United States Environmental Protection Agency
Office of Water Regulations and Standards Washington, DC 20460

Water June, 1985

EPA

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

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.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

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. Cadmium (Cd) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing), placed in a landfill, incinerated or ocean disposed.* This profile is a compilation of information that may be useful in determining whether Cd 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, landfilling, incineration and ocean disposal 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.

---

* 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 CADMIUM 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 Cadmium

The concentration of Cd in sludge-amended soil is expected to increase as the concentration of Cd in sludge and the sludge application rate increase (see Index 1).

B. Effect on Soil Biota and Predators of Soil Biota

The toxicity of Cd in sludge-amended soil to soil biota could not be evaluated due to lack of data (see Index 2).

Landspreading of sludge may increase the toxic hazard due to Cd for predators of soil biota above the pre-existing toxic hazard due to background concentrations of Cd in soil. This increase may be substantial when sludge containing a high concentration of Cd is applied at a high cumulative rate (see Index 3).

C. Effect on Plants and Plant Tissue Concentration

A phytotoxic hazard may exist only when sludges containing the worst-case Cd concentration are applied to soil at the highest cumulative rate (500 mt/ha) (see Index 4).

Except when typical sludge is applied at a low rate (5 mt/ha), the concentration of Cd in plants consumed by animals and humans is expected to increase as the concentration of Cd in sludge and the application rate increase (see Index 5).

The increases in the concentration of Cd in crop plants which are expected to occur as a result of amending soil with sludge are sufficiently low to permit survival of the plants, although growth may be reduced (see Index 6).

D. Effect on Herbivorous Animals

Animals which feed upon plants grown in sludge-amended soil are not threatened by a toxic hazard due to Cd in plant tissues (see Index 7). A toxic hazard due to Cd is not expected for grazing animals which incidentally ingest sludge-amended soil (see Index 8).

E. **Effect on Humans**

For toddlers, a health threat due to Cd in crop plants is expected only when typical sludge is applied to soil at the highest cumulative rate (500 mt/ha) and when the worst sludge is applied at 50 mt/ha or greater. For adults, Cd in plants grown in sludge-amended soil is a health threat except when typical sludge is applied at the lowest rate (see Index 9).

A human health threat due to Cd in animal products derived from animals which had been fed plants grown on sludge-amended soil is expected only for adults when sludge is applied at the highest cumulative rate (500 mt/ha) (see Index 10).

A human health threat due to Cd in animal products derived from animals which had incidentally ingested sludge-amended soil is expected only for adults when sludge with a high concentration of Cd is applied (see Index 11).

A human health threat due to Cd in sludge-amended soil which is ingested directly is expected only for toddlers when sludge is applied at a high cumulative rate (500 mt/ha) and when pure sludge is ingested (see Index 12).

An aggregate threat of Cd toxicity to humans is expected when sludge with a typical concentration of Cd is applied to soils at the rate of 50 mt/ha or greater. When sludges with a high concentration of Cd are applied, a human health threat due to Cd is expected at all application rates (see Index 13).

II. LANDFILLING

The groundwater concentration of Cd at the well is expected to increase, especially when the worst-case sludge is landfilled, or when worst-case conditions prevail in the saturated zone or both unsaturated and saturated zones (see Index 1). A human health threat due to Cd in groundwater is expected only when worst-case conditions prevail for all conditions (see Index 2).

III. INCINERATION

Concentrations of Cd in air are expected to substantially increase above the background concentration when sludge is incinerated (see Index 1). The increased air concentrations of Cd resulting from sludge incineration are expected to substantially increase the human cancer risk due to inhalation of Cd above the risk posed by background urban air concentrations of Cd (see Index 2).

IV. OCEAN DISPOSAL

Increases .in the seawater concentration of Cd occur in all the scenarios evaluated. The highest increases occur when sludge containing worst concentrations of Cd are dumped at the typical and worst sites (see Index 1).

Increases of Cd concentrations occur in all cases with the largest increases being evident when sludges containing worst concentrations are dumped at the worst site (see Index 2).

A toxic condition may not exist for aquatic organisms at the site. However, incremental increases due to sludge dumping is evident in all of the scenarios evaluated (see Index 3).

No increase of human health risk is apparent from the typical intake of seafood residing at the typical and worst sites after disposal of sludges with typical concentrations of Cd. Moderate increases of risk were seen only when the site conditions, sludge concentration, and seafood intake were assigned worst-case values (see Index 4).

SECTION 3

PRELIMINARY HAZARD INDICES FOR CADMIUM IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Cadmium

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	8.15 µg/g DW
Worst	88.13 µg/g DW

The typical and worst sludge concentrations are the median and 95th percentile values statistically derived from sludge concentration data from a survey of 40 publicly-owned treatment works (POTWs) (U.S. EPA, 1982). (See Section 4, p. 4-1.)

ii. **Background concentration of pollutant in soil (BS) = 0.2 μg/g DW**

The mean background soil level in 3001 field samples across the United States was 0.27 ppm, while the median was 0.20 ppm (Holmgren, 1985). The value of 0.2 ppm was selected as representative for this analysis. (See Section 4, p. 4-1.)

d. **Index 1 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	1	1.1	2.0	9.0
Worst	1	2.1	12	89

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds background when sludge is applied. (A value of 2 indicates concentration is doubled; a value of 0.5 indicates reduction by one-half.)

f. **Preliminary Conclusion** - The concentration of Cd in sludge-amended soil is expected to increase as the concentration of Cd in sludge and the sludge application rate increase.

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

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 0.2 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)** = 0.2 μg/g DW

See Section 3, p. 3-2.

iii. **Uptake slope of pollutant in soil biota (UB)** = 13.7 μg/g tissue DW (μg/g soil DW)$^{-1}$

The uptake slope is the highest value available for earthworms and represents the worst case. The uptake slope was calculated from data in Beyer et al. (1982). (See Section 4, p. 4-19.)

iv. **Background concentration in soil biota (BB) = 4.8 μg/g DW**

The value selected is the geometric mean based on whole body analyses of earthworms from four sites (Beyer et al., 1982). This particular value was selected because it was obtained for earthworms from a relatively large sample size (24 plots) of representative agricultural soils. (See Section 4, p. 4-19.)

v. **Feed concentration toxic to predator (TR) = 3 μg/g DW**

Among soil biota predators, chickens appear to be one of the more sensitive species to Cd. The value selected represents the lowest concentration at which undesirable effects, e.g., decreased egg production, occur (Leach et al., 1979). (See Section 4, p. 4-15.)

d. **Index 3 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	1.6	1.7	2.5	8.9
Worst	1.6	2.6	11	82

e. **Value Interpretation** - Value 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** - Landspreading of sludge may increase the toxic hazard due to Cd for predators of soil biota above the pre-existing toxic hazard posed by background concentrations of Cd in soil. This increase may be substantial when sludge containing a high concentration of Cd is applied at a high cumulative rate.

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

1. **Index of Phytotoxicity (Index 4)**

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

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

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 0.2 μg/g DW

See Section 3, p. 3-2.

iii. **Soil concentration toxic to plants (TP)** = 2.5 μg/g DW

This value is the lowest, most conservative, concentration associated with considerable reductions in yields for lettuce (40 percent) and moderate reductions in growth for wheat (21 percent) and soybeans (10 percent) (Haghiri, 1973). (See Section 4, p. 4-8.)

d. **Index 4 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.080	0.088	0.16	0.72
Worst	0.080	0.17	0.94	7.1

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

f. **Preliminary Conclusion** - A phytotoxic hazard may exist only when sludges containing the worst-case Cd concentration are applied to soil at the highest cumulative rate (500 mt/ha).

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.

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) = 0.2 μg/g DW**

See Section 3, p. 3-2.

iii. **Conversion factor between soil concentration and application rate (CO) = 2 kg/ha $(\mu g/g)^{-1}$**

Assumes pollutant is distributed and retained within upper 15 cm of soil (i.e. plow layer) which has an approximate mass (dry matter) of 2×10^3.

iv. **Uptake slope of pollutant in plant tissue (UP)**

Animal diet:
Field corn 0.14 μg/g tissue DW $(kg/ha)^{-1}$

Human diet:
Swiss chard 0.85 μg/g tissue DW $(kg/ha)^{-1}$

The uptake rate for Swiss chard represents the plant consumed by humans (Council for Agricultural Science and Technology (CAST), 1980). The uptake rate for field corn (silage) was selected because it represents the highest worst-case value available for a common animal feed (Telford et al., 1982). Although uptake slopes one or two orders of magnitude greater have been calculated (see Section 4, pp. 4-13 and 4-14), they were not selected because they were obtained for plant parts in a form not usually fed to animals or had sludge applied over the growing plant, thus biasing the uptake rate.

v. **Background concentration in plant tissue (BP)**

Animal diet:
Field corn 0.29 μg/g DW

Human diet:
Swiss chard 0.87 μg/g DW

Background concentrations of Cd in Swiss chard and field corn were reported in the same studies which provided the uptake slopes. (See Section 4, pp. 4-13 and 4-14.)

d. **Index 5 Values**

Diet	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Animal	Typical	1.0	1.0	1.2	2.5
	Worst	1.0	1.2	3.1	18
Human	Typical	1.0	1.0	1.4	4.1
	Worst	1.0	1.4	5.2	35

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** - Except when typical sludge is applied at a low rate (5 mt/ha), the concentration of Cd in plants consumed by animals and humans is expected to increase as the concentration of Cd in sludge and the application rate increase.

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:
Corn 78.4 μg/g DW

Human diet:
Swiss chard 153 μg/g DW

The concentrations selected for Swiss chard and corn were associated with at least 25 percent reductions in growth (Mahler et al., 1980) and are taken to be the threshold concentrations at which adverse effects would be observed. (See Section 4, p. 4-11.)

ii. **Background concentration in plant tissue (BP)**

Animal diet:
Corn 0.46 µg/g DW

Human diet:
Swiss chard 1.25 µg/g DW

The values given were the concentrations observed in plant tissue for the same set of experiments (Mahler et al., 1980) from which the phytotoxic concentrations (PP) were taken. (See Section 4, p. 4-11.)

d. **Index 6 Values**

Plant	Index Value
Corn	170
Swiss chard	120

e. **Value Interpretation** - Value gives the maximum factor of tissue concentration increment (above background) which is permitted by phytotoxicity. Value is compared with values for the same or similar plant tissues given by Index 5. The lowest of the two indices indicates the maximal increase which can occur at any given application rate.

f. **Preliminary Conclusion** - The increases in the concentration of Cd in crop plants which are expected to occur as a result of amending soil with sludge are sufficiently low to permit survival of the plants, although growth may be reduced.

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) = 0.29 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) = 5 μg/g DW**

The value given is the lowest available at which deleterious effects have been seen in sheep, which are taken to be representative of herbivores (Doyle et al., 1974; Doyle and Pfander, 1975). (See Section 4, p. 4-15.)

d. **Index 7 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.058	0.059	0.069	0.15
Worst	0.058	0.070	0.18	1.0

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** - Animals which feed upon plants grown in sludge-amended soil are not threatened by a toxic hazard due to Cd in plant tissues.

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	8.15 μg/g DW
Worst	88.13 μg/g DW

See Section 3, p. 3-1.

ii. **Background concentration of pollutant in soil (BS)** = 0.2 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)** = 5 μg/g DW

See Section 3, p. 3-9.

d. **Index 8 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.0020	0.082	0.082	0.082
Worst	0.0020	0.88	0.88	0.88

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** - A toxic hazard due to Cd is not expected for grazing animals which incidentally ingest sludge-amended soil.

E. **Effect on Humans**

1. **Index of Human Toxicity 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 acceptable daily intake (ADI) 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 as the most responsive plant(s) (as chosen in Index 5). 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 a human diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.87 µg/g DW**

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

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 (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 estimated dry-weight consumption of all non-fruit crops.

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

Toddler	10.9 µg/day
Adult	34.3 µg/day

The values given are the means of the average levels of Cd consumed during FY75 to FY77 and FY74 to FY77 by toddlers (FDA, 1980a) and adults (FDA, 1980b), respectively. (See Section 4, p. 4-3.)

v. **Acceptable daily intake of pollutant (ADI) = 64 µg/day**

The Food and Agriculture Organization/World Health Organization (FAO/WHO) (1972) proposed the provisional tolerable, total daily intake of Cd to be in the range of 57 to 71 µg/day. Thus, the value selected is the midpoint of the provisional range and represents the value most likely to be generally applicable. (See Section 4, p. 4-4.)

d. **Index 9 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.17	0.21	0.55	3.3
	Worst	0.17	0.60	4.4	35
Adult	Typical	0.54	0.64	1.6	9.2
	Worst	0.54	1.7	12	96

e. **Value Interpretation** - Value equals factor by which expected intake exceeds ADI. Value > 1 indicates a possible human health threat. 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** - For toddlers, a health threat due to Cd in crop plants is expected only when typical sludge is applied to soil at the highest cumulative rate (500 mt/ha) and when the worst sludge is applied at 50 mt/ha or greater. For adults, Cd in plants grown in sludge-amended soil is a health threat except when typical sludge is applied at the lowest rate.

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

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

b. **Assumptions/Limitations** - Assumes that all animal products are from animals receiving all their feed from sludge-amended soil. The uptake slope of 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) = 0.29 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) = 5.5 μg/g tissue DW (μg/g feed DW)$^{-1}$**

Data for several animal species show that Cd is accumulated in tissues of kidney and liver, but not in muscle to any significant degree (see Section 4, pp. 4-17 and 4-18). Uptake slopes for kidney tend to exceed those for liver, but the kidney values were not used because very little kidney is consumed in the United States. Among data for liver, slopes (wet-weight tissue basis) for cattle and swine were lower with a range of 0.05 to 0.135 μg/g tissue WW (μg/g feed DW)$^{-1}$, and slopes for sheep and chicken were higher with a range of 0.2 to 1.65 μg/g tissue WW (μg/g feed DW)$^{-1}$. The highest uptake slope for liver was observed in chicken (Sharma et al., 1979), and was obtained using a metal salt ($CdCl_2$), rather than sludge or a sludge-grown plant, in the diet. However, the high slope cannot be attributed to the use of metal salt alone, since studies in sheep gave similar uptake slopes for liver whether $CdCl_2$ or sludge-grown corn silage was used. Therefore, the highest value for liver is considered valid and will be used to represent all liver in the human diet. The values in Table 4-4 are reported on a wet-weight tissue basis; division by 0.30 gives a dry-weight value of 5.5 μg/g tissue DW (μg/g feed DW)$^{-1}$.

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 freshweight 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 U.S. Department of Agriculture (1975). Thus, the values above for toddlers and adults were obtained by multiplying 2.2 and 13.2 g/day FW by 44 percent, respectively, in order to convert to dry weight.

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

Toddler 10.9 μg/day
Adult 34.3 μg/day

See Section 3, p. 3-12.

vi. **Acceptable daily intake of pollutant (ADI) = 64 μg/day**

See Section 3, p. 3-12.

d. **Index 10 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.17	0.17	0.17	0.21
	Worst	0.17	0.18	0.22	0.58
Adult	Typical	0.54	0.54	0.56	0.76
	Worst	0.54	0.57	0.83	3.0

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

f. **Preliminary Conclusion** - A human health threat due to Cd in animal products derived from animals which had been fed plants grown on sludge-amended soil is expected only for adults when sludge is applied at the highest cumulative rate (500 mt/ha).

3. **Index of Human Toxicity 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 ADI.

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 three years old.

c. **Data Used and Rationale**

i. **Animal tissue** = Chicken liver

See Section 3, p. 3-14.

ii. **Background concentration of pollutant in soil (BS)** = 0.2 μg/g DW

See Section 3, p. 3-2.

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

Typical	8.15 μg/g DW
Worst	88.13 μg/g DW

See Section 3, p. 3-1.

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

See Section 3, p. 3-10.

v. **Uptake slope of pollutant in animal tissue (UA)** = 5.5 μg/g tissue DW (μg/g feed DW)$^{-1}$

See Section 3, p. 3-14.

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

Toddler	0.97 g/day
Adult	5.76 g/day

See Section 3, p. 3-14.

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

Toddler	10.9 μg/day
Adult	34.3 μg/day

See Section 3, p. 3-12.

viii. **Acceptable daily intake of pollutant (ADI)** = 64 μg/day

See Section 3, p. 3-12.

d. **Index 11 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.17	0.20	0.20	0.20
	Worst	0.17	0.54	0.54	0.54
Adult	Typical	0.54	0.74	0.74	0.74
	Worst	0.54	2.7	2.7	2.7

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

f. **Preliminary Conclusion** - A human health threat due to Cd in animal products derived from animals which had incidentally ingested sludge-amended soil is expected only for adults when sludge with a high concentration of Cd is applied.

4. **Index of Human Toxicity from Soil Ingestion (Index 12)**

a. **Explanation** - Calculates the amount of pollutant in the diet of a child who ingests soil (pica child) amended with sludge. Compares this amount with ADI.

b. **Assumptions/Limitations** - Assumes that the pica child consumes an average of 5 g/day of sludge-amended soil. If an ADI specific for a child is not available, this index assumes that the ADI for a 10 kg child is the same as that for a 70 kg adult. It is thus assumed that uncertainty factors used in deriving the ADI provide protection for the child, taking into account the smaller body size and any other differences in sensitivity.

c. **Data Used and Rationale**

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

See Section 3, p. 3-2.

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

Typical	8.15 μg/g DW
Worst	88.13 μg/g DW

See Section 3, p. 3-1.

iii. **Background concentration of pollutant in soil (BS) = 0.2 μg/g DW**

See Section 3, p. 3-2.

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	10.9 μg/day
Adult	34.3 μg/day

See Section 3, p. 3-12.

vi. **Acceptable daily intake of pollutant (ADI) = 64 μg/day**

See Section 3, p. 3-12.

d. **Index 12 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500	Pure Sludge
Toddler	Typical	0.19	0.19	0.20	0.31	0.81
	Worst	0.19	0.20	0.35	1.6	7.1
Adult	Typical	0.54	0.54	0.54	0.54	0.54
	Worst	0.54	0.54	0.54	0.54	0.56

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

f. **Preliminary Conclusion** - A human health threat due to Cd in sludge-amended soil which is ingested directly is expected for toddlers only when sludge is applied at a high cumulative rate (500 mt/ha) and when pure sludge is ingested.

5. **Index of Aggregate Human Toxicity (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 ADI.

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**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.19	0.26	0.62	3.5
	Worst	0.19	1.0	5.0	37
Adult	Typical	0.54	0.85	1.8	9.6
	Worst	0.54	3.9	15	100

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

f. **Preliminary Conclusion** - An aggregate threat of Cd toxicity to humans is expected when sludge with a typical concentration of Cd is applied to soils at the rate of 50 mt/ha or greater. When sludges with a high concentration of Cd are applied, a human health threat due to Cd is expected at all application rates.

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 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 (CDM, 1984a).

(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, 1984a.

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

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 8.15 mg/kg DW
Worst 88.13 mg/kg DW

See Section 3, p. 3-1.

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

The degradation rate in the unsaturated zone is assumed to be zero for all inorganic chemicals

(c) **Soil sorption coefficient (K_d)**

Typical	423 mL/g
Worst	14.9 mL/g

K_d values were obtained from Gerritse et al. (1982) using sandy loam soil (typical) or sandy soil (worst). Values shown are geometric means of a range of values derived using sewage sludge solution phases as the liquid phase in the adsorption experiments.

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).

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) = 1 μg/L**

This value was selected from available surface water data in lieu of groundwater data which were not available. Of the data available, the value chosen was the lowest, most conservative, specific value (NAS, 1977). (See Section 4, p. 4-2.)

(c) **Soil sorption coefficient (K_d) = 0 mL/g**

Adsorption is assumed to be zero in the saturated zone.

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** - The groundwater concentration of Cd at the well is expected to increase, especially when the worst-case sludge is landfilled, or when worst-case conditions prevail in the saturated zone or both unsaturated and saturated zones.

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

1. **Explanation** - Calculates human exposure which could result from groundwater contamination. Compares exposure with acceptable daily intake (ADI) of pollutant.

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

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

Site Characteristics	Condition of Analysis[a,b,c]							
	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	1.2	3.4	1.2	1.2	2.1	3.8	510	0
Index 2 Value	0.54	0.61	0.54	0.54	0.57	0.62	16.5	0.54

[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).

3. **Data Used and Rationale**

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

See Section 3, p. 3-26.

b. **Background concentration of pollutant in groundwater (BC) = 1 μg/L**

See Section 3, p. 3-25.

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) = 34.3 μg/day**

See Section 3, p. 3-12.

e. **Acceptable daily intake of pollutant (ADI) = 64 μg/day**

See Section 3, p. 3-12.

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

5. **Value Interpretation** - Value equals factor by which pollutant intake exceeds ADI. Value >1 indicates a possible human health threat. Comparison with the null index value indicates the degree to which any hazard is due to landfill disposal, as opposed to preexisting dietary sources.

6. **Preliminary Conclusion** - A human health threat due to Cd in groundwater is expected only when worst-case conditions prevail for all conditions.

III. INCINERATION

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

1. **Explanation** - Shows the degree of elevation of the pollutant concentration in the air due to the incineration of sludge. An input sludge with thermal properties defined by the energy parameter (EP) was analyzed using the BURN model (CDM, 1984a). This model uses the thermodynamic and mass balance relationships appropriate for multiple hearth incinerators to relate the input sludge characteristics to the stack gas parameters. Dilution

and dispersion of these stack gas releases were described by the U.S. EPA's Industrial Source Complex Long-Term (ISCLT) dispersion model from which normalized annual ground level concentrations were predicted (U.S. EPA, 1979a). The predicted pollutant concentration can then be compared to a ground level concentration used to assess risk.

2. **Assumptions/Limitations** - The fluidized bed incinerator was not chosen due to a paucity of available data. Gradual plume rise, stack tip downwash, and building wake effects are appropriate for describing plume behavior. Maximum hourly impact values can be translated into annual average values.

3. **Data Used and Rationale**

a. **Coefficient to correct for mass and time units (C) =** 2.78×10^{-7} hr/sec x g/mg

b. **Sludge feed rate (DS)**

i. **Typical** = 2660 kg/hr (dry solids input)

A feed rate of 2660 kg/hr DW represents an average dewatered sludge feed rate into the furnace. This feed rate would serve a community of approximately 400,000 people. This rate was incorporated into the U.S. EPA-ISCLT model based on the following input data:

EP = 360 lb H_2O/mm BTU
Combustion zone temperature - 1400°F
Solids content - 28%
Stack height - 20 m
Exit gas velocity - 20 m/s
Exit gas temperature - 356.9°K (183°F)
Stack diameter - 0.60 m

ii. **Worst** = 10,000 kg/hr (dry solids input)

A feed rate of 10,000 kg/hr DW represents a higher feed rate and would serve a major U.S. city. This rate was incorporated into the U.S. EPA-ISCLT model based on the following input data:

EP = 392 lb H_2O/mm BTU
Combustion zone temperature - 1400°F
Solids content - 26.6%
Stack height - 10 m
Exit gas velocity - 10 m/s
Exit gas temperature - 313.8°K (105°F)
Stack diameter - 0.80 m

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

Typical	8.15 mg/kg DW
Worst	88.13 mg/kg DW

See Section 3, p. 3-1.

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). Where data were not available from the EPA study, a more recent report which thoroughly researched heavy metal emissions was utilized (CDM, 1983).

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) = 3 x 10^{-3} $\mu g/m^3$**

The median background concentration for urban air is less than 6 x 10^{-3} $\mu g/m^3$, which is the detection limit for Cd (see Section 4, p. 4-2). Therefore, the background concentration selected was conservatively taken to be 1/2 of the detection limit.

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	3.0	37
	Worst	1.0	23	393
Worst	Typical	1.0	3.7	49
	Worst	1.0	31	520

[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.

6. **Preliminary Conclusion** - Concentrations of Cd in air are expected to substantially increase above the background concentration when sludge is incinerated.

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

1. **Explanation** - Shows the increase in human intake expected to result from the incineration of sludge. Ground level concentrations for carcinogens typically were developed based upon assessments published by the U.S. EPA Carcinogen Assessment Group (CAG). These ambient concentrations reflect a dose level which, for a lifetime exposure, increases the risk of cancer by 10^{-6}. For non-carcinogens, levels typically were derived from the American Conference of Governmental and Industrial Hygienists (ACGIH) threshold limit values (TLVs) for the workplace.

2. **Assumptions/Limitations** - The exposed population is assumed to reside within the impacted area for 24 hours/day. A respiratory volume of 20 m^3/day is assumed over a 70-year lifetime.

3. **Data Used and Rationale**

   a. **Index of air concentration increment resulting from incinerator emissions (Index 1)**

   See Section 3, p. 3-29.

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

   See Section 3, p. 3-29.

   c. **Cancer potency = 7.8 $(mg/kg/day)^{-1}$**

   The cancer potency given is estimated for inhalation of Cd by U.S. EPA (1984b). (See Section 4, p. 4-5.)

   d. **Exposure criterion (EC) = 0.45 x 10^{-3} μg/m^3**

   A lifetime exposure level which would result in a 10^{-6} cancer risk was selected as ground level concentration against which incinerator emissions are compared. The risk estimates developed by CAG are defined as the lifetime incremental cancer risk in a hypothetical population exposed continuously 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	6.7	20	250
	Worst	6.7	150	2600
Worst	Typical	6.7	25	330
	Worst	6.7	200	3500

[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** - The increased air concentrations of Cd resulting from sludge incineration are expected to substantially increase the human cancer risk due to inhalation of Cd above the risk pose by background urban air concentrations of Cd.

IV. OCEAN DISPOSAL

For the purpose of evaluating pollutant effects upon and/or subsequent uptake by marine life as a result of sludge disposal, two types of mixing were modeled. The initial mixing or dilution shortly after dumping of a single load of sludge represents a high, pulse concentration to which organisms may be exposed for short time periods but which could be repeated frequently; i.e., every time a recently dumped plume is encountered. A subsequent additional degree of mixing can be expressed by a further dilution. This is defined as the average dilution occurring when a day's worth of sludge is dispersed by 24 hours of current movement and represents the time-weighted average exposure concentration for organisms in the disposal area. This dilution accounts for 8 to 12 hours of the high pulse concentration encountered by the organisms during daylight disposal operations and 12 to 16 hours of recovery (ambient water concentration) during the night when disposal operations are suspended.

A. Index of Seawater Concentration Resulting from Initial Mixing of Sludge (Index 1)

1. **Explanation** - Calculates relative concentrations (compared to the background concentration of the pollutant) (unitless) of pollutant in seawater around an ocean disposal site assuming initial mixing.

2. **Assumptions/Limitations** - Assumes that the background seawater concentration of pollutant is finite and known. The index also assumes that disposal is by tanker and that the daily amount of sludge disposed is uniformly distributed along a path transversing the site and perpendicular to the current vector. The initial dilution volume is assumed to be determined by path length, depth to the pycnocline (a layer separating surface and deeper water masses), and an initial plume width defined as the width of the plume four hours after dumping. The seasonal disappearance of the pycnocline is not considered.

3. **Data Used and Rationale**

   a. **Disposal conditions**

	Sludge Disposal Rate (SS)	Sludge Mass Dumped by a Single Tanker (ST)	Length of Tanker Path (L)
Typical	825 mt DW/day	1600 mt WW	8000 m
Worst	1650 mt DW/day	3400 mt WW	4000 m

The typical value for the sludge disposal rate assumes that 7.5 x 10^6 mt WW/year are available for dumping from a metropolitan coastal area. The conversion to dry weight assumes 4 percent solids by weight. The worst-case value is an arbitrary doubling of the typical value to allow for potential future increase.

The assumed disposal practice to be followed at the model site representative of the typical case is a modification of that proposed for sludge disposal at the formally designated 12-mile site in the New York Bight Apex (City of New York, 1983). Sludge barges with capacities of 3400 mt WW would be required to discharge a load in no less than 53 minutes traveling at a minimum speed of 5 nautical miles (9260 m) per hour. Under these conditions, the barge would enter the site, discharge the sludge over 8180 m and exit the site. Sludge barges with capacities of 1600 mt WW would be required to discharge a load in no less than 32 minutes traveling at a minimum speed of 8 nautical miles (14,816 m) per hour. Under these conditions, the barge would enter the site, discharge the sludge over 7902 m and exit the site. The mean path length for the large and small tankers is 8041 m or approximately 8000 m. Path length is assumed to lie perpendicular to the direction of prevailing current flow. For the typical disposal rate (SS) of 825 mt DW/day, it is assumed that this would be accomplished by a mixture of four 3400 mt WW and four 1600 mt WW capacity barges. The overall daily disposal operation would last from 8 to 12 hours. For the worst-case disposal rate (SS) of 1650 mt DW/day, eight 3400 mt WW and eight 1600 mt WW capacity barges would be utilized. The overall daily disposal operation would last from 8 to 12 hours. For both disposal rate scenarios, there would be a 12 to 16 hour period at night in which no sludge would be dumped. It is assumed that under the above described disposal operation, sludge dumping would occur every day of the year.

The assumed disposal practice at the model site representative of the worst case is as stated for the typical site, except that barges would dump half their load along a track, then turn around and dispose of the balance along the same track in order to prevent a barge from dumping outside of the site. This practice would effectively halve the path length compared to the typical site.

b. Sludge concentration of pollutant (SC)

Typical	8.15 mg/kg DW
Worst	88.13 mg/kg DW

See Section 3, p. 3-1.

c. Disposal site characteristics

	Depth to pycnocline (D)	Average current velocity at site (V)
Typical	20 m	9500 m/day
Worst	5 m	4320 m/day

Typical site values are representative of a large, deep-water site with an area of about 1500 km^2

located beyond the continental shelf in the New York Bight. The pycnocline value of 20 m chosen is the average of the 10 to 30 m pycnocline depth range occurring in the summer and fall; the winter and spring disappearance of the pycnocline is not considered and so represents a conservative approach in evaluating annual or long-term impact. The current velocity of 11 cm/sec (9500 m/day) chosen is based on the average current velocity in this area (CDM, 1984b).

Worst-case values are representative of a near-shore New York Bight site with an area of about 20 km^2. The pycnocline value of 5 m chosen is the minimum value of the 5 to 23 m depth range of the surface mixed layer and is therefore a worst-case value. Current velocities in this area vary from 0 to 30 cm/sec. A value of 5 cm/sec (4320 m/day) is arbitrarily chosen to represent a worst-case value (CDM, 1984c).

d. **Ambient water concentration of pollutant (CA) = 0.02 µg/L**

This value was reported by Bruland and Franks (1983) and Boyle and Huested (1983) for unpolluted seawater. The implication of an unpolluted background concentration is that it amplifies the relative impact of sludge disposal.

4. **Factors Considered in Initial Mixing**

When a load of sludge is dumped from a moving tanker, an immediate mixing occurs in the turbulent wake of the vessel, followed by more gradual spreading of the plume. The entire plume, which initially constitutes a narrow band the length of the tanker path, moves more-or-less as a unit with the prevailing surface current and, under calm conditions, is not further dispersed by the current itself. However, the current acts to separate successive tanker loads, moving each out of the immediate disposal path before the next load is dumped.

Immediate mixing volume after barge disposal is approximately equal to the length of the dumping track with a cross-sectional area about four times that defined by the draft and width of the discharging vessel (Csanady, 1981, as cited in National Oceanic and Atmospheric Administration (NOAA), 1983). The resulting plume is initially 10 m deep by 40 m wide (O'Connor and Park, 1982, as cited in NOAA, 1983). Subsequent spreading of plume band width occurs at an average rate of approximately 1 cm/sec (Csanady et al., 1979, as cited in NOAA, 1983). Vertical mixing is limited by the depth of the pycnocline or ocean floor, whichever is shallower. Four hours after disposal, therefore, average plume width (W) may be computed as follows:

W = 40 m + 1 cm/sec x 4 hours x 3600 sec/hour x 0.01 m/cm = 184 m = approximately 200 m

Thus the volume of initial mixing is defined by the tanker path, a 200 m width, and a depth appropriate to the site. For the typical (deep water) site, this depth is chosen as the pycnocline value of 20 m. For the worst (shallow water) site, a value of 10 m was chosen. At times the pycnocline may be as shallow as 5 m, but since the barge wake causes initial mixing to at least 10 m, the greater value was used.

5. **Index 1 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	1.0	1.8	1.8
	Worst	1.0	9.8	9.8
Worst	Typical	1.0	7.9	7.9
	Worst	1.0	76	76

6. **Value Interpretation** - Value equals the relative pollutant concentration increase in seawater around a disposal site as a result of sludge disposal after initial mixing compared to the background concentration of the pollutant. The null index value at 0 mt DW/day equals 1.

7. **Preliminary Conclusion** - Increases in the seawater concentration of Cd occur in all the scenarios evaluated. The highest increases occur when sludges containing worst concentrations of Cd are dumped at the typical and worst sites.

B. **Index of Seawater Concentration Representing a 24- Hour Dumping Cycle (Index 2)**

1. **Explanation** - Calculates relative effective concentrations (compared to the background concentration of the pollutant) (unitless) of pollutant in seawater around an ocean disposal site utilizing a time weighted average (TWA) concentration. The TWA concentration is that which would be experienced by an organism remaining stationary (with respect to the ocean floor) or moving randomly within the disposal vicinity. The dilution volume is determined by the tanker path length and depth to pycnocline or, for the shallow water site, the 10 m effective

mixing depth, as before, but the effective width is now determined by current movement perpendicular to the tanker path over 24 hours.

2. **Assumptions/Limitations** - Incorporates all of the assumptions used to calculate Index 1. In addition, it is assumed that organisms would experience high-pulsed sludge concentrations for 8 to 12 hours per day and then experience recovery (no exposure to sludge) for 12 to 16 hours per day. This situation can be expressed by the use of a TWA concentration of sludge constituent.

3. **Data Used and Rationale**

See Section 3, pp. 3-22 to 3-34.

4. **Factors Considered in Determining Subsequent Additional Degree of Mixing (Determination of TWA Concentrations)**

See Section 3, p. 3-36.

5. **Index 2 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day)		
		0	825	1650
Typical	Typical	1.0	1.2	1.4
	Worst	1.0	3.4	5.8
Worst	Typical	1.0	2.9	4.9
	Worst	1.0	22	43

6. **Value Interpretation** - Value equals the relative effective pollutant concentration expressed as a TWA concentration in seawater around a disposal site experienced by an organism over a 24-hour period compared to the background concentration of the pollutant. The null index value at 0 mt DW/day equals 1.

7. **Preliminary Conclusion** - Increases of Cd concentrations occur in all cases with the largest increases being evident when sludges containing worst concentrations are dumped at the worst site.

C. **Index of Toxicity to Aquatic Life (Index 3)**

1. **Explanation** - Compares the relative effective concentration (compared to the background concentration of the pollutant) of pollutant in seawater around the disposal site resulting from the initial mixing of sludge (Index 1) with the marine ambient water quality criterion of the pollutant, or with another value judged protective

of marine aquatic life. For Cd, this value is the criterion that will protect marine aquatic organisms from both acute and chronic toxic effects.

Wherever a short-term, "pulse" exposure may occur as it would from initial mixing, it is usually evaluated using the "maximum" criteria values of EPA's ambient water quality criteria methodology. However, under this scenario, because the pulse is repeated several times daily on a long-term basis, potentially resulting in an accumulation of injury, it seems more appropriate to use values designed to be protective against chronic toxicity. Therefore, to evaluate the potential for adverse effects on marine life resulting from initial mixing concentrations, as quantified by Index 1, the chronically derived criteria values are used.

2. **Assumptions/Limitations** - In addition to the assumptions stated for Indices 1 and 2, assumes that all of the released pollutant is available in the water column to move through predicted pathways (i.e., sludge to seawater to aquatic organism to man). The possibility of effects arising from accumulation in the sediments is neglected since the U.S. EPA presently lacks a satisfactory method for deriving sediment criteria.

3. **Data Used and Rationale**

   a. **Concentration of pollutant in seawater around a disposal site (Index 1)**

      See Section 3, p. 3-35.

   b. **Ambient water quality criterion (AWQC) = 8.7 μg/L**

      Water quality criteria for the toxic pollutants listed under Section 307(a)(1) of the Clean Water Act of 1977 were developed by the U.S. EPA under Section 304(a)(1) of the Act. These criteria were derived by utilization of data reflecting the resultant environmental impacts and human health effects of these pollutants if present in any body of water. The criteria values presented in this assessment are excerpted from the ambient water quality criteria document for Cd.

      The 8.7 μg/L value chosen as the value to protect saltwater organisms from acute and chronic toxic effects is expressed as an average concentration (U.S. EPA, 1985).

c. **Ambient water concentration of pollutant (CA)** = 0.02 μg/L

See Section 3, p. 3-34.

4. **Index 3 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	0.0023	0.0042	0.0042
	Worst	0.0023	0.023	0.023
Worst	Typical	0.0023	0.018	0.018
	Worst	0.0023	0.17	0.17

5. **Value Interpretation** - Value equals the factor by which the relative effective seawater concentration of Cd exceeds the protective value. A value >1 indicates that acute or chronic toxic conditions may exist for organisms at the site.

6. **Preliminary Conclusion** - The index values indicate that a toxic condition may not exist for aquatic organisms at the site. However, incremental increases due to sludge dumping is evident in all of the scenarios evaluated.

D. **Index of Human Toxicity Resulting from Seafood Consumption (Index 4)**

1. **Explanation** - Estimates the expected increase in human pollutant intake associated with the consumption of seafood, a fraction of which originates from the disposal site vicinity, and compares the total expected pollutant intake with the acceptable daily intake (ADI) of the pollutant.

2. **Assumptions/Limitations** - In addition to the assumptions listed for Indices 1 and 2, assumes that the seafood tissue concentration will increase proportionally to the water concentration increase. It also assumes that, over the long term, the seafood catch from the disposal site vicinity will be diluted to some extent by the catch from uncontaminated areas.

3. **Data Used and Rationale**

a. **Concentration of pollutant in seawater around a disposal site (Index 2)**

See Section 3, p. 3-36.

Since bioconcentration is a dynamic and reversible process, it is expected that uptake of sludge pollutants by marine organisms at the disposal site will reflect TWA concentrations, as quantified by Index 2, rather than pulse concentrations.

b. **Background concentration of pollutant in seafood (CF) = 0.138 μg/g WW**

The background concentration of Cd is the average concentration in 50 varieties of seafood weighted according to mean consumption (Meaburn et al., 1981; Stanford Research Institute (SRI) International, 1980).

c. **Dietary consumption of seafood (QF)**

Typical	14.3 g WW/day
Worst	41.7 g WW/day

Typical and worst-case values are the mean and the 95th percentile, respectively, for all seafood consumption in the United States (SRI International, 1980).

d. **Fraction of consumed seafood originating from the disposal site (FS)**

For a typical harvesting scenario, it was assumed that the total catch over a wide region is mixed by harvesting, marketing and consumption practices, and that exposure is thereby diluted. Coastal areas have been divided by the National Marine Fishery Service (NMFS) into reporting areas for reporting on data on seafood landings. Therefore it was convenient to express the total area affected by sludge disposal as a fraction of an NMFS reporting area. The area used to represent the disposal impact area should be an approximation of the total ocean area over which the average concentration defined by Index 2 is roughly applicable. The average rate of plume spreading of 1 cm/sec referred to earlier amounts to approximately 0.9 km/day. Therefore, the combined plume of all sludge dumped during one working day will gradually spread, both parallel to and perpendicular to current direction, as it proceeds down-current. Since the concentration has been averaged over the direction of current flow, spreading in this dimension will not further reduce average concentration; only spreading in the perpendicular dimension will reduce the average. If stable conditions are assumed over a period of days, at least 9 days would be required to reduce the average concentration by one-half. At that time, the original plume length of approximately 8 km (8000 m) will have doubled to approximately 16 km due to spreading.

It is probably unnecessary to follow the plume further since storms, which would result in much more rapid dispersion of pollutants to background concentrations are expected on at least a 10-day frequency (NOAA, 1983). Therefore, the area impacted by sludge disposal (AI, in km^2) at each disposal site will be considered to be defined by the tanker path length (L) times the distance of current movement (V) during 10 days, and is computed as follows:

$$AI = 10 \times L \times V \times 10^{-6}\ km^2/m^2 \qquad (1)$$

To be consistent with a conservative approach, plume dilution due to spreading in the perpendicular direction to current flow is disregarded. More likely, organisms exposed to the plume in the area defined by equation 1 would experience a TWA concentration lower than the concentration expressed by Index 2.

Next, the value of AI must be expressed as a fraction of an NMFS reporting area. In the New York Bight, which includes NMFS areas 612-616 and 621-623, deep-water area 623 has an area of approximately 7200 km^2 and constitutes approximately 0.02 percent of the total seafood landings for the Bight (CDM, 1984b). Near-shore area 612 has an area of approximately 4300 km^2 and constitutes approximately 24 percent of the total seafood landings (CDM, 1984c). Therefore the fraction of all seafood landings (FS_t) from the Bight which could originate from the area of impact of either the typical (deep-water) or worst (near-shore) site can be calculated for this typical harvesting scenario as follows:

For the typical (deep water) site:

$$FS_t = \frac{AI \times 0.02\%}{7200\ km^2} = \qquad (2)$$

$$\frac{[10 \times 8000\ m \times 9500\ m \times 10^{-6}\ km^2/m^2] \times 0.0002}{7200\ km^2} = 2.1 \times 10^{-5}$$

For the worst (near shore) site:

$$FS_t = \frac{AI \times 24\%}{4300\ km^2} = \qquad (3)$$

$$\frac{[10 \times 4000\ m \times 4320\ m \times 10^{-6}\ km^2/m^2] \times 0.24}{4300\ km^2} = 9.6 \times 10^{-3}$$

To construct a worst-case harvesting scenario, it was assumed that the total seafood consumption for an individual could originate from an area more limited than the entire New York Bight. For example, a particular fisherman providing the entire seafood diet for himself or others could fish habitually within a single NMFS reporting area. Or, an individual could have a preference for a particular species which is taken only over a more limited area, here assumed arbitrarily to equal an NMFS reporting area. The fraction of consumed seafood (FS_w) that could originate from the area of impact under this worst-case scenario is calculated as follows:

For the typical (deep water) site:

$$FS_w = \frac{AI}{7200\ km^2} = 0.11 \qquad (4)$$

For the worst (near shore) site:

$$FS_w = \frac{AI}{4300\ km^2} = 0.040 \qquad (5)$$

e. **Average daily human dietary intake of pollutant (DI) = 34.3 μg/day**

See Section 3, p. 3-12.

f. **Acceptable daily intake of pollutant (ADI) = 64 μg/day**

See Section 3, p. 3-12.

4. **Index 4 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration[a]	Seafood Intake[a,b]	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	Typical	0.54	0.54	0.54
	Worst	Worst	0.54	0.56	0.58
Worst	Typical	Typical	0.54	0.54	0.54
	Worst	Worst	0.54	0.61	0.69

[a] All possible combinations of these values are not presented. Additional combinations may be calculated using the formulae in the Appendix.

[b] Refers to both the dietary consumption of seafood (QF) and the fraction of consumed seafood originating from the disposal site (FS). "Typical" indicates the use of the typical-case values for both of these parameters; "worst" indicates the use of the worst-case values for both.

5. **Value Interpretation** - Value equals factor by which the expected pollutant intake exceeds the ADI. A value >1 indicates a possible human health threat. Comparison with the null index value at 0 mt/day indicates the degree to which any hazard is due to sludge disposal, as opposed to preexisting dietary sources.

6. **Preliminary Conclusion** - No increase of human health risk is apparent from the typical intake of seafood residing at the typical and worst sites after disposal of sludges with typical concentrations of Cd. Moderate increases of risk were seen only when the site conditions, sludge concentration and seafood intake were assigned worst-case values.

SECTION 4

PRELIMINARY DATA PROFILE FOR CADMIUM IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

84 to 87 percent	U.S. EPA, 1982 (pp. 41 and 49)

2. Concentration

Minimum	0 μg/g DW	Statistically derived from sludge concentration data presented in U.S. EPA, 1982
Median	8.15 μg/g DW	
Mean	46 μg/g DW	
90th percentile	85 μg/g DW	
95th percentile	88.13 μg/g DW	
Maximum	1320 μg/g DW	

B. Soil - Unpolluted

1. Frequency of Detection

Virtually 100 percent

2. Concentration

"Normal" mean	0.09 to 0.18 μg/g DW	Beyer et al., 1982 (p. 383)
"Normal" range	0.06 to 0.5 μg/g DW	Ryan et al., 1982 (p. 280)
Range	0.01 to 22 μg/g DW	

The mean background soil level in 3001 field samples across the U.S. was 0.27 ppm DW, while the median was 0.20 ppm.	Holmgren, 1985
Ohio farm soils Mean 0.2 μg/g DW Range <0.1 to 2.9 μg/g DW	Logan and Miller, 1983 (p. 14)
Minnesota soils Mean (±SD) 0.39(±0.17) μg/g DW	Pierce et al., 1982 (p. 418)

Baltimore, MD garden soils Mean 1.2 µg/g DW Median 0.56 µg/g DW Range 0.02 to 13.6 µg/g DW	Mielke et al., 1983

C. **Water - Unpolluted**

1. **Frequency of Detection**

Data not immediately available.

2. **Concentration**

a. **Freshwater**

1 µg/L	NAS, 1977
"Rarely above 10 µg/L"	Hem, 1970 (p. 204)
"Usually <1 µg/L	Booz Allen and Hamilton, Inc. 1983 (p. 8)

b. **Seawater**

Range 0.10 to 0.15 µg/L	Ryan et al., 1982 (p. 255)

c. **Drinking Water**

Mean 1.3 µg/L Maximum 110 µg/L, 0.15% exceed 10 µg/L	Ryan et al., 1982 (p. 255)

D. **Air**

1. **Frequency of Detection**

<30 percent	U.S. EPA, 1979b (pp. 19 and 23)

2. **Concentration**

a. **Urban**

Median <6 ng/m^3 Range <6 to 200 ng/m^3 (detection limit = 6 ng/m^3)	U.S. EPA, 1979b

b. **Rural**

Median <6 ng/m^3 Range <6 to 38 ng/m^3 (detection limit = 6 ng/m^3)	U.S. EPA, 1979b

E. Food

1. Total Average Intake

Infants:	Mean 7.8 μg/day (FY75 to FY77)	FDA, 1980a (p. 10)
Toddlers:	Mean 10.9 μg/day (FY75 to FY77)	FDA, 1980a (p. 10)
Adults (15 to 20 years old, male):	Mean 34.3 μg/day (FY74 to 77)	FDA, 1980b (p. 14)

Contribution of Food Groups to Total Daily Adult Intake — FDA, 1980b (p. 14)

Food Group	μg Cd/day	% Total Cd Intake
Dairy products	1.87	5.1
Meat, fish and poultry	0.75	2.0
Grain and cereal	8.36	22.7
Potatoes	7.04	19.1
Leafy vegetables	2.52	6.8
Legume vegetables	0.39	1.1
Root vegetables	12.2	33.0
Garden fruits	1.03	2.8
Fruits	1.12	3.0
Oils and fats	0.81	2.2
Sugars and adjuncts	0.49	1.3
Beverages	0.32	0.9
Total	36.9	100

2. Concentration

Mean 12.5 ng/g WW 50 ng/g DW	Ryan et al., 1982 (p. 280)
Range 3 to 48 ng/g WW	U.S. EPA, 1980 (p. C-4)
Organ meats 100 to 1400 ng/g WW	Dorn, 1979 (pp. 332 to 335)

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity

U.S. EPA, 1984b (pp. 3 and 4)

a. Qualitative Assessment

IARC Scheme Group 2A: "probably carcinogenic to humans" based on inhalation exposures.

b. Potency

None demonstrated for ingestion route.

c. Effects

None demonstrated for ingestion route.

2. Chronic Toxicity

a. ADI

FAO/WHO provisionally tolerable daily intake (from all sources): 57 to 71 µg/day (i.e., 400 to 500 µg/week)	FAO/WHO, 1972 in FDA, 1980a (p. 10)
Threshold effect level: 12 µg absorbed Cd/day corresponds to 200 µg ingested Cd/day for non-smokers, or 170 µg ingested Cd/day for smokers	Comm. Eur. Communities, 1978 in U.S. EPA, 1980 (p. C-65)

b. Effects

Renal tubular damage

3. Absorption Factor

5 to 10 percent	U.S. EPA, 1980 (pp. C-67 and C-68)

4. Existing Regulations

Ambient Water Quality Criteria = 10 µg/L	U.S. EPA, 1980 (p. C-66)
Drinking water standard = 10 µg/L	

B. Inhalation

1. Carcinogenicity

a. Qualitative Assessment

IARC Scheme Group 2A and EPA Scheme IB: "probably carcinogenic to humans"	U.S. EPA, 1984b (pp. 68 and 162)

b. Potency

Cancer potency = 7.8 $(mg/kg/day)^{-1}$ (as Cd fume)	U.S. EPA, 1984b (p. 155)

c. Effects

Respiratory cancer and possibly prostate cancer	U.S. EPA, 1984b (p. 155)

2. Chronic Toxicity

a. Inhalation Threshold or MPIH

A threshold effect level of 12 µg absorbed Cd/day corresponds to 48 µg inhaled Cd/day for non-smokers (2 $\mu g/m^3$ in ambient air) 40.4 µg inhaled Cd/day for smokers (1.7 $\mu g/m^3$ in ambient air)	U.S. EPA, 1980 (pp. C-65 and C-67)

b. Effects

Renal tubular damage, emphysema

3. Absorption Factor

25 to 50 percent (normally 25%)	U.S. EPA, 1980 (p. C-67)

4. Existing Regulations

ACGIH TLV-TWA = 0.05 mg/m^3	ACGIH, 1981 (p. 11)
OSHA Standard (8-hour TWA) = 0.1 mg/m^3, fume; 0.2 mg/m^3, dust	Centers for Disease Control, 1983 (p. 85)
NIOSH Recommended Exposure Limit (TWA) = 0.04 mg/m^3	

III. PLANT EFFECTS

A. Phytotoxicity

See Table 4-1.

B. Uptake

See Table 4-2.

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

See Table 4-3.

0.5 ppm Cd in diet is maximum tolerable level for cattle, sheep, swine and poultry based on human food residue considerations.	NAS, 1980 (pp. 5-7 and 107)

B. Uptake

See Table 4-4.

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. Freshwater

Concentrations exceeding criteria:

Hardness (mg/L as $CaCo_3$)	Criterion (96-hour avg.)	
50	0.66 µg/L	U.S. EPA, 1985
100	1.1 µg/L	
200	2.0 µg/L	

2. Saltwater

8.7 µg/L as a 96-hour average concentration; should not exceeed one-hour average of 40 µg/L.	U.S. EPA, 1985

B. Uptake

Bioconcentration Factor

	Mean	Range
Fish muscle	16	3 to 151
Whole fish	525	33 to 2200
Edible shellfish	165	5 to 2600

VI. SOIL BIOTA EFFECTS

A. Toxicity

Data not immediately available.

B. Uptake

See Table 4-5.

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Cadmium (Cd)

Molecular wt.: 112.41 — Weast, 1976
Specific gravity (20°C): 8.642
Solubility (water): insoluble
Distribution constant (K_d) — Gerritse et al., 1982
  Sandy soil
    range (mL/g): 7.09-31.3
    mean (mL/g): 14.9
  Sandy loam soil
    range (mL/g): 104.7-1710
    mean (mL/g): 423

Cadmium Chloride ($CdCl_2$)

Molecular wt.: 183.32 — Weast, 1976
Specific gravity (25°C): 4.047
Solubility (g/mL)
  water (20°C): 1.4
  water (100°C): 1.5

Cadmium Carbonate ($CdCO_3$)

Molecular wt.: 172.41
Specific gravity (4°C): 4.258
Solubility (water): insoluble

Cadmium Sulfide (greenockite, CdS)

Molecular wt.: 144.46
Specific gravity (20°C): 4.82
Solubility (g/mL)
  water (18°C): 1.3×10^{-6}

Cadmium Sulfate ($CdSO_4$)

Molecular wt.: 208.46
Specific gravity
  (at 20°C relative to water 4°C): 4.691
Solubility (g/mL)
  water (0°C): 0.755
  water (100°C): 0.608

TABLE 4-1. PHYTOTOXICITY OF CADMIUM

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Soil Concentration (µg/g DW)	Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Soybean/tops	$CdCl_2$	6.7	2	2.5	NR[a]	7	10% reduced yield, discoloration	Haghiri, 1973 (p. 94)
				30	NR	20	70% decreased yield, chlorosis	
Wheat/tops	$CdCl_2$	6.7	1	2.5	NR	3	21% decreased yield	
				100	NR	20	70% decreased yield	
Lettuce	$CdCl_2$	6.7	2.8	2.5	NR	11.5	40% decreased yield	
				10	NR	27.1	58% decreased yeild	
Oat/roots	$CdCl_2$	NR	NR	10	NR	NR	24.5% decreased root biomass	Khan and Frankland, 1984 (p. 70)
				100	NR	NR	76.7% decreased root biomass	
Wheat/roots	$CdCl_2$	NR	NR	50	NR	NR	61.3% decreased root biomass	
	$CdCl_2$	NR		100	NR	NR	67.7% decreased root biomass	
	$CdSO_4$	NR		100	NR	NR	67.7% decreased root biomass	
	$CdCO_3$	NR		100	NR	NR	13.8% decreased root biomass	
	CdO	NR		100	NR	NR	47.5% decreased biomass	
Radish/roots	$CdCl_2$ and CdO (1:1)	NR		50	NR	NR	31.9% decreased root biomass	
	$CdCl_2$ and CdO (1:1)		100		NR	NR	42.6% decreased root biomass	
Lettuce/leaves (roots)	$CdCl_2$	5.1	12.2 (8.5)	40	NR	51 (295)	No effect on yield	John, 1973 (pp. 10 and 11)
				200		668 (1628)	Yield reduced 91% (60%)	

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (μg/g DW)	Soil Concentration (μg/g DW)	Application Rate (kg/ha)	Experimental Tissue Concentration (μg/g DW)	Effect	References
Spinach/leaves (roots)	$CdCl_2$	5.1	12.2 (8.5)	40	NR	207 (214)	Yield reduced 96% (96%)	John, 1973 (pp. 10 and 11)
Broccoli/leaves (roots)	$CdCl_2$	5.1	2.7 (6.5)	40	NR	36 (153)	No effect on yield	
				200	NR	269 (1647)	Yield reduced 63% (15%)	
Cauliflower/leaves (roots)	$CdCl_2$	5.1	4.8 (1.8)	40	NR	18.5 (203)	No effect on yield	
					NR	199 (1357)	Yield reduced 97% (90%)	
Radish/tops (tubers)	$CdCl_2$	5.1	9.8 (3.6)	40	NR	265 (55)	Yield reduced 24% (28%)	
				200	NR	398 (123)	Yield reduced 82% (93%)	
Carrots/tops (tubers)	$CdCl_2$	5.1	6.6 (2.4)	40	NR	79.3 (26.8)	No effect on yield	
				200	NR	294 (29.8)	Yield reduced 92% (96%)	
Peas/seeds (pods)	$CdCl_2$	5.1	5.4 (5.7)	40	NR	10.1 (9.5)	Yield reduced 38% (30%)	
				200	NR	19.7 (28.2)	Yield reduced 99% (82%)	
Oats/grain (leaves)	$CdCl_2$	5.1	3.9 (3.9)	40	NR	20.8 (45.4)	Yield reduced 36% (NS)[b]	
				200	NR	33.6 (177)	Yield reduced 57% (NS)	
Spinach/leaf	$CdSO_4$ enriched sludge	7.5	3.6	4	NR	75	Yield reduced 25%	Bingham et al., 1975 (pp. 208 and 210) and Bingham, 1979 (p. 40)

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Soil Concentration (µg/g DW)	Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Soybean/seed (leaf)	$CdSO_4$-enriched sludge	7.5	0.6 (0.4)	5	NR	7.0 (7.0)	Yield reduced 25%	Bingham et al., 1975 (pp. 208 and 210) and Bingham, 1979 (p. 40)
Curlycress/leaf	same as above	7.5	2.4	8	NR	80	Yield reduced 25%	
Lettuce/head (leaf)	same as above	7.5	NR	13	NR	70 (48)	Yield reduced 25%	
Sweet corn/kernel (leaf)	same as above	7.5	0.05 (3.9)	18	NR	19 (35)	Yield reduced 25%	
Carrot/tuber (leaf)	same as above	7.5	0.9	20	NR	19 (32)	Yield reduced 25%	
Turnip/tuber (leaf)	same as above	7.5	<0.1	28	NR	15 (120)	Yield reduced 25%	
Field bean/seed (leaf)	same as above	7.5	0.05 (0.6)	40	NR	1.7 (15)	Yield reduced 25%	
Wheat/grain (leaf)	same as above	7.5	<0.1 (0.1)	50	NR	12 (33)	Yield reduced 25%	
Radish/tuber (leaf)	same as above	7.5	0.2	96	NR	21 (75)	Yield reduced 25%	
Tomato/fruit (leaf)	same as above	7.5	<0.1 (0.1)	160	NR	7.0 (125)	Yield reduced 25%	
Zucchini/fruit (leaf)	same as above	7.5	<0.1	160	NR	10 (68)	Yield reduced 25%	
Cabbage/head (leaf)	same as above	7.5	0.2	170	NR	11 (160)	Yield reduced 25%	
Swiss chard/leaf	same as above	7.5	1.4	250	NR	150	Yield reduced 25%	

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Soil Concentration (µg/g DW)	Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Rice/grain (leaf)	same as above	7.5	<0.1	640	NR	2.9 (3.0)	No effect on yield	
Lettuce/tops	sludge	6.7	1.6	5.0	NR	7-14	Toxicity, but not attributed to Cd	Singh, 1981 (p. 22)
	various inorganic forms	6.7	1.6	5.0	NR	38-52	No significant effect on yield	
		6.7	1.6	5.0	NR	49-52	Yield decreased ~16%	
Corn/shoots	$CdSO_4$-enriched sludge	7.6	0.46	20	NR	78.4	Lowest concentration causing ≥25% growth reduction	Mahler et al., 1980 (p. 360)
Tomato/shoot	same as above	7.4-7.8	0.90-1.52	≥160	NR	100-253	Same as above	
Swiss chard/shoots	same as above	7.5	1.25	40	NR	153	Same as above	
Lettuce	sludge	6.0-6.7	0.3	NR	11.2	10.4	Yield generally higher with sludge	Giordano et al., 1979 (p. 235)
Broccoli	sludge	6.0-6.7	0.27	NR	11.2	1.02	Same as above	
Eggplant	sludge	6.0-6.7	0.54	NR	11.2	1.64	Same as above	
Tomato	sludge	6.0-6.7	0.52	NR	11.2	1.23	Same as above	
Potato	sludge	6.0-6.7	0.11	NR	11.2	0.24	Same as above	
Squash	sludge	6.0-6.7	0.11	NR	11.2	0.24	Yields generally higher with sludge	Giordano et al., 1979 (p. 235)
Pepper	sludge	6.0-6.7	0.15	NR	11.2	1.70	Same as above	

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Soil Concentration (µg/g DW)	Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Bean/seeds (pods)	sludge	6.0-6.7	0.07 (0.14)	NR	11.2	0.32(0.49)	Same as above	Giordano et al., 1979 (p. 235)
Cabbage	sludge	6.0-6.7	0.19	NR	11.2	0.35	Same as above	
Carrot	sludge	6.0-6.7	0.96	NR	11.2	2.29	Same as above	
Cantaloupe	sludge	6.0-6.7	0.21	NR	11.2	0.88	Same as above	
Corn/grain (leaf)	sludge	6.0-6.7	0.10 (0.29)		11.2	1.83(19.1)	Same as above	
Corn/grain (stover)	sludge	7.6	0.01 (0.20)	5.23 (M)[c]	19.2	0.12(2.05)	No signs of phytotoxicity	Webber and Beauchamp, 1979 (pp. 465 and 466)
Corn/grain (stover)	sludge	5.5	0.08 (1.2)	30.1 (M)	170 (during 11 years)	1.83(44.4)	No phytotoxicity or Cd-related yield reduction	Hinesly et al., 1982 (p. 473)
Barley grain	sludge	6.0	0.08 (0.12)	5.57 (M)	22.5	1.27(4.57)	No significant reduction of weight	Chang et al., 1982 (pp. 410 and 411)
Fescue/above ground portion	sludge	6.2	4	NR NR	3.2	72[d]	No effect on production	Boswell, 1975 (p. 271)
Corn seedlings	sludge	NR	NR	NR	74	13	No effect on growth	Shammas, 1979

[a] NR = Not reported.
[b] NS = Not significant.
[c] M = Measured.
[d] Sludge applied over growing fescue (tissue rinsed before analysis).

TABLE 4-2. UPTAKE OF CADMIUM BY PLANTS

Plant/Tissue	Chemical Form Applied	Soil pH	Range (N)[a] of Application Rates (kg/ha)	Control Tissue Concentration (µg/g DW)	Uptake[b] Slope	References
Tomato/fruit	sludge	6.2-6.5			0.05	Dowdy and Larson, 1975[c]
Lettuce/leaf	sludge	6.2-6.5			0.60	Dowdy and Larson, 1975[c]
	sludge	5.5-5.7			0.42	CAST, 1980 (Table 15)[c]
	sludge	6.1-6.4			0.15	CAST, 1980 (Table 15)[c]
Swiss chard/leaf	sludge	5.5-5.7		0.87	0.85	CAST, 1980 (Table 15)[c]
	sludge	6.1-6.4			0.43	CAST, 1980 (Table 15)[c]
	sludge	NR[d]			0.51	Chang et al., 1978[c]
Turnip/greens	sludge	5.6	0-5.1 (3)	1.0	0.67	Miller and Boswell, 1979 (p. 1362)
Carrot/tuber	sludge	6.2-6.5			0.20	Dowdy and Larson, 1975[c]
Radish/tuber	sludge	6.2-6.5			0.05	Dowdy and Larson, 1975[c]
	sludge	NR[d]			0.02	Chang et al., 1978[c]
Potato/tuber	sludge	6.2-6.5			0.03	Dowdy and Larson, 1975[c]
Sweet corn/grain	sludge	6.2-6.5			0.009	Dowdy and Larson, 1975[c]
		5.0-5.5			0.08	Giordano and Mays, 1977[c]
String bean/bean	sludge	5.0-5.5			0.01	Giordano and Mays, 1977[c]
Wheat/grain	sludge	NR[d]			0.02	Sabey and Hart, 1975[c]
Oats/grain	sludge	6.1-6.4			0.01	CAST, 1980 (Table 15)[c]
	sludge	5.5-5.7			0.02	CAST, 1980 (Table 15)[c]
Field corn/grain	sludge	4.9-5.4			0.001	CAST, 1980 (Table 17)[c]
	sludge	5.8-6.4			0.001	CAST, 1890 (Table 17)[c]
	sludge	6.5	0-38.7 (2)		0.004	Lisk et al., 1982 (p. 617)

TABLE 4-2. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Range (N)[a] of Application Rates (kg/ha)	Control Tissue Concentration (μg/g DW)	Uptake[b] Slope	References
Field corn/leaf	sludge	6.5[e]	0-3.0 (4)	0.83	3.4	Pepper et al., 1983 (p. 272)
	sludge	4.6[e]	0-3.0 (4)	1.01	3.4	Pepper et al., 1983 (p. 272)
	sludge	6.5[f]	0-3.0 (4)	0.2	1.5	Pepper et al., 1983 (p. 272)
	sludge	4.6[f]	0-3.0 (4)	0.2	0.83	Pepper et al., 1983 (p. 272)
Field corn/silage	sludge	7.0	0-21.6 (2)	0.05	0.077	Heffron et al., 1980 (p. 59)
	sludge	5.4	0-25.3 (2)	0.29	0.14	Telford et al., 1982 (p. 79)

[a] N = Number of application rates, including control (i.e., zero).
[b] Slope = y/x; x = kg/ha applied; y = μg/g plant tissue DW.
[c] As reported in Ryan, et al., 1982 (p. 283).
[d] Assumed to be >pH 7.
[e] Silt loam soil, limed or unlimed.
[f] Sandy loam soil, limed or unlimed.

TABLE 4-3. TOXICITY OF CADMIUM TO DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Feed Concentration (µg/g)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration of Study	Effects	References
Swine	sludge-grown corn	0.56			56 days	Decreased RBC number, microsomal enzyme activity liver Fe and kidney Mn	Hansen and Hinesly, 1979 (pp. 52 to 54)
Swine (4)	$CdCl_2$	50			42 days	Decreased hematocrit	Cousins et al., 1973
		150				Decreased weight gain and renal leucine aminopeptidase	
Swine (12)	$CdCl_2$	83			63 days	Microcytic, hypochromic anemia, reduced weight gain	Osuna et al., 1981 (pp. 1543 to 1545)
	50% sludge in diet	83			63 days	Hematologic parameters normal, depressed growth and toxicosis due to sludge.	
Cattle (2)	Cd succinate	50			343 days	Reduced weight gain, feto-toxicity	Wright et al., 1977
Sheep (6)	$CdCl_2$	5			191 days	Decreased liver Fe and Cu	Doyle et al., 1974; Doyle and Pfander, 1975
		15				Increased liver and kidney Zn	
		30				Decreased weight gain, increased kidney Cu	
		60				Decreased hematocrit and liver Mn	
Chicken (5-20)	$CdCl_2$	75			21 days	Decreased body weight, hematocrit, hemoglobin, liver and kidney Fe and serum Zn; increased serum TIBC and kidney Zn and Cu	Freeland and Cousins, 1973
Chicken (10)	$CdSO_4$	3,12,48			12 weeks	Decreased egg production	Leach et al., 1979

TABLE 4-3. (continued)

Species (N)[a]	Chemical Form Fed	Feed Concentration (μg/g)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration of Study	Effects	References
Chicken (15)	$CdSO_4$	3			48 weeks	No adverse effect	Leach et al., 1979
Chicken (12-15)		12,48			48 weeks	Decreased eggshell thickness	Leach et al., 1979
Japanese quail (80)	$CdCl_2$	75			28 days	Decreased body weight, hematocrit, total plasma proteins and albumin, increased transferring and mortality	Jacobs et al., 1969; Fox et al., 1971
Mallard	NR	200			90 days	Kidney tubule degeneration	U.S. EPA, 1980 (pp. 8 to 44)
Rabbit	$CdCl_2$		160		200 days	Decreased growth	Stowe et al., 1972
Dog (2)	$CdCl_2$		0.5, 2.5		4 years	No adverse effects	Anwar et al., 1961
			5, 10			Some fat droplets in glomeruli; some tubular atrophy and inflammatory cells	
Rat (46)	Cd acetate		1-25 50		30 months	Increased blood pressure Decreased weight gain	Perry et al., 1977
Rat (100)	Cd acetate		5		lifetime	Increased mortality, hypertension, kidney damage, heart damage, neurological disease	Schroeder et al., 1965 (p. 63)
Rat		31			7 months	Anemia	U.S. EPA, 1978 (p. 143)
Rat		45			6 months	Slight toxic symptoms	Gough et al., 1979 (p. 16)
Mouse	soluble Cd		10		2 generations	Dead litters, young deaths, runts, decreased number of offspring, failure to breed	Schroeder and Mitchener, 1971

[a] N = Number of animals per treatment group.

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

Species (N)[a]	Chemical Form Fed	Range (and N)[b] of Feed Tissue Concentrations (µg/g DW)	Tissue Analyzed	Control Tissue Concentration (µg/g WW)[c]	Uptake[d] Slope	References
Cattle (6)	sludge	0.77-12.2 (2)	kidney	0.31	0.15	Beyer et al., 1981 (p. 286)
			liver	0.08	0.12	
			muscle	0.02	NS	
Cattle (6)	sludge	0.14-10.6 (2)	kidney	0.27	0.27	Johnson et al., 1981 (p. 112)
			liver	0.057	0.135	
			muscle	<0.002	0.0006	
Cattle (9-13)	grass, alfalfa grown near smelter	0-07-1.72 (2)	kidney	0.05	0.20[e]	Munshower, 1977 (p. 412)
			liver	0.018	0.05[e]	
Swine (6-14)	barley grown near smelter	0.08-0.65 (2)	kidney	0.09	0.24[e]	
			liver	0.42	0.054[e]	
Swine (28)	sludge-grown corn grain	0.08-0.24 (2)	kidney	0.15	1.24	Lisk et al., 1982 (p. 617)
			liver	0.04	0.15	
			muscle	0.006	NS	
Swine (3)	sludge-grown corn grain	0.10-0.47 (2)	kidney	0.15	0.45	Hansen and Hinesly, 1979 (p. 52)
			liver	0.06	0.11	
Sheep (6)	$CdCl_2$	0.2-15 (3)	kidney	1.0	2.8	Sharma et al., 1979
			liver	0.5	1.0	
			muscle	0.025	0.004	
Sheep (6)	$CdCl_2$	0.7-12.3 (4)	liver	0.29	0.20	Mills and Dalgarno, 1972
Sheep (10)	sludge-grown corn silage	0.26-3.14 (2)	kidney	0.67	1.19	Telford et al., 1982 (p. 79)
			liver	0.09	0.30	
			muscle	0.006	NS	
Sheep (5-9)	sludge-grown corn silage	0.072-1.39 (2)	kidney	1.24	2.28	Heffron et al., 1980 (p. 60)
			liver	0.35	1.04	
			muscle	0.001	0.0013	

TABLE 4-4. (continued)

Species (N)[a]	Chemical Form Fed	Range (and N)[b] of Feed Tissue Concentrations (μg/g DW)	Tissue Analyzed	Control Tissue Concentration (μg/g WW)[c]	Uptake[d] Slope	References
Chicken (15)	$CdSO_4$	0.22-12.22 (3)	kidney	3.2	13	Leach et al., 1979
			liver	0.7	1.0	
			Muscle	0.029	0.017	
Chicken	$CdCl_2$	0.32-13.06 (3)	kidney	3	15	Sharma et al., 1979
			liver	0.2	1.65	
			muscle	0.063	0.019	

[a] N = Number of animals per treatment group.
[b] N = Number of feed concentrations, including control.
[c] When tissue values were reported as dry weight, unless otherwise indicated a moisture content of 77% was assumed for kidney, 70% for liver, and 72% for muscle (cattle, sheep, swine). When reported on fat-free dry weight basis, moisture plus fat content were assumed as follows: kidney, 81%; chicken breast muscle, 76%.
[d] Uptake slope = y/x; x = μg/g feed (DW); y = μg/g tissue (WW).
[e] Slope may actually be higher than shown since the diet also contained feed supplements which would have lowered the total Cd concentration of the contaminated diet.
[f] NS = No significant increase in tissue Cd.

TABLE 4-5. UPTAKE OF CADMIUM BY SOIL BIOTA

Species	Soil Type	Soil pH	Soil Concentration Range (and N)[a] (µg/g DW)	Tissue Analyzed	Control Tissue Concentration (µg/g DW)	Uptake Slope	References
Earthworms	sludge-amended soil	4.6-6.4	0.06-8.2 (2)	whole body	4.8	13.7[b,c]	Beyer et al., 1982 (p. 383)
Earthworms	sludge-amended soil	6.5	0-21.4 kg/ha (2)[d] (over 8 years)	whole body	17	1.36[e]	Beyer et al., 1982 (pp. 382 and 383)
	CdO-amended soil	6.5	0-35.8 kg/ha (2)[d] (over 8 years)	whole body	17	0.64[e]	
Earthworms	sludge-amended soils		0.13-18.8 kg/ha (2)[d] (single application)	whole body whole body minus gut	5.5 3.3	2.77[e] 0.77[e]	Wade et al., 1982 (p. 559)
Earthworms	soils near highways	6.9-7.0	0.66-1.59 (15)	whole body	5.9-8.5	NA[f]	Gish and Christensen, 1973 (p. 1061)
Earthworms	natural soils	NR[g]	0.23-0.80 (6)	whole body	3.1-9.3	NA	Van Hook, 1974 (p. 510)

[a]N = Number of soil concentrations (including control).
[b]Slope = y/x: x = soil concentration; y = tissue concentration.
[c]Mean slope for four locations.
[d]Cd application rate.
[e]Slope = y/x: x = application rate; y = tissue concentration.
[f]NA = Not applicable.
[g]NR = Not reported.

SECTION 5

REFERENCES

Abramowitz, M., and I. A. Stegun. 1972. Handbook of Mathematical Functions. Dover Publications, New York, NY.

American Conference of Governmental and Industrial Hygienists. 1981. Threshold Limit Values for Chemical Substances and Physical Agents in the Working Environment with Intended Changes for 1981. Cincinnati, OH.

Anwar, R. A., R. F. Langham, C. A. Hoppert, B. V. Alfredson, and R. U. Byerrum. 1961. Chronic Toxicity Studies. II. Chronic Toxicity of Cadmium and Chromium in Dogs. Arch. Environ. Health. 3:92. (Cited in NAS, 1980).

Bertrand, J. E., M. C. Lutrick, G. T. Edds, and R. L. West. 1981. Metal Residues in Tissues, Animal Performance and Carcass Quality with Beef Steers Grazing Pensacola Bahiagrass Pastures Treated with Liquid Digested Sludge. J. Ani. Sci. 53:1.

Beyer, K. W., J. W. Jones, S. K. Linscott, W. Wright, W. Stroube, and W. Cunningham. 1981. Trace Element Levels in Tissues from Cattle Fed a Sewage Sludge-Amended Diet. J. Toxicol. Environ. Health. 8:281-295.

Beyer, W. N., R. L. Chaney, and B. M. Mulkern. 1982. Heavy Metal Concentrations in Earthworms from Soil Amended with Sewage Sludge. J. Environ. Qual. 11(3):381-385.

Bingham, F. T. 1979. Bioavailability of Cd to Food Crops in Relation to Heavy Metal Content of Sludge-Amended Soil. Environ. Health Perspect. 28:39-43.

Bingham, F. T., A. L. Page, R. J. Mahler, and T. J. Ganje. 1975. Growth and Cadmium Accumulation of Plants Grown on a Soil Treated with a Cadmium Enriched Sewage Sludge. J. Environ. Qual. (4)2:207-211.

Booz Allen and Hamilton, Inc. 1983. A Background Document on Cadmium in Municipal Sewage Sludge. Revised Draft. Prepared for U.S. EPA Sludge Task Force. April 29.

Boswell, F. C. 1975. Municipal Sewage Sludge and Selected Element Applications to Soil: Effect on Soil and Fescue. J. Environ. Qual. 4(2):267-273.

Boyle, E., and S. Huested. 1983. Aspects of the Surface Distributions of Copper, Nickel, Cadmium, and Lead in the North Atlantic and North Pacific. In: Trace Metals in Sea Water. C. S. Wong et al., eds., 1983. Plenum Press, New York, NY.

Bruland, K. W., and R. P. Franks. 1983. Mn, Ni, Cu, Zn, and Cd in the Western North Atlantic. In: Trace Metals in Sea Water. C. S. Wong et al. (eds.), 1983. Plenum Press, New York, NY.

Camp Dresser and McKee, Inc. 1983. New York City Special Permit Application - Ocean Disposal of Sewage Sludge. Prepared for the City of New York Department of Environmental Protection.

Camp Dresser and McKee, Inc. 1984a. Development of Methodologies for Evaluating Permissible Contaminant Levels in Municipal Wastewater Sludges. Draft. Office of Water Regulations and Standards, U.S. Environmental Protection Agency, Washington, D.C.

Camp Dresser and McKee, Inc. 1984b. Technical Review of the 106-Mile Ocean Disposal Site. Prepared for U.S. EPA under Contract No. 68-01-6403. Annandale, VA. January.

Camp Dresser and McKee, Inc. 1984c. Technical Review of the 12-Mile Sewage Sludge Disposal Site. Prepared for U.S. EPA under Contract No. 68-01-6403. Annandale, VA. May.

Centers for Disease Control. 1983. NIOSH Recommendations for Occupational Health Standard. Morbid. Mortal. Weekly Rep. 32:7S-22S.

Chaney, R. L., and C. A. Lloyd. 1979. Adherence of Spray-Applied Liquid Digested Sewage Sludge to Tall Fescue. J. Environ. Qual. 8(3):407-411.

Chang, A. C., A. L. Page, L. J. Lund, P. E. Pratt, and G. R. Bradford. 1978. Land Application of Sewage Sludge: A Field Demonstration. Final Report. Regional Wastewater Solids Management Program, Los Angeles/Orange County Metropolitan Area. Univ. of California, Riverside, CA. (Cited in Ryan et al., 1982).

Chang, A. C., A. L. Page, K. W. Foster, and T. W. Jones. 1982. A Comparison of Cadmium and Zinc Accumulation by Four Cultures of Barley Grown in Sludge-Amended Soil. J. Environ. Qual. 11(3):409-412.

City of New York Department of Environmental Protection. 1983. A Special Permit Application for the Disposal of Sewage Sludge from Twelve New York City Water Pollution Control Plants at the 12-Mile Site. New York, NY. December.

Council for Agricultural Science and Technology. 1980. Effects of Sewage Sludge on the Cadmium and Zinc Content of Crops. Rep. No. 83. Ames, IA.

Cousins, R. J., A. K. Barber, and J. R. Trout. 1973. Cadmium Toxicity in Growing Swine. J. Nutr. 103:964. (Cited in NAS, 1980).

Donigian, A. S. 1985. Personal Communication. Anderson-Nichols & Co., Inc., Palo Alto, CA. May.

Dorn, C. R. 1979. Cadmium and the Food Chain. Cornel Vet. 69:323-343.

Dowdy, R. H., and W. E. Larson. 1975. The Availability of Sludge-Borne Metals to Various Vegetable Crops. J. Environ. Qual 4(2):278-282.

Doyle, J. J., and W. H. Pfander. 1975. Interaction of Cadmium with Copper, Iron, Zinc, and Manganese in Ovine Tissues. J. Nutr. 105:599-606.

Doyle, J. J., W. H. Pfander, S. E. Grebing, and J. O. Pierce. 1974. Effects of Dietary Cadmium on Growth, Cadmium Absorption, and Cadmium Tissue Levels in Growing Lambs. J. Nutr. 104:160. (Cited in NAS, 1980).

Farrell, J. B., and H. Wall. 1981. Air Pollutional Discharges from Ten Sewage Sludge Incinerators. Draft Review Copy. U. S. Environmental Protection Agency, Cincinnati, OH. February.

Food and Agriculture Organization/World Health Organization. 1972. Sixteenth Report of the Joint FAO/WHO Expert Committee on Food Additives. WHO Tech. Rep. Ser. No. 505. FAO Nutr. Rep. Ser. No. 51.

Food and Drug Administration. 1980a. FY77 Diet Studies - Infants and Toddlers (7320.74). FDA Bureau of Foods. October 22.

Food and Drug Administration. 1980b. FY77 Total Diet Studies - Adult (7320.73). FDA Bureau of Foods. December 11.

Fox. M. R. S., B. E. Fry, Jr., B. F. Harland, M. E. Schertel, and C. E. Weeks. 1971. Effect of Ascorbic Acid on Cadmium Toxicity. J. Nutr. 101:1295. (Cited in NAS, 1980).

Freeland, J. H., and R. J. Cousins. 1973. Effect of Dietary Cadmium on Anemia, Iron Absorption, and Cadmium Binding Protein in the Chick. Nutr. Rep. Int. 8:337. (Cited in NAS, 1980).

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, NJ.

Gelhar, L. W., and C. J. Axness. 1981. Stochastic Analysis of Macrodispersion in 3-Dimensionally Heterogenous Aquifers. Report No. H-8. Hydrologic Research Program, New Mexico Institute of Mining and Technology, Soccorro, NM.

Gerritse, R. G., R. Vriesema, J. W. Dalenberg, and H. P. DeRoos. 1982. Effect of Sewage Sludge on Trace Element Mobility in Soils. J. Environ. Qual. 11(3):359-364.

Giordano, P. M., and D. A. Mays. 1977. Effect of Land Disposal Applications of Municipal Wastes on Crop Yields and Heavy Metal Uptake. EPA 600/2-77-014. U.S. Environmental Protection Agency, Cincinnati, OH. (Cited in Ryan et al., 1982).

Giordano, P. M., D. A. Mays, and A. D. Behel, Jr. 1979. Soil Temperature Effects on Uptake of Cadmium and Zinc by Vegetables Grown on Sludge-Amended Soil. J. Environ. Qual. 8(2):233-236.

Gish, C. D., and R. E. Christensen. 1973. Cadmium, Nickel, Lead, and Zinc in Earthworms from Roadside Soil. Environ. Sci. Technol. 7(11):1060-1062.

Gough, L. P., H. T. Schacklette, and A. A. Case. 1979. Element Concentrations Toxic to Plants, Animals, and Man. Geologic Survey Bulletin 1466. U.S. Government Printing Office, Washington, D.C.

Haghiri, F. 1973. Cadmium Uptake by Plants. J. Environ. Qual. 2(1):93-96.

Hansen, L. G., and T. D. Hinesly. 1979. Cadmium from Soil Amended with Sewage Sludge: Effects of Residues in Swine. Environ. Health Perspect. 28:51-57.

Heffron, C. L., J. T. Reid, D. C. Elfving, et al. 1980. Cadmium and Zinc in Growing Sheep Fed Silage Corn Grown on Municipal Sludge Amended Soil. J. Agric. Food Chem. 28:58-61.

Hem, J. D. 1970. Study and Interpretation of the Chemical Characteristics of Natural Water. Geological Survey Water Supply Paper 1473. U.S. Government Printing Office, Washington, D.C.

Hinesly, T. D., D. E. Alexander, K. E. Redborg, and E. L. Ziegler. 1982. Differential Accumulation of Cadmium and Zinc by Corn Hybrids Grown on Soil Amended with Sewage Sludge. Agron. J. 74:469-474.

Holmgren, G. 1985. Personal Communication. National Soil Survey Laboratory. Soil Conservation Service. USDA, Lincoln, NE.

Jacobs, R. M., M.R.S. Fox, and M. H. Aldridge. 1969. Changes in Plasma Proteins Associated with the Anemia Produced by Dietary Cadmium in Japanese Quail. J. Nutr. 99:119. (Cited in NAS, 1980).

John, M. K. 1973. Cadmium Uptake by Eight Food Crops as Influenced by Various Soil Levels of Cadmium. Environ. Pollut. 4:7-15.

Johnson, D. E., E. W. Kienholb, J. C. Baxter, E. Spangler, and G. M. Wood. 1981. Heavy Metal Retention in Tissues of Cattle Fed High Cadmium Sewage Sludge. J. Anim. Sci. 52:108.

Khan, D. H., and B. Frankland. 1984. Cellutolytic Activitiy and Root Biomass Production in Some Metal Contaminated Soils. Environ. Pollut. (Series A). 33:63-74.

Leach, R. M., Jr., K. W. L. Wang, and D. E. Baker. 1979. Cadmium and the Food Chain: The Effect of Dietary Cadmium on Tissue Composition in Chicks and Laying Hens. J. Nutr. 109:437. (Cited in NAS, 1980).

Lisk, D. J., R. D. Boyd, J. N. Telford, et al. 1982. Toxicological Studies with Swine Fed Corn Grown on Municipal Sewage Sludge-Amended Soil. J. Ani. Sci. 55(3):613-619.

Logan, T. J., and R. H. Miller. 1983. Background Levels of Heavy Metals in Ohio Farm Soils. Research Circular 275. Ohio State Univ., Ohio Agric. Res. and Development Center, Wooster, OH.

Mahler, R. J., F. T. Bingham, G. Sposito, and A. L. Page. 1980. Cadmium-Enriched Sewage Sludge Application to Acid and Calcareous Soils: Relations Between Treatment, Cadmium in Saturation Extracts and Cadmium Uptake. J. Environ. Qual. 9(3):359-364.

Meaburn, G. M., K. B. Bolton, H. L. Seagran, T. S. Siewicki, S. M. Bingham, and P. J. Eldridge. 1981. Application of a Computer Simulation Model to Estimate Dietary Intake of Cadmium from Seafood by U.S. Consumers. NOAA Tech. Memorandum NMFS SEFC-74. 31 pp.

Mielke, H. W., J. C. Anderson, K. J. Berry, P. W. Mielke, R. L. Chaney, and M. Leech. 1983. Lead Concentration in Inner-City Soils as a Factor in the Child Lead Problem. Amer. J. Pub. Health. 73(12):1366-1369.

Miller, J., and F. C. Boswell. 1979. Mineral Content of Selected Tissues and Feces of Rats Fed Turnip Greens Grown on Soil Treated with Sewage Sludge. J. Agric. Food Chem. 27(6):136101365.

Mills, C. F., and A. C. Dalgarno. 1972. Copper and Zinc Status of Ewes and Lambs Receiving Increased Dietary Concentrations of Cadmium. Nature. 239:171.

Munshower, F. F. 1977. Cadmium Accumulation in Plants and Animals of Polluted and Nonpolluted Grasslands. J. Environ. Qual. 6(4):411-413.

National Academy of Sciences. 1977. Drinking Water and Health, NAS Safe Drinking Water Committee Report.

National Academy of Sciences. 1980. Mineral Tolerances of Domestic Animals. NAS: Subcommittee on Mineral Toxicity in Animals. Washington, D.C.

National Oceanic and Atmospheric Administration. 1983. Northeast Monitoring Program 106-Mile Site Characterization Update. NOAA Technical Memorandum NMFS-F/NEC-26. U.S. Department of Commerce National Oceanic and Atmospheric Administration. August.

Osuna, O., G. T. Edds, and J. A. Popp. 1981. Comparative Toxicity of Feeding Dried Urban Sludge and an Equivalent Amount of Cadmium to Swine. Am. J. Vet. Res. 42:1541-1546.

Pennington, J. A. T. 1983. Revision of the Total Diet Study Food Lists and Diets. J. Am. Diet Assoc. 82:166-173.

Pepper, I. L., D. E. Bezdicek, A. S. Baker, and J. M. Sims. 1983. Silage Corn Uptake of Sludge-Applied Zinc and Cadmium as Affected by Soil pH. J. Environ. Qual. 12(2):270-275.

Perry, H. J., Jr., M. Erlanger, and E. F. Perry. 1977. Elevated Systolic Pressure Following Chronic Low-Level Cadmium Feeding. Am. J. Physiol. 232:H114. (Cited in NAS, 1980).

Pettyjohn, W. A., D. C. Kent, T. A. Prickett, H. E. LeGrand, and F. E. Witz. 1982. Methods for the Prediction of Leachate Plume Migration and Mixing. U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, OH.

Pierce, F. J., R. H. Dowdy, and D. F. Grigal. 1982. Concentrations of Six Trace Metals in Some Major Minnesota Soils Series. J. Environ. Qual. 11(3):416-422.

Ryan, J. A., H. R. Pahren, and J. B. Lucas. 1982. Controlling Cadmium in the Human Food Chain: A Review and Rationale Based on Health Effects. Environ. Res. 28:251-302.

Sabey, B. R., and W. E. Hart. 1975. Land Application of Sewage Sludge: I. Effect on Growth and Chemical Composition of Plants. J. Environ. Qual. 4(2):252-256.

Schroeder, H. A., J. J. Balasa, and W. H. Vinton. 1965. Chromium, Cadmium, and Lead in Rats: Effects on Life Span, Tumors, and Tissue Levels. J. Nutr. 86:51-66.

Schroeder, J. A., and M. Mitchener. 1971. Toxic Effects of Trace Elements on the Reproduction of Mice and Rats. Arch. Environ. Health. 23:102. (Cited in NAS, 1980).

Shammas, A. T. 1979. Bioavailability of Cadmium in Sewage Sludge. Diss. Abst. Int. 40(7):2940-B. Order No. 7919813, 1980. Abstract.

Sharma, R. P., J. C. Street, M. P. Verma, and J. L. Shupe. 1979. Cadmium Uptake from Feed and its Distribution of Food Products of Livestock. Environ. Health Perspect. 28:59-66.

Sikora, L. J., W. D. Burge, and J. E. Jones. 1982. Monitoring of a Municipal Sludge Entrenchment Site. J. Environ. Qual. 2(2):321-325.

Singh, S. S. 1981. Uptake of Cadmium by Lettuce (Lactuca sativa) as Influenced by Its Addition to a Soil as Inorganic Forms or in Sewage Sludge. Can. J. Soil Sci. 61:19-28.

Stanford Research Institute International. 1980. Seafood Consumption Data Analysis. Final Report, Task 11. Prepared for U.S. EPA under Contract No. 68-01-3887. Menlo Park, CA. September.

Stowe, H. D., M. Wilson, and R. A. Goyer. 1972. Clinical and Morphologic Effects of Oral Cadmium Toxicity in Rabbits. Arch. Pathol. 94:389. (Cited in NAS, 1980).

Telford, J. N., M. L. Thonney, D. E. Hogue, et al. 1982. Toxicological Studies in Growing Sheep Fed Silage Corn Cultured on Municipal Sludge-Amended Acid Subsoil. J. Toxicol. Environ. Health. 10:73-85.

Thornton, I. and P. Abrams. 1983. Soil Ingestion - A Major Pathway of Heavy Metals into Livestock Grazing Contaminated Land. Sci. Total Environ. 28:287-294.

U.S. Department of Agriculture. 1975. Composition of Foods. Agricultural Handbook No. 8.

U.S. Environmental Protection Agency. 1977. Environmental Assessment of Subsurface Disposal of Municipal Wastewater Treatment Sludge: Interim Report. EPA 530/SW-547. Municipal Environmental Research Laboratory, Cincinnati, OH.

U.S. Environmental Protection Agency. 1978. Reviews of the Environmental Effects of Pollutants: IV. Cadmium. EPA 600/1-78-026. Health Effects Research Laboratory, Cincinnati, OH.

U.S. Environmental Protection Agency. 1979a. Industrial Source Complex (ISC) Dispersion Model User Guide. EPA 450/4-79-30. Vol. 1. Office of Air Quality Planning and Standards, Research Triangle Park, NC. December.

U.S. Environmental Protection Agency. 1979b. Air Quality Data for Metals 1976 from the National Air Surveillance Networks. EPA 600/4-79-054. Environmental Monitoring and Support Laboratory, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 1980. Ambient Water Quality Criteria for Cadmium. EPA 440/5-80-025. Washington, D.C.

U.S. Environmental Protection Agency. 1982. Fate of Priority Pollutants in Publicly-Owned Treatment Works. EPA 440/1-82/303. Washington, D.C.

U.S. Environmental Protection Agency. 1983a. Assessment of Human Exposure to Arsenic: Tacoma, Washington. Internal Document. OHEA-E-075-U. Office of Health and Environmental Assessment, Washington, D.C. July 19.

U.S. Environmental Protection Agency. 1983b. Rapid Assessment of Potential Groundwater Contamination Under Emergency Response Conditions. EPA 600/8-83-030.

U.S. Environmental Protection Agency. 1984a. Air Quality Criteria for Lead. External Review Draft. EPA 600/8-83-028B. Environmental Criteria and Assessment Office, Research Triangle Park, NC. September.

U.S. Environmental Protection Agency. 1984b. Updated Mutagenicity and Carcinogenicity Assessment of Cadmium. External Review Draft. EPA 600/8-83-025B.

U.S. Environmental Protection Agency. 1985. Water Quality Criteria for Cadmium. (Unpublished).

Van Hook, R. I. 1974. Cadmium, Lead, and Zinc Distributions Between Earthworms and Soils: Potentials for Biological Accumulation. Bull. Environ. Contam. Toxicol. 12(4):509-512.

Wade, S. E., C. A. Bache, and D. J. Lisk. 1982. Cadmium Accumulation by Earthworms Inhabiting Municipal Sludge-Amended Soil. Bull. Environ. Contam. Toxicol. 28:557-560.

Weast, R. C. (Ed.). 1976. Handbook of Chemistry and Physics, 57th ed. CRC Press, Inc., Cleveland, OH.

Webber, L. R., and E. G. Beauchamp. 1979. Cadmium Concentration and Distribution in Corn (Zea mays L.) Grown on a Calcareous Soil for Three Years after Three Annual Sludge Applications. J. Environ. Sci. Health. B14(5):459-474.

Wright, F. C., J. S. Palmer, J. C. Riner, M. Houfler, J. A. Miller, and C. A. McBeth. 1977. Effects of Dietary Feeding of Organocadmium to Cattle and Sheep. J. Agr. Food. 25(2):293-297.

APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR CADMIUM IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Cadmium

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

$$1.1 = \frac{(8.15\ \mu g/g\ DW \times 5\ mt/ha) + (0.2\ \mu g/g\ DW \times 2000\ mt/ha)}{0.2\ \mu g/g\ DW\ (5\ mt/ha + 2000\ mt/ha)}$$

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

$$1.69 = [(1.1 - 1)\ (0.2\ \mu g/g\ DW \times 13.7\ \mu g/g\ DW\ [\mu g/g\ soil\ DW]^{-1}) + 4.8\ \mu g/g\ DW] \div 3\ \mu g/g\ DW$$

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

$$0.088 = \frac{1.1 \times 0.2\ \mu g/g\ DW}{2.5\ \mu g/g\ DW}$$

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**

$$1.02 = \frac{(1.1 - 1) \times 0.2\ \mu g/g\ DW}{0.29\ \mu g/g\ DW} \times \frac{2\ kg/ha}{\mu g/g\ soil}$$

$$\times \frac{0.14\ \mu g/g\ tissue}{kg/ha} + 1$$

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**

$$170.4 = \frac{78.4\ \mu g/g\ DW}{0.46\ \mu g/g\ DW}$$

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**

$$0.059 = \frac{1.02 \times 0.29\ \mu g/g\ DW}{5\ \mu g/g\ DW}$$

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**

$$\text{If } AR = 0, \quad 0.0020 = \frac{0.2\ \mu g/g\ DW \times 0.05}{5\ \mu g/g\ DW}$$

$$\text{If } AR \neq 0, \quad 0.0815 = \frac{8.15\ \mu g/g\ DW \times 0.05}{5\ \mu g/g\ DW}$$

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)**

$$0.211 = \frac{[(1.02 - 1) \times 0.87\ \mu g/g\ DW \times 74.5\ g/day] + 10.9\ \mu g/day}{64\ \mu g/day}$$

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)**

$$0.171 = \frac{[(1.04-1) \times 0.29\ \mu g/g\ DW \times 5.5\ \mu g/g\ tissue[\mu g/g\ feed]^{-1} \times 0.97\ g/day] + 10.9\ \mu g/day}{64\ \mu g/day}$$

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

a. **Formula**

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

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)**

$$0.204 = \frac{(8.15\mu g/g\ DW \times 0.05 \times 5.5\ \mu g/g\ tissue\ [\mu g/g\ feed]^{-1} \times 0.97\ g/day\ DW) + 10.9\ \mu g/day}{64\ \mu g/day}$$

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

a. **Formula**

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

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

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)
ADI = Acceptable daily intake of pollutant (μg/day)

b. Sample calculation (toddler)

$$0.187 = \frac{(1.1 \times 0.2 \ \mu g/g \ DW \times 5 \ g \ soil/day) + 10.9 \ \mu g/day}{64 \ \mu g/day}$$

Pure sludge:

$$0.807 = \frac{(8.15 \ \mu g/g \ DW \times 5 \ g \ soil/day) + 10.9 \ \mu g/day}{64 \ \mu g/day}$$

5. Index of Aggregate Human Toxicity (Index 13)

a. Formula

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

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 toxicity resulting from soil ingestion (unitless)
DI = Average daily dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

$$0.262 = (0.211 + 0.171 + 0.204 + 0.187) - \left(\frac{3 \times 10.9\ \mu g/day}{64\ \mu g/day}\right)$$

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:

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

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

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

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

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)

$V^* = \frac{Q}{\theta \times R}$ (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 = Soil sorption coefficient (mL/g)

$\mu^* = \frac{365 \times \mu}{R}$ $(years)^{-1}$

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^* = $\alpha \times V^*$ (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 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)
∅ = 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:

$$t_o = [\int_o^{\infty} C\, dt] \div C_u$$

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

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 $C(\Delta \ell,t)$ calcuiated in Equation 1 (μg/L)
BC = Background concentration of pollutant in groundwater (μg/L)

2. **Sample Calculation**

$$1.221 = \frac{0.221\ \mu g/L + 1\ \mu g/L}{1\ \mu g/L}$$

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

1. **Formula**

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

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)
ADI = Acceptable daily intake of pollutant (μg/day)

2. **Sample Calculation**

$$0.543 = \frac{[(1.221 - 1) \times 1\ \mu g/L \times 2\ L/day] + 34.3\ \mu g/day}{64\ \mu g/day}$$

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 (μg/m^3)
BA = Background concentration of pollutant in urban air (μg/m^3)

2. **Sample Calculation**

$$3.049 = [(2.78 \times 10^{-7}\ \text{hr/sec} \times \text{g/mg} \times 2660\ \text{kg/hr DW} \times 8.15\ \text{mg/kg DW} \times 0.30 \times 3.4\ \mu\text{g/m}^3) \div 3 \times 10^{-3}\ \mu\text{g/m}^3] \div 3 \times 10^{-3}\ \mu\text{g/m}^3$$

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 (μg/m^3)
EC = Exposure criterion (μg/m^3)

2. **Sample Calculation**

$$20.33 = \frac{[(3.049 - 1) \times 3 \times 10^{-3}\ \mu\text{g/m}^3] + 3 \times 10^{-3}\ \mu\text{g/m}^3}{0.45 \times 10^{-3}\ \mu\text{g/m}^3}$$

IV. OCEAN DISPOSAL

A. **Index of Seawater Concentration Resulting from Initial Mixing of Sludge (Index 1)**

1. **Formula**

$$\text{Index 1} = \frac{SC \times ST \times PS}{W \times D \times L \times CA} + 1$$

where:

SC = Sludge concentration of pollutant (mg/kg DW)
ST = Sludge mass dumped by a single tanker (kg WW)
PS = Percent solids in sludge (kg DW/kg WW)
W = Width of initial plume dilution (m)
D = Depth to pycnocline or effective depth of mixing for shallow water site (m)
L = Length of tanker path (m)
CA = Ambient water concentration of pollutant (μg/L)

2. **Sample Calculation**

$$1.815 = \frac{8.15 \text{ mg/kg DW} \times 1600000 \text{ kg WW} \times 0.04 \text{ kg DW/kg WW} \times 10^3 \text{ µg/mg}}{200 \text{ m} \times 20 \text{ m} \times 8000 \text{ m} \times 0.02 \text{ µg/L} \times 10^3 \text{ L/m}^3} + 1$$

B. **Index of Seawater Concentration Representing a 24-Hour Dumping Cycle (Index 2)**

1. **Formula**

$$\text{Index 2} = \frac{SS \times SC}{V \times D \times L \times CA} + 1$$

where:

SS = Daily sludge disposal rate (kg DW/day)
SC = Sludge concentration of pollutant (mg/kg DW)
V = Average current velocity at site (m/day)
D = Depth to pycnocline or effective depth of mixing for shallow water site (m)
L = Length of tanker path (m)
CA = Ambient water concentration of pollutant (µg/L)

2. **Sample Calculation**

$$1.22 = \frac{825000 \text{ kg DW/day} \times 8.15 \text{ mg/kg DW} \times 10^3 \text{ µg/mg}}{9500 \text{ m/day} \times 20 \text{ m} \times 8000 \text{ m} \times 0.02 \text{ µg/L} \times 10^3 \text{ L/m}^3} + 1$$

C. **Index of Toxicity to Aquatic Life (Index 3)**

1. **Formula**

$$\text{Index 3} = \frac{I_1 \times CA}{AWQC}$$

where:

I_1 = Index 1 = Index of seawater concentration resulting from initial mixing after sludge disposal
AWQC = Criterion or other value expressed as an average concentration to protect marine organisms from acute and chronic toxic effects (µg/L)
CA = Ambient water concentration of pollutant (µg/L)

2. **Sample Calculation**

$$0.00417 = \frac{1.815 \text{ µg/L} \times 0.02 \text{ µg/L}}{8.7 \text{ µg/L}}$$

D. **Index of Human Toxicity Resulting from Seafood Consumption (Index 4)**

1. **Formula**

$$\text{Index 4} = \frac{[(I_2-1) \times CF \times FS \times QF] + DI}{ADI}$$

where:

I_2 = Index 2 = Index of seawater concentration representing a 24-hour dumping cycle
QF = Dietary consumption of seafood (g WW/day)
FS = Fraction of consumed seafood originating from the disposal site (unitless)
CF = Background concentration of pollutant in seafood (μg/g)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

2. **Sample Calculation**

$$0.536 = \frac{[(1.22 - 1) \times 0.138\ \mu g/g \times 0.000021 \times 14.3\ g\ WW/day) + 34.3\ \mu g/day}{64\ \mu g/day}$$

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)	8.15	88.13	8.15	8.15	8.15	8.15	88.13	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)	423	423	14.9	NA	423	423	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, ø (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)	2040	22000	2040	2040	2040	2040	22000	N
Peak concentration, C_u (µg/L)	2.80	30.3	63.0	2040	2.80	2.80	22000	N
Pulse duration, t_o (years)	3640	3640	162	5.00	3640	3640	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)	2.80	30.3	63.0	2040	2.80	2.80	22000	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (µg/L)	0.221	2.39	0.222	0.222	1.11	2.80	510	N
Index of groundwater concentration increment resulting from landfilled sludge, Index 1 (unitless) (Equation 4)	1.22	3.39	1.22	1.22	2.11	3.80	511	0
Index of human toxicity resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	0.543	0.611	0.543	0.543	0.571	0.623	16.5	0.536

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