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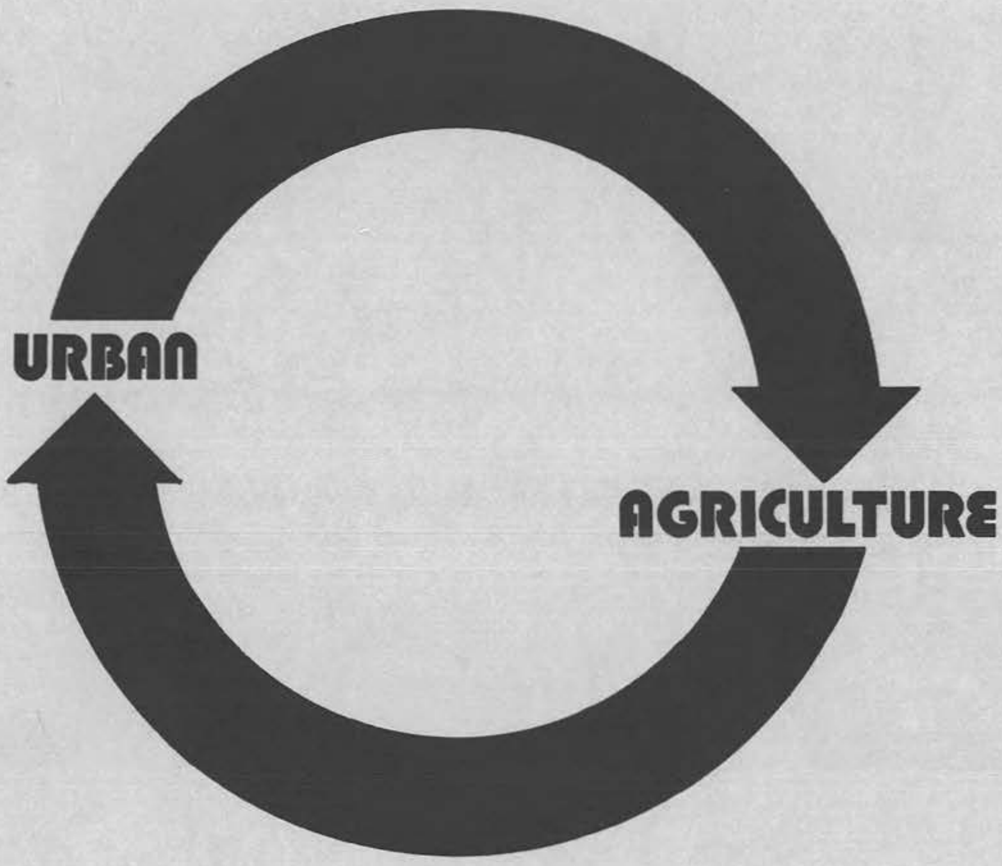
GUIDELINES FOR THE APPLICATION OF WASTEWATER SLUDGE TO AGRICULTURAL LAND IN WISCONSIN



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PREFACE

This publication gives guidelines for applying processed (i.e., not raw) sewage sludge to agricultural and forest lands. It has been prepared to assist Wisconsin Department of Natural Resources personnel in the granting of discharge permits (Chapter 147, 1973 Assembly Bill 128). Section 147.02, Water Pollutant Discharge Elimination; Permits, Terms and Conditions, states that "the disposal of sludge from a treatment work by any person shall be unlawful unless such disposal is done under a permit issued by the department". Section 147.26, Design of Publicly Owned Treatment Facilities, states that "the department shall encourage the design of publicly owned treatment works which provide for: (a) The recycling of sewage pollutants by using them in agriculture, silviculture or aquaculture; (b) The ultimate disposal of sludge in a manner not resulting in environmental hazards".

Municipalities constructing wastewater sewage treatment plants under the state and federal cost-sharing grant programs must prepare a Facilities Plan. Sludge application on land must be considered as an alternative disposal method. This guideline can be used for screening the land application alternative, evaluating of environmental effects, assessing of other important non-monetary effects, and for developing a land application program in consultation with qualified specialists if this alternative is selected. The guideline addresses the properties of sludge and alternative handling methods, factors that determine environmentally-acceptable loading rates, current application technology and site selection, management and monitoring. It does not consider specifics of all possible site properties, handling options and management variables. It was prepared by the University of Wisconsin Soil Science Department and the Wisconsin Department of Natural Resources.

These guidelines are based on current knowledge and should be revised as new information becomes available. Factors affecting the limitations to sludge application rates from heavy metals are not well understood, and new technology for sludge application should become available in the near future.

Addendum to Technical Bulletin 88: EPA Regulations

Since the original printing of the Wisconsin DNR Technical Bulletin 88, "Guidelines for the Application of Wastewater Sludge to Agricultural Land in Wisconsin," many additional reports, guidelines and regulations have been published by the U.S. Environmental Protection Agency. In addition to this, practical experience has been attained in the field of land spreading of municipal sewage sludge in Wisconsin. The basic concepts contained in the document are still correct, however, this addendum summarizes the latest federal regulations and necessary changes required in sludge management.

The following is a summary of the federal regulations which supersede previous Wisconsin guidelines. These regulations are contained in "Criteria for the Classification of Solid Waste Disposal Facilities and Practices", Federal Register, September 13, 1979.

1. Land disposal of sludge must meet the following cadmium (Cd) criteria:

   a) The pH of the sludge/soil mixture must be 6.5 or greater at the time of each application, except where sludge cadmium concentrations are 2 mg/kg or less (dry weight).

   b) Annual cadmium application must not be more than 0.5 kg/ha on land used for production of tobacco, leafy vegetables or root crops grown for human consumption. For other food-chain crops annual cadmium must not exceed:

Time Period	Annual Cd application rate (kg/ha)	(lbs/A)
Present to June 30, 1984	2.0	1.8
July 1, 1984 to Dec. 31, 1986	1.25	1.12
Beginning Jan. 1, 1987	0.5	0.4

   c) The cumulative cadmium application must not exceed:

Soil cation exchange capacity (meq/100g)	Maximum cumulative application: Background soil pH less than 6.5		Background soil pH 6.5 or greater	
	kg/ha	lb/A	kg/ha	lb/A
Less than 5	5	4	5	4
5-15	5	4	10	9
Greater than 15	5	4	20	18

d) For soils with background pH of less than 6.5, the cumulative cadmium rate can be the same as the right-hand column in section c (e.g. 5, 10, or 20 kg/ha) under the following conditions:

i) Soil/sludge mixture pH is 6.5 or greater whenever food-chain crops are grown,

ii) animal feed is the only food-chain crop grown,

iii) there is a facility plan which describes how animal feed is distributed to preclude ingestion by humans and how shift of land use to food-chain crops is avoided, and

iv) future property owners are notified that cadmium had been applied and food-chain crops should not be grown.

2. If sludge contains 10 or more mg/kg PCB's (dry weight), it should be incorporated into the soil when used to grow animal feed (includes pasture for dairy cattle). Incorporation is not required if PCB content of animal feed is less than 0.2 mg/kg or less than 1.5 mg/kg (fat basis) in milk.

3. For the purpose of disease control, sewage sludge and septic tank pumpings are considered the same and must meet the following criteria:

a) Sludge applied to land must be treated with a Process to Significantly Reduce Pathogens.a/ Public access is controlled for at least 12 months and grazing by animals whose products are consumed by humans is prohibited for at least 1 month.

b) If crops for direct human consumption are grown within 18 months after sludge application, sludge must be treated by a Process to Further Reduce Pathogens in addition to 3a) above.b/ This additional treatment is not required if there is no contact between the sludge and the edible portion of the crop.

Additional EPA guidelines have been published which suggest the following lifetime heavy metal loading limits for disposal sites based on the cation exchange capacity (CEC) of the soil.

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a/ Processes to Significantly Reduce Pathogens include aerobic and anaerobic digestion, air-drying, composting and lime stabilization.

b/ Processes to Further Reduce Pathogens include composting, heat-drying, heat treatment and thermophilic aerobic digestion. If used with any of the Processes to Significantly Reduce Pathogens the following are also applicable - gamma ray irradiation and pasteurization.

HEAVY METAL LOADING LIMITS
(Pounds/Acre)

	Cation Exchange Capacity (meq/100g)		
Site Lifetime Limits	Less than 5	5-15	Greater than 15
Lead	445	890	1,750
Zinc	225	445	890
Copper	110	225	445
Nickel	45	90	180

This table supersedes the heavy metal loading recommendations on pages 13 and 14 of TB 88.

The application of the guidelines in TB 88 for the last 5 years has revealed that from a practical standpoint, the ratings of many of the soil series in Appendix A should be modified. Recommendation 3 on page 29 states that at least 2 feet and preferably 4 feet, of soil should exist between the sludge application zone and bedrock, any impermeable layer or the water table. Since sludge should be either incorporated or injected into the top 12 inches of soil, the depth to bedrock and/or high groundwater table in suitable soils should be at least 3 feet and preferably 5 feet. This classification also correlates better with the standard USDA Soil Conservation Service description and ratings of uses for the various soil series in Wisconsin. The ratings for sludge disposal will, therefore, be changed as follows:

- Severe: Shallow to high groundwater level and bedrock ($<$3 feet)
- Moderate: High groundwater level and bedrock 3-5 feet
- Slight: High groundwater level and bedrock $>$5 feet

The final determination of site suitability should be based on site specific evaluation.

Finally, as more federal regulations are adopted and additional experience is gained, the Municipal Sludge Management program will be adjusted. These changes will be noted in future Municipal Wastewater Guidance (MWG) Memorandums.

GUIDELINES FOR THE APPLICATION OF WASTEWATER SLUDGE TO AGRICULTURAL LAND IN WISCONSIN

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I. INTRODUCTION

Disposal of wastewater sludge is the pivotal question in wastewater processing. Sludges contain the concentrated wastes of the community, and certain components of some sludges may be toxic and hazardous, depending on their concentration and the intended means of disposal. The hazardous components of sludges are the heavy metals [principally cadmium (Cd), chromium (Cr), lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), and mercury (Hg)], pathogenic bacteria and virus. Discharge of these components as well as the nutrients, nitrogen (N) and phosphorus (P), to surface and ground waters must be minimized to prevent degradation in water quality. The high salt content of sludges can inhibit plant growth if applied to soils at the wrong time.

The concept of "recycling" sludge nutrients to agricultural land is feasible and desirable. Sewage sludge is a low-analysis fertilizer of extremely variable composition. Transportation, handling, application and monitoring costs often put sludges at an economic disadvantage to the farmer compared to high-analysis commercial fertilizers. However, increasing fertilizer prices due to energy and supply shortages have put sludge in a more competitive position.

Aside from economics, the major problems involved in land application of sludge are public acceptance, possible surface and ground water contamination by overloading of nitrogen and phosphorus, pathogens, yield reductions due to overloading with heavy metals, and food chain contamination of toxic elements. Problems due to overloading of nitrogen can be controlled by using yearly loading rates approximating the nitrogen needs of the crop being grown. Phytotoxicity due to heavy metals is more difficult to predict, and affects the total loading of sludge (i.e., site lifetime). Disease transmission from land application of digested sludge does not appear to be a problem. However, toxic element contamination of the food chain, particularly by Cd, is not completely understood at present.

Overview of Sludge Production and Disposal

As wastewater treatment plants have been upgraded to improve effluent quality, the quantity of sludge produced has increased. This trend will doubtless continue. Farrell (1974) estimates an increase from 4.7 million dry tons in 1972 to 6.6 million tons in 1985 in the United States. For Wisconsin with a 3,115,000 sewered population and 80% (Konrad and Kleinert, 1974) on secondary treatment (.2 lb of solids/cap./day) and 20% on primary treatment (0.12 lb of solids/cap./day) an estimated total of 104,600 dry ton/year of sludge is generated currently. Assuming a 1985 sewered population of 3,500,000, all on secondary treatment, an estimated production of 127,750 dry tons/year can be predicted. Chemical treatment to remove phosphorus would increase the amount of sludge produced by 2 to 3 times that from conventional secondary systems (EPA, 1974). Assuming 3.5% N (50% available) and fertilizer application rates (150 lbs available N/acre), leads to an average application rate of 4.3 tons/acre. Thus, only about 24,000 acres (or less than 1% of the corn acreage) are needed to dispose of all of the sludge from Wisconsin municipalities. The point here is that land application of sludge has only a minimal impact on the fertilizer requirements of Wisconsin agriculture.

The current sludge treatment technology is covered in detail in a number of publications. Especially recommended are the Process Design Manual for Sewage Sludge Treatment and Disposal (EPA, 1974), Chapter 8 in Bolton and Klein (1971) and the Proceedings of the National Conference on Municipal Sludge Management held at Pittsburgh in June 1974. The conventional stabilization processes are anaerobic and aerobic digestion, while heavy chlorination, lime treatment, pasteurization (70°C), radiation and heat treatment (195°C) and various combinations of these methods have been used (Farrell, 1974). Digested sludges may be dewatered by various mechanical means such as the rotary vacuum filter, centrifuge, drying beds, or the filter press.

The main methods of sludge disposal in inland states at present are landfills, permanent lagoons, incineration and land application to (a) dispose of the material, (b) fertilize agricultural or recreational land, or (c) reclaim marginal land. Landfills specifically designed and operated for the disposal of sludges carrying high concentrations of hazardous materials can be used for sludge disposal. Proper incineration, while a satisfactory disposal method of volume reduction, suffers from increasingly higher operating costs, and the sophisticated technology involved. Promising future disposal schemes, at least for larger municipalities, include composting with carbonaceous solid wastes. Also co-incineration and co-pyrolysis of sludge with solid waste, which does not require supplemental fuel and yields some usable byproducts, is under development.

Sludge Properties

Sewage sludges vary so widely in chemical and physical composition that no truly average value for the content of solids, nutrients or metals can be given. This heterogeneity occurs from city to city, depending upon the treatment process used and major industries, and also from day to day in the same city. Thus one must recognize the limitations in dealing with a product of variable and largely uncontrollable quality.

Table 1 gives the ranges in various chemical constituents found in sludges from 35 Wisconsin municipalities. These data are from a recent Department of Natural Resources survey. Also, a survey by Kelling (1974) of the day-to-day variation in sludge composition of the Janesville Sewage Treatment Plant showed that, over a 2-week period, the solids content varied by as much as 100%, and the concentration of various elements varied from 10 to 100%.

To translate the results of Table 1 into more meaningful terms, one acre-

TABLE 1. *Range of concentration of various constituents in anaerobic liquid digested sludge from 35 Wisconsin municipalities. Metals data reported in Konrad and Kleinert (1974).*

Constituent	Range*
Total-N (moist)	3.4 - 9.5
Total-N (dried)	2.4 - 3.1
NH_4-N (moist)	0.8 - 4.1
NH_4-N (dried)	0.02 - 0.26
Organic C	25.7 - 38.5
P	2.7 - 6.1
K	1.2 - 1.9
Ca	4.2 - 18.0
Mg	0.8 - 1.2
Na	0.6 - 2.2
Al	0.36 - 1.2
Fe	0.8 - 7.8
Cd/Zn	0.15 - 33
Zn	490 - 12,200
Cu	140 - 10,000
Ni	15 - 1,700
Cd	5 - 400
Pb	40 - 4,600
Cr	50 - 32,000
Hg	0.6 - 31
B	150 - 750
Mn	180 - 1,130
Ba	530 - 1,340
Sr	52 - 7,810

*Range for the first 13 constituents is given in % of solids and in mg/kg for the last 11 constituents.

inch of sludge could add up to 550 lbs of N, 200 lbs of P (450 lbs of P_2O_5), 100 lbs of K (120 lbs of K_2O), 1,000 lbs of Ca, 100 lbs of Mg and Na, and as much as 300 lbs of Cr, 100 lbs of Cu and Zn, 50 lbs of Pb, 15 lbs of Ni, 2 lbs of Cd and 0.1 lb of Hg. Thus, it is obvious that problems from the high concentration of these elements may occur. The N load is the limiting factor on a short-term (yearly) basis, while accumulation of heavy metals may limit the amount of material applied over longer time periods.

While sufficient information is not available on the pathogenic agents in sludges, Ewing and Dick (1970) feel that the disease transmission hazard is not great, based mainly on the fact that no incidence of disease has been traced to sludge-disposal operations. However, since possible disease transmission is one of the greatest causes for public concern with waste handling operations, this subject must be carefully considered in drawing up guidelines.

The reviews by Ewing and Dick (1970) and Dean and Smith (1973) cite references indicating that fecal coliforms, *Salmonella, Pseudomonas* and *Endamoeba hystolytica* populations have high die-off rates in aerobic and anaerobic digesters. However, tubercle bacilli, some parasite ova, ascarids and hookworms appear to survive during digestion and even during drying of sludge. Lime (pH 11.5), pasteurization and direct steam injection will effectively destroy most pathogens, but these methods are expensive. Prolonged storage (two months or longer) appears to be an inexpensive and effective method of pathogen reduction.

II. FACTORS DETERMINING SLUDGE APPLICATION RATES TO AGRICULTURAL SOILS

There are a number of interrelated factors which affect the *annual* and *total* loading of sludges. *Annual rates,* assuming the recycling concept (i.e., use of the sludge as a fertilizer) will be influenced by mode of application, soil productivity and crops grown and level of site management.

Mode of Application

When liquid sludge is applied on the soil surface, clogging of the soil occurs, and drying and infiltration is slow. Thus, unless the sludge is incorporated, most of the sludge water will evaporate, rather than infiltrate the soil. On evaporation, considerable ammonium-N will be volatilized. The actual amount lost to the atmosphere will vary, but best estimates indicate that, on the average, about 50% of the sludge ammonium-N will be removed. This represents a loss of resources, and means that the actual N applied must be adjusted upward to compensate for ammonium volatilization.

If the sludge is incorporated immediately after application or applied by knife-plow-down equipment, volatilization losses are minimal.

Year-to-year variations in the weather will also affect application rates. Less sludge can be applied during rainy spells, and sludge should not be applied on frozen sloping land with snow cover.

Soil Productivity Potential and Crops Grown

Due to differences in climate and soil properties, there is considerable difference throughout the state in the maximum obtainable yields of crops such as corn. These differences must be taken into account when making recommendations for sludge disposal, just as they are taken into account in fertilizer recommendations. For example; maximum corn yields in the northern part of the state are limited by the much shorter frost-free growing season.

Crops use different amounts of nutrients. Corn and sorghum-sudan, for example, require more N than do such short-season crops as oats. Also, corn for silage removes more N than does corn grain. Legumes, such as alfalfa and soybeans, do not require any fertilizer N since they are capable of fixing their own supply from the N in the atmosphere. However, legumes will use available soil N when present in preference to fixation of atmospheric N.

Site Management

The level of management of the site will have considerable effect on nutrient recycling. For example, if an essential nutrient such as potassium (K) is in short supply, crop growth would be reduced and less N would be used by the crop. In some instances, use of a fall cover crop or double cropping will increase nutrient utilization. Site management plans should remain somewhat flexible to permit maximal nutrient utilization and economic returns.

To more adequately understand the factors involved in using sludge as a fertilizer, the "cycles" of N, P, and K are briefly reviewed.

Nitrogen*

The atmosphere contains about 78% nitrogen gas (N_2). However, most plants cannot use nitrogen as it exists in the atmosphere. For plants to use atmospheric nitrogen, it must be converted biologically or chemically.

Rhizobia and other bacteria which live in the roots of legumes take nitrogen from the air and fix it in a form which is usable by the plants. This mutually beneficial relationship between micro-organisms and plants is called symbiosis.

Nitrogen in Soils

Sources. Natural sources of nitrogen (other than from fertilizers) include organic matter, legumes, and precipitation.

Soils often contain 2,000 to 6,000 lbs/A of organic N, but almost all of this N is combined in stable organic matter (humus) which contains about 5% N and decomposes very slowly. Research shows that mineral soils in Wisconsin supply only about 25 to 75 lbs/A of available N annually. As a result, more nitrogen generally must be applied on nonlegume crops to achieve optimum yields.

Legumes inoculated with the proper strain of nodule-forming bacteria use atmospheric N by symbiotic fixation (Reaction 1, Fig. 1). If sufficient soil N is not available, legumes fix all the N they need and thus do not need N fertilizer. Many legumes will also supply substantial amounts of N to the next crop. An estimate of the nitrogen credit which should be given to various legume crops is given in Table 2.

In rural areas in Wisconsin precipitation adds about 10 lbs/A of available N (ammonium + nitrate nitrogen) annually. This is a small addition on a per-acre basis, but it is a significant contribution to the total N budget for the state. In fact, the total amount of N added to the state in precipitation exceeds the amount of N presently applied as fertilizer on croplands.

Processes. The following are microbiological processes that nitrogen undergoes in the soil:

Ammonification (or mineralization) is the conversion of organic N into ammonium by soil microbes (Reaction 2, Fig. 1). Plants can use ammonium N and it is not lost by leaching. Negatively charged particles of clay minerals and soil organic matter hold the positively charged ammonium ion (NH_4^+). This greatly restricts its movement by percolating water.

In the manufacture of chemical nitrogen fertilizer, atmospheric nitrogen is combined with hydrogen (H_2) to form ammonia (NH_3). Ammonia is sold for direct application, or it can be used to manufacture other forms of nitrogen fertilizer such as ammonium nitrate (NH_4NO_3) or urea (NH_2-CO-NH_2).

Nitrogen tends to be a rather elusive element because it exists in many different forms, and its availability to plants is affected by several physical, chemical and biological processes. These transformations, collectively called the nitrogen cycle, are illustrated in Fig. 1.

Nitrification is the transformation of NH_4-N to NO_3-N by soil bacteria (Reaction 3, Fig. 1). Nitrate is readily available to plants, but it is negatively charged and thus remains in solution in the soil. Therefore, it may be leached below the root zone as water percolates through the soil. Nitrification occurs rapidly in warm, well-aerated and properly limed soils (pH of 5.6-8.0). Under favorable conditions, the ammonium form of N is changed to the nitrate form in one to two weeks after application.

Immobilization is the process whereby crop residues rich in carbon, such as straw or corn stalks, are plowed under, and the available ammonium or nitrate is temporarily immobilized by the bacteria that decompose the residues (Reaction 5, Fig. 1). But soon after the crop residues begin

TABLE 2. *Suggested nitrogen credits for various legume crops.*

Legume Crop	Nitrogen Credit (lbs/A)
Sod alfalfa	
60-100% stand	80-100
20- 60% stand	40- 60
0- 20% stand	0- 20
Red Clover	40- 60
Green-Manure*	
Alfalfa	40- 60
Sweet clover	60- 80
Cash Crops**	
Peas, snapbeans, lima beans, soybeans	10- 20

*Based on plowing under the green manure crop after the growing season of the seedling year.

**Based on plowing under the vines or other plant residues.

TABLE 3. *Percentages of nitrogen considered deficient, low, sufficient, and high for major Wisconsin field crops.*

Crop	Plant Part Sampled	Time of Sampling	Interpretation (in % N)			
			Deficient	Low	Sufficient	High
Corn	ear leaf	silking	$<$1.75	1.75-2.75	2.76-3.75	$>$3.75
Oats, wheat, barley	top leaves	boot stage	$<$1.50	1.50-2.00	2.01-3.00	$>$3.00
Alfalfa*	top 6 inches	early bud	$<$1.25	1.25-2.50	2.51-3.70	$>$3.70

*First Crop

*Adapted from U.W. Extension Fact Sheet A2519, Soil and Applied Nitrogen, by L.M. Walsh.

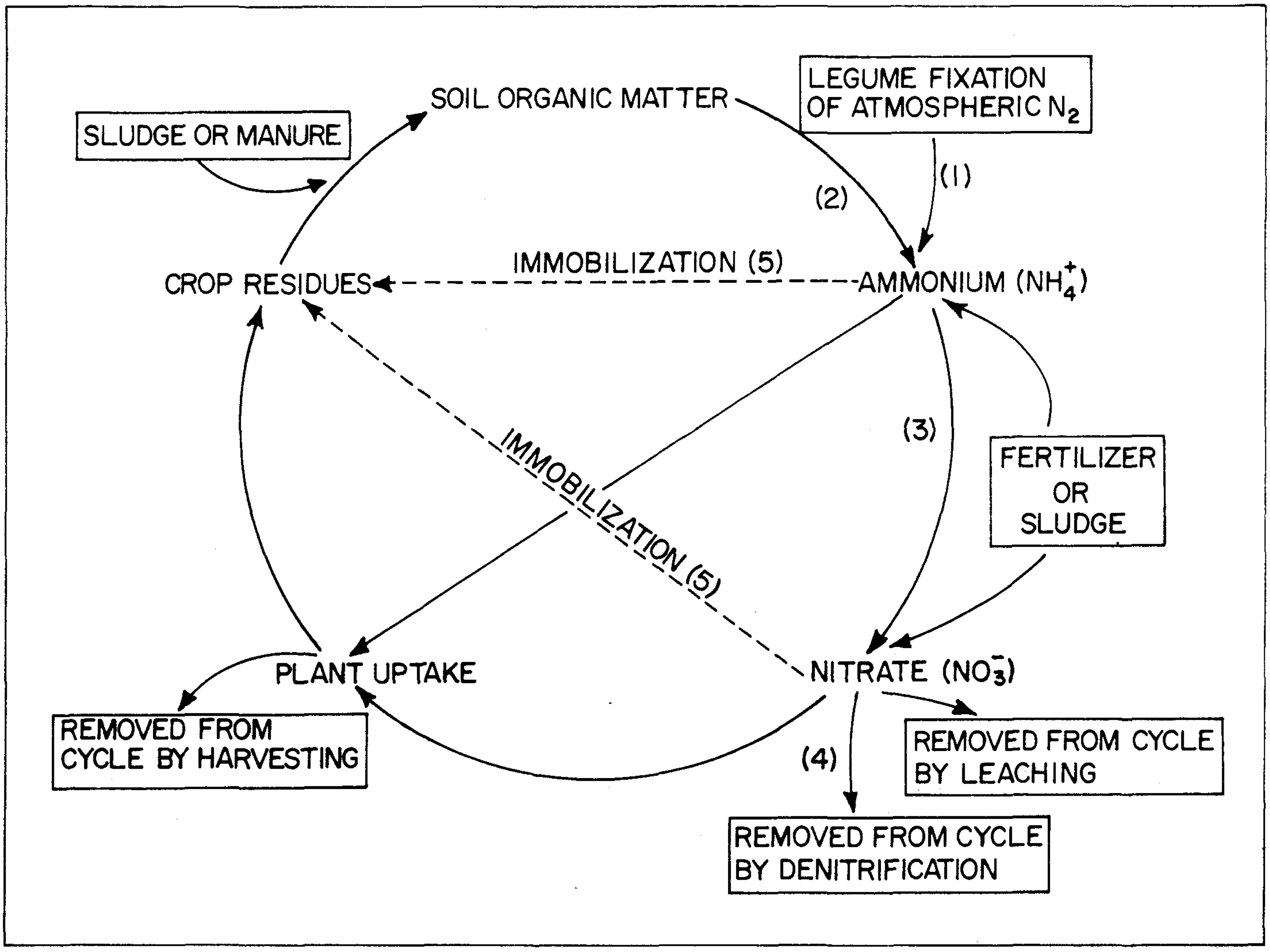

FIGURE 1. *The nitrogen cycle.*

to decompose, N immobilized as microbial protein is released again in an available form. Under ideal weather conditions, release of immobilized N begins about one month after plowing or discing of the organic matter.

Losses. Nitrogen is lost from the soil profile by several means. Leaching of nitrate can be a serious problem, especially on sandy soils. Since sandy soils retain only about one inch of water per foot of soil, relatively small amounts of rain or irrigation water readily move nitrate below the root zone. Well-drained silt and clay soils retain about three inches of water per foot of soil, so much less leaching occurs on these soils, except when rainfall is abnormally high. Ammonium-N is held on soil particles and is essentially nonleachable. Nitrate is not held by soil particles and can be leached below the root zone. But this does not mean that ammonium is more effective than nitrate. As pointed out previously, soil bacteria rapidly convert ammonium to nitrate under optimum soil conditions. As a result, very little difference in N loss occurs between ammonium and nitrate forms of N.

A second means of nitrogen loss is volatilization. When sludge is surface applied and not worked into the soil, some nitrogen can be lost as ammonia gas. Injection or immediate incorporation of liquid sludge eliminates most of the volatilization losses.

Nitrogen is also lost by **denitrification.** In poorly aerated, water-logged soils, soil bacteria change available nitrate into unavailable atmospheric N (Reaction 4, Fig. 1). For denitrification to occur, decomposable organic matter must be present as a source of energy. Because of this energy requirement, denitrification does not take place deep in the sub-soil or in groundwater. Denitrification takes place very rapidly. If water stands on the soil for only two or three days during the growing season, most of the nitrate will be lost by denitrification. Yellowing of corn and other crops grown on poorly aerated soils is due in large part to a N deficiency.

Environmental Hazards

If nitrate-N is applied in amounts greater than can be removed by plant uptake, the excess nitrates can potentially contaminate groundwater or surface waters by leaching or runoff. Through groundwater contamination, excessive nitrate in drinking water may cause human and animal health problems. The US EPA and World Health Organization drinking water standard is 10 mg/liter of nitrate-N. Surface water contamination with excess nitrate and other nitrogen compounds may hasten deterioration of streams and lakes by promoting excessive growth of algae and weeds. The same hazards exist when N fertilizer or farm animal wastes are used on croplands. However, if the recommendation of annual sludge application rates, which is usually limited by available N, is closely observed, excessive accumulation of nitrate will not be a problem.

Diagnostic Techniques

Deficiency Symptoms. Lack of N first appears as a light green coloring of the plant. As the deficiency becomes more severe, leaves turn yellow and may "fire". The deficiency appears on the lower leaves first and gradually progresses up the plant. On corn the yellowing first starts at the midrib of the leaf with the edge of the leaf remaining green. Corn, small grain and forage grasses have a relatively high N requirement and show deficiency symptoms whenever N is in short supply.

Plant Analysis. Analysis of the plant tissue gives a good indication of whether the plant contains sufficient N. The amount of total N (crude protein) in a plant decreases as the plant grows. Therefore, it is important to specify the stage of growth when sampling a crop for N analysis. An interpretation of the results of N analyses for the major agronomic crops grown in Wisconsin is presented in Table 3.

Phosphorus*

Soils generally contain 1,000-2,000 lbs/A of total P, but most of this P is in an unavailable or "fixed" form and cannot be used by plants. Furthermore, soluble P is quickly "fixed" when added to the soil. Because of the relative low quantity of total P in the soil and the fixation of native and applied P, continued use of P fertilizer is required on most Wisconsin soils.

Phosphorus in Soils

Phosphorus in soils is classified into two main categories: organic and inorganic. The organic part is found in humus and other organic materials. The inorganic portion occurs in numerous combinations with iron, aluminum, and other elements, most of which are insoluble in water.

Acid soils fix more P than neutral soils. Therefore, liming acid soils tends to increase the availability of both soil and fertilizer P.

Phosphorus in Organic Matter. The relative amount of P in the organic and inorganic forms varies considerably. In Wisconsin, organic P accounts for 30-50% of the total P in most mineral soils.

Organic forms of P can be mineralized to inorganic forms. This occurs during the decomposition of organic matter. As with the mineralization of organic N, organic P is released more rapidly in warm, well-aerated soils. This explains why crops grown in cold wet soils often respond to row-applied P in Wisconsin, even though the soil may be well supplied with available soil P or broadcast P fertilizer.

Environmental Hazards

Since soil particles contain a very high degree of retention capacity for phosphate, ground water is usually protected from P contamination. Although the ultimate capacity for P fixation by soil is not unlimited, it is unlikely that sludge application will exceed this capacity. Some evidence exists that organic forms of P are more mobile in soils, but to date no documented evidence for extensive leaching of P below feedlots or sludge application sites has been reported. However, surface water contamination with phosphates is of more concern. When excessive amounts of P are added to a lake or stream, luxurious growth of weeds and algae often results. Of the plant nutrients, P is the most closely related to over-production of weeds and algae. Therefore, surface runoff and erosion of sludge-applied lands into surface waters should be minimized.

Phosphorus Fixation. Phosphorus forms a negatively charged phosphate ion ($H_2PO_4^-$). Since the soil particles are also negatively charged, it might appear that phosphate could leach away like nitrate. But this does not occur because phosphate reacts rapidly with the soil solids. It is then "fixed" in an unavailable form.

One of the unique characteristics of P is its immobility in soil. Practically all soluble P in sludges or fertilizer is converted to water-insoluble P within a few hours after application. Hence, P does not leach, even on sandy soils. Studies on highly fertilized, intensively farmed land indicate that the annual loss of P in drainage water seldom exceeds 0.1 lb/A. Furthermore, 98-99% of the fertilizer phosphorus is usually found in the plow layer of the soil, indicating that very little phosphorus moves through the subsoil.

Diagnostic Techniques

Deficiency Symptoms. The leaves of P-deficient plants most often appear dark bluish green, frequently combined with tints of purple or bronze. On corn, purpling occurs around the margins of the leaf and the plant is short and dark green. Reddening of corn leaves and stalks in the fall is not an indication of P deficiency. Phosphorus-deficient alfalfa appears short and dark green, but purpling does not occur.

Soil Analysis. Many methods exist for measuring available P in soils. A test developed at Illinois—the Bray P_1—is used in Wisconsin and throughout the midwest. The interpretation of the Bray P_1 test for Wisconsin soils is shown in Table 4. Recommendations for P fertilizer vary with crop species, yield goal, soil type and level of management. If soils tests are below optimum levels, both corrective and maintenance fertilizer is required.

Plant Analysis. Analysis of plant tissue gives a good indication of the P nutrition of the plant. Since phosphorus levels in the plant change with age, it is best to indicate the stage of maturity at sampling. An interpretation of phosphorus levels in the leaf tissue for the major Wisconsin field crops is given in Table 5.

Estimation of P Sorption Capacity

When a sample of soil is shaken with a phosphate solution, much of the P is sorbed on the soil. If the concentration of phosphate is varied keeping the weight of soil constant, and the residual phosphate in solution determined, the data can be treated with an equation known as the Langmuir adsorption isotherm (Ellis, 1973). This equation gives a number of soil-related parameters, including a maximum sorption capacity. Ellis (1973) has proposed using this value to rate soils in terms of the amount of phosphorus they will adsorb in the top 3 feet. This rating was used by Schneider and Erickson (1972) to classify Michigan soils in terms of suitability for use in municipal waste water irrigation. The approach is still being evaluated at Michigan, and is not recommended for site evaluation at this time. However, further research may show its utility, and if P sorption capacity tests are contemplated, consultation with U.W. Soils Dept. personnel is advised.

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*Adapted from U.W. Extension Fact Sheet A2520, Soil and Applied Phosphorus, by L.M. Walsh.

Potassium*

Soils commonly contain over 20,000 lbs/A of total K. However, nearly all of this K is a structural component of mica, feldspar and other soil minerals and is not available to the plant. Plants can use only the exchangeable K on the surface of the soil particles. This often amounts to less than 200 lbs/A of K.

Crops such as corn silage and alfalfa remove large quantities of K. Most Wisconsin soils need rather large quantities of K fertilizer because of removal by crops and because Wisconsin soils were not initially well supplied with exchangeable K.

TABLE 4. *Soil test level for phosphorous.*

Crop Type	Concentration of Available P (in lbs/A)		
	Minimum	Optimum	Excessive
Field crops including sweet corn and peas	30-50	50-100	over 125
Vegetable crops and irrigated field crops	50	75-150	over 200

TABLE 5. *Percentages of phosphorus considered deficient, low, sufficient, and high for major Wisconsin field crops.*

Crop	Plant Part Sampled	Time of Sampling	Interpretation (in % P)			
			Deficient	Low	Sufficient	High
Corn	ear leaf	silking	<.16	.16-.24	.25-.50	>.50
Alfalfa	top 6 inches	early bud	<.20	.20-.25	.26-.70	>.70
Oats	top leaves	boot stage	<.15	.15-.20	.21-.50	>.50

TABLE 6. *Soil test level for potassium.*

Crop Type	Concentration of Available K (in lbs/A)		
	Minimum	Optimum	Excessive
Field crops including sweet corn and peas	200	200-300	over 400
Vegetable crops and irrigated field crops	250	250-350	over 500

TABLE 7. *Percentages of potassium considered deficient, low, sufficient and high for major Wisconsin field crops.*

Crop	Plant Part Sampled	Time of Sampling	Interpretation (in % K)			
			Deficient	Low	Sufficient	High
Corn	ear leaf	silking	<1.25	1.25-1.74	1.75-2.75	>2.75
Alfalfa	top 6 inches	early bud	<1.80	1.80-2.40	2.41-3.80	>3.81
Oats	top leaves	boot stage	<1.25	1.25-1.59	1.60-2.50	>2.50

Potassium in Soils

Forms of Soil K. Three forms of soil K are often described; unavailable, slowly available or "fixed", and readily available or exchangeable. Unavailable soil K is contained in micas, feldspars, and clay minerals. Plants cannot use K in these crystalline, insoluble forms. Over long periods these minerals weather or decompose and their K is released as the available K^+ ion. This process is far too slow to take care of the K needs of field crops. However, trees and long-term perennials obtain a substantial portion of the K they require from the weathering of minerals containing K. Slowly available K is trapped between the layers or "plates" of certain kinds of clay particles. This is sometimes called "fixed" K. Plants cannot use much of the slowly available K during a single growing season. However, the soil's ability to supply K over a longer period of time is related closely to its supply of fixed K. For instance, compared to other soils in Wisconsin, the sandy and silty soils in the central and northcentral regions of the state have lower soil tests for available K because they have a very low supply of fixed K.

Readily available K is held on the surface of clay and other soil particles. Plants easily absorb K in this form. Soil tests for available K are designed to extract only the readily available form. Most soil tests do not remove the unavailable and slowly available forms of K. Since sewage sludge typically is low in K relative to its N and P contents, K fertilizer often will need to be added. The most common K fertilizer for use on field crops is KCl (muriate of potash). This is the least expensive source of K and it is just as effective as the other sources. For that reason it is usually recommended except when the crop also needs sulfur (S) or magnesium (Mg). Also, some specialty crops require the use of the sulfate form of K (K_2SO_4) to maintain crop quality. For example, tobacco will not burn properly when chloride (Cl) is added to the soil; so it should be fertilized with sulfate forms of K.

Environmental Hazards

Potassium is not an environmental hazard, as it possesses no harm to higher life and is not related to eutrophication in lakes or streams. Furthermore, K is readily and tightly held by soil particles, and there is little potential of K leaching into ground or surface waters.

Diagnostic Techniques

Deficiency Symptoms. On corn, soybeans and other field crops K deficiency appears as a yellowing or scorching on the margins of the leaves. The area affected increases as the deficiency becomes more severe. Since K is a very mobile element within the plant, the deficiency appears on the older leaves first. On alfalfa the deficiency appears as whitish-grey spots along the outer margin of the recently matured and older leaflets.

*Adapted from U.W. Extension Fact Sheet A2521, Soil and Applied Potassium, by L.M. Walsh.

Soil Analysis. Available K is estimated by measuring the exchangeable K; that is, the potassium on the surface of the soil particles. Interpretation of the exchangeable or available K test for Wisconsin soils is listed in Table 6. Recommendations for K fertilizer vary with crop specie, yield goal, soil type and level of management. If soil tests are below optimum levels, both corrective and maintenance fertilizer is required; for optimum soil tests only maintenance fertilizer is required; and for excessively high tests part or possibly all the maintenance fertilizer can be eliminated.

Plant Analysis. Critical concentrations of K for the crops of major economic importance are fairly well known. Like N, the amount of K in the plant decreases as it matures. Therefore, to interpret the results of K analysis, it is important to know the stage of growth. Also, the K content usually decreases from top to bottom of the plant, so the portion of the plant sampled must be known as well. Interpretation of K levels in the leaf tissue for the major Wisconsin field crops is given in Table 7.

Calculation of Annual Sludge Application Rates Based On Nitrogen

Corn Yield Potentials and Nitrogen Needs

Soil surveys give yield potentials of all soils mapped in the county. These surveys should be consulted when available. If such information is not available, the following tables should be consulted.

Table 8 gives the expected corn yields under very high levels of management, and Table 9 gives the yield potential for each county for sands and loamy soils (coarse-textured soils) and for finer textured soils (sandy loams, silt loams and clay loams). The corn yield potential for each soil series is given in Appendix A.

Table 10 gives the N fertilizer recommendations taking into account N released from the soil organic matter over the growing season.

Nitrogen Availability from Sewage Sludge

When sewage sludge is added to soil, its organic matter slowly decomposes releasing available N. Experimental evidence suggests that on silt loam and clay soils about 15 to 20% of the sludge N is mineralized the first year, whereas on sands and sandy loams, which are better aerated, the mineralization rate will be greater. After initial sludge application, about 6, 4, and 2% of the remaining N is released for the subsequent three years (Table 11). This must be taken into account in repeated sludge applications. Thus, sludge application rates are based on crop needs, the quantity of NH_4-N in the sludge, the N released during sludge decomposition and the N from the soil.

Nutrient Utilization by Various Crops

Table 12 gives the N, P, and K uptake by various crops. These values can be used to estimate N needs by other

TABLE 8. *Relative yield potential of the soil and expected corn yield.*

Yield Potential Code	Relative Yield Potential of the Soil*	Expected Yield (bu/A)
1	Very high	120-140
2	High	100-120
3	Medium	80-100
4	Low	60- 80

*With exceptionally high management, 20 bu/A more can be expected.

TABLE 9. *Yield potential codes by county.*

County	Yield Potential Code*: Sandy Loams, Silts and Clay Loams**	Yield Potential Code*: Sands and Loams	County	Yield Potential Code*: Sandy Loams, Silts and Clay Loams**	Yield Potential Code*: Sands and Loams
Adams	2	3	Marathon	3	4
Ashland	3	4	Marinette	3	4
Barron	3	4	Marquette	1	3
Bayfield	3	4	Menomonie	3	4
Brown	2	3	Milwaukee	2	3
Buffalo	2	3	Monroe	1	3
Burnett	3	4	Oconto	3	4
Calumet	2	3	Oneida	3	4
Chippewa	2	3	Outagamie	2	3
Clark	2	3	Ozaukee	2	3
Columbia	1	3	Pepin	2	3
Crawford	1	3	Pierce	2	3
Dane	1	3	Polk	2	3
Dodge	1	3	Portage	2	3
Door	3	4	Price	3	4
Douglas	3	4	Racine	1	3
Dunn	2	3	Richland	1	3
Eau Claire	2	3	Rock	1	3
Florence	3	4	Rusk	3	4
Fond du Lac	1	3	St. Croix	2	3
Forest	3	4	Sauk	1	3
Grant	1	3	Sawyer	3	4
Green	1	3	Shawano	3	4
Green Lake	1	3	Sheboygan	2	3
Iowa	1	3	Taylor	3	4
Iron	3	4	Trempealeau	2	3
Jackson	2	3	Vernon	1	3
Jefferson	1	3	Vilas	3	4
Juneau	2	3	Walworth	1	3
Kenosha	1	3	Washburn	3	4
Kewaunee	2	3	Washington	1	3
LaCrosse	1	3	Waukesha	1	3
Lafayette	1	3	Waupaca	2	3
Langlade	3	4	Waushara	2	3
Lincoln	3	4	Winnebago	2	3
Manitowoc	2	3	Wood	2	3

*The relative yield potential of the soil for corn is coded as follows: 1. Very high; 2. High; 3. Medium; 4. Low.

**All irrigated sands are included in this group.

TABLE 10. *Nitrogen needed by corn (in lbs/A of N needed).**

Yield Potential	Organic matter content 0-20 Tons/A	21-35 Tons/A	36-50 Tons/A	50 Tons/A
1. Very high**	160	140	120	100
2. High	140	120	100	80
3. Medium	120	100	80	60
4. Low	100	80	60	60

*Of nonsludged soil, no data are available to evaluate nitrogen availability of soil organic matter from sludge-treated soil.

**With exceptionally high management, 20 lbs additional N is needed.

TABLE 11. *Release of available nitrogen per ton of solids during sludge decomposition.*

Years after Sludge Application	Mineralization Rate, %	Organic N Content of Sludge* 2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
First	15.0	6.0**	7.5	9.0	10.5	12.0	13.5	15.0
Second	6.0	2.4	3.0	3.6	4.2	4.8	5.4	6.0
Third	4.0	1.6	2.0	2.4	2.8	3.2	3.6	4.0
Fourth	2.0	0.8	1.0	1.2	1.4	1.6	1.8	2.0

*Expressed in lbs N released/ton sludge added.

**2000 lb/ton x 0.02 x 0.15 where 0.02 is the percent organic N and 0.15 is the mineralization rate/100.

TABLE 12. *Nitrogen, phosphorus, and potassium uptake by various crops.*

Crop	Yield per acre*	Uptake (in lbs/A)*** N	P_2O_5	K_2O
Corn	120 bu	150	65	170
	140 bu	185	80	185
Corn silage	32 tons	200	80	240
Soybeans	50 bu	257**	50	120
	60 bu	336**	65	145
Grain sorghum	8000 lbs	250	90	200
Wheat	60 bu	125	50	110
	80 bu	186	55	160
Oats	100 bu	150	55	150
Barley	100 bu	150	55	150
Alfalfa	8 tons	450**	80	480
Orchard grass	6 tons	300	100	375
Brome grass	5 tons	166	65	255
Tall fescue	3.5 tons	135	65	185
Bluegrass	3 tons	200	55	180

*Values reported are for the total above-ground portion of the plants. Where only grain is removed from the field, a significant proportion of the nutrients are left in the residues. However, since most of these nutrients are temporarily tied up in the residues, they are not readily available for crop use. Therefore, for the purpose of estimating nutrient requirements for any particular crop year, complete crop removal can be assumed.

**Legumes get most of their N from the air so additional N sources are not normally needed.

***P_2O_5 x 0.437=P and K_2O x 0.83=K.

TABLE 13. *Corrective phosphorus and potassium recommendations for corn.**

Phosphorus Soil Test (lb/A)	Potassium soil test 0-100 lb/A	100-140 lb/A	140-180 lb/A	180-240 lb/A	>240 lb/A
0-15					
P_2O_5	90	90	90	90	90
K_2O	240	180	120	60	0
16-30					
P_2O_5	60	60	60	60	60
K_2O	240	180	120	60	0
31-45					
P_2O_5	30	30	30	30	30
K_2O	240	180	120	60	0
>45					
P_2O_5	0	0	0	0	0
K_2O	240	180	120	60	0

*Applied once during corn-oats rotation. Expressed in lbs/A recommended.

TABLE 14. *Maintenance phosphorus and potassium recommendations for alfalfa.**

Phosphorus Soil Test (lb/A)	Potassium soil test 0-240 lb/A	240-360 lb/A	>360 lb/A
0-40			
P_2O_5	50	50	50
K_2O	200	150	0
>40			
P_2O_5	0	0	0
K_2O	200	150	0

*Expressed in lbs/A recommended.

crops. However, in Wisconsin relative yield values have not been developed for crops other than corn. The P needs of all crops are similar, but the K needs vary considerably.

Tables 13 and 14 give the corrective applications of P and K needed for corn and alfalfa depending on soil test results. From these tables, one can calculate supplemental fertilizer needs in a sludge application program.

Since sewage sludge contains considerable P relative to the nitrogen needs of crops, sludge application based on the N requirements of the crop will invariably over-fertilize with respect to P. However, there is no information at present on the availability of the P in sludge from various treatment processes. Preliminary data indicate that the P in anaerobically digested sludges which have not received chemical treatment is equivalent to fertilizer P.

Calculations

The sludge application rate based upon crop nitrogen requirements can be calculated as outlined in Figure 2.

WITH SOIL TEST RECOMMENDATION

(1) Obtain nitrogen recommendation in lb/A = [A] from soil test results.

(2) Calculate the available N in sludge using the following formulas:

$$\% NH_4\text{-N in sludge} \times \frac{2000 \text{ lb/ton}}{100 \text{ (conversion from \%)}}$$

= % NH_4-N x 20 = [B] lb NH_4-N/ton sludge

If surface applied and not incorporated immediately, reduce this value by one-half.

$$\% \text{ organic N} \times \frac{2000 \text{ lb/ton}}{100 \text{ (from \%)}} \times 0.15 \text{ (mineralization rate, 15\%)}$$

= % org. N x 3 = [C] lb org. N/ton

(3) Residual sludge N in soil = [D] lb N/A

If soil has received sludge in the past three years, calculate residual N from Table 11.

(4) Sludge application rate, tons/A

$$= \frac{\text{Nitrogen recommendation, lb/A} - \text{Residual N, lb/A}}{\text{available N/ton sludge}}$$

$$= \frac{[A] - [D]}{[B] + [C]} \text{ tons/A}$$

Example Calculation

Corn; Green County; yield potential, very high

Soil test results	Fertilizer Recommendations
Texture: silt loam	Corrective and Maintenance
Organic matter: 15 tons/A	N; 160 lb/A
Available P: 20 lb/A	P_2O_5; 100 lb/A
Available K: 110 lb/A	K_2O; 220 lb/A

Sludge Analyses

NH_4-N; 1.5% Organic N; 2.5% P; 2.0% K; 0.2% Surface application, 3rd year; 5 tons/A applied in year 1 and 2.

(1) Fertilizer N recommended = 160 lb/A = [A]

(2) Available N in sludge;

1.5 (% NH_4-N) x 20 x 0.5 (for surface application) = 15 lb/ton = [B]

2.5 (% organic N) x 3 = 7.5 lb/ton = [C]

(3) Residual N, from Table 11 for 2.5% organic N

Sludge added 1 year previous 5 tons/A x 3 = 15.0 lb/A

Sludge added 2 years previous 5 tons/A x 2.0 = 10 lb/A

Total residual N = 15 + 10 = 25 lb/A = [D]

(4) Sludge application rate $= \frac{[A] - [D]}{[B] + [C]} = \frac{160 - 25}{15 + 7.5} = \underline{6.0 \text{ tons/A}}$

(5) P added = 6.0 tons/A x 0.02 (% P) x 2000 lb/ton

= 240 lb P/A = 550 lb P_2O_5/A

No P_2O_5 needed.

(6) K added = 6.0 tons/A x 0.002 (% K) x 2000 lb/ton

= 24 lb K/A = 30 lb K_2O/A

K needed = 220 lb/A – 30 lb/A = 190 lb K_2O/A as fertilizer

WITHOUT SOIL TEST RECOMMENDATION

(1) Obtain N requirement from Tables 10 and 12 = [A] lb/A

(2) Calculate available N in sludge as in (a) above, [B] and [C] lb/A

(3) Residual sludge N in soil = [D] lb/A

If soil has received sludge in past three years, calculate residual N from Table 11.

(4) Sludge application rate, tons/A

$$= \frac{\text{crop N requirement} - \text{residual N}}{\text{available N in sludge}} = \frac{[A] - [D]}{[B] + [C]} \text{ tons/A}$$

Example Calculation

From Table 10, N needed for corn = 160 lb/A = [A]. The remainder of the calculations are as shown previously.

FIGURE 2. *Calculation of sludge application rate based on nitrogen loading.*

Heavy Metal Factors Affecting Total Sludge Loading

Total sludge loading may be limited by crop damage due to phytotoxic metals (Zn, Ni and Cu) and to Cd uptake by edible portions of the crop. Zinc and Cu are also required by plants in small amounts. Insufficient information is presently available to provide firm estimates of the amounts of these metals which may be added. The recommendations presented are based on the best information currently available and are conservative.

Toxicity of these elements is presented in Table 15, while Table 16 summarizes the main sources of these elements to the environment.

Retention Mechanisms in Soil

The main factors governing entry of an element into the above-ground portions of plants (excluding aerial contamination) are its availability in the soil, uptake by the roots and translocation.

The retention mechanisms in soils for these elements are numerous, complex, interrelated and predictably, poorly understood. Hodgson (1963) has grouped these reactions into: (1) ion exchange, (2) adsorption and precipitation, and (3) complexation. Figure 3 outlines the mechanisms that may operate to affect plant availability of metals. Several reviews of sorption mechanisms are available (Hodgson, 1963; Jenne, 1968; Ellis and Knezek, 1972; Ellis, 1973).

Cation exchange involves interaction of electrostatic bonding forces, and by definition are the ions that can be readily displaced from the soil by a neutral salt solution without decomposition of the solid matrix.

Soil cation exchange capacity (CEC) is usually estimated by saturating the soil exchange sites with a cation (such as Ca^{++} or NH_4^+), and displacing this cation by leaching with a salt solution such as KCl. Then the amount of cation displaced is measured, and CEC calculated. It is expressed as milligram equivalents (meq) per 100 g of soil. Although soil solids can possess both negative and positive charges, the net negative charge predominates in most temperate zone soils unless they are extremely acidic. The general concensus is that, for the elements in Table 15, nonspecific sorption reactions do not play an important role in their mobility in soils. This is based on the fact that only a small proportion are exchangeable with neutral salts, and that sorption studies with intact soils and with soil components indicate that sorption sites with higher activation energies are involved.

In arable soils, and at background levels, sorption and complexation reactions would appear to control the mobility of these elements. When they are added to soils, the relative dominance of precipitation of discrete compounds over other sorption mechan-

TABLE 15. *Potential toxicity of heavy metals.*

	Essentiality		Toxicity	
Element	Plants	Animals	Plants*	Animals
Cadmium	No	No	Moderate	High**
Chromium	No	No	Low	Low
Copper	Yes	Yes	High	Moderate
Lead	No	No	Low	High**
Mercury	No	No	Low	High**
Nickel	No	Yes	High	Moderate
Zinc	Yes	Yes	Moderate	Low

*When metal is applied to the soil.
**Cumulative effects.

TABLE 16. *Sources of metals to the environment.*

	Source	
Element	General	Specific
Cd	Agricultural	Impure phosphate fertilizers
	Industrial	Electroplating, pigments, chemicals, alloys, automobile radiators and batteries
Cr	Industrial	Refractory bricks, plating of metals, dying and tanning, corrosion inhibitors
Cu	Electrical	Wire, apparatus
	Plumbing	Copper tubing, sewage pipes
	Industrial	Boilers, steampipes, automobile radiators, brass
	Agricultural	Fungicides, fertilizers
Pb	Plumbing	Caulking compounds, solders
	Industrial	Pigments, production of storage batteries, gasoline additives, anti-corrosive agents in exterior paints, ammunition
Hg	Electrical	Apparatus
	Industrial	Electrolytic production of chlorine and caustic soda, measuring and control instruments, pharmaceuticals, catalysts, lamps (neon, fluorescent and mercury-arc), switches, batteries, rectifiers, oscillators, paper and pulp industries
	Household	Paints, floor-waxes, furniture polishes, fabric softeners, antiseptics
	Agricultural	Fungicides
Ni	Industrial	Electroplating, stainless and heat-resisting steels, nickel alloys, pigments in paints and lacquers
Zn	Agricultural	Pesticides, superphosphates
	Household	Pipes, utensils, glues, cosmetic and pharmaceutical powders and ointments, fabrics, porcelain products, oil colors, antiseptics
	Industrial	Corrosion-preventive coating, alloys of brass and bronze, building, transportation and appliance industries
	Plumbing	Galvanized sewage pipes

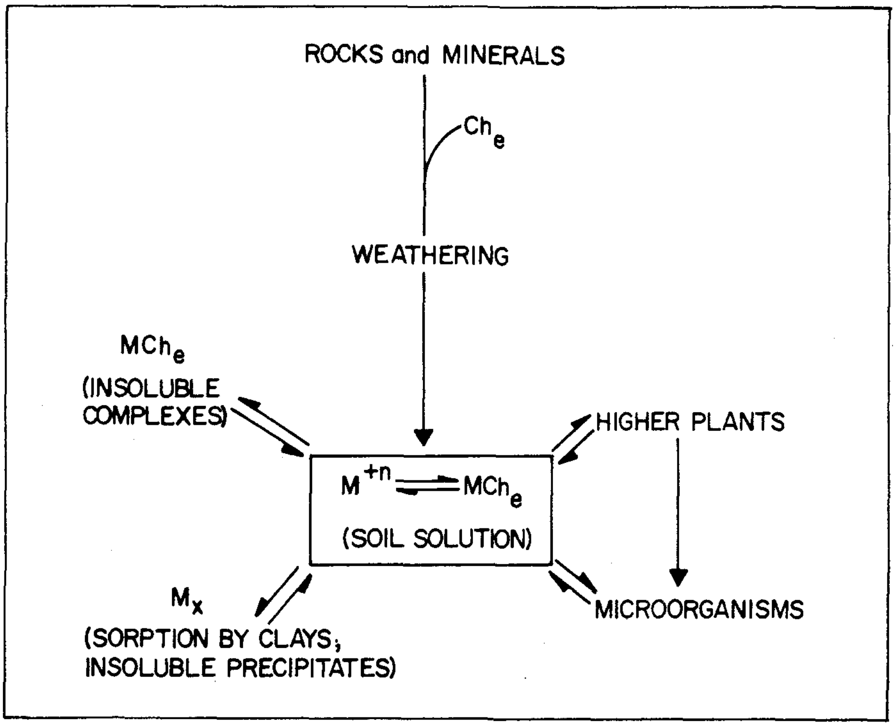

FIGURE 3. *Pathways for metal reactions in soils; M=metal, Ch_e=complex or chelate, x=clay (Stevenson and Ardakani, 1972).*

isms is a function of the concentration added as well as pH (Lindsay, 1972). Lindsay (1972) points out the difficulties of applying solubility product data to Zn and Cu availability in soils.

There is considerable evidence that sorption of metals in soils is predominantly by chelation and by hydrous metal oxides, particularly Fe, Mn, and Al. These oxides, which occur in variable forms ranging from discrete minerals to amorphous coatings, have high surface areas and are quite reactive. The Fe and Mn oxides are quite labile, since their formation and dissolution is dependent on pH and oxidizing-reducing conditions in soils. Jenne (1968) has postulated that the continual formation-dissolution of Fe and Mn hydrous oxides can explain many of the observations on heavy metal mobility in soils as related to flooding, organic matter content and pH.

In a general sense, heavy metal availability decreases as pH increases, and is minimal above pH 6.5. It has also been observed that immobilization of heavy metals in soils will continue slowly for months or years. This is referred to as "reversion" and is often attributed to solid state diffusion into crystalline materials, including clays and may be extremely important in diminishing the phytotoxic effects of over-application of metals.

Stevenson and Ardakani (1972) discussed the possibilities and mechanisms of organic-metallo complexes in soils. Figure 3 outlines these reactions. Deductive reasoning for the importance of these reactions involves (1) biochemical compounds having chelating characteristics are continuously produced (but also degraded) in soils; (2) humic and fulvic acids (the heterogeneous mixture of molecules forming the organic matter of soils) and extracts of plants exhibit strong complexation tendencies; and (3) heavy metal sorption is often related to the organic matter content of soils. Retention of Cu and Ni seems to be closely related to complex formation; conversely, soluble organic complexes can increase heavy metal mobility in soils (Stevenson and Ardakani, 1972). Jenne (1968) noted that metal sorption in soils is related closely to the chemistry of the hydrous metal oxides.

Environmental Hazards

(a) **Phytotoxicity.** The conclusion that phytotoxicity from land application of sludges will result mainly from Zn, Cu, and Ni has resulted in attempts to provide some common index of toxicity related to the amounts of these metals applied. This was first proposed by Chumbley (1971) as the "Zn equivalents" based on observations that Cu is twice as toxic and Ni eight times as toxic as Zn. Chaney (1973) elaborated on the concept, and proposed that soil sorption properties be accounted for by limiting the total "Zn equivalents" applied to 5% of the CEC (cation exchange capacity) of the soil. This approach is essentially being proposed by the U.S. EPA, although the limit has been raised to 10% of the CEC and Ni toxicity relative to Zn lowered to four. Chaney (1973) recommended overcoming the Cd problem by prohibiting land application of sludges with a Cd content greater than 1% of the Zn content.

None of these approaches are based on conclusive experimental evidence, since the data are not yet available. A number of complications which would result from a simplistic approach are readily apparent. For one, metals may not be equally available from sludges of different sources (Cunningham et al., 1975). For another, marked interactions between Cu, Zn, and Ni, and between these metals and other soil constituents (clay, organic matter, phosphate) will likely occur to affect their availability in different soils with similar CEC's. Also, secondary effects on the availability of other metals, principally Fe, might be expected.

Sorption of metals by soil colloids has commonly been observed to occur in amounts in excess of their cation exchange capacities (Ellis and Knezek, 1972). The bondings are probably at specific adsorption sites through covalent bonding to certain functional groups on the clay surfaces and to soil organic molecules. This bonding is often sufficiently stable to compete successfully with precipitation mechanisms, rendering solubility product considerations of little value.

Some specific results of interest include those of Halstead et al. (1969), who found that increasing organic matter or pH depressed Ni availability. Roth et al. (1971) noted that Cu and Ni toxicity to soybeans influence the P and Fe nutrition of the plant. Cunningham et al. (1975) noted that Cu, Zn and Ni interact to enhance their toxic effects. This work also indicated that, with the crops studied, the relative toxicities of Zn:Cu:Ni were 1:2:1.

It is important to note, however, that to date no documented reports of heavy metal toxicity to crops from sewage sludge application have appeared. This includes the evaluation of long-term disposal sites in Europe and Australia, and the University of Illinois' work in which soils were overloaded by 4.5 to 6.4 times their calculated "Zn equivalence" values (Hinesley, 1974).

(b) **Cadmium in the Food Chain.** The uniqueness of Cd in this group lies primarily in the fact that it is relatively mobile in soil and is not excluded by plants (Lagerwerff, 1974). Since Cd occurs commonly in Zn, Pb-Zn and Pb-Cu-Zn ores at about 0.4% of the Zn content, and has a number of industrial uses, it is being added to the environment at a significant level (Page and Bingham, 1973). Fleischer (1973) estimates that about 90% of the Cd discharged to the atmosphere and streams is from man's activities (Table 17).

The toxicity of Cd to man is well documented (Fleischer et al., 1974; Page and Bingham, 1973; Flick et al., 1971), and its effects are particularly insidious due to the cumulative nature of its deleterious effects on the kidney and liver. Sanjour (1974) reviewed the dietary intake of Cd. He reported results of on-going FDA and Canadian work that the Cd content of foods is typically 0.05 ppm or less. This gives an average dietary intake of 50 to 100 ug of Cd/day for the U.S. population (Table 18; FAO/WHO recommends < 70 μ g/day).

As noted in Table 18, cigarette smoking constitutes another major source of Cd. Obviously, further analysis of the Cd level of foods is needed. For example, some shellfish are known accumulators (Sanjour, 1974) and a fish-leafy vegetable diet could constitute a high Cd intake.

The availability of Cd in soils follows closely the principles established for other metals, particularly Zn (for a comprehensive review of factors influencing Zn uptake and availability, see Mortvedt et al., 1972). Species effects are always present (e.g., Page and Bingham, 1972; Bingham et al. 1975) and soil pH is an important variable. John et al. (1972) found that Cd uptake decreased with increasing soil pH, while Lagerwerff (1971) observed that increasing the pH of the soil from 5.9 to 7.2 had no effect on Cd uptake by radishes.

Cadmium may form organic complexes similar to those observed with Zn (Miller and Ohlrogge, 1958), although Haghiri (1974) obtained evidence that soil organic matter interacted with Cd only through exchange reactions. John et al. (1972) found that Cd uptake by plants decreased as soil organic matter content increased.

TABLE 17. *Cadmium emissions to water.*

Source	100 kg per year	% of total
From electroplating	900	44
From other industry	390	19
From sewage (water supply)	490	24
Mines, etc.	?	?
Leaching-agricultural et al.	?	?
Air emissions	250	12
Total	2,030+	

TABLE 18. *Typical American daily Cd intake.*

Source	Concentration	Daily intake (in ug)	Daily absorbed (in ug)
Total diet	0.04 ppm	75.0	4.5
Drinking water	0.0014 ppm	2.8	0.17
Air	0.006 μ g/m3	0.12	0.04
Cigarettes (20/day)	---	---	1.5

(c) **Water Contamination.** The extent of contamination of groundwater with heavy metals from sludge application is dependent upon chemical characteristics of sludge, chemical properties of the soil and the distance to the water table. The potential contamination would be greatest where a shallow water table occurred beneath a sandy soil with low organic matter content. Where the water table occurs at the great distances from the surface, the probability of heavy metal contamination of groundwater is greatly diminished.

As further protection, metal uptake by plants can be used to estimate metal mobility and thereby potential for leaching. If metal uptake exceeds established limits, application of metal-laden sludge will be stopped, thereby indirectly protecting the groundwater from metal contamination.

Since heavy metals applied to soil are largely concentrated in the erodible surface soils, runoff and erosion may contribute to heavy metal contamination of waterways. Concentrations of heavy metals in water may have serious harmful effects on certain species of aquatic life. Therefore, surface runoff of sediment into surface waters should be minimized by use of recommended erosion control practices.

The heavy metal content of sludges can be expected to decline, as the waste discharge provisions of PL 92-500 are implemented. This, however, will likely take considerable time and expense.

Recommendations and Calculations of Total Sludge Application Based on Heavy Metals

As an interim guide, U.S. EPA has recommended the following equation to calculate maximum sludge loading in relation to metal toxicity to plants:

$$\frac{32{,}500 \times CEC}{(\text{ppm Zn}) + 2(\text{ppm Cu}) + 4(\text{ppm Ni})}$$

where CEC = cation exchange capacity of nonsludged soil in meq/100 g and ppm = sludge metals, mg/kg dry solids. This equation includes a number of conversion factors and is based on the hypotheses that (a) CEC is related to soil factors controlling metal availability in soils and (b) that Cu is 2 times and Ni 4 times as toxic to plants as Zn. It limits metal additions to 10% of soil CEC. There is to date no experimental evidence to support or refute this equation, and it must be regarded as empirical and subject to revision.

The equation is difficult to use because of the inherent variability of sludges with source and time. However, it can readily be modified to permit calculation of total metal loadings on a lbs/A basis as:

$$65 \times (\text{CEC})$$

where metal equivalents (lb/ton of sludge) are:

$$\frac{(\text{ppm Zn}) + 2(\text{ppm Cu}) + 4(\text{ppm Ni})}{500}$$

The total sludge loading is thus a matter of an accounting of yearly metal equivalent loadings until the maximum permitted is reached.

Table 19 presents an alternative approach where soil CEC values are not available. It estimates metal loadings as a function of clay and organic matter content, and is intended for use in preliminary planning and in small sites where complete soil characterization is not required. However, whenever possible, analytically determined CEC should be used.

In addition to the metal equivalents' limitations, Cd additions must be limited to a maximum of 2 lb/A/yr with a total site lifetime maximum of 20 lb/A. The 2 lb/A recommendation is based on work in Wisconsin showing that, in general, about 2 lb/A of sludge-derived Cd had to be added before a marked increase in Cd content of the vegetative tissue of crops over control values occurred (Tables 20, 21 and 22). These limitations on heavy metal loading based on plant toxicity effects also will protect the ground water from metal contamination due to overloading of sludge on sites which meet the criteria outlined in Section VII.

An example calculation for sludge application rate based on the Zn, Cu, Ni, and Cd content is presented in Figure 4.

TABLE 19. *Estimated total metal equivalent loadings based on soil texture and soil organic matter content.* *

Soil Texture	Soil organic matter content 5-10 tons/A	11-20 tons/A	21-30 tons/A	31-40 tons/A	41-50 tons/A	51-70 tons/A	>70 tons/A
Sand	260	360	490	630	750	940	1140
Loamy sand	330	440	570	700	830	1020	1220
Sandy loam	420	520	650	780	910	1110	1300
Loam	590	680	810	940	1070	1200	1330
Silt loam	750	850	980	1110	1240	1370	1500
Silty clay loam	1240	1330	1460	1590	1720	1850	1980
Clay loam	1400	1500	1630	1760	1890	2020	2150
Clay	2050	2150	2280	2410	2540	2670	2800

*Expressed in total metal equivalents (lb/A). Based on 10% of CEC as (Zn + 2 Cu + 4 Ni); CEC=(0.50) x (% clay) + 2.00 x (% OM). (Helling et al., 1964).

TABLE 21. *Effect of sludge applied on a Waupun silt loam (Arlington Experimental Farm) in 1972 on the uptake of Cd by subsequent crops.* *

Rate of application: Sludge (T/A)	Cd** (lbs/A)	Cd Concentration in Crop (in ppm): 1972-73 Rye***	1973 Corn Grain	1973 Corn Stover	1974 Corn Grain	1974 Corn Stover
0	0	0.23	0.08	0.15	0.07	0.07
2	0.28	0.25	0.06	0.20	0.07	0.10
4	0.56	0.35	0.07	0.18	0.07	0.07
8	1.12	0.45	0.07	0.25	0.07	0.16
16	2.24	0.40	0.02	0.25	0.07	0.13
32	4.48	0.50	0.05	0.27	0.19	0.13

*Sludge was applied only in the summer of 1972.
**The Cd content of the sludge was 70 ppm.
***Rye was planted in the fall of 1972 and harvested in May of 1973. Corn was planted following harvest of the rye.

TABLE 20. *Effect of sludge applied on a Waupun silt loam (Arlington Experimental Farm) in 1971 on the uptake of Cd by subsequent crops.* *

Rate of application: Sludge (T/A)	Cd** (lbs/A)	Cd Concentration in Crop (in ppm): 1971-72 Rye***	1972 Corn Grain	1972 Corn Stover	1973 Corn Grain	1973 Corn Stover	1974 Corn Grain	1974 Corn Stover
0	0	0.10	0.09	0.03	0.06	0.08	---	0.07
2	0.28	0.25	0.09	0.06	0.05	0.05	---	0.07
4	0.56	0.30	0.13	0.04	0.05	0.09	---	0.07
8	1.12	0.25	0.08	0.09	0.08	0.07	---	0.07
16	2.24	0.30	0.11	0.25	0.05	0.25	---	0.07
32	4.48	0.30	0.09	0.30	0.05	0.24	---	0.07

*Sludge was applied only in the summer of 1971.
**The Cd content of the sludge was 70 ppm.
***Rye was planted in the fall of 1971 and harvested in May of 1972. Corn was planted following harvest of the rye.

TABLE 22. *Effect of sludge applied on a Waupun silt loam (Arlington Experimental Farm) in 1973 on the uptake of Cd by subsequent crops.* *

Rate of application: Sludge (T/A)	Cd** (lbs/A)	Cd Concentration in Crop (in ppm): 1973 Sorghum-Sudan	1974 Corn Grain	1974 Corn Stover
0	0	0.53	0.07	0.07
2	0.28	0.50	0.07	0.19
4	0.56	0.75	0.07	---
8	1.12	0.75	0.07	0.13
16	2.24	0.85	0.07	0.13
32	4.48	0.95	0.12	0.19

*Sludge was applied in May and June of 1973.
**The Cd content of the sludge was 70 ppm.

Example calculation:

Sludge metals(ppm); Zn = 5,300; Cu = 1,300; Ni = 900; Cd = 100. Application site soil CEC= 10 meg/100 g soil.

(1) Total metal equivalent loading = 65 X CEC = 650 lb/A

(2) Sludge metal equivalent per ton = $\frac{5,300 + 2(1,300) + 4(900)}{500} = \frac{11,500}{500}$

= 23 lb metal equivalents per ton of sludge

(3) Total loading permitted = $\frac{650}{23}$ = 28.3 tons

(4) Yearly loading limit due to Cd = $\frac{2 \text{ X } 500}{\text{ppm Cd}} = \frac{2 \text{ X } 500}{100}$ = 10 tons/A for 2 lb. of Cd.

(5) Total Cd loading permitted = 20 lb/A = 100 tons/A

Therefore, Cd loading is limiting on a yearly basis (10 tons/A/year) while metal equivalents (Zn, Cu and Ni) are limiting on the lifetime of the site (28.3 tons/A).

FIGURE 4. *Calculation of sludge application rate based on metals loading.*

III. SLUDGE APPLICATION SYSTEMS AND EQUIPMENT

Three interdependent phases of sludge handling for land application can be identified (White et al., 1975). These are (a) type and quantity of sludge produced, (b) transportation and storage, and (c) application. The degree of treatment affects both transportation and application modes directly since slurry (liquid) sludges have much different handling characteristics than the cake (solid) materials.

Sludge Production and Treatment

Farrell (1974) estimates daily per capita sludge production as primary, 0.12 lb; primary plus secondary, 0.20 lb; primary plus secondary plus chemical, 0.25 lb. Thus, a city of 10,000 without any industries and with a secondary treatment plant would produce about 365 tons of dry solids yearly, or at 4% solids, 9,125 wet tons (2.2 x 10^6 gallons). On the other hand, the Metropolitan Sanitary District of Greater Chicago produced over 800 tons of solids per day in 1973 (Graef, 1974). These two extremes illustrate the fact that different sludge disposal systems will be needed depending on quantities of sludge produced.

Transport and Storage

The physical characteristics (solids content) of the sludge will be a primary factor influencing the type of transportation and application equipment selected. If the slurry has a solids' content of up to 8%, it may be easily pumped. When the sludge is dewatered to a solids' content of 15% or higher, it must be handled as a solid material (White et al., 1975). Table 23, adapted from White et al. (1975), outlines the transport modes that are available. Selection will also depend on production rate, distance to application site, proximity to railway, seasonality of application and planned lifetime of the site.

Pipelines, especially buried pipelines, are probably uneconomical for small communities. Tank trucks provide considerable flexibility with regard to site selection and hauling schedule and have the additional advantages that liquid sludge can be applied directly from the truck (Figs. 5, 6 and 7). They have the disadvantage of not being suited, unless modified with flotation tires, to adverse weather and soil conditions. Gravity discharge is most commonly used, although pressurized tanks or pumps can be used to increase the rate of discharge (Fig. 8). Also, settling of solids during transport has been a problem, and some method of agitation might be required to resuspend solids after long hauls.

Dewatered sludge should not be allowed to air-dry before storage. Experience with the Imhoff-process dewatered sludge at Oshkosh has shown that this sludge forms an extremely hard cake on drying, and considerable effort is required to break up the cake for loading and application.

Due to the inclement weather, frozen soil and snow cover which exist during Wisconsin winters, as well as variations in sludge production and the possibility of equipment breakdown, some storage facilities must be provided. These are usually tanks or lagoons, and if room is available, should be at the treatment site due to the maintenance and public acceptance problems which may occur if extended storage is required at the disposal site. Some provision for resuspension of settled solids must be provided.

Field Application

The application method or methods chosen will depend on factors such as physical properties and quantity of sludge, application rate, site characteristics and management, crop grown, and public acceptance.

Systems are available for surface and for subsurface (plow-down or injection) application of sludge (Table 24 and Figs. 9 to 15). The product file issue of *Implement and Tractor Magazine* provides an annual listing of irrigation and tankwagon manufacturers. Surface application of liquid sludge is generally accomplished by spray (Fig. 16), ridge and furrow irrigation or by tank truck (Fig. 5-7) or farm wagon. Due to the requirement that sludge be applied to soils at fertilizer rates, fixed irrigation systems such as a center pivot system, would most likely be uneconomical. Portable irrigation systems using a single large-nozzle gun (3/4-inch to 2-inch orifice) at 80 to 100 psi have been used (Fig. 16). Spray irrigation has the possible, but not proven, disadvantage of aerial pathogen contamination, and is not suited for use with sludges and/or locations where odor, either real or imagined, is a problem. Further, runoff is a potential problem unless the site is carefully managed, and plant damage may result if sludge is sprayed on growing crops.

Ridge and furrow irrigation requires prior preparation of the land, and only relatively level land can be used. It has the advantage that it is suitable for row crops during the growing season.

To date, the most commonly used surface application methods, especially by smaller communities, are the tank truck and farm tank wagons. The tank truck has the advantage that it can also be used for sludge transport, but use of either a truck or a wagon requires suitable soil conditions. Further, they cannot be used on row crops, and experience at Janesville has shown that tank truck traffic severely damaged established alfalfa stands within one year.

Soil incorporation of liquid sludge has a number of advantages over

TABLE 23. *Sludge transport methods.* *

Sludge State and Mode of Transport	Characteristics	Comments
Liquid		
Rail Tank Car	Capacity, 100 wet tons (24,000 gal.). Need loading and disposal sites near RR.	Solids will settle while in transit; some form of agitation desirable.
Fixed Pipeline (buried)	Suitable for year-round use.	As diameter of pipe increases, pressure loss due to friction decreases (inversely proportional to pipe diameter to the fifth power). Need minimum velocity of 1 f.p.s. to keep solids in suspension. High capital costs.
Portable Pipeline (surface)	Will freeze if used intermittently, not suitable for winter use unless provision made for draining.	Use at disposal site to provide flexibility in selecting field for disposal.
Tank Truck	Capacity, 500 gal. up to maximum allowed on road. Can have gravity discharge or forced (pressure or pump) discharge.	Can use for highway transport and field application. Can use large tractor trailer rig for highway transport but must transfer for field application. If flotation tires used for field travel, not recommended for long distance highway travel.
Farm Tractor and Tank Wagon	Capacity, 800 to 3,000 gal.	Low speed; principal use would be field application, not distance hauling.
Solid		
Rail Hopper Car	Need special unloading site and equipment for field disposal.	Possible use when final disposal is of landfill type. Sludge can be flushed from cars to a lagoon for disposal as a slurry.
Trucks, dump or other type	Suitable for wastes or sludges in solid, nonslurried form.	Trucks can be fitted with equipment to spread waste on ground surface. If dump truck used, will need to level sludge piles. Soil incorporation desirable.
Farm Wagons or Manure Spreaders	Suitable for wastes or sludges in solid, nonslurried form.	Principal use would be field application, not distance hauling. Soil incorporation desirable.

*Adapted from White et al., 1975.

FIGURE 5. *Elevating tank to give more uniform discharge and remove solids (Pullman, Wash., 1972).*

FIGURE 6. *Discharging slurried waste in narrow swath from a tank wagon.*

FIGURE 7. *Immediately covering discharged waste with a four-moldboard plow.*

FIGURE 8. *Commercial tank truck with pump discharge. Courtesy of Gorman–Rupp Co., Mansfield, Ohio.*

surface application. Odors and pests are not a problem, N is conserved since ammonia volatilization and runoff are minimized, and public acceptance may be better. It must be remembered that the soil depth requirement to be presented in Section VII (Table 28) of 2-4 feet for moderate limitations and >4 feet for slight limitations is measured at the depth of application. Thus, for example, injection to 1 foot reduces the soil depth by this amount.

Soil incorporation of liquid sludge can be done in a number of ways. The main methods used are plow-furrow-cover (Fig. 7) and subsurface injection (Figs. 9-15). Reed (1974) has described developments in New Jersey on this equipment, and has had particular success with the plow-furrow-cover method. This approach involves discharging the sludge in a narrow swath from a wagon and immediately covering the waste with a plow. This approach is obviously tied to season, weather and soil conditions, and is best suited for high loading rates (a minimum of 8 to 10 dry tons/A of 5% slurry). Other tillage methods which adequately incorporate the sludge may be suitable (e.g., disc or chisel), but reports of successful use of these have not appeared to date.

Subsurface injection tillage involves a tool such as a chisel or sweep to open a channel in the soil, and the liquid then flows into the opening, either by gravity or under pressure. It may be necessary to use pressure to close the channel, and normally the waste takes considerable time to dissipate into the soil. Our experience has been that a waiting period of 1 to 2 weeks after the injection is required before a vehicle can be driven over the injection site.

Several manufacturers offer liquid animal manure handling systems which have been found suitable for sludge application. Colorado State University (at Boulder) has developed a subsurface injection system (Smith, 1974), which involves a crawler tractor as the prime mover and a flexible hose to supply sludge from the field perimeter. This unit is capable of delivering from 4 to 16 tons of solids/A at 5% solids. It has 7 injector sweeps covering about 10 feet. Most commercial units have 2 to 4 injectors mounted on a tool bar, and some can be used to sidedress crops.

Reed (1974) has developed an injection plow system in which the landsides of a right-hand and a left-hand plow were fastened together, and the liquid waste transferred through a 6-inch pipe to the cavity created by the plow. This system has potential for applying sludge to sod, park lands and roadways as well as agricultural land.

Commercially available pull and truck mounted box-type manure spreaders are available for application of dewatered sludge (Fig. 17). Incorporation should be by conventional disc, chisel or mold board plow.

TABLE 24. *Field application methods.* *

Sludge State and Mode of Transportation	Characteristics	Topographical and Seasonal Suitability	Comments
Liquid (Surface Application)			
Irrigation Spray (sprinkler)	Large orifices required for nozzle. Large power requirement. Wide selection of commercial equipment.	Can be used on rough or steep land. Can be used year-round with provision for draining in winter. Not suitable for application to some crops during growing season. Sludges must be flushed from pipes when irrigation stops.	Application rate not recommended to be over 1/4 in/hr.; less if runoff begins to occur. Permanent irrigation set can be used on pasture and woodlands.
Ridge and Furrow irrigation	Less power requirement than spray irrigation. Land preparation needed.	Between 1/2 and 1-1/2% slope, depending on percent solids. Can be used in furrows between row crops during growing season. Can be used year-round with provision for draining pipes in winter.	
Tank Truck	Capacity, 500 to 2,000 gallons. Larger volume trucks require flotation tires.	Smooth and level or slightly sloping land. Not usable with row crops or on soft ground.	Can be used for transport and disposal.
Farm tractor and Tank Wagon	Capacity 800 to 3,000 gals.	Smooth and level or slightly sloping land. Not usable with row crops or on soft ground.	
Liquid (Subsurface Application)			
Tank Truck with Plow Furrow Cover	Capacity, 500 gals. Single furrow plow mounted.	Smooth and level or slightly sloping land. Not usable on wet or frozen soil.	Not suitable for long transport.
Farm Tractor and Tank Wagon Plow Furrow Cover	Sludge discharge into furrow ahead of single plow. Sludge spread in narrow swath and immediately covered with plows.	Smooth and level or slightly sloping land Not usable on wet or frozen soil.	Additional tractor power needed to pull plow.
Subsurface Injection Equipment	Sludge placed in channel opened by tillage tool.	Smooth and level or slightly sloping land. Not usable in wet, hard, or frozen soil.	Additional tractor needed to pull tillage tool. Vehicles should not traverse injected area for a week or more.
Solid			
Spreading, either truck mounted or farm spreaders	Waste spread evenly over ground. Normally followed by soil incorporation, disking or plowing. Use plow or disc large enough to give complete coverage.	Very light applications (less than 2 dry tons/acre) need not be incorporated unless surface runoff is likely to occur.	
Reslurry and handle as liquid sludge		Suitable for long hauls where rail transport is available.	

*Adapted from White et al. (1975).

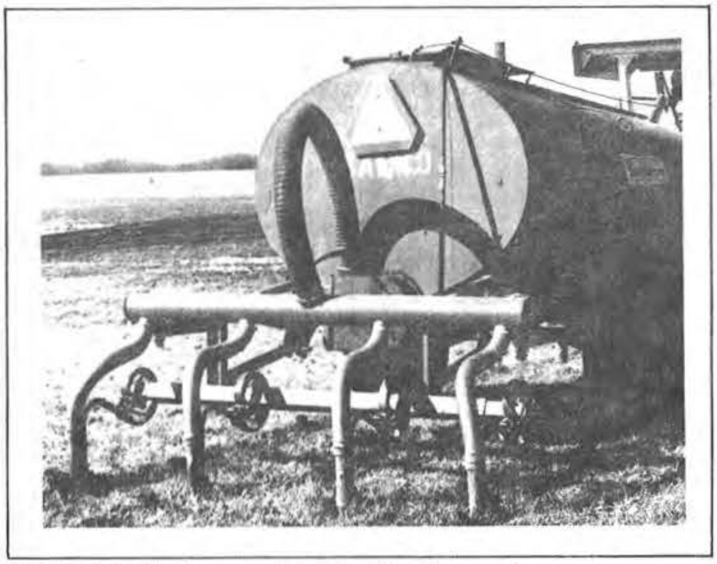

FIGURE 9. *Tank wagon injecting liquid waste into soil.*

FIGURE 10. *Tank wagon with sweep-shovel injectors.*

FIGURE 11. *Second type of injection plow with 1,000-gal. tank trailer with gooseneck tongue. Injector mounted on three-point hitch of tractor. Courtesy of C.H. Reed, Rutgers University.*

FIGURE 12. *Sub-sod injection plow in the ground. Courtesy of Prof. C.H. Reed, Rutgers University.*

FIGURE 13. *Sweep-shovel injectors with covering spoons.*

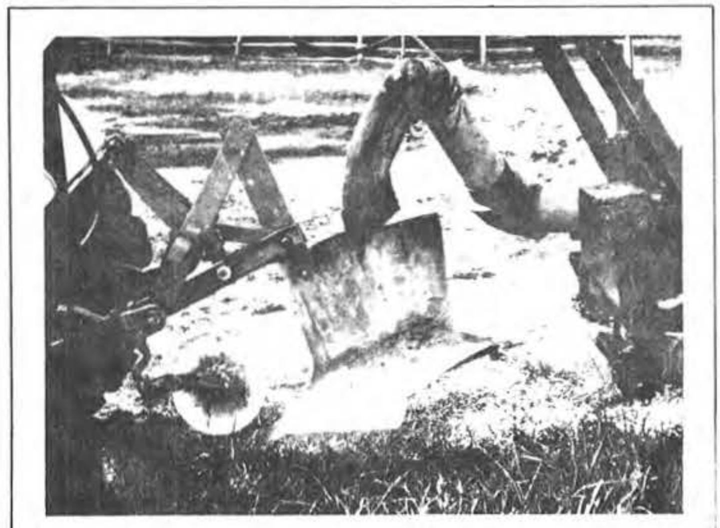

FIGURE 14. *Sub-sod injection plow made from mold boards.*

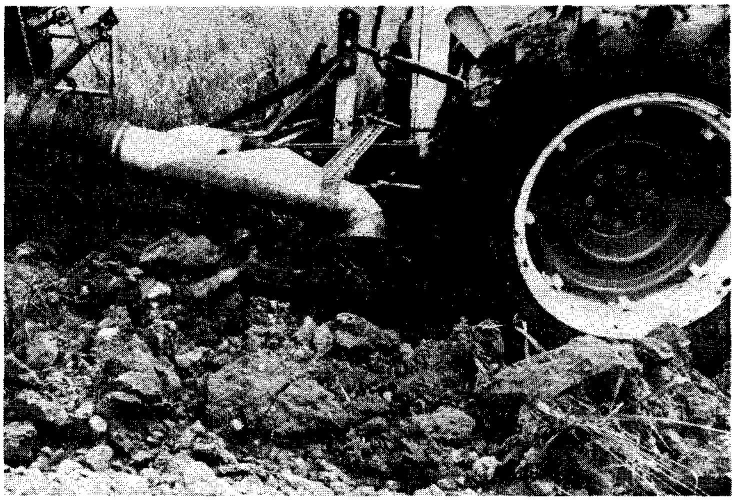

FIGURE 15. *Covering of slurried waste with a single, moldboard plow. Courtesy of Prof. C.H. Reed, Biological and Agricultural Engineering, Rutgers University.*

FIGURE 16. *Big gun nozzle for portable irrigation system.*

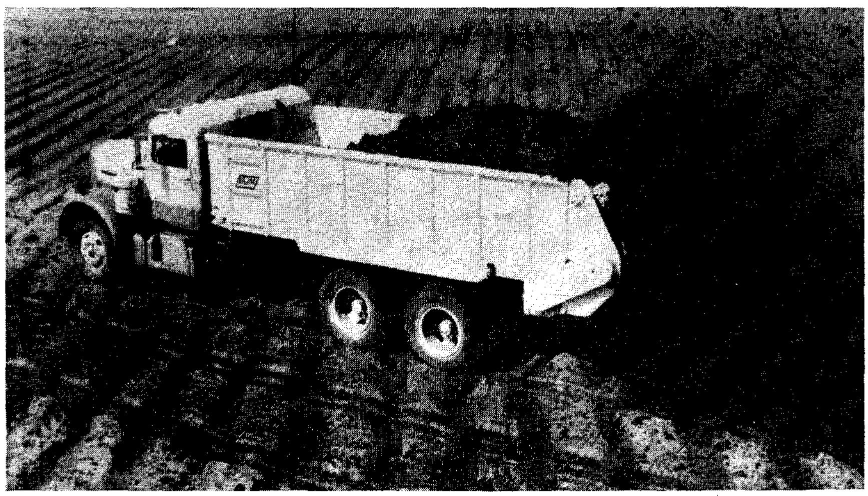

FIGURE 17. *Large, commercial spreader. Courtesy of BJ Manufacturing Co., Dodge City, Kan.*

IV. ECONOMICS OF SLUDGE APPLICATION TO LAND

The economics of sludge application to land is a very dynamic and difficult situation to evaluate. It is affected not only by general economic conditions but also by technological advances in sludge handling and legal constraints imposed by regulatory agencies for adequate public health and environmental protection.

At present, and in the foreseeable future, the municipality or sanitary district should regard sludge as a liability and design its handling system around the least-cost acceptable means of disposal. The acceptable alternatives at present include landfilling, permanent lagoons, incineration and land application.

Landfilling expenses include costs of site acquisition and operation, and the energy and equipment costs of dewatering and transport. Protection of groundwaters from N, P and metal contamination from this material must be evaluated in any economic consideration. The analysis by Ewing and Dick (1970) is the most recent study to consider the available alternatives. Their results indicate that, as of about 1966 and before the marked increase in fuel costs and implementation of the Clean Air Act to control emissions from incinerator stacks, the relative cost per ton of sludge for landfilling was about twice that of land application and one-half that of incineration without adding in transportation costs. For cities of 100,000 or less, the point where landfilling became cheaper than land application was about 25 miles of transport to the disposal site.

The economics of incineration for further solids reduction before disposal of the ash in a landfill is greatly affected by cost and availability of fossil fuels. Incineration reduces the solids content by 60 to 65%, but requires much fuel in order to burn the high water content sludge. Lue-Hing et al. (1974) estimate that, for the Metropolitan Sanitary District of Greater Chicago, the cost of incineration is about $90 to $100 per dry ton exclusive of emission control costs. About 50 gallons of fuel oil on the average are required to combust one ton of sludge. Lue Hing et al. (1974) estimate 900 million gallons of oil would be required yearly to incinerate all the sludge produced in the U.S. In addition, fertilizer nutrients, particularly N, are lost.

Other alternate disposal systems include sludge composting with wood chips, composting of sludge and solid waste mixtures, incineration of sludge and solid waste and pyrolysis or anaerobic digestion to recover methane. Some of these operations are in the experimental stage at the moment, and due to high capital and operating costs, many probably will not prove economical for smaller municipalities.

Sludge composting with added wood chips as the carbonaceous source is being evaluated in an extensive study at Beltsville, Maryland (Walker, 1973). Intital results are quite promising, and a 250-ton-per-day capacity is anticipated. The economics of this approach have not been reported. However, the final product is pathogen-free, odorless, and an excellent soil amendment. Other composting systems using solid wastes (garbage) as the carbon source are feasible and may be economical.

Evaluation of the economics of a land application system must take into account all facets of the operation. White et al. (1975) have summarized these alternatives in a flow-diagram model with all possible alternatives. Their conception has been simplified in Figure 18.

Steps 1 and 2 are largely dictated by in-plant economics and design, while storage is dependent on sludge pretreatment and available space. Transportation costs to the disposal site can represent a significant portion of the disposal cost. Bauer (1973) estimated trucking costs of about $0.10/wet ton/mile. Lagooning will likely be the least expensive storage method at the site. Land application costs will vary depending on the methods chosen. Bauer (1973) estimated that lagooning of sludge at the treatment plant, followed by trucking of the partially dewatered (15% solids) material 20 miles and applying the sludge to land would cost $48.30 per dry ton. At 5% solids (no dewatering) the corresponding cost would be $59.90 per ton.

The fertilizer value of the sludge must also be included in a benefit-cost analysis. Since sludges do have wide variance with respect to their N, P and K contents, average figures would be misleading. However, for an example, at an "available" analysis of 3.5% N, 11.1% P_2O_5 (5% P) and 0.57% K_2O (0.48% K), the current fertilizer value of a sludge would be about $63.00 per dry ton (1974-75 prices of 25, 20 and 8 cents/lb of N, P_2O_5 and K_2O).

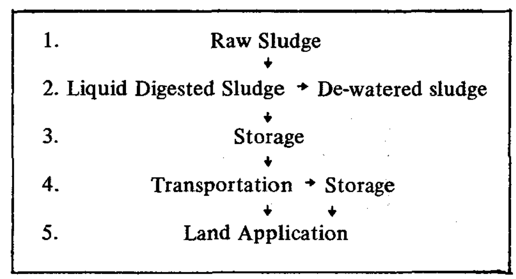

FIGURE 18. *Flow-diagram model showing all stages in sludge treatment and application.*

V. PUBLIC ATTITUDES AND ACCEPTANCE OF LAND APPLICATION

The late 1960's and early 1970's saw several reasonably well-designed land application systems that met with strong public criticism. Brooks (1974) and Bevins (1974) discussed this problem in a regional workshop, "Educational Needs Associated with the Utilization of Wastewater Treatment Products on Land." Brooks pointed out that sociologists have not been involved with these types of projects in the past, and that the available technology is far ahead of our knowledge of the societal effects. He also pointed out that much of the general public, through years of health education, perceives all human by-products as unsanitary, i.e., that these by-products cannot be used for anything useful under any condition. Even when this resistance is overcome, the general concern about aesthetics may limit public acceptance.

Resistance to change (i.e., acceptance of a land disposal system) is often great in rural communities due to the autonomy of the farmers, and conformity to the norms of the social group (Brooks, 1974). In developing programs for a sludge-use program, "grass roots" support is essential. Obtaining this support involves extensive education programs coupled with explanation of the product involved, definition of terms used, benefits and risks, and small-scale demonstration plots.

Bevins (1974) offered the policy approach or format by which educators and public officials can minimize heated conflicts on a controversial project. These are: (1) define the problem; (2) consider goals and objectives; (3) develop alternative solutions; (4) explore the consequence of alternatives; and (5) leave the decision of alternative selection to the people.

Defining the problem

This is a difficult step. The community may see the problem as disposal of wastes, while the people in the receiving area may view the problem as receiving unwanted materials. The problem must be identified so all groups can identify with the statement (e.g., a long-term waste management system for the area).

Identifying the goals and objectives

Identifying goals involves thinking through the views of the various people and groups involved, and expressing these in terms of what (not how) goals should be accomplished.

Identifying alternate approaches

Example alternatives might include to : take no action; develop an incineration system; apply sludge to land; lower the environmental standards; or some combination of these.

Evaluating alternatives

In evaluating the alternatives, public reaction, group conflicts, vested interests, economics and environmental benefits must be evaluated in terms of positive statements, i.e., refrain from becoming an advocate of a certain position. As much as possible, this evaluation should include second and third order effects such as effects of taking land out of production or off the tax roles on the economy of the region or effects of a waste disposal operation on land values.

VI. HEALTH ASPECTS OF SLUDGE APPLICATION TO LAND

The public concept that wastewaters and sludges are "dirty," "impure" or "unhealthy" can be one of the major deterrents to acceptance of a land application program. This is especially true with systems using surface application, where mere sight of the waste brings a conditioned response. Since waste processing as practiced currently in most sewage treatment plants does not render the sludge completely free of pathogenic organisms, sludge must always be handled with caution.

The pathogenic agents found in wastes can be classified in four groups: viruses, bacteria, protozoans and intestinal worms (helminths) (Burge, 1974). The adult forms of the latter two perish quickly external to their hosts, while the cysts of protozoans and the ova of the helminths are capable of survival and are very persistent in wastes. The sludges produced by primary and secondary processes may contain all four groups of pathogenic agents, including *Salmonella*, tubercle bacilli, *Endamoeba*, ascarids, and hookworms. Fortunately, spore-forming bacteria such as *Clostridium tetani* and *Bacillus anthracis*, which are very persistent in soil, do not occur in sewage wastes (Burge, 1974).

Methods for disinfecting sludge include pasteurization, composting, heat drying and lime treatment (Farrell, 1974). Chlorination cannot easily disinfect sludges because of their solid nature. Pasteurization implies heating to a specific temperature for a time period that will destroy undesirable organisms in sludge. While pasteurization at 70°C for 30 to 60 minutes is effective for digested sludge, it is an expensive process. The addition of lime in sufficient quantities to maintain a high pH (between 11.0 to 11.5) destroys pathogenic bacteria. By liming, *Salmonella* and *Pseudomonas* were totally eliminated, and >99% of the fecal coliform and fecal streptococci were destroyed (EPA, 1974). The addition of lime, however, is expensive and significantly increases the amount of sludge to be disposed of. Composting and heat drying can be effective means of destroying pathogens, but costs, energy requirements and marketing requirements restrict the use of these methods.

Anaerobic digestion is a highly effective process for reduction of fecal coliforms. Virus levels are also greatly reduced by anaerobic digestion (MSDG Chicago, 1974). Figure 19 shows the reduction of a bacterial virus (coliphage) and an enteric virus. About 90% of the virus were inactivated in 24 hours and 99% in 48 hours. Molina et al. (1974) observed that the activated sludge process inactivated 99% of the poliovirus in sludge in 24 hours. The reviews by Ewing and Dick (1970) and Dean and Smith (1973) cited references indicating that fecal coliform, (*Salmonella, Pseudomonas* and *Endamoeba histolytica)* populations have a high die-off rate in aerobic and anaerobic digestors.

The most acceptable, effective and economically feasible method for pathogen reduction may prove to be prolonged sludge storage. Table 25 shows the fecal coliform decline resulting from the storage of liquid digested sludge (MSDG Chicago, 1974). After seven days of lagooning, the coliform decline was 99% of the original. The rapidity with which many pathogenic organisms die away after digested sludge is applied on the soil is shown in Table 26. After seven days of drying, the number of fecal coliforms declined to less than 1% of the one-day counts (Lue-Hing et al., 1974). However, Moe (1974) observed that, even 25 days after application of sludge from the Menominee Falls plant to a poorly drained Blount silt loam, fecal coliform counts remained high. This work was conducted during the summer and the plot area received considerable rainfall. Therefore, it would appear that sufficient precautions should be taken to minimize human contact with sludge and limit public access to disposal sites.

From laboratory studies, Berg (1966) determined the time required for 99.9% reduction in the number of viruses and bacteria by storage at different temperatures (Table 27). At 20°C, 41 days were sufficient. Lue-Hing et al. (1974) concluded that an

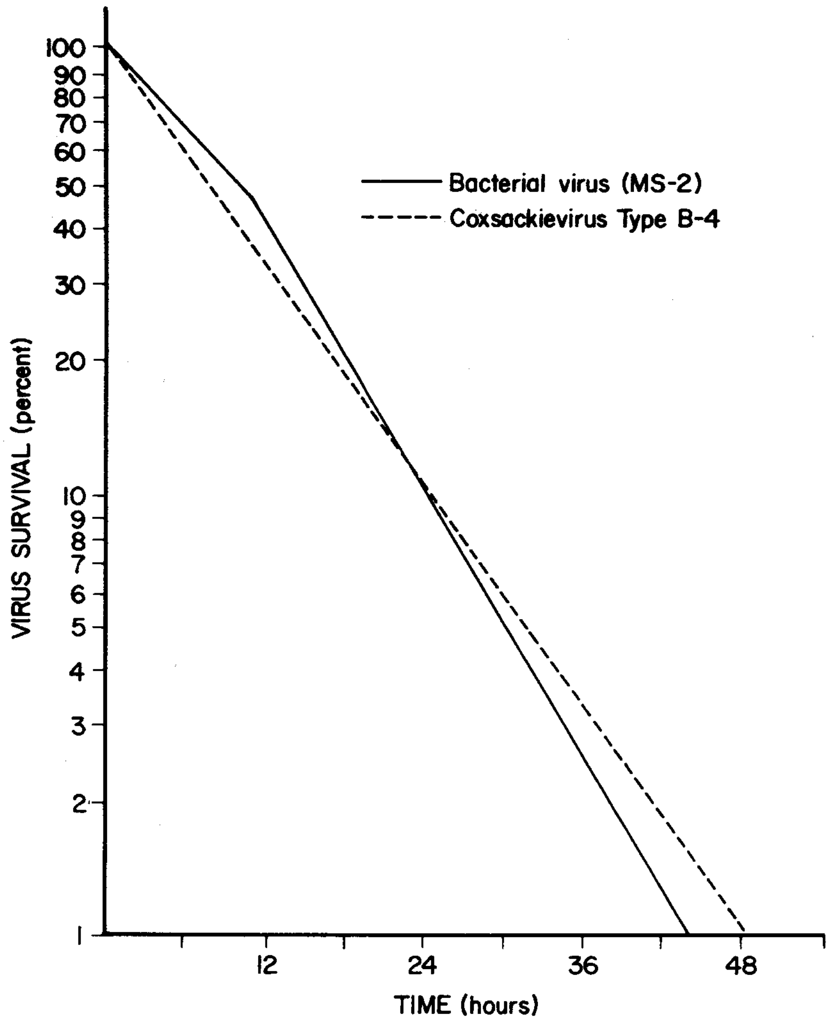

FIGURE 19. *Inactivation of viruses with time in anaerobically digesting sludge (MSDG Chicago, 1974).*

TABLE 25. *Fecal coliform counts of stored digester supernatant exposed to atmospheric conditions (MSDG Chicago, 1974).*

Days	Fecal Coliform Counts (per 100 ml)	Percent Survival
0	800,000*	100.00
2	20,000**	2.50
7	8,000	1.00
14	6,000	0.75
21	<2,000	<0.25
35	<20	<0.01

*Fecal coliform count just prior to lagooning.
**Fecal coliform count after lagooning.

TABLE 26. *Disappearance of fecal coliforms in sludge cake covering a soil surface (Lue-Hing et al., 1974).*

No. Days after Sludge Application	No. of Fecal coliforms per gm Sludge Cake (Dry Weight)
1	3,680,000
2	655,000
3	590,000
5	45,000
7	30,000
12	700

TABLE 27. *Laboratory study on days of storage required for 99.9% reduction of virus and bacteria in sludge (Berg, 1966).*

	No. of days at		
Organism	4^0C	20^0C	28^0C
Poliovirus 1	110	23	17
Echovirus 7	130	41	28
Echovirus 12	60	32	20
Coxsackievirus A9	12	---	6
Aerobacter aerogenes	56	21	10
Escherichia coli	48	20	12
Streptococcus faecalis	48	26	14

additional margin of safety against pathogens could be achieved by holding digested sludge in reservoirs for at least two months before it is applied on land.

Pathogens are readily removed by soils through filtration, sorption-inactivation and die-off, and their movement is usually limited to within a few feet from the source, unless soil is of very coarse texture or contains cracks and channels.

In general, it appears that there is little evidence for the dissemination of disease to humans or animals by land spreading of digested sewage sludge. To insure surface water and groundwater protection from pathogenic organisms which might survive the digestion and storage period, conservation practices of avoiding runoff are recommended for the management of sludge disposal sites.

From the available data, we recommend:

1. Raw sludge should not be applied to agricultural land.
2. At least 2 feet, and preferably greater than 4 feet of soil exist between the sludge application zone and bedrock, any impermeable layer, or the water table.
3. Sludge should not be applied to soil in the year the soil is used for any root vegetables, or other vegetables that are consumed uncooked.
4. If sludge is surface applied, runoff should be minimized by use of contour strips, terraces, and border areas. Also, runoff can be reduced by injection or immediate incorporation of the sludge.
5. Pasture land should not be grazed by milk cows for at least two months after sludge application. Other animals should not graze pasture land for at least two weeks after sludge application.
6. Green-chop forage should not be fed to milk cows for two months or to other animals for at least two weeks after sludge application.
7. To ensure adequate protection of water supplies, the sludge application site should be a minimum of 1,000 ft from the nearest public water supply well and 500 feet from the nearest private water supply well.

VII. SITE SELECTION

Communities planning systems for land application of sewage sludge will have to consider a number of factors. These include: (1) location relative to the treatment plant to minimize transportation distance; (2) availability of sufficient land in relation to local and regional land use plans, desirability of private farmer vs. short- or long-term lease *vs.* outright land purchase; (3) need for on-site storage facilities; (4) population density; and (5) soil suitability. The first four factors are quite objective, and when considered in total with their political and economic ramifications, will likely restrict considerably the availability of sites. The sites remaining must be subjected to a number of suitability criteria with the ultimate aim of choosing the most suitable sites in relation to landscape and soil properties. Oftentimes the available sites will not be ideal. Therefore, some flexibility in requirements must be maintained. In most cases, some site alteration and careful management practices will overcome the potential objections to the site. On-site inspection by qualified personnel should be conducted to evaluate the site in relation to the management system being proposed. Assistance can be obtained from a number of organizations including: the U.S. Soil Conservation Service; the University of Wisconsin Department of Soil Science and Cooperative Extension Service; the Wisconsin Geological and Natural History Survey; professional consultants; and the Wisconsin Department of Natural Resources.

The basic objective of a sludge application system is to maximize nutrient utilization and minimize environmental problems. With regard to the site chosen, landscape features and soil properties must be evaluated. The most restrictive property is then used to provide a suitability rating. These ratings are given with regard to limitations to use of the site for sludge application at nitrogen fertilizer rates. They are defined as: slight (no limitations or limitation easy to overcome), moderate (limitations can be overcome with average management), or severe (limitations are difficult to overcome). The criteria used are summarized in Table 28. Appendix A gives the suitability ratings for the major soil series in Wisconsin.

Landscape Properties

Many soils are underlain by horizons that are less permeable to water than is the surface soil. This can be due to increases in the clay content of the horizon or compaction due to plowing. When water reaches these layers, it can move laterally downslope and discharge later as a surface spring or seep, or move to the water table and reach a more permeable layer. These situations must be evaluated by a hydrologist.

Soils and landscapes are quite complex, and within an area of uniform parent material, soils can differ markedly due to differences in drainage. Soils on ridge tops and steep slopes are well drained, well oxidized, usually thinner, and subject to erosion. Soils on concave land positions and on broad flats are more poorly drained, receive water and sediment from soils higher on the landscape, and commonly have an accumulation of organic matter and clay and waterlogged conditions part of the year. The soils between these two extremes will have intermediate properties with respect to drainage and organic matter accumulation.

Soil Properties

Soil texture, organic matter content and pH are probably the most important soil properties. Texture is defined as the relative proportion of sand, silt and clay in the soil material, and for convenience has been divided into 12 groupings (Fig. 20). In most soils, the clay fraction represents only about 10 to 40%, and the organic matter only about 2 to 10% of the total soil. However, because of the colloidal nature and hence large reactive surface areas of these materials, they govern most of the physical and chemical reactions in the soil.

Soils high in clay often contain much more pore space (the volume of soil not occupied by solids, which usually is in the range of 30 to 60%), but these pores are very small and transmit water slowly. Also, the clay tends to swell when wetted, and thus any cracks or channels which may be present seal when water is added. Therefore, the infiltration rate on soils high in clay is quite low, especially if the rain is of very high intensity. This favors runoff and erosion from the

TABLE 28. *Soil limitations for sewage sludge application to agricultural land at nitrogen fertilizer rates.* *

Soils Features Affecting Use	Degree of soil limitation		
	Slight	Moderate	Severe
Slope**	Less than 6%	6 to 12%	More than 12%
Depth to seasonal water table	More than 4 ft.	2 to 4 ft.	Less than 2 ft.
Flooding & ponding	None	None	Occasional to frequent
Depth to bedrock	More than 4 ft.	2 to 4 ft.	Less than 2 ft.
Permeability of most restricting layer above 3 feet	0.6 to 2.0 in/hr	2.0 to 6.0 in/hr 0.2 to 0.6 in/hr	Less than 0.2 in/hr More than 6 in/hr
Available water capacity	More than 6 in.	3 to 6 in.	Less than 3 in.

*The assistance of A.J. Klingelhoets, USDA-SCS is gratefully acknowledged.

**Slope is an important factor in determining the runoff that is likely to occur. Most soils on 0 to 6 percent slopes will have very slow or slow runoff; soils on 6 to 12 percent slopes generally have medium runoff; and soils on steeper slopes generally have rapid to very rapid runoff.

landscape. Further, surface application of sludge effectively seals soil pores. The general experience has been that surface-applied sludge does not infiltrate into soil and that it will effectively prevent any infiltration. Thus, control of runoff is imperative, even on coarse-textured soils.

The rate of water movement through soils is also an important factor as this governs the residence time of soluble materials in the root zone. When quite moist, sandy soils, due to their large pores, transmit water very rapidly. This coupled with the fact that sandy soils are low in clay (by definition) and usually low in organic matter, makes them poor choices for sludge disposal.

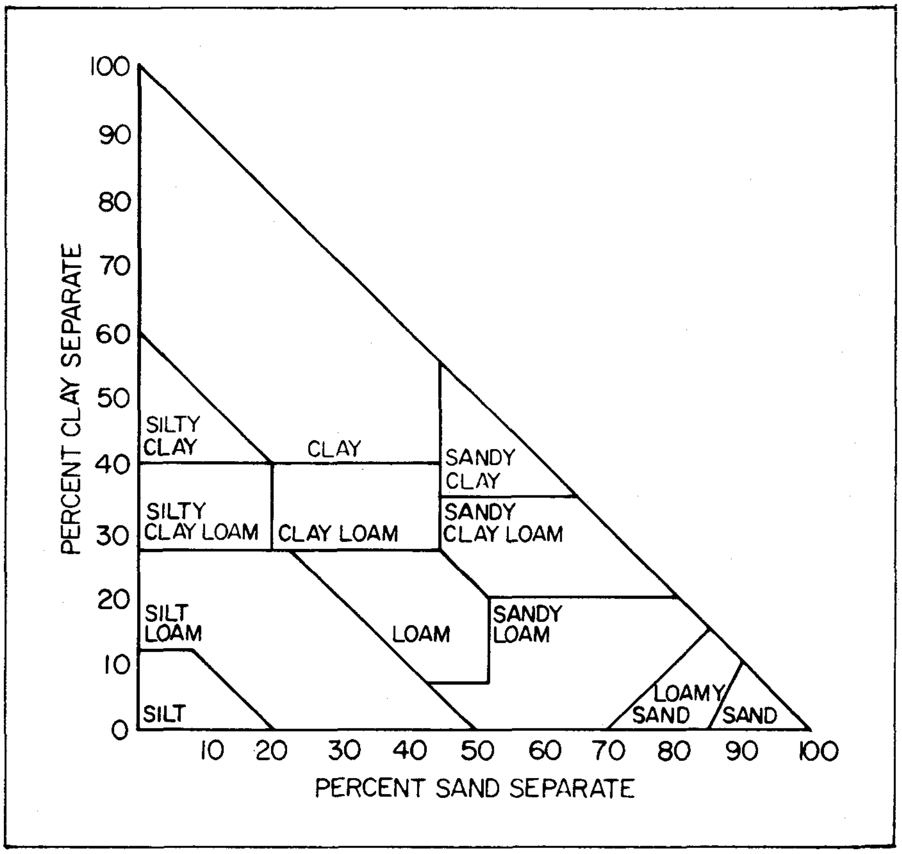

FIGURE 20. *Diagram for determining soil textural classes based on the particle-size classification of the U.S. Department of Agriculture. A point representing the percentages of clay and sand in a soil is plotted on the graph in the normal manner. The labeled area in which the plotted point falls identifies the textural class name of the soil.*

VIII. SITE MANAGEMENT

The sludge application site(s) must be managed to minimize: (1) risks of nitrogen, phosphorus and pathogen contamination of surface and ground waters; (2) risks of soil degradation by metal overloading and of toxic metal uptake by crops; (3) risks of pathogen transmission via insect and animals; and (4) offensive odors.

The degree of site management can be expected to vary widely depending on such factors as site ownership, size and planned lifetime, site properties, transportation and application systems and unpredictables such as yearly weather variations. Site management plans should have considerable flexibility.

If the sites are farmer owned and controlled, application must be in harmony with normal farmer operations, whereas long-term lease or community-owned sites can permit more flexible operations. If the site has moderate limitations for any reason, management must take these limitations into account. Inclement weather can upset the best intentions and may dictate marked deviations from any plan.

In some cases, it may be advantageous in terms of site management to double or triple the annual loading rate the year in which sludge application is made and follow this treatment with two or three years of cropping without applying additional sludge. Since subsequent crops would depend heavily on the residual benefits of the sludge, this type of system would work best on medium or heavy textured soils. Such a system would not be recommended on sandy soils, due to the fact that much of the nitrogen would be leached below the root zone during the first year following application.

Contamination of Water Supplies

Runoff must be controlled to minimize the risks of surface water contamination. There are several approaches for runoff control including standard soil conservation practices such as contour farming, strip cropping and terracing. Additionally, catch basins could be constructed to detain runoff water. The latter would be quite expensive, especially if designed for low-probability events (e.g., 100-year storm). A minimum of 100 feet of buffer strip, in a perennial such as alfalfa or grass, should be maintained adjacent to any watercourse. Subsurface applications will minimize runoff problems and should be practiced where feasible.

Since frozen soils do not have the ability to transmit water, extensive runoff can be expected especially during the spring. Therefore, sludge should not be applied to moderately to severely sloping lands when they are frozen. Groundwater contamination can be minimized by use of recommended sludge application rates, and maximizing crop species and yield to ensure adequate crop uptake. Supplemental fertilizer and lime recommendations as indicated by soil test results should be followed. To this end, it is essential that soil sampling for available P and K, and pH (lime requirement) be conducted each fall so that corrective fertilizer and lime applications can be made before the next crop. Proper site selection is essential to prevent pathogen transmission to groundwater.

Sludge should not be surface applied to sloping (>6%) land at any time of the year when a high potential for runoff due to intensive rainstorms exists. Normally, this potential is highest in the spring and late fall, but exists throughout the year in Wisconsin. Therefore, subsurface application or immediate incorporation is advised on all sloping land to overcome the moderate limitation imposed in Table 28.

If a seasonally high groundwater table condition exists, spring application of sludge is not recommended. Therefore, these soils should be managed so that they receive sludge only in the summer and fall.

Liquid sludge is high in soluble salts. Germination and seedling growth of most crops will be inhibited if applied in the seed bed within about two weeks before or after planting. Sufficient time must be given for soluble salts to dissipate before planting.

Metals

Aside from following current recommendations on total metal loading and proper site selection, the major site management variable is soil pH. The soil pH must be maintained at 6.5 or greater at all times, and the soils should be sampled to check on the possible need for liming.

Since some crop species tend to accumulate Cd, care must be taken to avoid these crops, especially if high Cd sludges are being applied. In general, these accumulator crops are the leafy vegetables.

Pathogen Transmission

The best preventive method to minimize pathogen transmission is incorporation of the sludge as soon as possible. Depending on location, it may be advisable to fence the site to limit access by children, pets and the general public.

Odors

If the sludge has offensive odors, the only practical approaches are either location of the site away from populated areas or subsurface application. Sludge application sites should be at least 500 feet from the nearest residence. If the sludge is injected or incorporated into the soil, a reduction in this distance may be possible.

Timing of Application

Timing of application can also be an important management variable. Application too close to planting could result in germination failure due to salt toxicity, while application on growing plants could result in injury to the leaves. Application in the fall could result in less efficient use of nitrogen due to denitrification and/or nitrate leaching. Similarly, application during wet periods, particularly in the spring when the soil is near saturation, could result in a low degree of retention of some pollutants. Therefore, facilities for off-season storage of sludge are required with most agricultural sludge application systems.

IX. SYSTEM MONITORING

Any decision on the intensity of system monitoring must consider: (a) size of the sewage treatment plant and industrial sources of metals; (b) site ownership, site size and planned lifetime; and (c) site properties and management. The system, in this case, refers to the sludge and the site (soil, plants, and surface and groundwater).

Sludge Monitoring

In developing a land application program, representative sludge samples and adequate analyses of the sludge are required. To obtain a representative sample, a number of samples collected periodically over a 24-hour period should be bulked. Samples should be stored in sealed glass or plastic bottles in a refrigerator and analyzed as soon as possible.

It is beyond the scope of this document to give details on how to conduct analyses of sludge. These methods are given elsewhere (Standard Methods, 1971; EPA, 1973). Certain of these analyses, particularly the metals, require complicated instrumentation and trained technicians and, except for larger municipalities, should not be undertaken by the community. Care must be taken with the nitrogen analyses, as ammonia volatilizes readily from the sample and an underestimate of the nitrogen content of the wet sludge can result.

The recommended amount of sludge monitoring is based on sewage treatment plant size. Plants with a treatment capacity of less than 50,000 gallons per day (gpd) require a single sludge analysis yearly which consists of: solids, total nitrogen, ammonium nitrogen, total phosphorus, total potassium, and total metals (including copper, zinc, nickel, chromium, lead and cadmium).

Plants with a treatment capacity of 50,000 to 1,000,000 gpd require all of the analyses listed above plus total arsenic and mercury required once yearly.

Plants with a treatment capacity of > 1,000,000 gpd require all of the analyses listed above, and at least three times during the year.

Site Monitoring

The recommendations for site monitoring are based on the following criteria:

(a) The site meets the qualifications outlined in the section on site selection, and runoff is minimized.

(b) Sludge is being added at fertilizer N rates and nutrient recycling by use of grain, forage or vegetable crops is being practiced.

(c) The sludge is digested or otherwise treated so that pathogen levels are minimal.

(d) Metals and phosphorus are tightly sorbed in the surface soil.

Thus, using recommended practices, ground and surface water contamination can be expected to be essentially at "background" levels, that is, no greater than might occur if commercial fertilizers or animal manures were used rather than sludge.

The recommended monitoring intensity varies with the extent of site use. These are:

(a) Occasional use: Sludge applied at a maximum once every two to three years as part of a normal rotation. This use requires only a soil test every three years to ensure that P, K and pH are adequate for maximum crop yields. Analysis of selected plant material for Cd after three sludge applications may be desirable.

(b) Continuous use: Sludge applied yearly on leased or community-owned land. This use also requires a soil test for K and pH and plant tissue monitoring to evaluate nutrient status and metal uptake. Plant analyses should include Cd, Cu, Mn, Ni, Zn and B. Each site receiving sludge should be tested once every three years.

The plant integrates the various soil and environmental variables involved in the mobility of elements in soil. Therefore, plant tissue analysis will provide the most sensitive and accurate assessment of heavy metal problems. The drawback to plant analysis is that, if a problem is indicated, it may be too late to apply remedial action.

Table 29 lists the range in elemental composition normally encountered in samples of plant tissue in the field and suggested tolerance levels (Melsted, 1973). The tolerance levels given are preliminary values, at this time, and are for succulent vegetative tissue only.

The tolerance levels suggested in Table 29 assume that:

1. The same tolerance levels can be used for the common agronomic crops.
2. The designated plant part and stage of development will be used.
3. The municipal sludges and effluents are being recycled or used as fertilizer. This implies a rate of application commensurate with crop needs.
4. The land is productive agricultural land to be used for crop production for generations to come.
5. Many of the noxious compounds in the wastes become immobile when added to the soil and will remain there indefinitely.
6. The crop will probably absorb a part of any toxic heavy metal or noxious compound added to the soil.
7. The tolerance level includes an acceptable safety factor. Therefore, the suggested levels are only one-half, or less, of the values the literature suggested as being: toxic levels for animals; plant levels at which appreciable transfer of the element from the vegetative portion of the plant to the grain occurs; and the level known to be toxic to the plant itself.

In addition to plant analyses, research on metals extractable from the soil as related to plant toxicity and uptake are being evaluated currently. We hope soon to be able to recommend a "toxic" range of DTPA-extractable Zn, Cu, Ni and Cd in soil. This will be useful to monitor the site and predict possible problems before they occur.

TABLE 29. *Range in normal elemental composition and suggested tolerance level for various elements in succulent vegetative tissue* of agronomic crops, legumes and grasses (Melsted, 1973).*

Element	Normal range (μg/g)	Suggested maximum tolerance level (μg/g)
Cadmium	0.05 - 0.2	3
Cobalt	0.01 - 0.3	5
Copper	3 - 40	150
Manganese	15 - 150	300
Mercury	0.001 - 0.01	0.04
Nickel	0.01 - 1.0	3
Lead	0.1 - 5.0	10
Zinc	15 - 150	350
Arsenic	0.01 - 0.1	2
Boron	7 - 75	150
Molybdenum	0.2 - 1.0	3
Selenium	0.05 - 2.0	3
Vanadium	0.1 - 1.0	2

*Values are for corn leaves at or opposite and below ear level at tassel stage; soybeans–the youngest mature leaves and petioles on the plant after first pod formation; legumes–upper stem cuttings in early flower stage; cereals–the whole plants at boot stage; grasses–while plants at early hay stage. All plant samples should be washed with deionized-distilled water before drying to remove any surface contamination. In some cases it may be necessary to wash with a detergent solution or a weak acid solution before the final washing with deionized-distilled water. Samples should be dried (65°C) as quickly as possible, ground, and stored for analysis. If the undried samples cannot be processed immediately, they should be placed in polyethylene bags and stored under refrigeration. Preparation for analysis involves: (1) Wet digestion. For all elements except N and B. Digest in boiling nitric-perchloric acids. Treatment with HF may be necessary for recovery of some of the heavy metals from the silica which precipitates in the digest. (2) Dry ashing. At low temperature (450 to 500°C). Dissolve ash in HCl. This is the only method to be used for B analysis. Not suitable for Hg, S, Se, As, Ag, Fe, Sb, and N. (3) Kjeldahl (H_2SO_4) digestion. For total N, P, and K.

X. SLUDGE APPLICATION TO NONAGRICULTURAL LANDS

Forests offer a viable alternative for sludge disposal, particularly during adverse weather and for small communities. The sites chosen may often be in National, State or locally-owned forests. To date, little long-term information is available on the impact of sludge disposal on the forest environment, but results of the few short-term studies indicate that if the site is properly managed, environmental impact is minimal and some stimulation in tree growth can occur. Further studies may well show highly beneficial effects of sludge for stimulation of regrowth on whole-tree harvested sites, Christmas tree plantations, and fast-growth chipwood systems such as hybrid poplar. In these systems a high degree of nutrient recycling can be expected and the pathogen problems will be minimal as compared to agricultural systems.

Since forested sites can often be located in isolated areas, problems with odors and public acceptance will be minimized, and the main potential problem will be nitrate pollution of the groundwater. Thus nitrogen loading should be limited to an annual total of 100 lb/A of available nitrogen, and monitoring wells established to ensure that excessive nitrate-nitrogen contamination of the groundwater does not occur. Further, background levels of metals in adjacent foliage should be established, and monitoring of foliage for excessive metals conducted every third year. Due to the difficulty in raising soil pH in forested sites, metals may prove to be a particularly difficult problem, necessitating low total loadings.

Park lands also offer an alternative application site, especially during adverse weather. Since these lands are also publicly owned, site acquisition problems are minimal. However, easy public access and low rates of nutrient recycling present problems. Subsurface application is a necessity, and low rates (150 to 200 lb/A) of available nitrogen once every three to four years would be a maximum loading rate.

Several studies have shown that sewage sludge is excellent for rejuvenation of despoiled land, such as strip-mine spoils, mine tailings, scalped land and other areas where the land has been grossly altered. The quantity of sludge needed to restore such areas depends on the nature of the land being treated. For example, acid coal mine spoil reclamation in southern Illinois required about 200 to 250 dry tons per acre, while with calcareous and strongly alkaline spoils, about 100 to 200 dry tons per acre of sludge markedly improved plant growth (Lue-Hing et al., 1974). Of course, at these rates, substantial amounts of NO_3-N will be leached. However, restoring these lands to productive use more than offsets the temporary high nitrate hazards of a localized area.

SUMMARY

Wastewater sludges contain the concentrated wastes of the community. This includes all of the plant nutrients, but in particular nitrogen and phosphorus. Certain sludges also contain potentially toxic and hazardous components, principally the heavy metals, pathogenic bacteria and virus.

In many instances, disposal of sludge on agricultural land is the most cost-effective (for the community) and environmentally sound approach. This involves the concept of "recycling" the plant nutrients. However, a number of precautions must be taken to minimize the possibilities of disease transmission, water quality degradation by nitrogen and phosphorus and soil contamination by the heavy metals to levels detrimental to crop yields. These must be taken into account in facilities' planning of new sewage treatment systems receiving state and federal grants.

Sludge is a low analysis fertilizer of extremely variable quality. The economics of sludge disposal from the farmer standpoint is a dynamic situation depending on fertilizer cost and availability.

Another major potential problem which has occurred with many of the wastewater and sludge land application projects to date is acceptance of the project by the local population. A thorough educational program, complete with alternatives to the proposed plan, is required. A major public acceptance problem is the odor, real or imagined, associated with sludge. One way to minimize this problem is to incorporate the material in the soil as soon as possible.

Commercially available equipment may be readily modified for surface or subsurface application of sludge. Dewatered sludge ($>$ 15% solids) can be handled as a solid by using equipment designed for farm animal manures, while liquid sludge ($<$ 15% solids) may be applied to the surface by tank truck or spray irrigation, or injected by equipment designed for use with liquid farm wastes.

Several studies have shown that sewage sludge applied at the proper rates will supply the nitrogen and phosphorus needs of agronomic crops and that sludge treated fields will produce yields comparable to that attained with use of commercial fertilizers. Sewage sludge nitrogen is in the form of ammonium and organic nitrogen. The ammonium nitrogen is readily available to crops, but a considerable amount of this nitrogen can be lost to the atmosphere by volatilization if the sludge is applied to the soil surface and allowed to dry. A ton of sludge solids might contain up to 30 or 40 pounds of ammonium-nitrogen and 50 pounds of organic nitrogen. However, only 15 to 20% of the organic nitrogen is available through the decomposition process the year of application. Thus, the available nitrogen in a ton of sludge solids might be around 40 to 50 pounds if injected and 25 to 30 pounds if surface applied.

This nitrogen must be balanced against crop needs. Depending on the length of the growing season, the type of soil, the supply of available nitrogen from the soil and the level of management, a corn crop may need from 60 to 200 pounds of fertilizer nitrogen/acre. At fertilizer nitrogen rates, and assuming that proper site preparation has been used, environmental contamination by nitrate should be minimal and ground water monitoring is not required.

The phosphorus in sludge is also beneficial. A ton of sludge solids would contain from 40 to 100 pounds of phosphorus. Thus, if sludge is added at nitrogen fertilizer rates, much more phosphorus is added than needed by the crop. Experience to date has indicated that this excess phosphorus is not a problem when sludge is used at fertilizer nitrogen rates. Sludge is deficient in potassium relative to crop needs (corn, for example, has an N:P:K ratio of 5:1:5), and a management program must involve soil tests for available potassium and supplemental addition of potassium fertilizer as required.

Sewage sludge, as it comes from the digester, contains a variety of pathogens, including bacteria, larvae, worms and virus. Available evidence indicates that, with time, these pathogens die off so that in about 2 months or so of storage, about a 90 to 99% decrease in their numbers occurs. Several sterilization methods are also available to reduce the pathogen content of sludges. When the sludge is added to soil, these pathogens are not able to compete with the native soil microorganisms, and they practically disappear in a few weeks. There have been no documented reports of disease problems with sludge, but to be on the safe side, precautions must be taken. This includes limiting public access to the application site, minimizing runoff, and restrictions on grazing or growing of vegetables on the site the year of application.

Another potential problem is the heavy metals in sludges, particularly those from communities with certain types of industries. These metals may be toxic to plant life if added in sufficient amounts, thus leaving the soil unusable for agricultural pursuits. Certain of these metals may also accumulate in the plant tissue and be a hazard to animals and humans consuming the plant tissue. These metals are tightly held by the organic and inorganic constituents in soils. As soil pH increases, availability of these metals decreases. The more organic matter and clay a soil contains, the more metals can be added before problems occur. Thus the metal retention capacity of a soil and the metal load of the sludge must also be taken into account when designing a sludge application program.

RECOMMENDATIONS

The following recommendations are made regarding the application of wastewater sludge to agricultural land in Wisconsin:

1. Raw sludge should not be applied to agricultural land.
2. Sludges should be applied to soils consistent with the nitrogen needs of the crops being grown.
3. At least 2 feet and preferably greater than 4 feet of soil should exist between the sludge application zone and bedrock, any impermeable layer, or the water table.
4. To ensure adequate protection of water supplies, the sludge application site should be a minimum of 1,000 feet from the nearest public water supply well and 500 feet from the nearest private water supply well.
5. Sludge should not be applied to soil in the year the area is used for any root crops or other vegetables which are consumed uncooked.
6. If sludge is surface applied to sloping land, runoff should be minimized by use of contour strips, terraces and border areas. Also, runoff can be reduced by injection or immediate incorporation of the sludge.
7. Pasture land (or crops which are harvested green) should not be used for milk cow feeding for two months following sludge application. Other animals should not graze pasture land or be fed green chop material for at least two weeks after sludge application.
8. Metal loadings must be kept within acceptable limits to minimize the potential of crop damage or food chain accumulation. The soil pH must be maintained at 6.5 or greater.
9. Application systems must be such that they minimize the runoff potential and odor problems while remaining cost-effective.
10. Sludge application sites should be at least 500 feet from the nearest residence. If the sludge is injected or incorporated into the soil a reduction in this distance may be possible.
11. Site management must be such that nutrient deficiency and soil acidity problems do not occur, public access is limited, and crop yields are maximized.
12. Site monitoring should be the responsibility of the municipality. If sludge additions consistent with nitrogen requirements are used, monitoring needs include only sludge and plant analyses as well as routine soil testing. If higher rates are to be applied on dedicated land, comprehensive ground water monitoring must be included.

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APPENDIX

A. YIELD POTENTIAL AND LIMITATIONS OF MAJOR WISCONSIN SOIL SERIES FOR APPLICATION OF WASTEWATER SLUDGE*

Name of Soil Series	Yield Pot.[a]	Limitation[b] Rating	Factor
Adolph	3	Severe	2, 3
Adrian	1	Severe	2, 9
Ahmeek	4	Moderate	7
Alban	3	Slight	
Alcona	3	Moderate	6
Allendale	4	Moderate	1
Almena	3	Moderate	1
Alstad	3	Moderate	1
Altdorf	3	Severe	2, 3
Amery	2	Slight	
Angelica	3	Severe	2, 3
Antigo	2	Slight	
Arcola	3	Moderate	7
Arenzville	1	Severe	3
Arland	3	Slight	
Ashdale	1	Slight	
Ashkum	2	Severe	2, 3
Auburndale	3	Severe	2, 3
Au Gres	4	Severe	1, 9
Aztalan	1	Moderate	1, 7
Baraboo	2	Moderate	4
Barrington	1	Slight	
Barronett	2	Severe	2, 3
Basco	2	Moderate	4
Batavia	1	Slight	
Beecher	2	Moderate	7
Bellevue	1	Severe	3
Bergland	4	Severe	3, 8
Bertrand	1	Slight	
Bevent	3	Moderate	6
Bibon	4	Severe	9
Billett	3	Moderate	6
Blount	2	Moderate	1, 7
Boaz	2	Severe	3
Bohemian	3	Slight	
Bonduel	2	Moderate	1
Boone	4	Severe	9
Boots	1	Severe	2, 3
Borth	2	Moderate	7
Boyer	3	Moderate	6
Braham	3	Slight	
Brems	3	Severe	9
Brickton	2	Severe	2, 7
Briggsville	2	Moderate	7
Brill	2	Moderate	1
Brimley	3	Moderate	1
Brookston	1	Severe	2, 3
Bruce	3	Severe	2, 3
Brule	3	Severe	3
Burkhardt	3	Moderate	6
Cable	4	Severe	2, 3
Cadiz	1	Slight	
Cadott	2	Moderate	1, 6
Calamine	1	Severe	2, 8
Campia	2	Slight	
Carbondale	1	Severe	2, 3
Carlisle	1	Severe	2, 3
Caryville	2	Severe	3, 9
Casco	3	Moderate	6
Cathro	1	Severe	2
Channahon	3	Severe	5, 9
Chaseburg	1	Severe	3
Chelsea	4	Severe	9
Chetek	3	Moderate	6
Clifford	3	Moderate	1, 7
Cloquet	3	Moderate	6
Clyde	2	Severe	2, 3
Coloma	4	Severe	9
Colwood	1	Severe	2, 3
Comstock	2	Moderate	1
Crivitz	4	Moderate	6
Cromwell	3	Moderate	6
Croswell	4	Severe	1, 9
Crown	3	Moderate	1, 6
Crystal Lake	2	Slight	
Curran	1	Moderate	1, 7
Cushing	3	Slight	
Dakota	2	Moderate	6
Dalbo	3	Moderate	1, 7
Dancy	3	Severe	2, 3
Darroch	1	Moderate	1
Dawson	1	Severe	2, 3
Deford	4	Severe	2, 3
Dells	2	Moderate	1, 6
Del Rey	2	Moderate	1, 7
Delton	2	Slight	
Denrock	1	Moderate	1, 7
De Pere	2	Severe	3, 8
Derinda	2	Moderate	7
Dickinson	2	Moderate	6
Dickman	3	Moderate	6
Dodge	1	Slight	
Dodgeville	2	Moderate	4
Dolph	3	Severe	1, 8
Downs	1	Slight	
Dresden	2	Slight	
Dubuque	2	Moderate	4
Duelm	3	Moderate	6
Duluth	3	Slight	
Dunbarton	3	Severe	5
Dunnville	1	Slight	
Durand	1	Slight	
Dusler	3	Moderate	7
Eagle	2	Slight	
East Lake	4	Severe	9
Eau Pleine	2	Slight	
Edmund	2	Severe	5
Edwards	1	Severe	2, 3
Elburn	1	Severe	2, 3
Elderon	4	Slight	
Elroy	1	Slight	
Eleva	3	Moderate	4
Elkmound	3	Severe	5
Elliott	2	Moderate	7
Elm Lake	3	Severe	2, 3
Elvers	1	Severe	2, 3
Emmert	4	Severe	9
Emmet	3	Slight	
Ettrick	1	Severe	2, 3
Fabius	3	Moderate	1, 6
Fairchild	3	Moderate	1, 6
Fall Creek	1	Moderate	1, 7
Fayette	1	Slight	
Fence	3	Slight	
Fenwood	2	Slight	
Fifield	3	Moderate	1
Flagg	1	Slight	
Floyd	2	Moderate	1, 3
Fox	2	Slight	
Freeon	3	Slight	
Freer	3	Moderate	1, 7
Friendship	3	Severe	1, 9
Friesland	2	Slight	
Gaastra	3	Moderate	1
Gale	2	Moderate	4
Garwin	1	Severe	2, 3
Gilford	3	Severe	2, 3
Gogebic	4	Slight	
Goodman	3	Slight	
Gotham	3	Moderate	6
Granby	4	Severe	3, 9
Gratiot	1	Moderate	1, 7
Grays	1	Slight	
Greenwood	1	Severe	2, 3
Grellton	2	Slight	
Griswold	2	Slight	
Guenther	3	Moderate	6
Halder	3	Moderate	1, 3
Hebron	1	Moderate	7
Hennepin	2	Slight	
Hertel	4	Moderate	6
Hesch	3	Moderate	4
Hiawatha	4	Severe	9
Hibbing	4	Moderate	7
Hiles	2	Moderate	4
Hitt	2	Slight	
Hixton	3	Moderate	4
Hochheim	2	Slight	
Hortonville	2	Slight	
Houghton	1	Severe	2, 3
Hubbard	3	Severe	9
Humbird	4	Moderate	4, 6
Huntsville	1	Severe	3
Iosco	3	Moderate	1
Iron River	4	Slight	
Isanti	3	Severe	2, 9
Jackson	1	Slight	
Jericho	1	Moderate	7
Jewett	2	Slight	
Joliet	2	Severe	2, 5
Joy	2	Moderate	1
Juda	1	Slight	
Jump River	3	Severe	3
Juneau	1	Severe	3
Kane	2	Moderate	1
Karlin	3	Moderate	6

A. (Cont.)

Name of Soil Series	Yield Pot.[a]	Limitation[b] Rating	Factor
Kato	2	Severe	2, 3
Kaukauna	2	Moderate	7
Kegonsa	2	Slight	
Keltner	1	Slight	
Kendall	1	Slight	
Kennan	3	Slight	
Kenyon	2	Slight	
Keowns	2	Severe	2, 3
Kert	2	Moderate	1, 4
Kewaunee	2	Moderate	7
Kibbie	2	Moderate	1
Kickapoo	1	Severe	3
Kidder	2	Slight	
Kinross	4	Severe	1, 9
Kiva	4	Moderate	6
Knowles	2	Moderate	4
Kolberg	3	Moderate	4
Kranski	3	Severe	9
La Farge	2	Slight	
Lafont	3	Slight	
Lamartine	1	Moderate	1
Lamont	3	Moderate	6
Langlois	1	Slight	
Lapeer	2	Slight	
Lawler	2	Moderate	1
Lawson	1	Severe	1, 3
Leola	4	Moderate	1, 6
LeRoy	3	Slight	
Lindstrom	1	Slight	
Lino	3	Moderate	1, 6
Linwood	1	Severe	2, 3
Lobo	1	Severe	2, 3
Lomira	2	Slight	
Longrie	3	Moderate	4
Lorenzo	3	Moderate	6
Lows	3	Severe	2, 3
Loyal	2	Slight	
Ludington	4	Moderate	4, 6
Lunds	3	Moderate	1, 6
Lupton	1	Severe	2, 3
Mackinac	3	Moderate	1, 6
Magnor	3	Moderate	1, 6
Manawa	2	Moderate	1, 7
Manistee	4	Moderate	7
Manitou	4	Severe	2, 3
Mann	3	Severe	2, 3
Marathon	2	Slight	
Marcellon	2	Moderate	1
Markesan	2	Slight	
Markey	1	Severe	2, 3
Markham	2	Slight	
Marshan	2	Severe	2, 3
Marshfield	2	Severe	2, 3
Martinsville	2	Slight	
Martinton	2	Moderate	1, 7
Matherton	2	Moderate	1
Maumee	4	Severe	2, 3
Mayville	1	Slight	
McHenry	2	Slight	
Meadland	2	Moderate	1, 7
Mecan	3	Moderate	6
Medary	2	Moderate	7
Meehan	3	Severe	1, 9
Menchgo	4	Severe	9
Mendota	2	Slight	
Menominee	3	Moderate	6
Mequon	2	Moderate	1, 7
Meridian	3	Slight	
Merrillan	3	Moderate	1, 4
Metamora	2	Moderate	1, 6
Metea	3	Moderate	6

Name of Soil Series	Yield Pot.[a]	Limitation[b] Rating	Factor
Miami	2	Slight	
Mifflin	3	Slight	
Military	3	Moderate	4
Milladore	2	Moderate	1
Minocqua	3	Severe	2, 3
Monico	4	Severe	2
Montello	2	Moderate	7
Montgomery	2	Severe	2, 3
Montmorenci	1	Slight	
Morley	2	Moderate	7
Morocco	3	Severe	1, 9
Mosel	1	Moderate	1, 7
Mosinee	3	Slight	
Moundville	3	Moderate	1, 6
Mt. Carroll	1	Slight	
Mundelein	1	Moderate	1
Munising	4	Moderate	7
Muscatine	1	Moderate	1
Muskego	1	Severe	2, 3
Mussey	3	Severe	2, 3
Mylrea	2	Moderate	1
Myrtle	1	Slight	
Namur	3	Severe	5
Navan	1	Severe	2, 3
Neda	2	Slight	
Nemadji	4	Severe	1, 9
Nenno	2	Moderate	1
Newaygo	3	Slight	
New Glarus	2	Moderate	4
Newson	3	Severe	2, 9
Newton	4	Severe	2, 9
Nichols	2	Slight	
Nickin	3	Moderate	4
Nippersink	2	Slight	
Norden	2	Moderate	4
Norgo	3	Severe	5
Norrie	2	Slight	
Northfield	3	Severe	5
Nymore	3	Severe	9
Oakville	3	Severe	9
Ockley	1	Slight	
Oconto	3	Moderate	6
Odell	1	Moderate	1
Oesterle	3	Moderate	1
Ogden	1	Severe	2, 3
Okee	3	Slight	
Omega	4	Severe	9
Omena	2	Slight	
Omro	2	Moderate	7
Onamia	3	Moderate	6
Onaway	3	Slight	
Ontonagon	3	Moderate	7
Orienta	4	Moderate	6
Orion	1	Severe	3

Name of Soil Series	Yield Pot.[a]	Limitation[b] Rating	Factor
Oshkosh	2	Severe	8
Oshtemo	4	Moderate	6
Ossian	1	Severe	2, 3
Otter	1	Severe	2, 3
Otterholt	2	Slight	
Ottokee	4	Moderate	6
Ozaukee	2	Moderate	7
Padus	3	Slight	
Palms	1	Severe	2, 3
Palsgrove	2	Slight	
Pardeeville	2	Slight	
Parr	1	Slight	
Pearl	4	Severe	9
Pecatonica	1	Slight	
Peebles	3	Moderate	7
Pella	1	Severe	2, 3
Pence	3	Moderate	6
Pickford	3	Severe	2, 8
Pillot	2	Slight	
Pinconning	4	Severe	2, 3
Plainbo	4	Severe	9
Plainfield	4	Severe	9
Plano	1	Slight	
Pleine	4	Severe	2, 3
Plover	3	Moderate	1
Point	3	Moderate	1
Port Byron	1	Slight	
Poskin	3	Moderate	1
Poy	2	Severe	2, 9
Poygan	2	Severe	2, 9
Puchyan	2	Moderate	6
Racine	2	Slight	
Radford	1	Severe	1, 3
Renova	2	Slight	
Rib	3	Severe	2, 3
Richford	4	Moderate	6
Richter	3	Moderate	1
Richwood	1	Slight	
Rietbrock	2	Moderate	1, 4
Rifle	1	Severe	2
Rimer	3	Moderate	1
Ringwood	2	Slight	
Ripon	2	Moderate	4
Ritchey	3	Severe	5
Rockers	4	Moderate	1
Rockton	2	Moderate	4
Rodman	4	Severe	9
Roscommon	4	Severe	2, 9
Rosholt	3	Moderate	6
Rotamer	3	Slight	
Rousseau	4	Severe	9
Rowley	1	Moderate	1
Rozellville	2	Slight	
Rubicon	4	Severe	9

* The assistance of A.J. Klingelhoets, USDA-SCS is gratefully acknowledged.

a Yield potential for corn: 1. Very high, 2. High, 3. Moderate, 4. Low.

b The soil series listed here have been rated in accordance with the following limitation factors:

1. Water table at 2-4 ft
2. High water table (< 2 ft)
3. Occasional flooding, ponding
4. Bedrock at 2-4 feet
5. Shallow to bedrock (< 2 ft)
6. Permeability: moderately rapid (2 to 6 in/hr)
7. Permeability: moderately slow (0.2 to 0.6 in/hr)
8. Permeability: slow (less than 0.2 in/hr)
9. Permeability: rapid (more than 6 in/hr)

Final determination of the rating by the site investigator must be based on separate consideration of slope limitations: Slight limitations, 0 to 6%; Moderate limitations, 6 to 12%; Severe limitations, greater than 12%. For a particular site, then, the final limitation is determined by the most restrictive rating.

A. (Cont.)

Name of Soil Series	Yield Pot.[a]	Limitation[b] Rating	Factor
Rudolph	3	Moderate	7
Rudyard	3	Moderate	1, 3
Ruse	4	Severe	2, 4
Sable	1	Severe	2, 3
St. Charles	1	Slight	
Salter	2	Slight	
Santiago	2	Slight	
Sargeant	2	Severe	2
Sartell	3	Severe	9
Sattre	3	Slight	
Sawmill	1	Severe	2, 3
Saylesville	2	Moderate	7
Schapville	2	Moderate	7
Scott Lake	3	Slight	
Seaton	1	Slight	
Sebewa	2	Severe	2, 3
Seelyeville	1	Severe	2, 3
Selkirk	3	Moderate	7
Seward	3	Moderate	6
Shawano	4	Severe	9
Sheboygan	1	Severe	2, 3
Sherry	2	Severe	2, 3
Shiffer	3	Moderate	1
Shiocton	2	Moderate	1
Shullsburg	2	Moderate	4
Sisson	2	Slight	
Skillet	2	Moderate	1, 4
Skyberg	2	Moderate	1, 7
Sogn	4	Severe	5
Solona	3	Moderate	1
Spalding	1	Severe	2, 3
Sparta	4	Severe	9
Spencer	2	Slight	
Spinks	4	Moderate	6
Spirit	3	Moderate	1
Stambaugh	3	Slight	
Strawn	2	Slight	
Stronghurst	2	Moderate	1
Summerville	3	Severe	5
Superior	4	Moderate	7
Sylvester	2	Moderate	4
Symco	2	Moderate	1
Symerton	1	Moderate	7
Tama	1	Slight	
Tawas	1	Severe	2, 3
Tedrow	3	Severe	1, 9
Tell	2	Slight	
Terril	1	Severe	3
Thackery	1	Moderate	1
Theresa	2	Slight	
Tilleda	3	Slight	
Toddville	1	Slight	
Trempe	4	Severe	9
Trempealeau	2	Moderate	6
Trenary	3	Moderate	7
Troxel	1	Severe	3
Tula	4	Moderate	1
Tustin	3	Slight	
Underhill	3	Slight	
Urne	3	Moderate	4
Valton	2	Moderate	7
Varna	2	Moderate	7
Veedum	3	Severe	2, 3
Vesper	2	Severe	2, 3
Vilas	4	Severe	9
Virgil	1	Moderate	1
Vlasaty	2	Slight	
Wacousta	2	Severe	2, 3
Wainola	4	Severe	1, 9
Wakefield	3	Slight	
Wallkill	1	Severe	2, 3
Warman	3	Severe	2, 3
Warsaw	2	Slight	
Wasepi	3	Moderate	6
Washburn	3	Slight	
Washtenaw	2	Severe	2, 3
Waterloo	2	Slight	
Watseka	4	Severe	1, 9
Waubesa	1	Severe	2, 3
Wauconda	1	Moderate	1
Waukechon	3	Severe	2
Wauseon	2	Severe	2
Wautoma	2	Severe	2
Waymor	2	Slight	
Wea	1	Slight	
Westland	1	Severe	2
Westville	2	Slight	
Whalan	2	Moderate	4
Whitehall	2	Slight	
Will	2	Severe	2, 3
Willette	1	Severe	2, 3
Wilton	2	Moderate	7
Winnebago	1	Slight	
Winneconne	2	Severe	8
Winneshiek	2	Moderate	4
Withee	2	Moderate	1
Worchester	3	Moderate	1
Worthen	1	Severe	3
Wyeville	3	Moderate	6
Wykoff	3	Slight	
Wyocena	3	Moderate	6
Yahara	2	Moderate	1
Zittau	2	Moderate	7
Zurich	1	Slight	
Zwingle	2	Severe	2, 3

* The assistance of A.J. Klingelhoets, USDA-SCS is gratefully acknowledged.

[a] Yield potential for corn: 1. Very high, 2. High, 3. Moderate, 4. Low.

[b] The soil series listed here have been rated in accordance with the following limitation factors:
1. Water table at 2-4 ft
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7. Permeability: moderately slow (0.2 to 0.6 in/hr)
8. Permeability: slow (less than 0.2 in/hr)
9. Permeability: rapid (more than 6 in/hr)

Final determination of the rating by the site investigator must be based on separate consideration of slope limitations: Slight limitations, 0 to 6%; Moderate limitations, 6 to 12%; Severe limitations, greater than 12%. For a particular site, then, the final limitation is determined by the most restrictive rating.

B. FIELD INFORMATION SHEET

Part A
Characteristics of Digested Sludge

Name of Treatment Plant ______________________________

Permit No. WI– ______________________________

Analysis of Digested Sludge*

Total N ______ %		As ______ ppm		Ni ______ ppm	
NH_4-N ______ %		Cd ______ ppm		Zn ______ ppm	
Total P ______ %		Cu ______ ppm			
Total K ______ %		Cr ______ ppm			
pH ______		Pb ______ ppm			
Solids ______ %		Hg ______ ppm			

Laboratory Doing Analysis ______________________________

Date of Analysis ______________________________

*All analysis on a dry weight basis except percent solids.

Part B
Site Evaluation and Application Rate Calculations

Name of Treatment Plant ______________________________

Permit No. WI– ______________________________

Sludge Application Site

(Attach soil survey map of field location and soil test results)

Location Township ________ Range ________ Section ________ County ________

Owner's Name ______________________ Address ______________________

____

Operator's Name ______________________ Address ______________________

____

Predominant Soil Series ______________________________

Predominant Soil Texture ______________________________

Slope: ☐ Nearly Level (0-6%) ☐ Sloping (6-12%) ☐ Steep (>12%)

Distance To The Nearest Residence (In Feet) ______________________

Distance To The Nearest Public Water Supply (In Feet) ______________________

Distance To The Nearest Private Water Supply (In Feet) ______________________

Sludge To Be Used For ☐ Cropland ☐ Reclaiming Marginal Land

☐ Other ______________________

Application Method ______________________________

Describe Any Special Problems In Cropping In This Field ______________________

____

Soil Test Results

Testing Lab ____________		Date Tested ____________	Recommendations
Soil pH ____________		For ____________	(Crop)
Organic Matter ____________	Tons/A	Lime ____________	Tons/A
Available P ____________	Lbs/A	Fertilizer	
Exchangeable K ____________	Lbs/A	N ____________	Lb/A = (A)
		P_2O_5 ____________	Lb/A = (P)
		K_2O ____________	Lb/A = (K)

I. CALCULATION OF SLUDGE APPLICATION RATE (DRY SOLIDS BASIS) BASED ON NITROGEN

Sludge Analysis:

NH_4-N ______ % Organic N (Equals Total N Minus NH_4-N) ______ %

P ______ % K ______ %

1. Available N in Sludge
   ______ (% NH_4-N) x 20 x 0.5 (If Surface Application) = (B) ______ Lb/Ton
   ______ (% Org. N) x 3 = (C) ______ Lb/Ton
2. Residual N From Table 11
   (D) ____ Lb/A = ______ (2nd Year) + ______ (3rd Year) + ______ (4th Year)
3. Sludge Application Rate, Tons/A/Year = $\frac{(A) - (D)}{(B) + (C)}$ = ______ Tons/A/Yr = (E)

II. CALCULATION OF SLUDGE APPLICATION RATE BASED ON HEAVY METALS

Sludge Analysis:

Zn ________ ppm   Cu ________ ppm
Ni ________ ppm   Cd ________ ppm

1. Total Metal Equivalent Loading Based On Soil CEC
   = 65 x CEC = ____________ Lb. Metal Equivalents/A Or Estimate From Table 19 = (F)
2. Metal Equivalents/Ton of Sludge =

$$\frac{\text{ppm Zn} + 2(\quad \text{ppm Cu}) + 4(\quad \text{ppm Ni})}{500}$$

   = ____ Lb. Metal Equivalents/Ton = (G)
3. Metal Loading Per Year Based On Nitrogen Fertilizer Rates
   = (E) _____ Ton/A/Yr x (G) _____ Lb/Ton = _____ Lb/A/Yr = (H)
4. Site Lifetime Based On Use Of Sludge At Nitrogen Fertilizer Rates
   = (F) Total Lb. Metal Equivalents/A
   (H) _____ Metal Equivalents, Lb/A, Yr. = _____ Yr.

III. YEARLY AND MAXIMUM LOADING LIMITS BASED ON Cd

1. Yearly Limit of 2 Lb. Cd/A = $\frac{2 \times 500}{\_\_\_\_ \text{ ppm Cd}}$ = ________ Tons/A/Yr = (I)
2. Maximum Loading, 20 Lb. Cd/A = $\frac{20 \times 500}{\_\_\_\_ \text{ ppm Cd}}$ = ________ Tons/A = (J)

IV. POTASSIUM FERTILIZER NEEDS

1. Maximum Yearly Application Rate = (E) or (I), Whichever Is Smaller.
2. K_20 Added in Sludge = Sludge Rate, (E) or (I) Ton/A/Yr x $\frac{\%K}{100}$ x 2,000 Lb/Ton x 1.2
   = ________ Ton/A/Yr x 24 Lb/Ton = ________ Lb. K_20/A/Yr = (J)
   = (K) ________ – (J) ________ = ________ Lb/A

C. SOME USEFUL CONVERSION FACTORS

1. 1 acre = 4,840 yards^2 = 43,560 feet^2 = 4,047 meters^2 = 0.4047 hectare
2. 1 acre-inch of liquid = 27,154 gallons = 3,630 ft.^{3} = 102,787 liters
3. 1 acre-inch of 5% (by weight) sludge = 6 tons of solids/acre = 13.45 metric tons/hectare
4. acre-inches X 0.226 X mg/liter = lb/acre
5. hectare-cm X 0.1 X mg/liter = kg/hectare
6. hectare-cm
7. hectare-cm of liquid = 100,000 liters = 100m^3
8. 1 metric ton = 1,000 kg = 2,205 lb
9. English-Metric Conversions
   a. acre-inch X 102.8 = meter^3
   b. quart X 0.946 = liter
   c. English ton X 0.907 = metric ton
   d. English ton/acre X 2.242 = metric ton/hectare
   e. lb/acre X 1.121 = kg/hectare
   f. 1 ft^3 = 7.48 gallons = 28.3 liters = 62.4 lbs water
   g. 1 lb = 0.454 kg

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