#73-67-2

February 1982 2
Report No. Env. E. 68-82-1

Bench Scale Studies of Leachate Treatment By Land Application To A Forest Soil

Robert J. Drake
Research Assistant

Donald D. Adrian
Professor of Civil Engineering

Donald L. Mader
Professor of Forestry

The research upon which this publication is based was supported in part by the Division of Water Pollution Control, Massachusetts Water Resources Commission, Contract No. 73-10(2) and by the U.S. Forest Service, Northeastern Forest Experiment Station, Grant No. 23-041.

ENVIRONMENTAL ENGINEERING PROGRAM
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MASSACHUSETTS
AMHERST, MASSACHUSETTS 01003

February 1982
Report No. Env. E. 68-82-1

BENCH SCALE STUDIES OF LEACHATE TREATMENT BY LAND APPLICATION TO A FOREST SOIL

By

Robert J. Drake
Research Assistant

Donald D. Adrian
Professor of Civil Engineering

Donald L. Mader
Professor of Forestry

Division of Water Pollution Control
Massachusetts Water Resources Commission
Contract No. 73-10(2)

U. S. Forest Service
Northeastern Forest Experiment Station
Grant No. 23-041

Environmental Engineering Program
Department of Civil Engineering
Amherst, Massachusetts 01003

February 1982

PREFACE

This report is a reproduction of a portion of Mr. Robert J. Drake's Master's Thesis which was directed by Drs. Donald Dean Adrian and Donald L. Mader. The research described herein concerns the effectiveness of a forest soil in treating sanitary landfill leachate and the effects of leachate on three local varieties of seedlings.

The authors would like to acknowledge Dr. Enrique J. La Motta, Dr. Aaron Jennings, Ms. H. Patricia Hynes, Mr. David Leland, and Mr. Kevin Sheehan, all of whom provided invaluable assistance through the course of this research. The contributions of Mrs. Dorothy Pascoe and Ms. Christina Moore in the final preparation of the report are also greatly appreciated.

This research was performed with support from the Massachusetts Division of Water Pollution Control, Research and Demonstration Project Number 73-10(2) and the United States Forest Service, Northeastern Forest Experiment Station, Grant Number 23-041.

ABSTRACT

In this study, the effectiveness of land application as a method of treating lagooned sanitary landfill leachate was examined. Leachate was collected from both primary and secondary lagoons at the Barre Landfill in Barre, Massachusetts. Leachate was then applied to seedlings planted in plexiglas containers on Barre sand soil, on the grounds of the University of Massachusetts pilot wastewater treatment facility in Amherst. Leachate applications were made at different strengths and loading rates over a single growing season. Comparisons were made between the chemical composition of the leachate before and after land applications. In addition, the effects of the leachate on three types of seedlings were noted at the bench scale level.

Land treatment of the landfill leachate resulted in COD removals of approximately 70 percent and ammonia removals of about 80 percent. Nitrification was thought to be the major mechanism for ammonia removal. Of the three types of seedlings tested, white pine (Pinus strobus) was the only one shown to be leachate tolerant. Red maple (Acer rubrum) was leachate sensitive, and red oak (Quercus rubrum) did not survive transplanting in sufficient numbers to be evaluated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Overview

The sanitary landfill has been the most economical and acceptable method of ultimate disposal of solid wastes on land. Although a great improvement over its predecessor, the open dump, the sanitary landfill has many environmental defects. One of these is the generation of leachate by infiltrating rainfall, and its subsequent movement through the surrounding soil to surface and ground waters.

Leachate increases the concentrations of minerals and organic compounds in the receiving waters, lowering water quality and affecting the suitability of those waters for beneficial uses (1). Leachates have been implicated in problems with water supplies from both surface and ground waters (2,3). The problems associated with water supplies involve increased levels of inorganics (nitrogen, heavy metals, and other metals), organics and bacterial and viral pathogens (4,5).

Because the composition of solid waste is extremely variable, the general characterization of leachate becomes difficult. Table 1 presents ranges of values for many of the contaminants found in leachate (6). The treatability of leachate is obviously related to its chemical composition, and the large degree of variability makes the selection of treatment processes troublesome.

TABLE 1. General Characteristics of Leachate (6)

Parameter*	Maximum	Minimum
COD	89,520	40
BOD_5	33,360	81
TOC	28,000	256
pH	8.5	3.7
Total Solids	59,200	0
TDS	44,900	584
TSS	700	10
Specific Conductance**	16,800	2,810
Alkalinity***	20,850	0
Hardness***	22,800	0
Total P	130	0
Ortho-P	85	6.5
Ammonia-N	1,105	0
Nitrate & Nitrite	10.3	0.2
Calcium	7,200	60
Chloride	2,467	4.7
Sodium	7,700	0
Potassium	3,770	28
Sulfate	1,550	1
Manganese	125	.09
Magnesium	15,600	17
Iron	2,820	0
Zinc	370	0
Copper	9.9	0
Cadmium	17	.03
Lead	2.0	.10

*All values are in mg/ℓ unless otherwise noted.

**μ-mhos/cm

***mg/ℓ as $CaCO_3$

The organic constituents of leachate are primarily the end products of acid fermentation of the biodegradable portions of the landfilled wastes, primarily the fatty acids (acetic, propionic, butyric, and valeric) (7). The biodegradation is a two-step process . The first step involves the conversion of organic compounds to organic acids. The fatty acids are converted to methane and carbon dioxide in the second, rate controlling step. As the second step is slower and more environmentally sensitive than the first, there is usually (at least in a "young" landfill) an excess of volatile acids which are removed via leaching. The heavy metals and other constituents of the leachate are essentially solubilized by the reducing conditions within the landfill. As the landfill ages, the production of volatile acids decreases, but the leachate can still be a serious problem (3).

Leachate Management Alternatives

There are three basic alternatives in leachate management. The first involves the exclusion of water from the landfill, via use of impermeable soil cover, choice of vegetative cover, and diversion of surface flow (8). This management technique is particularly susceptible to groundwater level fluctuations, which can negate the effect of rain and surface water exclusion. This is also a difficult technique to use while the landfill is being filled.

The second management technique involves the collection and recycling of leachate through the landfill. This technique results in more rapid stabilization of the landfill and significant reductions in many contaminants in the final leachate (7). However, with this process there are residual pollutants in the leachate which require further treatment before release.

The final alternative involves the collection and direct treatment of the leachate. Many options have been investigated and have shown varying degrees of potential utility. Most of these studies have dealt with conventional processes such as activated sludge/extended aeration or anaerobic digestion and all have resulted in significant residual pollutant loads which require further treatment.

Research Objectives

This research examined, at the bench scale level, a relatively low-cost method of leachate treatment: land application to a forest soil. The net removal of contaminants by the shallow Barre sand soil at various loading rates and strengths of leachate was analyzed and the general effects of leachate application to three species of tree seedlings were assessed.

More specifically, the study was designed to document changes in the levels of the following leachate constituents as they passed through the soil: ammonia, copper, iron, manganese, zinc, COD, total dissolved solids (through specific conductance), and pH. The leachate used in the study was taken from primary and secondary lagoons at the landfill in

Barre, Massachusetts and experimental soil columns were set up at the site of the University of Massachusetts' pilot wastewater treatment facility in Amherst. Some of the columns were planted with local seedlings and maintained out-of-doors to approximate natural growing conditions. Soil columns without seedlings, used as controls to gauge the effect of seedlings on leachate treatment, were kept indoors for ease of sampling.

In addition to monitoring changes in leachate composition, three types of seedlings (red maple (Acer rubrum), red oak (Quercus rubrum), and white pine (Pinus strobus)) were tested for reactions to leachate additions at a variety of strengths and loading rates. Collected rainwater was applied to some seedlings of each type at the same rate that the leachate was being applied to others. Thus, the effects of hydraulic loading alone on the health of the plants could be controlled for. The leachate effects on seedlings were assessed by examination of the following plant characteristics: height, foliar metal content, basal area, and actual mortality.

II. LITERATURE SURVEY

Leachate Treatment

Both biological and physico-chemical processes have been examined with respect to leachate treatment. Chian and DeWalle (9) evaluated an anaerobic filter, an aerated lagoon (extended aeration), and co-treatment with municipal sewage in an activated sludge system. The anaerobic filter (with recycle of effluent) essentially duplicated the same two-step digestion process found in the leachate recycling management scheme, with phosphorus added as a nutrient. For hydraulic detention times greater than seven days, better than 95 percent chemical oxygen demand (COD) reductions were achieved. However, with an influent of 54,000 mg/ℓ COD, the residual in the effluent exceeded 2000 mg/ℓ COD. The extended aeration lagoon was able to reduce COD concentrations by 96.8 percent (75,900 mg/ℓ to 1800 mg/ℓ), and both iron and zinc were reduced by 99.9 percent (0.5 mg/ℓ Fe and 0.25 mg/ℓ Zn residuals). Co-treatment with municipal wastewater at a rate of 0.5 percent (leachate/sewage) produced an initial deterioration of effluent quality which was later reversed.

Cameron and Koch (10) found substantial treatment of leachate by anaerobic digestion with little toxicity displayed by heavy metals in the system. COD removals of 80 percent (8,000 mg/ℓ COD residual) with 20 day detention times were achieved. Metal removals were also significant, with 85 percent of zinc and 40-70 percent manganese removals recorded. There were still significant residuals of iron, however (26.0-61.7 mg/ℓ).

Physico-chemical treatment of leachate was examined by Ho, et al. (11) and focused on precipitation, chemical coagulation, chemical oxidation, and activated carbon adsorption. Precipitation using lime removed most iron but sodium sulfides had little effect. Chemical coagulation with alum removed most of the iron but produced a great deal of sludge. Ferric chloride showed 30 percent iron removal but only 10 percent COD removal. Chemical oxidation with chlorine resulted in lowering COD concentrations by 10-25 percent, and removing some iron but increased the chlorides and total solids. Calcium hypochlorite performed similarly, with an increase in hardness as well. Ozone produced COD removals of up to 37 percent with a four hour contact time with some iron removal in addition. Activated carbon adsorption, with a 45.7 minute minimum column contact time, produced 53 percent COD removals, 75 percent iron removals, 29 percent hardness removals, and 23.5 percent total solids removal.

Thornten and Blanc (12) found that lime produced the best results of all precipitation/coagulants, but that large doses were required (with concomitant generation of sludge) and that the process was only effective when coupled with other treatment processes.

In general, physico-chemical processes were not effective in leachate treatment. Biological treatment was more effective; however there were significant residuals in all operations except municipal co-treatment.

Land Treatment and Leachate

The most important considerations in leachate application to land should include effects on local vegetation and the treatment capacity of the soil for critical contaminants (nitrogen and heavy metals). While extensive research has been done on applications of secondary effluent to forest soils (13), there have only been limited investigations of application of leachate to forest soils. Menser, et al. (14) and Bennet, et al. (15) used an application rate of 1.5 inches per week of lagooned leachate to a forest site. COD was reduced from 10,000 mg/ℓ to 1000 mg/ℓ, but metals tended to leach through the soil. Nitrogen was retained in the first six inches of soil, but iron, zinc, and especially manganese moved freely through the soil matrix.

The major form of nitrogen in leachate is ammonia. Soil reactions involving ammonia include nitrification, volatilization, and ammonia immobilization (chelation and exchange). The Environmental Protection Agency (EPA) (16) and Overcash and Pal (17) have compiled the applicable information available on soil removal of nitrogen (as well as other critical contaminants). Although kinetic rate constants have been developed under steady-state conditions for nitrification, these are not readily applicable to soil studies because of varying environmental conditions within the soil. At best a determination of inhibition or enhancement of nitrification can be made, utilizing the appearance (or non-appearance) of the well-documented "nitrate wave" phenomenon (16). Optimum conditions for nitrification include an aerobic environment (at least 0.5 mg/ℓ dissolved oxygen (DO)), a pH that is neutral to slightly alkaline, and a temperature between 24° and 35° Celsius (17). Bouwer (18) found that intermittent flooding (and hence, aeration) enhanced nitrification.

Ammonia volatilization is essentially pH dependent, with very little NH_3 available at pH's below 8.0 (19). Overcash and Pal (17) present a previously developed ammonia volatilization model which has a major drawback in that pH is not considered as a parameter in the model. It follows simple first order reaction kinetics:

$$TAN_t = TAN_o \, e^{-kt};$$

where

TAN_t = total ammonia nitrogen at time t

TAN_o = total ammonia nitrogen at time 0

t = time in days

k = a kinetic rate constant

The rate constant, k, can be corrected for temperature and cation exchange capacity of the soil.

Ammonia immobilization involves two processes: the exchange and adsorption of NH_4^+ within the soil matrix and the chelation with organics. Keeney and Wildung (20) have shown that the principal factors involved in these reactions are the cation exchange capacity and the amount of organic matter in the soil.

The heavy metals are removed or immobilized in the soil matrix by mechanisms including precipitation, ion exchange, plant uptake, and chelation with organics (17). Precipitation is governed by the solubility of the specific metal under the pH and redox conditions present in the soil and is the main removal mechanism when large concentrations of metals are present (17). Ion exchange depends on cation exchange capacity and chelation with soil organic content; both of these mechanisms become important as metal concentrations become smaller. While Freundlich and Langmuir isotherms have been proposed for soil adsorption of metals (16), the widely varying conditions within the soil and the non-continuous nature of the hydraulic application in land treatment make the determination and effective use of the isotherms difficult. Jennings, et al. (21) found that iron which was sorbed from leachate by Barre sand soil under anaerobic conditions was later released. Walsh, et al. (22) found that sandy soils especially had a low capacity for retaining nutrients and metals, and that toxic concentrations could be reached with lower loading rates.

Toxicity of Leachate to Trees

Several of the studies conducted with leachate have attempted to gauge the toxic effects which may limit treatment effectiveness. Cameron and Koch (23) identified ammonia, tannin, copper and hydrogen ion concentration (pH) as major sources of toxicity to rainbow trout from leachates. They were also able to demonstrate that leachate recycling was an effective means of attenuating toxicity. Walker and Adrian (24) showed inhibitory growth effects on algae (Scenedesmus dimorphous) and found specific conductance to be the best indicator of toxicity. Specific conductance measurements of greater than 375 micro-mho/cm were found to indicate toxicity to the algae, while readings of greater than 200 micro-mho/cm indicated an inhibitory effect.

Menser, et al. and Bennet, et al. (14,15) showed mortality in red maple (Acer rubrum) saplings due to leachate applications while mature trees were unaffected. Understory vegetation was drastically affected. Toxicity most likely was due to metals, as the uptake by maples was dramatic. Leaves of red maple showed a five-fold increase in iron content, a three-fold increase in manganese content, and a doubling of zinc. Dirr (25) found a sensitivity of red maples to increased salt concentrations, another possible explanation for the toxicity.

Flooding represents another possible adverse effect to red maples in land application of leachate residuals . Vosburgh (26) found increased mortality and decreased growth due to flooding conditions in the Lake Champlain region. The mechanism suggested to explain toxicity was continued depletion of oxygen in the root zone which inhibits respiration, enhances build-up of carbon dioxide, and can contribute to a build-up of toxic materials due to reducing conditions.

Environmental tolerances of red oak (Quercus rubrum) have been documented. Seidel (27) found poor drought resistance in red oak seedlings, while Buckner and Maki (28) found very low growth and survival rates in red oaks when fertilized and irrigated. Dirr (25) found red oak to be moderately sensitive to salts. Red oaks were also found to have a large variation in growth, making them hard to categorize (29).

White pines (Pinus strobus) are relatively insensitive to salt concentrations (30), while McColl found no significant effect on growth or nutrient uptake due to soil moisture (flooding or drought). White pines also seem well adapted to acid rain conditions; Wood and Bormann (31) found increasing productivity in white pine seedlings with decreasing pH. The greatest amount of growth was at pH 2.3 and the least at pH 5.2.

III. EXPERIMENTAL PROCEDURE

Land Application of Leachate Residuals

Leachate residuals were collected from the Barre Landfill which is operated by the Martone Trucking Company. Leachate is collected at the landfill and treated in a series of shallow lagoons. The lagoons are operated as a two-stage batch system; the first stage (primary treatment) utilizes aeration and precipitation as the major treatment processes. The second stage involves more significant biological treatment by bacteria, algae, and some aquatic plants (Lemna, sp.). Leachate collected from primary lagoons will henceforth be termed "primary leachate", while that from secondary lagoons will be termed "secondary leachate".

The land application of leachate to seedlings was carried out from May to September, 1979. The three representative seedling types were Red Maple (Acer rubrum), Red Oak (Quercus rubrum), and White Pine (Pinus strobus). Pine seedlings were obtained from a local nursery, while maple and oak seedlings were found in local forests. Barre sand soil, obtained from a forest site near the Barre Landfill, was placed in an 18 inch deep plexiglas container to a depth of approximately one foot. The container was arranged so that leachate could be collected from the bottom (Figure 1).

Soil treatment was divided into two categories, each with characteristic loading rates: an indoor soil-only(no seedlings) study which examined COD reduction and monitored ammonia

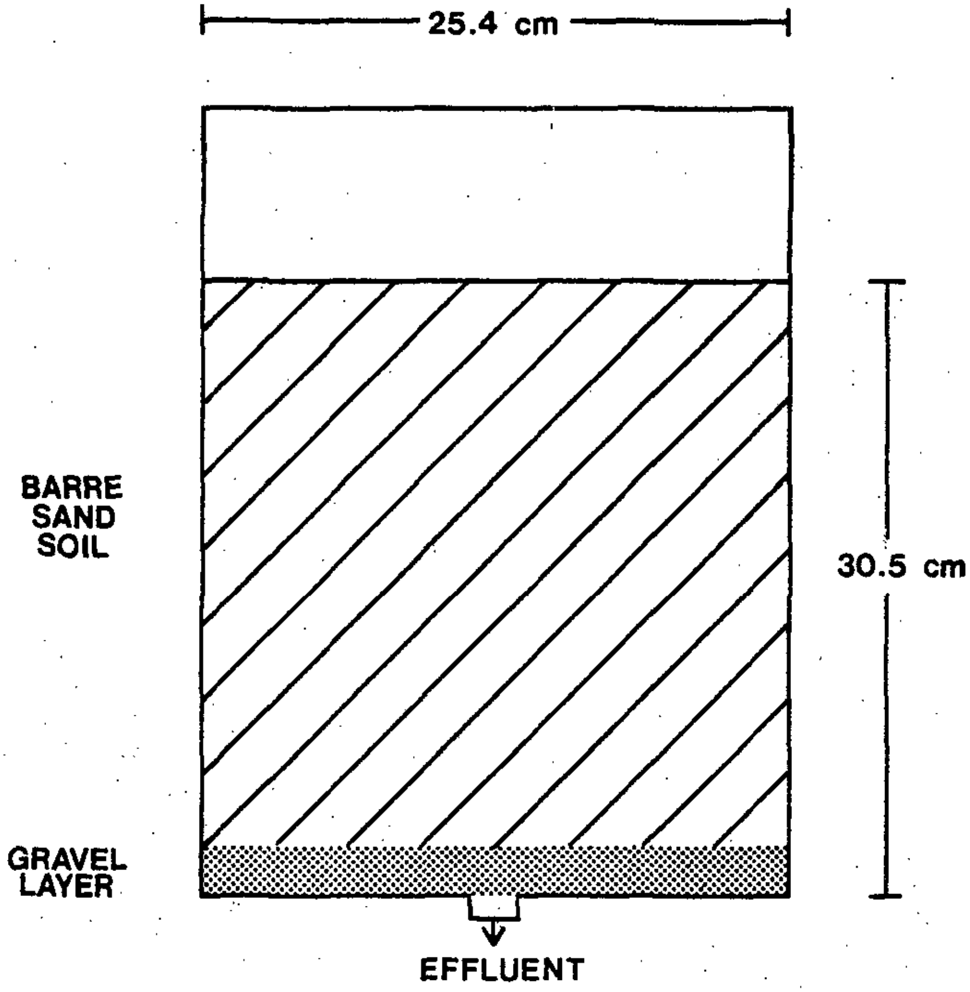


Figure 1. Seedling Container.

removal and subsequent nitrification (the "nitrate wave" phenomenon); and a series of outdoor applications to seedlings where, in addition to COD and ammonia, changes in concentrations of iron, copper, zinc, and manganese were monitored. Preliminary tests made on the soil were particle size distribution, soil pH (33), cation exchange capacity, soil Total Kjeldahl nitrogen (TKN), and extractable metal concentrations for the four metals mentioned. Cation exchange capacity was determined by the micro-Kjeldahl technique (33), while metals were extracted with hot HCL-HNO_3 and determined by atomic absorption (32).

In the soil-only study, once preliminary tests were completed, rainwater and primary leachate residuals were alternately applied, with three days allowed for drying between each application. Artificial rainwater was prepared by adjusting deionized-distilled water to a pH of approximately 4.5 with concentrated sulfuric acid. This was to simulate the acid rain which New England receives. The volume of effluent was recorded, and the drained leachate itself tested for specific conductance, pH, ammonia, nitrate, and COD. Similar analyses were made on the raw leachate.

In the seedling study, application rates of 1.27 cm, 2.54 cm, 5.08 cm, and 7.62 cm per week of secondary leachate and 5.08 cm per week of primary leachate were made to designated containers planted with seedlings. Each seeding type received all of the application rates. The controls of each of the species were maintained with hydraulic loading rates paralleling the application rates of the leachate-applied pots. Collected rainwater was used (when possible) for control applications. Filtrate analysis included volume, pH, TKN, iron, manganese, copper, zinc, ammonia, specific conductance, and COD.

Statistical analysis in this study was two-fold. First, a two-tailed test was employed to determine whether differences between filtrate concentrations and applied leachate concentrations were significant at the .05 level of confidence. This test was also employed to determine whether the leachate-filtrate was significantly different than the control-filtrate for the various parameters measured. A two-factor test was employed to discern trends due to increasing loading rates, leachate strength, and interrelations between the two. The two factor analysis was also considered significant at the .05 level of confidence (34).

Leachate Effects on Seedlings

As mentioned above, local species of maple, oak and pine were selected as representative flora of New England forests. The experimental procedure envisioned nine containers of each species with four seedlings per container and the application rates mentioned above. Seedling analysis included height, basal area, foliar metal content, and observation of toxicity.

Detrimental effects on the seedlings were analyzed statistically by using the two-factor test, first with mean growth as the parameter. Toxicity and foliar metal content were similarly employed as parameters. The confidence limit was again chosen to be .05.

IV. RESULTS AND DATA ANALYSIS

Lagooned Leachate Analysis

The general characteristics of the lagoon-treated leachate are presented in Table 2. Although there appear to be minor differences in the parameters due to lagoon type, the only significant divergence is seen in the COD data, where the secondary lagoon shows a lower concentration. Statistical analysis (two-tailed t-test) bore out this observation, finding only the COD data to be significantly different at the .05 level of confidence between the two ponds (34).

The pH was neutral to slightly alkaline in both ponds, and the specific conductance was approximately 2000 in both systems. Ammonia concentrations varied widely in both ponds, with an average concentration of about 100 mg/ℓ in the primary lagoon and about 50 mg/ℓ in the secondary lagoon. Organic nitrogen was a lesser constituent of the total nitrogen, with concentrations approximately one-fifth of those for ammonia.

Metal concentrations, with the exception of iron, were not very large (average concentrations less than 1 mg/ℓ) but varied more than an order of magnitude.

Land Treatment Results.

Soil characteristics. Soil characteristics obviously play an important role in the treatment capacity of the soil. Pertinent properties of Barre sand are compiled in Table 3.

TABLE 2. Primary and Secondary Leachate Lagoon Characteristics

	Primary Leachate			Secondary Leachate		
Parameter*	Mean	Maximum	Minimum	Mean	Maximum	Minimum
pH	7.56	8.0	7.0	7.86	8.0	7.15
Specific Conductance**	2200	3100	1630	1880	2200	1675
COD	1090	2580	340	340	1045	110
Ammonia-N	99.4	381.2	39.2	49.2	126.8	27.1
Organic-N	17.4	50.8	2.2	9.8	18.9	0.5
Copper	.10	.27	.001	0.12	0.50	0.01
Iron	16.22	56.96	2.31	9.00	40.14	1.34
Manganese	0.48	2.36	.001	0.94	6.00	0.06
Zinc	0.11	0.61	.001	0.05	0.18	.001

*All values except pH and specific conductance in mg/ℓ.
**μ-mhos/cm.

TABLE 3. Characteristics of Barre Sand Soil

Parameter	Mean
pH	5.25
Cation exchange capacity	9.5 milliequivalents/100 gm
% Organic content	9.4
Extractable iron	493 mg/kg
Extractable copper	25 mg/kg
Extractable manganese	85 mg/kg
Extractable zinc	22 mg/kg

Soil pH was acidic, while both the cation exchange capacity and the soil organic content were substantial. The particle size distribution is shown in Figure 2. From this distribution, it can be concluded that the soil is a well-graded sand soil.

COD treatment. The leachate applied to soil only was different from that used in the other systems. The characteristics are summarized in Table 4. COD data were collected both for soil alone and for the three types of seedlings. Initial drainage from the soil only indicated a base level of COD of about 80 mg/ℓ. Upon application of leachate, there was an initial reduction in COD concentration of between 65-86 percent, as shown in Table 5. When "rainwater" was applied there was a slight "washout" of COD; the effluent concentration was greater than the base level but less than that of initial treatment. There appeared to be little carry-over from application to application.

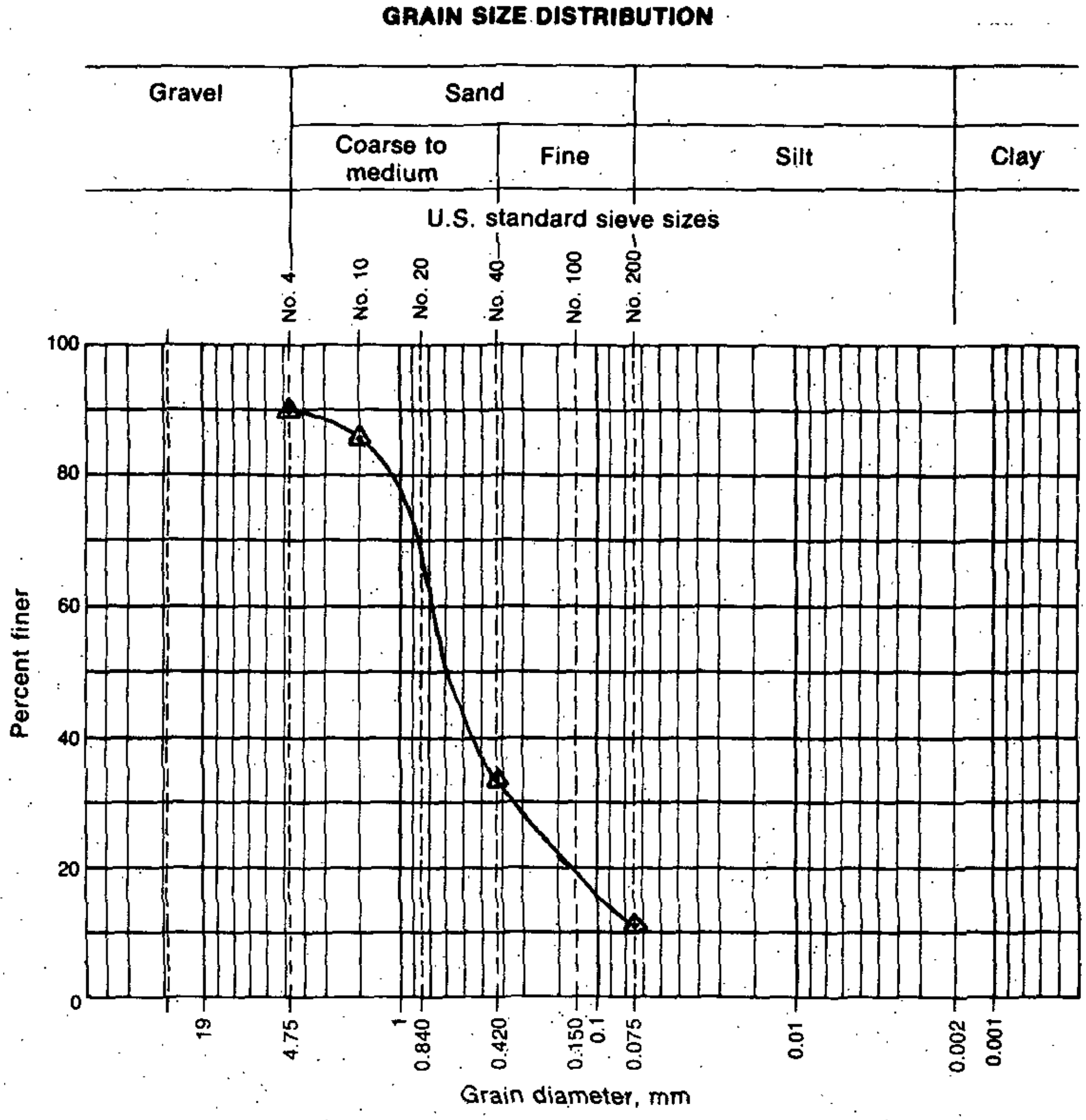


Figure 2. Particle Size Distribution of Barre Sand.

TABLE 4. Characteristics of Leachate Applied to Soil Only

Parameter	Mean*	Maximum	Minimum
pH	6.49	6.65	6.35
Specific Conductance**	2560	2830	2170
COD	3530	3630	3370
Ammonia-N	167	183	151
Nitrate-N	1.2	1.5	0.8

*all values except pH and specific conductance in mg/ℓ.

**μ-mhos/cm.

These results were essentially confirmed in the field tests. Applications of primary leachate and secondary leachate (Table 2) were made and the effluent examined from the three seedling types. Effluent results from these systems are summarized in Table 5. COD reductions of between 65-79 percent were achieved with average residuals between 225-383 mg/ℓ. Average base values for controls were between 76 and 46 mg/ℓ. The type of vegetation in the systems appeared not to be significant while differences with respective controls were significant (.05 level of confidence).

Metal results. Data on soil treatment with respect to metals were collected only for systems with seedlings. Both primary and secondary leachate were examined for metal treatability. Results for each application rate

TABLE 5. COD Residuals in Land Treatment

System	Mean*	Maximum	Minimum	% RDN**
Soil alone	770	1266	515	78
Maples	225	452	147	79
Oaks	383	666	165	65
Pines	229	302	183	79
Maple Controls	46	71	26	-
Oak Controls	76	103	60	-
Pine Controls	75	110	51	-

---

*all values in mg/ℓ.

**% decrease in average levels in soil filtrate compared with average levels in applied leachate.

andseedling type are summarized in Tables 6-9.

There was no significant removal of copper by any treatment scheme at any application rate. Effluent concentrations showed no significant trend with either loading rate or strength of leachate. Using levels of extractable copper in the soil as a guide, leachate appeared to increase the amount of copper removed from the soil. There were also significant effects due to loading rate; at higher loading rates more copper was leached. Significant interactive effects (both loading rate and leachate strength) were also noted. Throughout the entire study, copper levels were higher in soil leachate than in lagooned (primary or secondary) leachate. In general, iron was removed by land application.

There were significant reductions in iron concentrations in the primary leachate application schemes, the 5.08 cm and 7.62 cm per week applications of secondary leachate to pines, and the 2.54 and 5.08 cm per week application of secondary leachate to maples. Reductions of 80 and 86 percent were recorded for the pines, while reductions in concentration of 94 and 89 percent (respectively) were found for maples. In the pine system, the two loading rates which showed significant treatment also showed a significant increase over controls for these rates. This was duplicated by the 5.08 cm per week of secondary leachate loading rate for the maples, but not for the 2.54 cm per week rate. This non-duplication was caused in part by the wide variation in

TABLE 6. Copper in Land Application Filtrate

System/Loading	Mean	Control	% RDN****
Pine Seedlings			
1.27 cm/wk (S)**	0.37	0.12	-208
2.54 cm/wk (S)	0.21	0.14	-75
5.08 cm/wk (S)	0.10	0.11	17
7.62 cm/wk (S)	0.09	0.07	25
5.08 cm/wk (P)***	0.13	0.11	-30
Maple Seedlings			
1.27 cm/wk (S)	0.09	0.09	25
2.54 cm/wk (S)	0.10	0.11	17
5.08 cm/wk (S)	0.08	0.07	20
7.62 cm/wk (S)	0.11	0.11	8
5.08 cm/wk (P)	0.08	0.07	20
Oak Seedlings			
5.08 cm/wk (P)	0.09	0.62	10

---

*All values in mg/ℓ.

**Secondary leachate applied

***Primary leachate applied.

**** % decrease of average levels in soil filtrate compared with average levels in applied leachate.

TABLE 7. Iron in Land Application Filtrate

System/Loading	Mean*	Control	% RDN****
Pine Seedlings			
1.27 cm/wk (S)**	3.39	4.51	59
2.54 cm/wk (S)	7.28	4.56	11
5.08 cm/wk (S)	1.62	0.37	80
7.62 cm/wk (S)	1.16	0.50	86
5.08 cm/wk (P)***	2.73	0.37	83
Maple Seedlings			
1.27 cm/wk (S)	0.53	8.86	94
2.54 cm/wk (S)	0.46	4.21	94
5.08 cm/wk (S)	1.19	0.34	85
7.62 cm/wk (S)	6.34	0.81	22
5.08 cm/wk (P)	1.86	0.34	89
Oak Seedlings			
5.08 cm/wk (P)	2.43	0.45	85

---

*All values in mg/ℓ.

**Secondary leachate applied.

***Primary leachate applied.

**** % decrease of average levels in soil filtrate compared with average levels in applied leachate.

TABLE 8. Manganese in Land Application Filtrate

System/Loading	Mean*	Control	% RDN****
Pine Seedlings			
1.27 cm/wk (S)**	3.19	1.67	-240
2.54 cm/wk (S)	1.08	1.29	-15
5.08 cm/wk (S)	1.86	0.73	-98
7.62 cm/wk (S)	1.07	1.38	-14
5.08 cm/wk (P)***	2.75	0.73	-473
Maple Seedlings			
1.27 cm/wk (S)	1.37	1.63	-46
2.54 cm/wk (S)	1.62	1.33	-72
5.08 cm/wk (S)	2.11	0.76	-124
7.62 cm/wk (S)	1.48	0.99	-57
5.08 cm/wk (P)	1.52	0.76	-217
Oak Seedlings			
5.08 cm/wk (P)	0.56	1.07	-17

---

*All values in mg/ℓ.

**Secondary leachate applied.

***Primary leachate applied.

**** % decrease in average levels in soil filtrate compared with average levels in applied leachate.

TABLE 9. Zinc in Land Application Filtrate

System/Loading	Mean*	Control	% RDN****
Pine Seedlings			
1.27 cm/wk (S)**	1.09	0.43	-2080
2.54 cm/wk (S)	0.49	0.43	-880
5.08 cm/wk (S)	0.18	0.10	-260
7.62 cm/wk (S)	0.08	0.11	-60
5.08 cm/wk (P)***	0.65	0.10	-491
Maple Seedlings			
1.27 cm/wk (S)	0.32	0.22	-540
2.54 cm/wk (S)	0.23	0.32	-360
5.08 cm/wk (S)	0.17	0.17	-240
7.62 cm/wk (S)	0.08	0.12	-60
5.08 cm/wk (P)	0.20	0.17	-82
Oak Seedlings			
5.08 cm/wk (P)	0.11	0.12	0

---

*All values in mg/ℓ.

**Secondary leachate applied.

***Primary leachate applied.

**** % decrease in average levels in soil filtrate compared with average levels in applied leachate.

concentration levels for both treatment and control samples, and in part by the generally high concentrations of iron (greater than 1 mg/ℓ) in the ground water. Indeed, the applications which did not result in significant reductions in iron also did not differ significantly from their respective controls.

Reductions of 83 and 89 percent were found in the three treatment schemes for primary leachate, with no significant difference between any one system. Using two-factor analysis, no significant trend was found in secondary leachate applications. When the change in levels of soil extractable iron is examined (two factor analysis) it is found that the decrease in soil iron is related to both loading rate and an interaction between leachate strength and loading rate. At higher loading rates of leachate, the extractable iron reduction was much less. Higher loading rates of controls also produced similar results. This is contrary to what would be expected.

In general, manganese was not reduced by land application treatment. Indeed, in the 1.27 cm of secondary and 5.08 cm per week application of primary leachate to pines, levels of manganese were significantly higher in the effluent than in the influent. These levels were also significantly higher than the controls for the same loading rates. Although no other differences were significant, most of the effluent was slightly higher in manganese than the influent. Two-factor analysis showed no discernable trend with respect to loading rate or leachate strength. Although the above data indicate a general leaching of manganese from the soil, the results of analysis of soil extractable manganese do not bear this out. There was no significant trend in the amount of extractable manganese leached from the soil.

Zinc concentrations were not decreased by any treatment scheme. The 1.27 cm and 2.54 cm per week applications of secondary leachate showed significant increases in zinc concentration in the effluent. Only in the case of the 1.27 cm per week application to pines was this significantly greater than the control. Two factor statistical analysis showed no significant trend (in the effluent concentrations) with respect to loading rate or leachate strength. Likewise, there was no trend in soil extractable zinc.

In summation, only iron was significantly reduced in the soil treatment. This was observed by a decrease in soil effluent concentration and minimal leaching from the soil at higher leachate loading rates. While all metals investigated seemed to be removed to some extent, only with copper was there a definite correlation between leachate loading and increased removal. In most cases, soil effluent concentrations did not differ significantly between test and control samples, and both were somewhat larger than the concentrations applied. In all cases concentrations varied widely.

Nitrogen results. Three basic phenomena were investigated in the nitrogen portion of the study: breakthrough of ammonia; breakthrough of organic nitrogen; and the nitrate wave signalling the onset of nitrification. The nitrate wave phenomenon was monitored in the soil-only study, organic nitrogen in the seedling study, and ammonia breakthrough in both.

Nitrate test results are presented graphically in Figure 3. Both applied and effluent levels of nitrate are shown. Concentrations of nitrate are consistently lower in the applied leachate (less than 2 mg/ℓ nitrate-N) than in the effluent from the system. The effluent concentration remains essentially constant for about 15 days, then increases to almost 50 mg/ℓ nitrate-nitrogen after 37 days. Since high levels of ammonia were constantly applied, this increase in effluent nitrate must signal nitrification.

The organic nitrogen results are presented in Table 10. There was no significant reduction in organic nitrogen from secondary leachate. In the 7.62 cm per week application rate to pines there was a significant increase in filtrate concentrations compared with the control, while all rates above 1.27 cm per week in maples showed a significant increase. Applications of primary leachate did result in significant reductions in organic nitrogen in both the pine and maple systems, but this was not duplicated with the oak system. Both maple and oak effluents from primary leachate applications were significantly greater in organic nitrogen than their

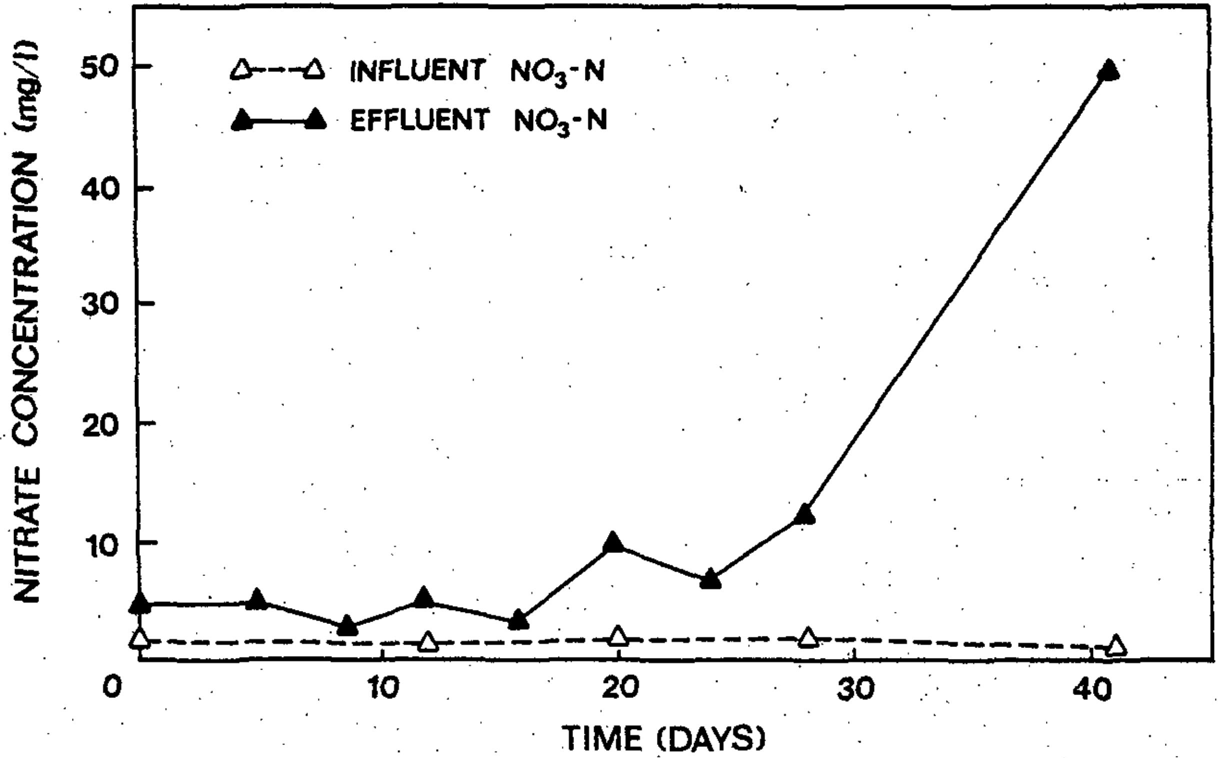


Figure 3. Nitrate in Land Application.

TABLE 10. Organic Nitrogen in Land Application Filtrate

System/Loading	Mean*	Control	% RDN****
Pine Seedlings			
1.27 cm/wk (S)**	3.58	2.35	63
2.54 cm/wk (S)	5.40	2.71	45
5.08 cm/wk (S)	3.06	2.68	69
7.62 cm/wk (S)	8.16	1.02	17
5.08 cm/wk (P)	4.41	2.68	75
Maple Seedlings			
1.27 cm/wk (S)	3.06	1.85	68
2.54 cm/wk (S)	4.86	1.96	50
5.08 cm/wk (S)	7.10	1.23	27
7.62 cm/wk (S)	5.61	1.76	43
5.08 cm/wk (P)	5.58	1.23	43
Oak Seedlings			
5.08 cm/wk (P)	4.87	1.03	50

---

*All values in mg/ℓ.

**Secondary leachate applied.

***Primary leachate applied.

**** % decrease in average levels in soil filtrate compared with average levels in applied leachate.

respective controls. Only the pine system showed a significant reduction in organic nitrogen without a significant increase in the effluent (compared with the control). Two factor analysis of organic nitrogen effluent concentrations showed no significant trend with either loading rate or leachate strength.

The ammonia results are presented in Table 11. Ammonia in the effluent was significantly less than that applied in all systems and at all loading rates. This also resulted in significantly larger concentrations of ammonia in the effluent of test subjects than in their respective controls, with the exception of the 1.27 cm per week loading rate on maples. Ammonia concentrations in test subjects tended to decrease with time until, at the end of the experimental period, they were equivalent to those found in the controls.

Two factor analysis of ammonia results showed a positive correlation of filtrate concentration with leachate strength (secondary over controls), but no significant correlation with loading rate or interactive effects between the two.

Specific conductance and pH. Specific conductance results are presented in Table 12. There was a significant reduction in specific conductance in all treatment schemes at all loading rates. The reductions were between 21 percent and 62 percent, indicating a build-up of salts within the soil. However, in all cases the effluent specific conductance was significantly greater than the respective controls. Two factor analysis showed a significant trend only in the strength of the

TABLE 11. Ammonia in Land Application Filtrate

System/Loading	Mean*	Control	% RDN*****
Soil only			
5.08 cm/wk (SL)**	21.75	2.30	80
Pine Seedlings			
1.27 cm/wk (S)***	13.38	4.71	73
2.54 cm/wk (S)	11.45	5.81	77
5.08 cm/wk (S)	22.79	2.43	54
7.62 cm/wk (S)	16.90	1.05	66
5.08 cm/wk (P)****	13.26	2.43	88
Maple Seedlings			
1.27 cm/wk (S)	7.25	4.96	85
2.54 cm/wk (S)	8.05	3.35	84
5.08 cm/wk (S)	30.13	2.83	39
7.62 cm/wk (S)	27.55	4.36	44
5.08 cm/wk (P)	20.78	2.83	81
Oak Seedlings			
5.08 cm/wk (P)	15.99	3.89	86

---

*All values in mg/ℓ.

**Leachate for soil only applied.

***Secondary leachate applied.

****Primary leachate applied.

***** % decrease in average levels in soil filtrate compared with average levels in applied leachate.

TABLE 12. Specific Conductance in Land Application Filtrate

System/Loading	Mean*	Control	% RDN
Soil Only			
5.08 cm/wk (SL)**	963	170	62
Pine Seedlings			
1.27 cm/wk (S)***	1112	344	41
2.54 cm/wk (S)	1157	314	39
5.08 cm/wk (S)	1481	142	21
7.62 cm/wk (S)	1325	135	30
5.08 cm/wk (P)****	1217	142	45
Maple Seedlings			
1.27 cm/wk (S)	883	306	53
2.54 cm/wk (S)	918	208	51
5.08 cm/wk (S)	1336	151	29
7.62 cm/wk (S)	1150	159	39
5.08 cm/wk (P)	1043	151	53
Oak Seedlings			
5.08 cm/wk (P)	870	284	60

---

*All values in μ-mhos/cm.

**Leachate for soil only applied.

***Secondary leachate applied.

****Primary leachate applied.

specific conductance of leachate applied vs. controls. One trend which was observed but which was not found to be significant by two factor analysis was the progressively diminishing specific conductance in the controls with increasing loading rate. This was paralleled by an increase in specific conductance with increased loading rate in test subjects.

The pH results are presented in Table 13. The pH of the filtrate was significantly lower than that of the applied leachate at all loading rates for both primary and secondary leachates. The application of leachate tended to raise the pH of filtrate from the test subjects significantly over that of their respective controls. There seemed to be a trend that increased loading rates of leachate resulted in higher pH's in the filtrate; however, two factor analysis showed no significant trend due to loading rate, leachate vs. control, or interactive effects.

Hydraulic loading results. Hydraulic loading results for land application are presented in Figures 4 and 5. The most striking effect noted is the consistency of fluid retention across different loading rates. Despite the varying amounts applied, most systems retained between 15 and 30 cm of fluid in the maple system, and slightly (but not significantly) higher limits in pine seedlings. Two factor analysis showed no trend in fluid retention due to loading rate, leachate application, or interactive effects between the two.

TABLE 13. pH of Filtrate from Land Application

System/Loading	Mean	Control	% Increase*
Soil Only			
5.08 cm/wk (SL)**	4.77	4.20	14
Pine Seedlings			
1.27 cm/wk (S)***	4.38	4.46	-2
2.54 cm/wk (S)	5.42	4.32	25
5.08 cm/wk (S)	5.59	4.70	19
7.62 cm/wk (S)	5.42	4.55	19
5.08 cm/wk (P)****	4.92	4.70	5
Maple Seedlings			
1.27 cm/wk (S)	4.20	4.09	3
2.54 cm/wk (S)	4.37	4.18	5
5.08 cm/wk (S)	4.72	4.24	11
7.62 cm/wk (S)	5.74	4.26	34
5.08 cm/wk (P)	4.91	4.24	16
Oak Seedlings			
5.08 cm/wk (P)	5.66	4.47	27

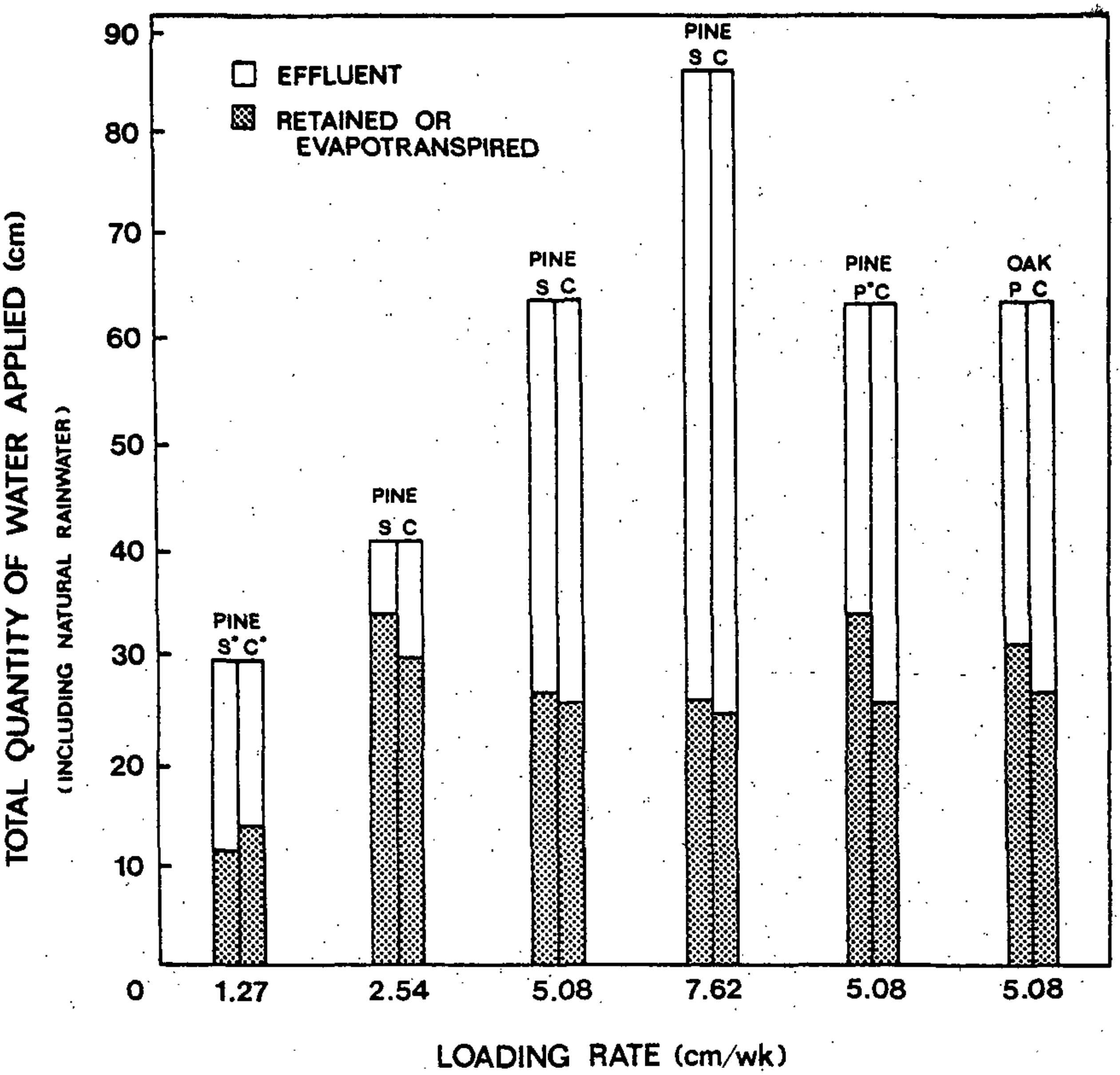
---

*% increase over control.

**Leachate for soil only applied.

***Secondary leachate applied.

****Primary leachate applied.



* S = SECONDARY LEACHATE APPLIED
C = COLLECTED RAINWATER APPLIED (CONTROL)
P = PRIMARY LEACHATE APPLIED

Figure 4. Hydraulic Loading: Pine and Oak Seedlings.

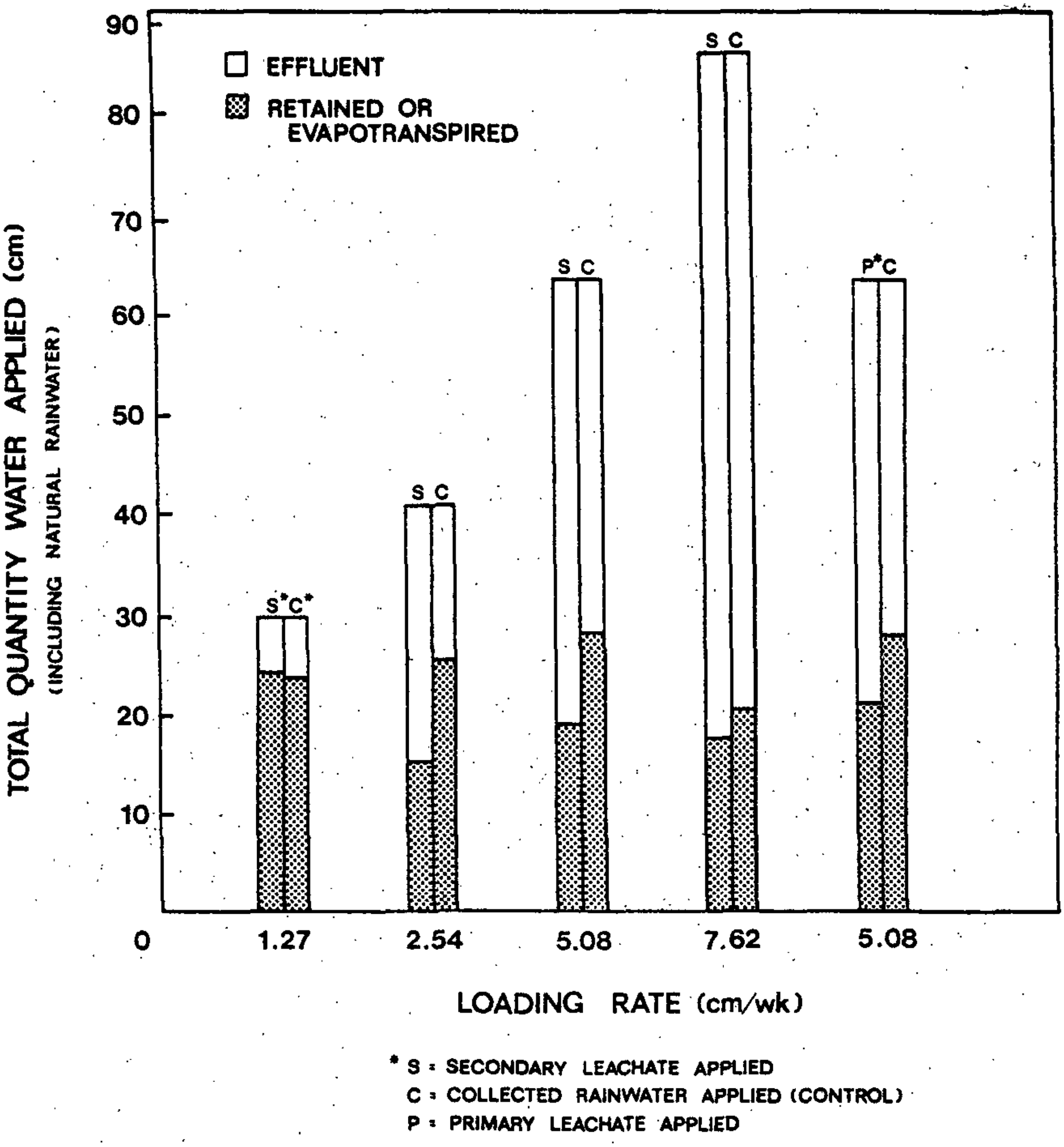


Figure 5. Hydraulic Loading: Maple Seedlings.

Effects on Seedlings

As stated above, transplantation of seedlings began in May, 1979. Unfortunately, this coincided with a two-week drought. The deciduous seedlings lost their foliage, and there was a delay of several weeks before maples could be used, and even longer for the oaks. Indeed, only two containers of oaks, each with three seedlings, recovered sufficiently to be used at all. Because of size considerations, only two pine seedlings could be fitted to each container. Nevertheless, application of leachate residuals to pine seedlings began on July 6 and to maple seedings on July 13. Effects on maples were dramatic. Within a week all seedlings receiving 2.54 and 5.08 cm of secondary leachate per week were dead. Strangely, the seedlings receiving 7.62 cm of secondary and 5.08 cm of primary leachate per week survived the first week. Applications were continued, and on August 3, the two containers of oak seedlings were added (5.08 cm of primary leachate per week and control).

The parameters to be used in assessing effects on the seedlings were growth (height), basal area, general toxicity (mortality), and foliar metal content. The two factor analysis was the statistical procedure chosen to gauge these effects. Circumstances, however, limited which tests could be used, which subjects could be usefully tested, and the applicability of the information gained.

First, the massive mortality of transplanted oak seedlings (21 out of 27 seedlings died) essentially eliminated them from use for statistically valid operations; only one loading rate (5.08 cm per week of primary leachate) and its control were available. Therefore, only the observation of mortality was performed on these subjects.

Secondly, the basal area measurement was found to be too error-prone (non-reproducible) for all test subjects and was discontinued.

Thirdly, the mortality evidenced in maples by leachate application made measurement of growth superfluous, and qualitative descriptions were employed for the survivors.

Finally, laboratory analysis problems limited foliar metal content determinations to that for iron in pine seedlings.

Generally mortality results for all three seedling types are presented in Table 14. The few oak seedlings which survived transplantation also survived leachate application. Pine seedlings showed no mortality at any loading rate with any applicant type. The only mortality (during the test period) was found in the maple seedlings. There was a 100 percent mortality in both the 2.54 cm and 5.08 cm per week application of secondary leachate. The 7.62 cm per week loading rate showed one death for both test subject and control.

TABLE 14. Mortality in Land Application

System/Loading	# of Deaths	Control
Pine Seedlings		
1.27 cm/wk (S)*	0	0
2.54 cm/wk (S)	0	0
5.08 cm/wk (S)	0	0
7.62 cm/wk (S)	0	0
5.08 cm/wk (P)**	0	0
Maple Seedlings		
1.27 cm/wk (S)	0	0
2.54 cm/wk (S)	4	0
5.08 cm/wk (S)	4	0
7.62 cm/wk (S)	1	1
5.08 cm/wk (P)	0	0
Oak Seedlings		
5.08 cm/wk (P)	0	0

---

*Secondary leachate.

**Primary leachate.

Two factor analysis did not confirm the trend of increased mortality with leachate application to a significant degree. Nor was a significant trend with loading rate or interactive effects demonstrated.

Growth results were collected only for the pine seedlings and are presented in Table 15. At the .05 level of confidence, there was no trend with either leachate loading or a combination of effects. However, at the .20 level of confidence, a trend was observed of increased growth with increased loadings of leachate.

As previously mentioned, foliar metal content was limited by unforeseen circumstances to determination of tissue iron concentrations. Results are presented in Table 16. While concentrations in test subjects were slightly greater than respective controls, the wide variation in values precluded statistical significance for the observed differences. Two factor analysis was likewise inconclusive.

TABLE 15. Growth in Pine Seedlings

Loading Rate	Mean Growth*	Control
1.27 cm/wk (S)**	1.11	1.56
2.54 cm/wk (S)	0.32	0.95
5.08 cm/wk (S)	1.91	0.64
7.62 cm/wk (S)	2.03	0.90
5.08 cm/wk (P)***	0.64	0.64

---

*Growth in cm.

**Secondary leachate.

***Primary leachate.

TABLE 16. Pine Foliar Iron Content

Loading Rate	Initial	Final	Increase
1.27 cm/wk (S)**	177.9	120.6	-57.3
1.27 cm/wk (C)***	127.0	93.1	-33.9
2.54 cm/wk (S)	42.0	100.8	58.8
2.54 cm/wk (C)	122.2	12.5	-109.7
5.08 cm/wk (S)	150.7	131.8	-18.9
5.08 cm/wk (C)	25.3	77.8	52.5
7.62 cm/wk (S)	117.8	427.5	309.8
7.62 cm/wk (C)	102.1	139.5	37.4
5.08 cm/wk (P)****	89.9	114.6	24.7

---

*All values in mg/kg.

**Secondary leachate applied.

***Hydraulic control.

****Primary leachate applied.

V. DISCUSSION

Land Application

COD Results. Unlike results found for anaerobic conditions (35), where little attenuation of organics was noted, reductions of 65-79 percent of applied COD were achieved. Organic acids, a major organic component of leachate, have been shown to be decomposable by aerobic soil organisms (17). Filtering of suspended and colloidal material may also account for some of the reduction (36). However, even with these reductions, COD effluents from test subjects were significantly higher than the controls, indicating a possible threat to water quality by longterm, continuous application.

Metal Results. Of the four metals examined, only iron was significantly reduced in the treatment process. However, only the applied levels of iron exceeded those in control filtrates. The other metals often exhibited smaller concentrations in the primary or secondary leachate than in the control filtrate. Therefore, the metal of most concern in this study is iron.

The primary removal mechanism of iron (and other metals) at higher concentrations in the soil is precipitation (17) as oxides and hydroxides. At lower concentrations, chelation and ion exchange play more significant roles. Thus, once out of the aerobic zone, presumably lesser amounts of iron would be removed. Indeed, attenuative capacity for iron under anaerobic conditions in Barre sand soil was shown to be somewhat temporary, with washouts common (35). While there was some desorption of iron from the aerobic treatment systems (especially following heavy rainfall), in general iron was retained within the soil matrix.

Nitrogen Results. Nitrogen results were very informative in this study. First, although many of the environmental conditions were not favorable (pH too low, ammonia too high), nitrification of applied ammonia was demonstrated. While ammonia, usually in its ionic form, is a cation strongly held within the soil matrix, nitrification results in an anion for which soil has little or no attraction (37). Intermittent flooding, such as that used in this study, has been shown to enhance nitrification (35). Since applied levels of nitrogen are very high, this could lead to water quality problems in terms of nitrate pollution.

Secondly, organic nitrogen was substantially attenuated by soil treatment and, hence, built up in the soil. This, through mineralization, can increase ammonia levels (and hence, nitrate levels) in the soil. However, the amount of organic nitrogen accumulated was much less than that from ammonia nitrogen.

Specific Conductance and pH. As noted above, there was a net removal of salts as delineated by specific conductance in land application, also indicating a build up of salts within the soil. Specific conductance levels did not tend to increase with time, indicating that the capacity for soil retention was not totally exhausted. However, since effluent levels were significantly higher than controls, a groundwater contamination threat cannot be discounted.

Some increase in pH of the filtrate occurred due to leachate application, especially towards the end of the study. Lower pH's can increase the solubility of metals and, hence, their transport into groundwater. Extremely high pH's (8.0 or above) can precipitate metals to the extent that porous soil can be sealed off (39) with little or no subsequent groundwater contamination. While leachate residuals often equalled or exceeded those high pH's, acid rains would tend to mitigate any large pH increases.

Effects on Flora

Effects on Pines. There was no mortality in pine seedlings due to leachate application. Indeed, a trend was noticed of increased growth with increasing leachate loading rate. While applications of secondary effluent and sewage sludge have been shown to be beneficial to pines (40), this is the first indication that leachate residuals could be beneficial, rather than harmful, to flora. Foliar iron concentrations tended to be higher in treatment subjects than in the controls, although only at the highest loading rate of leachate was the difference significant. In general, pines were not adversely affected by leachate residual applications.

Effects on Maples. Red maples were the only test subjects to which applications of leachate residuals proved lethal. While secondary effluent applications have been shown to be beneficial to red maples (41), other researchers (26,27,42) have indicated that the salt (specific conductance) and flooding aspects of leachate applications could be detrimental. Bennet *et al.* (15) also showed tremendous increases in foliar metal concentrations due to leachate loadings.

While statistically there was no significant correlation of mortality with either loading rate or leachate application, there seemed to be a trend that leachate residual applications above 1.27 cm per week were toxic to maples. It is difficult to select one basic cause for this toxicity, as red maples are both salt sensitive and more sensitive to flooding than other bottomland species. Therefore, in general, maples must be assumed to be leachate intolerant.

Effects on Oaks. As reported above, the major problem with oaks was their mortality after late season (May-June) transplanting. These losses may have resulted from poor drought resistance (28) or poor vigor and variable growth rates (29,30). Those individuals which survived transplanting also survived leachate application. Red oaks have been shown to be either indifferent (43) or enhanced by secondary effluent applications. However, because of the very low number of individuals and single loading rate, little can be concluded from this portion of the study.

In general, the effects on flora can be summarized as follows: leachate residual applications to white pine seedlings were non-lethal and may even have been beneficial; applications to red maples showed a trend of toxicity; and no conclusion can be drawn from the red oak study.

VI. CONCLUSIONS

The first objective of this research was to determine the treatment capacity of Barre sand soil in terms of heavy metal, nitrogen, and COD removal from leachate. While most of the metals examined were not present in the leachate in significantly greater concentrations than were found in the soil controls, some conclusions can be made concerning iron treatment. Reductions of between 11 and 94 percent of applied iron concentrations were obtained; however, there were significant increases in iron concentrations in test subjects over controls due to leachate applications. Thus, while some treatment capacity in terms of iron removal can be achieved, there is also an indication of a possible pollutant effect to ground waters due to increased iron concentrations in the filtrate.

While ammonia concentrations were reduced substantially by land application (39-88 percent), residual concentrations in the filtrate were still rather high (7.25-30.13 mg/ℓ). In addition, much of the removed ammonia may be converted to nitrates through the process of nitrification, which constitutes another threat to groundwater quality.

Reductions in COD ranged from 65 to 79 percent of the applied leachate levels. While this reflects substantial treatment, the residual levels passing beyond the aerobic zone (225-770 mg/ℓ) constitute a definite pollution hazard.

Thus, while there are substantial reductions in most of the pollutants examined, residual concentrations are still high enough to indicate possible groundwater quality problems with prolonged usage. Barre sand soil is therefore not recommended as a treatment medium for leachate residuals.

The final objective of this research was to assess potentially toxic effects of leachate residuals on three seedling types. No toxic effects were noted for white pine (*Pinus strobus*) and, indeed, the leachate may have had a fertilizing effect. Toxicity was indicated in red maples (*Acer rubrum*), with increased salt and hydraulic loading rates suggested as the major factors involved. No conclusions could be drawn with regard to red oaks (*Quercus rubrum*) because of massive mortality in the transplantation phase.

VII. RECOMMENDATIONS

The small number of replicates in the land application flora study made statistically significant conclusions difficult. Larger numbers of seedlings would perhaps have made final analysis of leachate effects much easier. Red oaks especially require further study because of the limited nature of the information gathered here. Formal bioassay studies are also indicated to determine the exact causative agents of toxicity.

Further recommendations on the land application/ seedling study include the insuring of an adequate adaptation period for the seedlings to their new environment before any sort of pollutant loading begins. This study was also somewhat short-term (a single growing season) and longer term studies would certainly shed more light on leachate effects on overall growth. Soil types other than sand should also be investigated.

VIII. BIBLIOGRAPHY

1. Coe, J. J., "Effect of solid waste disposal on ground water quality", Jour. American Water Works Association, Vol. 62, #12, 1970, p. 776.

2. Hopkins, G. J. and Popalisky, J. R., "Influence of an industrial waste landfill operation on a public water supply", J. Water Pollution Control Federation, Vol. 42, #3, 1970, p. 431.

3. Cameron, R. D., "The effects of solid waste landfill leachates on receiving waters", Jour. American Water Works Association, Vol. 70, #3, 1978, p. 173.

4. Cooper, R. C., Potter, J. L., and Leong, C., "Virus survival in solid waste leachates", Water Research, Vol. 9, 1975, p. 733.

5. Anderson, J. R. and Dornbush, J. N., "Influence of sanitary landfill on ground water quality", Jour. American Water Works Association, Vol. 59, #4, 1967, p. 457.

6. Chain, E. S. K. and DeWalle, F. B., "Evaluation of Leachate Treatment; Vol. I: Characterization of Leachate", EPA-600/2-77-186a, September, 1977.

7. Pohland, F. G. and Brunner, D., "Sanitary landfill stabilization with leachate recycle and residual treatment.", EPA-600/2-75-043, October, 1975.

8. Remson, I., Fungaroli, A. A., and Lawrence, A. W., "Water movement in an unsaturated sanitary landfill", Jour. Sanitary Engineering Division, American Society of Civil Engineers, Vol. 94, SA2, 1968, p. 307.

9. Chain, E. S. K. and DeWalle, F. B., "Evaluation of leachate treatment, Vol. II: Biological and physical-chemical processes", EPA-600/2-66-186b, 1977.

10. Cameron, R. D. and Koch, F. A., "Trace metals and anaerobic digestion of leachate", Jour. Water Pollution Control Federation, Vol. 52, #2, 1980, p. 282.

11. Ho, S., Boyle, W. C., and Ham, R. K., "Chemical treatment of leachates from sanitary landfills", Jour. Water Pollution Control Federation, Vol. 49, #7, 1974, p. 1776.

12. Thornton, R. J. and Blanc, F. C., "Leachate treatment by coagulation and precipitation", Jour. Environmental Engineering Division, American Society of Civil Engineers, Vol. 99, EE4, 1973, p. 535.

13. Kardos, L. T. and Sopper, W. E., "Renovation of municipal wastewater through land disposal by spray irrigation." from Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland, Ed. by Sopper and Kardos, Pennsylvania State University Press, 1973, p. 148.

14. Menser, H. A., Wintant, W. M., and Bennet, O. L., "The application of landfill leachate to a forest and grass biome", Paper presented at the Sanitary Landfill Leachate Collection and Treatment Symposium, UMASS, Amherst, MA, December 8-9, 1977.

15. Bennet, O. L., Menser, H. A., and Winant, W. M., "Land disposal of leachate water from a municipal sanitary landfill", Proc. of the Second National Conference on Complete Water Reuse, Chicago, Ill, AIChE, 1975, p. 789.

16. U.S.E.P.A., "Process design manual for land treatment of municipal wastewater", EPA-625/1-77-008.

17. Overcash, M. R. and Pal, D., Design of Land Treatment Systems for Industrial Wastes-Theory and Practice, Ann Arbor Science Publishers, Inc., Ann Arbor, 1979.

18. Bouwer, H., "Renovating secondary effluent by groundwater recharge with infiltration basins", In Recycling Treated Municipal Wastewater and Sludges on Forests and Cropland, Ed. by Sopper and Kardos, Pennsylvania State University Press, 1973, p. 164.

19. Metcalf and Eddy, Inc., Wastewater Engineering: Treatment/Disposal/Reuse, McGraw Hill Book Company, New York, 1979, 920 pp.

20. Keeney, D. R. and Wildung, R. E., "Chemical properties of soils" from Soils for Management of Organic Wastes and Wastewaters, Ed. by Elliot, and Stevenson, Soil Sci. Soc. Am. 1977, p. 75.

21. Jennings, A. A., Tirsch, F. S. and Adrian, D. D., "Soil attenuative capacity and transport potential of solid waste leachates", 3rd Annual Purdue Industrial Waste Conference, Purdue University, May 9-11, 1978.

22. Walsh, L. M., Sumner, M. E., and Corey, R. B., "Consideration of soils for accepting plant nutrients and potentially toxic non-essential elements", from Land Applications of Waste Materials, Soil Conservation Society of America, Ankeny, 1976, p. 22.

23. Cameron, R. D., and Koch, F. A., "Toxicity of landfill leachates", Jour. Water Pollution Control Federation, Vol. 52, #4, 1980, p. 760.

24. Walker, P. A. and Adrian, D. D., "The effects of sanitary landfill leachate on algal growth", Rpt. No. Env. E. 57-77-3, University of Massachusetts, Amherst, 1977.

25. Dirr, M. A., "Salts and woody plant interactions in the urban environment", In Better Trees for Metropolitan Landscapes, USDA Forest Service General Technical Report, NE-22, 1976, p. 103.

26. Vosburgh, R. R., "Response of wetland maples to a changing hydrologic regime", M.S. Thesis, University of Massachusetts/ Amherst, MA, 1979, 102 pp.

27. Seidel, K. W., "Drought resistance and internal water balance of oak seedlings", Forestry Science, Vol. 18, #1, 1972, p. 34.

28. Buckner, E. and Maki, T. E., "Seven year growth of fertilized and irrigated yellow-poplar, sweet-gum, northern red oak, and loblolly pine planted on two sites", Forest Science, Vol. 23, #4, 1977, p. 402.

29. Farmer, R. E., "Growth and assimilation rate of juvenile northern red oak: effect of light and temperature", Forest Science, Vol. 21, #4, 1975, p. 373.

30. McColl, J. G., "Soil moisture influence on growth, transpiration, and nutrient uptake of pine seedlings", Forest Science, Vol. 19, #4, 1973, p. 281.

31. Wood, J. and Bormann, F. H., "Short term effects of a simulated acid rain upon the growth and nutrient relations of pinus storbus", Proceeding International Symposium on Acid Rain, p. 815.

32. American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 13th Edition, 1971.

33. Mader, D. L., A Laboratory Manual for Forest Soils, Department of Forestry and Wildlife Management, University of Massachusetts, Amherst, MA, 1975, 88 pp.

34. Walple, R. E. and Myers, R. H., Probability and Statistics for Engineers and Scientists, MacMillan Publishing Company, Inc., New York, 1972.

35. Tirsch, F. S.and Jennings, A. A., "Leachate reactions with soils under anaerobic conditions", Report # Env. E. 60-78-3, University of Massachusetts/Amherst, September,1978.

36. Miller, R. H., "The soil as a biological filter", from Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland, ed. by Sopper and Kardos, 1973, Pennsylvania State University Press.

37. Breuer, D. W., Cole, D. W., and Schiess, P., "Nitrogen transformation and leaching associated with wastewater irrigation in Douglas Fir, Poplar, grass, and unvegetated systems, from Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land, ed. by Sopper and Kerr, Pennsylvania State University Press, 1979, p. 19.

38. Broadbent, F. E., "Factors affecting nitrification-denitrification in soils", from Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland, ed. by Sopper and Kardos, Pennsylvania State University Press, 1973, p. 232.

39. Lancy, L. E., "The fate of heavy metals from metal finishing, land disposal of solid waste" from Land Application of Residual Materials, Engineering Foundation Conference, Eastern Maryland, September 26-October 1, 1976, p. 61.

40. Riekerk, H. and Zasoski, R. J., "Effects of dewatered sludge applications to a Douglas Fir forest soil on the soil, leachate, and ground water composition" from Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land, ed. by Sopper and Kerr, Pennsylvania State University Press, 1979, p. 35.

41. Sopper, W. E. and Kardos, L. T., "Vegetation responses to irrigation with treated municipal wastewater" from Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland, ed. by Sopper and Kardos, Pennsylvania State University Press, 1973, p. 271.

42. Hosner, J. F., "The Effects of complete innundation upon seedlings of six bottomland species", Ecology, Vol. 39, #2, p. 371.

43. Brockway, D. G., Schnieder, G., and White, D. P., "Dynamics of a municipal wastewater renovation in a young confier-hardwood plantation in Michigan", from Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land, ed. by Sopper and Kerr, Pennsylvania State University Press, 1979, p. 87.

44. Cooley, J. H., "Effects of irrigation with oxidation pond effluent on tree establishment and growth on sand soils", from Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land, ed. by Sopper and Kerr, Pennsylvania State University Press, 1979, p. 145.