks	Renal adenocarcinomas	U.S. EPA, 1983c (p. 8-2)

[a]NR = Not reported.

SECTION 5

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APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR TRICHLOROETHYLENE IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Trichloroethylene

1. Index of Soil Concentration (Index 1)

a. Formula

$$CS_s = \frac{(SC \times AR) + (BS \times MS)}{AR + MS}$$

$$CS_r = CS_s \left[1 + 0.5^{(1/t_{\frac{1}{2}})} + 0.5^{(2/t_{\frac{1}{2}})} + \ldots + 0.5^{(n/t_{\frac{1}{2}})}\right]$$

where:

CS_s = Soil concentration of pollutant after a single year's application of sludge (µg/g DW)
CS_r = Soil concentration of pollutant after the yearly application of sludge has been repeated for n + 1 years (µg/g DW)
SC = Sludge concentration of pollutant (µg/g DW)
AR = Sludge application rate (mt/ha)
MS = 2000 mt ha/DW = assumed mass of soil in upper 15 cm
BS = Background concentration of pollutant in soil (µg/g DW)
$t_{\frac{1}{2}}$ = Soil half-life of pollutant (years)
n = 99 years

b. Sample calculation

CS_s is calculated for AR = 0, 5, and 50 mt/ha only

$$0.0018\ \mu g/g\ DW = \frac{(0.46\ \mu g/g\ DW \times 5\ mt/ha) + (0.00063\ \mu g/g\ DW \times 2000\ mt/ha)}{(5\ mt/ha\ DW + 2000\ mt/ha\ DW)}$$

CS_r is calculated for AR = 500 mt/ha

$$0.0925\ \mu g/g\ DW = \frac{(0.46\ \mu g/g\ DW \times 500\ mt/ha) + (0.00063\ \mu g/g\ DW \times 2000\ mt/ha)}{(500\ mt/ha\ DW + 2000\ mt/ha\ DW)}$$

B. Effect on Soil Biota and Predators of Soil Biota

1. Index of Soil Biota Toxicity (Index 2)

a. Formula

$$\text{Index 2} = \frac{I_1}{TB}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
TB = Soil concentration toxic to soil biota (μg/g DW)

b. Sample calculation - Values were not calculated due to lack of data.

2. Index of Soil Biota Predator Toxicity (Index 3)

a. Formula

$$\text{Index 3} = \frac{I_1 \times UB}{TR}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
UB = Uptake factor of pollutant in soil biota (μg/g tissue DW [μg/g soil DW]$^{-1}$)
TR = Feed concentration toxic to predator (μg/g DW)

b. Sample calculation - Values were not calculated due to lack of data.

C. Effect on Plants and Plant Tissue Concentration

1. Index of Phytotoxic Soil Concentration (Index 4)

a. Formula

$$\text{Index 4} = \frac{I_1}{TP}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
TP = Soil concentration toxic to plants (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

2. **Index of Plant Concentration Caused by Uptake (Index 5)**

a. **Formula**

$$\text{Index 5} = I_1 \times UP$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge - amended soil (μg/g DW)
UP = Uptake factor of pollutant in plant tissue (μg/g tissue DW [μg/g soil DW]$^{-1}$)

b. **Sample Calculation** - Values were not calculated due to lack of data.

3. **Index of Plant Concentration Increment Permitted by Phytotoxicity (Index 6)**

a. **Formula**

$$\text{Index 6} = PP$$

where:

PP = Maximum plant tissue concentration associated with phytotoxicity (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

D. **Effect on Herbivorous Animals**

1. **Index of Animal Toxicity Resulting from Plant Consumption (Index 7)**

a. **Formula**

$$\text{Index 7} = \frac{I_5}{TA}$$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Formula**

If AR = 0; Index 8 = 0

$$\text{If AR} \neq 0;\ \text{Index 8} = \frac{SC \times GS}{TA}$$

where:

AR = Sludge application rate (mt DW/ha)
SC = Sludge concentration of pollutant (μg/g DW)
GS = Fraction of animal diet assumed to be soil
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

E. **Effect on Humans**

1. **Index of Human Cancer Risk Resulting from Plant Consumption (Index 9)**

a. **Formula**

$$\text{Index 9} = \frac{(I_5 \times DT) + DI}{RSI}$$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
DT = Daily human dietary intake of affected plant tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

2. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)**

a. **Formula**

$$\text{Index 10} = \frac{(I_5 \times UA \times DA) + DI}{RSI}$$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
UA = Uptake factor of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW]$^{-1}$)
DA = Daily human dietary intake of affected animal tissue (g/day DW) (milk products and meat, poultry, eggs, fish)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

3. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Formula**

$$\text{If AR} = 0;\ \text{Index 11} = \frac{(\text{BS} \times \text{GS} \times \text{UA} \times \text{DA}) + \text{DI}}{\text{RSI}}$$

$$\text{If AR} \neq 0;\ \text{Index 11} = \frac{(\text{SC} \times \text{GS} \times \text{UA} \times \text{DA}) + \text{DI}}{\text{RSI}}$$

where:

AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
SC = Sludge concentration of pollutant (μg/g DW)
GS = Fraction of animal diet assumed to be soil
UA = Uptake factor of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW]$^{-1}$)
DA = Daily human dietary intake of affected animal tissue (g/day DW) (milk products and meat only)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

4. **Index of Human Cancer Risk Resulting from Soil Ingestion (Index 12)**

a. **Formula**

$$\text{Index 12} = \frac{(I_1 \times \text{DS}) + \text{DI}}{\text{RSI}}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
DS = Assumed amount of soil in human diet (g/day)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

5. **Index of Aggregate Human Cancer Risk (Index 13)**

a. **Formula**

$$\text{Index 13} = I_9 + I_{10} + I_{11} + I_{12} - \left(\frac{3DI}{RSI}\right)$$

where:

I_9 = Index 9 = Index of human cancer risk resulting from plant consumption (unitless)
I_{10} = Index 10 = Index of human cancer risk resulting from consumption of animal products derived from animals feeding on plants (unitless)
I_{11} = Index 11 = Index of human cancer risk resulting from consumption of animal products derived from animals ingesting soil (unitless)
I_{12} = Index 12 = Index of human cancer risk resulting from soil ingestion (unitless)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

II. LANDFILLING

A. Procedure

Using Equation 1, several values of C/C_o for the unsaturated zone are calculated corresponding to increasing values of t until equilibrium is reached. Assuming a 5-year pulse input from the landfill, Equation 3 is employed to estimate the concentration vs. time data at the water table. The concentration vs. time curve is then transformed into a square pulse having a constant concentration equal to the peak concentration, C_u, from the unsaturated zone, and a duration, t_o, chosen so that the total areas under the curve and the pulse are equal, as illustrated in Equation 3. This square pulse is then used as the input to the linkage assessment, Equation 2, which estimates initial dilution in the aquifer to give the initial concentration, C_o, for the saturated zone assessment. (Conditions for B, minimum thickness of unsaturated zone, have been set such that dilution is actually negligible.) The saturated zone assessment procedure is nearly identical to that for the unsaturated zone except for the definition of certain parameters and choice of parameter values. The maximum concentration at the well, C_{max}, is used to calculate the index values given in Equations 4 and 5.

B. Equation 1: Transport Assessment

$$\frac{C(\chi,t)}{C_o} = \frac{1}{2} [\exp(A_1)\ \text{erfc}(A_2) + \exp(B_1)\ \text{erfc}(B_2)] = P(\chi,t)$$

Requires evaluations of four dimensionless input values and subsequent evaluation of the result. $\text{Exp}(A_1)$ denotes the exponential of A_1, e^{A_1}, where $\text{erfc}(A_2)$ denotes the complimentary error function of A_2. $\text{Erfc}(A_2)$ produces values between 0.0 and 2.0 (Abramowitz and Stegun, 1972).

where:

$$A_1 = \frac{\chi}{2D^*} [V^* - (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}]$$

$$A_2 = \frac{\chi - t\ (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}}{(4D^* \times t)^{\frac{1}{2}}}$$

$$B_1 = \frac{\chi}{2D^*} [V^* + (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}]$$

$$B_2 = \frac{\chi + t\ (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}}{(4D^* \times t)^{\frac{1}{2}}}$$

and where for the unsaturated zone:

C_o = SC x CF = Initial leachate concentration (μg/L)
SC = Sludge concentration of pollutant (mg/kg DW)
CF = 250 kg sludge solids/m^3 leachate =

$$\frac{PS \times 10^3}{1 - PS}$$

PS = Percent solids (by weight) of landfilled sludge = 20%
t = Time (years)
χ = h = Depth to groundwater (m)
D^* = $\alpha \times V^*$ (m^2/year)
α = Dispersivity coefficient (m)

$$V^* = \frac{Q}{\Theta \times R} \text{ (m/year)}$$

Q = Leachate generation rate (m/year)
Θ = Volumetric water content (unitless)

$R = 1 + \frac{P_{dry}}{\Theta} \times K_d$ = Retardation factor (unitless)

P_{dry} = Dry bulk density (g/mL)
$K_d = f_{oc} \times K_{oc}$ (mL/g)
f_{oc} = Fraction of organic carbon (unitless)
K_{oc} = Organic carbon partition coefficient (mL/g)

$\mu^* = \frac{365 \times \mu}{R}$ $(\text{years})^{-1}$
μ = Degradation rate (day^{-1})

and where for the saturated zone:

C_o = Initial concentration of pollutant in aquifer as determined by Equation 2 (μg/L)
t = Time (years)
$\chi = \Delta \ell$ = Distance from well to landfill (m)
$D^* = \alpha \times V^*$ (m^2/year)
α = Dispersivity coefficient (m)

$V^* = \frac{K \times i}{\emptyset \times R}$ (m/year)
K = Hydraulic conductivity of the aquifer (m/day)
i = Average hydraulic gradient between landfill and well (unitless)
$\emptyset$ = Aquifer porosity (unitless)

$R = 1 + \frac{P_{dry}}{\emptyset} \times K_d$ = Retardation factor = 1 (unitless) since $K_d = f_{oc} \times K_{oc}$ and f_{oc} is assumed to be zero for the saturated zone.

C. Equation 2. Linkage Assessment

$$C_o = C_u \times \frac{Q \times W}{365\ [(K \times i) \div \emptyset] \times B}$$

where:

C_o = Initial concentration of pollutant in the saturated zone as determined by Equation 1 (μg/L)
C_u = Maximum pulse concentration from the unsaturated zone (μg/L)
Q = Leachate generation rate (m/year)
W = Width of landfill (m)
K = Hydraulic conductivity of the aquifer (m/day)
i = Average hydraulic gradient between landfill and well (unitless)
$\emptyset$ = Aquifer porosity (unitless)
B = Thickness of saturated zone (m) where:

$$B \geq \frac{Q \times W \times \emptyset}{K \times i \times 365} \quad \text{and } B \geq 2$$

D. **Equation 3. Pulse Assessment**

$$\frac{C(\chi,t)}{C_o} = P(\chi,t) \text{ for } 0 \leq t \leq t_o$$

$$\frac{C(\chi,t)}{C_o} = P(\chi,t) - P(\chi,t - t_o) \text{ for } t > t_o$$

where:

t_o (for unsaturated zone) = LT = Landfill leaching time (years)

t_o (for saturated zone) = Pulse duration at the water table (χ = h) as determined by the following equation:

$$t_o = [\ {}_0\int^{\infty} C\ dt] \div C_u$$

$P(\chi,t) = \frac{C(\chi,t)}{C_o}$ as determined by Equation 1

E. **Equation 4. Index of Groundwater Concentration Resulting from Landfilled Sludge (Index 1)**

1. **Formula**

Index 1 = C_{max}

where:

C_{max} = Maximum concentration of pollutant at well = maximum of $C(\Delta\ell,t)$ calculated in Equation 1 (μg/L)

2. **Sample Calculation**

0.0125 μg/L = 0.0125 μg/L

F. **Equation 5. Index of Human Cancer Risk Resulting from Groundwater Contamination (Index 2)**

1. **Formula**

$$\text{Index 2} = \frac{(I_1 \times AC) + DI}{RSI}$$

where:

I_1 = Index 1 = Index of groundwater concentration resulting from landfilled sludge (μg/L)
AC = Average human consumption of drinking water (L/day)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

2. **Sample Calculation (when DI is unknown)**

$$0.00680 = \frac{(0.0125\ \mu g/L \times 2\ L/day)}{3.68\ \mu g/day}$$

III. INCINERATION

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

IV. OCEAN DISPOSAL

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

TABLE A-1. INPUT DATA VARYING IN LANDFILL ANALYSIS AND RESULT FOR EACH CONDITION

Input Data	Condition of Analysis							
	1	2	3	4	5	6	7	8
Sludge concentration of pollutant, SC (μg/g DW)	0.46	17.85	0.46	0.46	0.46	0.46	17.85	N[a]
Unsaturated zone								
Soil type and characteristics								
Dry bulk density, P_{dry} (g/mL)	1.53	1.53	1.925	NA[b]	1.53	1.53	NA	N
Volumetric water content, θ (unitless)	0.195	0.195	0.133	NA	0.195	0.195	NA	N
Fraction of organic carbon, f_{oc} (unitless)	0.005	0.005	0.0001	NA	0.005	0.005	NA	N
Site parameters								
Leachate generation rate, Q (m/year)	0.8	0.8	0.8	1.6	0.8	0.8	1.6	N
Depth to groundwater, h (m)	5	5	5	0	5	5	0	N
Dispersivity coefficient, α (m)	0.5	0.5	0.5	NA	0.5	0.5	NA	N
Saturated zone								
Soil type and characteristics								
Aquifer porosity, ∅ (unitless)	0.44	0.44	0.44	0.44	0.389	0.44	0.389	N
Hydraulic conductivity of the aquifer, K (m/day)	0.86	0.86	0.86	0.86	4.04	0.86	4.04	N
Site parameters								
Hydraulic gradient, i (unitless)	0.001	0.001	0.001	0.001	0.001	0.02	0.02	N
Distance from well to landfill, Δℓ (m)	100	100	100	100	100	50	50	N
Dispersivity coefficient, α (m)	10	10	10	10	10	5	5	N

TABLE A-1. (continued)

Results	Condition of Analysis 1	2	3	4	5	6	7	8
Unsaturated zone assessment (Equations 1 and 3)								
Initial leachate concentration, C_o (μg/L)	115	4460	115	115	115	115	4460	N
Peak concentration, C_u (μg/L)	55.2	2140	115	115	55.2	55.2	4460	N
Pulse duration, t_o (years)	10.4	10.4	5.00	5.00	10.4	10.4	5.00	N
Linkage assessment (Equation 2)								
Aquifer thickness, B (m)	126	126	126	253	23.8	6.32	2.38	N
Initial concentration in saturated zone, C_o (μg/L)	55.2	2140	115	115	55.2	55.2	4460	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (μg/L)	0.0125	0.485	0.0125	0.0125	0.0664	0.501	103	N
Index of groundwater concentration resulting from landfilled sludge, Index 1 (μg/L) (Equation 4)	0.0125	0.485	0.0125	0.0125	0.0664	0.501	103	0
Index of human cancer risk resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	0.00680	0.264	0.00680	0.00680	0.0361	0.272	56.1	0

[a]N = Null condition, where no landfill exists; no value is used.
[b]NA = Not applicable for this condition.