THESIS

OPTIMIZATION OF MUNICIPAL SEWAGE SLUDGE INJECTION

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ABSTRACT OF THESIS

OPTIMIZATION OF MUNICIPAL SEWAGE SLUDGE INJECTION

A major obstacle to the application of continuous subsurface injection as an effective sludge disposal method is the lack of techniques for planning and implementing sludge injection systems. This thesis is based upon research conducted in an effort to develop the technology for planning cost-effective and environmentally sound sludge disposal systems.

The environmental dangers of on-land disposal of municipal sludge are discussed and the economics of subsurface injection are developed in some detail. These environmental and economic factors are then incorporated into a dynamic programming model which defines an optimal injection program. This optimization code is used as a screening model to evaluate the relative importance of several input parameters. Finally, the systems analysis techniques of dynamic programming and simulation are applied to an example problem based on conditions at Boulder, Colorado, in order to illustrate a systems approach to planning sludge injection systems.

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Chapter 1

INTRODUCTION

One of the more difficult parts of the overall municipal waste treatment process is the ultimate disposal of sewage sludge. The problem is becoming even more difficult as a result of strict environmental standards and rapid population growth. Municipal sewage sludge is a liquid slurry which contains the solids removed from municipal wastewater. The solids removal is accomplished at the wastewater treatment plant through the processes of primary sedimentation and secondary biological treatment. About 90% of the solids are removed from wastewater in these processes. The solids are then contained in sludge which has a solids concentration of 3 to 8% (Hecht *et al.*, 1975).

This sludge must then be disposed of in an operation which generally has three basic steps: treatment, transport, and ultimate disposal. There are many alternative methods for each of the three steps. Generally the method of final disposal will have a significant effect on the selection of handling and treatment methods. It is, therefore, impossible to consider handling, treatment, and disposal completely independent of one another.

Treatment:

Sludge treatment may be divided into two parts, stabilization and dewatering, either one or both of which may be omitted in certain waste treatment operations.

Stabilization is necessary because of the organic material content of sludge (Hecht and Duvall, 1975). This organic material provides food for microorganisms, many of which are pathogenic. Decomposition of this organic material, therefore, greatly reduces the health hazard posed by these microorganisms. There are many methods of sludge stabilization, the most common of which are the following: (1) anaerobic digestion, (2) aerobic digestion, (3) composting, (4) lagooning, (5) heat treatment, and (6) chemical stabilization.

In order to limit the scope of this discussion, anaerobic digestion will be the only stabilization method described and, unless otherwise specified, anaerobic digestion will be the starting point of all sludge disposal systems under consideration.

Anaerobic digestion is a biological process involving the decomposition of sludge organic material by microorganisms which function in the absence of free oxygen (Hecht and Duvall, 1975). The process occurs in two stages occurring simultaneously. In the first stage, acid forming bacteria break down complex organic compounds into simpler organic acids. In the second stage, methane forming bacteria convert the organic acids to methane gas and carbon dioxide.

The second stage of sludge treatment, dewatering, reduces the volume and moisture content of the sludge, thereby reducing the cost of transportation and final disposal. Common dewatering methods include: (1) sand bed drying, (2) centrifugation, (3) vacuum filtration, (4) filter press, (5) heat drying, and (6) vibration (Hecht and Duvall, 1975). Sand bed drying is the most common dewatering method and is probably the least expensive as well. This method is most popular in small communities, but is also used in many large cities. Almost any final solids content is attainable using this method, depending on the allowable drying time. Vacuum filtration is the most common of the mechanical dewatering methods. In vacuum filtration, chemicals are frequently added to improve sludge dewatering characteristics. The final solids content achieved in this method varies from about 15 to 35%.

Transport:

The more common methods of sludge transport as described in Bauer (1973) include (1) railroad, (2) pipeline, (3) truck, and (4) barging. Pipeline transport of sludge is very economical for long-term projects involving large quantities of sludge. This method is limited to the transport of liquid sludges of solids content less than about 5%. Barging is most common in coastal cities which practice ocean dumping as a final sludge disposal mechanism, but is also practical in areas near inland waterways. Railroads and trucks are capable of transporting sludges of any solids content. Truck transport is the most flexible of all transport systems and is very popular in smaller communities.

Final disposal:

Final disposal methods include: (1) ocean dumping, (2) incineration, (3) dumping in a sanitary landfill or lagoon, (4) land reclamation, and (5) land disposal by surface spreading or subsurface injection. The selection of the final disposal method will depend on economic feasibility, degree of pollution tolerated, and public health protection.

Ocean dumping is an economical method for coastal cities, but it is causing numerous pollution problems and may be banned in the near future. Incineration is also economical, but this method will probably become less popular with increasing fuel costs and stricter air pollution standards. Dumping in sanitary landfills or lagoons may be both economical and environmentally safe for many situations. However, like the first two methods, dumping does not take advantage of the potential of sludge as a reusable resource.

Land disposal methods, including land reclamation, are among the oldest disposal techniques. They involve the reuse of sludge nutrients for various purposes, including land improvement and crop production. These methods are often able to compete economically with other methods simply from a disposal standpoint and offer the additional benefits of recycling nutrients. Since considerable research has indicated that environmental problems associated with land disposal will be negligible with proper system design and operation, it appears that land disposal of sludges is one of the most promising methods for the future.

<u>Subsurface injection</u>:

A continuous subsurface injector has been developed at Colorado State University as an economical and environmentally safe means of disposal and recycling of sewage sludge. This technique has several advantages over other methods (Smith, 1974).

(1) Potential for odors, flies, and other insects is practically eliminated.

(2) Visual aesthetics are improved.

(3) The possibility of runoff pollution is greatly reduced.

(4) Personal contact with sludge is practically eliminated, reducing the chance of transmission of pathogens.

Since 1973, the Agricultural Engineering Department of Colorado State University, in cooperation with the city of Boulder, Colorado, has been operating a subsurface injection system, disposing of approximately one third of the city's sludge. The sludge is injected at a depth of 3 to 6 inches using a modified chisel plow injector pulled by a 44 hp crawler tractor. Injection rates of 800 gpm or 60,000 gal/acre are obtained with this system. The sludge is delivered to the plow through a 4.5 inch, 660 ft flexible hose attached to the injector and is then supplied to outlets behind seven high-lift sweeps. In this way the sludge is thoroughly mixed with soil. The system is capable of injecting sludge at solids content up to 6%. Thus, application rates of 5 dry tons/ac can easily be accomplished in a single trip through the field. A more detailed description of the injection equipment is presented in Gold (1973), Gold, Smith, and Hall (1973), and Smith, McWhorter, and Ward (1975).

At the Boulder site sludge has been injected at rates of up to 50 dry tons/ac. The environmental effects have been extensively studied through a program of soil analysis and monitoring of percolate water and groundwater. The results of these studies are presented in Trout (1975) and Trout, Smith and McWhorter (1975).

An analysis of the costs of subsurface injection is presented in Chapter 3. The economics of subsurface injection may then be compared with economic information for other types of disposal systems. General cost information may be found in Culp, Wesner, and Culp (1974) and Smith and Eilers (1975). Manson and Merrit (1973) and Hyde and Boyle (1973) present the costs of specific disposal systems. An economic analysis of a specific sludge irrigation system is found in Troemper (1974). The actual selection of the disposal method will have to be based upon a combination of engineering, economic, sociological, and legal factors, all of which must be evaluated by the local decision makers.

Problem definition:

Since the technique of subsurface injection is relatively new, there are, as yet, no well-established guidelines for its use. Such guidelines should logically be developed by assimilation and evaluation of the available environmental and economic data concerning subsurface injection. A basis should be provided for comparison of the injection technique to existing disposal methods, and strategies should be introduced for the effective implementation of an injection system.

An implementation plan should present answers to several important questions about the injection system.

(1) What land area will be required for operation of the system and what sites should be acquired in order to satisfy the requirements?

(2) What will be the capital outlay and operation costs of the system?

(3) How should the system be operated in order to result in the least cost and an acceptable level of environmental degradation?

Another important question will provide the basis for answering the first three. What is the optimal injection rate of sludge on each injection site? That is, how much sludge should be injected each year for minimum cost without unacceptable pollution effects? The answer to this question will determine the land area required and the operating requirements directly.

The optimal application rate, however, will depend upon site characteristics, sludge characteristics, and the cropping system used to recycle sludge nutrients. Formulating the implementation plan will, therefore, involve the calculation of the optimal application rate for various potential sites and cropping systems and evaluation of the costs and other characteristics of each.

Objectives:

The basic goal of this project is to synthesize a set of planning guidelines for continuous subsurface injection from existing environmental and economic data. These guidelines would be used throughout the planning process in the comparison of the injection technique with other disposal methods and in the actual design, installation, and operation of the injection system. In support of this goal, the specific objectives were established as follows:

(1) To identify and evaluate the environmental factors which are critical in determining the optimal application rate of sludge.

(2) To prepare detailed cost estimates of the sludge injection process.

(3) To determine a method and formulate a computer code for calculating the optimal application rates, based upon environmental and economic factors.

(4) To perform a sensitivity analysis, operating the computer code over a range of input data.

(5) To indicate those areas where necessary background data are lacking as targets for future research.

(6) To specify general guidelines for using the computer code in preparing implementation plans.

Chapter 2

ENVIRONMENTAL CONSIDERATIONS

Nitrogen:

The nutrient content of sludges gives them considerable value as fertilizer, particularly as a source of nitrogen. As an example of typical sludge makeup, the composition of Boulder and Denver sewage sludges is shown in Table 1. It should be remembered, though, that sludge composition is highly variable from one location to the next. In addition to being a valuable resource, the nitrogen content of sludge presents a pollution problem. Heavy applications of sludge can easily result in the leaching of nitrogen into the groundwater and the subsequent increase in nitrogen content above the drinking water standard of 10 ppm set by the U. S. Public Health Service. According to Dotson (1973), Trout (1975), and other researchers, it is the nitrogen component of sludge that usually first limits its application.

Metals:

Another characteristic of digested sludge that can cause environmental problems is the heavy metals content. Those elements of greatest concern are B, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn. Repeated application of sludge will usually result in concentrations of these elements in the soil which greatly exceed normal concentrations. This can possibly result in toxic effects to plants and to animals which consume those plants. Chaney (1973) presents a comprehensive discussion of the effects of toxic metals on crops and the food chain and presents information for management of disposal systems in order to avoid undesirable effects. The most important management consideration in

Table 1. Composition of Municipal Digested Sewage Sludge

Element[1]	Boulder, East Pearl[2]	Metro Denver[3]
N (total)	3.3	6 to 8
NH_4-N	1.3	3 to 4
P (total)	4.7	3.0
K	0.12	--
Iron	8,700	15,000
Zinc	1,110	3,000
Copper	820	1,600
Titanium	--	1,500
Lead	768	1,083
Barium	--	1,300
Chromium	639	690
Manganese	162	413
Nickel	21	403
Tin	--	180
Cadmium	8.6	20
Molybdenum	--	27
Cobalt	--	67
Arsenic	--	50
Boron	73	--
Mercury	3.2	--
Silver	60	--
Calcium	23,000	--
Magnesium	2,600	--
Sodium	1,100	--
Chlorine	729	--
pH	6.7	
Solids, %	4.3	4.0

[1]First four elements listed are measured in percent of dry weight; other elements listed are measured in ppm.

[2](Trout, 1975)

[3](CH2MHILL, 1973)

relation to heavy metals is the objective of keeping the metals tied up in the soil so that they do not leach into the groundwater and they remain unavailable to plants. The specific factors to consider are the following:

1. The heavy metals content of the sludge. Sludges with high metal content, such as those from heavy industrial areas may be regarded as unsuitable for agricultural application.

2. The soil pH. Metals become more available at a pH below 6.5 - 7.0; therefore, maintaining a high soil pH is desirable. An important consideration is that addition of sludge generally results in a lowering of soil pH, and corrective measures, such as liming, may become necessary.

3. Organic matter content of soil and soil cation exchange capacity. Soils of high cation exchange capacity (CEC) have a greater capacity for binding metallic ions and are thus safer for disposal purposes. Addition of sludge organic matter will increase the CEC of soil, but the added matter will be mineralized over a period of years. The resulting decrease in soil CEC could cause increasing availability of toxic elements already added to the soil.

4. Phosphate content of the amended soil. Sludges generally contain sufficient phosphate, PO_4, to reduce the availability and toxic effects of heavy metals to plants. In some cases, the phosphate itself could have some damaging effects on sensitive crops, but it will usually not be the limiting factor.

5. Crop selection. Crops vary widely in their tolerance of heavy metals, and it may be necessary to select more tolerant crops in the

later years of application as heavy metals accumulation reaches significant levels.

6. Monitoring. Periodic checking of sludge, soil, and plant heavy metals content will provide the most effective safeguard against toxic effects.

It is generally accepted that toxic heavy metals will represent the long-term limitation in the land application of sludge. It will generally be necessary to establish the maximum acceptable levels of heavy metals in the soil and to stop application of sludge when this level is reached for any element. Some recommendations for maximum allowable concentrations are given in Table 2. The soil will remain unacceptable for sludge application at any future time since the removal rates for metals are very low as indicated in Table 3. The length of time sludge could be applied on any one site would vary greatly, depending on the particular sludge. According to CH2MHILL (1973), Denver sludge could be applied at the rate of 10 dry ton/acre for a period of 20 years before any limitations were reached.

Pathogens:

Almost all of the pathogenic organisms found in municipal sewage sludge are destroyed through the anaerobic digestion process. However, in some cases a significant number may survive digestion and enter the soil upon land application. These organisms will create a health hazard only if they survive long enough to move with percolating water into the groundwater, are washed into surface water supplies, or appear on the surface of food crops grown on the soil. Normally no such hazards will exist, because the soil is an effective treatment

Table 2. Heavy Metals Limitations (CH2MHILL, 1973)

Metal	Design Concentration Assumed for Metro (ppm)	Maximum Recommended Concentration Added to Top 12" of Soil (ppm)	Sludge Application Limit (tons)
Arsenic	30	328	21,800
Cadmium	53	8	302
Chromium	690	164	475
Cobalt	67	816	24,400
Copper	1,600	816	1,020
Iron	15,000	3,260	435
Lead	1,083	1,632	3,120
Manganese	413	1,632	7,910
Molybdenum	27	8	640
Nickel	403	328	1,620
Selenium	40	4	200
Zinc	3,100	1,632	1,020

mechanism. Soil filtration properties cause pathogens to be retained near the surface, and the die-off rate is high because the soil environment is a hostile one for pathogenic microorganisms.

In a study of the environmental effects of subsurface injection of municipal sewage sludge, Trout (1975) concluded that "Pathogenic dangers, as indicated by fecal coliforms, will not extend more than 120 to 150 cm into the soil profile, nor last more than 2.5 months near the soil surface." Other researchers have found that pathogenic organisms may survive in soil for only a few hours or as long as several months.

Table 3. Removal of Toxic Elements in Soils (Chaney, 1973)

	Estimated Soil Balance after 100 years of Application of Effluent at 3 ac-ft/ac-yr			
Element	Concentration ppm	Accumulation lb/ac	Crop Removal lb/ac	% of Added
B	0.75	600	10.0	1.7
Cd	0.010	8	0.2	2.5
Co	0.050	40	1.0	2.5
Cu	0.20	160	10.0	6.2
Pb	5.0	4,000	0.05	--
Mo	0.010	8	0.5	6.3
Ni	0.20	160	5.0	3.1
Zn	2.00	1,600	200.0	12.5

Dotson (1973) suggests that percolation of water through unsaturated soil should remove pathogenic organisms. If soil treatment should prove unacceptable, however, pathogens may be destroyed before land disposal by pretreating the sludge in any of several ways. He suggests storing, pasteurizing, adding lime, chlorination, and adding other chemicals.

Salts:

Soluble metallic cations, such as Mg^{++}, Ca^{++}, and Na^{+}, are often present in sludge in large concentrations. Thus, heavy sludge loadings could result in inhibition of crop growth. CH2MHILL (1973) estimates that application of Denver sludge at low rates as a fertilizer would not interfere with crop production. However, yield reductions could become significant at salt concentrations resulting from application of 220 dry tons/acre. Trout (1975) suggests that salinity problems could occur with moderately heavy application of sludge in semi-arid areas. He concludes that salt accumulation is a short-term problem, however, since leaching of salts through the soil profile will prevent long-term buildup.

Salt accumulation is not a problem where large amounts of irrigation water can be applied, since salts are easily leached out of the root zone. Leaching of large amounts of salts could cause an undesirable increase of total dissolved solids (TDS) in groundwater, but from the observations of Trout, it appears that this would generally not be a problem where application rates are in the range of 20 dry tons/acre. At any rate, salt concentration in soils and percolating water is easily monitored and can easily be controlled by regulating sludge applications.

Importance of nitrogen:

Since it appears that nitrogen will be the first limiting factor for sludge application on a yearly basis, nitrogen was selected as the only environmental constraint to be considered directly in determining the optimal application rate of sludge. Other limiting factors, such as heavy metals and salts will have to be considered independently.

The nitrogen cycle:

Assuming that the quantity of applied nitrogen is the immediate limiting factor in the application of sludge to land, it becomes very important to understand the nitrogen cycle, especially the effects of sludge application upon the cycle. Nitrogen occurs in several forms within the soil profile and passes repeatedly through these various forms and through the bodies of living organisms. A most important characteristic of the nitrogen cycle is that it is an open cycle. Nitrogen can be added to the cycle or removed in different ways so that the total quantity of nitrogen within the system (soil and living organisms) is not constant. In a land disposal operation, the addition of nitrogen from sludge overshadows the other sources of nitrogen and becomes the most important. The removal of nitrogen by various mechanisms is then very important in that it will determine the maximum rate at which sludge may be added without causing pollution problems. A brief summary of the various forms, sources, and removal mechanisms of soil nitrogen as discussed by Thompson and Troeh (1973) follows:

Forms of soil nitrogen:

Soil organic matter may contain about 3000 lb/ac of nitrogen per acre in an average furrow slice. Most of this nitrogen is tied up in large complex molecules and is unavailable to plants. Through the process of mineralization about 1% (30 lb/ac) of this nitrogen will become available to plants each year. The quantity of nitrogen mineralized may range up to 100 lb/ac in some soils.

The two principal forms of soil nitrogen which are available to plants are ammonium ions, NH_4^+, and nitrate ions, NO_3^-. Both of these ions are produced through the mineralization of soil organic matter. Ammonium ions are released from decomposing organic materials through the process of ammonification. These ammonium ions are available to plants but are generally held on soil cation exchange sites and consequently are not subject to leaching. The principal form of nitrogen utilized by plants is the nitrate ion. NO_3^- is produced by the oxidation of ammonium ions in the process of nitrification. The nitrate ion is contained within the soil solution and is therefore highly subject to leaching. Both of the processes of ammonification and nitrification are microbial actions and are therefore extremely dependent upon moisture and temperature conditions.

Nitrogen sources:

The principal source of soil nitrogen in unamended soils is the decay of organic materials. Soil organic matter nitrogen then becomes available to plants through the process of mineralization, which has already been discussed.

Atmospheric nitrogen may be combined with another element and added to the soil through the process of nitrogen fixation. Nitrogen may be fixed by lightning and added to the soil in rainfall (generally in small amounts), or it may be fixed by soil microorganisms. Nitrogen fixing bacteria are found in most soils; however, the quantity of nitrogen fixed is usually significant only in soils where legumes are grown.

Nitrogen may also be added in the form of fertilizer. Inorganic nitrogen fertilizers generally add nitrogen in the form of NH_4^+ or NO_3^- which are immediately available to plants. Organic nitrogen fertilizers such as animal manures, green manures, fish, and compost become available to plants through mineralization over a period of time. Sewage sludge may be regarded as both an organic and inorganic nitrogen fertilizer since it contains significant amounts of both NH_4^+ and organic-material nitrogen. A portion of the sludge nitrogen will, therefore, be immediately available to plants, and also subject to leaching, and another portion will become available over a period of years through the process of mineralization.

Nitrogen removal mechanisms:

Nitrogen may be removed from the root zone through erosion, leaching, gaseous losses, and uptake by plants. Plant use represents complete removal only to the extent that the plants are harvested and removed from the field. A portion of this nitrogen will almost always be returned to the system through the decay of roots or other crop residue. Removal of the entire plant, as in harvesting a sod crop, would be the exception.

The gaseous loss of nitrogen occurs largely through the mechanisms of ammonia volatilization and denitrification. Ammonia volatilization is generally not significant since the ammonium ion is readily adsorbed on soil particles or converted to nitrate through nitrification. An exception would be the presence of large amounts of NH_4^+ in sandy soils having low cation exchange capacity and having conditions which do not favor microbial activity. The more important mechanism for gaseous loss of nitrogen is that of denitrification. In this process, anaerobic bacteria in the soil reduce nitrates to a gaseous form such as N_2O, NO, or N_2, which is then lost to the atmosphere. Since this is an anaerobic process, it is normally thought to occur at significant rates only in poorly drained soils or areas of high moisture due to rainfall or irrigation. However, certain researchers investigating sludge nitrogen removal mechanisms in soils, including Ryan, Keeney, and Walsh (1973) and King (1973), have found evidence to the contrary. They suggest that denitrification may often occur at significant rates in well drained soils where aerobic conditions predominate. This phenomenon would be possible because of the presence of anaerobic "pockets" within the predominantly aerobic soil.

The leaching of nitrogen from the soil removes primarily the nitrate form, which is held within the soil solution and is thus highly mobile. Leaching occurs primarily where nitrates are present in excess of crop needs and sufficient moisture is present so that water is moving downward through the soil profile toward the water table. Leaching losses can therefore be minimized by applying nitrogen such that it becomes available at roughly the same rate that it is needed by a growing crop and limiting application of water so that little percolates to the water table. On the other hand, it may sometimes be desirable to apply water in excess of crop needs in order to promote leaching and thus prevent the buildup of nitrates and other salts within the root zone.

Nitrogen is also lost any time that soil is removed from the field be erosion. This mechanism principally affects nitrogen contained in soil organic matter. Nitrogen loss can also occur in surface runoff water and may lead to pollution of surface streams, but this mechanism is generally important only when a nitrogen source such as fertilizer or sludge has been applied to the surface and has not been incorporated into the soil. According to Jackson, Asnussen, Hauser, and White (1973), nitrate is usually low in surface runoff except where considerable runoff occurs.

Nitrogen may be temporarily removed from availability to plants through assimilation by soil microorganisms, or immobilization. Immobilized nitrogen remains in the soil, however, and is eventually returned to the soil organic matter upon the death and decomposition of the microorganisms.

The most important nitrogen removal mechanisms to be considered in designing a subsurface application system are plant removal, nitrate leaching, and denitrification. It is assumed that erosion would be controlled as a normal part of farming practice and conditions favoring ammonia volatilization would not exist in most desirable disposal sites. In fact, researchers have shown that ammonia volatilization losses may be considered insignificant. In laboratory experiments designed to determine the fate of nitrogen in sludge incorporated into soil, Ryan, Keeney, and Walsh (1973) found that ammonia volatilization accounted for less than 1% of the added nitrogen. They stated that losses were probably minimized due to the mixing of sludge with soil. In similar experiments, King (1973) found that gaseous loss of ammonia was only a very small fraction of the total nitrogen loss.

The nitrogen balance:

The nitrogen problem from the standpoint of designing a sludge disposal system is one of determining how much nitrogen may be added to the soil without causing excessive leaching losses. Taking a mass balance approach, the total nitrogen removal from a soil-plant-microorganism system is equal to the total amount of nitrogen added to the system, less the amount added to storage within the system. Several assumptions can be made in order to quantify the mass balance.

(1) Nitrogen is added to the soil only by the application of sludge.

(2) Nitrogen is stored within the soil only in the organic form, (either soil organic matter or sludge organic material).

(3) Nitrogen is removed in significant amounts only by denitrification, leaching, and crop uptake.

These assumptions imply that all of the available form of nitrogen which is not utilized by plants or lost through denitrification will be leached into the groundwater. This assumption becomes valid when sufficient irrigation water is applied to leach salts out of the root zone.

It is therefore possible to predict the leaching loss if the amount of nitrogen applied and the rates of denitrification, crop uptake, and mineralization are known. On the other hand, it is also possible to assume a value of nitrate leached and determine the amount of sludge nitrogen to be applied which would result in that amount of leaching.

This approach is presented by Trout (1974) and is illustrated in the sample calculations in the appendix which are reproduced from his thesis. Obviously this approach depends upon an accurate prediction of the rate of nitrogen removal by the mechanisms of crop uptake and denitrification, as well as the rate of mineralization from unavailable (organic) to available forms.

Plant requirements for nitrogen in relation to specific yield levels are known for most crops, and the amount of nitrogen removed from the system by the crop can be predicted, assuming that crop growth is not severely limited by other factors such as lack of water or other nutrients.

The rate of denitrification is much more difficult to predict, and experimental results indicate considerable variation in this rate. The same difficulties exist in predicting mineralization rates for applied sludge organic-material nitrogen. The results of several experimenters are summarized below.

The data reported by King (1973) indicate a denitrification rate of 22% of the applied nitrogen or 36% of the total available nitrogen after 18 weeks of incubation under laboratory conditions. The experiment involved incorporating sludge in soil at a concentration of 380 ppm total nitrogen (approximately 14 tons/ac). In the same experiment King reports 41% mineralization of the applied organic-material nitrogen after 18 weeks and nearly complete nitrification of the applied NH_4^+ nitrogen in the same period. In another experiment involving an initial total nitrogen concentration of 437 ppm (approximately 16 tons/ac), King (1973) reports an apparent denitrification rate of 15% of the applied nitrogen after 22 weeks of incubation.

In similar laboratory experiments, Ryan, Keeney, and Walsh (1973) report complete nitrification of NH_4^+ nitrogen, mineralization of only 4% of the applied organic-material nitrogen, and no denitrification of available nitrogen after 16 weeks of incubation where the initial nitrogen concentration was 235 ppm total nitrogen (approximately 8 tons/ac). At an initial concentration of 940 ppm total nitrogen (approximately 34 tons/ac), their data indicates that only 54% of the initial NH_4^+ nitrogen was nitrified after 16 weeks, that 25% of the initial sludge organic-material nitrogen was mineralized, and that 24% of the total applied nitrogen or 44% of the available nitrogen was lost through denitrification within the same time period. With an initial concentration of 1880 ppm total nitrogen (approximately 68 tons/ac sludge loading) and the same 16 week study period, they reported observations which indicate nitrification of 25% of the initial NH_4^+ nitrogen, mineralization of 28% of the initial organic-material nitrogen, and denitrification of 38% of the total applied nitrogen or 67% of the total available nitrogen. Other experimenters cited in Trout (1974) have reported similar variations in results.

The range in experimental values of denitrification is from roughly 20% to 60% of available sludge nitrogen in a single growing season with the denitrification rate increasing with increasing sludge application. The reported rate of mineralization of applied organic-material nitrogen ranges from about 5% to 30% in a single growing season with the higher values reported at higher application rates. The reported rates of nitrification vary from 100% at lower nitrogen concentrations to less than 50% at higher concentrations. The nitrification rate is less important in mass balance calculations than the rates of mineralization or denitrification since it simply involves the conversion of nitrogen from one available form (NH_4^+) to another (NO_3^-). Nitrification is of interest, however, in that the nitrate form is highly subject to leaching while the ammonium form is not.

Obviously these results are not conclusive, even for laboratory conditions, and it is likely that there would be considerable variation between laboratory conditions and those which exist in the field, especially with respect to temperature conditions. A great deal of additional research is needed in this area. Sufficient information needs to be obtained so that one may accurately predict the rates of denitrification and mineralization of sludge nitrogen for given average field temperature and moisture conditions over the practical range of sludge application rates.

At the present time, only very rough estimates of the denitrification and mineralization rates can be made. Trout (1974) assumes a gaseous loss rate of 20% of the applied NH_4^+ nitrogen and a mineralization rate of 6% of the applied organic-material nitrogen for the purpose of sample calculations. In a sludge-disposal project study for the city of Denver, Colorado, CH2MHILL (1973) assumes a rate of mineralization of 25% the first year, 5% of the remaining sludge organic-material nitrogen the second year, 4% of the remaining the third year, 2% the fourth year, and 1% the fifth year. They suggest that the effect of mineralization is negligible after the third or fourth year. CH2MHILL also assumes a gaseous loss rate of 25% of the available nitrogen each year.

All of these estimates are probably reasonable in light of the available experimental data, and improved estimates for specific site conditions will surely become available in the future. At present, the best the designer can do is to make reasonable estimates with the assistance of agronomists who are familiar with local conditions and to carefully evaluate the effects of error in his estimates.

Chapter 3

ECONOMICS OF SLUDGE INJECTION

In order to determine the optimal application rate of sludge for a particular injection program, it is necessary to determine the cost of injection as a function of the application rate. It is also necessary to determine the expected return from crop production as a function of the level of fertilizer nitrogen furnished by the sludge. The sum of the cost function and crop return function will represent the net cost of disposal. The application rate which results in the minimum net cost while satisfying the environmental constraints is then selected as the optimum.

The general economic concepts involved are illustrated in Figure 1. The injection cost will decrease with increasing application rate. The return from crop production will increase with increasing application of sludge nitrogen until a maximum is reached and will then decrease.

The sum of the two functions, representing the net injection cost will reach a minimum at some point corresponding to an application rate greater than that for maximum crop production. Finding this minimum is the objective of the optimization process. It must be remembered that in some cases the environmental constraints may limit the application rate before the true minimum cost is reached.

The development of the injection cost and crop return functions must be performed individually for each injection program. The general procedure, however, will be similar for most situations. The method of developing these functions is illustrated in this chapter, using the Boulder, Colorado injection program as an example.

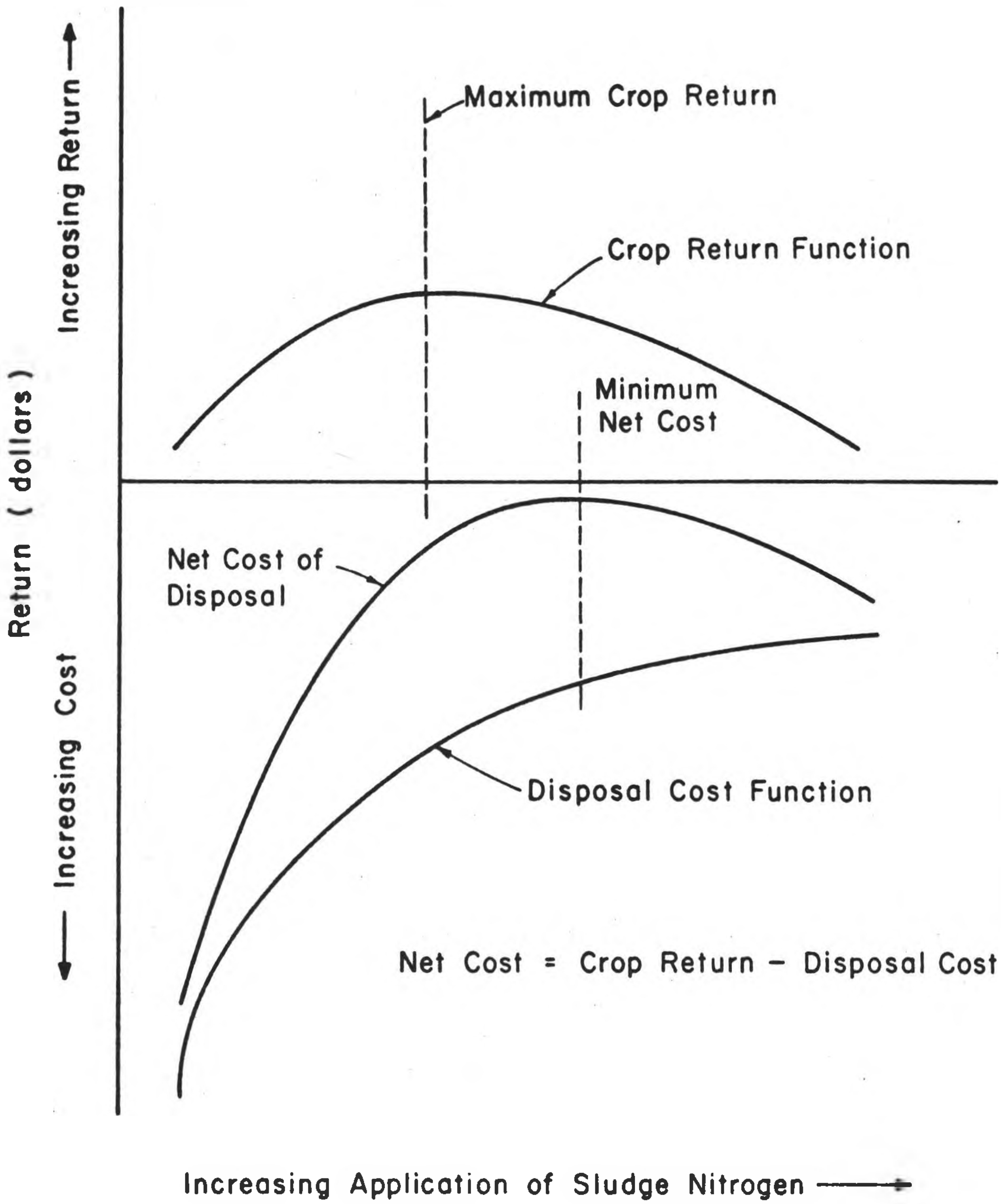

Figure 1. Generalized Disposal Cost and Crop Return Functions.

<u>The crop return function</u>:

In many cases, it will be possible to obtain crop response curves of the form necessary for input into the dynamic programming model directly from the literature, the most comprehensive source being Ibach and Adams (1968). However, it will often be necessary to estimate these curves, particularly in the range of applications of nitrogen greater than the optimal rate. The general shape of the crop return curve is indicated in Figure 2. Curves may be extrapolated to conform to this general shape, but the results must be regarded as highly inaccurate. In any case, local agronomists or agricultural extension personnel, who are familiar with cropping systems and fertilizer requirements for the particular region, should be consulted in the collection and application of crop response information. In this way, such data can be modified to reflect field conditions as accurately as possible.

For the Boulder area, the profit expected from crop production as a function of fertilizer nitrogen supplied by sludge is calculated for both corn and wheat, based upon data from Ibach and Adams (1968). For purposes of these calculations, it is assumed that the costs of crop production are $50 per acre for dryland wheat and $150 per acre for irrigated corn (excluding land costs). Cash prices are assumed to be $4.00 per bushel for wheat and $20.00 per ton for corn silage.

The crop response curves used are shown in Figures 3 and 4, and the calculated returns are presented in Tables 4 and 5. From the standpoint of maximizing nitrogen removal, it is generally more desirable to harvest corn as silage rather than producing a grain

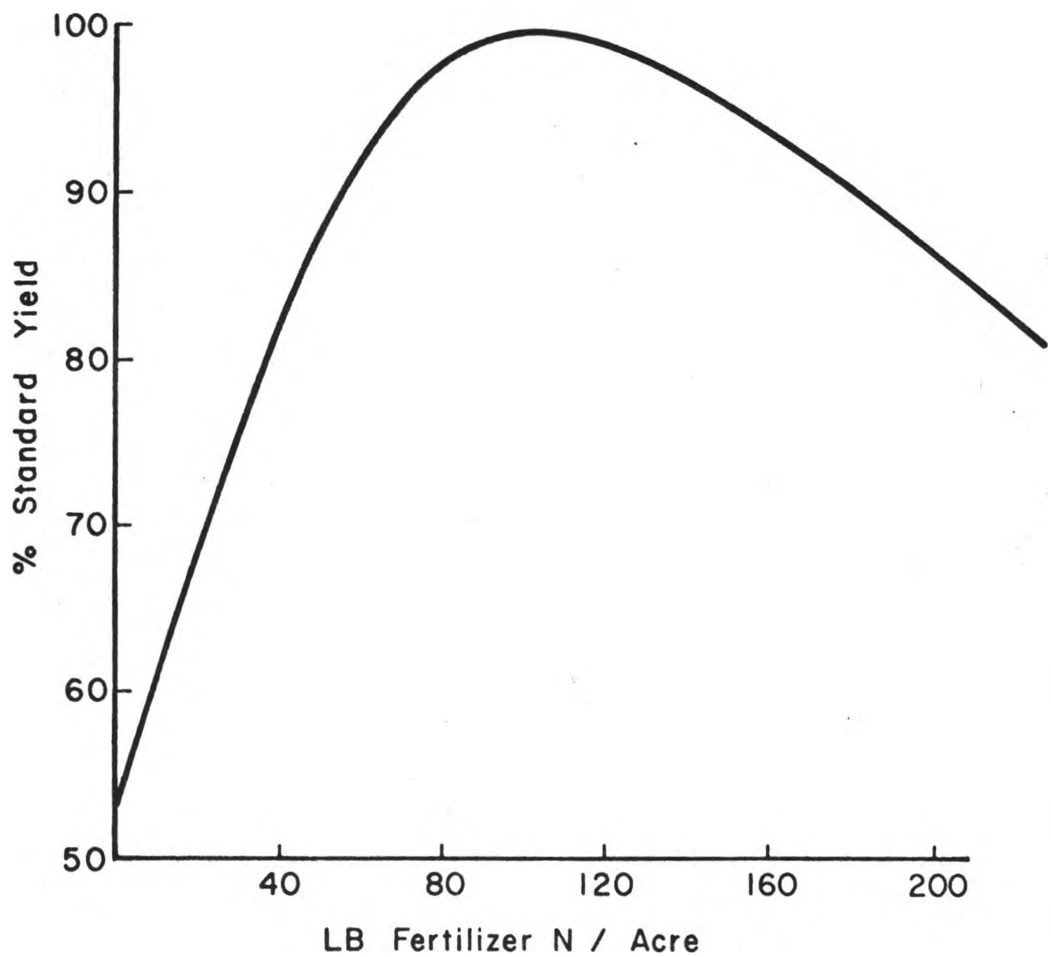

Figure 2. Yield Response of Wheat to Nitrogen Fertilization.

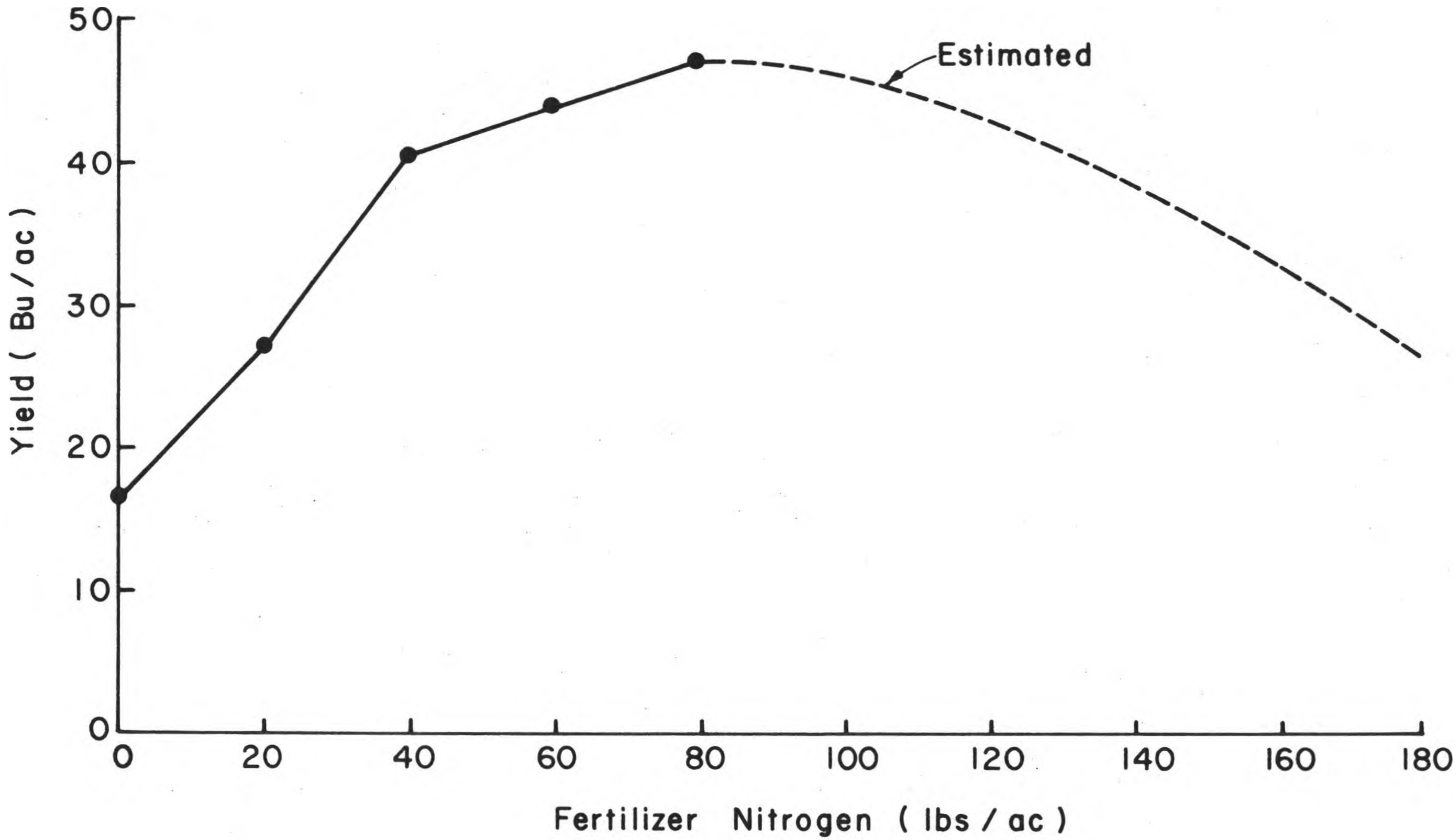

Figure 3. Yield Response of Wheat to Nitrogen Fertilization (Colorado).

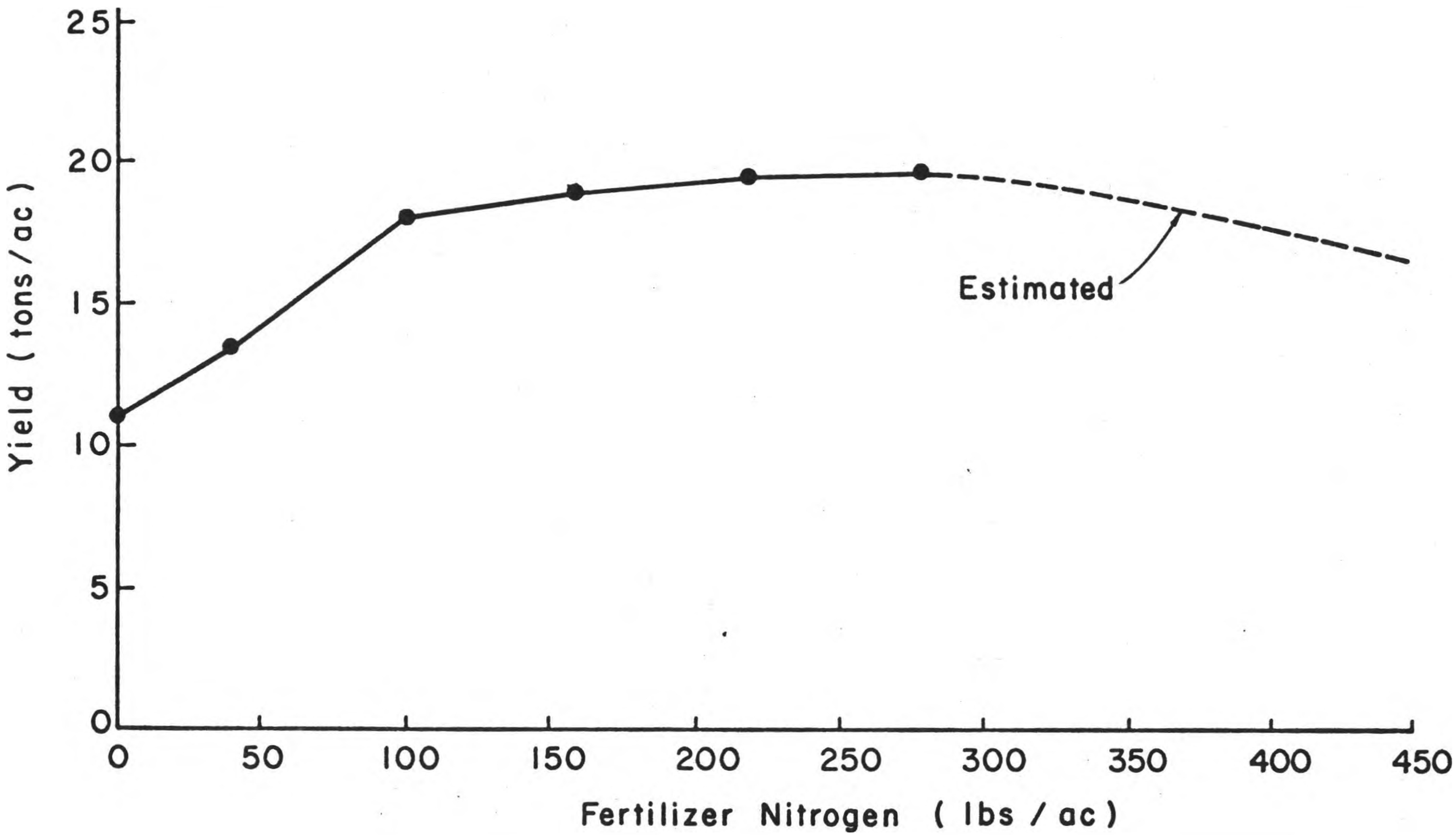

Figure 4. Yield Response of Corn Silage to Nitrogen Fertilization (Colorado).

Table 4. Crop Response of Corn Silage (Irrigated)

Fertilizer N (lbs/ac)	Yield (T/ac)	Return* ($/ac)	Net Return ($/ac)
0	11.2	244	74
25	12.7	254	104
50	14.1	282	132
75	16.2	324	174
100	18.2	324	214
125	18.6	372	222
150	18.9	378	228
175	19.1	382	232
200	19.2	384	234
225	19.5	390	240
250	19.6	392	242
275	19.7	394	244
300	19.5	390	240
325	19.0	380	230
350	18.6	372	222
375	18.0	360	210
400	17.5	350	200
425	17.0	340	190
450	16.5	330	180

*Based on cash price of $20/ton; cost of crop production of $150/acre.

Table 5. Response of Wheat to Nitrogen Fertilizer (Dryland)

Fertilizer N (lbs/ac)	Yield (bu/ac)	Return* ($/ac)	Net Return ($/ac)
0	16.5	66.00	16.00
20	27.8	111.20	61.20
40	40.6	162.40	112.40
60	44.0	176.00	126.00
80	47.0	188.00	138.00
100	45.2	180.80	130.80
120	43.0	172.00	122.00
140	39.0	156.00	116.00
160	33.0	132.00	82.00
180	26.0	104.00	54.00
200	20.0	80.00	30.00
220	15.0	60.00	10.00

*Based on cash price of $4.00/bu; cost of crop production of $50/acre.

crop. The calculation of the return for a corn grain crop would be performed in exactly the same way.

<u>The injection cost function</u>:

The layout of the Boulder injection operation is shown in Figure 5 and the estimated capital costs and given conditions of the system are presented in Table 6.

The estimated initial costs and economic lives of the various components of the injection system were obtained from the City of Boulder, sanitary engineering department (Smith, 1975). These initial costs were multiplied by the appropriate capital recovery factor (obtained from Grant and Ireson, 1970) for specified life at an interest rate of 7% to obtain the equivalent annual costs. The analysis ignores the effect of inflation and assumes replacement of each component at the initial cost.

The Boulder system is designed to handle 3,000 to 4,000 tons (dry basis) of sludge per year. However, capital costs (excluding land and additional piping) would remain roughly the same for a system of up to 10,000 tons/yr capacity, since a single tractor and injection plow would be sufficient for systems of that size. Larger systems would require the use of more than one injector.

The operating costs of the system were estimated from data presented by Houck (1974) as $14.40 per dry ton of sludge injected. This operating costs includes the cost of transporting sludge from the treatment plant to the site and the cost of injection.

The development of the actual injection cost function of the form shown in Figure 1 is presented in Table 7. For a first approximation of application rates and land area required, it is assumed that land

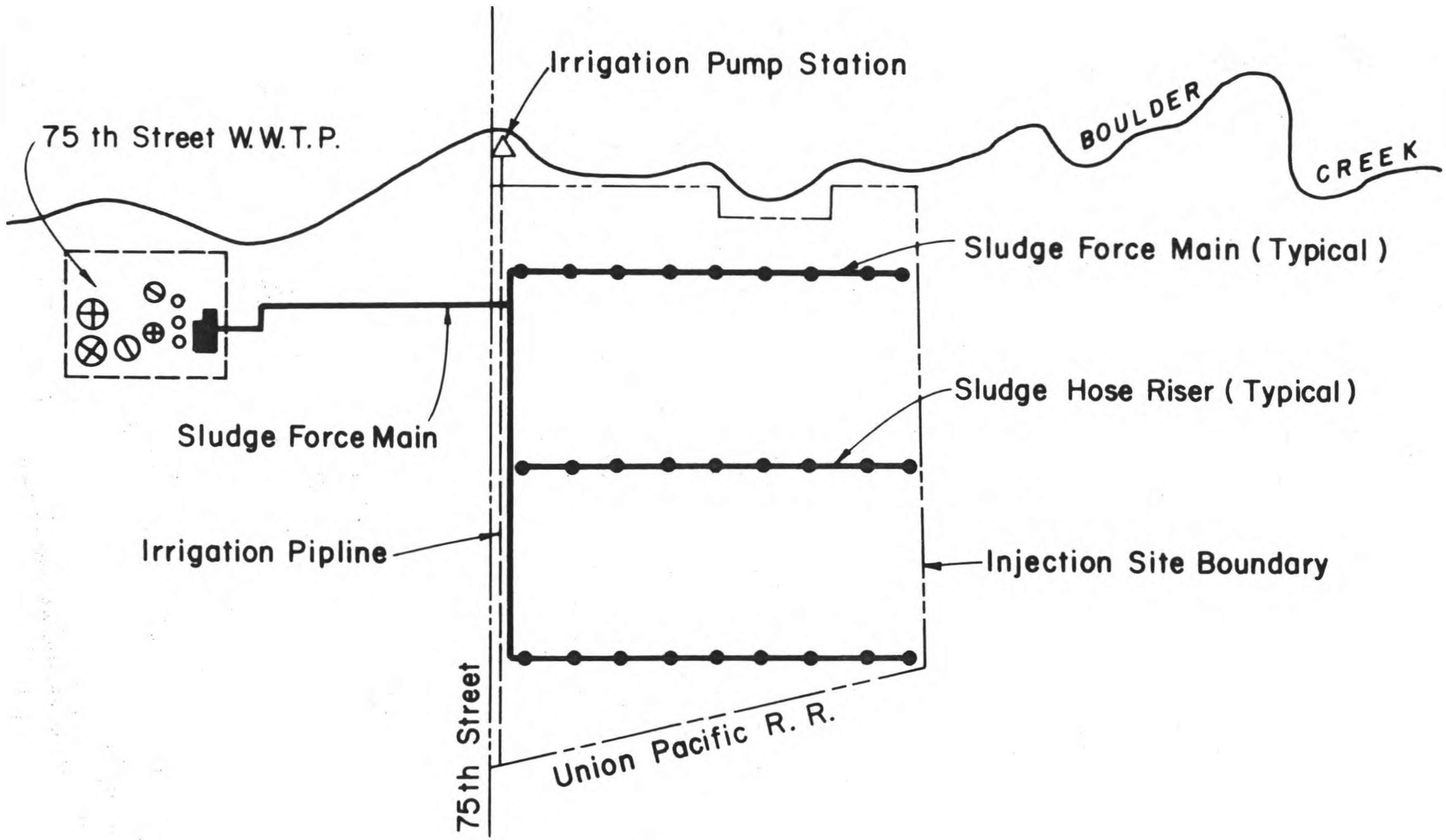

Figure 5. Proposed Sludge Injection System for the 75th Street W.W.T.P., Boulder, Colorado.

Table 6. Estimated Capital and Operating Costs for Sludge Injection at Boulder, Colorado*

System Component	Initial Cost	Economic Life (yrs)	Capital Recovery Factor (i = 7%)	Annual Cost
Sludge pump	$ 24,000	15	0.10979	$ 2,635
Tractor	40,000	10	0.14238	5,695
Hoses (2)	7,000	3	0.38105	2,667
Plow	6,000	10	0.14238	854
Piping to site (6 in. @$15/ft)	22,500	30	0.08059	1,813
Valves	4,000	15	0.10979	439
Access roads	56,000	30	0.08059	4,513
Monitoring equipment	10,000	5	0.24389	2,439
Interceptor drain	15,000	30	0.08059	1,208
Totals	$194,500			$22,263

Operating Cost = $14.40/ton x 3270T = $47,000

Total cost = 69,263

Total cost per ton = 21.18

*Design capacity = 3270 tons/year (dry basis)

Table 7. Injection Costs as a Function of Application Rate*

Injection Rate (tons/acre)	Total Cost (from Table 4) ($/ton-yr)	Land Area Required (ac)	Annual Cost of Land ($/ton-yr)	Annual Cost of Piping ($/ton-yr)	Total Cost ($/ton-yr)
2	21.18	2,043	109.33	38.74	169.25
3	"	1,362	72.89	25.82	119.89
4	"	1,022	54.69	19.38	95.25
5	"	818	43.78	15.51	80.47
6	"	681	36.44	12.91	70.53
7	"	584	31.25	11.10	63.53
8	"	511	27.35	9.69	58.22
9	"	454	24.30	8.61	54.09
10	"	404	21.89	7.75	50.82
11	"	372	19.91	7.05	48.14
12	"	341	18.25	6.47	45.90
13	"	314	16.86	5.95	43.93
14	"	292	15.63	5.54	43.35
15	"	273	14.61	5.18	40.97
16	"	255	13.64	4.83	39.65
17	"	240	12.84	4.55	38.57
18	"	227	12.15	4.30	37.63
19	"	215	11.51	4.08	36.77
20	"	204	10.92	3.87	35.97
21	"	194	10.38	3.68	35.24
22	"	186	9.95	3.53	34.66
23	"	177	9.47	3.36	34.01
24	"	170	9.10	3.22	33.50
25	"	163	8.72	3.09	32.99

*System capacity = 3270 ton/yr
Land cost = $2,500/ac : $175/ac-yr
Piping cost = $15/ft : $ 62/ac-yr

will be available in any amount at uniform cost. It is also assumed that operating costs will be constant over the range of injection rates under consideration and that the cost of distribution piping for the system is constant on a per-acre basis. In reality the piping costs are incremented for each 16.5 acres of land used, since a single center pivot will service 16.5 acres with the 660 ft hose attached. Each 16.5 acre plot must, therefore, have a center pivot outlet and be connected to the next by 848 ft of distribution piping. Using these assumptions the cost function is calculated initially by adding the costs of land and distribution piping required for discrete values of the injection rate to the constant portion of the capital and operation costs of the system.

The annual cost of distribution piping on a per-acre basis is calculated using a cost of \$15 per foot (including valves) for 6 in piping, a 30-year life, and an interest rate of 7%. For a 16.5 acre plot:

$$\text{Piping cost} = \frac{(848 \text{ ft of pipe})(\$15/\text{ft})}{16.5 \text{ ac}}$$

$$= \$770/\text{ac}$$

$$\text{Annual cost of pipe} = (\text{total cost})(\text{capital recovery factor})$$

$$= (\$770/\text{ac})(0.08059)$$

$$= \$62/\text{ac}$$

The land costs anticipated by the City of Boulder are \$2,500 per acre. Since it can be assumed that land values will not depreciate, the annual cost of land may be regarded as merely the interest on the initial investment. Using an interest rate of 7%

Annual cost of land = ($2,500/ac)(0.07)

= $175.00/ac

The rows of Table 7 are developed as shown in the following example. For an injection rate of 5 tons/ac, the capital plus operating cost, excluding land and distribution piping, is $21.18 per ton, as developed in Table 6. The land area required for injection is equal to the quantity of sludge to be injected divided by the injection rate.

$$\text{Area required} = \frac{3270 \text{ tons}}{5 \text{ tons/ac}}$$

$$= 654 \text{ ac}$$

Including a safety margin of 25%,

Area required = (654 ac)(1.25)

= 818 ac

Annual cost of the land = (818 ac)($175/ac-yr)

= $143,150/yr

$$\text{Land cost per ton of sludge} = \frac{\$143{,}150/\text{yr}}{3270 \text{ tons}}$$

$$= \$43.77/\text{ton}$$

$$\text{Cost of distribution piping} = \frac{(818 \text{ ac})(\$62/\text{ac-yr})}{3270 \text{ tons}}$$

$$= \$15.51/\text{ton}$$

Total cost = (Cost from Table 6) + (Land Cost) + Distribution Piping Cost)

= ($21.18 + $3.77 + $15.51)/ton

= $80.47/ton

The cost function is developed in this manner over the entire range of injection rates under consideration.

A more realistic cost function may be developed for illustrative purposes by considering land to be purchased in adjacent, 40-acre plots. The land actually used for disposal of the sludge will be divided into 16.5 acre plots and each plot developed as needed to dispose of the sludge. To account for the fact that distribution piping costs will be incremented every 16.5 acres, the piping costs are calculated as shown below.

For each 16.5 acres of land used,

$$\text{Piping cost per plot} = \frac{(848\ \text{ft})(\$15/\text{ft})(0.08059)}{3270\ \text{tons/yr}}$$

$$= \$0.3135/\text{ton}$$

Therefore, the total cost of distribution piping =

(Number of 16.5 acre plots required)($0.3135/ton)

For example, if 240 acres of land were required for disposal, this would correspond to 13 plots of 16.5 acres (204/16.5), and the distribution piping cost would be (13)($0.3135/ton) or $4.07/ton. In these calculations, it is important to use the amount of land required (204 ac) for injection, rather than the amount purchased (240 ac). A cost function based on amount of land purchased is presented in Table 8.

The crop return data can be expressed in dollars per ton of sludge injected by dividing the net return by the application rate

$$(\text{Return }(\frac{\$}{\text{acre}})/\text{Application Rate }(\frac{\text{tons}}{\text{acre}}) = \text{Return }(\frac{\$}{\text{ton}})$$

This calculation permits a quantitative expression of Figure 1, as is illustrated in Figure 6, using the Boulder data. The data for Figure 6 are developed in Table 9.

Table 8. Injection Cost Function for Land Available in 40-acre Plots*

Injection Rate (tons/acre)	Total Cost (from Table 4) ($/ton-yr)	Land Area Required (acres)	Land Area Purchased (acres)	Annual Cost of Land ($/ton-yr)	Annual Cost of Pipe ($/ton-yr)	Total Cost ($/ton-yr)
2	21.18	2,043	2,080	111.31	38.87	171.36
3	"	1,362	1,400	74.92	26.02	122.12
4	"	1,022	1,040	55.65	19.43	96.23
5	"	818	840	44.95	15.68	81.81
6	"	681	680	36.39	13.17	70.74
7	"	584	600	32.11	11.29	64.58
8	"	511	520	27.83	9.72	58.73
9	"	454	480	25.69	8.78	55.65
10	"	409	440	23.55	7.84	52.57
11	"	372	400	21.41	7.21	49.80
12	"	341	360	19.27	6.58	47.03
13	"	314	320	17.13	5.97	44.28
14	"	292	320	17.13	5.64	43.95
15	"	273	280	14.98	5.33	41.49
16	"	255	280	14.98	5.02	41.18
17	"	240	240	12.84	4.70	38.72
18	"	227	240	12.84	4.38	38.40
19	"	215	240	12.84	4.38	38.40
20	"	204	240	12.84	4.07	38.06
21	"	194	200	10.70	3.76	35.64
22	"	186	200	10.70	3.76	35.64
23	"	177	200	10.70	3.45	35.33
24	"	170	200	10.70	3.45	35.33
25	"	163	200	10.70	3.13	35.01

*System capacity = 3270 tons/yr
Land cost = $2,500/ac : $175/ac-yr
Piping cost = $15/ft : $62/ac-yr

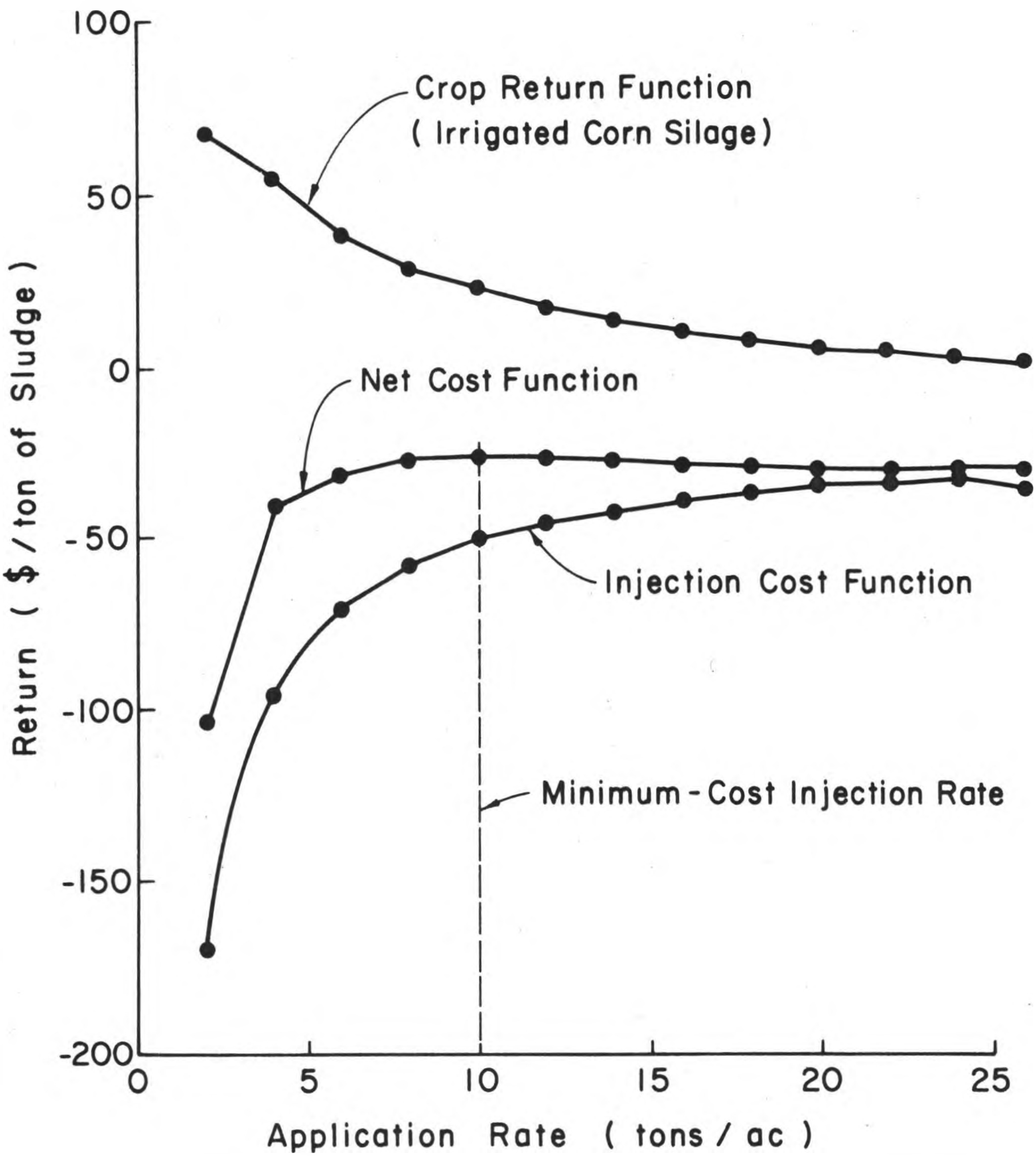

Figure 6. Estimated Cost and Return Functions for Boulder, Colorado.

Table 9. Estimated Crop Return and Net Disposal Costs for Sludge Injection at Boulder, Colorado.

Application Rate (tons/ac)	Fertilizer N Supplied[1] (lbs/ac)	Yield--Corn Silage (from Table 1) (tons/ac)	Crop Return[2] (from Table 1) ($/ac)	Crop Return[3] ($/ton of sludge)	Injection Cost (from Table 7) ($/ton of sludge)	Net Disposal Cost[4] ($/ton of sludge)
2	60	14.2	134	67.00	169.25	102.25
4	120	18.4	218	54.50	95.25	40.75
6	180	19.1	232	38.67	70.53	31.86
8	240	19.4	238	29.75	58.22	28.47
10	300	19.4	238	23.80	50.82	27.02
12	360	18.3	216	18.00	45.90	27.90
14	420	17.2	194	13.86	42.35	28.49
16	480	16.0	170	10.63	39.65	29.02
18	540	14.8	146	8.11	37.63	29.52
20	600	13.6	122	5.55	35.97	30.42
22	660	12.4	98	4.45	34.66	30.21
24	720	11.2	75	3.08	33.50	30.42
26	780	10.0	50	1.92		

[1]Based on sludge composition of 1.5% available N.

[2]Based on cash price of $20/ton; cost of crop production of $150/ac

[3]Return ($/ac)/application rate (tons/ac) = Return ($/ton)

[4]Net disposal cost = injection cost - crop return.

Use of cost and crop return functions:

Based upon the above cost function and the crop return functions, the dynamic programming model will approximate the optimal application rates and land area required by the system. This information can then be used as a rough guide for the study of land availability and costs. After it is known what parcels of land can be acquired by the community and their actual cost, a second injection cost function can be constructed. The new cost function will accurately reflect the land costs and will include the exact cost of transportation and distribution piping which would be required for given ranges of the injection rate. Subsequent runs of the dynamic programming model will then determine which parcels of land which should actually be acquired, as well as the actual optimal injection rate on those parcels. Several computer runs may be necessary to accomplish this task, depending upon the number of parcels of land under consideration.

Chapter 4

THE DYNAMIC PROGRAMMING CODE

The basic question underlying the planning objectives outlined in Chapter 1 is that of how much sludge should be applied on a particular site. To answer this question, a mathematical model was devised which integrates the environmental and economic factors relating to the injection system. The problem formulation, model construction, and dynamic programming solution are discussed in this section.

Problem definition:

In order to formulate a computer code to calculate optimal application rates of sludge on a site, it was necessary to define a specific problem which could be easily solved and was yet general enough to apply to most sludge injection situations. The problem is defined as follows. Given:

(1) Unlimited amount of land suitable for injection and specified annual cost.

(2) Estimated cost of injection as a function of application rate.

(3) Estimated return from crop as a function of sludge nitrogen available as fertilizer.

(4) The number of years sludge is to be injected on any one site--based on heavy metals limitations, etc.

(5) Specific maximum quantity of nitrogen leaching into the groundwater.

Determine:

(1) Optimal application rate of sludge for each year of operation.

(2) Average cost of injection on a per ton basis.

The amount of land required for any year is then simply the total quantity of sludge to be disposed of divided by the injection rate.

Since this is obviously an optimization problem, it would seem logical to use some technique of systems analysis to attempt to solve it. Systems analysis has been widely applied in the field of water resources and environmental engineering, but there have been very few attempts to apply these techniques to problems of sludge disposal. White and Hamdy (1972) suggest the use of linear programming to formulate a cost-minimization model to evaluate alternative equipment and processes in sludge disposal. Sietz and Swanson (1973) also suggest the use of a cost-minimization model in the sludge disposal problem and discuss the use of a simulation model in a land reclamation type sludge disposal project.

A computer analysis which compares the costs of many different disposal systems is discussed by Smith and Eilers (1975). However, there do not seem to be any cost-minimization models related to a specific sludge disposal system in operation as yet.

The sludge disposal problem may be conceptually viewed as a sequential decision problem. This type of problem has a special structure that lends itself to solution by dynamic programming. The form of a sequential decision problem is illustrated in Figure 7.

Some of the special characteristics of a sequential decision problem indicated by the figure are presented in Dracup, Budhraha, and Grant (1972).

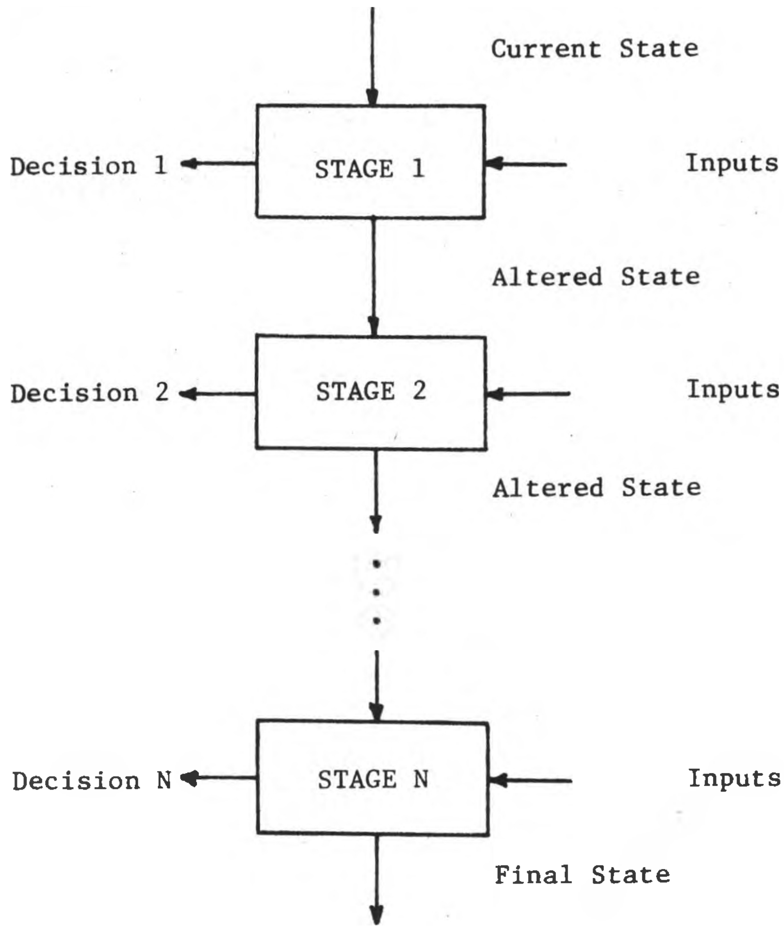

Figure 7. Illustration of Sequential Decision Problems.

(1) The problem can be divided into stages with a policy decision required at each stage.

(2) Each stage has one or more states associated with it.

(3) The effect of the policy decision at each stage is to transform the current state into a problem associated with the next stage.

The purpose of dynamic programming is to find the optimal decision at each stage such that the cumulative effect of all the decisions result in an optimal operating policy (i.e., minimum cost, maximum profit, etc.). In the sludge injection problem the decision at each stage corresponds to the application rate of sludge in each year of operation. The states are described by the nitrogen balance in the soil, as discussed in Chapter 3. The optimal operating policy is the one resulting in the minimum total cost of injection over all the years of operation.

Problem solution:

The problem of finding the optimal application rate of sludge for each year of operation may be placed in the general format for sequential decision problems and may then be solved by dynamic programming. The use of the technique of dynamic programming (as opposed to other systems analysis techniques, such as linear programming) has many advantages. It is quite simple, highly efficient computationally, and it eliminates any problems which might be associated with nonlinear relationships between the system parameters.

The general format for sequential decision problems is:

$$\text{(1)} \qquad \underset{u_i,\, x_i}{\text{maximize}} \sum_{i=1}^{N} f_i\,(x_i,\, u_i)$$

$$\text{(2)} \quad \text{s.t.} \qquad x_1 = C \quad \text{(given)}$$

$$\text{(3)} \qquad x_{i+1} = g_i(x_i,\, u_i)$$

$$\text{(4)} \qquad x_{i+1} \in X_{i+1}$$

$$\text{(5)} \qquad u_i \in U_i$$

$$\text{(6)} \qquad \underline{h}_i\,(x_i,\, u_i) \leq 0$$

$$(i = 1,\ldots,N)$$

where i is the stage

N is the number of stages

x_i is the state variable

u_i is the decision variable

$x_{i+1} = g_i(x_i,\, u_i)$ is the state equation

$\underline{h}_i(x_i,u_i)\leq 0$ is a set of control constraints.

In a sequential decision problem, one wishes to maximize an objective function over a number of stages, subject to a number of constraints. The objective at each stage, i, is a function of a state variable, x_i, and a decision variable, u_i. The constraints for a sequential decision problem in the general format are such that x_1 is given (initial condition), the state variable at each succeeding stage, x_{i+1}, is a function of the state variable and decision variable of the previous stage (state equation), each x_{i+1} and u_i is contained in specified sets, X_{i+1} and U_i, respectively, and certain other analytical relationships exist between each x_i and u_i (control constraints).

For the sludge injection problem, the decision variable becomes the injection rate of sludge (dry tons/acre). The state variable may be chosen as the quantity of sludge organic-material nitrogen which is present in the soil at the beginning of stage (year) i. The problem may be placed in the general format as follows:

(1) Minimize $\sum_{i=1}^{N}$ (cost of injection for year i)

(2) s.t. x_1 is given

(Usually x_1 will be 0 since no sludge has been applied).

(3) The quantity of sludge organic-material nitrogen at each succeeding stage, x_{i+1}, will be a function of the sludge organic-material nitrogen present at the previous stage, x_i, and the amount of sludge applied during that stage, u_i.

(4) There are limits on the level of sludge organic-material nitrogen which should be present at each stage.

(5) There are minimum and maximum allowable application rates.

(6) A control constraint limits the allowable application of sludge in relation to the amount of sludge organic-material nitrogen present so that the quantity of nitrogen which is leached into the groundwater will be within acceptable limits.

A Fortran IV optimization model was written for the solution of this problem using the CDC 6400 computer. The model is based on DPCON, a generalized dynamic programming code prepared by J.W. Labadie, Assistant Professor of Civil Engineering, Colorado State University. The program calculates the application rate of sludge for each year of operation which results in the least total cost while satisfying the constraints.

The required inputs to the program include (1) a yield-response curve which presents the expected profit in dollars per acre from crops produced on the injection site as a function of available nitrogen present, (2) an injection cost curve which presents the total cost of injection (including transport, injection, and land acquisition) as a function of the injection rate, and (3) a number of parameters which relate to the nitrogen balance for the particular site. The profit and cost curves are read in as discrete points using subscripted variables.

Specifically, the program variables are as follows:

NITROGEN BALANCE

Variable Name	Description
AMFR	Fraction of sludge solids composed of ammonium nitrogen
OMFR	Fraction of sludge solids composed of organic-material nitrogen
RMN1	Rate of mineralization of organic-material nitrogen in the first year after application
RMN2	Rate of mineralization of organic-material nitrogen in succeeding years (assumed constant for all years after first year)
RLOSS	Nitrogen loss rate--fraction of available sludge nitrogen which will be lost each year by denitrification or ammonia volatilization
EFF	Crop uptake efficiency--percentage of available nitrogen present which will be utilized by the crop
ALLOW	Allowable rate of nitrate leaching, lb/ac-yr
SNA	Quantity of nitrogen which becomes available to plants each year from mineralization in unamended soil, lb/ac-yr
BNIT	Fraction of available nitrogen which leaches out during fallow years

OTHER INPUT VARIABLES

Variable Name	Description
ILAST	Number of stages (years of operation) being considered
M1	Number of data points read in from profit curve
N1	Number of data points read in from cost curve
Y(M)	Profit from crop yield associated with the M th data point (M th level of available nitrogen), dollars/bu
C(N)	Cost of injection associated with the N th data point (N th level of sludge application), dollars/ton
KROP(I)	Cropping system indicator variable
DELX	Discretization interval for X, the state variable
DELU	Discretization interval for U, the decision variable
DELN	Discretization interval for the level of available sludge nitrogen
XMIN	Minimum level of sludge organic-material nitrogen in the soil, lb/ac
XMAX	Maximum level of sludge organic-material nitrogen in the soil, lb/ac
UMIN(I)	Minimum application rate of sludge in dry tons/acre
UMAX(I)	Maximum application rate of sludge for each stage, I, in dry tons/acre
SMIN	Minimum value of total soil nitrogen available--minimum abscissa of the crop response curve, lb/ac

OPERATIONAL PROGRAM VARIABLES

Variable Name	Description
I	Stage (year of operation)
X	State variable--quantity of sludge organic-material nitrogen present in the soil, lb/ac
U	Decision variable--sludge application rate, dry tons/acre-year

OPERATIONAL PROGRAM VARIABLES (Continued)

Variable Name	Description
USTAR(I,J)	Optimal application rate for each stage, I, and level of the state variable, J
J	Integer associated with a particular value of the state variable, X
M	Integer value associated with the level of available nitrogen present in the soil
N	Integer associated with a particular value of the decision variable, U
R	Quantity of available nitrogen which is retained in the soil after a fallow year, lb/ac
G	Value of the state variable at stage I+1 -- amount of sludge organic-material nitrogen which will be present at the beginning of the next year, lb/ac
L	Integer value associated with G
FOPT	Temporary value of the optimal return function (minimum total cost of injection)
TCF	Total cost of injection for a particular year, injection rate, and value of the state variable, $/ton
UOPT	The value of the decision variable which will result in the least cost of injection (FOPT)
FMIN(J)	Final value of the optimal return function associated with a given value of the state variable
PROFIT	Same as Y(M)
COST	Same as C(N)
SLGNA	Quantity of sludge nitrogen which becomes available to plants during a year, lb/ac
ALOSS	Quantity of nitrogen removed during a year through gaseous losses, lb/ac
CUSE	Quantity of nitrogen used by the growing crop during a year, lb/ac
BLEACH	Quantity of nitrogen available for leaching into the groundwater during a year, lb/ac

Nitrogen balance:

An important feature of the program is the nitrogen balance, contained in five Fortran statements. For each stage, i, the value of the state variable, x_{i+1} or G, is a function only of the present value of the state variable, x_i, and of the decision variable, u_i. In this case G is the sum of the organic material nitrogen added in stage i plus the unmineralized fraction of the stored organic nitrogen. The organic material nitrogen added is given by (U, $\frac{\text{tons}}{\text{ac}}$) (OMFR)(2000, lb/ton) and the unmineralized fraction is (U, $\frac{\text{tons}}{\text{ac}}$) (OMFR)(1.-RMN1)(2000 lb/ton). The unmineralized residual organic nitrogen is (X, lb/ac)(1.-RMN2). Therefore G is given by the following expression:

(G, lb/ac) = (U, tons/ac)(OMFR)(1.-RMN1)(2000, lb/ton) +
+(X, lb/ac)(1.-RMN2).

Fortunately, it is now possible to obtain U as an explicit function of X and G as follows:

(U, tons/ac) = ((G, lb/ac) - (X, lb/ac)(1.-RMN2))/
((OMFR)(1.-RMN1)(2000, lb/ton)) .

This equation is the first Fortran statement of the nitrogen balance.

The second statement computes SLGNA, the amount of sludge nitrogen to become available to plants during the year. This available sludge nitrogen will be supplied from three sources: the ammonium nitrogen fraction of sludge applied during the year, the mineralized fraction of the sludge organic-material nitrogen applied during the year, and the mineralized fraction of the sludge organic-material nitrogen left in the soil from previous sludge applications. Therefore:

(SLGNA, lb/ac) = ((U, tons/ac)(AMFR) + U, ton/ac)(OMFR)(RMN1))

(2000, lb/ton) + (X, lb/ac)(RMN2) .

Next, the gaseous loss of sludge nitrogen, ALOSS, is calculated as a fraction of the available sludge nitrogen, (ALOSS, lb/ac) = (RLOSS)(SLGNA, lb/ac). Crop uptake of nitrogen is calculated as a fraction of the total available nitrogen minus losses, (CUSE, lb/ac) = (EFF)((SLGNA, lb/ac) + (SNA, lb/ac) - (ALOSS, lb/ac)). Finally the amount of nitrogen which can leach into the groundwater is assumed to be the difference between the nitrogen present in available forms and that removed by plants and gaseous losses, (BLEACH, lb/ac) = (SNA, lb/ac) + (SLGNA, lb/ac) - (ALOSS, lb/ac) - (CUSE, lb/ac).

Several important assumptions have been made in order to facilitate these simple calculations.

(1) Mineralization will occur at a rate which can be determined and reasonably approximated by the input rate RMN1 for the first year and the constant rate RMN2 for succeeding years.

(2) The gaseous loss rate, RLOSS, can be approximated and will remain reasonably constant from year to year.

(3) Crop removal efficiency will remain reasonably constant with the amount of available nitrogen and will not vary significantly from year to year.

(4) During each year of crop production, all of the nitrogen which is not removed by crop uptake or gaseous losses will leach into the groundwater. There will be no storage of available nitrogen within the soil profile except in years when no crop is produced.

The present knowledge of the behavior of sludge nitrogen in soils is limited to the extent that any computations based on the above assumptions can be expected to give only a very rough approximation at best. Therefore, estimates of the input parameters such as RLOSS, RMN1, RMN2, and EFF should be made conservatively, and the consequences of error in these estimates should be carefully considered. It is assumed that increasing knowledge in the field of sludge nitrogen removal mechanisms will lead to greater confidence in the accuracy of such nitrogen balance calculations.

Program Operation:

The operation of the dynamic programming code is relatively simple. The calculations begin at the last stage, ILAST. The state variable for this stage, x_i, and the state variable for the next stage, G, are each initialized at their minimum value, XMIN. The nitrogen model then computes the corresponding values of SLGNA, ALOSS, CUSE, and BLEACH. The total cost of disposal for the current stage may then be determined since the cost of application is a function of U, and the profit from crops produced is a function of SLGNA. The value of G is then incremented and the process is repeated. The optimal decision, USTAR, is selected as the application rate which results in the lowest cost for a particular value of X, and the value of the optimal return function is this lowest cost. The optimal decision, USTAR, and the value of the optimal return function, FMIN, are computed and stored for each possible value of the state variable.

Moving to the next to the last stage, the process is repeated. For each possible value of G, U (the resulting value of the decision variable for the last stage) is calculated in the nitrogen model.

Associated with G will be a value of the optimal return function which has been calculated in the last stage. This value of the optimal return function is then added to the calculated cost of disposal for the next to the last stage. Thus, the optimal return function for this stage represents the sum of the disposal costs for the last two years when an optimal decision is made at the last stage.

This procedure is continued until the first stage is reached. At each stage a value of the optimal return function is calculated for each possible value of the state variable. The optimal return function in general represents the sum of the disposal costs over all succeeding stages, assuming that optimal decisions are made at each stage. For example, the optimal return function for some given value of the state variable at stage 3 of a 5-stage decision problem would represent the minimum possible sum of the disposal costs for years 3, 4 and 5.

When the first stage is reached, there is only one possible value of the state variable. Therefore, the optimal return function will have only one value, and the application rate which results in this optimal return will be accepted as the optimal decision for stage 1.

It is now possible to go back through the stages calculating the value of the optimal decision at each stage. The optimal decision for stage 1 is known. This decision will result in a specific value of the state variable for stage 2. The optimal decision for stage 2 which is associated with that value of the state variable is then recalled from the computer memory. This decision will then result in a specific value of the state variable for stage 3 and so on, until the final stage is reached.

The minimum sum of disposal costs for all stages is represented by the single value of the optimal return function at stage 1. The yearly disposal cost is simply that value divided by the number of stages.

It is important to note that as the application rate varies from year to year, so will the amount of land required to dispose of a fixed quantity of sludge. This fact should be accurately reflected in the cost curve. Any limitations on the amount of land available may define the minimum allowable application rates.

Another important characteristics of the program is that numerous checks insure that only those values of the decision variable are considered which result in allowable values of nitrate leaching and which result in values of the state variable which are less than the maximum value.

Alternative cropping systems:

Since it is not possible to inject sludge on a site where a crop is growing, it will be necessary to have some sites fallow during the growing season. It will, therefore, be impossible to produce a crop on every site every year under a system using a single crop to recycle nutrients. Provision for fallow years has been included in the computer program.

For each year of operation, the computer will read a value of an indicator variable, KROP(I). A zero value corresponds to a fallow year; the nitrogen balance and crop return segments of the program are bypassed. The least-cost application rate is simply the maximum quantity of sludge which can be applied without exceeding the leaching allowance or causing an excessive buildup of organic material in the soil.

The quantity of nitrogen which leaches into the groundwater during a fallow year is assumed to be a constant fraction of the total nitrogen in available form during that year. The fraction is an input variable, BNIT, which can be varied to determine the effect of error in estimating its value. For actual design situations, this fraction should be determined in field experiments or at least estimated and then verified through a monitoring program.

For each stage representing a fallow year, the least-cost application rate is calculated algebraically. The optimal return function is then simply the corresponding injection cost, since the profit from crops for a fallow year is zero.

Thus, the program has the capability to calculate optimal injection rates for any almost cropping system or pattern of injection and crop rotation that the designer mav wish to consider.

Chapter 5

DYNAMIC PROGRAMMING MODEL RESULTS

The environmental information from Chapter 2 and the economic information of Chapter 3 were used to establish input data for the dynamic programming model described in Chapter 4. Since the data used was gathered from the subsurface injection project at Boulder, Colorado, the results generated will be applicable to Boulder and other areas with similar situations. The actual values of the variables used for Boulder are given in Table 10 (along with the range of each variable considered in the sensitivity analysis).

When the representative values for Boulder are used, the model indicates an optimum application rate of 4.7 tons/acre at a cost of $29.33 per dry ton. The question immediately arises as to how sensitive is this "optimum" solution to variation in the values of the input variables or parameters. This is especially true in this case where many assumptions are made to obtain data for the model.

Consequently, one of the primary purposes of the dynamic programming model in this study is to serve as a screening model which provides an understanding of how the various parameters of the system affect the cost of disposal and influence the optimal operating policy. For any set of given input conditions describing a system, the model will determine the optimal application rate for each year of operation and calculate the average cost of injection over the entire operating period as noted above for Boulder. However, at this time sufficient data to accurately describe the environmental factors relating to the sludge injection process do not exist. Therefore, in the absence of good input data, the absolute numerical values

Table 10. Sensitivity Analysis--Variation of Input Parameters

Input Parameter	Fortran Variable Name	Representative Value	Range of Test Values
Nitrate leaching loss	ALLOW	150 lbs/acre	35 lbs/acre - 300 lbs/acre
Maximum sludge organic nitrogen	XMAX	2000 lbs/acre	1000 lbs/acre - 3000 lbs/acre
Mineralization rate (first year)	RMN1	0.20	0.10 - 0.35
Mineralization rate (all other years)	RMN2	0.04	0.02 - 0.06
Ammonium nitrogen fraction of sludge	AMFR	0.015	0.010 - 0.020
Organic nitrogen fraction of sludge	OMFR	0.020	0.010 - 0.030
Total nitrogen fraction of sludge	AMFR + OMFR	0.035	0.020 - 0.050
Gaseous nitrogen loss rate	RLOSS	0.30	0.10 - 0.50
Nitrogen uptake efficiency of crop	EFF	0.75	0.50 - 0.90
Available nitrogen--unamended soil	SNA	30.0	30 lbs/acre - 400 lbs/acre

Table 10. Sensitivity Analysis--Variation of Input Parameters (continued)

Input Parameter	Fortran Variable Name	Representative Value	Range of Test Values
N-fraction leached--fallow years	BNIT	0.50	0.40
Land cost	--	$2500/acre	$1000/acre - $5000/acre
Cash price of crop (corn silage)	--	$20/ton	$20/ton - $40/ton
Alternative crops	--	corn silage	corn silage wheat
Cropping systems	--	crop every year	crop every year crop 4 out of 5 years crop 3 out of 4 years crop 2 out of 3 years crop 1 out of 2 years
Period of operation	--	20 years	10 years - 30 years

of injection rates and costs produced by the model are of limited value. On the other hand, the relative values of solutions obtained from the model for different sets of input conditions can be used to examine the relative importance of each input parameter.

In order to examine the sensitivity of the model to variations in the individual input parameters, the dynamic programming model was operated over a wide range of input conditions. Sixteen parameters were selected for evaluation in this sensitivity analysis. A representative value (best estimate) was established for each. During the operation of the model, each parameter was varied individually, while the others were held constant at their representative values.

Nitrogen Variables

Leaching loss:

Determination of the allowable quantity of nitrates leached into the groundwater each year (ALLOW) is discussed by Trout (1975). The amount of leaching loss which will cause a given level of increase in the nitrate concentration in the groundwater is highly dependent on local conditions, and the allowable loss for different sites could easily vary by two orders of magnitude. Trout estimates that the leaching of about 100 lbs/ac of nitrate-N would cause a decrease in groundwater quality at the Boulder experimental site from 3 to 10 ppm nitrate concentration. The test variable ALLOW is, therefore, varied from 35 to 300 lbs/acre with 150 lbs/acre as the representative value. The average injection rate and injection cost produced by the model for each value of the variable is presented in Table 11, and the application rate for each year of operation is plotted in Figure 8.

Table 11. Sensitivity Analysis Results--Nitrogen Parameters

Input Parameter	Fortran Variable Name	Test Value	Average Injection Rate (tons/acre)	Average Injection Cost ($/ton)
Nitrate leaching loss	ALLOW	35 lbs/acre	2.8	45.75
		50 lbs/acre	4.3	30.94
		*100 lbs/acre	4.7	29.33
		*150 lbs/acre	4.7	29.33
		200 lbs/acre	4.7	29.33
		300 lbs/acre	4.7	29.33
Maximum sludge organic nitrogen	XMAX	1500 lbs/acre	3.4	32.73
		*2000 lbs/acre	4.7	29.33
		2500 lbs/acre	5.1	27.76
		3000 lbs/acre	5.8	27.75
Mineralization rate (first year)	RMN1	0.10	4.2	30.48
		0.15	4.3	30.59
		*0.20	4.7	29.33
		0.25	4.9	27.95
		0.35	5.0	29.15
Mineralization rate (all other years)	RMN2	0.02	3.9	31.69
		*0.04	4.7	29.33
		0.06	5.4	27.39

Table 11. Sensitivity Analysis Results--Nitrogen Parameters (continued)

Input Parameters	Fortran Variable Name	Test Value	Average Injection Rate (tons/acre)	Average Injection Cost ($/ton)
Ammonium nitrogen fraction of sludge	AMFR	0.010	4.7	30.57
		*0.015	4.7	29.33
		0.020	4.4	28.79
Organic nitrogen fraction of sludge	OMFR	0.01	7.1	28.51
		*0.02	4.7	29.33
		0.03	3.0	33.85
Total nitrogen fraction of sludge	AMFR + OMFR	0.020	9.2	26.39
		*0.035	4.7	29.33
		0.050	3.0	32.39
Gaseous nitrogen loss rate	RLOSS (ALLOW = 100)	0.1	4.7	29.33
		*0.3	4.7	29.33
		0.5	4.7	29.33
	RLOSS (ALLOW = 50)	0.1	3.2	36.49
		0.3	4.7	29.33
		0.5	4.7	29.33

Table 11. Sensitivity Analysis Results--Nitrogen Parameters (continued)

Input Parameters	Fortran Variable Name	Test Value	Average Injection Rate (tons/acre)	Average Injection Cost ($/ton)
Nitrogen uptake efficiency of crop	EFF	0.50	4.7	29.33
		*0.75	4.7	29.33
		0.90	4.7	29.33
Available nitrogen--unamended soil	SNA	*30 lbs/acre	4.7	29.33
		70 lbs/acre	4.7	29.33
		250 lbs/acre	4.7	29.33
		400 lbs/acre	4.5	29.37
N-fraction leached--fallow years	BNIT	0.40	4.6	46.49
		*0.50	4.6	45.71
		0.65	4.3	52.30

*Representative value

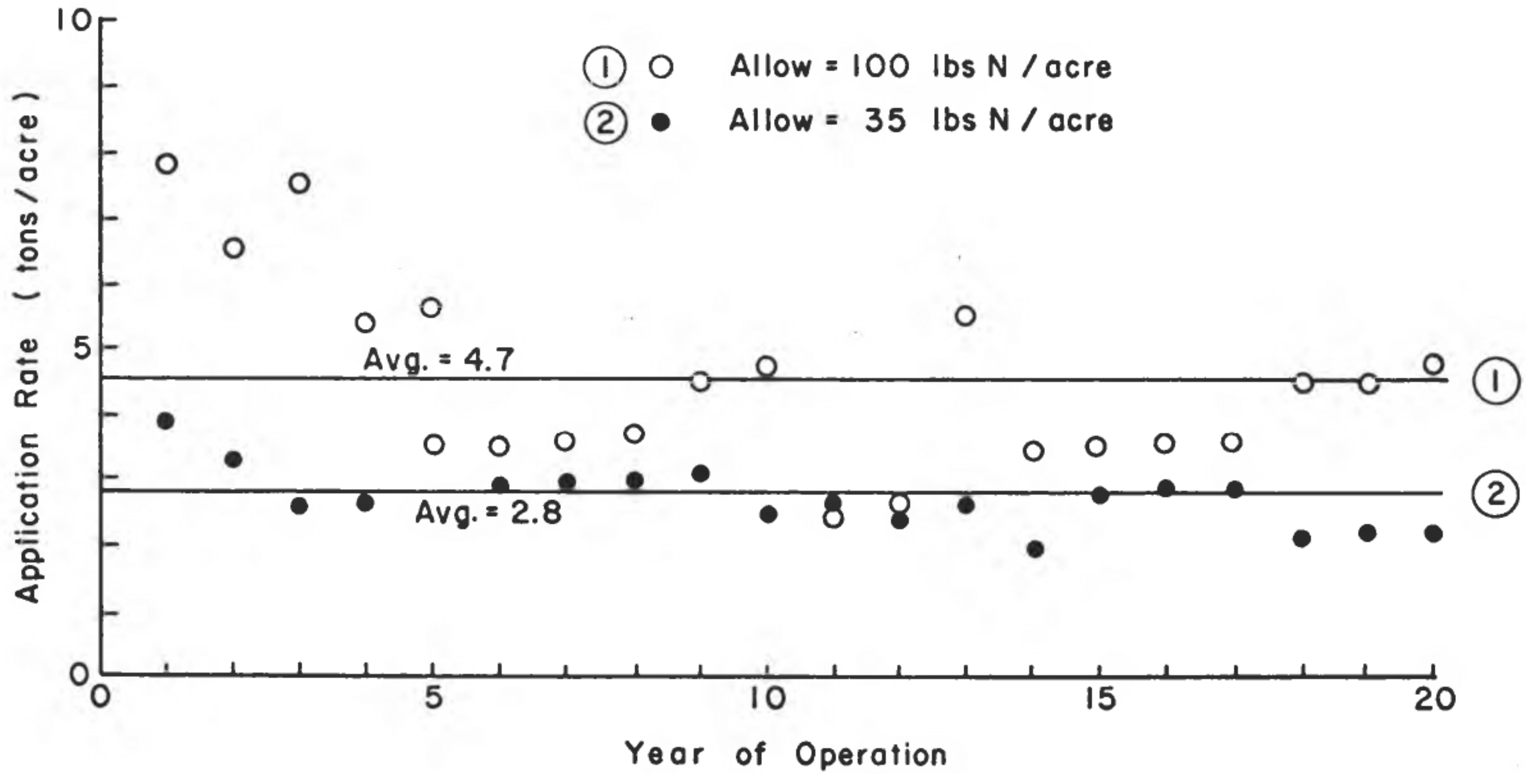

Figure 8. Variation of Application Rate with Allowable Nitrate Leaching Loss.

The straight lines in the plot are provided to indicate a constant application rate that could be used in a sludge injection program. It appears that the application rate is not limited by the allowable leaching loss for values of ALLOW greater than 100 lbs/acre. For smaller values of ALLOW, the application rates are lower and costs are higher.

The erratic nature of the injection pattern may cause some concern. One would naturally expect a monotonically decreasing injection rate as the nitrogen content of the soil increases through continued sludge application. The reason for the fluctuation is readily apparent, however. Referring back to Figure 6, one can see that the injection cost function for a single year is somewhat irregular.

This irregularity is compounded by the dynamic programming model which includes nitrogen constraints and operates over many years. Because of the tradeoffs between the disposal and crop production objectives, it is possible to have two very different application rates with very nearly the same cost. Thus, there is no guarantee that the optimal application rates for successive years would be close together. Although it would be impossible to operate a system in the "optimal" erratic fashion, the general tendencies of the system may be determined. A feasible injection pattern which would result in nearly optimal cost can then be devised.

<u>Organic nitrogen level</u>:

Unamended soils may contain thousands of pounds of organic material per acre, as discussed in Chapter 2. The allowable increase in organic material is somewhat arbitrary, but is quite important in determining the optimal application rates. The representative value of 2,000 lbs/acre as the maximum sludge organic material level in the soil (XMAX) with a test range of 1,500 to 3,000 lbs/acre was selected. The calculated application rates for each year of operation are plotted in Figure 9.

The data in Table 11 indicate that the average injection rate and cost are quite dependent upon the value of XMAX, ranging from 3.4 tons/acre and $32.73/ton at XMAX = 1,500 lbs/acre to 5.8 tons/acre and $27.75/ton at XMAX = 3,000 lbs/acre.

Mineralization rates:

The mineralization rate for the first year after application (RMN1) was varied from 0.10 to 0.35. The mineralization rate for all succeeding years (RMN2) was varied from 0.02 to 0.06. As indicated in Table 11, higher mineralization rates allow higher average application rates and result in lower costs.

Gaseous loss of nitrogen:

The rate at which the loss of nitrogen occurs through the mechanisms of denitrification and ammonia volatilization is highly speculative. However, the fraction of available nitrogen lost in gaseous forms (RLOSS) should lie somewhere in the range of 0.10 to 0.50.

The variation of RLOSS within this range did not produce any change in the calculated application rates or costs while the other parameters were held at their representative values. By tightening

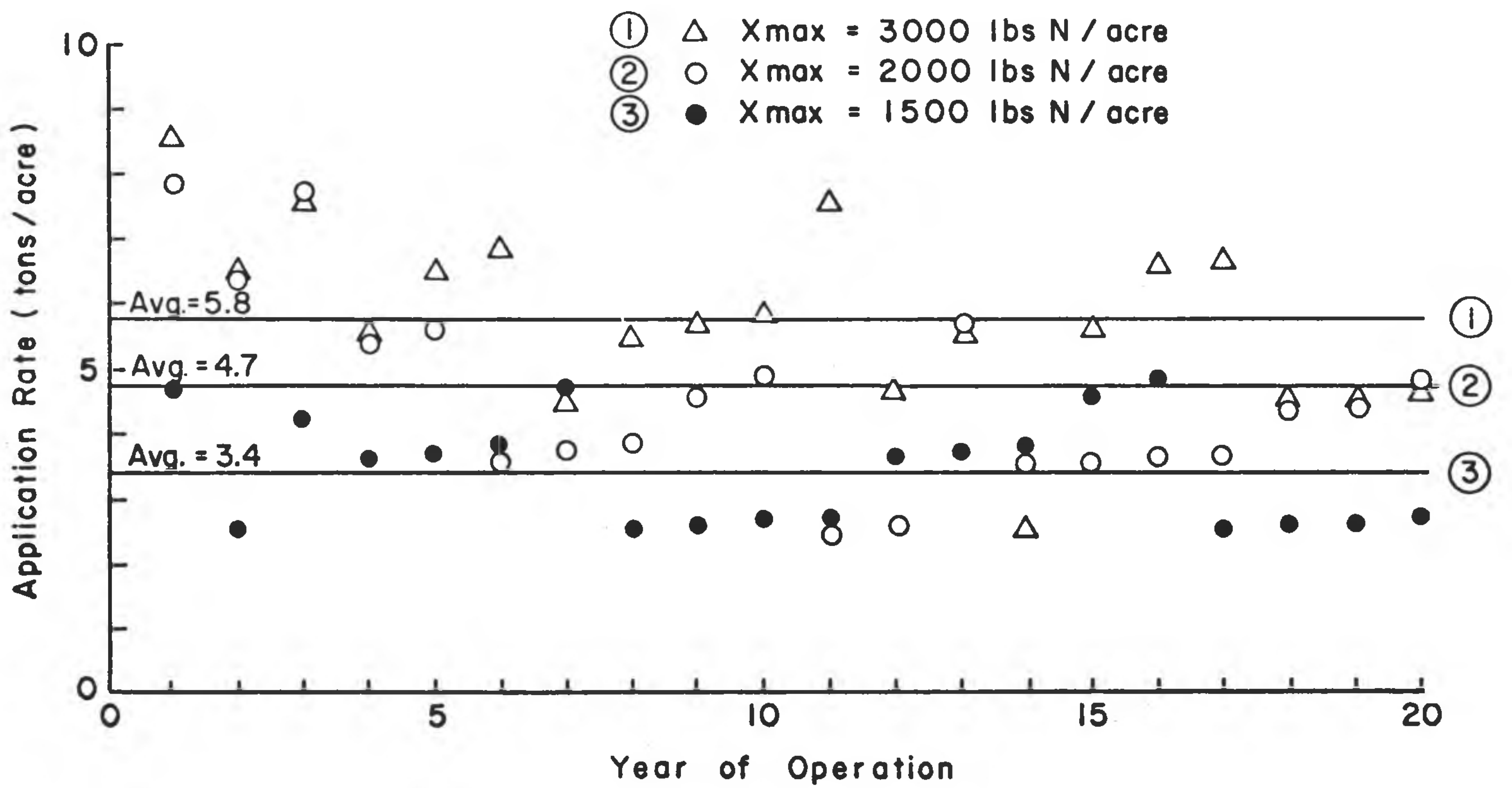

Figure 9. Variation of Application Rate with Maximum Organic Nitrogen Level.

the nitrate leaching constraint to ALLOW = 50 lbs/acre, it was revealed that an increasing gaseous loss rate permits higher application rates.

Crop uptake efficiency:

The rate at which a crop removes available nitrogen from the soil (EFF) is also discussed in Chapter 2. The variation of the removal efficiency from 50 to 90% had no effect upon the calculated application rates or costs, as indicated in Table 11.

Nitrogen from unamended soil:

The annual quantity of nitrogen which becomes available in an unamended soil is almost always less than 100 lbs/acre. Variation of this quantity (SNA) from 30 to 250 lbs/acre did not influence the calculated application rates. A decrease in the average injection rate was observed for SNA = 400 lbs/acre, but this value is far outside the range expected in field operation.

Nitrogen loss in fallow years:

There is little experimental evidence to indicate that one value of the fraction of available nitrogen lost by leaching in a fallow year (BNIT) is better than another. Therefore, a test range of 0.40 to 0.65 was accepted as reasonable. For a system of producing crops in two out of three years, the variation of BNIT resulted in average application rates ranging from 4.3 to 4.6 tons/acre. As one would expect, the lower leaching rates permit higher application rates, but much more experimental data are necessary before the importance of this parameter can be evaluated.

Nitrogen content of sludge:

Based on available sludge composition data (see Table 1), the ammonium nitrogen fraction of the sludge (AMFR) was varied from 1 to 2% and the organic matter fraction (OMFR) was varied from 1 to 3%. AMFR and OMFR were also varied simultaneously in order to evaluate the importance of total nitrogen content over a range of 2 to 5%.

Each of the two nitrogen components has a significant effect upon the calculated application rates. Increasing the total nitrogen content from 2% to 5% lowers the average application rage from 9.2 tons/acre to 3.0 tons/acre. The yearly application rates for three levels of total sludge nitrogen are plotted in Figure 10.

Operational Factors

Period of operation:

The dynamic programming model was operated for periods of 10, 20, and 30 years with all other input parameters held at their representative values. The resulting yearly application rates are plotted in Figure 11. Higher application rates are possible for shorter periods of operation because the maximum level of organic nitrogen in the soil can be reached in a shorter length of time.

From the average costs presented in Table 12, it appears that the cost increases for longer periods of injection. However, an accurate comparison of the costs for different operating periods is impossible because the operating period was not considered in the construction of the cost curve. For correctness, the operating period should be considered in determining the economic life of each system component. From a planning standpoint, though, the relative costs for

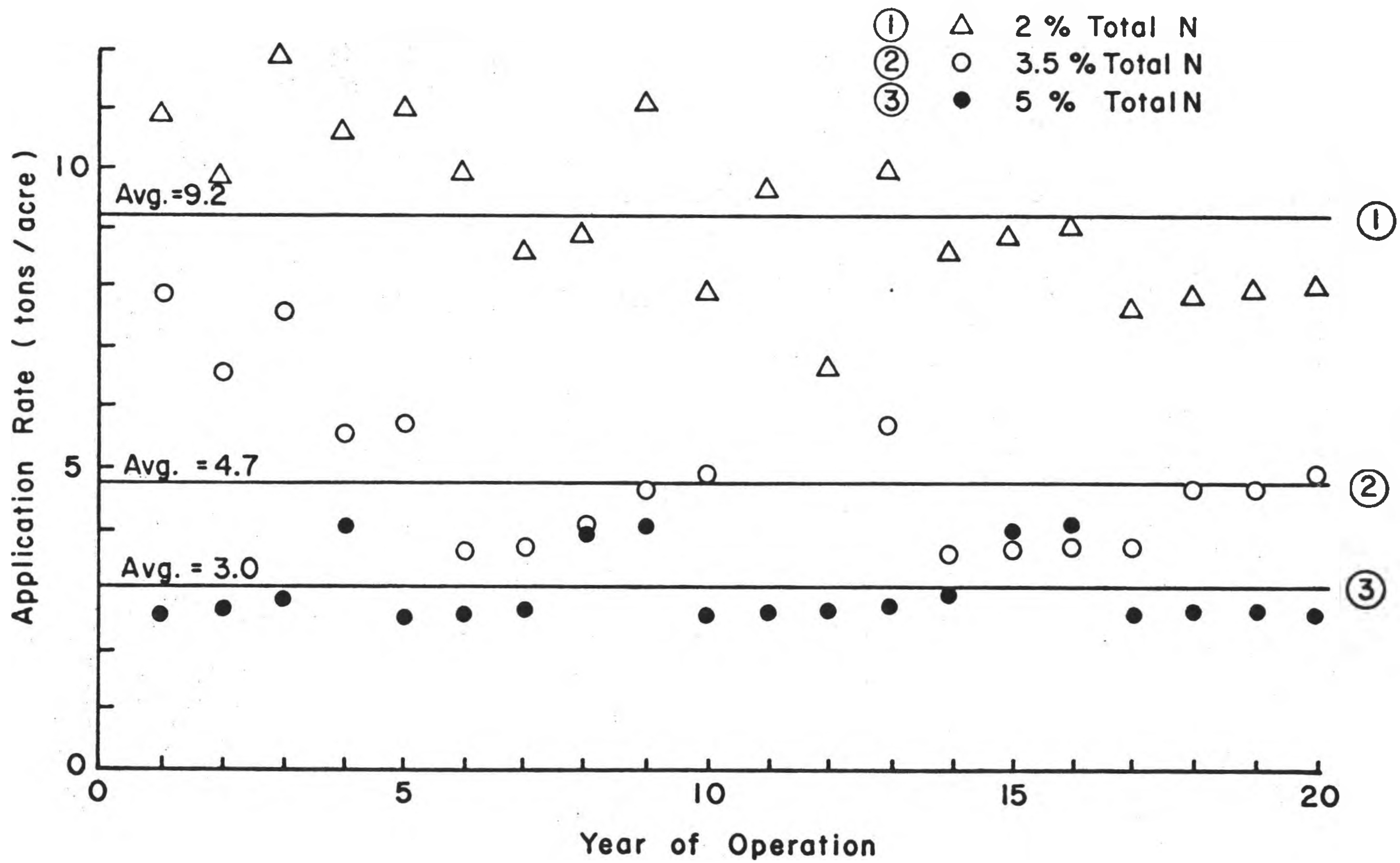

Figure 10. Variation of Application Rate with Total Sludge Nitrogen Content.

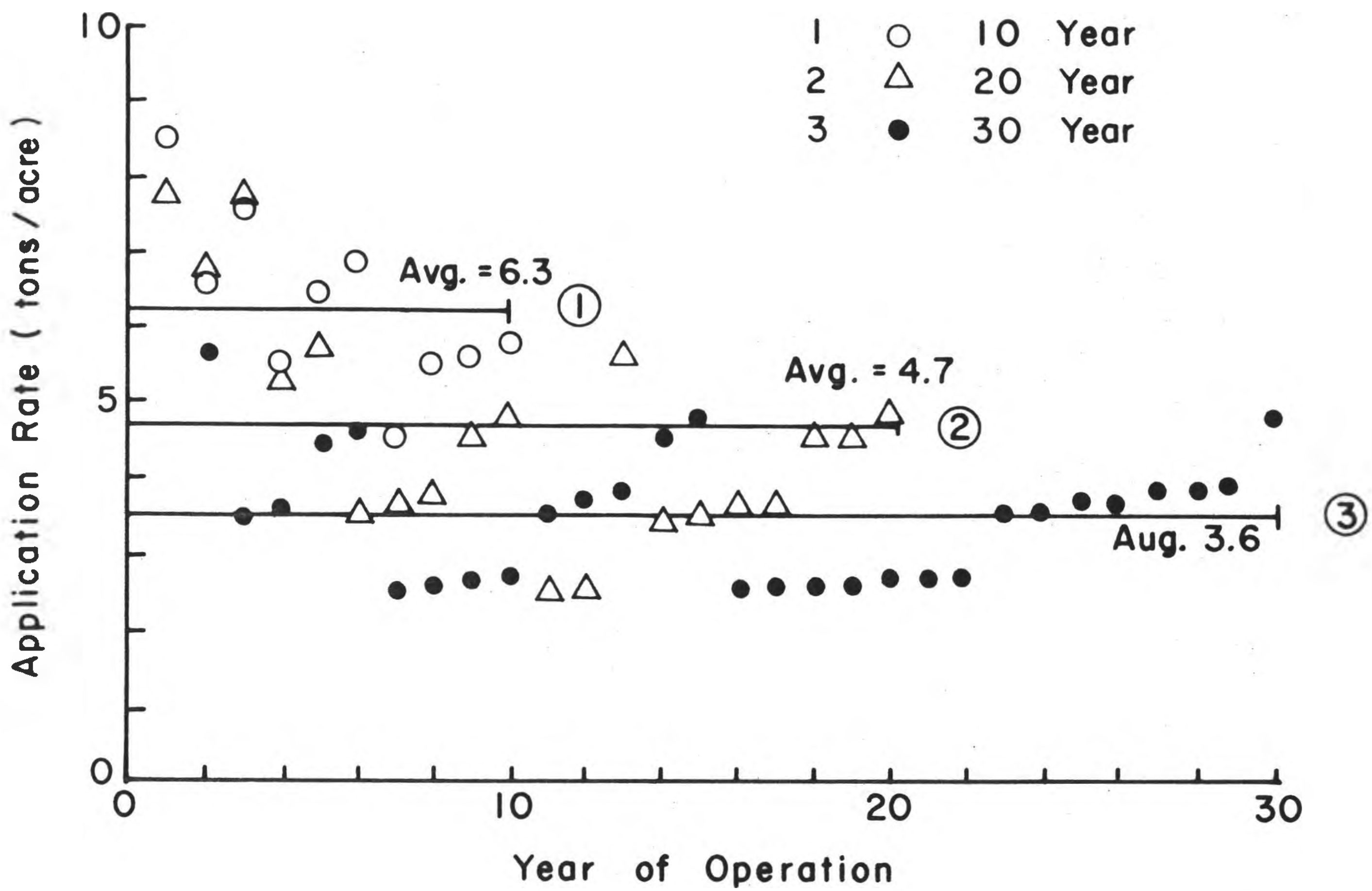

Figure 11. Sludge Application Rates for Varying Periods of Operation.

Table 12. Sensitivity Analysis Results--Operation Factors

Operation Factor	Test Value	Average Injection Rate (tons/acre)	Average Injection Cost ($/ton)
Cropping system	Crop every year	4.7*	29.33
	Crop 3 out of 4 years	4.5	40.17
	Crop 2 out of 3 years	4.6	45.71
	Crop 4 out of 5 years	4.6	37.97
	Crop every other year	4.6	51.83
Period of operation	10 years	6.3	27.38
	20 years	4.7*	29.33
	30 years	3.6	31.80

*Representative Value

different operating periods are probably of little concern since the length of time that a site may be used will depend upon the buildup of heavy metals and salts and other environmental factors which are not included in the present model.

Cropping system:

Five cropping systems were considered in this analysis: (1) producing a crop every year, (2) producing a crop in four out of five years, (3) producing a crop three out of four years, (4) producing a crop two out of three years, and (5) producing a crop every other year. Cropping every year was chosen as the representative system because of the uncertainty of the nitrogen balance for fallow years. In addition it was found that the individual effects of the other input parameters were easier to evaluate under the "every-year" cropping system.

In operating the model under the other systems, it was found that application rates will decrease and costs will increase with decreasing frequency of crop production (see Table 12). One would expect this result since higher application rates are facilitated by crop removal of nitrogen.

Economic Factors

Land costs:

The anticipated cost of land for expansion of the Boulder, Colorado, injection operation is $2,500/acre. That cost was selected as the representative value and two other costs, $1,000 and $5,000/acre were also evaluated. Actual costs anywhere within this range, or even outside of it, might well be encountered at other locations. The optimal injection rates vary slightly with land cost, but the average injection costs vary dramatically as indicated in Table 13. When the representative value of $2,500/acre was doubled, the cost was approximately doubled as well. On the other hand, when the cost was reduced to $1,000/acre, the system operated at a small profit. Land costs will, therefore, be extremely important in planning a sludge injection system.

Cash price of crop:

From the data of Table 13, it is apparent that the cash price received for crops produced has a tremendous impact upon the cost of operating the system. When the price of corn silage was doubled from the representative value of $20/ton to $40/ton, the system appeared to operate at a very large profit. This is not a realistic situation at all, even though it is a fairly common occurrence for the price of a crop to double (or be reduced by half) within a single year. This example does point out, however, that the total cost of operating an injection system may depend heavily upon the success of the farming operation used to recycle nutrients.

An interesting characteristic of some of the optimal injection patterns is reflected in the rate versus time plot of Figure 12. After several years of operation, the injection rate drops abruptly to a constant value, much lower than that for previous years. When the cash price of corn silage is $40/ton, the rate drops to about 2 tons/acre after five years. From the economic analysis presented in Chapter 3, one might conclude that the lower, constant injection rate corresponds to an equilibrium position in which maximum crop production is emphasized, while the higher injection rates reflect an emphasis on least-cost disposal. While the system is in equilibrium, the rate of nitrogen

Table 13. Sensitivity Analysis Results--Economic Factors

Economic Factors	Test Value	Average Injection Rate (tons/acre)	Average Injection Cost ($/ton)
Land cost	$1000/acre	3.8	-4.99
	*$2500/acre	4.7	29.33
	$5000/acre	4.6	74.86
Cash price of crop (corn silage	*$20/ton	4.7	29.33
	$30/ton	3.8	-29.91
	$40/ton	4.2	-105.70
Alternative crops	wheat @ $4/bushel	4.2	64.42
	corn silage @ $20/ton	4.7	29.33

*Representative value

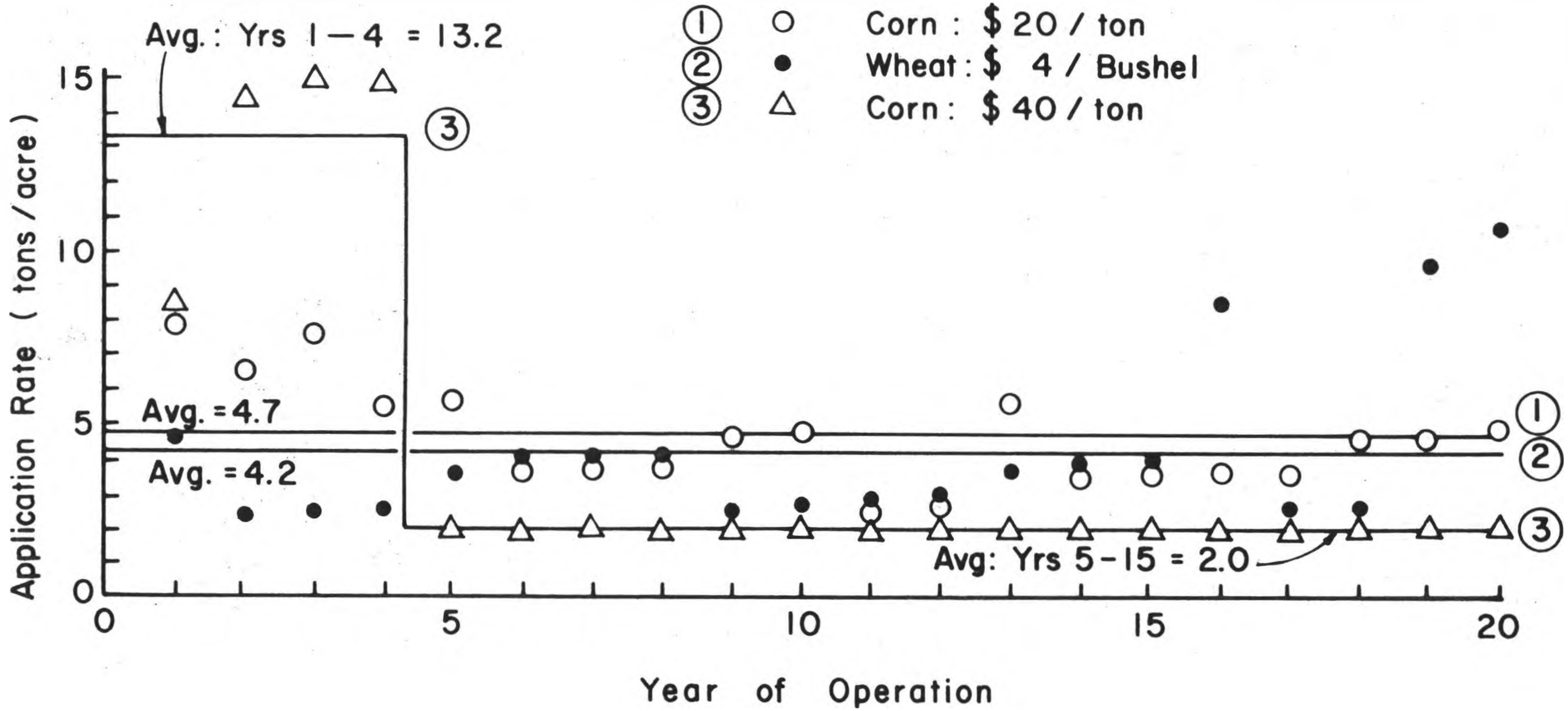

Figure 12. Variation of Application Rate with Type of Crop and Cash Price.

removal is equal to the rate of nitrogen addition. Thus, there is zero net accumulation of nitrogen in the soil. The transition from higher rates to lower rates occurs at a point when the level of organic nitrogen in the soil is high enough such that continued heavy applications are impossible due to environmental constraints. The plot of yearly application rates in Figure 12 indicates that when the price of the crop is increased, the crop production objective dominates the disposal objective over a large portion of the operating period.

Wheat was selected as an alternative crop for the purpose of comparison. This crop has some potential for use in a dual-cropping system with corn, but wheat is generally less desirable for recycling purposes because its use of nitrogen is less than that of corn. The sludge application rates on wheat land must, therefore, be lower than those for corn land, and the costs will be higher (Table 13).

Relative Importance of Parameters

Based on the assumptions previously mentioned and the data used, nitrate leaching loss, maximum sludge organic nitrogen, nitrogen content of sludge, mineralization rates, land cost, and cash price of crop are the more sensitive parameters in the model. Thus, based on the results of the sensitivity analysis, these parameters must be carefully defined before they are used in the model.

Chapter 6

APPLICATION OF SYSTEMS TECHNIQUES IN PLANNING

A summary and illustration of the concepts presented thus far can best be accomplished through the use of an example in which the systems analysis approach is applied to the planning of a hypothetical sludge disposal system. Specifically, the dynamic programming model is used to evaluate alternative implementation strategies for a particular situation.

The example problem is based on conditions similar to those for the planned expansion of the Boulder, Colorado, sludge injection operation.

Given: (1) 3,300 dry tons of sludge produced per year.

(2) Unlimited availability of land at distance of about one-half mile from the treatment plant.

(3) Land must be purchased in 40-acre parcels.

(4) Subsurface injection has been selected as the method of disposal.

(5) The quantity of nitrates leached on the injection site must not exceed 150 lbs/acre for any plot in any year.

The designers of the system wish to determine the amount of land to be purchased and to formulate a plan of operation of the system which would result in the minimum total cost.

There is a large number of ways in which such a disposal system could be implemented. In order to illustrate the evaluation procedure, two of the possible alternatives are selected. The methods of comparison can be extended for the more realistic situation in which several alternatives are under consideration. Details of the two alternatives are given below.

Alternative #1:

The first alternative is a single-cropping system using corn to recycle nutrients. Approximately one third of the land must be left fallow each year for injection during the summer while the corn crop is growing. The cropped portion of the land will receive sludge during the rest of the year. The injection site would be divided into three plots as shown in Figure 13, and the pattern of crop rotation would be designed such that each plot would be left fallow every third year and would produce a crop in the other two years.

Alternative #2:

The second alternative is a dual-cropping system in which winter wheat and corn are produced. The wheat land can receive sludge in late summer while the corn crop is growing, and sludge can be applied on the corn land during the winter after the wheat crop is planted. A certain amount of layout land is necessary to receive sludge during the period of about two months when both the corn and wheat crops are growing. The amount of layout ground required for this alternative will, however, be less than that for the single-crop system. The pattern of crop rotation would be such that each parcel of land produces a crop in four out of five years. Thus, about one fifth of the land will be left fallow each year (Figure 14).

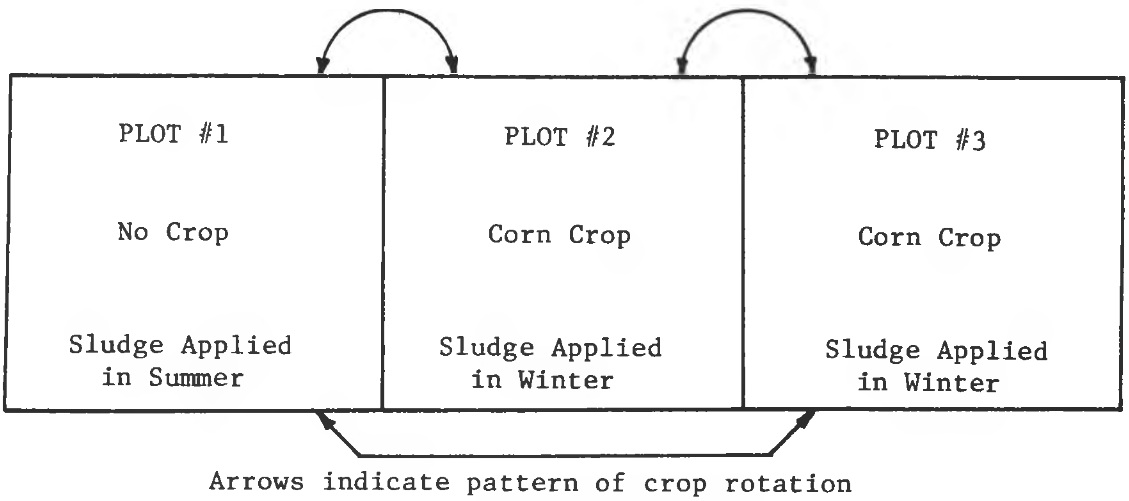

Figure 13. Rotating, Single-crop System, Alternative #1.

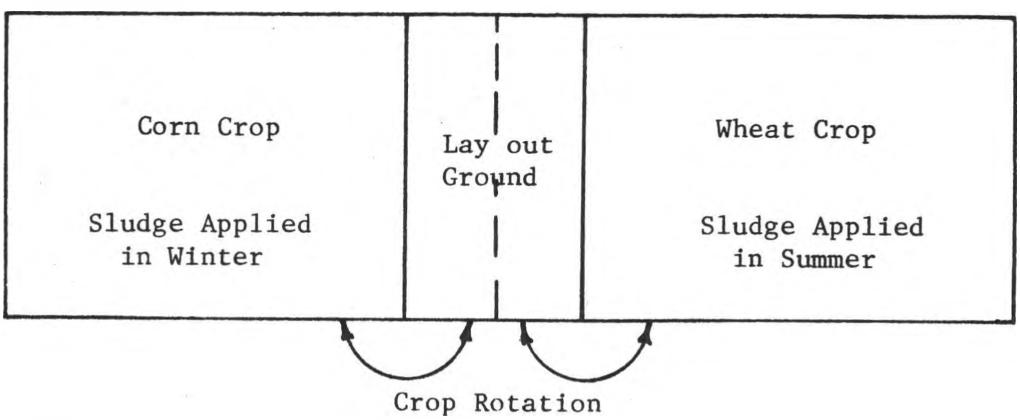

Figure 14. Dual-crop System, Alternative #2.

Analysis:

For all systems, it is assumed that sludge will be disposed of on sand beds when the ground becomes frozen to the extent that subsurface injection is impossible. It is further assumed that the nitrogen balance for the site is described by the representative values of all nitrogen-related parameters as discussed in the previous chapter. The period of operation selected for planning purposes is 20 years.

The injection cost function developed in Chapter 3 for land available in adjacent, 40-acre plots is applicable for this problem. The crop return functions for corn silage at $20/ton and wheat at $4/bushel will also apply. The dynamic programming model is used to calculate the optimal yearly application rates for each alternative. The results are presented in Table 14.

Since the optimal application rates calculated by the dynamic programming model fluctuate widely from year to year, it is necessary to devise an injection pattern which is based upon the results of the model operation and is also easy to implement.

This problem can be attacked by using the technique of simulation. It is possible to simulate any given injection pattern by using only the portions of the dynamic programming model which perform the nitrogen balance, calculate crop returns, and determine the overall disposal cost. These portions of the nitrogen balance constitute an algebraic simulation model which can calculate the total disposal cost and quantity of nitrates leached for each year of operation when supplied with any sequence of application rates as input data.

The number of feasible injection patterns that could be selected for evaluation by simulation is quite large. The simplest of these are

Table 14. Results of Optimization for Alternatives #1 and #2

Year of Operation	Optimal Application Rates (tons/acre)		
	Alternative #1	Alternative #2	
	Corn Land	Corn Land	Wheat Land
1	7.1	4.7	4.7
2	2.6	5.7	2.5
3	5.8	6.7	2.6
4	6.6	6.6	6.8
5	4.8	5.6	7.7
6	5.7	5.8	4.0
7	6.1	6.0	5.7
8	3.7	4.6	3.6
9	4.6	5.8	6.0
10	5.8	2.5	7.8
11	2.5	2.6	2.5
12	2.6	2.6	2.6
13	5.6	2.6	2.6
14	2.8	5.6	5.6
15	3.6	3.6	5.9
16	5.4	3.7	2.9
17	3.8	3.7	3.8
18	3.8	4.6	3.0
19	5.2	5.2	5.2
20	4.0	4.0	4.8
Average	4.6	4.6	4.5
Average cost ($/ton)	45.71	39.07	70.65

patterns in which sludge is injected at the same loading rate each year. An alternative is to apply sludge at a high loading rate on a small area for the first few years of operation and then to acquire additional land. The sludge loading rate can then be reduced on the old site while the majority of the sludge is injected on the new site. The process can be repeated any number of times so that the land is acquired in several stages. The sludge loading rates should change with each acquisition of land so that the newest sites are injected at the highest rates while the oldest sites are injected at the lowest rates. It is, of course, necessary that the average sludge injection rate times the total land area receiving sludge be equal to the quantity of sludge produced for each year of operation. For the sake of simplicity, only constant loading rates will be considered in the example problem.

As a starting point for alternative #1, a system is simulated using a constant application rate of 10 tons/acre. The resulting cost is $43.37/ton--less than the optimal cost calculated by the dynamic programming model. However, the nitrate leaching rate exceeds the allowable limit in each of the seven years in which no crop was produced. An injection rate of 6 tons/acre results in violation of the leaching constraint in four of the years, while application at 5 tons/acre causes no violation of the leaching limit. This rate is, therefore, acceptable.

If, on the other hand, the nitrate leaching rate for individual years is allowed to exceed the maximum so that the average leaching rate reaches the allowable limit of 150 lbs/acre-year the sludge application rate rises to 10 tons/acre-year and the cost decreases to $43.37/ton. This interpretation of the environmental constraints is not acceptable for the example problem as it was defined, but it could be a practical approach in some situations. The difference in cost between the application rates of 5 tons/acre and 10 tons/acre represents the additional degree of environmental quality provided by limiting the leaching rate on a yearly rather than on an average basis. The results of algebraic simulation of constant-rate injection programs for alternative #1 ranging from 2 tons/acre to 12 tons/acre are shown in Table 15.

For alternative #2, application patterns using constant injection rates of 4 tons/acre, 5 tons/acre, and 6 tons/acre are evaluated using the simulation program. For both the corn producing plots and wheat producing plots, the injection rate must be 5 tons/acre or less in order to satisfy the nitrate leaching constraint for all years of operation.

The two alternatives may now be considered as constant-rate injection programs for which the costs and land requirements are known. A summary of the data developed for each alternative is presented in Table 16.

If the constant-rate injection programs suggested by this analysis are considered to be desirable, the land requirements for both alternatives are the same. The decision between the two can then be made on the basis of disposal cost alone if no other factors seem to be of decisive importance. For alternative #1, the overall cost is \$50.91/ton, while alternative #2 has a projected cost of \$60.04/ton. Therefore, alternative #1 would probably be accepted.

<u>Summary of planning process</u>:

Almost any conceivable implementation strategy can be evaluated using the methods illustrated in this example. In a real planning

Table 15. Results of Simulation of Constant-rate Injection Patterns (for Alternative #1)

Year of Operation	Calculated Nitrate Leaching Loss (lbs/acre) for Various Constant Injection Rates						
	2 T/acre	3 T/acre	4 T/acre	5 T/acre	6 T/acre	10 T/acre	12 T/acre
1*	53	72	91	110	129	205**	243**
2	27	35	43	51	59	92	109
3	22	29	36	43	50	78	93
4*	57	78	98	119	140	223**	265**
5	28	37	46	55	64	99	118
6	23	31	38	46	54	84	100
7*	59	82	105	127	150	239**	285**
8	29	39	49	58	68	106	126
9	24	32	40	48	57	89	106
10*	63	87	111	134	159*	254**	302**
11	30	41	51	61	71	112	132
12	25	34	42	51	60	94	112
13*	65	91	116	140	167**	267**	318**
14	32	42	53	64	75	117	139
15	26	35	44	53	62	98	117
16*	68	94	120	146	173**	278**	331**
17	32	44	55	66	77	122	144
18	26	36	45	55	64	102	121
19*	69	97	125	150	179**	288**	343**
20	33	45	57	68	80	126	149
Average nitrate leaching loss (lbs/acre-year)	40	52	68	80	97	154	183
Average disposal cost ($/ton)	102.16	72.29	57.63	50.91	46.22	43.37	41.38

*Year of no crop production

**Allowable leaching loss of 150 lbs/acre exceeded

Table 16. Comparison of Alternatives for Disposal Program

Design Parameters	Alternative #1	Alternative #2
(1) Recycling method	Corn silage	Corn silage and wheat
(2) Pattern of crop rotation	Crop produced on each plot 2 out of 3 years	Crop produced on each plot 4 out of 5 years on both corn and wheat land
(3) Average injection rate from optimization model	7.8 ton/acre-year	Corn land -- 9.1 ton/acre-year Wheat land - 8.9 ton/acre-year
(4) Minimum disposal cost	$45.71/ton	Corn land -- $39.07/ton Wheat land - $70.65/ton
(5) Constant injection rate developed by simulation (trial and error)	5.0 ton/acre-year	Corn land -- 5.0 ton/acre-year Wheat land - 5.0 ton/acre-year
(6) Costs for constant-rate disposal	$50.91/ton	Corn land -- $43.65/ton Wheat land - $76.43/ton Overall -- $60.04/ton
(7) Land requirement for constant-rate disposal program (including 25% buffer)	680 acres	Corn land -- 340 acres Wheat land - 340 acres Total -- 680 acres

situation, more than two alternatives will usually be considered. For each proposed alternative, the dynamic programming model will determine the minimum disposal cost and find the optimal injection rates for each year. This optimal injection pattern will generally be impossible to implement, but it will suggest ways to construct different injection patterns which could easily be used. These possible injection patterns can then be evaluated by simulation, and the best of them can be used for comparison against the other alternatives.

A flow diagram of the sludge disposal planning process employing the systems analysis techniques previously discussed is presented in Figure 15. The stages of planning which are illustrated in the diagram are described below. As a starting point, it is assumed that subsurface injection has been selected as the sludge disposal technique, and a considerable amount of planning will have already taken place in order to reach that decision.

Discussion of flow diagram:

(1) The first stage is a data collection process. The information required will fall into four groups: social and political data, economic data, environmental data, and physical data. The details of the social and political aspects of the planning process are beyond the scope of this discussion. These considerations are included simply as "community priorities" in the diagram. The economic data includes all of the information required to make preliminary cost estimates for the system. The major items will be equipment costs and land costs. The physical data includes both the composition

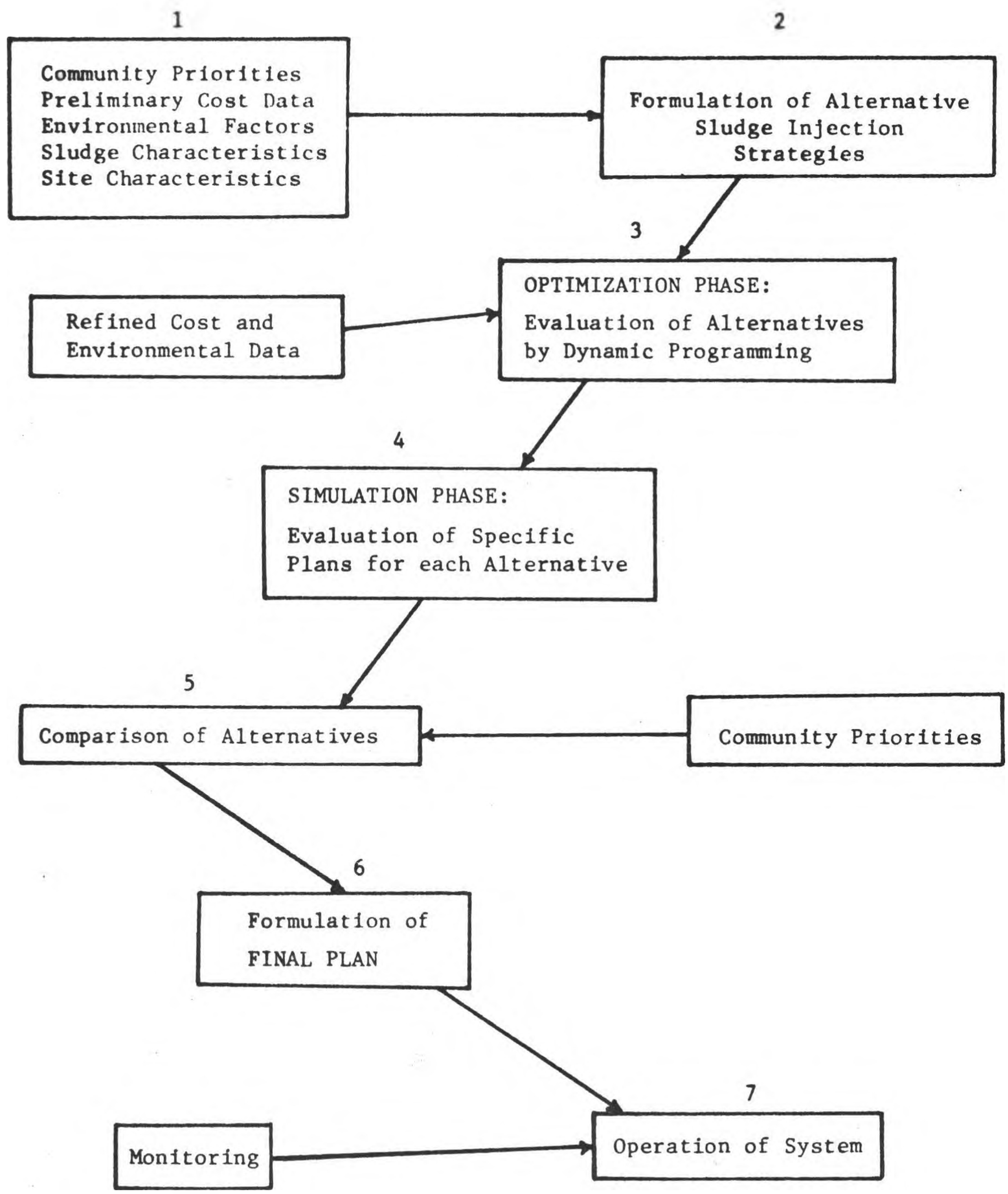

Figure 15. Flow Diagram--Planning the Injection System.

of the sludge to be injected and the characteristics of the various sites under consideration. Important site characteristics include location, soil characteristics, and groundwater characteristics. Environmental data consist of a description of possible pollution problems, suggested means of minimizing those problems, and limitations imposed on the injection system by environmental considerations.

(2) Based on information collected in the data-gathering phase, several alternative implementation strategies can be formulated. The main activities of this stage of planning are the selection of the more promising disposal sites and selection of possible crops, production methods, and patterns of crop rotation.

(3) The optimization phase of planning involves the evaluation of each of the proposed alternatives using the dynamic programming model. Prior to operating the model, additional environmental and economic data should be collected so that the required input data for the model can be developed as accurately as possible.

(4) In the simulation phase, several feasible injection patterns are proposed for each alternative, based upon the results of the optimization phase. The average cost and annual nitrate leaching rates are determined for each specific pattern by using the simulation model.

(5) The best of the feasible injection patterns for each alternative are then compared on the basis of cost and fulfillment of community objectives.

(6) One of the alternatives is selected and drawn up in the form of a final plan for implementing the continuous subsurface injection operation.

(7) The mathematical models can be used after planning is completed to make use of updated information from monitoring of the injection site for modifying the final plan and to serve as a guide for operating the system on a yearly basis.

Environmental-economic tradeoffs:

All of the preceding analysis has been based upon the criterion that there is some maximum level of environmental degradation (nitrate leaching) which must not be exceeded under any circumstances. This is certainly a valid approach from the standpoint of preserving environmental quality and is, of course, the necessary one when human life or health is at stake.

An alternative approach is to examine the tradeoffs between environmental quality and economics of injection and to establish the environmental constraints in light of the results. This approach might be acceptable in situations where the environmental considerations are somewhat less critical -- human life and health are not directly endangered.

The environmental-economic tradeoffs are illustrated qualitatively in Figure 16, which is based on the data in Table 15. Point #1 represents a very low injection rate for which the nitrate leaching rate is low but the net injection cost is high. Point #5 corresponds to a very high injection rate for which the cost is low but the nitrate leaching rate is very high. Point #2 and point #4 are simply reference points.

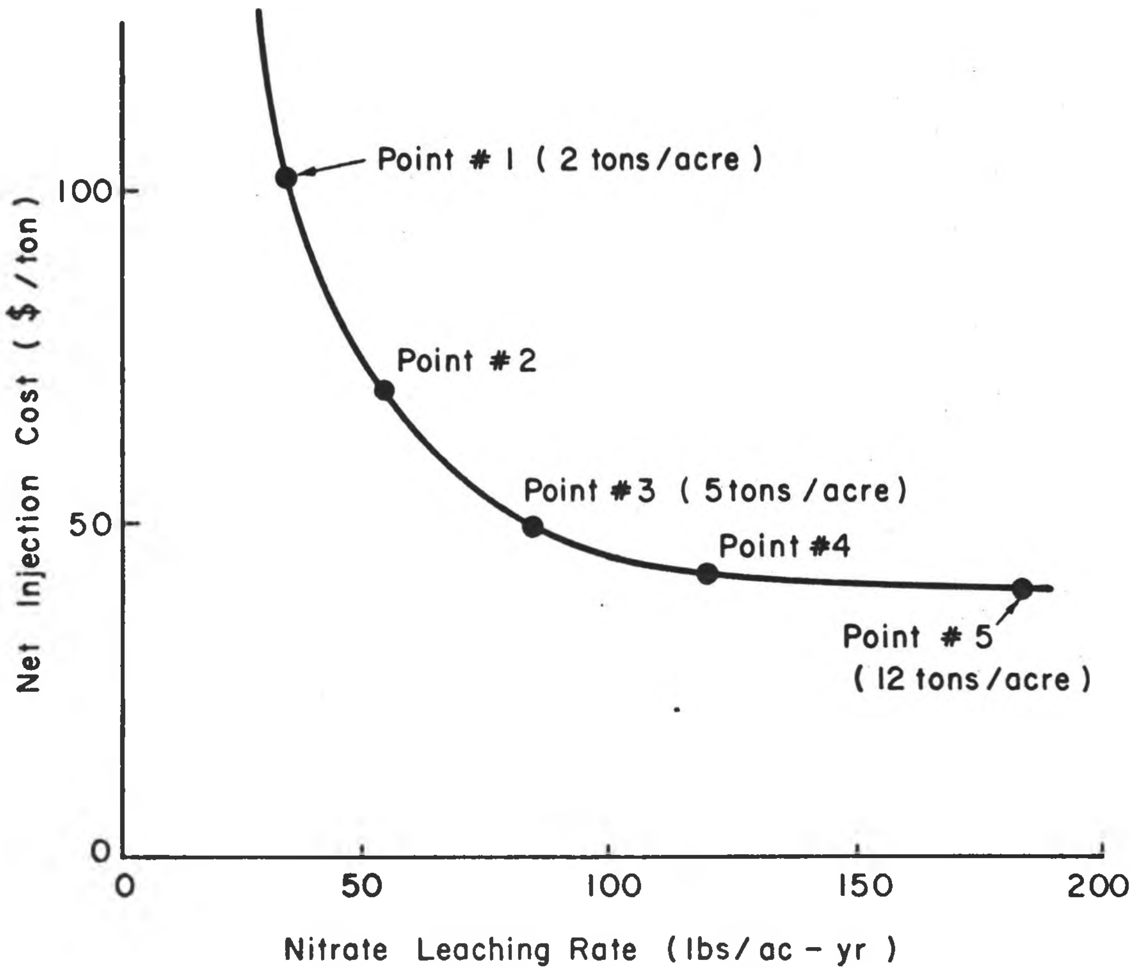

Figure 16. Tradeoffs Between Environmental and Economic Factors.

As one moves along the curve in the direction of increasing application rate from point #1 to point #2, a significant cost reduction occurs with little increase in nitrate leaching. Similarly, as one moves from point #5 to point #4 in the direction of decreasing application rates, a significant reduction in nitrate leaching occurs with little increase in cost. In the region between point #2 and point #4, however, significant benefits in cost can be achieved only at the expense of significant increase in nitrate leaching. This is the range in which tradeoffs become important, and it is this range in which the most desirable injection rate would probably lie.

The simulation model provides a quantitative basis for analyzing these tradeoffs by calculating the costs and leaching rates associated with various injection patterns. Using that information, one can easily determine the dollar cost of each increment of nitrate leaching. The exact point which is selected as the "best" will depend upon the financial resources and environmental concerns of the community.

Chapter 7

SUMMARY AND CONCLUSIONS

Summary:

Continuous subsurface injection is a new and promising technique for the disposal of digested municipal sewage sludge and recovery of sludge nutrients through crop production. One of the greatest drawbacks to its use at present is the lack of methodology for developing and evaluating alternative implementation strategies. The research described herein was undertaken in an effort to address this problem and to provide a basis for developing plans for continuous subsurface injection programs within the framework of systems analysis. The important steps in the research are outlined below.

I. The environmental problems related to sludge injection were discussed in some detail. These problems include the degradation of water quality and contamination of the soil due to nitrate build up and leaching, phosphate accumulation, addition of phosphates and other salts, pathogenic bacteria and viruses, and accumulation of heavy metals. Nitrogen was described as the most important limiting factor in the application of sludge on a yearly basis.

II. The economics of sludge injection were presented, based upon data developed for the Boulder, Colorado, area. A method was developed for determining the overall cost of disposal--including injection cost and return from crop production--as a function of the sludge application rate.

III. A dynamic programming model was developed which incorporated both environmental factors in the form of nitrogen constraints and economic factors in the form of the overall disposal cost function. The model was developed to determine the minimum possible overall disposal cost for a particular site and to indicate the application rates, on a yearly basis, which would be necessary to achieve that cost without violating certain environmental constraints.

IV. The model was operated in a screening procedure to determine the sensitivity of the calculated costs and application rates to variations in the values of each of the input parameters.

V. The sludge injection model was applied to a specific example problem in both an optimization and simulation capacity. Finally, an overall method for planning a subsurface injection operation using a systems approach was briefly discussed.

Conclusions:

(1) Mathematical modeling and systems analysis techniques have a very large potential for use in planning and managing systems for the land disposal of municipal sewage sludge.

(2) The dynamic programming model described herein is capable of determining least-cost injection rates for a given set of input conditions. However, the determination of a workable injection pattern requires the additional use of a simulation routine based on the dynamic programming model.

(3) At present, satisfactory input data for the model cannot be developed due to lack of experimental results relating to the fate of sludge nitrogen in soils. Therefore, confidence in the numerical results of the model operation is limited, and the model cannot presently serve as the primary basis for planning a sludge disposal system. It could have considerable value in supplementing the normal planning process, however.

(4) Sufficient economic data exists so that costs may be estimated for specific subsurface injection systems. The costs will be highly site specific, depending upon such factors as distance from disposal site to treatment plant, suitability of site for subsurface injection, land cost, etc.

(5) The overall cost-effectiveness of the sludge disposal system will depend largely upon the ability of the system to produce a return from recycling nutrients through crop production or some other means.

(6) Even though mathematical programming techniques might be employed to the fullest possible extent, the success of the planning venture is almost entirely dependent upon the ability and originality of the planners in the collection of input data, making of assumptions, and formulation of alternatives and upon the soundness of their judgement in adopting a final plan. There is not, a "cookbook" approach to planning a subsurface injection system at present, nor is there likely to be in the near future.

Suggestions for Further Research

(1) Additional research is needed for determining the rate of mineralization of sludge organic matter nitrogen under various field conditions.

(2) More information is needed for prediction of the gaseous loss of sludge nitrogen by denitrification and ammonia volatilization under various field conditions.

(3) A detailed mathematical model could be developed to predict the fraction of available sludge nitrogen which will leach into the groundwater.

(4) Considerable research is necessary to evaluate the importance of sludge disposal environmental problems other than nitrogen. These include heavy metals, salts, and pathogens.

(5) Field research is needed to accurately evaluate crop response to fertilization by sludge nutrients.

(6) The dynamic programming model of sludge injection should be further developed to include a more accurate nitrogen model as well as additional environmental factors such as heavy metals, salts, and pathogens.

(7) Systems analysis techniques other than dynamic programming--such as linear or nonlinear programming--could be applied to the problem of land disposal of sludge.

(8) The systems analysis techniques described in this thesis should be applied in the design of an actual injection system. The results of the field operation of the system would then be used to refine and calibrate the dynamic programming model.

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APPENDIX 1

Nitrogen Mass Balance Calculations (Trout, 1975).

FACTORS	AMOUNT ADDED OR REMOVED kg/ha	AMOUNT ADDED OR REMOVED lb/ac
1. TOTAL N IN SLUDGE 3.3% INORGANIC N IN SLUDGE 1.3% ORGANIC N IN SLUDGE 2.0%	+ 1.3%S	+ 1.3%S
2. TOTAL AMOUNT OF SLUDGE TO APPLY (CALCULATED BELOW)	S	S
3. AVAILABLE SOIL N (ORGANIC MATTER DECOMPOSITION)	+ 60	+ 54
4. SLUDGE ORGANIC N MINERALIZATION 6% x SLUDGE ORGANIC N	+ 0.12%S	+ 0.12%S
5. LOSSES (VOLITILIZATION AND DENITRIFICATION) 20% x SLUDGE INORGANIC N	- 0.26%S	- 0.26%S
6. CROP UPTAKE: CORN	- 170	- 150
7. LEACHING ALLOWANCE	- 70	- 61
8. TIMING: AS CLOSE AS PRACTICABLE TO CROPPING (APPLY LESS THAN ONE MONTH BEFORE PLANTING)		

CALCULATIONS	AMOUNT OF SLUDGE TO APPLY (DRY WT) m ton/ha	AMOUNT OF SLUDGE TO APPLY (DRY WT) ton/ac
AMOUNT AVAILABLE N ADDED = AMOUNT REMOVED		
$(1.3\% + 0.12\%)S$ kg/ha + 60 kg/ha = $(0.26\%)S$ kg/ha + 70 kg/ha + 170 kg/ha		
$S = \dfrac{170 + 70 - 60}{0.01(1.3 + 0.12 - 0.26)}$ = 15,500 kg/ha	15.5	6.9
IF LEACHING ALLOWANCE (FACTOR 7) = 0 S = 9,400 kg/ha	9.5	4.1
IF LOSSES (FACTOR 5) = 50% x SLUDGE INORGANIC N S = 23,400 kg/ha	23.4	10.4
IF LEACHING ALLOWANCE (FACTOR 7) = 114 kg S = 19,300 kg/ha	19.3	8.6

APPENDIX 2

Listing of Dynamic Programming Code.

```
      FM LOAD PLAIN WHITE PAPER
C PROGRAM SLUDGE--DEVELOPED BY JIM LOFTIS, AGRICULTURAL ENGINEERING DEPT.,
C COLORADO STATE UNIVERSITY, 1975
C
C OPTIMIZATION OF MUNICIPAL SEWAGE SLUDGE DISPOSAL BY SUBSURFACE INJECTION
C
C       DYNAMIC PROGRAMMING CODE TO CALCULATE THE LEAST-COST APPLICATION RATE OF
C       SLUDGE ON A SITE FOR EACH YEAR OF OPERATION
C
C       NECESSARY INPUT DATA INCLUDES A YIELD-RESPONSE OR PROFIT CURVE, AN
C       INJECTION COST CURVE, AND A NUMBER OF PARAMETERS DESCRIBING THE NITROGEN
C       BALANCE FOR THE PARTICULAR SITE
C
C       THE DECISION VARIABLE, U, IS THE APPLICATION RATE IN TONS/ACRE
C       THE STATE VARIABLE,X, IS THE AMOUNT OF RESIDUAL ORGANIC-MATTER NITROGEN
C       IN THE SOIL FROM PREVIOUS SLUDGE APPLICATIONS
C
C INPUT VARIABLES
C  AMFR - AMMONIUM FRACTION OF SLUDGE
C  OMFR - ORGANIC-MATERIAL FRACTION OF SLUDGE
C  RMN1 - MINERALIZATION RATE, FIRST YEAR
C  RMN2 - MINERALIZATION RATE, ALL OTHER YEARS
C  RLOSS - GASEOUS LOSS RATE OF NITROGEN (FRACTION)
C  EFF - NITROGEN UPTAKE EFFICIENCY OF CROP
C  SNA - AVAILABLE NITROGEN IN UNAMENDED SOIL
C  ALLOW - ALLOWABLE NITRATE LEACHING LOSS
C  BNIT - LEACHED FRACTION OF AVAILABLE NITROGEN FOR FALLOW YEARS
C  ILAST - NUMBER OF STAGES
C  C(N) - DISCRETE VALUE OF COST FUNCTION
C  Y(M) - DISCRETE VALUE OF CROP RETURN FUNCTION
C  UMIN - MINIMUM APPLICATION RATE
C  UMAX(I) - MAXIMUM APPLICATION APPLICATION RATE FOR STAGE I
C  XMIN - MINIMUM VALUE OF STATE VARIABLE
C  XMAX - MAXIMUM VALUE OF STATE VARIABLE
C  X1 - INITIAL VALUE OF STATE VARIABLE
C  DELX - DISCRETIZATION INTERVAL OF STATE VARIABLE
C  DELU - DISCRETIZATION INTERVAL OF DECISION VARIABLE
C  M1 - NUMBER OF DISCRETE POINTS OF CROP RESPONSE CURVE
C  N1 - NUMBER OF DISCRETE POINTS OF COST CURVE
C  DELN - DISCRETIZATION INTERVAL FOR AVAILABLE FERTILIZER NITROGEN
C  KROP(I) - CROPPING SYSTEM INDICATOR FOR STAGE I
C
C OPERATIONAL VARIABLES
C
C  BLEACH - QUANTITY OF NITRATES LEACHED
C  CUSE - CROP UPTAKE OF NITROGEN
C  FMIN - CURRENT MINIMUM COST VALUE
C  FOPT - MINIMUM VALUE OF DISPOSAL COST FOR A GIVEN X
C  F1 - DISPOSAL COST FOR A FALLOW YEAR
C  G - VALUE OF STATE VARIABLE FOR STAGE I+1
C  I - STAGE
C  J - INTEGER VALUE OF X
C  JMAX - MAXIMUM VALUE OF J
C  M - INTEGER VALUE OF FERTILIZER NITROGEN PRESENT
C  N - INTEGER VALUE OF INJECTION RATE
C  L - INTEGER VALUE OF G
C  R - QUANTITY OF AVAILABLE NITROGEN CARRIED OVER FROM FALLOW YEAR
C  SLGNA - SLUDGE NITROGEN IN AVAILABLE FORM
C  TCF - TOTAL DISPOSAL COST
C  U - DECISION VARIABLE, SLUDGE INJECTION RATE
C  UOPT - CURRENT MINIMUM-COST INJECTION RATE
C  USTAR (I,J) - STORED VALUE OF OPTIMAL DECISION FOR CROPPED YEAR
```

```
C  USTAR1(I,J) - STORED VALUE OF INJECTION RATE FOR FALLOW YEAR
C  X - STATE VARIABLE, QUANTITY OF SLUDGE ORGANIC-MATERIAL NITROGEN IN SOIL
C  XX - TEMPORARY STORAGE VALUE OF X
C  AIC - AVERAGE INJECTION COST
C  K - COUNTER FOR YEARS OF INJECTION
C  A - REAL NUMBER VALUE OF K
C  ALOSS - GASEOUS LOSS OF NITROGEN
C  COST - CURRENT VALUE OF C
C  PROFIT - CURRENT VALUE OF Y
      PROGRAM SLUDGE(INPUT=1018,OUTPUT=1018)
      DIMENSION USTAR(30,130),USTAR1(30,130)
      DIMENSION FMIN(200),UMAX(50),Y(100),C(100),KROP(50)
   11 CONTINUE
      READ 100, ILAST,M1,N1,DELX,DELU,XMIN,X1,XMAX
  100 FORMAT (3I10,5F10.4)
      READ 110,DELN,BNIT
  110 FORMAT (2F10.4)
      READ 101, AMFR,OMFR,RMN1,RMN2,RLOSS,EFF,ALLOW,SNA
      READ 99,UMIN
   99 FORMAT (F10.4)
      READ 101,(UMAX(I),I=1,ILAST)
      READ 101,(Y(M),M=1,M1)
      READ 101,(C(N),N=1,N1)
  101 FORMAT (8F10.5)
      READ 112, (KROP(I),I=1,ILAST)
  112 FORMAT (16I5)
C
C PRINT OUT INPUT DATA
C
      PRINT 200, ILAST,M1,N1,DELX,DELU,XMIN,XMAX,X1,DELN
  200 FORMAT (5X,11HINPUT DATA-,3I5,6F8.2)
      PRINT 101, AMFR,OMFR,RMN1,RMN2,RLOSS,EFF,ALLOW,SNA
      PRINT 99,UMIN
      PRINT 101,(UMAX(I),I=1,ILAST)
      PRINT 101,(Y(M),M=1,M1)
      PRINT 101,(C(N),N=1,N1)
C
C START AT LAST STAGE
C
      I=ILAST
      K=ILAST
      J=1
      JMAX=10000
C
C INITIALIZE STATE VARIABLE
C
  111 PRINT 102,I
  102 FORMAT (4X,6HSTAGE=,I3)
      F=0.
      IF(KROP(I).GE.1) GO TO 14
      K=K+1
   14 CONTINUE
      F1=0.0
      IF(I.LE.1) GO TO 20
      GO TO 21
   20 X=X1
      GO TO 22
   21 X=XMIN
   22 CONTINUE
      XX=X
C
C CHECK CROPPING SYSTEM
      IF(KROP(I).GE.1) GO TO 12
C SUBROUTINE FOR YEARS OF NO CROP PRODUCTION
      CALL CROP (ALLOW,BNIT,X,RMN2,SNA,AMFR,OMFR,RMN1,UMAX,UMIN,RLOSS,DE
     1LU,C,I,XMIN,DELX,USTAR1,J,F1,XX,R)
   12 CONTINUE
C
C INITIALIZE VALUE OF OPTIMAL RETURN FUNCTION
      FOPT=1000000.
      G=XMIN
```

```
C
C NITROGEN MODEL COMPUTES THE QUANTITY OF NITROGEN AVAILABLE FOR LEACHING
C AND COMPARES WITH THE ALLOWABLE
C
    1 U=(G-X*(1.-RMN2))/(OMFR*(1.-RMN1)*2000.)
      SLGNA=((U*AMFR)+(U*OMFR*FMN1))*2000.+(X*RMN2)+R
      IF(U.LE.UMIN) GO TO 3
      IF(U.GT.UMAX(I)) GO TO 7
      ALOSS=RLOSS*SLGNA
      CUSE=EFF*(SLGNA+SNA-ALOSS)
      BLEACH=SNA+SLGNA-ALOSS-CUSE
      IF(BLEACH.GT.ALLOW) GO TO 7
C
C DISCRETIZE THE LEVEL OF AVAILABLE NITROGEN
C
      M=SLGNA/DELN+1.4999
C
C DISCRETIZE THE LEVEL OF SLUDGE APPLICATION
C
      N=(U-UMIN)/DELU+1.4999
C
C PICK VALUES OF CROP RETURN AND DISPOSAL COST FROM CURVES
      PROFIT=Y(M)
      COST=C(N)+F1
C
C COMPUTE COST OF DISPOSAL FOR THIS STAGE
      TCF=COST-(PROFIT/U)
      L=(G-XMIN)/DELX+1.4999
      IF(I.LT.ILAST) GO TO 4
      GO TO 5
    4 TCF=TCF+FMIN(L)
    5 IF(TCF.GT.FOPT)GO TO 3
      FOPT=TCF
      UOPT=U
    3 CONTINUE
      IF (G.GE.XMAX) GO TO 7
      G=G+DELX
      GO TO 1
    7 CONTINUE
      X=XX
      J=(X-XMIN)/DELX+1.4999
C
C STORE VALUES OF OPTIMAL RETURN FUNCTION AND OPTIMAL CONTROLS FOR EACH VALUE OF
C THE STATE VARIABLE
C     J IS THE INTEGER VALUE OF THE STATE VARIABLE
C
      USTAR(I,J)=UOPT
      FMIN(J)=FOPT
      IF(I.LE.1) GO TO 30
   60 CONTINUE
      X=X+DELX
      IF (X.LE.XMAX) GO TO 22
   50 CONTINUE
      I=I-1
      IF(I.GE.1) GO TO 111
   30 CONTINUE
C
C COMPUTE AVERAGE DISPOSAL COST
C
      A=K
      AIC=FOPT/A
      PRINT 108, AIC
  108 FORMAT (10X,19HAVG INJECTION COST=,2X,F8.2,2X,10HDOLLARS/MT/)
      PRINT 106
  106 FORMAT (10X,40HOPTIMAL APPLICATION RATES FOR EACH STAGE)
C
C GO BACK THROUGH, COMPUTING OPTIMAL CONTROLS
C
```

```
      LL=1
      DO 6 I=1,ILAST
      L=LL
      IF(KROP(I).LT.1) GO TO 8
      USTAR1(I,L)=0.
    8 CONTINUE
      PRINT 105,I,X,USTAR(I,L),USTAR1(I,L)
  105 FORMAT (4X,6HSTAGE=,I5,10HSTATE VAR=,F10.4,4X,17HAPPLICATION RATE=
     1,F10.4,2X,5HMT/HA,4X,11HNO CROP YR-,F10.4,2X,5HMT/HA/)
      IF(KROP(I).GE.1) GO TO 9
      U=USTAR1(I,L)
      G=X*(1.-RMN2)+U*OMFR*(1.-RMN1)*2000.
      LL=(G-XMIN)/DELX+1.4999
      X=(LL-1)*DELX+XMIN
    9 CONTINUE
      U=USTAR(I,L)
      G=X*(1.-RMN2)+U*OMFR*(1.-RMN1)*2000.
      LL=(G-XMIN)/DELX+1.4999
      X=(LL-1)*DELX+XMIN
    6 CONTINUE
      GO TO 11
      STOP
      END
      SUBROUTINE CROP (ALLOW,BNIT,X,RMN2,SNA,AMFR,OMFR,RMN1,UMAX,UMIN,RL
     1OSS,DELU,C,I,XMIN,DELX,USTAR1,J,F1,XX,R)
C
C CALCULATES APPLICATION RATES FOR YEARS OF NO CROP PRODUCTION
C ASSUMES THAT MAXIMUM ALLOWABLE NITRATES WILL BE LEACHED
C
      DIMENSION UMAX(50),C(100),USTAR1(30,130)
      U=((ALLOW/BNIT)-(X*RMN2)-SNA)/(2000.*(AMFR+OMFR*RMN1))
      IF(U.GE.UMIN) GO TO 113
      U=UMIN
      GO TO 114
  113 CONTINUE
      IF(U.LE.UMAX(I)) GO TO 114
      U=UMAX(I)
  114 CONTINUE
      SLGNA=((U*AMFR)+(U*OMFR*RMN1))*2000.+(X*RMN2)
      ALOSS=RLOSS*SLGNA
      F=(1.-BNIT)*(SLGNA+SNA)-ALOSS
      G=X*(1.-RMN2)+U*OMFR*(1.-RMN1)*2000.
      L=(G-XMIN)/DELX+1.4999
      TEST=(U-UMIN)/DELU+1.4999
      N=TEST
      F1=C(N)
      T=N-1
      U1=U
      J=(X-XMIN)/DELX+1.4999
      USTAR1(I,J)=U1
      XX=X
      X=(L-1)*DELX+XMIN
      RETURN
      END
      EM UNLOAD PLAIN PAPER
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