Land disposal of anaerobically digested liquid sludge, Sept. 1974

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LAND DISPOSAL OF
ANAEROBICALLY DIGESTED LIQUID SLUDGE

by

Michael R. Parsons

A Research Report
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in
Civil Engineering

Lehigh University
August 1974
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CERTIFICATE OF APPROVAL

This research report is accepted and approved in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering.

September 23, 1974
(date)

Dr. Robert L. Johnson
Professor-in-Charge

Dr. David A. VanHorn
Chairman of the Department of Civil Engineering
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Finally, the author would like to thank his wife, Pamela, who typed the draft copies of this manuscript and who also provided encouragement during the entire research investigation.
ABSTRACT

This investigation was conducted to determine if the anaerobically digested liquid sludge produced at the Bethlehem Sewage Treatment Plant could be applied to nearby farms in a feasible and environmentally sound manner. This objective was accomplished by analyzing soil and sludge samples for their nutrient (nitrogen, phosphorus and potassium) and heavy metals (cadmium, chromium, copper, nickel and zinc) content. Concurrently a literature review of land disposal and the effects of sludge on plant growth and a review of the soils in the Lehigh and Northampton County areas were conducted.

The results of the analyses indicate that past sludge disposal practices have not damaged the soils under investigation and that the soils in the two-county area are generally well-suited for receiving liquid sludge. However, due to the extremely high cadmium metal levels in the Bethlehem sludge, it should not be applied to farmland. Furthermore, should the sources of cadmium be eliminated from the wastewater, the remaining high metal concentrations would be the limiting factor in determining an application rate and they would thus prohibit a feasible sludge disposal program.
INTRODUCTION

Each day, communities throughout the United States produce thousands of tons of residual solids known as sewage sludge. As the population increases, and as wastewater treatment improves, the quantities of sludge and the related disposal problems will grow at continually increasing rates. A major question confronting public officials, wastewater treatment personnel and engineers is: What methods should be used for the treatment and ultimate disposal of sewage sludge?

The nature of sewage sludge poses some difficult and expensive disposal problems. As Evans (11) points out, sludge handling and disposal are often the most difficult aspects of wastewater treatment and may also be the most expensive portion of the treatment scheme. Sludge captured and formed in wastewater treatment consists primarily of water. This water adds materially to the mass to be processed. Raw sewage sludge, a highly putrescible substance, is collected in the primary sedimentation unit of a treatment plant and only two to four percent of its total weight is solid matter, with the remaining ninety-eight to ninety-six percent being water. Because of public health dangers, offensive odors, high organic content and low concentration of poorly dewaterable solids, raw sludge is frequently treated in anaerobic digesters prior to disposal. The resulting digested sludge is a slurry with greatly reduced offensive properties and a solids content of four to seven percent. Although this substance is still difficult to dewater, the process is easier than when using raw sludge. It is this material for which many communities must provide ultimate
disposal. Because of the small mass of solids per unit volume of sludge, attempts are made to concentrate the solid matter. Water is bound so strongly to the solid particles that such operations generally have limited success and are quite expensive. Even after dewatering, ultimate disposal still remains a problem. Sludge disposal methods in the past have been landfill, ocean dumping, incineration, wet oxidation and spreading on farm land. The growth of concern with the effects on the environment created by each of the methods has resulted in stricter controls and is thus increasing the costs of disposal.

Locally, in the Lehigh and Northampton County areas, tremendous amounts of sludge are being produced daily. By 1980, the City of Bethlehem alone will have to contend with 11.75 tons of dry sludge per day which is equivalent to 235 tons of liquid digested sludge. Table 1 from the Joint Planning Commission Report (15), shows the amounts of sludge that will be produced in 1980 by the cities of Allentown, Bethlehem, and Easton and by the entire two-county area.

**TABLE 1**

*Sewage Systems - 1980*

<table>
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<th>System</th>
<th>Population Served</th>
<th>Dry Weight of Sludge</th>
<th>Liquid Weight</th>
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<tr>
<td>Bethlehem</td>
<td>106,700</td>
<td>11.75 ton/day</td>
<td>235 ton/day</td>
</tr>
<tr>
<td>Allentown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bethlehem</td>
<td>354,345</td>
<td>39 ton/day</td>
<td>780 ton/day</td>
</tr>
<tr>
<td>Easton</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-County</td>
<td>415,380</td>
<td>45.65 ton/day</td>
<td>913 ton/day</td>
</tr>
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*a Based on 0.22 lb. Solids/capita/day

*b Based on 5% Solids
These large amounts of sludge will pose new problems for many of the presently overloaded sewage treatment plants in the Lehigh Valley. Because much of the land in the two counties is used for agriculture, an investigation was made into the feasibility of the disposal of liquid digested sludge by spreading it on the farmlands. Such a disposal program would have several benefits as well as some potential hazards. A primary benefit with regard to the receiving water quality is obtained by disposing of the liquid sludge that comes directly from the digester, without any further treatment. This aspect is discussed in detail later in this report. Briefly, normal operations require that the digester supernatant be returned to the plant inlet along with any elutriation wash water and or filtrate from the dewatering process. The result is an additional solids and oxygen demanding organic material load on the treatment plant. Land as the receiving mantel also permits disposing of the supernatant and by excluding the elutriation and or dewatering process, these loadings are eliminated and the treatment plant efficiency increases.

The first step in this study was to determine the area that is available for land disposal. Figure 1 indicates the watersheds in the two counties. The drainage basins of Jordan Creek, Little Lehigh Creek, the Lehigh River north of Allentown and the Delaware River north of Easton are either currently utilized as water supplies or are planned to be used. Consequently, unless the sludge is incorporated into the soil as discussed later in this report, they should not be included in the area available for land disposal. The Monocacy Creek is a conservation type stream with natural trout breeding capabilities.
and this drainage basin may also be prohibited from the application of sludge. The result is that in the two-county area there are an estimated 9,000 acres of land that could be used for sludge disposal without immediate incorporation into the soil. This area is indicated by the hatched region in Fig. 1.

The following report is the result of an investigation to determine if land disposal of liquid digested sludge could be practiced in the Lehigh and Northampton County areas without detrimental effects to the environment. A general discussion on land disposal precedes the results of the analysis performed on the Bethlehem Sewage Treatment Plant sludge and on the soils of a previous land disposal site. The following subjects are included in the general sections:

1. The various approaches to land disposal and some of its history;
2. A description of this research project and the sampling and analysis program;
3. A review of the aspects of plant growth that are directly related to the spreading of sewage sludge;
4. The problems related to metal toxicity and pathogens;
5. The results of other research programs and the advantages of land disposal; and
6. A description of the Bethlehem sludge disposal situation at the present.

The sludge analyses are reviewed and safe application rates are predicted. The last section deals with the soils in the two-county area and their applicability to land disposal.
WATERSHED MAP
LEHIGH AND NORTHAMPTON COUNTIES, PENNSYLVANIA

LEGEND
- Watershed Boundary
- Stream
- County Line

Figure 1
DESCRIPTION OF LAND DISPOSAL

Land disposal is the application of sewage sludge to a plot of ground. This basic concept remains the same, regardless of whether the land is agriculturally barren or whether it is presently rich and fertile. The sludge to be spread on the land may be in the liquid, dewatered or dry form. The advantages of using liquid sludge will be discussed in another portion of this report.

History of Land Disposal

The application of sewage, not just sewage sludge, to the land has a long history. Ancient civilizations, such as China and India, have increased the fertility of their soils by applying human wastes and other organic materials to the agricultural land. Unfortunately, as the cities grew, it became more convenient to dispose of wastes by dumping them into nearby streams. More recent history finds land disposal being practiced in Berlin and Paris for a period of approximately ninety years. The records and present operational experiences of these two areas supply the only long-term sets of disposal data.

The practice of spreading liquid sewage sludge on the land has been accepted in Great Britain. In the late 1960's, England's Working Party on Sewage Disposal estimated that roughly forty percent of the inland sewage works in England and Wales applied sludge to the land. In their report (2) it was recommended that "whenever possible encouragement should be given to the application to agricultural land
of suitable sewage sludges."

Recently, certain communities in the United States have recognized the advantages of land disposal of sewage sludge on a large scale. The Metropolitan Sanitary District of Chicago, by actually purchasing farm land, committed itself to studying the feasibility of land disposal. The Metropolitan Denver Sewage Disposal District has also embarked on a research program to determine the compatibility of their sludge with the nearby soils.

 Communities in the state of Pennsylvania have also initiated land disposal programs. In 1967, approximately thirty municipalities were spreading digested sludge on rural lands (10). This number has decreased recently as a result of current awareness of the heavy metals in the sludges. In general, there is apprehension concerning the long-term effects that the metals will have on the soil. It appears that some of the programs will not continue until the farmers can be assured that their fields and crops will not be ruined by sludge application. However, Evans (11) reported in 1969, after making a state-wide survey, that the farmers were very pleased with the agricultural benefits they received from fields treated with sludge.

The discussion to this point has been concerned primarily with the disposal of sewage sludge. Another area of research, that is currently growing in the United States, is the disposal of treatment plant effluent. The Pennsylvania State University has conducted an extensive amount of research in this field (17,27,28). The disposal of effluent is most commonly accomplished by spray irrigation systems,
either in fields or in forests. The concepts for and the philosophy behind effluent disposal differ significantly from those for sludge disposal. Therefore, the remaining portions of this report shall refer exclusively to wastewater sludge.

Application of Anaerobically Digested Sludge

Current research in the area of sludge application to farmland is concerned primarily with anaerobically digested liquid sludge. Sabey (24) explains that health hazards are common in locations where raw sewage has been applied to the land, but that use of well-digested sludge has presented very few, if any, health problems. This reduction in health problems is due to the fact that most pathogenic organisms are killed during the digestion process and those that do survive usually die off rapidly in the soil. There are other reasons for avoiding raw sludges. While it decomposes in the soil, raw sludge requires oxygen and gives off carbon dioxide. This combination restricts root development. Also, during decomposition methane and ethylene gases are produced, both of which may be toxic to plants, and if quantities are sufficient, plant growth is inhibited (9).

There are other benefits derived from using anaerobically digested sludges. Digestion eliminates the offensive smell of raw sludge. The process of digestion destroys approximately one half of the sludge organic matter and thus the end product has a more favorable carbon-to-nitrogen ratio. Digestion also converts organic nitrogen to soluble ammonium salts, which is a form that is readily available to plants (2). It should also be noted that, if the sludge
is incorporated into the soil immediately, then the ammonium ions adsorb onto the clay particles and are less susceptible to leaching than are the nitrate ions.

Three basic philosophies have developed with regard to land disposal. Each one deals with a different reason for applying the sludge. The preceding paragraph alludes to sludge being used for its nitrogen content. In fact, sludge is often used to supply nutrients to crops. Used in this way, sludge is thought of as a fertilizer, even though the process is still termed "disposal". Farmers need to know the nutrient value of the sludge so that they can supplement it, if necessary. Under proper management such a disposal practice could continue for years.

A recent development has been the use of sludge in land reclamation. The countryside left behind by strip mining operations best illustrates this approach. These lands are often stripped of topsoil and void of organic material and plant life. In this case, sludge is applied for its organic content. Sludge has been shown to increase the water retention capacity of the soil by providing greater soil pore space and by decreasing the potential of surface sealing (9). Such reclamation operations usually cease after a good, rich top layer of soil has been developed. Those involved with soil reclamation are usually less conservative than the farmer, because the latter must protect his soil for future agricultural use.

The third type of application has the primary objective of disposing of the sludge. This type of program is designed so
that the disposal site may be utilized for many years without loss, or decrease, of the soil's ability to assimilate sludge. Generally, there are no future agricultural plans for the plot of land. The primary concern is that the neighboring surface and ground water supplies do not become polluted and that nuisance odors do not develop.

In the Lehigh and Northampton county areas most of the open land is currently being used for agricultural purposes. For this reason, this report is concerned with the agricultural value of sludge and safe application rates for crops will be developed in a later section.

**Application Techniques**

A variety of sludge application techniques have been developed as a result of the current interest in land disposal. These techniques can be divided into three categories: transportation of the sludge to the disposal site; application of the sludge to the field; and incorporation of the sludge into the soil.

Transportation of the sludge to the site is a straightforward process. The volumes of sludge and the transportation distance, along with the costs involved, determine which method is used. In the past, sludge has been moved by train, truck, barge and pipeline.

The method of sludge application is only partially influenced by the economics of the situation. The reason for sludge application may be more important than the cost aspects. For frequent and light applications, the sludge may be spread from a distribution mechanism.
mounted on the rear of a tank truck. Sludge may also be sprayed by using large bore nozzles. Another method is to lay irrigation pipes with holes large enough to permit sludge to flow freely. If the land is completely flat, the plot may be flooded with sludge, or, if there is a gentle slope, the sludge may be discharged at the top and spread by overland flow. If disposal is the objective, then trenching operations are often selected. One research project (3) reports having used trenches two feet wide by two feet deep with a spacing of two feet for disposing of large quantities of sludge. Applicating machines have been developed that plow a furrow, inject the sludge, and cover the furrow—all in one operation.

The last two methods include mixing the sludge with the soil. With simple spreading operations, this may be the third step in the application process. If odor problems develop, then immediate plowing or rotary tilling is necessary. However, many farmers find that it is possible to leave the sludge on top of the soil until they are ready to plow without any odor problems developing.
DESCRIPTION OF RESEARCH

Sampling Programs

This research investigation had the primary objective of determining agriculturally safe application rates for the anaerobically digested liquid sludge produced at the Bethlehem Sewage Treatment Plant. An "agriculturally safe rate" is one that will not inhibit plant growth and will not produce abnormally high concentrations of metals in the plants. A third limiting factor is that the rate must not lead to a long-term exhaustion of the soil as a result of applying an excess of heavy metals or other minerals.

It was also desired to determine, if possible, the effect of past land disposal practices on a field owned and managed by a local farmer. In recent years, this field has received sporadic sludge applications.

To accomplish these objectives, two sampling programs were developed. The first program consisted of obtaining five soil samples from the treated field and five samples from a bordering untreated field. These samples were taken in April before the crops were planted. The second program was developed to establish a data base for the anaerobically digested sludge produced at the Bethlehem Sewage Treatment Plant. Samples of either the digester sludge, the digester supernatant, or a mixture of the two, were taken weekly. Approximately fifteen sludge samples were obtained.
Analysis

Nitrogen (N), phosphorus (P), and potassium (K) are the primary nutrients that must be supplied for crop growth. The nitrogen content was measured by following the procedure outlined in Standard Methods (1) for the total Kjeldahl test (Sec. 216). Liquid sludge samples with a volume of 20 milliters (ml) and dry soil samples weighing approximately 5.0 grams were used.

Phosphorus was measured as described in Standard Methods (Sec. 223). In order to achieve a reliable test, 1.0 ml and 2.0 ml samples of the liquid sludge were diluted to 100 ml prior to the persulfate digestion. After digestion and before following the stannous chloride colorimetric method, the digested samples were filtered to remove the solids and further diluted by 1:10 or 1:20 so that the sample to be measured would contain less than 2.0 milligrams per liter (mg/l) of phosphorus. Dried soil samples weighing approximately 0.5 grams were used and the same procedure as above was followed. The orthophosphate ion concentration of the sludge and soil samples was also measured by using this same procedure, but with the elimination of the persulfate digestion step.

The available potassium content of the sludge and the soil samples was measured by an atomic absorption unit. Liquid sludge volumes of 2.0 ml and dry soil weights of 1.0 gram were washed with demineralized water and diluted to 20 ml before the analysis.

The atomic absorption unit was also used to determine the concentration of the following metals: cadmium (Cd), chromium (Cr),
copper (Cu), nickel (Ni), and zinc (Zn). Preparation of the samples included digestion with sulfuric acid as outlined in Standard Methods (Sec. 211 (II)A). Soil samples having a dry weight of approximately 5.0 grams and liquid sludge samples having a volume of 50 ml were prepared and stored in glass vials until the metals were analyzed. Results and comments on the analyses will be presented later in this report.
ASPECTS OF PLANT GROWTH THAT APPLY TO SLUDGE APPLICATIONS

It is essential for those who are connected with the land disposal of sewage sludge to have a basic knowledge of plant growth. Sludge contains most of the plant nutrients found in artificial fertilizers and many more that are not. An understanding of how plants react to various concentrations of these elements is very important in maintaining a successful land disposal program.

Nutrients

Sludge has been utilized successfully as a fertilizer because it contains significant amounts of two elements that are necessary for plant growth, namely, nitrogen and phosphorus. The process of applying sufficient amounts of these two nutrients is simplified by the fact that the ratio of nitrogen to phosphorus in sludges is generally within the application ranges of artificial fertilizers that are normally used in agriculture (6).

Nitrogen

Nitrogen is one of the main limiting factors in agricultural production. It is difficult to maintain a sufficient quantity of available nitrogen in the soil at all times. Nitrogen is a useful plant nutrient in either the ammonium (NH$_4^+$) or the nitrate (NO$_3^-$) form. Nitrogen also exists in the soil as organic nitrogen and for brief transitory periods, as nitrite (NO$_2^-$). Although the total nitrogen content of the soil may be high, there may be a nitrogen deficiency because plant growth can utilize only the "available" nitrate and
ammonium nitrogen forms. As much as 95 percent of the total nitrogen may be in the organic matter of the soil, where it is not in a readily available form (29).

The farmer must concern himself not only with supplying a sufficient amount of nitrogen when he fertilizes his fields, but also with what happens to the nitrogen that he has applied. Unfortunately the two forms of nitrogen that are readily available to plants are also the forms that are the most susceptible to removal from the soil and out of the root region by percolating rain or irrigation water. Nitrates can also be removed from the soil by microbial denitrification. This is a biological reaction in which bacteria reduce nitrates to nitrites and further, to nitrogen gas, which escapes from the soil. A corresponding microbial process, nitrogen fixation, fixes nitrogen directly from the air to the plants, where it is in the form of proteins. Legumes may fix from 50 to 100 pounds of nitrogen per year per acre (lb N/year/acre).

The ammonium form may also be converted to other nitrogen forms and then removed from the plant root zone. Bacteria transform some of the ammonium ions to nitrate ions which are then susceptible to the removal mechanisms that are described in the preceding paragraph. Volatilization, or transformation of the ammonium ion to ammonia gas (NH₃), also accounts for a portion of the nitrogen loss.

Efficient plant growth requires a continuous supply of available nitrogen in the root zone throughout the plant life cycle. In areas that receive a sufficient rainfall, such as the region east
of the Mississippi River, the nitrogen applied to the soil as ammonium or nitrate ions will not remain in the root zone for the entire growing season. However, organic nitrogen does not readily leach out of the soil and since nitrogen in this form is released slowly and continuously, it can be viewed as the storage form in the plant nutrient cycle.

Anaerobically digested sludge contains nitrogen in organic and in ammonium forms. Because the organic matter releases nitrogen slowly, it is possible when using sludge as a fertilizer, to apply it to the fields before the growing season and as a result, maintain a continuous supply of nitrogen. Surface applications of sludge may result in the loss of 25 percent or more of the ammonia nitrogen (29). This loss may or may not be desirable and it can be minimized by immediately incorporating the sludge with the soil. It should be emphasized that the slow release of nitrogen from the sludge organic matter is one of the main advantages of using sludge as a fertilizer.

Unfortunately, when plants are exposed to an excessive amount of nitrogen, toxic effects develop. Ammonia is generally identified as the problem-causing nitrogen form which can produce inhibition of germination and plant growth. The other potential toxicity problem occurs when excessive amounts of applied nitrogen lead to nitrates leaching into both ground water and surface water supplies. High nitrate concentrations in drinking water are toxic to humans, particularly infants, and to animals. The control of these two problems will be discussed later.
Phosphorus

Phosphorus ranks second among the plant nutrients in both the quantity and the frequency of application in agricultural practice. The phosphorus soil budget is very different from that of nitrogen. Soil minerals, soil organic matter and fertilizers are the sources of phosphorus. Plants utilize phosphorus when it is in a soluble inorganic phosphate form such as the orthophosphate ion. Microorganisms are required to decompose and mineralize organic phosphorus and to alter the solubilities of certain inorganic compounds of phosphorus so that these substances will also be available to the plant roots (8).

Most of the soil phosphorus is in a form that is not available to crops in a single growing season. One estimate is that the available phosphorus is approximately one percent of the total soil phosphorus (29). It has been established that the availability of phosphorus is at a maximum in the pH range of 6.5 to 7.0. Another characteristic of phosphorus is that it does not move through the soil to any significant extent. As a result, the phosphorus accumulations are in the top foot or so of soil. Dean (6) reports that soil minerals can adsorb virtually unlimited quantities of phosphates from the water that leaches through the soil.

The extensive adsorption capacity of the soil indicates that the risk of contaminating the ground water with phosphates is very small. However, a problem may develop concerning the build-up of phosphorus in the soil. Certain crops, such as soybeans, have a low tolerance to phosphorus accumulations. For these sensitive crops,
the phosphorus build-up may become the limiting factor in the sludge application rates.

Typical sewage treatment plants currently remove approximately one third of the influent phosphate concentration. As wastewater treatment technology expands and as governmental agencies enforce stricter guidelines, the percentage removal of phosphates and the fertilizer value of the corresponding sludge will both increase.

**Potassium**

Potassium is one of the three major fertilizer elements. It can be found in the soil in several forms which vary in solubility from soluble in water to insoluble in acid. Most soil potassium is not available to plants even after the field has been worked for years. This is because a major portion of it is in the minerals of the silt and sand fractions. Approximately one to three percent of the soil potassium is present as ions on the surfaces of clay particles and organic matter. This property of the surface retention of certain cations that can be readily replaced by other cations is referred to as the cation exchange capacity (CEC) of the soil. The exchangeable form is an important, readily available source of potassium for plants. Soluble potassium, the portion that moves freely in the soil water, represents only one to five percent of the exchangeable quantity (29). As the crops remove the soluble form from the soil water, it is immediately replaced by the exchangeable form because these two forms are in equilibrium. Microorganisms also affect the availability of this element. They possess the ability to liberate organically-bound...
potassium by decomposition and to transform insoluble forms to soluble ones (8).

Potassium may be lost from the soil as a result of leaching, erosion and crop removal. Since typical sewage sludges contain very small amounts of potassium, this nutrient may need to be supplied in addition to the sludge application program.

Heavy Metals

Many other elements are required for proper plant growth, usually in small or trace quantities. Sludge application supplies most of these trace elements but problems often develop when an excessive amount of a certain substance is incorporated with the soil. Heavy metals which are in this category, have recently been the subject of much debate. There are several schools of thought. The first is that the continued application of sludges containing these metals will eventually lead to the exhaustion of the agricultural land. Another fear is that the metals will enter the plants and thus enter the food chain and accumulate in humans and animals. Still others maintain that through proper land disposal programs, sludge containing heavy metals may be successfully applied to the land. With all these opinions being presented, it is important to understand the relationships between the heavy metals, the soil and the agricultural crops.

There are many heavy metals that are significant to the farmer utilizing sludge. Because this is a preliminary investigation, the analysis has been restricted to measuring the concentrations of
cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn).

Research has shown that the last three are clearly toxic to plants if they exist in high concentrations in the soil (2,4,5). Cadmium is of interest because it is not normally found in the soil and it is hazardous to the food chain at low levels, being toxic to both man and animals. Another reason for measuring the cadmium concentrations is that there have been reports of high cadmium levels in the air in the Lehigh Valley area. Chromium is often found in industrial wastewaters and can be considered an indicator of industrial discharges.

Metals are present in the soil in several different forms. It is the soluble form that presents a potential hazard to plant growth. Metals in the soil water are free to move about and come in contact with the plant roots and enter the plant. The key to a successful sludge application program is to maintain only the amount of metals that the plants need nutritionally in a soluble state. The remaining metals should be in an insoluble form so that they are not available to the plant roots. In this manner the crop uptake and thus removal of the metals from the soil is controlled. The restriction of supplying only the amount of metals that are removed may be the limiting factor in determining the sludge application rate.

The insoluble forms in which the metals may exist are related to the following soil characteristics: pH, organic matter, phosphate concentration and cation exchange capacity. The pH, or hydrogen ion concentration of the soil is one of the easiest parameters to control. General farming practice requires that the soil pH be adjusted to
near neutral conditions for efficient plant growth. Applications of lime are used to neutralize acid soils and to release the phosphates and potassium from the cation exchange sites in the soil. Soil pH is important because under acid conditions, when the pH is less than 6.5, the heavy metals are generally in the soluble form. In this pH range, there is approximately a 100-fold decrease in the Zn and Cu activity for each unit increase in pH (18). As the pH is increased, the metal ions form inert oxides and hydroxides, and most of them are no longer available to the plant roots (29). If the pH is increased excessively, the metal solubility may become so low that plant deficiencies occur. Frequent sludge applications may result in a lowering of the pH in the soil surface. Such depressions of the pH values are probably caused by the large applications of nitrogen in the sludge (14). Thus, the pH should be measured periodically and adjusted by liming, if necessary.

The soil organic matter has the capacity to prevent a portion of the metals from entering the plant roots. This is accomplished by chelating, or forming strong chemical organic complexes with the metals. This phenomena is especially important in binding Cu and Ni. Unlike a neutral pH which maintains most of the metals in an insoluble form indefinitely, the organic matter in the chelates decomposes and the protective effect decreases. Unless the organic content of a soil is kept at a constant level, a once normal field may become toxic. To avoid this, practices such as crop rotation and green manuring should be employed to ensure a high organic content.
A high phosphate concentration is known to reduce the availability of Zn to the plants and to decrease the plant injury caused by the excessive levels of metals. Unfortunately, this benefit could be reduced by the sensitivity of some crops to high phosphate concentrations. If the metal toxicity effects are reduced by the phosphates in the sludge then this is an additional benefit of land disposal. However, it is not recommended that a phosphate fertilizer be applied to the fields simply to reduce the metal toxicity.

The cation exchange capacity described previously is the fourth means of maintaining the metals in an insoluble state. Soils with a high CEC have more sites to which the metal ions can adsorb than do soils with a low CEC. Metal ions entering the soil will exchange positions with cations that had been previously adsorbed. This mechanism of preventing the metals from entering the soil water is limited by the number of cation adsorption sites in the soil. The result is that this phenomena may be successful for a while, but unless the crops remove significant amounts of metals, continuous sludge applications will deplete the adsorption capacity of the soil.

The previous paragraphs have alluded to the removal of metals from the soil by crops. Plants, as do humans, require very small quantities of metals to grow. Since metals do not percolate down through the soil, crop uptake is the only removal mechanism. After several years of sludge application, the soil must reach a metals equilibrium when the amount of metals applied equals the amount removed by the plants. This condition is necessary for a safe and
continuous sludge application program. If the metals application rate exceeds the removal rate, then toxic effects may develop and the soil may become exhausted.

Many studies have been made that concern plant growth and metal concentrations. Researchers (2,4,7) observing the toxic effects of Cu, Ni and Zn have adopted an expression that relates the toxic powers of these three metals and have termed it the "zinc equivalence". It appears that Cu is twice as toxic and that Ni is eight times as toxic as Zn. Thus, the zinc equivalent, in parts per million (ppm), is defined as:

\[
\text{Zn equiv.} = 1 \times \text{Zn(ppm)} + 2 \times \text{Cu(ppm)} + 8 \times \text{Ni(ppm)}
\]

The British (2) suggest that the maximum safe content of the topsoil in terms of zinc equivalence is 250 ppm on a dry soils basis. Assuming a topsoil (upper 4 inches) weight of 2 million pounds per acre (lb/acre) this amounts to 500 lb/acre. The removal rate of metals from the soil is very slow and based on a 30-year period with a low initial metals content, the maximum permissible average annual addition amounts to seventeen pounds of zinc equivalence per acre (2). These calculations assume that the soil pH is maintained above 6.5.

Up to this point, the discussion has considered the reaction of all plants to high metal concentrations to be the same. In fact, the tolerances of various plants to metals is quite different as shown in Table 2 (4). Until the effect of metals on plants is more thoroughly understood, it is recommended that the crops which are grown on sludge application plots be among those in the moderately tolerant or tolerant groups.
TABLE 2
Tolerance of Certain Plants to Heavy Metals

<table>
<thead>
<tr>
<th>Very Sensitive</th>
<th>Sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beets</td>
<td>Beans</td>
</tr>
<tr>
<td>Turnip</td>
<td>Cabbage</td>
</tr>
<tr>
<td>Kale</td>
<td>Spinach</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moderately Tolerant</th>
<th>Tolerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>Most grasses</td>
</tr>
<tr>
<td>Small grains</td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td></td>
</tr>
</tbody>
</table>

If the metal concentration is the limiting factor in sludge application, as many have predicted that it will be, then there are two factors to consider. The first is the concentration of the metals in the sludge and the second is the amount of sludge that is applied. Table 3 shows Chaney's recommended metal concentrations of a sludge that is appropriate for land application (4). Unfortunately, the author did not include rates with this table, but it is, nevertheless, an example of a suitable sludge. It should be emphasized that the metal concentrations shown in Table 3 are applicable only if the land is intended for general farming use. Sites with crops that will not be used for direct consumption may receive sludge with higher metal concentrations.

TABLE 3
Metal Content of a Sludge Appropriate for Land Application

<table>
<thead>
<tr>
<th>Metal</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc (Zn)</td>
<td>&lt;2000 ppm</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>&lt; 800 ppm</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>&lt; 100 ppm</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>&lt; 0.5 % of Zn</td>
</tr>
<tr>
<td>Boren (B)</td>
<td>&lt; 100 ppm</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>&lt;1000 ppm</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>&lt; 15 ppm</td>
</tr>
</tbody>
</table>
The problems created by the plant uptake of metals is twofold. The first is the toxic effect upon the plant itself, as discussed previously and the second is the manner in which the metals enter the food chain. Cadmium, copper and zinc are identified as being the most hazardous. Mercury (Hg) is not considered to be a problem because it does not accumulate in agriculture as it does in the oceans.

Very little detailed information is available concerning this subject although some guidelines have been established. The food chain appears to be protected from excessive amounts of zinc because crop yields are significantly reduced at zinc levels which are lower than the levels that injure the animal consuming the plant. Thus, the plant growth inhibition is a warning that the zinc levels may be too high and that the plant is unsuitable for consumption.

The only safe method for ensuring that excessive amounts of cadmium will not enter the food chain is by restricting its level in sludges to 0.5 percent of the Zn level. In this manner, the Zn content will harm the crop before any Cd hazard develops. The third metal, Cu, causes plant injury before it is toxic to most animals.

The problem concerning metals is still being widely discussed. One of the drawbacks to arriving at an agreement of opinion is the large number of variables that are involved. No two sludges or soils are the same, and plant reactions vary dramatically. Until the subject is more fully understood, the predicted application rates will probably be very conservative.
PUBLISHED RESULTS AND ADVANTAGES OF LAND DISPOSAL

One of the first concerns with spreading sludge on the land is the potential for disease transmission. This portion of the report discusses the survival of pathogenic organisms and viruses in the soil. Also included in this section is a brief review of the problems encountered and the solutions developed by researchers studying land disposal. Finally, a list is presented of the advantages that are unique to sludge application.

Pathogens

The number and life span of pathogenic bacteria in digested sludge is a subject upon which there is general agreement. Anaerobic digestion results in a significant reduction of pathogenic microorganisms, but does not result in their complete elimination. This is one of the reasons why digested sludge is preferred over raw sludge.

Since anaerobically digested sludge may contain some pathogens, a knowledge of their survival in the soil is very important. Results of a study by Lynam, Sosewitz and Hinesly (19) shown in Table 4, illustrate the die-off rate of fecal coliforms for a typical digested sludge that was applied to the land but not incorporated into the soil. Fecal coliforms are not pathogenic. They are conservative indicators whose presence means that pathogenic bacteria may be present. The authors also add that they are reasonably confident that their sludge is free of viable virus.
TABLE 4

Survival of Fecal Coliform After Sludge Application to Soil

<table>
<thead>
<tr>
<th>Days After Application of Freshly Digested Sludge</th>
<th>Number of Fecal Coliform Per Gram of Dry Digester Solids Cake</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,680,000</td>
</tr>
<tr>
<td>2</td>
<td>655,000</td>
</tr>
<tr>
<td>3</td>
<td>590,000</td>
</tr>
<tr>
<td>5</td>
<td>45,000</td>
</tr>
<tr>
<td>7</td>
<td>30,000</td>
</tr>
<tr>
<td>12</td>
<td>700</td>
</tr>
</tbody>
</table>

Aside from the fact that bacteria are present, another concern is that of their potential for travel through the soil and into ground water supplies. One report (3) of sludge application on a plot that had a water table ten feet below the surface, states that there were no organisms moving to the ground water. Ewing and Dick (12) indicate that, in general bacteria do not travel more than 100 feet through granular soil. These two results should be used to specify the minimum distance from a sludge application site to ground water supplies.

Certain countries in Europe, which have been practicing sludge application for many years have investigated the feasibility of disinfecting the sludge. Dotson (7) reports that storing or lagooning sludge for thirty days reduced the number of fecal coliforms by 99.9 percent. He also states that disinfection may be accomplished by injecting steam into the sludge to maintain a temperature of $70^\circ C$ for 25 to 30 minutes. Chlorine can also be utilized to destroy the pathogens. In the United States, certain groups are investigating composting sewage sludge and the resulting disinfection of bacteria.
and viruses due to the temperatures generated during the process.

There have not been any reports of disease transmission as a result of spreading sludge on farmlands. If human contact with the land is unavoidable, then disinfection of the sludge should be considered. It is recommended that fruits and vegetables that are eaten raw should not receive treatment with digested sludge (11,23). If the application plot is in a drinking water supply watershed basin, then the sludge should be incorporated into the soil immediately after spreading to avoid possible transport of bacteria in rainfall runoff. Generally, however, as Miller (20) states, "The presence of pathogens should not be a factor limiting the applicability of recycling wastes on land."

Disposal and Research Experiences to Date

Researchers have encountered and solved several problems that are associated with land disposal. Perhaps the situation that is most annoying to the general public is the development of nuisance odors and fly populations. These conditions existed when Denver initiated its disposal research, but were eliminated by applying the sludge below the soil surface (24). It should be noted that many programs do not have this problem.

There have been several reports of inhibited germination and plant growth when the sludge applications were made shortly before or after planting (3,7,24,30). Presently, there are two reasons which are suggested as causes of this reaction. Ammonia is believed to be
responsible for the inhibition of germination, and the volatile organics that are produced by the anaerobic decomposition of the sludge in the soil are known to be toxic to plant roots and seedlings. The solutions have been to:

1. Age the digested sludge before application;
2. Wait two to four weeks after sludge spreading to plant the crop;
3. Wait the same length of time after planting before disposing of the sludge.

The problem of saturating the soils with residual salts has been anticipated, but no solutions have been proposed. However, in regions where the total rainfall exceeds the potential evapo-transpiration, this is not viewed as a problem.

Another concern, previously mentioned, is the leaching of nitrates to the ground water. The nitrates that are in excess of that required by the growing plants will be subject to leaching. To avoid this, the amount of nitrogen supplied to the crops must not exceed the nutrient requirements of the crops plus the losses due to denitrification minus the amount released by the organic matter in the soil and sludge (20).

The fifth problem that has been encountered or anticipated is crop reduction due to metal toxicity. Rohde (23) investigated what he reported as the exhaustion of sewage-irrigated land in Paris and Berlin and concluded that high, root-soluble zinc and copper concentrations were responsible. Other investigators (22), noting this situation, have suggested liming the soil to raise the pH. A very similar situation existed in England where sludge applications had
reduced plant growth due to zinc poisoning. In this case, the condition was easily corrected by adding lime to the soil (6). Up to the present, heavy metals have not posed any significant problems.

Advantages of Land Disposal

There are several advantages of disposing of liquid digested sludge on the land. Perhaps the only truly significant one is the economics of land disposal. The cities of Chicago and Denver have satisfied themselves that land application is the least expensive means of disposing of sludge. Naturally, the cost is a function of many parameters and for some municipalities, this may not be the best solution. However, it appears that land disposal is a feasible option for many wastewater treatment districts.

An extremely important benefit from land disposal is the reduced load on the sewage treatment plants, as was mentioned briefly in the introduction. After the sludge has been treated in the anaerobic digesters, it normally must go through a dewatering process before disposal. The products of dewatering are a more concentrated sludge and water from the separation. This separation water contains fairly high concentration of organics and fine solids and must be returned to the plant to be treated again. In many cases, before a digested sludge can be dewatered, it is washed by a process termed elutriation which produces a wash water containing fine solids that must also be returned to the treatment plant. A third source of water that must be treated is the supernatant that is drawn off the anaerobic digester. The result is that when the digested sludge is being treated the plant
receives an additional solids and organic loading. Many treatment plants are presently at or above their capacity under normal flow conditions and this overload creates an inefficient operation. The advantage of land disposal is that the digested sludge requires no additional treatment. This eliminates the overload due to the elutriation and dewatering processes. If the digester supernatant is disposed of on the land, this overload is also avoided. The result is that the plant operates more efficiently and the effluent quality is improved.

There is an additional advantage when disposing of the sludge as it comes from the digester rather than disposing of dewatered or dried sludge. Dewatered sludge loses nitrogen to the separation water that is produced and nitrogen is leached out of sludge that is dried on sand beds. The result is that more sludge would have to be applied to agricultural lands to obtain the same nitrogen loading than if liquid sludge were being used.

In the anaerobic digestion process the supernatant contains significant amounts of nitrogen and phosphorous which are termed green plant nutrients. If this liquid is returned to the treatment plant, the nutrients will enter the receiving waters where they are not desired. However, by applying the supernatant to the land, these nutrients are conserved and the receiving waters are cleaner.

The organic content of sludge is a major element that is not obtained when applying artificial fertilizers. It has been mentioned previously that one of the main advantages of sludge is its organic, slow-release nitrogen content. The organic matter in
sludge also improves soil properties. The mixing of sludge and soil produces a soil structure that is more favorable to root penetration by promoting the aggregation of soil particles. The addition of sludge also increases the moisture retention capacity of the soil, as well as improving the soil permeability. The repeated applications of organic matter also increase the cation exchange capacity.

One of the most beneficial results of sludge application is the increase in farmland productivity. There have been many reports of improved crop yields testifying to the agricultural value of sludge. Another very significant benefit is that by applying sludge to farmlands, the nutrients are not lost as they are in conventional wastewater treatment.
SOILS

Desirable Soil Types

The soils of a land disposal site are a critical factor in determining the success of a sludge application program. Fortunately, few soils are unsuitable for the purpose of receiving sludge. Since there are many suitable soil types, it is easier to list those soils which should not be used for land disposal. The unsuitable soil types are:

1. Extremely coarse grained soils;
2. Extremely fine textured soils (e.g., clay);
3. Soils with shallow depths to water, bedrock, impermeable layers, or gravel;
4. Wet, undrained soils;
5. Frozen soils; and

The topography of the area is another important factor. Areas with gentle slopes are suitable for sludge application by overland flow. However, as the slope increases, the application rate should not exceed the infiltration capacity, otherwise the sludge will flow over the desired area onto neighboring land.

Suitability of Local Soils

The soil formations in the northeastern part of the United States were significantly affected by the glacial advances. Almost all of Northampton County and a large portion of Lehigh County are believed to have been covered by ice during the Illinoian Glacial Period. The soils in northeastern Pennsylvania, classified as Podzolic, were formed under forest vegetation in a relatively mild climate that favored microbial activity and, as a result, the organic content is
lower in these soils than in those further north. Another factor adding to the low organic content is that the soils are frequently used for cash crops. Such produce return lower amounts of organic matter to the soil than do other crops. Podzolic soils are generally acidic which is a condition that can be neutralized by lime additions. Such soils also usually have low nitrogen and fertility levels (29). It is interesting to note that the acid conditions exist even though the parent materials are limestone and shale.

Soils in Lehigh County

A study of the soils in Lehigh County reveals that there are eleven identified soil associations, as shown in Fig. 2, but only the four listed below are significant enough to be discussed in any detail (26). The soils that are suitable for sludge applications are:

a. Trexler Association - 3. This association prevails over much of the northwestern portion of the county. Usually of the nature of rolling terrain, it consists of deep and moderately deep soils overlying shale.

b. Washington-Duffield Association - 6. This is a large, well-drained area covered by deep soils and underlaid by limestone formations.

c. Chester-Brandywine-Fleetwood Association - 7. This region, which includes South Mountain, consists of deep and moderately deep soils covering the parent materials of granite, gneiss, and quartzite. Approximately half of this area is used for crops. Sludge disposal sites should be selected carefully because only portions of this region are level and well-drained.

d. Penn-Norton-Reading Association - 10. Only portions of this association are suitable for sludge disposal. The topography varies from rolling to steep, with only some of the soil being well-drained and deep. The underlying materials are sandstone and shale.

Provided that the regions do not form part of a water supply drainage basin, most of the soils in Lehigh County are well-suited for application of sludge.
1. Fleetwood--extremely stony land association: Soils and land types of the upper slopes of Blue Mountain.


3. Trexler association: Deep and moderately deep soils of rolling hills on shale.


5. Ryder-Duffield association: Moderately deep and deep soils on shaly limestone.


7. Chester-Brandywine-Fleetwood association: Deep and moderately deep soils of South Mountain on granite, gneiss, and quartzite.


9. Fleetwood-Chester very stony association: Deep and moderately deep, stony soils of the ridges of South Mountain on quartzite and gneiss.


Figure 2
Soils in Northampton County

Nine soil associations have been identified in Northampton County (25), as shown in Fig. 3, but only two of them cover a sufficient amount of area to make them significant. These two soil associations are:

a. Berks-Bedington-Comly Association - 4. These soils are shallow to deep, overlying shale, with a rolling to hilly topography. The fertility of these soils is moderate and the moisture retention capacity is low. Sludge applications would probably be quite successful in improving these two properties.

b. Washington-Urban Land Association - 7. These soils are deep and fertile with limestone as the underlying material. This area is farmed extensively and indications are that it is well-suited for land disposal programs.

In general, the soils of the Lehigh and Northampton County areas possess all of the necessary properties for the successful and continuous application of sewage sludge.
GENERAL SOIL MAP
NORTHAMPTON COUNTY, PENNSYLVANIA

SOIL ASSOCIATION
1. LAIDIG - STONY LAND
2. BUCHANAN - LAIDIG - ANDOVER
3. SWARTSWOOD-WURTSBORO-CHIPPEWA
4. BERKS-BEDINGTON-COMLY
5. BERKS-WIEKERT
6. DUFFIELD-CLARKSBURG-RYDER
7. WASHINGTON-URBAN LAND
8. CONESTOGA-HOLLINGER
9. CONOTTON-RED HOOK-URBAN LAND

Figure 3
BETHLEHEM LAND DISPOSAL PROGRAM

The History and Present Status of Land Disposal in Bethlehem

The City of Bethlehem has been applying liquid digested sludge to farmlands for a number of years in a sporadic and undocumented manner. There are no records of the rate or frequency of application and the treatment plant personnel and farmers know only the general areas upon which sludge has been spread.

The sludge application program continued in this manner until December 1973. At this point there developed among the farmers a concern about the long-term effects of applying heavy metals to their soils, and the program was terminated. Prior to this action, the farmers were pleased with the agricultural benefits they derived from the sludge. It was customary to use tank trucks to transport and spread the liquid sludge on top of the soil where it remained until the normal plowing time. This practice never created any fly problems or nuisance odors as was the experience of some disposal programs in other municipalities (24).

Presently, the sludge produced at the Bethlehem Sewage Treatment Plant is not being disposed of on farmland. It appears that this situation will persist until the local farmers can be reassured that their soils and crops will not suffer from any long-term effects that may result from sludge application programs.

Results of Soil Analysis

Ten soil samples were analyzed to determine what effects, if
any, the past sludge disposal program has had on the soil. To accomplish this objective, five soil samples were taken from a field treated with sludge and five from a field that did not receive any sludge. The ranges of the determined nutrient concentrations are shown in Table 5.

### TABLE 5

Results of Soil Nutrients Analyses

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.09 - 0.17% as N</td>
</tr>
<tr>
<td>Phosphorus - Total</td>
<td>0.026 - 0.058% as P</td>
</tr>
<tr>
<td>- Ortho</td>
<td>1.6 - 6.9% of Total P</td>
</tr>
<tr>
<td>Potassium (available)</td>
<td>0.0032 - 0.0054% as K</td>
</tr>
</tbody>
</table>

The soil nutrient analysis results shown in Table 5 are typical of soils in Pennsylvania and there is no evidence of sludge disposal adversely affecting the nutrient capacity of the soil. The soil samples were also analyzed for their heavy metal concentrations. These results are shown in Table 6 along with the typical ranges of these metals (21).

### TABLE 6

Results of Soil Metals Analyses

<table>
<thead>
<tr>
<th>Metal</th>
<th>Treated Soil ppm</th>
<th>Untreated Soil ppm</th>
<th>Typical Rangea ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium (Cd)</td>
<td>2 - 2.7</td>
<td>2 - 100</td>
<td>--</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>81 - 235</td>
<td>33 - 263</td>
<td>5 - 1,000</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>Negligible</td>
<td>Negligible</td>
<td>2 - 100</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>36 - 626</td>
<td>69 - 403</td>
<td>5 - 500</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>43 - 69</td>
<td>34 - 46</td>
<td>10 - 300</td>
</tr>
</tbody>
</table>

aRef. 21, p. 31
The soil metal analysis results indicate that the past disposal practices have not resulted in high or atypical metal concentrations in the soils treated with sludge. The one exception to this statement is the soil sample that has a nickel concentration that is above the typical range. However, this value is well below the observed maximum of 4,500 ppm (21) in soils which have received sludges.

The soil analysis program shows that the field under investigation has not received any agriculturally adverse effects from the application of digested sludge to date.

Results of Digested Sludge Analysis

Liquid digested sludge or supernatant samples were taken weekly during the sampling program. Because of the varying solids content of these samples, all of the results are expressed in terms of the sludge dry weight. The ranges of nutrient concentrations determined along with some typical values (5) are shown in Table 7.

TABLE 7

Results of Digested Sludge Nutrients Analyses

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Range</th>
<th>Typical Range</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>3.1 - 8.5% as N</td>
<td></td>
<td>3.5 - 6.4</td>
</tr>
<tr>
<td>Phosphorus - Total</td>
<td>0.8 - 2.2% as P</td>
<td>0.8 - 3.9</td>
<td></td>
</tr>
<tr>
<td>- Ortho</td>
<td>13 - 61% of Total P</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Potassium (available)</td>
<td>0.12 - 0.28% as K</td>
<td>0.2 - 0.7</td>
<td></td>
</tr>
</tbody>
</table>

aRef. 5, p. 43
The results of other municipal sludge analyses (2,12) also show that the above sludge nutrient concentrations are typical. It is important to note that although the soils in the Lehigh and Northampton County areas have high total phosphorus concentrations, they have very low amounts of available phosphorus. On the other hand, the digested sludge has the advantage of having a significant portion of its phosphorus in an available or orthophosphate form.

The ranges of the observed metal contents of the Bethlehem digested sludge are listed in Table 8, along with the ranges determined for sludges from other municipalities (4). Also included in Table 8 are the recommended concentrations of a sludge appropriate for land application as taken from Table 3.

TABLE 8

Results of Digested Sludge Metals Analyses

<table>
<thead>
<tr>
<th>Metal</th>
<th>Measured Range ppm</th>
<th>Observed Range ppm</th>
<th>Appropriate Content for Land Application, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium (% of Zn)</td>
<td>0.5 - 53%</td>
<td>0.1 - 40%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Chromium</td>
<td>95 - 308</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Copper</td>
<td>292 - 720</td>
<td>250 - 17,000</td>
<td>800</td>
</tr>
<tr>
<td>Nickel</td>
<td>82 - 664</td>
<td>25 - 8,000</td>
<td>100</td>
</tr>
<tr>
<td>Zinc</td>
<td>1057 - 1890</td>
<td>500 - 50,000</td>
<td>2,000</td>
</tr>
</tbody>
</table>

\[^a\text{Ref. 4, p. 130}\]
\[^b\text{Ref. 4, p. 137}\]

The cadmium concentrations in the Bethlehem sludge vary greatly and frequently reach very high levels. Over one third of the samples had a cadmium concentration greater than 10% of the Zn content. The level in one sample even exceeded the observed range for municipal
sludges. The nickel content is also higher than that desired for land application but within the typical range.

The results of the analyses performed on the Bethlehem digested sludge show that the nutrient concentrations are low, but typical. In general, the metal concentrations are high and in some cases, extremely high.

Application Rates

Three factors that may limit the rate of application are the nitrogen, organic matter and heavy metals content of the sludge. When nitrogen has been observed to be rate limiting, it is usually in the initial stages of a program. To avoid the leaching of nitrates to the ground water, it is generally recommended that the application rate be limited to the plant nitrogen requirements plus any anticipated nitrogen losses. However, Haith (13) qualifies this statement by noting that unless the sludge application rate is sufficiently low to produce a nitrogen starved crop, it is virtually impossible to prevent all of the nitrates from leaching through the soil.

It has also been observed (20) that large applications of organic matter could adversely affect plant growth due to the further decomposition of this material in the soil. However, organic matter rarely limits the application rate in practice.

The heavy metals concentration is generally the long-term limiting factor in sludge application. As previously mentioned, an equilibrium must be reached between the application rate of the
metals and the plant uptake. In some cases the metal content of the sludge may prohibit the use of that sludge for land disposal purposes.

This last point applies to this investigation. Because of the extremely high cadmium levels in the digested sludge produced at the Bethlehem Sewage Treatment Plant, the sludge should not be disposed of onto the land. The cadmium concentrations have been observed to exceed the admittedly conservative value of 0.5 percent of the zinc levels by factors of 10 and 100. This upper limit for the cadmium concentration of a sludge appropriate for land disposal ensures that the zinc content will affect the plant growth before the cadmium uptake will affect humans or animals. To exceed this limit would endanger the health of the consumer of the crops.

The sources of cadmium in a wastewater can usually be traced back to several industrial contributors since domestic wastes do not contain significant amounts of cadmium (16). If the City of Bethlehem were to eliminate the source of cadmium from its wastewater, then the sludge could be used for land disposal. Because of the high concentrations of copper, nickel and zinc, the application rate would be limited by the British (2) recommendation of 17 pounds of zinc equivalence per acre per year.

Characterizing the Bethlehem sludge as having metal concentrations of 1500 ppm Zn, 500 ppm Cu and 500 ppm Ni, the zinc equivalence is 6,500 ppm. Using this value the recommended sludge application rate would be 1.31 dry tons/acre/yr. By the year 1980 the City of Bethlehem would require 3,280 acres of land for sludge disposal. This
application rate is equivalent to spreading one quarter inch of liquid sludge on the land per year. If this rate were followed, then each acre would annually receive 131 lb nitrogen, 37 lb phosphorus and 5 lb potassium. Since these values are below normal crop requirements, an artificial fertilizer would also have to be used to supply the total nitrogen and phosphorus needs for the crops. Additional potassium would not be necessary only because it presently exists in high levels in the local soils.

These calculations demonstrate the infeasibility of disposing of a high metals content sludge onto farmland. Even if 3,280 acres of land were available, spreading liquid sludge to a depth of a quarter of an inch is impractical. In comparison, other municipalities have experimented with application rates in the area of two inches per year. Initially some programs (7) are exceeding the British limit and they are not experiencing any toxicity problems. However, in the long run it is believed that the conservative British figure of 17 lb zinc equivalence/acre/year should be observed.
CONCLUSIONS

The objective of this study was to determine if anaerobically
digested liquid sludge could feasibly be disposed of by application to
agricultural land. To accomplish this, both soil and sludge sampling
and analysis programs were required. Concurrently a literature review
of land disposal of sludge and a review of the soils in the Lehigh and
Northampton County areas were conducted. The results of the study lead
to the following conclusions.

1. The sludge presently being produced at the Bethlehem Sewage
   Treatment Plant is not acceptable for use in disposal onto
   farmland. The extremely high cadmium metal levels in the
   sludge are the prohibiting factor.

2. If the sources of cadmium were eliminated from the City's
   wastewater, the resulting sludge would be acceptable for land
   disposal but the process would not be feasible. The high metal
   concentrations other than cadmium would still limit the
   application rate to such an extent that it would be one fourth
   to one eighth of the rates presently being used by other
   municipalities. The result is that the land requirement
   would be extensive.

3. The soil of a field that was utilized for past sludge dispo­
sal practices has not received any apparent adverse effects.
   The soil metal concentrations are high but they do not appear
   to be a result of sludge application.

4. The soils in the Lehigh and Northampton County areas are
   generally well suited for sludge disposal programs. Large
   areas of farmland exist that could profit from the agricul­
tural benefits of an acceptable sludge.

5. If sludge disposal programs are conducted in such a manner
   that the sludge is not incorporated immediately into the soil,
   then there is only a small area of land in the two counties
   that is eligible for land disposal. This is because most of
   the land is part of some local watershed basin that is used
   to supply drinking water. Allowing the sludge to remain on
   top of the soil creates the potential for bacteria to enter
   the water supplies by the runoff of precipitation. Mixing
   the sludge with the soil restricts the mobility of the
   bacteria (3).

6. There is a need for further research in the area of the land
   disposal of sludge. The calculations in this study were
   based on conservative guidelines because little is known
   about plant uptake of heavy metals and their entrance into
   the food chain. Investigations into the effects of various
   sludge application rates on plant growth should be conducted.
The City of Bethlehem is limited in its choice of ultimate sludge disposal alternatives by the high metal concentrations in its wastewater which is the result of industrial discharges. Until the metals content can be reduced significantly the alternative of land disposal is not agriculturally safe nor is it feasible.
## APPENDIX

### Results of Nutrient Analysis

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<thead>
<tr>
<th>Sludge Sample Number</th>
<th>Date</th>
<th>Nitrogen a</th>
<th>Total a</th>
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<th>Orthophosphate</th>
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a Expressed as N, P or K in percent of dry solids weight
b Expressed as percent of Total Phosphorus
c Soil samples 1-5 from field treated with sludge, 6-10 from untreated field
## Results of Heavy Metals Analysis

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### Soil Sample

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a Concentration expressed as ppm dry weight basis

b Analysis performed Spring 1974 in Civil Engineering 103
REFERENCES

1. American Public Health Association
   STANDARD METHODS FOR THE EXAMINATION OF WATER AND WASTEWATER,

2. Anonymous
   AGRICULTURAL USE OF SEWAGE SLUDGE, Water and Pollution

3. Anonymous
   USE OF SEWAGE SLUDGE IN LAND IMPROVEMENT, Compost Science,
   13, 6, p 18-19, November-December 1972.

4. Chaney, R. L.
   CROP AND FOOD CHAIN EFFECTS OF TOXIC ELEMENTS IN SLUDGES
   AND EFFLUENTS, Proceedings of the Joint Conference on Re­
   cying Municipal Sludges and Effluents on Land, p 129-142,

5. Dean, R. D. and Smith, J. E., Jr.
   THE PROPERTIES OF SLUDGES, Proceedings of the Joint Conference
   on Recycling Municipal Sludges and Effluents on Land, p 39-

6. Dean, R. D.
   DISPOSAL AND REUSE OF SLUDGE AND SEWAGE--WHAT ARE THE OPTIONS?,

7. Dotson, G. K.
   SOME CONSTRAINTS OF SPREADING SEWAGE SLUDGE ON CROPLAND,

8. Drake, M.
   SOIL CHEMISTRY AND PLANT NUTRITION, Chemistry of the Soil,
   F. E. Bear, Editor, Reinhold Publishing Corporation, Chap.

9. Epstein, E.
   THE PHYSICAL PROCESSES IN THE SOIL AS RELATED TO SEWAGE
   SLUDGE APPLICATION, Proceedings of the Joint Conference on
   Recycling Municipal Sludges and Effluents on Land, p 67-74,

10. Evans, J. O.
    SOILS AS SLUDGE ASSIMILATORS, Compost Science, 14, 6, p

11. Evans, J. O.
    ULTIMATE SLUDGE DISPOSAL AND SOIL IMPROVEMENT, Water and Wastes
12. Ewing, B. B. and Dick, R. I.  

13. Haith, D. A.  

EFFECTS ON CORN BY APPLICATIONS OF HEATED ANAEROBICALLY DIGESTED SLUDGE, Compost Science, 13, 4, July-August 1972.

15. Joint Planning Commission--Lehigh and Northampton Counties  


17. Kardos, L. T.  

18. Lindsay, W. L.  

19. Lynam, B. T. et al.  
'LIQUID FERTILIZER' TO RECLAIM LAND AND PRODUCE CROPS, Water Research, 6, 4-5, p 545-549, April-May 1972.

20. Miller, R. H.  

21. Muskegon County Board and Department of Public Works  

22. Pound, C. E. and Crites, R. W.  
23. Rohde, G.


27. Sopper, W. E. and Kardos, L. T.


29. United States Department of Agriculture

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His undergraduate studies were conducted at Lehigh University and in 1973 he received a Bachelors of Science in Civil Engineering. He continued on at Lehigh University and received the degree of Master of Science in Civil Engineering, with an environmental major, in 1974. During his graduate career he was supported by the Byllesby Fellowship for the academic year and he was employed as a Research Assistant during the summer.