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

PREFACE

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

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

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SECTION 1

INTRODUCTION

This preliminary data profile is one of a series of profiles dealing with chemical pollutants potentially of concern in municipal sewage sludges. Copper (Cu) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing), placed in a landfill, or incinerated.* This profile is a compilation of information that may be useful in determining whether Cu 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, and incineration are included in this profile. The calculation formulae for these indices are shown in the Appendix. The indices are rounded to two significant figures.

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

SECTION 2

PRELIMINARY CONCLUSIONS FOR COPPER 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 Copper

The landspreading of municipal sewage sludge may slightly increase soil concentrations of Cu; this increase may be substantial when sludge containing a high concentration of Cu is applied at a high rate (see Index 1).

B. Effect on Soil Biota and Predators of Soil Biota

Landspreading of sludge is not expected to result in soil concentrations of Cu which pose a toxic hazard for soil biota, except possibly when sludge containing a high concentration of Cu is applied at a high rate (see Index 2). Sludge application does not appear to pose a Cu hazard to predators of soil biota. High sludge application (500 mt/ha) with worst Cu concentrations, however, may eliminate the possibility of predator toxicity because soil concentrations of Cu under these conditions may be toxic to soil biota (see Index 3).

C. Effect on Plants and Plant Tissue Concentration

Application of sludge at high rates (500 mt/ha) may pose a phytotoxic hazard to plants, especially if worst concentration sludge is applied (see Indices 4 and 6). Accordingly, at high sludge application rates (500 mt/ha), a substantial increase in plant tissue concentrations of Cu can be expected in plants normally consumed by animals or humans (see Index 5).

D. Effect on Herbivorous Animals

Copper may pose a toxic hazard to animals that graze on plants grown in sludge-amended soils that have received high applications (500 mt/ha) of worst concentration sludge (see Index 7). Direct or incidental ingestion of worst Cu concentration sludge appears to pose a toxic hazard to herbivorous animals (see Index 8).

E. Effect on Humans

Consumption of plants grown in sludge-amended soils is not expected to pose a toxic hazard to humans (see Index 9). A Cu hazard to humans consuming animal products derived from either animals that are fed pasture crops grown in sludge-amended soil, or animals that have ingested sludge or sludge-amended soil, is not expected to occur. Any hazard is likely to be precluded by Cu toxicity to the animals (see Indices 10 and 11). Direct ingestion of sludge or sludge-amended soil by humans is not anticipated to result in a Cu toxicity hazard to either toddlers or adults (see Index 12). Generally, the landspreading of municipal sewage sludge is not expected to pose a toxic hazard to humans from the ingestion of Cu. At the high application rate (500 mt/ha) of worst concentration sludge, phytotoxic effects on plants and toxic effects on animals may preclude any toxic hazard for humans (see Index 13).

II. LANDFILLING

Landfilling of municipal sewage sludge will generally result in moderate increases in Cu concentrations in groundwater. However, when the worst-site parameters are associated with the saturated zone, or the composite worst-case scenario is evaluated, these increases in Cu concentrations become substantial (see Index 1). Generally, the health risk associated with the ingestion of landfill-contaminated groundwater is expected to be slight. However, when the worst-case scenario is examined, a human health threat seems to exist (see Index 2).

III. INCINERATION

When municipal sewage sludge is incinerated at high feed rates (10,000 kg/hr DW), moderate increases in Cu concentrations in air are expected. At lower feed rates, the air concentration increases are slight (see Index 1). The incineration of sludge is not expected to result in a human health hazard due to the inhalation of Cu-contaminated emissions (see Index 2).

IV. OCEAN DISPOSAL

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

SECTION 3

PRELIMINARY HAZARD INDICES FOR COPPER IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Copper

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 preexisting hazard posed by background levels or other sources of the pollutant.
5 mt/ha	Sustainable yearly agronomic application; i.e., loading typical of agricultural practice, supplying ~50 kg available nitrogen per hectare.
50 mt/ha	Higher 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	409.6 μg/g DW
Worst	1427 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) = 25 μg/g DW**

Reported data indicate that the soil background concentrations are mostly in the range of 11 to 37 μg/g DW. (Pierce et al., 1982; Beyer et al., 1982; Logan and Miller, 1983). Gough et al. (1979) reported a geometric mean of 18 μg/g DW for U.S. soils. A value of 25 μg/g DW was adopted as the soil background concentration in this study. (See Section 4, p. 4-2.)

d. **Index 1 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	1	1.0	1.4	4.1
Worst	1	1.1	2.4	12

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** - Landspreading of sludge may slightly increase soil concentrations of Cu; this increase may be substantial when sludge containing a high concentration of Cu is applied at a high rate.

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) = 25 μg/g DW**

See Section 3, p. 3-2.

iii. **Soil concentration toxic to soil biota (TB) = 131.0 μg/g DW**

At a soil concentration of 131 μg/g DW, earthworms displayed a significant reduction in cocoon production and litter breakdown (Ma, 1984). This was the lowest concentration reported that brought about Cu toxicity to soil biota, so it was the conservative value to use. There is one report of a 50 μg/mL liquid culture medium inhibiting dentrification (Bollag and Barabasz, 1979) but there was no method of determining what this concentration would have been equal to as a soil concentration in μg/g DW. (See Section 4, p. 4-20.)

d. **Index 2 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.19	0.20	0.26	0.78
Worst	0.19	0.22	0.45	2.3

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** - Landspreading of sludge is not expected to result in soil concentrations of Cu which pose a toxic hazard for soil biota, except possibly when sludge containing a high concentration of Cu is applied at a high rate.

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) = 25 μg/g DW**

See Section 3, p. 3-2.

iii. **Uptake slope of pollutant in soil biota (UB) = 0.61 μg/g tissue DW (μg/g soil DW)$^{-1}$**

Data are available only for earthworms and an uptake slope of 0.61 reflects the worst case observed for earthworms exposed to sludge (Beyer et al., 1982). (See Section 4, p. 4-21.)

iv. **Background concentration in soil biota (BB) = 12.5 μg/g DW**

The above concentration is the mean value of the range of background concentrations that corresponds to the uptake slope of 0.61 μg/g tissue DW (μg/g soil DW)$^{-1}$ for earthworms (Beyer et al., 1982). (See Section 4, p. 4-21.)

v. **Feed concentration toxic to predator (TR) = 300 μg/g DW**

Since earthworms were used for the pollutant uptake slope, a bird was determined to be a suitable predator. With this in mind, a feed concentration toxic to chicken/turkey of 300 μg/g DW was selected because it is stated as the maximum tolerable level (NAS, 1980). (See Section 4, p. 4-18.)

d. **Index 3 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.042	0.044	0.061	0.20
Worst	0.042	0.049	0.11	0.61

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** - Sludge application does not appear to pose a Cu hazard to predators of soil biota. High sludge application (500 mt/ha) with worst Cu concentrations, however, may eliminate the possibility of predator toxicity because soil concentrations of Cu under these conditions may be toxic to soil biota.

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) = 25 μg/g DW**

See Section 3, p. 3-2.

iii. **Soil concentration toxic to plants (TP) = 100 μg/g DW**

The lowest concentration level where toxic effects occur is reported at 46 μg/g DW in corn plants (Cunningham, 1975a). However, in Cunningham, 1975b one can see a decrease in corn yields only at soil concentrations above 189 μg/g. In Maclean and Dekker, 1978, experiments were performed with added $CuSO_4$. Therefore, the proportion of "available" Cu is higher than in the sludge-amended soils. Since above the 100 μg/g DW range, wheat, rye, and corn are affected by Cu, it was decided that this level is the conservative value to use. (See Section 4, pp. 4-12 to 4-15.)

d. **Index 4 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.25	0.26	0.34	1.0
Worst	0.25	0.28	0.59	3.0

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

f. **Preliminary Conclusion** - Application of sludge at high rates (500 mt/ha) may pose a phytotoxic hazard to plants, especially if worst concentration sludge is applied.

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) = 25 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:
Arrowleaf clover forage
0.045 µg/g tissue DW $(kg/ha)^{-1}$

Human diet:
Snap beans
0.04 µg/g tissue DW $(kg/ha)^{-1}$

Snap beans appear to be the most responsive plant in the human diet (Latterall et al., 1978). The uptake slope for this reference was used because it corresponds to a definite background concentration in the plant tissue (BP). Dowdy et al. (1978) quoted a slope for snap beans of 0.044 µg/g DW $(kg/ha)^{-1}$, but a BP with a range of 2.9 to 7.5. The slope of 0.15 for turnip greens from Miller and Boswell (1979) was considered suspect because it was not supported by any other findings, including those for other leafy vegetables.

Arrowleaf clover forage uptake slope was derived from the given uptake slope of 0.09 by using the conversion factor. Arrowleaf was the forage crop most sensitive to Cu (Sheaffer et al., 1979).

Rye grass had a substantial uptake slope, 0.11 µg/g DW (Kelling, 1977), but was not used since this value represents the entire plant, roots included, and animals normally are not fed the root systems in forage. (See Section 4, pp. 4-16 and 4-17.)

v. Background concentration in plant tissue (BP)

Animal diet:
Arrowleaf clover forage 7.3 µg/g DW

Human diet:
Snap beans 4.1 µg/g DW

These values were given in the studies from which uptake slopes were selected (Latterall et al., 1978; Scheaffer et al., 1979). (See Section 4, pp. 4-16 and 4-17.)

d. **Index 5 Values**

Diet	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Animal	Typical	1	1.0	1.1	1.9
	Worst	1	1.0	1.4	4.4
Human	Typical	1	1.0	1.2	2.5
	Worst	1	1.1	1.7	6.5[a]

[a]Value exceeds comparable value of Index 6; therefore may be precluded by phytotoxicity.

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** - When sludge is applied to soil at high application rates (500 mt/ha), a substantial increase in plant tissue concentrations of Cu can be expected for plants normally consumed by animals or humans.

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

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

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

c. **Data Used and Rationale**

i. **Maximum plant tissue concentration associated with phytotoxicity (PP)**

Animal diet:
Corn plant 22.2 μg/g DW

Human diet:
Snap bean plant 40.0 μg/g DW

Data were selected from Table 4-1, pp. 4-12 to 4-15, to indicate the highest tissue concentration increment likely to be observed in the plants selected for Index 5.

Data for arrowleaf clover forage were not available. However, Cunningham et al. (1975b) reported reduced yield of corn plant at concentrations of 17.0 to 22.2 μg/g. Other studies reporting high tissue concentrations did not include comparable background concentrations.

Walsh et al. (1972) reported reduced yield of snap beans at whole-plant concentrations of 20 to 30 μg/g, and severe toxicity at levels >40 μg/g. A value of 40 μg/g will therefore be taken as the maximum concentration for snap beans.

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

Animal diet:
Corn plant 4.4 μg/g DW

Human diet:
Snap bean plant 8.3 μg/g DW

Values are from studies identified for each plant. Control tissue concentrations for snap bean plant ranged from 8.3 to 24.7 (Walsh et al., 1972). The lower value was used to maximize the increment, in keeping with a conservative approach. (See Section 4, pp. 4-12 to 4-15.)

d. **Index 6 Values**

Plant	Index Value
Corn plant	5.0
Snap bean plant	4.8

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 index value for the corn plant indicates a moderate tolerance for Cu by plants ingested by animals and does not indicate any phytotoxic hazard when compared to values found in

Index 5. The snap bean plant is slightly less tolerable of Cu and, when compared to Index 5, shows that at high application rates (500 mt/ha) of worst concentration sludge, a phytotoxic hazard may exist for plants ingested by humans.

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. 3-8).

ii. **Background concentration in plant tissue (BP) = 7.3 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-8).

iii. **Feed concentration toxic to herbivorous animal (TA) = 25 μg/g DW**

Sheep were selected since they are the most sensitive grazing animals with respect to Cu ingestion. Demayo et al. (1982) reported that the natural forage and food containing $CuCl_2$ were toxic to sheep when Cu levels in the respective feeds were 50 to 60 and 20 to 100 μg/g DW. NAS (1980) suggested a maximum tolerable level in sheep of 25 μg/g of diet. It is assumed that the data are reported in DW basis. (See Section 4, p. 4-18.)

d. **Index 7 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.29	0.30	0.32	0.57
Worst	0.29	0.30	0.42	1.3

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** - Copper may pose a toxic hazard to animals that graze on plants grown in sludge-amended soils that have received high application (500 mt/ha) of worst concentration sludge.

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	409.6 μg/g DW
Worst	1427 μg/g DW

See Section 3, p. 3-1.

ii. **Background concentration of pollutant in soil (BS)** = 25 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) = 25 μg/g DW**

See Section 3, p. 3-10.

d. **Index 8 Values**

Sludge Concentration	Sludge Application Rate (mt/ha)			
	0	5	50	500
Typical	0.05	0.82	0.82	0.82
Worst	0.05	2.8	2.8	2.8

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** - Direct or incidental ingestion of worst Cu concentration sludge appears to pose a toxic hazard to herbivorous animals.

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. 3-8).

ii. **Background concentration in plant tissue (BP) = 4.1 μg/g DW**

The background concentration value used is for the plant chosen for the human diet (see Section 3, p. 3-8).

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	1250 µg/day
Adult	3600 µg/day

According to NAS (1980), recommended daily allowance of Cu for 1 to 3 year old children is 1 to 1.5 mg/day. Thus a value of 1250 µg/day is assumed for the mean DI for toddlers (see Section 4, p. 4-4). The normal human intake of Cu reported by the U.S. EPA (1980) is 3.2 to 4.0 mg/day (see Section 4, p. 4-3). The mean value of this range (3.6 mg/day) was used for the adult DI.

v. **Acceptable daily intake of pollutant (ADI) = 15000 µg/day**

No ADI based on chronic effects has been established for Cu. Cu is required in the human diet; the recommended daily allowance (RDA) is 1.5 to 2.5 mg/day for children (0 to 10 years) and 2.0 to 3.0 mg/day for adults ($\geq$11 years) (U.S. EPA, 1984c). Ingestion of as little as 5.3 mg in water or beverages has caused acute effects (i.e., nausea, vomiting, diarrhea) in humans. However, greater amounts (i.e., >10 mg/day) are probably routinely ingested in the diet without effects (U.S. EPA, 1984c). Information is lacking on long-term effects of elevated dietary Cu levels in humans. Only a few studies using nonruminant animals are available. A dietary level of 250 µg/g $CuSO_4$ (approximately 3.2 mg/kg body weight) was determined to be a no-observed-effect level (NOAEL) in an 88-day feeding study with pigs (Kline et al., 1971, cited in U.S. EPA, 1984b). Assuming a human body weight of 70 kg, a human-equivalent NOAEL of 220 mg Cu/day is derived. However, it is difficult to determine an appropriate uncertainty factor to apply in order to derive an ADI, since the normal use of multiple 10-fold factors to account for subchronic study duration, interspecies extrapolation and intraspecies (human) variability would give a value well below the RDA. Taking the (geometric) midpoint of the range of human-equivalent NOAEL and the RDA of 3.0 mg/day, as suggested by U.S. EPA (FR 45 79356), would yield a value of 26 mg/day. However, as stated by U.S. EPA (1980), "It has been suggested that intakes of above 15 mg of copper per day may produce observable effects." Although supporting data for this statement are lacking, the value of 15 mg/day (or 15000 μg/day) will be used as an ADI for Cu in food, for purposes of this document. (See Section 4, pp. 4-4 and 4-18.)

d. **Index 9 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha): 0	5	50	500
Toddler	Typical	0.083	0.084	0.090	0.14
	Worst	0.083	0.086	0.11	0.28
Adult	Typical	0.24	0.24	0.26	0.39
	Worst	0.24	0.25	0.31	0.78[a]

[a]Value may be precluded by phytotoxicity; see Indices 5 and 6.

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** - Consumption of plants grown on sludge-amended soils is not expected to pose a toxic hazard to humans.

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. 3-8).

ii. **Background concentration in plant tissue (BP) = 7.3 µg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-8).

iii. **Uptake slope of pollutant in animal tissue (UA)** = 24.5 µg/g tissue DW $(\mu g/g \text{ feed DW})^{-1}$

Ruminants have a high capacity for hepatic storage of Cu (Demayo et al., 1982). Since data are not available for cattle, values for rams are used in estimating this index. (See Section 4, p. 4-19.)

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

Toddler	0.97 g/day
Adult	5.76 g/day

Pennington (1983) lists the average daily intake of beef liver 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).

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

Toddler	1250 µg/day
Adult	3600 µg/day

See Section 3, p. 3-14.

vi. **Acceptable daily intake of pollutant (ADI)** = 15000 μg/day

See Section 3, p. 3-14.

d. **Index 10 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.083	0.083	0.084	0.089
	Worst	0.083	0.084	0.086	0.10[a]
Adult	Typical	0.24	0.24	0.24	0.28
	Worst	0.24	0.24	0.26	0.37[a]

[a]Value may be precluded by phytotoxicity; see Indices 5 and 6.

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

f. **Preliminary Conclusion** - A Cu hazard to humans consuming animal products derived from animals feeding on sludge-amended pasture crops is not expected to occur. Any hazard is likely to be precluded by Cu toxicity to the animal.

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** = Rams (sheep) liver

See Section 3, p. 3-16.

ii. **Background concentration of pollutant in soil (BS)** = 25 µg/g DW

See Section 3, p. 3-2.

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

Typical	409.6 µg/g DW
Worst	1427 µg/g DW

See Section 3, p. 3-1.

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

See Section 3, p. 3-12.

v. **Uptake slope of pollutant in animal tissue (UA)** = 24.5 µg/g tissue DW (µg/g feed DW)$^{-1}$

See Section 3, p. 3-16.

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

Toddler	0.97 g/day
Adult	5.76 g/day

See Section 3, p. 3-16.

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

Toddler	1250 µg/day
Adult	3600 µg/day

See Section 3, p. 3-14.

viii. **Acceptable daily intake of pollutant (ADI)** = 15000 µg/day

See Section 3, p. 3-14.

d. **Index 11 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	0.085	0.12	0.12	0.12
	Worst	0.085	0.20	0.20	0.20
Adult	Typical	0.25	0.43	0.43	0.43
	Worst	0.25	0.91	0.91	0.91

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

f. **Preliminary Conclusion** - A Cu hazard to humans consuming products derived from animals that have ingested sludge-amended soil is not expected to occur. Any hazard is likely to be precluded by Cu toxicity to the animals.

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	409.6 μg/g DW
Worst	1427 μg/g DW

See Section 3, p. 3-1.

iii. **Background concentration of pollutant in soil (BS)** = 25 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	1250 μg/day
Adult	3600 μg/day

See Section 3, p. 3-14.

vi. **Acceptable daily intake of pollutant (ADI)** = 15000 μg/day

See Section 3, p. 3-14.

d. **Index 12 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500	Pure Sludge
Toddler	Typical	0.092	0.092	0.095	0.12	0.22
	Worst	0.092	0.093	0.10	0.18	0.56
Adult	Typical	0.24	0.24	0.24	0.24	0.24
	Worst	0.24	0.24	0.24	0.24	0.24

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

f. **Preliminary Conclusion** - Direct ingestion of sludge or sludge-amended soil by humans is not anticipated to result in a Cu toxicity hazard to either toddlers or adults.

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	0.094	0.12	0.13	0.21
	Worst	0.094	0.21	0.24	0.52[a]
Adult	Typical	0.25	0.44	0.46	0.62
	Worst	0.25	0.92	0.99	1.6[a]

[a]Value may be partially precluded by phytotoxicity; see Indices 9 and 10.

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

f. **Preliminary Conclusion** - Generally, the landspreading of municipal sewage sludge is not expected to pose a toxic hazard to humans from the ingestion of Cu. At the high cumulative application rate of 500 mt/ha of worst concentration sludge, phytotoxic effects on plants and toxic effects on animals may preclude any toxic hazards for humans.

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 (Camp Dresser and McKee, Inc. (CDM), 1984).

(c) Volumetric water content (θ)

Typical	0.195 (unitless)
Worst	0.133 (unitless)

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

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	409.6 mg/kg DW
Worst	1427 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 92.2 mL/g
Worst 41.9 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) = 10 μg/L**

No data are available for the background concentration of Cu in groundwater. Cu concentrations in surface water have been estimated at 0.006 to 0.4 mg/L with a median value of 0.01 mg/L (Demayo et al., 1982). Thus, the same median value was assumed as groundwater background concentration. (See Section 4, p. 4-3.)

(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** - Landfilling of municipal sewage sludge will generally result in moderate increases in Cu concentrations in groundwater. However, when the worst-site parameters are associated with the saturated zone, or the composite worst-case scenario is evaluated, these increases in Cu concentrations become substantial.

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.

3. **Data Used and Rationale**

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

See Section 3, p. 3-30.

b. **Background concentration of pollutant in groundwater (BC) = 10 μg/L**

See Section 3, p. 3-27.

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) = 0.0 μg/day**

Normal human intake of Cu is reported to be 3.2 to 4.0 mg/day (U.S. EPA, 1980) and 2 to 5 mg/day (Gough et al., 1979). The majority of this Cu is ingested in food. However, since the ADI described below relates strictly to Cu in drinking water, a DI value of 0 μg/day is appropriate for calculation of this index.

e. **Acceptable daily intake of pollutant (ADI) = 2600 μg/day**

No ADI based on chronic effects has been established for Cu. An ambient water quality criterion of 1 mg/L was established based on organoleptic effects, not toxicity (U.S. EPA, 1980). Quantities as little as 5.3 mg, when ingested in water or beverages, have resulted in acute gastrointestinal effects. Based on this finding, assuming daily ingestion of 2 L of drinking water, and applying an uncertainty factor of 2, U.S. EPA (1984c) has recommended 1.3 mg/L as a level protective against acute toxic effects and not overly restrictive of required Cu intake. Thus, a value of 2600 μg/day (= 1.3 mg/L x 2 L/day) will be used as an ADI for Cu in water, for purposes of this document.

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.

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)

	Condition of Analysis[a,b,c]							
Site Characteristics	1	2	3	4	5	6	7	8
Sludge concentration	T	W	T	T	T	T	W	N
<u>Unsaturated Zone</u>								
Soil type and characteristics[d]	T	T	W	NA	T	T	NA	N
Site parameters[e]	T	T	T	W	T	T	W	N
<u>Saturated Zone</u>								
Soil type and characteristics[f]	T	T	T	T	W	T	W	N
Site parameters[g]	T	T	T	T	T	W	W	N
Index 1 Value	2.1	4.9	2.1	2.1	6.9	40	830	0
Index 2 Value	0.0086	0.030	0.0086	0.0086	0.045	0.30	6.4	0

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

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

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

[d]Dry bulk density (P_{dry}) and volumetric water content (θ).

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

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

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

6. **Preliminary Conclusion** - Generally, the health risk associated with the ingestion of landfill-contaminated groundwater is expected to be slight. However, when the worst-case scenario is examined, a human health threat seems to exist.

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, 1984). 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, 1979). 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	409.6 mg/kg DW
Worst	1427 mg/kg DW

See Section 3, p. 3-1.

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

Typical	0.007 (unitless)
Worst	0.009 (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 μg/m^3
Worst	16.0 μg/m^3

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

f. **Background concentration of pollutant in urban air (BA) = 0.16 μg/m^3**

Stern et al. (1973) reported an urban air Cu concentration of 0.16 μg/m^3. Of the data available, the use of this value will project the conservative worst case. (See Section 4, p. 4-3.)

4. **Index 1 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	1	1.0	1.8
	Worst	1	1.0	2.0
Worst	Typical	1	1.2	3.8
	Worst	1	1.2	4.6

[a]The typical (3.4 μg/m³) and worst (16.0 μg/m³) 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** - When municipal sewage sludge is incinerated at high (10,000 kg/hr DW) feed rates, moderate increases in Cu concentration in air are expected. At lower feed rates, the air concentration increases are slight.

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

1. **Explanation** - Shows the increase in human intake expected to result from the incineration of sludge. 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 m³/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. 3-32.

b. **Background concentration of pollutant in urban air (BA)** = 0.16 μg/m^3

See Section 3, p. 3-31.

c. **Maximum permissible intake of pollutant by inhalation (MPIH)** = 70 μg/day

This value was derived from an ACGIH time-weighted average TLV for Cu fumes. (See Section 4, p. 4-5.)

d. **Exposure criterion (EC)** = 3.5 μg/m^3

The exposure criterion is the level at which the inhalation of the pollutant is expected to exceed the acceptable daily intake level for inhalation. The exposure criterion is calculated using the following formula:

$$EC = \frac{MPIH}{20\ m^3/day}$$

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	0.046	0.048	0.082
	Worst	0.046	0.048	0.092
Worst	Typical	0.046	0.053	0.17
	Worst	0.046	0.055	0.21

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

5. **Value Interpretation** - Value equals factor by which expected intake exceeds MPIH. Value > 1 indicates a possible human health threat. 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 incineration of municipal sewage sludge is not expected to result in a human health threat due to the inhalation of Cu-contaminated emissions.

IV. OCEAN DISPOSAL

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

SECTION 4

PRELIMINARY DATA PROFILE FOR COPPER IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

Occurred in 100% of sludges of 16 cities studied	Furr et al., 1976 (p. 684)
Occurred in 97% of 436 samples from 40 POTWs	U.S. EPA, 1982 (p. 41)
Occurred in 100% of 60 samples from 10 POTWs	U.S. EPA, 1982 (p. 45)

2. Concentration

961 μg/g (DW) in anaerobic sludge 703 μg/g (DW) in waste-activated sludge	Baxter et al., 1983a (p. 313)
1024 μg/g (DW) mean 700 μg/g median 84 to 10400 μg/g range (sewage sludges from 57 locations in Michigan)	Page, 1974 (p. 11)
Cu in sewage sludges at various locations in U.S.	Page, 1974 (p. 15)

Location	Cu Concentration (μg/g)
Athens, GA	350-530
Columbus, OH	282-728
Dayton, OH	6020
Cincinnati, OH	4200
Chicago, IL	385-1225
Milwaukee, WI	435
Des Moines, IA	315
Houston, TX	1035
Rochester, NY	1980
Maryland	100-490
Connecticut	465-1025
Southern California	136-800
Oklahoma	800-6000
Indiana	300-11700

22 to 5600 µg/g (DW) range 760 µg/g mean 580 µg/g median (224 sewage sludges in Michigan)	Jacobs et al., 1981 (p. 21)
93 to 5125 µg/g (DW) range 438 µg/g mean 300 µg/g median (44 sewage sludges in Iowa)	Tabatobai and Frankenberger, 1981 (p. 940)
458 to 2890 µg/g (DW) in sludges from 16 U.S. cities	Furr et al., 1976 (p. 684)
100 to 180,000 µg/L for 40 POTWs	U.S. EPA, 1982 (p. 41)
11 to 1090 µg/L for 10 POTWs	U.S. EPA, 1982 (p. 45)

B. Soil - Unpolluted

1. Frequency of Detection

Common: 20 µg/g dry soil, 55 µg/g igneous rock	Jenkins, 1980 (p. 27)

2. Concentration

(mean ± SE) 23 ± 4 µg/g (DW) surface soils; range 16 to 29 µg/g (DW) surface, subsoil, and parent materials in Minnesota	Pierce et al., 1982 (p. 418)
"control", 11 to 17 µg/g	Beyer et al., 1982 (p. 383)
Marsh sediment, 5.1 to 13.4 µg/g	Lindau and Hossner, 1982 (p. 540)
Marsh sediment, 12 to 38 µg/g (DW)	Murdoch, 1980 (p. 341)
"normal", 18 µg/g geometric mean, range <1 to 300 µg/g	Gough et al., 1979 (p. 23)
11 to 37 µg/g range, 19 µg/g mean in Ohio farm soils	Logan and Miller, 1983 (p. 12)

C. Water - Unpolluted

1. Frequency of Detection

74.4% frequency of detection in 1173 out of 1577 surface waters in U.S. (detection limit = 0.010 mg/L)	Page, 1974 (p. 25)

2. Concentration

a. Freshwater

0.015 µg/L mean 0.001 to 0.280 mg/L range (from 1173 U.S. surface waters)	Page, 1974 (p. 25)
0.01 mg/L median 0.006 to 0.4 mg/L range (in river water)	Demayo et al., 1982 (p. 184)

b. Seawater

0.0005 to 0.003 mg/L	Demayo et al., 1982 (p. 184)

c. Drinking Water

Data not immediately available.

D. Air

1. Frequency of Detection

0.15 to 0.36% in urban air 0.019 to 0.28% in rural air	Stern et al., 1973 (Table 7-3)

2. Concentration

0.16 µg/m^3 in urban air 0.060 to 0.078 µg/m^3 in rural air	Stern et al., 1973 (Table 7-3)
0.01 µg/m^3 in rural air 0.257 µg/m^3 in urban air	U.S. EPA, 1980 (p. C-19)

E. Food

1. Total Average Intake

Normal human intake of Cu is reported to be 3.2 to 4.0 mg/day	U.S. EPA, 1980
and 2 to 5 mg/day.	Gough et al., 1979

Cu intake for babies is 0.065 to 0.1 mg/kg/day. A recommended daily allowance for Cu for 1- to 3- year-old children is 1 to 1.5 mg/day. — U.S. EPA, 1980

Recommended Daily Allowance: — U.S. EPA, 1984c (p. VI-1)
1.5 to 2.5 mg/day Children 0 to 10 years
2.0 to 3.0 mg/day Adults $\geq$11 years

Thus, a DI value of 1250 µg/day is assumed. — NAS, 1980

2. **Concentration**

Cu in major raw agricultural crops — Wolnik et al., 1983 (p. 1245 to 1248)

	Cu Concentration (µg/g WW)	
Drop	Mean	Range
Lettuce	0.26	0.065- 0.76
Peanut	7.6	0.80 -19.0
Potato	0.96	0.14 - 2.7
Soybean	12.0	3.5 -29.0
Sweet corn	0.45	0.19 - 0.92
Wheat	4.4	2.2 - 8.7

II. HUMAN EFFECTS

A. Ingestion

1. **Carcinogenicity**

There is very little evidence to suggest that Cu has a carcinogenic effect in humans. — U.S. EPA, 1980 (p. C-39)

2. **Chronic Toxicity**

a. **ADI**

No ADI based on chronic effects has been established. — U.S. EPA, 1984c (p. VIII-12)

b. **Effects**

Dietary intake above 15 mg/day may produce observable effects. — U.S. EPA, 1980

Ingestion of amounts $\geq$5.3 mg in water or beverages has resulted in gastrointestinal disorders, vomiting, nausea, and diarrhea.	U.S. EPA, 1984c (p. VIII-8)

3. **Absorption Factor**

~50% from food	Jenkins, 1980 (p. 11)

4. **Existing Regulations**

1.0 mg/L in drinking water	U.S. EPA, 1980 (p. C-4)

B. **Inhalation**

1. **Carcinogenicity**

Data not immediately available.

2. **Chronic Toxicity**

a. **Inhalation Threshold or MPIH**

70 µg/day as fume 36 µg/day as dust	U.S. EPA, 1984b

Derived based on ACGIH Threshold Limit Values for Cu (see below: "Existing Regulations")

b. **Effects**

Causes some lung irritation. Overexposure to Cu in any form may cause a 24- to 28-hour illness with chills, fever, aching muscles and headache.	U.S. EPA, 1980 (p. C-18)

3. **Absorption Factor**

Data not immediately available.

4. **Existing Regulations**

Threshold Limit Values: 0.2 mg/m^3 time-weighted average (TWA) as Cu fumes 1.0 mg/m^3 time-weighted average (TWA) as Cu dust	ACGIH, 1983

III. PLANT EFFECTS

A. Phytotoxicity

1. Soil Concentration Causing Phytotoxicity

Cu is highly toxic to roots.	Bennet, 1972 in Gough et al., 1979 (p. 22)
Toxicity is usually manifested by chlorosis of foliage caused by Cu interference with Fe.	Gough et al., 1979 (p. 23)
Cu, although essential to plants, can be toxic at high concentrations. Sludges often contain appreciable amounts of Cu, but applications of sludges to soils result in only slight to moderate increases in the Cu content of plants.	CAST, 1976 (p. 3)
In substrates for plants, Cu activities greater than 0.1 to 0.3 µg/g damage and usually kill the roots. The recommended activity of Cu in a substrate for plants should be within the range of 0.02 to 0.04 µg/g. A toxicity of Cu to some plants on some soils can be expected when Cu added over a period of time exceeds 150 to 400 ppm.	Baker, 1974 (p. 1181)
Sludges used on agricultural land should be adjusted to pH 7 before spreading, so as to minimize any possible heavy metal toxicities to crops.	Bolton, 1975 (p. 295)
In pot experiments with Cu added as $CuSO_4$ at 60 to 480 µg/g, the addition of sewage sludge eliminated toxic effects of the added Cu.	MacLean and Dekker, 1978 (p. 381)
Based on visual observations, growth of wheat, oats, and rye was greater on sludge-amended plots (56 and 112 metric ton/ha sludge) than control plots. Larger plants were observed for crimson and arrowleaf clover on control plots; however, Cu concentrations in sludge were not provided.	Sheaffer et al., 1979 (p. 458)
Seeding of sorghum immediately following sludge application at 25 to	Sabey and Hart, 1975 (p. 252)

125 metric ton/ha resulted in severe inhibition of seed germination. No seed germination inhibition occurred when seeding was performed 3 months after sludge application.	
Laboratory studies indicated that factors causing inhibition were destroyed by combustion at 525°C and thus not caused by salts.	Sabey and Hart, 1975 (p. 255)
Sludge application rates below 125 metric tons/ha (11 kg/ha of Cu) caused no significant yield decrease in wheat. 25 and 50 metric tons/ha of sludge (2.2 and 8.8 kg/ha of Cu) increased yield significantly. 25 metric tons/ha of sludge significantly increased yields of sudangrass.	Sabey and Hart, 1975 (p. 255 to 256)
0.9 to 20 μg/g Cu in soil from sludge did not affect plants.	Garrigan, 1977 in Demayo et al., 1982 (p. 236)
26 to 37 μg/g Cu added to soil from sludge did not appreciably affect yield or Cu content of the fruit, root, leaf for bean, okra, peppers, tomatoes, squash, turnips, radishes, kale, lettuce, or spinach.	Giordano and Mays, 1977 in Demayo et al., 1982 (p. 236)
30 μg/g Cu added to soil as sludge increased Cu content but not yield of peas (Cu content increased 4.5 to 11.1 μg/g), potatoes (Cu content increased 8.6 to 19 μg/g), and lettuce (Cu content increased 1.6 to 11.9 μg/g).	Dowdy and Larson, 1975b in Demayo et al., 1982 (p. 236)
<1% of total Cu in polluted soil available to plants	Martin et al., 1982 (p. 151)
3.1 to 13.6 μg/g $CuSO_4$ in solution upper critical limit for barley	Beckett and Davis, 1977 (p. 98)
Upper critical limits of $CuSO_4$ in solution were 2.1 to 17.7 μg/g for barley, 1.1 to 4.1 μg/g for lettuce, 0.3 to 2.8 μg/g for rape, and 1.3 μg/g for wheat.	Davis and Beckett, 1979 (p. 29)

2. Plant Tissue Concentration Exhibiting Toxicity

Cu required at 2 to 4 µg/g 4 to 15 µg/g normal range >20 µg/g toxic to plants	Allaway, 1968 (p 241)
18.2 to 20.3 µg/g (DW) "upper critical limit" for barley; median 19.1; normal 11	Beckett and Davis, 1977 (pp. 98 and 104)
30 ppm upper critical limit for most plant species	Leeper, 1972 in Beckett and Davis, 1977 (p. 104)
37 µg/g in oat leaves exhibiting toxicity	Hunter and Vergnano, 1953 in Bolton, 1975 (pp. 300 to 302)
40 µg/g Cu in rye grass from sludge-amended soils affected yield of rye grass.	Bolton, 1975 (pp. 300 to 302)
Upper critical limits: 13.7 to 24.8 µg/g (DW) for barley (11 µg/g normal); 16.6 to 20.9 µg/g (DW) for lettuce (10 µg/g normal); 14.9 to 22.1 µg/g (DW) for rape (9 µg/g normal); 17.8 µg/g (DW) for wheat (11 µg/g normal); and 21 µg/g for ryegrass (11 µg/g normal)	Davis and Beckett, 1978 (pp. 29 and 30)
>21 µg/g (DW) Cu in oats associated with depression of yield 220 µg/g (DW) Cu in soybeans associated with depression of yield	Roth et al., 1971 (p. 339)

B. Uptake

See Table 4-1.

Sludge-applied Cu was not absorbed by barley from either acid (pH 5.9) or calcareous (pH 7.9) soil, even though the sludge contained 610 ppm Cu, an application of 830 µg/100 g soil. This agrees with observations by others that showed soil additions of 134 ton/ha sludge had no effect on Cu uptake by oat plants at pH 5.3 or 6.8.	Dowdy and Larson, 1975 (p. 232)

Uptake of Cu in sludge-amended soil (μg/g): Demayo et al., 1982 (p. 235)

	Soil	Corn Grain	Tomato Fruit
Control	17.5	2	26
Sludge	325	2	30

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

See Table 4-3.

In general, animal diets are deficient in Cu; hence, slightly elevated concentrations in animal feedings could be advantageous. Under good management practices, Cu in sludges will seldom be toxic to plants and should not present a hazard to the food supply. Cu toxicity in animals would be expected to occur only when Cu toxicity is severe in the plants used as feed. CAST, 1976 (p. 3)

Cu, however, was listed in the CAST 1976 report as an element "posing a potentially serious hazard". CAST, 1976 (pp. 29 and 32)

Cu toxicity for most mammals and birds is of little significance due to barriers to Cu absorption. Gough et al., 1979 (p. 24)

Required in animal diets at 1 to 10 ppm; dependent on Mo; low toxicity Allaway, 1968 (p. 241)

B. Uptake

Cu concentrations in soil and swine tissue for swine overwintered two seasons on sludge-amended plots: Hansen et al., 1981 (pp. 1013 to 1014)

Sludge Application Rate (t/ha)	Cu Soil Conc. (μg/g DW)	Swine Tissue Conc. (μg/g WW) Kidney	Liver	Muscle
0	18	5.3	6.2	0.7
126	41	3.7	13.2	0.7
252	72	5.5	3.5	0.6
504	122	6.4	5.4	0.6

Cu concentration (μg/g DW) in soil, forage, and cattle tissue from control (C) and sludge-amended (S) plots (sludge application rates not reported): — Baxter et al., 1983a (pp. 312 to 318)

Sludge	Soil C	Soil S	Forage C	Forage S
703-961	6.75-18.8	6.0-82.5	2.3	3.8-22.0

Cattle Tissue

Kidney C	Kidney S	Liver C	Liver S	Bone C	Bone S	Muscle C	Muscle S
16.3	16.1	19.0	4.6	0.5	1.3	2.9	2.5

See Table 4-4.

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. Freshwater

Freshwater organisms should not be affected unacceptably if at freshwater hardness levels corresponding to 50, 100, and 200 mg/L as $CaCO_3$ the four-day average concentrations of acid-soluble Cu are 6.5, 12, and 21 μg/L, respectively, and the one-hour average concentrations are 9.8, 18, and 34 μg/L. — U.S. EPA, 1985

2. Saltwater

Saltwater organisms should not be affected unacceptably if the one-hour average concentration of acid-soluble Cu does not exceed 2.9 μg/L more than once every three years on the average. — U.S. EPA, 1985

B. Uptake

Data not immediately available.

VI. SOIL BIOTA EFFECTS

50 μg/mL Cu inhibited dentrifying activity in soil (liquid culture medium).	Bollag and Barabasz, 1979 (p. 196)

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Copper:	Reddish, lustrous, ductile, malleable metal	U.S. EPA, 1980 (p. A-1)
Boiling point:	2595°C	
Melting point:	1083°C	
Solubility:	Insoluble in water	
Specific gravity:	8.90 g/cc	
Molecular wt:	63.54 g/mole	

TABLE 4-1. PHYTOTOXICITY OF COPPER

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (μg/g DW)	Experimental Soil Concentration (μg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (μg/g DW)	Effect	References
Corn/plant	Sludge	6.8	4.4	46	NA[a]	6.5	Increased yield	Cunningham et al., 1975a (p. 461-462)
Rye/plant	Sludge	6.8	7.5	46	NA	12.1	Increased yield	
Corn/plant	Sludge	6.8	10.4	46	NA	24.3	Decreased yield, tissue above 20 ppm toxic limit	
Barley/plant	Sludge	7.9	NR[b]	NR	0.83	NR	Increased yield	Dowdy and Larson, 1975a (p. 230)
Barley/plant	Sludge	5.9	NR	NR	0.83	NR	Increased yield	
Snap beans	Sludge	5.3-6.5	2.9-5.8	NR	0.855	4.2-11.3	Increased yield	Dowdy et al., 1978 (p. 255)
Snap beans	Sludge	5.3-6.5	4.5-7.5	NR	0.266	8.5-12.0	Increased yield	
Pearl millet/leaf	Sludge	5.5-6.9	5.2-6.6	NR	0.232	7.2-10.3	No effect	Korcak et al., 1979 (p. 65-67)
Corn/plant	$CuSO_4$	6.3	4.5	60	NA	5.7	23% reduction in yield	MacLean and Dekker, 1978 (p. 383)
Corn/plant	$CuSO_4$	6.3	4.5	60	NA	6.0	32% reduction in yield	
Corn/plant	$CuSO_4$	6.3	4.5	240	NA	8.6	50% reduction in yield	
Corn/plant	$CuSO_4$/Sludge	5.9	4.6	72	NA	5.2	14% increased yield with sludge	
Corn/plant	$CuSO_4$/Sludge	5.9	4.6	252	NA	4.5	30% increased yield with sludge	
Corn/plant	$CuSO_4$/Sludge	5.9	4.6	492	NA	5.5	48% increased yield	
Corn/plant	$CuSO_4$/Sludge	6.5 (limed)	3.5	72	NA	3.2	6% reduction in yield with sludge	
Corn/plant	$CuSO_4$/Sludge	6.5 (limed)	3.5	252	NA	3.1	9% increased yield with sludge	

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Experimental Soil Concentration (µg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Corn/plant	$CuSO_4$/Sludge	6.5 (limed)	3.5	492	NA	5.4	4% reduction in yield with sludge	
Corn/plant	Sludge	6.8	4.4	170	424	19.1	Reduced yield	Cunningham et al., 1975b (p. 449-453)
Corn/plant	Sludge	6.8	4.4	109-343	300-944	17.0-22.2	Reduced yield	
Rye/plant	Sludge	6.8	7.5	16-189	38-472	14.4-19.1	Increased yield	
Corn/plant	Sludge	6.8	4.4	16-189	38-472	7.4-15.8	Increased yield	
Corn/plant	Sludge/$CuCl_2$	6.8	NR	120	NA	56.1	Decreased yield	Cunningham et al., 1975c (p. 456-458)
Rye/plant	Sludge/$CuCl_2$	6.8	NR	194	NA	30.9	Decreased yield	
Lettuce/shoot	Sludge	7.5	6.2	160	NA	8.2	Signif. yield reduction	Mitchell et al., 1978 (p. 168)
Wheat/leaf	Sludge	7.5	11.5	320	NA	15.4	Signif. yield reduction	
Wheat/grain	Sludge	7.5	7.5	320	NA	9.1	Signif. yield reduction	
Lettuce/shoot	Sludge	5.7	7.0	320	NA	10.7	Signif. yield reduction	
Wheat/leaf	Sludge	5.7	10.5	160	NA	11.8	Signif. yield reduction	
Wheat/grain	Sludge	5.7	7.7	160	NA	11.0	Signif. yield reduction	
Snap bean/plant	$CuSO_4$	6.7	8.3-24.7	NR	486	>40	Severe toxicity	Walsh et al., 1972 (p. 197)
Snap bean/plant	$CuSO_4$	6.7	8.3-24.7	NR	162	20-30	Reduced yield	
Red beet/tops	Sludge	NR	NR	80	200	NR	27% yield reduction	Webber, 1972 (p. 405)
Red beet/tops				80	200	NR	73% yield reduction	
Red beet/whole	Sludge	NR	NR		187 (over 3 yrs)	NR	19% yield reduction, NS[c]	Webber, 1972 (p. 407)
					500	NR	25% yield reduction	
					1,000	NR	72% yield reduction	

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (µg/g DW)	Experimental Soil Concentration (µg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (µg/g DW)	Effect	References
Celery/ marketable	Sludge	NR	NR		187 (over 3 yrs)	NR	13% yield reduction, NS	Webber, 1972 (p. 407)
					1,000	NR	No yield reduction	
Lettuce/plant	$CuSO_4$/Sludge	6.3	12.8	42	NA	13.8	21% reduction in yield	MacLean and Dekker, 1978 (p. 384)
Lettuce/plant	$CuSO_4$/Sludge	6.3	12.8	72	NA	18.7	43% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.3	12.8	132	NA	20.0[a]	47% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.3	12.8	252	NA	21.4[a]	59% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.3	12.8	492	NA	22.0[a]	52% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	5.9	11.8	42	NA	11.5	4% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	5.9	11.8	72	NA	11.3	9% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	5.9	11.8	132	NA	14.3	2% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	5.9	11.8	252	NA	13.0	9% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	5.9	11.8	492	NA	15.7	5% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.5 (limed)	11.0	42	NA	11.0	2% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.5 (limed)	11.0	72	NA	12.7	2% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.5 (limed)	11.0	132	NA	12.5	9% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.5 (limed)	11.0	252	NA	12.9	8% reduction in yield	
Lettuce/plant	$CuSO_4$/Sludge	6.5 (limed)	11.0	492	NA	12.7	3% reduction in yield	
Rye grass/plant	Sludge	7.6	<11.6	--	59	15.7	Increased yield	King et al., 1974 (p. 363)

TABLE 4-1. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Control Tissue Concentration (μg/g DW)	Experimental Soil Concentration (μg/g DW)	Experimental Application Rate (kg/ha)	Experimental Tissue Concentration (μg/g DW)	Effect	References
Wheat/grain	$CuSO_4$	5.2	NR	100	NA	NR	14% reduction in yield	Bingham et al., 1979 (p. 203)
Wheat/grain	$CuSO_4$	5.2	NR	200	NA	NR	26% reduction in yield	
Wheat/grain	$CuSO_4$	6.7	NR	100	NA	NR	4% increase in yield	
Wheat/grain	$CuSO_4$	6.7	NR	200	NA	NR	9% reduction in yield	
Plants in general	Cu	NR	11	NR	NA	18.2-20.3	Upper critical limit	Beckett and Davis, 1977 (p. 104)
Rye grass/plant	Sludge	4.3-6.8	10.5	98.1		40	Reduced yield, 40 μg/g toxic limit	Bolton, 1975 (p. 295)
Red beet/ marketable	Sludge	NR	NR		250 (over 2 yrs)	NR	52% yield reduction	Webber, 1972 (p. 409)
					500	NR	63% yield reduction	
					1,000	NR	95% yield reduction	
Lettuce/	Sludge	NR	NR		250 (over 2 yrs)	NR	No yield reduction	
					500	NR	43% yield reduction	
					1,000	NR	41% yield reduction	

[a] NA = Not available.
[b] NR = Not reported.
[c] NS = Not a statistically significant reduction.

TABLE 4-2. UPTAKE OF COPPER BY PLANTS

Plant/Tissue	Chemical Form Applied	Soil pH	Range (and N)[a] of Application Rates (kg/ha)	Control Tissue Concentration (μg/g DW)	Uptake[b] Slope	References
Corn/plant	Sludge	6.8	+46 μg/g to soil	4.4	0.045[c]	Cunningham et al., 1975a (p. 461-62)
Rye/plant	Sludge	6.8	+46 μg/g to soil	7.5	0.10[c]	Cunningham et al., 1975a (p. 461-62)
Corn/plant	Sludge	6.8	+46 μg/g to soil	10.4	0.30[c]	Cunningham et al., 1975a (p. 461-62)
Barley/plant	Sludge	7.9	0-0.83 (2)	NR[d]	0	Dowdy and Larson, 1975a (p. 232)
Barley/plant	Sludge	5.9	0-0.83 (2)	NR	0	Dowdy and Larson, 1975a (p. 232)
Snap bean/edible	Sludge	5.3-6.5	0-266 (7)	2.9-7.5	0.044	Dowdy et al., 1978 (p. 255)
Corn/grain	Sludge	5.0-6.3	0.6-58 μg/g to soil	1.5	0.01[c]	Sheaffer et al., 1979 (p. 457)
Oats/forage	Sludge	5.3-6.3	0.6-58 μg/g to soil	1.5	0.02[c]	Sheaffer et al., 1979 (p. 458)
Wheat/forage	Sludge	5.3-6.3	0.6-58 μg/g to soil	2.1	0.3[c]	Sheaffer et al., 1979 (p. 458)
Crimson clover forage	Sludge	5.3-6.3	0.6-58 μg/g to soil	7.1	0.04[c]	Sheaffer et al., 1979 (p. 458)
Rye/forage	Sludge	5.3-6.3	0.5-58 μg/g to soil	4.5	0.05[c]	Sheaffer et al., 1979 (p. 458)
Arrowleaf clover forage	Sludge	5.3-6.3	0.6-58 μg/g to soil	7.3	0.09[c]	Sheaffer et al., 1979 (p. 458)
Snap bean/edible	Sludge	5.3	0-266 (6)	4.1	0.04	Latterell et al., 1978 (p. 255)
Wheat/grain	Sludge	sandy, loam	0-8.8	3.5	0.013	Sabey and Hart, 1975 (p. 255)
Fodder rape/plant	Sludge	NR	0-206 (2)	3.9	0.02	Baxter et al., 1983b (p. 45)
Lettuce/leaf	Sludge	6.4	0-164 (2)	5.2	0.03	CAST, 1976 (p. 48)
Broccoli/fruit	Sludge	6.4	0-164 (2)	7.5	0.03	CAST, 1976 (p. 48)
Potato/tuber	Sludge	6.4	0-164 (2)	7.8	0.005	CAST, 1976 (p. 48)
Tomato/fruit	Sludge	6.4	0-164 (2)	5.0	0.03	CAST, 1976 (p. 48)
Cucumber/fruit	Sludge	6.4	0-164 (2)	7.7	0.04	CAST, 1976 (p. 48)
Eggplant/fruit	Sludge	6.4	0-164 (2)	25.1	0.01	CAST, 1976 (p. 48)
String bean/fruit	Sludge	6.4	0-164 (2)	8.1	0.005	CAST, 1976 (p. 48)
Cantaloupe/leaf	Sludge	6.4	0-164 (2)	9.2	0.06	CAST, 1976 (p. 48)
Sorghum/plant	Sludge	6.0	0-7.3 (3)	5.7	0	CAST, 1976 (p. 60)
Sorghum/plant	Sludge	6.6	0-7.3 (3)	5.2	0	CAST, 1976 (p. 60)
Sorghum/plant	Sludge	6.9	0-7.3 (3)	5.9	-0.06	CAST, 1976 (p. 60)
Corn/leaf	Sludge	NR	50.4 average	8.1	0.004	Webber et al., 1983 (p. 190-3)
Bean/edible	Sludge	5.3	0-145 (2)	3.2	0.003	Furr et al., 1976 (p. 891)
Cabbage/edible	Sludge	5.3	0-145 (2)	3.0	0	Furr et al., 1976 (p. 891)
Cabbage/edible	Sludge	5.3	0-145 (2)	0.6	0.008	Furr et al., 1976 (p. 891)
Cabbage/edible	Sludge	5.3	0-145 (2)	2.0	0	Furr et al., 1976 (p. 891)

TABLE 4-2. (continued)

Plant/Tissue	Chemical Form Applied	Soil pH	Range (and N)[a] of Application Rates (kg/ha)	Control Tissue Concentration (μg/g DW)	Uptake[b] Slope	References
Millet/edible	Sludge	6.4	0-145 (2)	2.4	0.001	Furr et al., 1976 (p. 891)
Onions/edible	Sludge	5.3	0-145 (2)	3.4	-0.015	Furr et al., 1976 (p. 891)
Potatoes/edible	Sludge	5.3	0-145 (2)	3.1	0.010	Furr et al., 1976 (p. 891)
Tomatoes/edible	Sludge	5.3	0-145 (2)	2.2	-0.003	Furr et al., 1976 (p. 891)
Rye grass/plant	Sludge	5.0-6.0	0-86 (6)	3.9	0.11	Kelling et al., 1977 (p. 353)
Sorghum/plant	Sludge	5.0-6.0	0-86 (6)	6.1	0.04	Kelling et al., 1977 (p. 353)
turnip/green	Sludge	5.6	0-11.5 (3)	7.7	0.15	Miller and Boswell, 1979 (p. 1362)

[a] N = number of application rates.

[b] Slope = y/x: y = tissue concentration (μg/g); x = application rate of Cu at kg/ha.

[c] Slope = y/x: y = tissue concentration (μg/g); x = soil concentration (μg/g). To convert soil concentration to application rate of Cu at kg/ha, divide given slope by 2.

[d] NR = Not reported.

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

Species (N)[a]	Chemical Form Fed	Feed Concentration (µg/g DW)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration	Effects	Reference
Pigs/poultry	Cu	4	--	--	Daily	Adquate level of Cu	Demayo et al., 1982 (p. 229)
Pigs/poultry	Cu	250	--	--	Daily	Slight weight gain	Demayo et al., 1982 (p. 229)
Livestock	Cu	15	--	--	Daily	Safe level	Demayo et al., 1982 (p. 229)
Sheep	Cu	1-10	--	--	Daily	Daily requirement	Demayo et al., 1982 (p. 230)
Sheep	$CuCl_2$	20-100	--	--	NR[b]	Poisoned; death 24-48 hr.	Demayo et al., 1982 (p. 231)
Steer	Cu	2,000	--	--	122 days	"Toxic effects"	Demayo et al., 1982 (p. 231)
Goats	Cu	--	--	8-32	54-144 days	Lethal	Demayo et al., 1982 (p. 231)
Mallard	Cu	--	--	29	Daily	Tolerated	Demayo et al., 1982 (p. 231)
Chicken	Cu	--	--	60	Daily	Tolerated	Demayo et al., 1982 (p. 231)
Chicken/duck	Cu	--	--	300-1,500	--	Lethal dose	Demayo et al., 1982 (p. 231)
Calf	$CuSO_4$	115-300	--	--	129 days	Lethal	NAS, 1980 (p. 164)
Chicken	Cu	500	--	--	Daily	Minimal toxic level	NAS, 1980 (p. 164)
Geese	$CuSO_4$	--	100	--	NR	Acute copper toxicosis	NAS, 1980 (p. 168)
Sheep	Cu	25	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 170)
Cattle	Cu	100	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 170)
Swine	Cu	250	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 170)
Horse	Cu	800	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 170)
Chicken/turkey	Cu	300	--	--	Daily	Maximum tolerable level	NAS, 1980 (p. 170)
Sheep	Natural forage	50-60	--	--	Daily	"Poisoned"	Demayo et al., 1982 (p. 231)
Cattle (5)	$CuSO_4$	300	--	--	129 days	Hemolytic crisis; death	Weiss and Bauer, 1968
Cattle (32)	$CuSO_4$	0-900	--	--	98 days	No observed effects	Felsman et al., 1973 (p. 157)
Rat (8)	$CuSO_4$	500	--	500	7-70 days	No effect	Boyden et al., 1938 (p. 397)
Swine (12)	$CuSO_4$ (25% Cu)	0-64 as Cu	--	3.2	88 days	Accelerated weight gain	Kline et al., 1971 cited in U.S. EPA, 1984b (p. 18) and in U.S. EPA, 1984c (p. VIII-6)
Swine	$CuSO_4$ (25% Cu)	127 as Cu	--	6.4	NR	Depressed weight gain, hemoglobin and hematocrit	Same as above.

[a] N = Number of experimental animals.
[b] NR = Not reported.

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

Species	Chemical Form Fed	Range of Feed Concentration (μg/g)(N)[a]	Tissue Analyzed	Control Tissue Concentration (μg/g WW)	Uptake[b] Slope	References
Rams	$CuSO_4$	5.9-45 (2)	Liver	58	24.5	Demayo et al., 1982 (p. 231)
Vole	synthetic/herbage	5.0-13.67 (4)	Liver	4.40-4.71	0.14	Williams et al., 1978 (p. 453)
Vole	synthetic/herbage	5.0-13.67 (4)	Kidney	2.28-6.65	0.44	Williams et al., 1978 (p. 453)
Vole	synthetic/herbage	5.0-13.67 (4)	Muscle	2.14-4.04	0	Williams et al., 1978 (p. 453)

[a] N = Number of feed rates.
[b] Slope = y/x; y = tissue concentration (μg/g); x = feed concentration (μg/g).

TABLE 4-5. TOXICITY OF COPPER TO SOIL BIOTA

Species	Chemical Form Applied	Soil pH	Soil Concentration (μg/g DW)	Application Rate (kg/ha)	Duration	Effects	References
Soil bacteria	$Cu(NO_3)_2$	7.1-8.4	50 μg/mL liquid culture medium	--	4 days	Inhibition of denitrification	Bollag and Barabasz, 1979 (p. 196)
Earthworm	$CuSO_4$	NR[a]	150	--	NR	Population reduced 50%	Ma, 1984 (p. 208)
Earthworm	$CuSO_4$	NR	260	--	NR	Total population reduction	Ma, 1984 (p. 208)
Earthworm	$CuCl_2$	Sandy loam	1,000	--	6 weeks	LC_{50}	Ma, 1984 (p. 208)
Earthworm	$CuCl_2$	NR	500-2,000	--	NR	Inhibition of growth and cocoon production	Ma, 1984 (p. 208)
Earthworm	$CuCl_2$	4.8	131	--	6 weeks	Significant reduction in cocoon production and litter breakdown, increasing soil pH to 6.0 and 7.1 reduced toxic effects of high Cu soil concentration	Ma, 1984 (p. 211)
Earthworm	$CuCl_2$	4.8	372	--	6 weeks	17.55 mortality	

[a] NR = Not reported.

TABLE 4-6. UPTAKE OF COPPER BY SOIL BIOTA

Species	Chemical Form	Range (and N)[a] of Soil Concentrations (µg/g DW)	Tissue Analyzed	Control Tissue Concentration (µg/g DW)	Uptake[b] Slope	References
Earthworm	sludge	0-84 kg/ha (4)	whole body	8.8-9.5	0.20[c]	Helmke et al., 1979 (p. 325)
Earthworm	$CuSO_4$	0-432 kg/ha (2)[d]	whole body	11	0.097[c]	Beyer et al., 1982 (p. 382)
Earthworm	sludge	11-46 µg/g	whole body	12-13	0.61	Beyer et al., 1982 (p. 383)
Earthworm	sludge	0-120 kg/ha (2)[d]	whole body	11	0.30[c]	Beyer et al., 1982 (p. 382)

[a] N = Number of application rates.
[b] Slope = y/x; y = tissue concentration; x = soil concentration.
[c] Soil concentration estimated from application rate assuming 2 kg/ha = 1 µg/g.
[d] Cumulative application during 8 years.

SECTION 5

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APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR COPPER IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Copper

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

$$1.038364 = \frac{(409.6\ \mu g/g\ DW \times 5\ mt/ha) + (25\ \mu g/g\ DW \times 2000\ mt/ha)}{25\ \mu g/g\ DW\ (5\ mt/ha + 2000\ mt/ha)}$$

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**

$$0.198161 = \frac{1.038364 \times 25\ \mu g/g\ DW}{131\ \mu g/g\ DW}$$

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**

0.04361684 = [(1.038364 -1) (25 μg/g DW x

0.61 μg/g DW [μg/g soil DW]$^{-1}$) + 12.5 μg/g DW]

÷ 300 μg/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**

$$0.2595910224 = \frac{1.038364 \times 25\ \mu g/g\ DW}{100\ \mu g/g\ DW}$$

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**

$$1.0118245482 = \frac{(1.038364-1) \times 25\ \mu g/g\ DW}{7.3\ \mu g/g\ DW} \times \frac{2\ kg/ha}{\mu g/g\ soil}$$

$$\times \frac{0.045\ \mu g/g\ tissue}{kg/ha} + 1$$

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**

$$4.819277 = \frac{40\ \mu g/g\ DW}{8.3\ \mu g/g\ DW}$$

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**

$$0.295452 = \frac{1.0118245482 \times 7.3\ \mu g/g\ DW}{25\ \mu g/g\ DW}$$

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**

If AR = 0, $0.05 = \frac{25\ \mu g/g\ DW \times 0.05}{25\ \mu g/g\ DW}$

If AR ≠ 0, $0.8192 = \frac{409.6\ \mu g/g\ DW \times 0.05}{25\ \mu g/g\ DW}$

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)**

$$0.084011 = \frac{[(1.0118245482 - 1) \times 4.1\ \mu g/g\ DW \times 74.5\ g/day] + 1250\ \mu g/day}{15000\ \mu g/day}$$

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)**

0.083410 =

$$\frac{(1.0118245482-1) \times 7.3\ \mu g/g\ DW \times 24.5\ \mu g/g\ tissue[\mu g/g\ feed]^{-1} \times 0.97\ g/day] + 1250\ \mu g/day}{15000\ \mu g/day}$$

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)**

0.115780 =

$$\frac{(409.6\ \mu g/g\ DW \times 0.05 \times 24.5\ \mu g/g\ tissue\ [\mu g/g\ feed]^{-1} \times 0.97\ g/day\ DW) + 1250\ \mu g/day}{15000\ \mu g/day}$$

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)**

$$0.09198636 = \frac{(1.038364 \times 25.0\ \mu g/g\ DW \times 5\ g\ soil/day) + 1250\ \mu g/day}{15000\ \mu g/day}$$

Pure sludge:

$$0.21987 = \frac{(409.6\ \mu g/g\ DW \times 5\ g\ soil/day) + 1250\ \mu g/day}{15000\ \mu g/day}$$

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)

$$0.125188 = (0.084011 + 0.083410 + 0.115780 + 0.09198636) - \left(\frac{3 \times 1250\ \mu g/day}{15000\ \mu g/day}\right)$$

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:

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

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

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

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

and where for the unsaturated zone:

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

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

PS = Percent solids (by weight) of landfilled sludge = 20%
t = Time (years)
χ = h = Depth to groundwater (m)
D^* = α x 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)

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

μ = Degradation rate (day^{-1})

and where for the saturated zone:

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

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

$\emptyset$ = Aquifer porosity (unitless)

B = Thickness of saturated zone (m) where:

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

D. **Equation 3. Pulse Assessment**

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

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

where:

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

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

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

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

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 $C(\Delta\ell,t)$ calculated in Equation 1 (μg/L)

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

2. **Sample Calculation**

$$2.11 = \frac{11.1\ \mu g/L + 10.0\ \mu g/L}{10.0\ \mu g/L}$$

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**

$$0.00858 = \frac{[(2.11 - 1) \times 10.0\ \mu g/L \times 2\ L/day] + 0.0\ \mu g/day}{2600\ \mu g/day}$$

III. INCINERATION

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

1. Formula

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

where:

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

2. Sample Calculation

$$1.045055 = [(2.78 \times 10^{-7} \text{ hr/sec} \times \text{g/mg} \times 2660 \text{ kg/hr DW} \times 409.6 \text{ mg/kg DW} \times 0.007 \times 3.4 \text{ ug/m}^3) + 0.16 \text{ } \mu\text{g/m}^3] \div 0.16 \text{ } \mu\text{g/m}^3$$

B. Index of Human Toxicity Resulting from Inhalation of Incinerator Emissions (Index 2)

1. Formula

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

where:

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

2. Sample Calculation

$$0.04777394 = \frac{[(1.045055 - 1) \times 0.16 \text{ } \mu\text{g/m}^3] + 0.16 \text{ } \mu\text{g/m}^3}{3.5 \text{ } \mu\text{g/m}^3}$$

IV. OCEAN DISPOSAL

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

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

Input Data	Condition of Analysis							
	1	2	3	4	5	6	7	8
Sludge concentration of pollutant, SC (μg/g DW)	409.6	1427.0	409.6	409.6	409.6	409.6	1427.0	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)	92.2	92.2	41.9	NA	92.2	92.2	NA	N
Site parameters								
Leachate generation rate, Q (m/year)	0.8	0.8	0.8	1.6	0.8	0.8	1.6	N
Depth to groundwater, h (m)	5	5	5	0	5	5	0	N
Dispersivity coefficient, α (m)	0.5	0.5	0.5	NA	0.5	0.5	NA	N
Saturated zone								
Soil type and characteristics								
Aquifer porosity, ∅ (unitless)	0.44	0.44	0.44	0.44	0.389	0.44	0.389	N
Hydraulic conductivity of the aquifer, K (m/day)	0.86	0.86	0.86	0.86	4.04	0.86	4.04	N
Site parameters								
Hydraulic gradient, i (unitless)	0.001	0.001	0.001	0.001	0.001	0.02	0.02	N
Distance from well to landfill, Δℓ (m)	100	100	100	100	100	50	50	N
Dispersivity coefficient, α (m)	10	10	10	10	10	5	5	N

TABLE A-1. (continued)

Results	Condition of Analysis							
	1	2	3	4	5	6	7	8
Unsaturated zone assessment (Equations 1 and 3)								
Initial leachate concentration, C_o (μg/L)	102000	357000	102000	102000	102000	102000	357000	N
Peak concentration, C_u (μg/L)	645	2250	1130	102000	645	645	357000	N
Pulse duration, t_o (years)	793	793	454	5.00	793	793	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)	645	2250	1130	102000	645	645	357000	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (μg/L)	11.1	38.8	11.1	11.1	59.0	387	8260	N
Index of groundwater concentration increment resulting from landfilled sludge, Index 1 (unitless) (Equation 4)	2.11	4.88	2.11	2.11	6.90	39.7	827	0
Index of human toxicity resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	0.00858	0.0299	0.00857	0.00856	0.0454	0.298	6.35	0

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