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Regulations and Standards
Washington, DC 20460

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

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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PRELIMINARY CONCLUSIONS FOR ARSENIC 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 Arsenic

Landspreading of municipal sewage sludge is expected to slightly increase soil concentrations of As when sludge containing a high concentration of As is applied at 50 mt/ha or the cumulative rate of 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

Landspreading of municipal sewage sludge is not expected to pose a phytotoxic hazard due to As for plants grown in sludge-amended soils (see Index 4). Landspreading of sludge containing typical concentrations of As is not expected to increase the tissue concentration of As in plants used as animal feed or included in the human diet. Application of sludge containing a high concentration of As may result in moderate increases in concentrations of As for plants consumed by animals and humans (see Index 5). The predicted increases of As in the tissue concentrations of plants grown in sludge-amended soil should not be precluded by phytotoxicity (see Index 6).

D. Effect on Herbivorous Animals

Landspreading of sludge is not expected to pose a toxic hazard due to As for herbivorous animals that graze on plants grown in sludge-amended soil (see Index 7). Also, herbivorous animals ingesting either sludge adhering to forage crops, sludge-amended soils, or pure sludge are not expected to be subjected to a toxic hazard due to As (see Index 8).

E. Effect on Humans

Consumption of plants grown in sludge-amended soil is generally not expected to pose a toxic hazard due to As for either toddlers or adults. However, when sludge containing a high (worst) concentration of As is applied at the cumulative rate

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PRELIMINARY HAZARD INDICES FOR ARSENIC IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Arsenic

1. Index of Soil Concentration Increment (Index 1)

a. **Explanation** - Shows degree of elevation of pollutant concentration in soil to which sludge is applied. Calculated for sludges with typical (median if available) and worst (95th percentile if available) pollutant concentrations, respectively, for each of four sludge loadings. Applications (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 pre-existing 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 application as may be used on public lands, reclaimed areas or home gardens.
500 mt/ha	Cumulative loading after years of application.

b. **Assumptions/Limitations** - Assumes pollutant is distributed and retained within the upper 15 cm of soil (i.e., the plow layer), which has an approximate mass (dry matter) of 2×10^3 mt/ha.

c. **Data Used and Rationale**

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

Typical	4.6 µg/g DW
Worst	20.77 µg/g DW

The typical and worst sludge concentrations are the median and 95th percentile values statistically derived from sludge concentration data

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0 mt/ha No sludge applied. Shown for all indices for purposes of comparison, to distinguish hazard posed by sludge from pre-existing 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 application as may be used on public lands, reclaimed areas or home gardens.

500 mt/ha Cumulative loading after years of application.

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c. **Data Used and Rationale**

i. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 6.0 μg/g DW**

See Section 3, p. 3-2.

iii. **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. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 6.0 μg/g DW**

See Section 3, p. 3-2.

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

iv. **Background concentration in soil biota (BB)** - Data not immediately available.

c. **Data Used and Rationale**

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iii. Soil concentration toxic to plants (TP) = 45 µg/g DW

Several experimental studies were conducted which suggest that at concentrations of 40 to 100 µg/g DW, there are significant yield or plant growth reductions (i.e., 50 percent or more). Using bermuda grass as a representative forage grass, available evidence shows 75 percent growth reduction results from 45 µg/g DW of As_2O_3 in non-clay soils (Weaver et al., 1984). This value may be viewed as conservative for the forage grasses since the availability of As is greater in non-clay soils. (See Section 4, p. 4-12.)

d. **Index 4 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.13	0.13	0.13	0.13
Worst	0.13	0.13	0.14	0.20

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

f. **Preliminary Conclusion** - Landspreading of municipal sewage sludge is not expected to pose a phytotoxic hazard due to As for plants grown in sludge-amended soils.

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

a. **Explanation** - Calculates expected tissue concentration increment 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 a linear uptake slope. Neglects the effect of time; i.e., cumulative loading over several years is treated equivalently to single application of the same amount. 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.

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d. **Index 5 Values**

Diet	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Animal	Typical	1.0	0.99	0.90	0.21
	Worst	1.0	1.1	2.0	9.3
Human	Typical	1.0	0.99	0.85	-0.19
	Worst	1.0	1.2	2.5	14

e. **Value Interpretation** - Value equals factor by which plant tissue concentration is expected to increase above background when grown in sludge-amended soil.

f. **Preliminary Conclusion** - Landspreading of sludge containing typical concentrations of As is not expected to increase the tissue concentration of As in plants used as animal feed or included in the human diet. The tissue concentrations resulting from landspreading of sludge may actually be lower than background tissue concentrations because the typical sludge concentration is less than the background soil concentration and therefore landspreading of sludge is diluting concentrations normally present in soil. Application of sludge containing a high concentration of As may result in moderate increases in tissue concentration of As for plants consumed by animals and humans.

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

a. **Explanation** - Compares maximum plant tissue concentration associated with phytotoxicity with background concentration in same plant tissue. The purpose is to determine whether the plant concentration increments calculated in Index 5 for high applications are truly realistic, or whether such increases would be precluded by phytotoxicity.

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 phytotoxicity (PP)**

Animal diet:
Bermuda grass 45 µg/g DW

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f. **Preliminary Conclusion** - The index values for plant concentration increment permitted by phytotoxicity indicate that the Index 5 values are not precluded by a phytotoxic hazard.

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 food 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.37 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-6).

iii. **Feed concentration toxic to herbivorous animal (TA)** = 1000 μg/g DW

Information on feed concentrations toxic to smaller herbivorous (and other) animals suggests that a daily intake of 50 μg/g DW of inorganic As and 100 μg/g DW of organic As is the maximum tolerable level (National Academy of Sciences (NAS), 1980). However, for large domestic animals such as swine, As (in the form of sodium arsenite or arsenillic/sodium arsenite) feed concentrations of under 1000 μg/g DW have not been associated with deleterious effects like severe poisoning and death in the immediately available studies (Buck, 1978; Ledet and Buck, 1978). In the

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ii. **Background concentration of pollutant in soil (BS) = 6.0 μg/g DW**

See Section 3, p. 3-2.

iii. **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.

iv. **Feed concentration toxic to herbivorous animal (TA) = 1000 μg/g DW**

See Section 3, p.3-9.

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iv. **Feed concentration toxic to herbivorous animal (TA) = 1000 μg/g DW**

See Section 3, p.3-9.

iii. **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 (1984). 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 estimated dry-weight consumption of all non-fruit crops.

iv. **Average daily human dietary intake of pollutant (DI)**

Toddler	22.1 μg/day
Adult	66.5 μg/day

The average total intake of As for adults is estimated to range between 59.1 and 71.6 μg/day for the 1976-78 period (FDA, no date). The value chosen for adults represents the median intake for this period. The average daily intake of As for toddlers is assumed to be one-third that of an adult. (See Section 4, p. 4-3.)

v. **Acceptable daily intake of pollutant (ADI) = 260 μg/day**

Although inorganic As has been shown to cause skin cancer in humans when ingested in drinking water (U.S. EPA, 1980), organic forms of As, which predominate in food, have not been found to be carcinogenic. In a study of vegetables grown in soil treated with arsenic acid, Pyles and Woolson (1982) found that arsenite (the trivalent inorganic form) was not detectable. Arsenate (the pentavalent inorganic form) was present, probably due to soil contamination, but most of the As (i.e., 84-97%) was present as organic forms. Although there remains some ambiguity as to which form of As may be carcinogenic, it will be assumed in this document that As transferred via the food chain is noncarcinogenic and that hazard to humans should be assessed using an ADI based on the systemic toxicant properties of As.

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pollutant in animal tissue (UA) used is assumed to be representative of all animal tissue comprised by the daily human dietary intake (DA) used. 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.37 µg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-6).

iii. **Uptake slope of pollutant in animal tissue (UA)** = 0.56 µg/g tissue DW (µg/g feed DW)$^{-1}$

Uptake slopes for As in animal tissues consumed by humans were available for kidney, liver and muscle of swine (Ledet and Buck, 1978) and chicken (NAS, 1977). Slopes for organ tissues were higher than those for muscle by an order of magnitude. The highest slope was that for chicken liver. This value was chosen to represent all organ meats consumed by humans, not only because it is the highest value but also because chicken liver is commonly consumed. Also, the slopes for swine were derived from toxic feed concentrations of arsanillic acid, whereas those for chicken were from non-toxic concentrations of 3-nitro-4-hydroxyphenylarsenic acid. (See Section 4, p. 4-16.)

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

Toddler	0.97 g/day
Adult	5.76 g/day

The FDA Revised Total Diet (Pennington, 1983) lists average daily intake of beef liver (fresh weight) for various age-sex classes. The 95th percentile of liver consumption (chosen in order to be conservative) is assumed to be approximately 3 times the mean values. Conversion to dry weight is based on data from pollutant in animal tissue (UA) used is assumed to be representative of all animal tissue comprised by the daily human dietary intake (DA) used. 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.37 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-6).

iii. **Uptake slope of pollutant in animal tissue (UA)** = 0.56 μg/g tissue DW (μg/g feed DW)$^{-1}$

Uptake slopes for As in animal tissues consumed by humans were available for kidney, liver and muscle of swine (Ledet and Buck, 1978) and chicken (NAS, 1977). Slopes for organ tissues were higher than those for muscle by an order of magnitude. The highest slope was that for chicken liver. This value was chosen to represent all organ meats consumed by humans, not only because it is the highest value but also because chicken liver is commonly consumed. Also, the slopes for swine were derived from toxic feed concentrations of arsanillic acid, whereas those for chicken were from non-toxic concentrations of 3-nitro-4-hydroxyphenylarsenic acid. (See Section 4, p. 4-16.)

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

Toddler	0.97 g/day
Adult	5.76 g/day

The FDA Revised Total Diet (Pennington, 1983) lists average daily intake of beef liver (fresh weight) for various age-sex classes. The 95th percentile of liver consumption (chosen in order to be conservative) is assumed to be approximately 3 times the mean values. Conversion to dry weight is based on data from (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over three years old.

c. **Data Used and Rationale**

i. **Animal tissue** = Chicken liver

See Section 3, p. 3-15.

ii. **Background concentration of pollutant in soil (BS)** = 6.0 μg/g DW

See Section 3, p. 3-2.

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

Typical	4.6 μg/g DW
Worst	20.77 μg/g DW

See Section 3, p. 3-1.

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

See Section 3, p. 3-11.

v. **Uptake slope of pollutant in animal tissue (UA)** = 0.56 μg/g tissue DW (μg/g feed DW)$^{-1}$

See Section 3, p. 3-15.

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

Toddler	0.97 g/day
Adult	5.76 g/day

See Section 3, p. 3-15.

vii. **Average daily human dietary intake of pollutant (DI)**

Toddler	21.1 μg/day
Adult	66.5 μg/day

See Section 3, p. 3-13.

viii. **Acceptable daily intake of pollutant (ADI)** = 260 μg/day

See Section 3, p. 3-13.

(whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over three years old.

c. **Data Used and Rationale**

i. **Animal tissue** = Chicken liver

See Section 3, p. 3-15.

ii. **Background concentration of pollutant in soil (BS)** = 6.0 μg/g DW

See Section 3, p. 3-2.

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

Typical	4.6 μg/g DW
Worst	20.77 μg/g DW

See Section 3, p. 3-1.

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

See Section 3, p. 3-11.

v. **Uptake slope of pollutant in animal tissue (UA)** = 0.56 μg/g tissue DW (μg/g feed DW)$^{-1}$

See Section 3, p. 3-15.

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

Toddler	0.97 g/day
Adult	5.76 g/day

See Section 3, p. 3-15.

vii. **Average daily human dietary intake of pollutant (DI)**

Toddler	21.1 μg/day
Adult	66.5 μg/day

See Section 3, p. 3-13.

viii. **Acceptable daily intake of pollutant (ADI)** = 260 μg/day

See Section 3, p. 3-13.

iv. **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).

v. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.0 μg/day
Adult	0.0 μg/day

Since this index evaluates the potential cancer risk associated with direct ingestion of inorganic forms of As in sludge, the As typically ingested in food (which is primarily organic As and is not considered carcinogenic) is not used in the calculation. Instead, a value of zero is substituted.

vi. **Cancer potency** = 15.0 $(mg/kg/day)^{-1}$

The cancer potency was derived based on observation of human skin cancer when As in drinking water was ingested (U.S. EPA, 1984b). An ADI is used to assess food chain exposures to As (see Section 3, p. 3-13) but cancer potency is used for direct ingestion of sludge because carcinogenic inorganic forms of As may be prevalent. (See Section 4, p. 4-4.)

vii. **Cancer risk-specific intake (RSI)** = 4.7×10^{-3} 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:

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

iv. **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).

v. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.0 μg/day
Adult	0.0 μg/day

Since this index evaluates the potential cancer risk associated with direct ingestion of inorganic forms of As in sludge, the As typically ingested in food (which is primarily organic As and is not considered carcinogenic) is not used in the calculation. Instead, a value of zero is substituted.

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vii. **Cancer risk-specific intake (RSI)** = 4.7×10^{-3} 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:

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

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 Increment Resulting from Landfilled Sludge (Index 1)

1. **Explanation** - Calculates groundwater contamination which could occur in a potable aquifer in the landfill vicinity. Uses U.S. EPA 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; the pollutant source is a pulse input; no dilution of the plume occurs by recharge from outside the source area; the leachate is undiluted

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 Increment Resulting from Landfilled Sludge (Index 1)

1. **Explanation** - Calculates groundwater contamination which could occur in a potable aquifer in the landfill vicinity. Uses U.S. EPA 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; the pollutant source is a pulse input; no dilution of the plume occurs by recharge from outside the source area; the leachate is undiluted

ii. **Site parameters**

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

Sikora et al. (1982) monitored several landfills 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 of 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

ii. **Site parameters**

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

Sikora et al. (1982) monitored several landfills 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.

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Typical	5 m
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Eight landfills were monitored throughout the United States and depths to groundwater below them were listed. A typical depth of 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

plume more readily and with less dispersion and therefore represents a reasonable worst case.

(b) Aquifer porosity (∅)

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).

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

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).

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

Typical	100 m
Worst	50 m

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

5. **Value Interpretation** - Value equals factor by which expected groundwater concentration of pollutant at well exceeds the background concentration (a value of 2.0 indicates the concentration is doubled, a value of 1.0 indicates no change).

6. **Preliminary Conclusion** - Landfilling of sludge will generally result in moderate increases in As concentrations in groundwater. However, when the worst landfilling scenario is evaluated, a substantial increase in As contamination may occur.

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 increment resulting from landfilled sludge (Index 1)**

See Section 3, p. 3-29.

b. **Background concentration of pollutant in groundwater (BC)** = 1.0 μg/L

See Section 3, p. 3-26.

c. **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.

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

Daily ingestion of As in food is estimated to average 66.5 μg/day (see Section 3, p. 3-13). However, this As is primarily in organic form and is not considered carcinogenic, whereas the inorganic forms which could enter drinking water may be carcinogenic. Therefore, dietary As is not included in the calculation.

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

5. **Value Interpretation** - Value equals factor by which expected groundwater concentration of pollutant at well exceeds the background concentration (a value of 2.0 indicates the concentration is doubled, a value of 1.0 indicates no change).

6. **Preliminary Conclusion** - Landfilling of sludge will generally result in moderate increases in As concentrations in groundwater. However, when the worst landfilling scenario is evaluated, a substantial increase in As contamination may occur.

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 increment resulting from landfilled sludge (Index 1)**

See Section 3, p. 3-29.

b. **Background concentration of pollutant in groundwater (BC) = 1.0 μg/L**

See Section 3, p. 3-26.

c. **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.

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

Daily ingestion of As in food is estimated to average 66.5 μg/day (see Section 3, p. 3-13). However, this As is primarily in organic form and is not considered carcinogenic, whereas the inorganic forms which could enter drinking water may be carcinogenic. Therefore, dietary As is not included in the calculation.

TABLE 3-1. INDEX OF GROUNDWATER CONCENTRATION INCREMENT 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
<u>Unsaturated Zone</u>								
Soil type and characteristics[d]	T	T	W	NA	T	T	NA	N
Site parameters[e]	T	T	T	W	T	T	W	N
<u>Saturated Zone</u>								
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	1.1	1.6	1.1	1.1	1.7	6.0	120	0
Index 2 Value	53	240	53	53	280	2100	51000	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 (P_{dry}) and volumetric water content (θ).

[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).

TABLE 3-1. INDEX OF GROUNDWATER CONCENTRATION INCREMENT 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	1.1	1.6	1.1	1.1	1.7	6.0	120	0
Index 2 Value	53	240	53	53	280	2100	51000	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 (P_{dry}) and volumetric water content (θ).

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

[f]Aquifer porosity (ϕ) and hydraulic conductivity of the aquifer (K).

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

d. **Fraction of pollutant emitted through stack (FM)**

Typical 0.30 (unitless)
Worst 0.40 (unitless)

Emission estimates may vary considerably between sources; therefore, the values used are based on a U.S. EPA 10-city incineration study (Farrell and Wall, 1981).

e. **Dispersion parameter for estimating maximum annual ground level concentration (DP)**

Typical 3.4 μg/m^3
Worst 16.0 μg/m^3

The dispersion parameter is derived from the U.S. EPA-ISCLT short-stack model.

f. **Background concentration of pollutant in urban air (BA)** = 8.2 x 10^{-3} μg/m^3

The background concentration value reflects the As level in New York City (U.S. EPA, 1983a). Data from the National Air Sampling Network for ambient air levels of As nationally show the median value for 1979 is 5 x 10^{-3} μg/m^3 and 6 x 10^{-3} μg/m^3 for 1978 (U.S. EPA, 1983c). The mean concentrations of As ranged between 2.6 x 10^{-3} and 10.9 x 10^{-3} μg/m^3 for 1977-78. (See Section 4, p. 4-3.)

4. **Index 1 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	1.0	1.4	8.5
	Worst	1.0	1.6	11
Worst	Typical	1.0	2.9	35
	Worst	1.0	3.5	46

[a]The typical (3.4 μg/m^3) and worst (16.0 μg/m^3) dispersion parameters will always correspond, respectively, to the typical (2660 kg/hr DW) and worst (10,000 kg/hr DW) sludge feed rates.

5. **Value Interpretation** - Value equals factor by which expected air concentration exceeds background levels due to incinerator emissions.

d. **Fraction of pollutant emitted through stack (FM)**

Typical 0.30 (unitless)
Worst 0.40 (unitless)

Emission estimates may vary considerably between sources; therefore, the values used are based on a U.S. EPA 10-city incineration study (Farrell and Wall, 1981).

e. **Dispersion parameter for estimating maximum annual ground level concentration (DP)**

Typical 3.4 $\mu g/m^3$
Worst 16.0 $\mu g/m^3$

The dispersion parameter is derived from the U.S. EPA-ISCLT short-stack model.

f. **Background concentration of pollutant in urban air (BA) = 8.2×10^{-3} $\mu g/m^3$**

The background concentration value reflects the As level in New York City (U.S. EPA, 1983a). Data from the National Air Sampling Network for ambient air levels of As nationally show the median value for 1979 is 5×10^{-3} $\mu g/m^3$ and 6×10^{-3} $\mu g/m^3$ for 1978 (U.S. EPA, 1983c). The mean concentrations of As ranged between 2.6×10^{-3} and 10.9×10^{-3} $\mu g/m^3$ for 1977-78. (See Section 4, p. 4-3.)

4. **Index 1 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	1.0	1.4	8.5
	Worst	1.0	1.6	11
Worst	Typical	1.0	2.9	35
	Worst	1.0	3.5	46

[a]The typical (3.4 $\mu g/m^3$) and worst (16.0 $\mu g/m^3$) dispersion parameters will always correspond, respectively, to the typical (2660 kg/hr DW) and worst (10,000 kg/hr DW) sludge feed rates.

5. **Value Interpretation** - Value equals factor by which expected air concentration exceeds background levels due to incinerator emissions.

throughout their lifetime to the stated concentration of the carcinogenic agent. The exposure criterion is calculated using the following formula:

$$EC = \frac{10^{-6} \times 10^{3} \ \mu g/mg \times 70 \ kg}{\text{Cancer potency} \times 20 \ m^{3}/day}$$

4. **Index 2 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	36	51	300
	Worst	36	56	390
Worst	Typical	36	100	1200
	Worst	36	130	1600

[a]The typical (3.4 μg/m^3) and worst (16.0 μg/m^3) dispersion parameters will always correspond, respectively, to the typical (2660 kg/hr DW) and worst (10,000 kg/hr DW) sludge feed rates.

5. **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 kg/hr DW indicates the degree to which any hazard is due to sludge incineration, as opposed to background urban air concentration.

6. **Preliminary Conclusion** - Incineration of sludge is expected to substantially increase the cancer risk due to inhalation of As above the risk posed by background urban air concentrations of As. This increase is particularly evident at the high feed rate of 10,000 kg/hr DW.

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.

throughout their lifetime to the stated concentration of the carcinogenic agent. The exposure criterion is calculated using the following formula:

$$EC = \frac{10^{-6} \times 10^{3}\ \mu g/mg \times 70\ kg}{\text{Cancer potency} \times 20\ m^{3}/day}$$

4. **Index 2 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	36	51	300
	Worst	36	56	390
Worst	Typical	36	100	1200
	Worst	36	130	1600

[a]The typical (3.4 $\mu g/m^3$) and worst (16.0 $\mu g/m^3$) dispersion parameters will always correspond, respectively, to the typical (2660 kg/hr DW) and worst (10,000 kg/hr DW) sludge feed rates.

5. **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 kg/hr DW indicates the degree to which any hazard is due to sludge incineration, as opposed to background urban air concentration.

6. **Preliminary Conclusion** - Incineration of sludge is expected to substantially increase the cancer risk due to inhalation of As above the risk posed by background urban air concentrations of As. This increase is particularly evident at the high feed rate of 10,000 kg/hr DW.

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.

2. **Concentration**

"normal" 0.5 to 14.0 µg/g "treated areas" 1.8 to 830 µg/g	Ratsch, 1974 (p. 6)
"normal" <2.0 µg/g (WW)	Weaver et al., 1984 (p. 133)
"normal" 6 µg/g range 0.1 to 40 µg/g	Allaway, 1978 (p. 240)
Background levels range from <1 to 40 ppm, the latter reflecting agricultural practices as well as air fallout.	U.S. EPA, 1984b (p. 3-20)

C. **Water - Unpolluted**

1. **Frequency of Detection**

5.5% occurrence in 1,577 U.S. surface waters (detection limit = 0.100 µg/L)	Baxter et al., 1983c (p. 25)

2. **Concentration**

a. **Fresh water**

0.005 to 0.336 mg/L range 0.064 mg/L for 87 U.S. surface waters	Baxter et al., 1983c (p. 25)
0.004 mg/L mean value for river water	

b. **Seawater**

0.006 to 0.03 mg/L	Jenkins, 1980a (p. 18)
0.002 to 0.005 mg/L	NAS, 1980 (p. 42)

c. **Drinking water**

0.01 to 0.1 mg/L	Jenkins, 1980a (p. 18)

d. **Groundwater**

<0.001 mg/L for groundwater	Oak Ridge National Laboratory, 1976 (p. 449)

2. **Concentration**

"normal" 0.5 to 14.0 μg/g "treated areas" 1.8 to 830 μg/g	Ratsch, 1974 (p. 6)
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<0.001 mg/L for groundwater	Oak Ridge National Laboratory, 1976 (p. 449)

0.1 to 0.370 μg/g in 1978 total diet study	FDA, no date (Attachment F)
Arsenic Content of Vegetables (ppm of As, Dry Weight):	Pyles and Woolson, 1982 (p. 868)

Vegetable	Normal Levels
broccoli	0.34
beet	<0.1-0.4
cabbage	0.01-0.05
corn	0.01-0.40
green been	0.12
lettuce	0.01-0.2
potato flesh	0.02-2.4
potato peel	0.01
Swiss chard	0.01
tomato	0.01-0.08

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity (Inorganic Arsenic)

a. Qualitative Assessment

Skin cancer and lung cancer have been shown by numerous epidemiologic studies to have an association with arsenic exposure. As has not definitely been found to be a carcinogen in animal studies, however, under the IARC scheme, As would receive a rating of Group 1 indicating sufficient evidence of carcinogens in humans. — U.S. EPA, 1984b (p. 7-148)

b. Potency

Unit risk (at 1 μg As/L) = 4.3×10^{-4}
Cancer potency = 15 $(mg/kg/day)^{-1}$ — U.S. EPA, 1984b (p. 7-149)

c. Effects

Skin tumors — U.S. EPA, 1984b

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c. Effects

Skin tumors	U.S. EPA, 1984b

B. Inhalation

1. Carcinogenicity (Inorganic Arsenic)

a. Qualitative Assessment

There is considerable evidence that inhalation of As is carcinogenic.	U.S. EPA, 1980 (p. C-80)

b. Potency

Cancer potency (for absorbed dose) = 50.1 $(mg/kg/day)^{-1}$ Unit risk (at 1 µg As/m^3) = 4.29×10^{-3}	U.S. EPA, 1984b (p. 7-149)

c. Effects

Lung cancer in humans	U.S. EPA, 1984b (p. 9-5)

2. Chronic Toxicity

a. Inhalation Threshold or MPIH

See below "Existing Regulations"

b. Effects

Peripheral nervous system effects have been cited in occupationally exposed workers.	U.S. EPA, 1983c (p. 2-19)

3. Absorption Factor

Net absorption of 30% or greater	U.S. EPA, 1984b (p. 2-6, 7-133)

4. Existing Regulations

10 mg/m^3 (TWA)	OSHA	Center for Disease Control, 1983 (p. 7-S)
2 mg/m^3 ceiling (15 min.)	NIOSH	
0.05 mg/m^3 (TWA)		ACGIH, 1977

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Root growth of lemon plants grown in solution culture was enhanced by 1 ppm As as arsenate or arsenite; 5 ppm of either form of As was toxic and adversely affected both top and root growth.	Liebig et al., 1959, in Walsh and Keeney, 1975

See Table 4-1.

2. **Tissue concentration causing phytotoxicity**

30-140 μg/g As (DW) in bermuda grass roots associated with yield reduction	Weaver et al., 1984 (p. 137)
50 μg/g As (DW) in bermuda grass leaves and stems	Weaver et al., 1984 (p. 138)
>4.4 μg/g (DW) in cotton, yield limiting concentration	Deuel and Swoboda, 1972 (p. 317)
>1 μg/g (DW) in soybeans, yield limiting concentration	
2.1-8.2 μg/g in peach tree leaves exhibiting As injury symptoms (0.9-1.1 μg/g normal concentration	Lindner and Reeves, 1942, in NAS, 1977 (p. 121)

See Table 4-1.

B. **Uptake**

See Table 4-2.

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. **Toxicity**

See Table 4-3.

B. **Uptake**

1. **Normal range of tissue concentrations**

Normal animals usually have a background As concentration in kidney and liver tissues of <0.5 μg/g.	Buck, 1978 (p. 366)
Osprey, μg/g (WW) liver - <1.5 Chickens, μg/g (WW) control diet liver - 0.10 average kidney - 0.05 average	Wiemeyer et al., 1980 (p. 164)

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Osprey, μg/g (WW) liver - <1.5 Chickens, μg/g (WW) control diet liver - 0.10 average kidney - 0.05 average	Wiemeyer et al., 1980 (p. 164)

27 µg/g (DW) in liver of cattle fed 30 mg As per day for 7 days	NAS, 1980 (p. 45)

3. **Bioconcentration factor for tissue concentration versus feed concentration**

See Table 4-4.

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. **Freshwater**

Data not immediately available.

2. **Saltwater**

Four-day average concentration should not exceed 36 µg/L more than once every three years on the average.

B. Uptake

Data not immediately available.

VI. SOIL BIOTA EFFECTS

Data not immediately available.

VII. PHYSICOCHEMICAL DATA

Atomic weight = 74.92 g/mole Melting point = 817°C at 28 mm Hg Boiling point = Sublimes at 613°C	Handbook of Chemistry and Physics, 1976 (p. B-91)

Essentially insoluble in water.

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Essentially insoluble in water.

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (μg/g DW)	Experimental Soil Concentration (μg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (μg/g DW)	Effect	References
Green bean, lima bean, spinach, cabbage, tomatoes, radishes	Na_2HAsO_4	6.2	NR	500	--	NR	No growth at 10, 50, 100 μg/g, at 500 μg/g growth inversely proportional to soil conc.; As less phytotoxic at soil pH 5.5	NAS, 1977 (p. 122)
Apple/seedling	Na_2HAsO_4	NR	NR	50-100	--	NR	Growth reduced 50%	Ratsch, 1974 (p. 6)
Apple/seedling	Na_2HAsO_4	NR	NR	100-150	--	NR	Little growth	
Apple/seedling	Na_2HAsO_4	NR	NR	>150	--	NR	Killed seedlings	
Cotton/plant	As_2O_3	culture solution	NR	8	--	81	Wilted leaf/curly margins	Marcus-Wyner and Rains, 1982 (p. 716)
Cotton/root	As_2O_3	culture solution	NR	8	--	352	Stubby roots/brown tips	
Bermuda grass/plant	As_2O_3	4.7-7.7	2.7	90	--	--	Prevented growth	Weaver et al., 1984 (p. 135)
Bermuda grass/root	As_2O_3	4.7-7.7	2.7	45	--	440	75% growth	
Bermuda grass/root	As_2O_3	4.7-7.7	2.7	10	--	140	No effect	
Bermuda grass/stem	As_2O_3	4.7-7.7	3	45	--	20-45	75% growth reduction	
Bermuda grass/leaf	As_2O_3	4.7-7.7	2	45	--	20	Growth reduction	

[a]NR=Not reported.
[b]Water soluble as in parts per million in soil.

TABLE 4-1. *(continued)*

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (μg/g DW)	Experimental Soil Concentration (μg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (μg/g DW)	Effect	References
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Bermuda grass/stem	As_2O_3	4.7-7.7	3	45	--	20-45	75% growth reduction	
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[a]NR=Not reported.
[b]Water soluble as in parts per million in soil.

Table 4-3. TOXICITY OF ARSENIC TO DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Feed Concentration (μg/g)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration	Effects	References
Most animals	Inorganic As	50	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 46)
Most animals	Organic As	100	--	--	Daily	Maximum tolerable level	
Most animal species	Sodium arsenite	--	-	1-25	NR[b]	LD_{50}	Buck, 1978 (p. 359)
Swine	Sodium arsenite	500	--	--	2 weeks	No sign of acute arsenic poisoning	
Swine	Sodium arsenite	--	1,000	100-200	few hours	Death/severe poisoning	
Dog	Sodium thiacetarsamide	--	--	1.6	2 days	Used to treat heartworms	Buck, 1978 (p. 360)
Dog	Sodium thiacetarsamide	27	--	0.9	1 day	No effect	
Dog	As	--	--	1.8	5 days	Lethal	
Cattle	MSMA[c]	--	--	5	10 days	No effect	
Cattle	MSMA	--	--	10	5 days	Lethal	
Cattle	DSMA	--	--	10	10 days	No effect	
Cattle	DSMA	--	--	25	5 days	Lethal	
Sheep	MSMA	--	--	25	10 days	No effect	
Sheep	MSMA	--	--	50	6 days	Lethal	
Sheep	DSMA	--	--	10	10 days	No effect	
Sheep	DSMA	--	--	25	6 dyas	Lethal	
Chicken	MSMA/DSMA	--	--	250	10 days	No effect	Buck, 1978 (p. 361)
Swine/Poultry	Arsanilic acid/ sodium arsanilite	50-100	--	--	lifetime	Recommended for increased feed efficiency	Ledet and Buck, 1978 (p. 376)
Swine	Arsanilic acid/ sodium arsanilite	1,000	--	--	18 days	Severe poisoning	Ledet and Buck, 1978 (p. 379)

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Sheep	MSMA	--	--	25	10 days	No effect	
Sheep	MSMA	--	--	50	6 days	Lethal	
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TABLE 4-4. UPTAKE OF ARSENIC BY DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Range (and N)[a] of Feed Concentration (μg/g DW)	Tissue Analyzed	Control Tissue Concentration (μg/g DW)	Uptake[b] Slope	References
Guinea Pig (6)	Swiss chard grown on sludge	0.47-0.66 (2)	liver	0.06	0.37	Furr et al., 1976a (p. 87-88)
Guinea Pig (6)	Swiss chard grown on sludge	0.47-0.66 (2)	kidney	0.01	0.16	
Guinea Pig (6)	Swiss chard grown on sludge	0.47-0.66 (2)	muscle	0.06	0.32	
Swine (3)	Arsanilic acid (35% As)	350 (2)	kidney	<.087[c]	0.20[c]	Ledet and Buck, 1978 (p. 382)
Swine (3)	Arsanilic acid (35% As)	350 (2)	liver	<.067[c]	0.10[c]	
Swine (3)	Arsanilic acid (35% As)	350 (2)	muscle	<.071[c]	0.012[c]	
Chicken	3-Nitro-4-Hydroxy-Phenylarsonic acid (28% As)	0-14 (2)	kidney	0.22[c]	0.27[c]	NAS, 1977 (p. 156)
Chicken	3-Nitro-4-Hydroxy-Phenylarsonic acid (28% As)	0-14 (2)	liver	0.27[c]	0.56[c]	
Chicken	3-Nitro-4-Hydroxy-Phenylarsonic acid (28% As)	0-14 (2)	muscle	0.071[c]	0.013[c]	
Cowbird (2)	Copper aceto arsenite	25-225	liver	NR[d]	0.19	Wiemeyer et al., 1980 (p. 164)

[a] N = Number of feed rates or animals studied, when reported.
[b] Slope = y/x; y = tissue concentration (μg/g); x = feed concentration (μg/g).
[c] When tissue values were reported as wet weight, unless otherwise indicated a moisture content of 77% was assumed for kidney, 70% for liver, and 72% for muscle.
[d] NR = not reported.

TABLE 4-4. UPTAKE OF ARSENIC BY DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Range (and N)[a] of Feed Concentration (µg/g DW)	Tissue Analyzed	Control Tissue Concentration (µg/g DW)	Uptake[b] Slope	References
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APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR ARSENIC IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Arsenic

1. Index of Soil Concentration Increment (Index 1)

a. **Formula**

$$\text{Index 1} = \frac{(SC \times AR) + (BS \times MS)}{BS\ (AR + MS)}$$

where:

SC = Sludge concentration of pollutant (μg/g DW)
AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
MS = 2000 mt DW/ha = Assumed mass of soil in upper 15 cm

b. **Sample calculation**

$$0.999418 = \frac{(4.6\ \mu g/g\ DW \times 5\ mt/ha) + (6.0\ \mu g/g\ DW \times 2000\ mt/ha)}{6.0\ \mu g/g\ DW\ (5\ mt/ha + 2000\ mt/ha)}$$

B. Effect on Soil Biota and Predators of Soil Biota

1. Index of Soil Biota Toxicity (Index 2)

a. **Formula**

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

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in 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

$$\text{Index 3} = \frac{(I_1 - 1)(BS \times UB) + BB}{TR}$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
UB = Uptake slope of pollutant in soil biota (μg/g tissue DW [μg/g soil DW]$^{-1}$)
BB = Background concentration in soil biota (μg/g DW)
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 Phytotoxicity (Index 4)

a. Formula

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

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
TP = Soil concentration toxic to plants (μg/g DW)

b. Sample calculation

$$0.133255749\text{5} = \frac{0.999418 \times 6.0\ \mu g/g\ DW}{45.0\ \mu g/g\ DW}$$

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

a. **Formula**

$$\text{Index 5} = \frac{(I_1 - 1) \times BS}{BP} \times CO \times UP + 1$$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
CO = 2 kg/ha $(\mu g/g)^{-1}$ = Conversion factor between soil concentration and application rate
UP = Uptake slope of pollutant in plant tissue (μg/g tissue DW $[kg/ha]^{-1}$)
BP = Background concentration in plant tissue (μg/g DW)

b. **Sample calculation**

$$0.985162 = \frac{(0.999418-1) \times 6.0\ \mu g/g\ DW}{0.16\ \mu g/g\ DW} \times \frac{2\ kg/ha}{\mu g/g\ soil}$$

$$\times \frac{0.34\ \mu g/g\ tissue}{kg/ha} + 1$$

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

a. **Formula**

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

where:

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

b. **Sample calculation**

$$20 = \frac{1\ \mu g/g\ DW}{0.05\ \mu g/g\ DW}$$

C. Effect on Herbivorous Animals

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

a. Formula

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

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. Sample calculation

$$0.000366 = \frac{0.985162 \times 0.37\ \mu g/g\ DW}{1000\ \mu g/g\ DW}$$

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

a. Formula

$$\text{If } AR = 0, \quad I_8 = \frac{BS \times GS}{TA}$$

$$\text{If } AR \neq 0, \quad I_8 = \frac{SC \times GS}{TA}$$

where:

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

b. Sample calculation

$$\text{If } AR = 0, \quad 0.0003 = \frac{6\ \mu g/g\ DW \times 0.05}{1000\ \mu g/g\ DW}$$

$$\text{If } AR \neq 0, \quad 0.00023 = \frac{4.6\ \mu g/g\ DW \times 0.05}{1000\ \mu g/g\ DW}$$

E. Effect on Humans

1. Index of Human Toxicity Resulting from Plant Consumption (Index 9)

a. Formula

$$\text{Index 9} = \frac{[(I_5 - 1)\ BP \times DT] + DI}{ADI}$$

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (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)
ADI = Acceptable daily intake of pollutant (μg/day)

b. Sample calculation (toddler)

$$0.084319 = \frac{[(0.985162 - 1) \times 0.16\ \mu g/g\ DW \times 74.5\ g/day] + 22.1\ \mu g/day}{260\ \mu g/day}$$

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

a. Formula

$$\text{Index 10} = \frac{[(I_5 - 1)\ BP \times UA \times DA] + DI}{ADI}$$

where:

I_5 = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
UA = Uptake slope 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)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

0.084992 =

$$\frac{(0.985162-1) \times 0.37\ \mu g/g\ DW \times 0.56\ \mu g/g\ tissue[\mu g/g\ feed]^{-1} \times 0.97\ g/day] + 22.1\ \mu g/day}{260\ \mu g/day}$$

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

a. **Formula**

If AR ≠ 0, $\text{Index 11} = \frac{(SC \times GS \times UA \times DA) + DI}{ADI}$

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 (unitless)
UA = Uptake slope of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW^{-1}])
DA = Average daily human dietary intake of affected animal tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

0.085480 =

$$\frac{(4.6\ \mu g/g\ DW \times 0.05 \times 0.56\ \mu g/g\ tissue\ [\mu g/g\ feed]^{-1} \times 0.97\ g/day\ DW) + 22.1\ \mu g/day}{260\ \mu g/day}$$

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

a. **Formula**

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

Pure sludge ingestion: $\text{Index 12} = \frac{(SC \times DS) + DI}{RSI}$

where:

I_1 = Index 1 = Index of soil concentration increment (unitless)
SC = Sludge concentration of pollutant (μg/g DW)
BS = Background concentration of pollutant in soil (μg/g DW)
DS = Assumed amount of soil in human diet (g/day)
DI = Average daily dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. Sample calculation (toddler)

$$6379.26460 = \frac{(0.999418 \times 6.0\ \mu g/g\ DW \times 5\ g\ soil/day)}{0.0047\ \mu g/day}$$

Pure sludge:

$$4893.617 = \frac{(4.6\ \mu g/g\ DW \times 5\ g\ soil/day)}{0.0047\ \mu g/day}$$

5. Index of Aggregate Human Toxicity or Cancer Risk (Index 13)

a. Formula

$$\text{Index 13} = I_9 + I_{10} + I_{11} + I_{12} - \frac{3DI}{ADI\ or\ RSI}$$

where:

I_9 = Index 9 = Index of human toxicity resulting from plant consumption (unitless)
I_{10} = Index 10 = Index of human toxicity resulting from consumption of animal products derived from animals feeding on plants (unitless)
I_{11} = Index 11 = Index of human toxicity 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 dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated because of the combination of ADI and RSI usage earlier in the text.

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, 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

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

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

where:

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

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

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

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

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^* = α x 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)

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

P_{dry} = Dry bulk density (g/mL)
K_d = Soil sorption 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)
χ = $\Delta \ell$ = Distance from well to landfill (m)
D^* = α x V^* (m^2/year)
α = Dispersivity coefficient (m)

$$V^* = \frac{K \times i}{\phi \times R} \text{ (m/year)}$$

K = Hydraulic conductivity of the aquifer (m/day)
i = Average hydraulic gradient between landfill and well (unitless)
ϕ = Aquifer porosity (unitless)

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

since K_d is assumed to be zero for the saturated zone

C. Equation 2. Linkage Assessment

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

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)
Ø = Aquifer porosity (unitless)
B = Thickness of saturated zone (m) where:

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

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:

$$t_o = [\int_0^\infty C\,dt] \div C_u$$

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

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

1. **Formula**

$$\text{Index 1} = \frac{C_{max} + BC}{BC}$$

where:

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

2. **Sample Calculation**

$$1.1250807 = \frac{0.12508066\ \mu g/L + 1.0\ \mu g/L}{1.0\ \mu g/L}$$

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

1. **Formula**

$$\text{Index 2} = \frac{[(I_1 - 1)\ BC \times AC]\ + DI}{RSI}$$

where:

I_1 = Index 1 = Index of groundwater concentration increment resulting from landfilled sludge
BC = Background concentration of pollutant in groundwater (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 not known)**

$$53.225812 = \frac{[(1.1250807 - 1) \times 1.0\ \mu g/L \times 2\ L/day]}{0.0047\ \mu g/day}$$

III. INCINERATION

A. **Index of Air Concentration Increment Resulting from Incinerator Emissions (Index 1)**

1. **Formula**

$$\text{Index 1} = \frac{(C \times DS \times SC \times FM \times DP) + BA}{BA}$$

where:

C = Coefficient to correct for mass and time units (hr/sec x g/mg)
DS = Sludge feed rate (kg/hr DW)
SC = Sludge concentration of pollutant (mg/kg DW)
FM = Fraction of pollutant emitted through stack (unitless)
DP = Dispersion parameter for estimating maximum annual ground level concentration ($\mu g/m^3$)
BA = Background concentration of pollutant in urban air ($\mu g/m^3$)

2. **Sample Calculation**

$$1.423126 = [(2.78 \times 10^{-7} \text{ hr/sec} \times \text{g/mg} \times 2660 \text{ kg/hr DW} \times 4.6 \text{ mg/kg DW} \times 0.30 \times 3.4 \ \mu\text{g/m}^3) + 0.0082 \ \mu\text{g/m}^3] \div 0.0082 \ \mu\text{g/m}^3$$

B. **Index of Human Cancer Risk Resulting from Inhalation of Incinerator Emissions (Index 2)**

1. **Formula**

$$\text{Index 2} = \frac{[(I_1 - 1) \times BA] + BA}{EC}$$

where:

I_1 = Index 1 = Index of air concentration increment resulting from incinerator emissions (unitless)
BA = Background concentration of pollutant in urban air ($\mu g/m^3$)
EC = Exposure criterion ($\mu g/m^3$)

2. **Sample Calculation**

$$50.7375659 = \frac{[(1.423126 - 1) \times 0.0082 \ \mu\text{g/m}^3] + 0.0082 \ \mu\text{g/m}^3}{0.00023 \ \mu\text{g/m}^3}$$

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)	4.6	20.77	4.6	4.6	4.6	4.6	20.77	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
Soil sorption coefficient, K_d (mL/g)	19.4	19.4	5.86	NA	19.4	19.4	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, ϕ (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)	1150	5190	1150	1150	1150	1150	5190	N
Peak concentration, C_u (μg/L)	34.3	155	89.7	1150	34.3	34.3	5190	N
Pulse duration, t_o (years)	168	168	64.1	5.00	168	168	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)	34.3	155	89.7	1150	34.3	34.3	5190	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (μg/L)	0.125	0.565	0.125	0.125	0.665	4.95	120	N
Index of groundwater concentration increment resulting from landfilled sludge, Index 1 (unitless) (Equation 4)	1.12	1.57	1.12	1.12	1.66	5.95	121	0
Index of human cancer risk resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	53.2	240	53.2	53.2	283	2110	51100	0

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