Environmental Engineering

Interim Report
Literature Review

Variation of Heavy Metals Concentrations in Municipal Wastewater Treatment Plant Sludges

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by

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Abstract

This literature review was written as part of a study on heavy metals in municipal sewage sludge and sludge compost. It provides background information on sources of heavy metals in municipal wastewater and sludge, the variability of the heavy metals concentrations, treatment and land disposal options for municipal sludges, the environmental impacts of heavy metals in land applied sludges, and federal and state regulations on land application of sludge with respect to heavy metals. The remaining portion of the project is an investigation of factors affecting the variability of heavy metals concentrations in composted municipal sludge.

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I. INTRODUCTION

Heavy metals cause several problems in municipal wastewater treatment systems. High concentrations of metals in wastewater are toxic to biological treatment processes. Metals discharged in the treated effluent can cause environmental damage. Metals are concentrated in wastewater sludges to levels that impose limitations on sludge disposal options.

Biological treatment processes remove metals from the liquid stream and concentrate them in the solid stream. Metal levels in sludges may be three or four orders of magnitude higher than in the influent. In the past, this process has been used to remove metals from the liquid stream and control effluent metal levels. Sludge disposal has typically been by incineration or landfilling.

In recent years, restrictions on incineration of metal-bearing wastes and decreases in available landfill space, along with increasing disposal costs have limited the sludge disposal options for many cities and towns. As a result, many municipalities are finding land disposal of sludge to be a suitable option.

Land disposal is subject to restrictions based on the metal content of the sludge. These restrictions increase the land area required for disposal and hence the cost of disposal.

This literature review examines the impacts of metals on land disposal of sludge and sludge products. The following subtopics are addressed:

1. Which metals are typically found in wastewaters and sludges and at what concentrations.
2. What factors affect the incorporation of metals into the sludge.
3. What are the sources of the metals.
4. What are the environmental impacts of the metals during land disposal.
5. How are metals in sludge and land disposal of sludge regulated.
6. What options are available to deal with the problems caused by the metals.

II. LITERATURE REVIEW

2.1 METALS IN MUNICIPAL WASTEWATER TREATMENT PLANTS

Typical Levels and Variability: Wastewater and Sludges

A number of studies have been conducted to characterize the composition of municipal wastewaters (3,8,38,39,46,51,76), POTW effluents (3,8,46,51,76), and municipal sludges (4,8,39,62,70,71,73). The elements selected for analysis differed from study to study, but certain ones were common to all studies. Furr *et al.* (33) and Mumma *et al.* (57) conducted the most detailed studies of metals in sludge. Furr *et al.* analyzed sludge from 16 cities for 68 elements. Mumma *et al.* analyzed 30 sewage sludges for 59 elements.

While individual values vary widely, mean values for metals in sludge are more constant. EPA (27) sampled 50 treatment plants 24 hours a day for at least six days, measuring the levels of priority pollutants in the influent, effluent and sludge. Fricke *et al.* (32) compared the mean values in sludge from this study with those from other available municipal sludge data bases. The values obtained by EPA for metals in sludge were within approximately a factor of two of the data base values.

Olthof *et al.* (62) studied literature values for metals' levels in wastewater treatment processes. They developed accumulation factors for metals in sludge. These are ratios of metals in sludge to metals removed from wastewater (expressed as mg metal/kg dry wt sludge per mg/liter metal removed from the wastewater). Values obtained ranged from 3270 to 24700. Digested sludge had higher values than raw sludge. They concluded that as a rule of thumb, 10,000 was a reasonable estimate.

Table 1 presents some typical values from the literature for the composition of raw wastewater and treated effluent. Table 2 presents ranges of metals' levels measured in sludges The variability in metal content of sludges from city to city is a reflection of the variability of sources of metals entering the treatment plants (71). For an individual are a function of influent concentration.

Sommers *et al.* (71) examined the variability of the composition of sludge. The coefficient of variation (standard deviation as a percent of the mean) for the metals studied ranged from 32% to 72% for studies conducted within a city and from 77% to 146% for studies of variability between cities. According to the studies conducted within individual cities, zinc, nickel, lead, and copper were moderately variable (C.V. 25-50%), while cadmium was highly variable (C.V.>50%). Doty *et al.* (22) sampled six plants on

TABLE 1. METAL CONCENTRATIONS IN WWTP INFLUENTS AND EFFLUENTS (micrograms per liter)

Reference		Al	As	Be	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn
Hanley (39)	influent	865	--	--	0	30	230	1600	70	170	0.4	20	--	10	200
	effluent	200	--	--	0	10	65	290	40	95	0.1	0	--	0	90
Brown _et_ _al._ (8)	influent	--	--	--	18	59	170	--	160	--	0.6	--	--	--	353
	effluent	--	--	--	16	13	67	--	92	--	0.5	--	--	--	182
Yost and Wukasch (83)	influent	--	--	--	33	786	168	17300	51	--	--	115	--	--	2070
	effluent	--	--	--	6.3	16.7	25.2	335	2.6	--	--	81.2	--	--	233
Aulenbach _et_ _al._ (3)	influent	2006	7.6	0.5	7.6	182	392	--	872	--	0.3	1000	10.8	23.4	580
	effluent	534	7.5	--	0.9	18.6	65.5	--	150	--	0.2	--	10.2	2.5	300

TABLE 2 RANGE OF METAL CONCENTRATIONS IN SLUDGE (ppm)

	Reference					
	Sommers (70)		Solotto *et al.* (69)		Bastian & Whittington (4)	
Metal	Range	Avg	Range	Avg	Range	Avg
Al	---	---	7750-36000	17360	---	---
As	6-230	43	---	---	10-50	9
Ba	---	---	100-4010	1360	nd-3000	1460
Be	---	---	1.2-6.5	2.5	---	---
B	4-760	77	3-1490	46	200-1430	430
Cd	3-3410	110	1-500	264	nd-1100	87
Cr	10-99000	2620	100-11000	2280	22-30000	1800
Co	1-18	5.3	---	---	nd-800	350
Cu	84-10400	1210	10-16000	1650	45-16030	1250
Fe	---	---	10900-60000	30650	---	---
Pb	13-19700	1360	180-7520	1890	80-2600	1940
Mn	18-7100	380	60-6040	976	100-8800	1190
Hg	0.5-10600	733	---	---	0.1-89	7
Mo	5-39	28	2-1290	254	---	---
Ni	2-3520	320	30-3000	372	nd-2800	410
Ag	---	---	80-500	195	nd-960	225
Sr	---	---	---	260	nd-2230	440
Sn	---	---	500-700	600	---	---
Ti	---	---	1000-20000	14200	---	---
V	---	---	320-10000	5200	nd-2100	510
Zn	101-27800	2790	500-11000	4040	51-28360	3483
Zr			100-5000	2030	---	---

nd-not detected

a biweekly basis for one year. The coefficients of variation for the metals studied ranged from 21-47%.

Sommers *et al.* recommends sampling every two to three months for a year to characterize sludge composition prior to land application. Doty *et al.* concluded that three to five biweekly samples are sufficient. EPA (28) recommends taking weekly samples for five weeks or more until the average value for the element being analyzed is within the 95 percent confidence interval.

Physical, Chemical and Biological Factors

Metals removal from wastewater and incorporation into sludge occurs primarily through two physicochemical processes: precipitation and adsorption. Settling processes dominate in primary treatment (39). Metals removed in primary treatment are in the insoluble form or are adsorbed to organic solids or to iron or manganese oxyhydroxide particles (61). Soluble metals and metals associated with non-settleable particles are discharged to secondary treatment (activated sludge). In the activated sludge process, metals are removed in two ways. Particulate metals are enmeshed in the biological flocs and settled out. Metal ions in solution are adsorbed onto microbial surfaces or onto extracellular polymers produced by the microorganisms (50). Adsorption sites in the biomass may be surface hydroxyl groups (hexose and pentose molecules on neutral polysaccharides), surface carboxyl groups on anionic polymers (77), or phosphoryl, carboxyl, sulphydryl and hydroxyl groups of membrane proteins and lipids and of cell wall structural components (58). Table 3 gives literature values for percent removal of metals by treatment process.

PRIMARY TREATMENT

The factors that affect metal removal in primary treatment process are the efficiency of suspended solids removal and the chemical species of the metal. Suspended solids removal is affected by basin design, surface loading rate, flow rate and influent suspended solids concentration. The chemical species is dependent upon the metal concentration, COD (a measure of dissolved organic carbon), hardness, alkalinity and pH of the influent wastewater (50).

The percent removal of metals in primary treatment can vary widely temporally at a single plant. The ratio of day to night metal loading can be as high as 8:1. There is no evidence of correlation between influent concentration and percent removal except for cadmium. The percent removal of cadmium decreases at increased influent concentrations (50). Rossin et al. (67) found that at a constant influent metal concentration the percent removal of cadmium, chromium, copper and zinc decreased as flow rate increased. Removal of lead was higher at higher flow rates. Brown et al. (8)

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TABLE 3. PERCENT REMOVAL OF METALS BY UNIT PROCESS

Reference	Al	Cd	Cr	Co	Cu	Fe	Pb	Hg	Mn	Ni	Zn
<u>Primary Treatment</u>											
Oliver and Cosgrove (61)	--	60	55	50	33	49	66	60	33	15	54
Hanley (39)	42	--	17	--	7	21	29	20	0	0	30
Lester *et al.* (51)	--	72	--	--	70	--	73	--	--	--	--
Stoveland *et al.* (76)	--	--	51	--	--	--	--	--	--	23	74
Brown *et al.* (8)	--	25	36	--	70	--	59	54	--	--	68
Hannah *et al.* (40)	--	12	7	--	19	--	30	--	--	4	--
<u>Activated Sludge</u>											
Oliver and Cosgrove (61)	--	50	54	--	60	--	79	--	--	1	50
Hanley (39)	84	--	99	--	82	74	67	94	29	55	60
Lester *et al.* (51)	--	63	--	--	79	--	73	--	--	--	--
Stoveland *et al.* (76)	--	--	33	--	--	--	--	--	--	61	78
Brown *et al.* (8)	--	11	78	--	61	--	43	--	--	--	48
Hannah *et al.* (40)	--	24	82	--	82	--	65	--	--	43	--
<u>Trickling Filter</u>											
Hanley (39)	55	--	33	--	32	60	14	41	17	73	33
Hannah *et al.* (40)	--	28	52	--	60	--	48	--	--	30	--
<u>Extended Aeration</u>											
Hanley (39)	70	--	77	--	82	72	40	37	28	50	39
<u>Aerated Lagoon</u>											
Hannah *et al.* (40)	--	--	71	--	74	--	58	--	--	35	--

parameters, physical/chemical factors and biological factors. Process parameters are sludge volume index, sludge age, suspended solids removal, dissolved oxygen concentration and settling time. Physical/chemical factors are temperature, pH, metal ion concentration, metal solubility, metal valency, concentration of complexing agents and particle size. The biological factor is the concentration of extracellular polymers. Sterritt et al. (72) state that sludge volume index, MLSS, effluent suspended solids and effluent COD affect metal removal. In the activated sludge process these are all a function of sludge age. Nelson et al. (58) concluded that system pH is the single most important factor influencing chemical speciation of metals and their distribution between bacterial solids and solution phases.

Several studies have examined the effect of sludge age on metal removal by activated sludge (58,66,72,74,77). In general, metal uptake by the sludge increases with sludge age . Maximum uptake occurred at a sludge age of 12 to 15 days. Nelson et al. (58) state that this is due to increased amounts of extracellular polymers. Rossin et al. (66) speculate that increased MLSS is not the only factor. Sterritt et al. (72) and Stoveland and Lester (77) note that effluent COD decreases as sludge age increases. Maximum metals removal coincided with minimum effluent COD at a sludge age of 12 days. Minimum metal removal was at a sludge age of six days which coincided with maximum effluent COD. These results suggest that soluble organic compound compete with the sludge for the adsorption of metals. Failure of the biomass to degrade these compounds resulting in poor effluent quality may result in decreased metal removal efficiency (72).

Values for average removal of individual metals indicate that some metals are typically removed more efficiently than others. Different metals are removed to various degrees by the different processes in primary and secondary treatment.

Literature values indicate that nickel is removed least efficiently of all the metals, usually less than 40%. Stoveland and Lester (77) attribute this to a high affinity for soluble ligands. Cantwell et al. (12) found no detectable free nickel in raw sewage; all was complexed. Rossin et al. (66) state that nickel removal may only be by sedimentation of precipitated nickel. Chen (15) found that nickel forms very little precipitate and that most precipitated nickel exists as particles less than eight microns, whereas most cadmium, chromium and copper are associated with larger particles that settle more readily. Gould and Genetelli (37) state that adsorption of nickel by activated sludge may be site specific.

Some metals are removed primarily through precipitation rather than adsorption. Sterritt *et al.* (72) concluded that lead and trivalent chromium are removed by precipitation while other metals are removed by adsorption. Rossin *et al.* (67) found that removal of lead is related to suspended solids removal, indicating that lead is primarily in an insoluble form in wastewater. In the activated sludge process, as dissolved oxygen decreases, hexavalent chromium is reduced to the trivalent form which then precipitates (8,77).

Addition of chelating agents reduces uptake of metals by sludge (16). These may be organic ligands, nitriloacetic acid (NTA), which is used in detergents, ethylenediaminetetraacetic acid (EDTA), which is used in industry, or others (10). Perry *et al.* (65) found that NTA was 90% degraded after nine to thirteen days in the activated sludge process, but that metal interaction with NTA interferes with biodegradation. Cheng *et al.* (16) found that the order of strength of competition for metal ions is: sludge<glycine<oxalate<NTA<EDTA.

Adsorption of various metals by activated sludge can vary depending on the concentrations of the other metals present. According to Lester (50), activated sludge is a dynamic process; the influent metal concentrations are continually changing hence equilibria between the phases of the metals are constantly shifting. Gould and Genetelli (37) found that metals could be "salted out" of sludge by addition of other metals except nickel. They concluded that the order of strength of competition was Cu>Cd>≈Zn>Ni. Sterritt and Lester (74) found the order of affinity of metals for sludge to be Cr>Cd>Ag>Pb>Zn>Cu>Ni,Co,Mn,Mo. Cheng *et al.* (16) obtained similar results but also found that the order varies with pH. Sterritt *et al.* (72) concluded that while some metals may compete for adsorption sites, competition for binding sites is generally negligible.

DIGESTION

During the digestion process some of the metals in sludge will solubilize (7). Metals in digester supernatants can be 10 to 300 times the influent concentration (8). If the supernatant is recycled through the treatment plant it can be a significant source of metals in the sludge.

Any sulfate that enters the digester will be reduced to sulfide. Excess sulfide will precipitate the soluble metals. Typically less than one percent of the sulfate in the wastewater ends up in the digester. This is not enough to precipitate all the soluble metals present in the supernatant (54).

During digestion the mass of the sludge is reduced as organics are degraded in the stabilization process. Digested sludges are typically higher in metals than raw or undigested sludges from which they derive because metals are concentrated during digestion (64).

COMPOSTING

Composting is the aerobic thermophilic decomposition of the organic constituents in sludge producing a relatively stable, inoffensive humus-like material (24). During the composting process temperatures between 55 and 65 degrees Celsius are attained, destoying pathogens and driving the evaporation of water. Volatile organics are reduced to carbon dioxide and water as the sludge is stabilized (29). Composted sludge is easier to handle, store and transport than raw sludge. Composted sludge is suitable for use as landfill cover.

In the composting process, sludge is mixed with organic amendments. These amendments act as a bulking agent, increasing the porosity of the mix and reducing the moisture content. The amendments also can be added to supply a source of limiting nutrients, such as carbon. The mixture is aerated by repeatedly turning the pile or by forcing air through the pile. In some processes the bulking agent is separated from the compost after composting and recycled for subsequent use.

There is very little information in the literature concerning the fate of metals during composting. The concentrations of heavy metals in the final compost will depend on several factors. These are:

1. the concentrations of heavy metals in the parent sludge,
2. the loss of metals through leaching,
3. increase in the organic content of the compost due to addition of organic amendments,
4. decrease in the organic content of the compost due to degradation of organics,
5. addition of metals in the composting amendments and
6. physical/chemical interactions between the compost and the bulking agent.

Metals are essentially conserved during composting; less than one percent are lost through leaching (60). The concentration of metals in compost will be determined primarily by the percent change in organic matter during composting and any metals that may be added to the sludge in the composting amendments (41,42,64).

The metals levels of compost will vary with the composting practice, the extent of digestion and the amount of amendments blended with the sludge (6). During the composting process volatile organics are lost from the sludge as the organic matter is degraded. Approximately 40% of the initial total solids will be degraded due to organic matter destruction. This will result in a corresponding increase in the final metals concentration (42). Parent sludges that have been previously digested will have higher metal concentrations than undigested sludges. Degradation of organics during the composting process will be less than for undigested sludges (64). Organic amendments such as woodchips, peanut hulls or leaves can provide a dilution effect lowering the metals concentration below that of the parent sludge (2,56,64).

The composting amendment can directly influence the metals content of the final compost. If the amendment is not separated from the compost at the end of the process, then any metals in the amendment will increase the mass of metals in the compost. The use of recycled compost that contains metals as a bulking agent is an example (41).

Physical and chemical interactions between amendments and sludge can affect the metals content of the compost. Shredded tires are used as a bulking agent. They contain metals, primarily iron and zinc, which become incorporated into the compost raising the metals levels (41).

Sorption of sludge metals onto the amendments has not been specifically studied. In a related study, however, Benson (5) examined the sorption of metals in landfill leachate onto sawdust. He determined that the sawdust had a fixing capacity of 113 meq/kg. Part of this fixing capacity was due to cation exchange reactions and part was due to complexation reactions.

Table 4 gives metal concentrations for several composts and their parent sludges.

2.2 SOURCES, FATE AND IMPACTS OF METALS

Non-industrial Sources

Sources of metals in sludge include background levels in the domestic water supply, domestic additions, industrial discharges, surface runoff and sewer infiltrations (81).

Klein *et al.* (46) studied the sources of cadmium, copper, chromium, nickel and zinc in New York City wastewater. They concluded:

1. Except for nickel at 62%, the electroplating industry does not contribute the major portion of the metals in the wastewater.
2. Other industries contribute less than 9% of metals.
3. Residential contribution of metals varies from 25-49%. Residential discharge of copper, cadmium, and zinc is considerably greater than industrial discharge.

TABLE 4 METAL CONCENTRATION OF COMPOST (AND PARENT SLUDGE)
(Parts Per Million)

Ref.	Amends.	Cd	Cr	Cu	Fe	Ni	Pb	Zn
64	wood chips	8 (10)	-- --	300 (420)	-- --	55 (85)	290 (425)	770 (980)
64	wood chips	9 (19)	-- --	250 (725)	-- --	-- --	320 (573)	1000 (1760)
41	shredded tires + recycled compost	39 (35)	-- --	633 (520)	20177 (8096)	85 (86)	513 (439)	2200 (1043)
41	shredded tires + wood shavings	36 (35)	-- --	591 (520)	18284 (8096)	77 (86)	489 (439)	1950 (1043)
21	wood chips	1.5 (4)	30 (90)	140 (600)	-- --	7 (50)	43 (80)	360 (600)
21	brush chips	0.5 (2.4)	96 (870)	60 (340)	-- --	17 (13)	74 (230)	80 (390)
56	bark	0.7 (4.8)	17 (28.6)	83.9 (278)	4173 (7550)	25.2 (22.6)	118 (408)	154 (453)

4. Water distribution systems contributes 67% more copper than electroplaters and half as much zinc.
5. Storm water runoff contributes more copper and zinc than electroplaters and about 10% of the other metals.

Yost and Wukasch (83) studied the metals contributions by industrial and residential discharges in Kokomo, Indiana. Residential inputs of these metals did not exceed 7% of the industrial inputs. Davis and Jacknow (18) investigated metals in urban wastewater. They found that residential loadings supplied 19 to 63% of the metals studied. Table 5 gives values for the percent contribution of metals by residential sources to municipal wastewater. Table 6 gives measured values for metals in urban runoff.

Gurnham et al. (38) conducted a detailed analysis of the sources of metals in domestic wastewater. Metals concentrations and loadings for sources such as household products, foodstuffs, runoff, tapwater and soils were studied. Table 7 gives per capita mass loading of metals by various residential sources.

Data from some treatment plants suggest that the water supply system is the major source of metals in wastewater (9,18,30,71). Corrosion of distribution piping and home plumbing along with the use of corrosion inhibitors are sources of cadmium, copper, zinc, and lead. This occurs

TABLE 5 PERCENTAGE OF METAL LOADING FROM RESIDENTIAL SOURCES

	Reference	
	Davis and Jacknow (17)	Klein et al. (46)
Cd	63	49
Cr	23	28
Cu	96	47
Ni	63	25
Pb	19	--
Zn	32	42

TABLE 6 CONCENTRATIONS OF METALS IN URBAN *RUNOFF* (*mg/l*)

Cd	0.025
Cr	0.16
Cu	0.46
Ni	0.15
Zn	1.6

Source: Klein et al. (46)

TABLE 7 HEAVY METAL MASS FLOW FROM RESIDENTIAL SOURCES (micrograms per capita per day)

Metal	*Tap Water*	*Foods*	*Commodities*	Total
Cd	518	482	81	842
Cr	845	364	662	1,871
Cu	7,580	2,909	510	10,996
Pb	2,612	331	272	3,215
Hg	110	27	7.5	144
Ni	4,590	699	23,449	28,738
Zn	12,204	11,953	738	24,895

Source: Gurnham et al. (38)

with low alkalinity, low pH surface waters or low pH, high dissolved CO_2 groundwaters (9).

Brown (9) estimated the minimum concentrations of metals in tap water that would result in metal levels in sludge in excess of land application guidelines. He compared these values with data for drinking water in Boston and Seattle. The metals concentrations in these waters were above the calculated value for copper.

Hazards Posed by Metals

There is some variation in the literature concerning precisely which metals present the more serious hazards. Chaney (14), states that the elements in sludge and effluent that are potential hazards to plants or the food chain are B, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn. Elinder and Kessler (25) state that possibly toxic elements are Al, V, Co, Ni, Mo, Sn, and Sb, while elements causing major health problems are Hg, Pb, Cd, and As. Dean and Seuss (20) concluded that with the exception of cadmium, heavy metals in sludge are not expected to affect human health through accumulation in food and fodder plants. EPA (17) identified those elements posing relatively little hazard as Mn, Fe, Al, Cr, As, Se, Sb, Pb, and Hg. Elements posing a potentially serious hazard were Cd, Cu, Mo, Ni, and Zn. Brown and Lester (10) identify metals of concern as Cr, Mn, Fe, Co, Cu, Zn, Mo, Ag, Hg, Cd, and Ni. Gleason *et al.* (35) note that elements such as Cu, Zn, Mo, and Fe, present in sewage sludge added to agricultural soils at agronomic rates can help alleviate trace metal deficiencies in plants. An increase in plant trace metal content following sewage sludge application can also reduce the need for supplements of such elements as Se and Mo in animal diets.

Zenz et al. (84), commenting on proposed EPA regulations to control land application of sludge, cited several studies to argue that the regulations were too restrictive. They stated that:

1. The metals may be precipitated to sparingly soluble inorganic forms that are not available to plant growth.
2. The metals are absorbed by organic matter reducing their activity.
3. Metals are held back by the soil-root barrier. The rejection of metals varies not only with species but even with strains.
4. Metals taken up by roots accumulate preferentially in the stems and leaves and are not translocated to the fruits or grains. Total metal uptake by young plants is a poor indication of the hazard to human food.
5. Metal toxicity usually inhibits growth before concentrations toxic to humans have been reached in the parts used for food.

6. Not all metals resent in foods are assimilated into the body burden. Cadmium, for example, is rapidly excreted in the feces; only three to eight percent is slowly excreted and contributes to the body burden.

Individual Metals

CADMIUM

It is widely agreed upon that cadmium is the element that poses the most serious health hazard in the food chain. Cadmium is readily taken up and accumulated by plants without phytotoxic effects (14,20). Chronic health effects may result through diet and cigarettte smoking, which are the main routes of uptake for most people (26).

Cadmium is not an essential element. It resembles zinc in its chemical and physical properties. The average dietary intake in nonpolluted areas is 10-25 ug/day. Simultaneous intake of calcium, zinc or iron at low levels can increase cadmium absorption. Cadmium toxicity is affected by the quantity and quality of protein in the diet. Only about 5-6% of the cadmium in food or beverage is taken up by the body, but 50-75% of this amount is deposited in the liver and kidneys (79). Long term exposure can result in kidney or liver damage (26).

Cadmium is taken up by plants and translocated to other parts of the plant. Leafy vegetables and root crops accumulate cadmium in their tissues. Tobacco also accumulates cadmium, increasing the exposure of cadmium for smokers (26).

Cadmium is found in low levels in rocks, soil and water (79). The chemistry of cadmium in the soil is not well understood. It is apparently influenced by organic matter, clay content and type, hydrous oxide content, pH and redox potential (17). At pH levels between 6 and 9, metal hydroxide and carbonate precipitates form, limiting cadmium availability (20).

Industrial uses of cadmium include low melting alloys and solders, electroplating, batteries, and photoelectric cells. Cadmium is found as an impurity in zinc and superphosphate fertilizers. It is used in pigments, plastics, detergents, heating and lubricating oils and coal. Cadmium can be found in industrial, commercial and residential wastewaters as well as storm runoff (19,46,79).

COPPER

EPA (17), classified copper as an element posing a potentially serious hazard. Chaney (14), considers copper a significant food chain hazard. He also states that copper will cause severe plant injury before it reaches levels toxic to animals, except sheep. Dean and Seuss (20), state that plants are an effective barrier against copper toxicity in animals.

Copper is an essential element for all organisms. Copper is essential to plants but it can be phytotoxic at higher concentrations. Under toxic conditions most copper remains in the roots-very little is transported to aerial portions. Sheep are the most susceptible to copper toxicity, followed by cattle, swine and poultry. Swine, sheep and cattle can accumulate copper in the liver. Molybdenum deficiency is antagonistic to copper toxicity. Controlling molybdenum intake can prevent copper toxicity. High levels of copper in the diet are beneficial to swine and chickens. Debate concerning the addition of high levels of copper to animal diets has focused primarily on copper toxicity to plants grown on land treated with the animal wastes (17).

Copper is found in all soils, usually in the range of 10-80 ppm (48). In soils it is associated with hydrous oxides of Mn and Fe, and soluble and insoluble complexes with organic matter (17). Copper toxicity usually occurs on acid soils. Control of pH can limit copper availability to plants (20).

Sources of copper include pulp and paper, petroleum refining, and metal works industries. Other sources are soft drink production, laundries, food processing, algal control chemicals, residential wastewater and urban and rural runoff (19,46). Water supply systems can be a major source of copper. Water supplies can be high in copper due to erosion and corrosion of residential plumbing by low alkalinity waters (9).

CHROMIUM

Chromium exists naturally either in trivalent or hexavalent forms. Hexavalent chromium is toxic to plants, animals and humans. Trivalent chromium is an essential element for all organisms--required for glucose metabolism (25). The main source of chromium in humans is food. Meat, whitefish, vegetables, unrefined sugar and vegetable oil are the largest sources to man (79).

In the soil chromium(VI) is rapidly reduced to soluble chromium(III), which is converted to insoluble chromium(III). In the wastewater treatment process chromium(VI) is reduced to chromium(III) so sludge usually does not contain hexavalent chromium. Decomposition of sludge in soil is slow enough that there is no buildup of soluble chromium (17).

Dean and Seuss (20), state that sludge borne chromium has no effect on plants or animals. EPA (17), classified chromium as an element posing relatively little hazard. Sources of chromium include pulp and paper, chemical, and fertilizer manufacturing, petroleum refining, metal works, metal plating, glass, cement, asbestos and textile manufacturing, and steam generation (19). Chromium is also used in leather tanning, dyeing, photography and lithography (79). Sources of chromium in commercial wastewater include bakeries, food processing, laundries and car washes.

LEAD

Lead is a non-essential element that is capable of causing major health problems. The major sources of exposure in humans are food, wine, water, dust and paint (25).

Lead in sludge poses relatively little hazard. Lead forms insoluble compounds or is sorbed in soils becoming unavailable to plants. Soluble lead in the soil reacts with clay, phosphate, carbonate, hydroxide, sesquioxide and organic matter to greatly reduce solubility. Lead is taken up by plants in ionic form. Uptake decreases with pH, cation exchange capacity and available phosphorus (17). Any lead that is taken up by plants tends to remain in the roots. The shoots obtain very little soil lead (20). The main source of lead in plants is atmospheric deposition (79).

Other routes of lead transfer provide the only health risks to humans and animal. Direct ingestion of sludge or sludge amended soil by animals or humans is the most serious health risk. This may be due to direct soil ingestion by animals while grazing, ingestion by animals or humans of plants on which sludge or soil deposition has occurred, or pica soil ingestion by humans. About 90% of the lead deposited in the body is in the skeleton, so intake of lead through ingestion of animal products is not a major health risk to humans (20).

Sources of lead include pulp and paper, chemical and fertilizer manufacturing, petroleum refining and metal works and battery manufacturing. Other sources include paints, dyes, solders, automobile and smelter emissions, corrosion of plumbing, food, soil and dust (19,20,79).

NICKEL

Nickel is an essential element in animals that is found in nearly all soils, plants and waters. Soils typically contain 10-100 ppm nickel. In the soil, nickel is adsorbed onto hydrous oxides of iron or manganese or is strongly chelated by organic matter (17).

The only form of nickel known to cause systemic effects in humans is nickel carbonyl. Insoluble forms of nickel have been linked to respiratory cancer (25). Nickel in sludge or sludge fertilized crops fed to animals has not led to bioaccumulation. Nickel ingested by humans is relatively nontoxic except to persons who are sensitive to nickel (20).

Nickel is not known to be essential to plants. It is toxic to plants at levels greater than 50 ppm. Chaney (14) states that nickel will be phytotoxic before reaching levels hazardous in the food chain. Toxicity usually occurs on acid soils. Controlling pH will reduce nickel toxicity in plants (17).

Nickel is found in fossil fuels, batteries, alloys, inks and varnishes. The most significant route of exposure in humans is by dermal contact. Concentrations in food vary up to approximately 6 ppm (79). Sources of nickel in wastewater include pulp and paper and fertilizer manufacturing, petroleum refining, metal works, bakery wastes and runoff (19,46).

ZINC

Zinc is essential for the functioning of various enzymes in all organisms. Zinc is commonly deficient in crops and is typically added with fertilizers. Normal plant levels range from 10 to 100 ppm. Higher levels in plants can be phytotoxic and can be a food chain hazard (14,25). Toxicity in plants occurs at tissue concentrations of several hundred ppm. A wide margin of safety exists between normal dietary intake and toxic levels in birds and mammals (17).

In the soil, zinc is sorbed onto clay and hydrous iron oxides and chelated by organic matter. In general, if the pH of the sludge-treated soil is maintained at recommended levels, zinc should not be a serious hazard to plants or the food supply unless the sludge contains exceptionally high levels of zinc (17).

Sources of zinc include pulp and paper, chemical and fertilizer manufacturing, petroleum refining, metal works and steam generation (19). Other sources are fat rendering, food processing, soft drink manufacturing, dyeing and laundries (46).

IRON AND ALUMINUM

Iron and aluminum are common elements in the soil. Most soils contain large amounts of iron and aluminum so that addition of sludges high in these elements will not significantly alter the soil composition. Typically, iron and aluminum are not limiting factors in sludge application (17).

Iron and aluminum are soluble in the soil only at low pH or under reducing conditions. Aluminum toxicity in plants is common below pH 5.0. At pH above 5.5 iron and aluminum form sparingly soluble oxides and hydroxides. Iron is mobile in the soil solution in minute amounts chelated with organic anions. With good soil management practices, most iron and aluminum in the soil solution will rapidly precipitate out as hydroxides (17,48).

Sources of iron and aluminum include chemical and fertilizer manufacturing, petroleum refining and metal works (19).

MANGANESE

Manganese is an essential element. Like iron and aluminum, manganese is available in the soil only at low pH or under reducing conditions. At pH above 5.5 manganese forms insoluble tetravalent oxides or some stable organic complexes. Under these conditions manganese can be toxic to plants. Manganese may accumulate in plants if large amounts are present in the soil. High levels of soluble iron in the soil may induce manganese deficiency in plants. Typically, manganese is not a limiting factor in sludge application (17,48).

MOLYBDENUM

Molybdenum is an essential element in plants and animals. It is a cofactor in seven enzymes. In plants it is essential for nitrogen fixation and nitrate reduction (49). Molybdenum does not appear to be phytotoxic at high concentrations in plants (17).

Tolerance of animals to molybdenum varies with species and age. Excessive molybdenum in the diet of animals causes copper and phosphorus deficiencies. The condition is correctable with copper and phosphorus supplements. It is doubtful that molybdenum in sludge would present a serious health hazard to grazing animals except where forages from sites treated with sludge high in molybdenum form the major part of the animal diet (17).

In the soil molybdenum exists primarily in an anionic form. The soil has no general mechanisms for retaining molybdenum. It can pass through the soil and enter the groundwater. It is precipitated at high pH by calcium, and at low pH by iron and aluminum (48). Molybdenum has a great affinity for iron oxide particles. Maximum sorption of molybdenum is at pH 4.2. Availability increases with pH. Keeping the pH near neutral does not limit availability. Phosphorus can replace molybdenum on oxide particles (17).

SELENIUM

Selenium is essential for some animals. A narrow range exists between deficiency and toxicity in animals--0.5 to 4 ppm. Selenium can counteract mercury toxicity in some animals. There is little evidence that selenium is essential to plants, but it is taken up by plants (17).

In the soil selenium is least soluble at low pH. Under neutral to alkaline conditions it exists as the selenate anion which is quite soluble and does not sorb onto clay particles. Cappon (13) found that sludge and compost were less effective in maintaining selenium buildup in the soil. Selenium volatilization from the soil may be enhanced by sludge or compost. More information is needed to evaluate the potential hazard from selenium in sludge (17).

BORON

Boron is essential for plant growth. There is a very narrow margin between soil levels of boron that produce deficiency symptoms and that cause toxicity in plants. Deficiency symptoms occur at 0.04 mg/l water soluble boron. Toxicity occurs at soil solution concentrations above 1.0 mg/l (28).

In wastewater boron exists mainly in the form of the undissociated boric acid molecule. Being uncharged, it passes through the soil more readily than other elements. In humid and semihumid regions rainfall is usually sufficient to leach applied boron from the root zone (28).

Environmental Pathways

The EPA, in developing its regulations on sludge disposal, created a list of chemicals selected for environmental profile development. These chemicals then underwent further risk assessment to rate the hazards that they present in sludge (52).

The EPA also identified the pathways by which these chemicals would impact the environment during sludge disposal. The metals and pathways identified for land application and landfilling of sludge are listed in Table 8 (52).

2.3 REGULATIONS

Land application of sludge is regulated by the federal government and by most state governments. The EPA has limited regulations on land application and defers to state regulations in most matters. Many states have incorporated EPA regulations and guidelines into their regulations.

There are two types of regulations. Some regulations control the disposal process. They specify how the land application process is to be managed and/or set limitations based on characterisitics of the disposal site. The force of these regulations is typically on the operator of the land application site. Other regulations control the sludge to be utilized in the land application process. They limit the land application process according to the sludge characteristics. The force of these regulations is

TABLE 8 METALS AND ENVIRONMENTAL PATHWAYS STUDIED FOR DEVELOPMENT OF REGULATIONS

LAND APPLICATION OR DISTRIBUTION OF SLUDGE PRODUCTS

Soil Biota Toxicity: Copper

Toxicity to Soil Biota Predators: Cadmium, Zinc, Lead

Phytotoxicity: Cadmium, Chromium, Copper, Nickel, Lead, Zinc, Selenium

Animal Toxicity from Plant Consumption: Zinc, Molybdenum, Selenium, Copper, Cadmium, Iron

Human Toxicity from Plant Consumption: Cadmium, Zinc, Nickel, Lead, Selenium, Arsenic, Iron, Mercury

Human Toxicity from Animal Products: Selenium, Zinc, Mercury, Cadmium

Human Toxicity from Incidental Ingestion: Arsenic, Lead, Mercury, Cadmium, Iron

LANDFILLING OF SLUDGE

Human Consumption of Contaminated Groundwater: Arsenic, Lead, Copper, Mercury, Nickel

Source: Lomnitz et al. (52)

typically on the operator of the treatment facility or the distributor of the sludge product. In many states these regulations provide little or no regulatory control once the sludge has been distributed to the end user.

Currently, the only metal regulated by the EPA is cadmium. Cadmium loadings are subject to both annual and cumulative restrictions. The maximum annual loading is 0.5 kg Cd/ha. The maximum cumulative loading varies from 5 to 20 kg Cd/ha with the pH and cation exchange capacity (CEC) of the soil. These cumulative loading restrictions are given in Table 9.

EPA regulations also contain a second approach to cadmium control. Unlimited application of cadmium is allowed providing that four specific control measures are taken. First, the crop grown can only be used for animal feed. Second, the pH of the soil must be maintained at 6.5 or above as long as the food chain crops are grown. Third, a facility operating plan must describe how the animal feed will be distributed to prevent human ingestion. The plan must describe measures that will be taken to prevent cadmium from entering the human food chain due to alternative future land uses of the site. Fourth, future owners are provided notice (through provision in land record or property deed) that there are high levels of cadmium in the soil and food chain crops should not be grown (26).

In addition to regulating cadmium, the EPA has also issued guidelines on the maximum cumulative loadings for lead, zinc, copper and nickel. The maximum loadings vary with the CEC of the soil. Table 9 lists these maximum loadings.

The impact of heavy metals in municipal sludge on land application programs will vary from state to state depending on each state's regulations. States differ in the extent of regulation, what aspects of the sludge disposal process are regulated as well as the actual standards that are set.

States' regulations vary in the number of standards and requirements that are explicit. For example, some states limit the cumulative metals loadings of the soil, others set maximum permissible sludge metals concentrations and some states use both standards. States' regulations can also vary in the number of land disposal options that are explicitly regulated. Some states regulations refer only to land application in general, while others have separate standards for such options as agricultural use, land reclamation, roadside use, composting and distribution, etc.

Most states require that each sludge application site be approved by the regulating agency. A typical site application contains a physical description of the proposed site and explains how the land application program will be

TABLE 9 MAXIMUM CUMULATIVE METAL LOADINGS ON LAND

Metal	Soil Cation Exchange Capacity (meq/100g) 0-5	5-15	>15
	Maximum Cumulative Loading (kg/ha)		
Cd (1)	5	10	20
Cu (2)	125	250	500
Pb (2)	500	1000	2000
Ni (2)	125	250	500
Zn (2)	250	500	1000

(1) EPA regulation
(2) EPA guideline

disposal options may be selected based on the metals levels in the sludge.

Pretreatment

The EPA requires wastewater treatment plants to implement an industrial pretreatment program to control entry of potentially harmful wastes into the system (47). Zenz et al. (84) and Lue-Hing et al. (53) examined the effect of the pretreatment program of the Metropolitan Sanitary District of Greater Chicago on the sludge cadmium content. Zenz et al. found that enforcing an industrial discharge standard of 2.0 mg/l cadmium reduced sludge cadmium levels by as much as 72%. In spite of this, sludge cadmium levels were still well in excess of 25 ppm. Lue-Hing et al. concluded that further reductions in the discharge standard would cause only minimal improvement in reducing cadmium loadings to the wastewater treatment plants.

Koch et al. (47) estimated the impact of a pretreatment program on the heavy metals content of sludge in two regional wastewater treatment districts in New Jersey. They concluded that in one district a 70% reduction in cadmium levels of the sludge was achievable. However, this would only result in a 10% increase in the amount of sludge that could be land applied because copper would then become the limiting element. They concluded that in some areas pretreatment would provide only minor benefits to land application programs.

Pretreatment programs can reduce both zinc and cadmium levels. The net effect can be a reduction, no effect or an increase in Zn/Cd ratios. This may not benefit land application in states that regulate the Zn/Cd ratios of sludge (84).

Brown (9) notes that when a water supply system is responsible for significant metal loadings to a POTW, treatment practices can be instituted to control the problem. The major obstacle is usually achieving interagency cooperation between the governing bodies of the water supply and wastewater treatment systems to deal with the problem.

Additional Treatment

Additional treatment to remove metals from wastewater or sludge is not commonly practiced. A number of studies investigating various treatment processes have been published. Most are laboratory or pilot studies. Few have been implemented on a large scale. Recovery of metals from sludge is not economical at this time (23).

The most commonly investigated treatment process is acid extraction of metals from sludge. The sludge is acidified to a pH between 1.5 and 3.0 to solubilize the metals. Contact times studied vary from 15 minutes (68) to 24 hours

(82). Metal removal is dependent upon the pH attained, the metal being removed, percent solids of the sludge and contact time (82).

Additional treatment is required to precipitate and remove the metals from the acid extract. Also, the pH of the original sludge must be returned to a level near neutral (44). Acid extraction approximately doubles the cost of sludge treatment and disposal (11).

Jenkins et al. (44) compared acid treatment of sludge with extraction using EDTA. Results of the EDTA treatment varied for primary, waste activated and digested sludges. The EDTA treatment was more effective removing camium, copper and lead and less efficient for iron, chromium, nickel and zinc. The EDTA treatment is also much more expensive than acid treatment. They concluded that acid treatment of digested sludges was the better choice for metal removal.

Alibhai et al. (1) examined EDTA treatment of sludge. They concluded that treatment with EDTA can:

1. extract metals from sludge generating more sites for adsorption.
2. extract extracellular polymers and perhaps reduce the metal binding capacity of the sludge.
3. change the nature of the binding sites.
4. render the sludge inactive. Inactivation does not

affect binding capacity.

5. reduce the alkalinity of the sludge.

At one time chlorine stabilization was practiced as an alternative to anaerobic digestion. In this process chlorine gas is applied to the sludge in an enclosed tank. The chlorine reacts with the water to form HCl, lowering the pH and solubilizing the metals in the sludge (60,75). The results obtained are similar to those for acid treatment. The release of metals is a function of the final pH, the type of sludge and the species of metal present. The filtrate from the chlorine oxidation process also has increased phosphorus and COD (63,78).

Chlorination of sludge can have adverse effects on the sludge and the environment after disposal. Chlorine oxidation forms a large number of chlorinated hydrocarbons in the sludge. Chlorinated sludge has been shown to reduce the growth of plants compared with unchlorinated sludge (45). Sukenik *et al.* (78) concluded that the benefits of chlorine oxidation come from the acid effects while the chlorine effects could be deleterious.

Farooq and Aklaque (31) investigated ozone oxidation of sludge to remove metals. They found that ozone released metals from sludge with only a slight decrease in pH. The alkalinity and COD of the sludge were also lowered by the treatment.

Huang (43) conducted pilot plant studies using coprecipitation with lime in an upflow expanded sand bed. Calcium carbonate and the metal precipitates were plated onto the sand grains. The sand grain increased in size and eventually formed large dry chemical pebbles a few millimeters in diameter that were easy to handle in the disposal process.

Optimum removal was at pH 10.0-10.5 at pH 10.5 COD was reduced 21%, suspended solids 38%, volatile suspended solids 43% and total P 64%.

Fronk et al. (33) investigated centrifugal treatment of sludge. A continuous countercurrent bowl centrifuge was used to separate sludge into two fractions. The heavier fraction contained precipitated metals and heavy organics (including pesticides). The efficiency of removal varied with the source of the metal. Better removals were obtained for most metals using digested sludge. They concluded that the process may be cost effective for upgrading sludge for composting or land application.

Bloomfield and Pruden (7) investigated the effects of anaerobic and aerobic digestion on metal solubilization. They found that aerobic digestion or anaerobic digestion followed by aerobic digestion increased the amount of metals that were leachable with water.

Land Disposal Options

Several land disposal options are available for sludge. Land application is the application of sludge to land to enhance plant growth. Landfilling is disposal of sludge in a sanitary landfill with an impervious liner and cover. Dedicated land disposal is burial of sludge in unconfined sites. Land reclamation is the application of sludge to restore severely disturbed land such as strip mining sites. Distribution is the distribution or sale of dewatered or dried sludge or sludge products such as compost.

While the impact of metals on each of these options will vary from state to state based on individual state regulations, some general effects may be noted.

Land application is typically most heavily influenced by the metals content of the sludge. Some states' regulations distinguish between different land uses in land application. Land which is to be used for growing food chain crops is subject to more restrictions than other uses such as horticultural crops, forestry crops, recreational land or roadside development.

Dedicated land disposal and land application are less subject to impacts by the metals content of the sludge. Larger quantities of sludge and lower quality sludge typically may be used.

Landfilling, where allowed, is the least impacted disposal option. Sludge disposal in a landfill is usually unrestricted as long as the metals content does not classify it as a hazardous waste. This is typically not the case with municipal sludge. Landfills are often used to dispose of nonhazardous sludges that are too contaminated for other disposal options.

User oriented regulations promulgated to control land application of sludge are usually inadequate to control distribution of sludge products. Distribution of sludge products is usually controlled by product oriented regulations. Typically these regulations are as restrictive or more restrictive than those controlling land application.

For any land disposal option, the regulations for the different metals will not have the same impact on the suitability of the sludge for disposal. Typically only one or two metals in the sludge will control the disposal options. The other metals usually are not present in sufficient quantities relative to the regulated maximum levels to effect disposal.

Mercury is usually one of the more tightly regulated metals found in sludge. Mercury, however, is typically found in sludges at such low levels that it is rarely a limiting element in sludge disposal schemes.

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APPENDIX A
SUMMARY OF STATE REGULATIONS ON LAND APPLICATION

Connecticut

Regulating Agency: Department of Environmental Protection
Type of Rules: Guidelines
Type of Approval Required: Site approval
Typical Interval Between Sludge Analyses: 3 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application
Criteria for Metals Regulations: Maximum permissible metals concentrations, maximum cumulative loading limits (See Table A1)

Delaware

Regulating Agency: Department of Natural Resources and Environmental Control
Type of Rules: Draft regulations (published May, 1987)
Type of Approval Required: Site Approval
Typical Interval Between Sludge Analyses: 4 months
Metals Regulated: Cd, Cr, Cu, Ni, Pb, Hg, Zn
Disposal Options Specified: Agricultural use, land reclamation, surface land disposal, and sludge distribution
Criteria for Metals Regulations: Land application must conform to federal regulations and guidelines. Maximum sludge metals concentrations set for sludge distribution (table A2)

Maine

Regulating Agency: Department of Environmental Protection
Type of Rules: Regulations
Type of Approval Required: Site approval or program approval
Typical Interval Between Sludge Analyses: 1,3 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Criteria for Metals Regulation: Maximum Permissible Concentrations (Table A3) and Maximum cumulative loading (Table A4)

Table A1 Connecticut Sludge Metals Limitations

Metal	Maximum Permissible Concentration (mg/kg)	Maximum Cumulative Loading (kg/ha)
Cd	25	3.37
Cr	1000	336.8
Cu	1000	84.2
Pb	1000	336.8
Hg	10	not regulated
Ni	200	33.7
Zn	2500	168.4

Table A2 Delaware Maximum Sludge Metals Concentrations for Sludge Distribution (mg/kg)

Cd	12.5
Cu	500
Pb	500
Hg	5
Ni	100
Zn	1250

Table A3 Maine Maximum Permissible Sludge Metals Concentrations (mg/kg)

Cd	10
Cr	1000
Cu	1000
Pb	700
Hg	10
Ni	200
Zn	2000

Table A4 Maine Maximum Cumulative Metals Loading (kg/ha)

	Soil Cation Exchange Capacity		
	<5	5-15	>15
Cd	2.5	5	5
Cr	250	500	1000
Cu	125	250	500
Pb	500	1000	2000
Ni	250	500	1000
Zn	50	100	200

Massachusetts

Regulating Agency: Department of Environmental Quality Engineering
Type of Rules: Regulations
Type of Approval Required: Site approval required for Type II and Type III sludges
Typical Interval Between Sludge Analyses:1, 3 or 6 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn, Mo, B
Disposal Options Specified: Land application and distribution
Criteria for Metals regulation: Sludge classified Type I, II or II by metals concentrations (Table A5). Type II and III subject to maximum cumulative loading limits (Table A6), maximum annual cadmium loading and maximum annual soil lead concentration.

New Hampshire

Regulating Agency: Department of Environmental Services
Type of Rules: Regulations and guidelines
Type of Approval Required: Site approval required (except for small scale manual application).
Typical Interval Between Sludge Analyses: 4 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Agricultural use, land reclamation, forest application, governmental use, composting and landfilling
Criteria for Metals Regulations: Maximum permissible concentration for agricultural use (Table A7), maximum lifetime loading rate for agricultural use (Table A8), reclaimed land, highway buffer zones and forested land (Table A9) and maximum annual cadmium loading.

New Jersey

Regulating Agency: Department of Environmental Protection
Type of Rules: Regulations
Type of Approval Required: Permit required
Typical Interval Between Sludge Analyses: 1,3,6 or 12 months
Metals Regulated: As, Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified:Land application, composting and landfiling
Criteria for Metals Regulation: Maximum permissible concentrations (Class A sludge can be applied to a site for 40 years and Class B sludge can be applied for 20 years before cumulative load limits are reached) (Table A10)

Table A5 Massachusetts Sludge Classification Criteria (mg/kg)

	Type I	Type II	Type III
Cd	<2	25	>Type II
Cr	<1000	1000	>Type II
Cu	<1000	1000	>Type II
Ni	<200	200	>Type II
Pb	<300	1000	>Type II
Hg	<10	10	>Type II
Zn	<2500	2500	>Type II
Mo	<10	10	>Type II
B	<300	300	>Type II

Table A6 Massachusetts Maximum Cumulative Metals Loadings (lb/ac)

	Soil Cation Exchange Capacity (meq/100g)	
	<5	>5
Cd	2	25
Cu	125	250
Ni	50	100
Zn	250	500

Table A7 New Hampshire Maximum Permissible Metals Concentrations for Agricultural Use (mg/kg)

Cd	10
Cr	1000
Cu	1000
Pb	700
Hg	10
Ni	200
Zn	2000

Table A8 New Hampshire Maximum Lifetime Application Rate for Agricultural Use (lb/ac)

	Soil Cation Exchange Capacity <5	5-15	>15
Cd	2.2	4.5	9
Cr	125	250	500
Cu	125	250	500
Pb	500	1000	2000
Hg	0.5	1	2
Ni	50	100	200
Zn	250	500	1000

Table A9 New Hampshire Maximum Lifetime Application Rates (lb/ac)

	Highway Buffer Zones	Reclaimed Land	Forested Land
Cd	9	4.5	4.5
Cr	500	250	250
Cu	500	250	250
Pb	2000	1000	1000
Hg	2	1	1
Ni	200	100	100
Zn	1000	500	500

Table A10 New Jersey Maximum Permissible Metals Concentrations (mg/kg)

	Class A	Class B
Cd	20	40
Cr	600	1200
Pb	2400	4800
Ni	625	1250
Zn	1200	1200
Cr	1000	1000
Hg	10	10
As	10	10

New York

Regulating Agency: Department of Environmental Conservation
Type of Rules: Regulations and Guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: 1,3 or 6 months for land application and weekly, monthly or semiannually for composting and distribution
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Agricultural use, land reclamation, other vegetative covers and composting and distribution
Criteria for Metals Regulation: Maximum permissible concentration for land application (Table A11), maximum permissible concentration for composting and distribution (Table A12), cumulative loading limits for land application (Table A13) and annual cadmium loading limits

Pennsylvania

Regulating Agency: Bureau of Waste Management
Type of Rules: Proposed Regulations (published June, 1987)
Type of Approval Required: Site approval required for land application. Program approval required for composting.
Typical Interval Between Sludge Analyses: 4 months
Disposal Options Specified: Agricultural use, land reclamation, land disposal and composting and distribution
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Criteria for Metals Regulation: None specified

Vermont

Regulating Agency: Agency of Natural Resources
Type of Rules: Guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: 6 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application and landfilling
Criteria for Metals Regulation: Maximum Permissible Concentrations (Table A14)

Table A11 New York Maximum Permissible Metals Concentrations for Land Application (mg/kg)

Cd	25
Cr	1000
Cu	1000
Pb	1000
Hg	10
Ni	200
Zn	2500

Table A12 New York Maximum Permissible Metals Concentrations for Composting and Distribution (mg/kg)

Cd	10
Cr	1000
Cu	1000
Pb	250
Hg	10
Ni	200
Zn	2500

Table A13 New York Cumulative Metals Loading Limits (kg/ha)

Cd	5
Cu	125
Pb	500
Ni	50
Zn	250

Table A14 Vermont Maximum Permissible Metals Concentrations (mg/kg)

Cd	25
Cr	1000
Cu	1000
Pb	1000
Hg	10
Ni	200
Zn	2500

Virginia

Regulating Agency: State Water Control Board
Type of Rules: Regulations and guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: not specified
Metals Regulated: B, Cd, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application and land reclamation
Criteria for Metals Regulation: Maximum permissible concentrations (Table A15) and maximum cumulative loading guidelines

Table A15 Virginia Maximum Permissible Metals Concentration (mg/kg)

B	100
Cd	25
Cu	1000
Pb	1000
Hg	15
Ni	200
Zn	2500