Land Treatment of Municipal Wastewater Effluents

Case Histories

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LAND TREATMENT OF MUNICIPAL WASTEWATER EFFLUENTS

CASE HISTORIES

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The information in Chapters I-IV was prepared by Frank M. D'Itri, Ph.D., Michigan State University, East Lansing, Michigan, with assistance from Thomas P. Smith, P.E., City of Tallahassee, Florida; Herman Bouwer, Ph.D., U.S. Dept. of Agriculture, Phoenix, Arizona; Earl A. Myers, Ph.D., Williams and Works, Thomasville, Pennsylvania; and Allen R. Overman, Ph.D., Univerisity of Florida, Gainesville, Florida. The information in Chapter V was prepared by Gordon Culp, Culp/Wesner/Culp, El Dorado Hills, California.

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INTRODUCTION

With the advent of the Water Quality Amendments of 1972, which require that all discharge of pollutants into the nation's waterways cease by 1985, major technological advances have become necessary. New methods of wastewater treatment must be devised, and responsible development will hinge on learning much in a short time.

A number of experimental/operational systems have been designed to renovate wastewater by land application.[1] Where sufficient land is available and the hydrological conditions are favorable, wastewater can be renovated through infiltration basins, ridge and furrow, overland flow, or sprinkler systems, all of which recharge groundwater and are viable alternatives to chemical or biological tertiary treatment systems. In a properly managed system, the wastewater, as it moves through the soil, removes or greatly reduces suspended solids, biochemical oxygen demand, microorganisms, phosphorus, fluorides, heavy metals, nitrogens, and many other substances.

This publication presents case histories of five properly managed systems of land application of municipal wastewater. In terms of purpose, natural conditions, and problems of implementation, the projects presented have somewhat different histories. The design criteria and operation of each facility are described, as well as the soil characteristics and the monitoring schedules used to assess the chemical and biological parameters. The five facilities considered are:

- The Michigan State University Water Quality Management Project (WQMP)
- The City of Tallahassee Spray Irrigation Project (TSIP)
- The Flushing Meadows Project (FMP)
- The Pennsylvania State University Wastewater Renovation and Conservation Project (WRCP)
- The City of Boulder Colorado Project (BCP)

Several points differentiate the five facilities. The most significant is that three of them were designed initially as pilot plants to provide alternative methods of wastewater removal from currently operating sewage treatment facilities.

The Michigan State University WQMP was designed exclusively as a research and development project to study alternative aquatic and terrestrial applications of wastewater to utilize the components as food for plants and animals. Because the facility was created with research in mind and did not fit into an existing sewage treatment plan, except that the effluent is pumped from the East Lansing sewage treatment plant after being given secondary treatment, the land could be studied in its natural state before the project was implemented and can be charted as time goes on to determine whether changes occur in the groundwater, soil, or other variables at the site. For this purpose and because the site is experimental, the quantity of waste can be carefully monitored and controlled.

At Boulder, Colorado, local conditions were such that land treatment showed an economic advantage. Local conditions have a major effect on applicability and cost. Although estimated costs for one locale may not be applicable elsewhere, the techniques used to reach the cost estimates and other conclusions generally apply. The purpose of the BCP presentation is to describe the factors to be considered in evaluating alternative treatment approaches. The costs presented are based on July 1974 price levels and are obviously outdated. However, the elements to be considered in making such estimates are unchanged and are more important in this context than are the precise values.

Both WQMP and WRCP have seasonal variables that affect their operations, whereas year-round operation is possible at TSIP and FMP. The latter has no spray irrigation system. Instead, the water is pumped into infiltration basins, from which it is rapidly absorbed into the soil.

All three of the pilot plant programs were begun to determine whether land disposal could provide an alternative for or addition to the conventional sewage treatment systems, and all are now being expanded to meet the demand of the increasing population. At Tallahassee, it was decided to apply all of the city's wastewater to the land by sprinkler irrigation as soon as possible. At Penn State, the expansion plan drawn up in 1968 provided for land application of all of the wastewater, but budget constraints limited construction to only three-quarters of the system, which will be operational in the spring of 1976. Phoenix has recently constructed four 10-acre rapid infiltration basins to renovate approximately 15 mgd of secondary effluent for unrestricted use by an irrigation district. The design of the project was based on data from the FMP to plan the hydraulic loadings and anticipated quality of the renovated water. If this project is also successful, a third and larger rapid infiltration basin system will be constructed. Although Boulder has two secondary trickling filter treatment plants with capacity adequate to handle projected 1985 flows, they cannot provide treatment required to meet pending discharge requirements.

Chapter I

THE MICHIGAN STATE UNIVERSITY WATER QUALITY MANAGEMENT PROJECT

After the initial concept was developed, financial support and approval to implement the design were received from the Michigan State University Board of Trustees in December, 1966. In 1968, the 500-acre project site was designated on the south end of the campus. Shortly thereafter, the Rockefeller, Ford, and Kresge Foundations pledged $1.2 million in support of the project. During the summer of 1972, funding approval was also received from the Environmental Protection Agency and the State of Michigan through the Clean Water Bond Act. Construction began in April, 1973. In September, 1973, the lakes were filled with wastewater and a number of types of aquatic plants were sown. The Water Quality Management Project (WQMP) facility was completed in the spring of 1974 and officially dedicated that October.

THE WQMP FACILITY AND ITS OPERATION

This $2.3 million outdoor laboratory on the Michigan State University campus consists of four artificial lakes with a total surface area of 40 acres and an average depth of 8 feet. The site also includes three 1-acre marshes and 320 acres of land, 150 acres of which are equipped for spray irrigation (see figure I-1). Municipal wastewater undergoes primary and secondary treatment at the East Lansing sewage treatment plant before being delivered to the lakes through 4.5 miles of 21-inch asbestos-concrete pipe. Up to 2 million gallons can be transported per day. The wastewater undergoes chemical, biological, and physical renovation over 30 to 60 days while it passes sequentially through the four lakes. The water can then be released into surface streams or sprayed onto the land.

The prime challenge of wastewater treatment is to concentrate and remove pollutants from very dilute solutions. The WQMP offers the opportunity to evaluate the potential for productive waste removal by a number of individual and combined natural aquatic and terrestrial ecosystems. The great flexibility of this project allows researchers to test various methods of using fields, forests, marshes, and lakes to produce more food and fiber from wastewater in a manner that will protect public health. Moreover, the risk of causing new problems by adding more chemicals for treatment is diminished because most of the treatment is biological. By themselves, plants and sediments remove substantial quantities of the waste constituents from the solutions.

For example, one aspect of the project takes advantage of the fact that solar energy generates photosynthesis in algae and rooted aquatic plants. As these plants grow in the lakes, they take up the abundant nutrients in the wastewater and alter their chemical composition to accelerate the physical and chemical removal of the remaining pollutants. They settle to

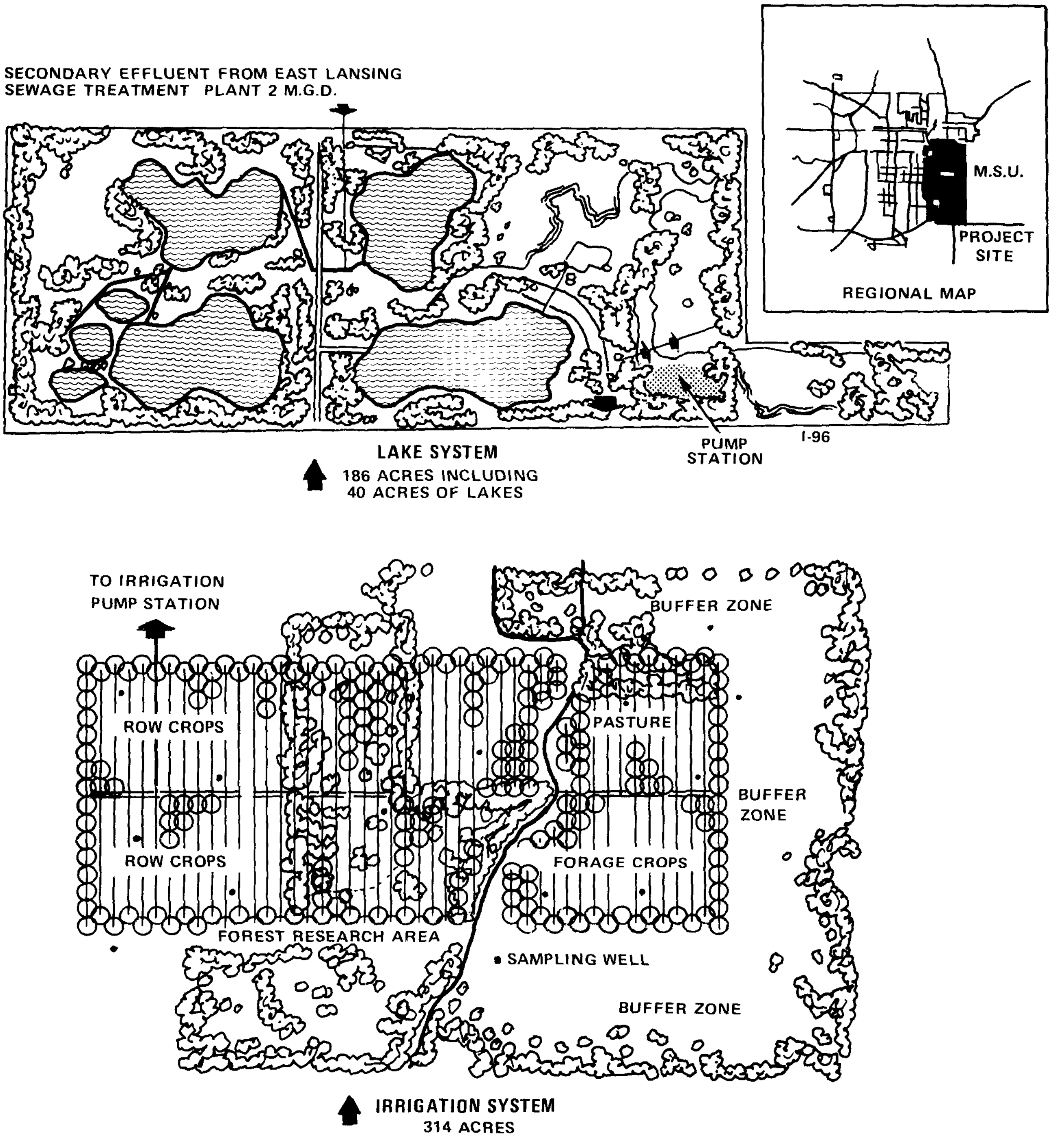


Figure I-1. Michigan State University Water Quality Management Project.

the bottom of the lakes and then are pumped through the irrigation system to the terrestrial site where the concentrated wastes accelerate plant growth. Both aquatic and terrestrial plants are to be harvested for animal food or soil conditioners.

CHEMICAL, PHYSICAL, AND BIOLOGICAL MONITORING PROGRAM

The WQMP Laboratory is monitoring over 50 chemical, physical, and biological parameters as the effluent passes through various stages from the treatment plant through the lake and irrigation site. These parameters and the sampling timetable are presented in table I-1. The average concentrations and ranges of selected chemical parameters for the system are presented in tables I-2 and I-3. This analytical program will provide a data base for all scientists conducting research on the project.

Daily 24-hour composite samples are collected to represent raw, primary, and secondary effluent at the East Lansing sewage treatment plant. At the site of the WQMP, 24-hour composite samples are collected from the influent to each lake and the final effluent concentration from Lake 4. The aquatic plants and sediments are also sampled periodically. From these data, the percentage of elements for each parameter can be ascertained to facilitate tracing their translocation into either the sediments or the aquatic plants.

Possible groundwater contamination at both the lakes and spray irrigation sites is monitored by monthly analyses of well water. Forty-one drift wells, 14 shallow rock wells, and 4 deep rock wells have been positioned throughout the study area (figure 1-2). All wells are 4 inches in diameter and have a 3-foot copper screen point and sanitary seals to prevent bacteriological contamination. The drift wells, the shallowest of the three, are positioned in the glacial drift between 40 and 60 feet deep. Samples are obtained by pressurizing the drift wells and forcing the water through a plastic pipe which extends to the bottom of the well. Both shallow and deep rock wells extend into the aquifer which provides the water supply for the university. The shallow rock wells are approximately 85 feet deep on the average, and the deep rock wells average about 180 feet. All are equipped with submersible pumps for sampling. Guarding against contamination, particularly from potential sources of viruses, was the most severe constraint in planning the sampling program from these wells. Comparing post-operational data with background levels should detect contamination from the lake or spray irrigation water.

A little surface runoff in the study area is channeled into Felton Drain. Although it now flows only in the spring and summer, this will probably increase significantly when spray irrigation begins. Therefore, monthly samples will also be analyzed to determine the chemical characteristics of this water. Effluent from Lake 4 can be discharged from an experimental stream into the Red Cedar River via Herron Creek. At present this creek, like Felton Drain, has an intermittant flow, but operational flow levels will also be monitored. After the effluent has been sprayed on the irrigation site, analyses will be conducted of water collected in soil suction infiltrometers and plant tissue. These data will indicate how much of the remaining nutrients is absorbed by the soil and terrestrial systems after the water has gone through the lake system.

A data management system is being implemented to handle the large volume of data that are generated. This system is designed to:

- Store, retrieve, prepare, manipulate, and display all data

Table I-1.—*The Michigan State University Water Quality Management Project monitoring program experimental analyses design*

Chemical, biological, or physical parameter	Sampling frequency						
	STP	Lake water	Lake sediments	Campus and test wells	Felton and Herron Creek	Soil samples	Analyses per year
1. Temperature	CONT	CONT	4Y	MIS	MIS	2Y	1032
2. pH	CONT	CONT	4Y	MIS	MIS	2Y	1032
3. Dissolved oxygen	CONT	CONT	NSR	MIS	MIS	NSR	828
4. Specific conductance	CONT	CONT	4Y	MIS	MIS	NSR	924
5. Turbidity	CONT	CONT	NSR	MIS	MIS	NSR	828
6. Light penetration	CONT	CONT	NSR	NSR	NSR	NSR	-0-
7. Redox potential	CONT	CONT	4Y	MIS	MIS	2Y	1032
8. Ammonia	D24C	2D12C	4Y	MG	M168C	2Y	5777
9. Nitrate	D24C	2D12C	4Y	MG	M168C	2Y	5777
10. Nitrite	D24C	2D12C	4Y	MG	M168C	2Y	5777
11. Kjeldahl nitrogen	D24C	2D12C	4Y	MG	M168C	2Y	5777
12. Ortho phosphate	D24C	2D12C	4Y	MG	M168C	NSR	5669
13. Total inorganic phosphorus	D24C	2D12C	4Y	MG	M168C	NSR	5669
14. Total phosphorus	D24C	2D12C	4Y	MG	M168C	2Y	5777
15. Chloride	D24C	2D12C	4Y	MG	M168C	2Y	5777
16. COD	D24C	2D12C	4Y	MG	M168C	2Y	5777
17. Silicon	W168C	W168C	NSR	MG	M168C	NSR	1244
18. Hardness	D24C	2D12C	NSR	MG	M168C	NSR	5573
19. Cyanide	W168C	W168C	NSR	MG	M168C	NSR	1244
20. Sulfide	W168C	W168C	4Y	MG	M168C	NSR	1340
21. Alkalinity	D24C	D24C	NSR	MG	M168C	NSR	2748
22. Phenol	W168C	W168C	NSR	MG	M168C	NSR	1244
23. Dichromate	W168C	W168C	NSR	MG	M168C	NSR	1244
24. Fluoride	W168C	W168C	NSR	MG	M168C	2Y	1352
25. Sulfate	W168C	W168C	4Y	MG	M168C	2Y	1448
26. Boron	D24C	2D12C	4Y	MG	M168C	2Y	5777
27. Total carbon	D24C	2D12C	4Y	MG	M168C	2Y	5777
28. Total filterable carbon	D24C	2D12C	NSR	MG	M168C	NSR	5573
29. Filterable organic carbon	D24C	2D12C	NSR	MG	M168C	NSR	5573
30. Total organic carbon	D24C	2D12C	4Y	MG	M168C	2Y	5777
31. BOD_5	D24C	2D12C	4Y	MG	M168C	NSR	5669
32. Suspended solids	D24C	2D12C	NSR	MG	M168C	NSR	5573
33. Settleable solids	D24C	2D12C	NSR	MG	M168C	NSR	5573
34. Dissolved solids	D24C	2D12C	NSR	MG	M168C	NSR	5573
35. Hexane extractables	D24C	2D12C	4Y	MG	M168C	2Y	5777
36. Aluminum	W168C	W168C	4YDC	MG	M168C	2Y	1400
37. Arsenic	W168C	W168C	4YDC	MG	M168C	2Y	1400
38. Cadmium	W168C	W168C	4YDC	MG	M168C	2Y	1400
39. Calcium	W168C	W168C	4YDC	MG	M168C	2Y	1400
40. Chromium	W168C	W168C	4YDC	MG	M168C	2Y	1400
41. Cobalt	W168C	W168C	4YDC	MG	M168C	2Y	1400
42. Copper	W168C	W168C	4YDC	MG	M168C	2Y	1400

Table I-1.—*The Michigan State University Water Quality Management Project monitoring program experimental analyses design (Continued)*

Chemical, biological, or physical parameter	Sampling frequency						
	STP	Lake water	Lake sediments	Campus and test wells	Felton and Herron Creek	Soil samples	Analyses per year
43. Iron	W168C	W168C	4YDC	MG	M168C	2Y	1400
44. Lead	W168C	W168C	4YDC	MG	M168C	2Y	1400
45. Magnesium	W168C	W168C	4YDC	MG	M168C	2Y	1400
46. Manganese	W168C	W168C	4YDC	MG	M168C	2Y	1400
47. Mercury	W168C	W168C	4YDC	MG	M168C	2Y	1400
48. Nickel	W168C	W168C	4YDC	MG	M168C	2Y	1400
49. Potassium	W168C	W168C	4YDC	MG	M168C	2Y	1400
50. Sodium	W168C	W168C	4YDC	MG	M168C	2Y	1400
51. Residual chlorine	D24C	SAR	NSR	NSR	SAR	NSR	365

KEY

Type of Sampling

C	= Composite	SAR	= Sample as required
G	= Grab	NSR	= No sample required
DC	= Core sampling	IS	= In situ analysis

Frequency of Sampling

CONT	= Continuous	W	= Weekly
H	= Hourly	M	= Monthly
D	= Daily	Y	= Yearly

Integers preceding the frequency code letter designate the numbers of samples taken within that period.
Integer preceding the letter C indicates that the number of hours of the sample is composited

Table I-2.—*Average concentrations (ppm) and ranges (within parentheses) or selected chemical parameters in East Lansing wastewater during the period of October, 1973 - March, 1975*

Chemical parameter	Raw	Primary	Secondary
Total phosphorus mg/l-P	7.0 (3.6-9.5)	5.0 (2.6-10.5)	2.6 (0.5-9.1)
Soluble phosphorus mg/l-P	3.0 (2.7-5.7)	1.1 (2.1-3.8)	1.1 (0.3-7.9)
Ammonia nitrogen mg/l-N	9.3 (4.1-32)	16 (8.6-25)	9.7 (5.2-22)
Nitrate nitrogen mg/l-N	0.005 (<0.005-0.03)	0.25 (<0.005-0.13)	0.25 (0.07-0.90)
Nitrate nitrogen mg/l-N	0.54 (0.16-3.1)	0.2 (0.09-2.33)	1.07 (0.16-7.0)
Kjeldahl nitrogen mg/l-N	25.3 (4.4-38)	26.3 (18.7-45)	12.7 (8.5-28)
Total carbon mg/l-C	183 (67-202)	171 (55-215)	120 (60-227)
Total organic carbon mg/l-C	73 (43-105)	50 (38-97)	30 (12-111)
Boron mg/l-B	0.33 (0.49-0.19)	0.31 (0.35-0.29)	0.33 (0.42-0.21)
Calcium mg/l-Ca	108 (95-125)	110 (85-125)	113 (90-129)
Sodium mg/l-Na	103 (58-295)	110 (59-295)	119 (63-300)
Magnesium mg/l-Mg	25 (20-29)	26 (20-30)	24 (20-28)
Manganese mg/l-Mn	0.16 (0.10-0.39)	--- ---	0.09 (0.03-0.18)

Table I-3.—*Average concentrations (ppm) and ranges (within parentheses) of selected chemical parameters in the WQMP lake system during the period of October, 1973 - March, 1975*

Chemical parameter	Lake 1	Lake 2	Lake 3	Lake 4
Total phosphorus mg/l-P	1.91 (0.86-3.23)	1.34 (0.57-2.62)	1.37 (0.55-3.35)	0.54 (0.22-1.27)
Soluble phosphorus mg/l-P	1.49 (0.55-2.66)	1.24 (0.57-2.62)	1.06 (0.51-2.32)	0.34 (0.12-0.80)
Ammonia nitrogen mg/l-N	4.87 (0.36-9.7)	4.91 (0.26-10.6)	3.77 (0.27-8.1)	3.36 (0.10-8.3)
Nitrite nitrogen mg/l-N	0.15 (0.006-0.33)	0.09 (0.03-0.18)	0.16 (0.02-0.15)	0.06 (0.20-0.09)
Nitrate nitrogen mg/l-N	1.64 (0.06-12.3)	1.64 (0.06-10.9)	1.02 (0.10-1.72)	0.77 (0.10-1.25)
Kjeldahl nitrogen mg/l-N	9.75 (1.16-21)	9.45 (3.30-15)	8.53 (4.50-15)	5.73 (2.0-14)
Total carbon mg/l-C	55 (27-80)	47 (24-69)	43 (24-60)	31 (10-46)
Total organic carbon mg/l-C	14 (6-48)	8.6 (0-11)	9 (4-13)	7 (3-20)
Boron mg/l-B	0.33 (0.41-0.26)	0.25 (0.30-0.20)	0.25 (0.31-0.23)	0.25 (0.29-0.19)
Calcium mg/l-Ca	49 (39-71)	46 (30-70)	45 (34-68)	33 (15-51)
Sodium mg/l-Na	82 (68-111)	79 (49-108)	78 (60-108)	59 (16-79)
Magnesium mg/l-Mg	20 (14-32)	19 (13-32)	19 (14-32)	12 (4-20)
Manganese mg/l-Mn	0.05 (<0.05-0.10)	0.05 (<0.05-0.09)	<0.05 (<0.03-<0.05)	<0.05 (<0.03-<0.05)

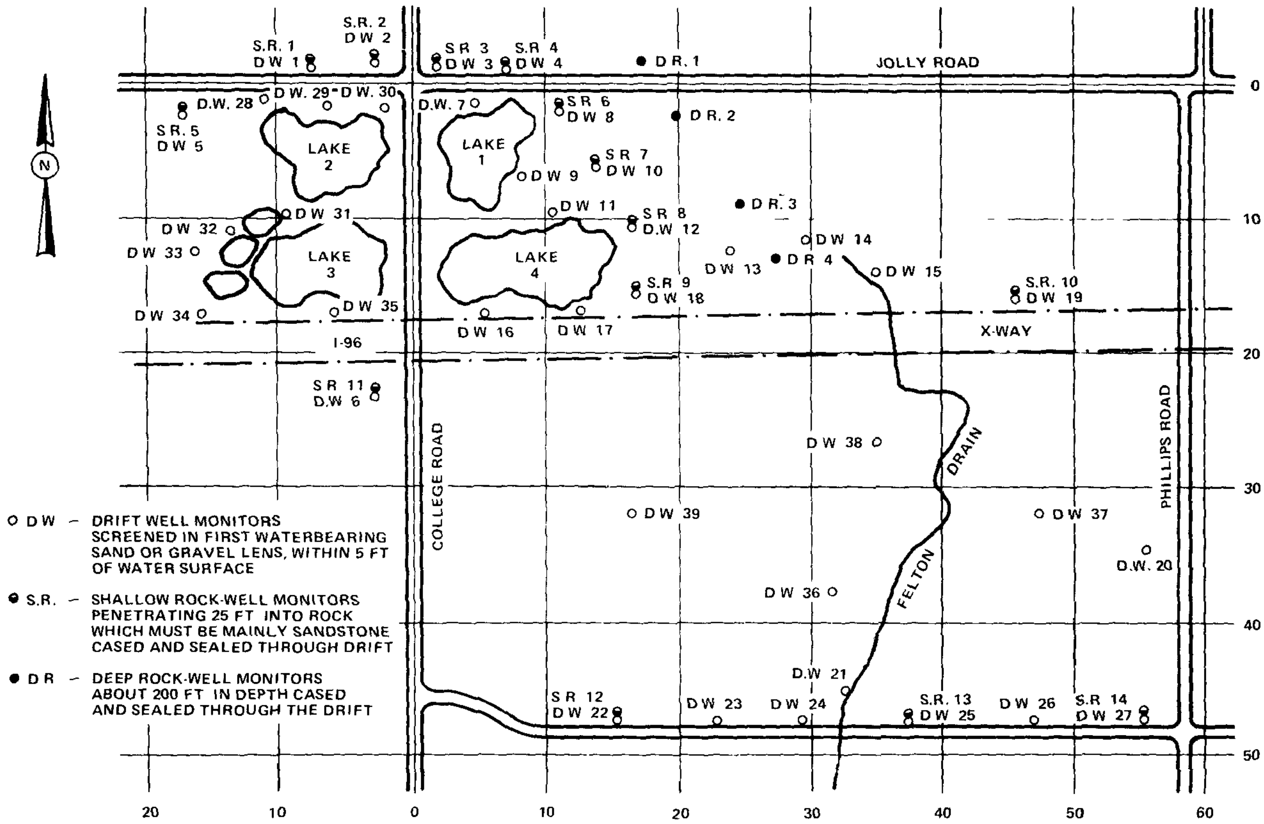


Figure I-2. WQMP study area.

- Transfer data from the producer to all authorized users
- Prevent its loss, destruction, or unauthorized use

The data are stored in the Michigan State University CDC 6500 computer under the mnemonics and code acquisition numbering of the STORET data management system whenever it can be used.

MICROBIOLOGICAL AND VIRAL MONITORING

Microbiological and Viral Studies[2]

At the East Lansing plant, the wastewater treatment does not remove all of the pathogens from the sewage, especially the viruses which are difficult to destroy even by chlorinating the treated water. Forty percent of the samples still contained viruses after the effluent was chlorinated at the East Lansing plant. They remained in water that was discharged into the Red Cedar River just downstream from the Kalamazoo Street bridge.

Viruses also remained in 44 percent of the samples of river water taken as far as 500 feet downstream from the chlorinated effluent. The samples ran as high as 70 percent when the effluent was not chlorinated.[3]

The WQMP microbiological and viral research program is designed to find methods of preventing public health hazards when municipal wastewater is eliminated and/or reused. The primary objectives of the program are to:

- Measure the pathogens, bacteria, and viruses in the East Lansing wastewater, in the WQMP lakes, and on the land after spray irrigation.

- Determine the rate and efficiency of removing these pathogens during processing by the East Lansing wastewater treatment plant and as the water passes through the WQMP wastewater renovation system.

- Monitor the water from the wells drilled around the WQMP lakes to detect contamination of the aquifer.

- Monitor the purity of the University's water supply.

Analyses for viruses will be accomplished with methods that have been used at the East Lansing wastewater plant for many years to isolate pathogenic *Salmonella* and *Shigella.*[4] Studies at the original[5] and present water treatment plant have authenticated the value of one method for isolating viruses in wastewater.[6] Pad samplers, 4-inch squares of absorbent cotton, are placed between two layers of cheesecloth and are held in place by sewing the three layers together. They will be used on all flowing water to trap bacteria and virus particles. After the pad accumulates and concentrates the bacteria and viruses, they can be isolated with standard methods.[7] Careful concentration and strict culture procedures are required to isolate the complex viruses. The fluid in the pad is expressed and approximately 100 ml is concentrated by ultracentrifugation. The resulting "sediment" is then suspended in approximately 3 ml of the supernatant fluid in about a 1:95 volume concentration. After the bacteria are eliminated with antibiotics, the sample is centrifuged at slow speeds. If the bacterial sterility controls are then negative, the sample is introduced on cultures of African green monkey kidney cells. The isolated viruses are subsequently passed into secondary cultures to be identified by serological methods if that is necessary.

Water samples from the monitoring wells are collected in gallon volumes and are passed through the continuous flow ultracentrifuge to remove the viruses. Specific polyethylene imines are added to the water sample to enhance survival of the infective virus particles. After concentration, the samples are tested for sterility and introduced into the cell cultures as previously described. If samples of water from the monitoring wells contain viruses, the quantity will be determined by plaque counting. These methods are routinely used in this laboratory for the isolation of viruses from sewage and water.[3,5]

More enteric bacteria and viruses are in wastewater in the late summer and early fall.[4] Therefore, more water samples are collected during these periods. Pad samples will be taken at various stages of treatment in the East Lansing wastewater plant as well as from the inflow and outflow of the WQMP lakes to compare the recovery of pathogens. In both systems, more effort will be exerted to recover and analyze viruses than the pathogenic bacteria which are more readily destroyed.

While water samples from all the monitoring wells will be tested for bacteria and viruses, those wells located close to the WQMP lakes will be tested the most frequently. By recovering the coliform organisms, bacterial slippage through the soil will be detected. If this occurs, repeated tests will be initiated to determine the amount of slippage and the radial spread of the viruses.

Aerosol samples will be collected for bacterial studies with such sampling devices as the Anderson sampler,[8] silt sampler,[9] all glass impinger,[10] and syringe sample. Since no satisfactory method is now available to sample enteric viruses in aerosols, it will be necessary to develop methods at the spray irrigation site. Exposing live animals to the aerosol is probably the only solution at this time. Studying the animals' immunity response before and after exposure will give evidence of infection from enteric viruses in the aerosol, as exposing the animals at various times and distances from the aerosol jets will determine the relative hazards, if any.

SCOPE OF RESEARCH

The project site on the Michigan State University campus was designed to encourage maximum cooperative research by scientists from such diverse areas as limnology, botany, crop and soil sciences, economics, engineering, entomology, fisheries, forestry, horticulture, hydrology, geology, sociology, zoology, and chemistry.

The research can characterize the dynamics of wastewater constituents in an integrated system of wastewater treatment and nutrient recycling. First, the magnitude and direction of the biotic and abiotic factors are being identified to determine how they affect the movement of phosphorus, nitrogen, and carbon in aquatic and terrestrial systems. The movement of these nutrients, especially phosphorus, is being monitored through several significant subunits of the WQMP.

The Aquatic System

In the aquatic system, the nutrients and other pollutants are being stripped from the water by various chemical, biological, and physical methods.

- Some of them are adsorbed onto particulates which are sedimented or directly adsorbed onto bottom sediments.
- Some wastes are removed by direct chemical precipitation whenever photosynthesis by algae and plants causes the pH of the system to increase.
- Some of these materials are taken up by photoplankton and algae which die and transport them to the sediments. A unique feature of the aquatic system is the marsh area located between Lakes 2 and 3. This was included to investigate how a marsh ecosystem removes nutrients, especially through denitrification.
- Some nutrients have a secondary uptake into aquatic animals such as zooplankton, insects, crayfish, tadpoles, minnows, and fish.

- Aquatic macrophytes also remove nutrients as they grow. This, in turn, provides vast adsorptive surfaces which also remove these pollutants. To take advantage of these removal mechanisms, the following 10 species of aquatic macrophytes were transplanted into the lake system: *Potamogeton foliosus, P. pectinatus, P. crispus, Elodea canadensis, E. nuttallii, Myriophyllum spicatum, Najas flexilis, Ranunculus sp.*, and *Vallisneria americana.* Preliminary studies of these macrophytes indicate that ash-free dry weight net yields of approximately 2.1 kg/m^2 can be expected over a 6-month growing season. The phosphorus and nitrogen content of the harvested plants are typically about 1.5 and 5 percent, respectively.[11]

The Terrestrial System

Research on the terrestrial system involves delinating the short- and long-term effects of wastewater effluent on soil hydrology, texture, and composition. In conjunction with these research programs, the survival and growth of various types of trees, weeds, and cultivated crops are also being investigated.

Hydrologic Studies[12]

Studies are underway at the terrestrial site to explain the hydrological response as the watershed receives spray irrigation with treated municipal wastewater. Inasmuch as major producing wells are situated nearby, the groundwater flow beneath the WQMP must be carefully monitored to assess the impact of the spray irrigation and lake operations on the aquifer system. A comprehensive groundwater study has been underway for over 2 years with the ultimate objective of being able to predict and monitor the dispersive nature of water with varying degrees of quality in the flow regions of the aquifer.

A digital computer program has also been developed and implemented to make use of triangular finite elements.[13] With the Galerkin method, the space variables can be distinguished in the basic unsteady flow equation. Coupled with a central difference time step formulation, this can solve the resulting systems of algebraic equations. The computer model is designed to handle a variety of regional situations, including steady or unsteady and confined or unconfined flows. Finite element methods have definite advantages to model complex boundaries and variable inputs such as recharge, pumping, and field properties. Numerical solutions for single-well systems can be compared with known analytical results to show some of the limitations of the model. Applications to field situations emphasize flow analyses at the WQMP site. A 6-year simulation of the hydrodynamic response of the aquifer is also being compiled with historical pumping data.

In another aspect of this project, flows are being analyzed in the glacial drift overlying the aquifer. Once these flows have been traced more accurately, the percolation of recharged water downward into the main aquifer can be estimated and its response studied. In addition, the unsteady flow model will be coupled with the convective-dispersion equations to predict water quality in the aquifer. In the future, isoparametric elements in the flow model will be used to ease data input manipulation and reduce the required computer storage. At the same time, the available numerical techniques will be reviewed to solve the convective dispersion equations and determine which ones are best suited for the present system. Then comprehensive analyses of surface hydrology and runoff will be combined with subsurface flow at the spray irrigation site to explain the total movements of irrigation water.

The piezometric surface and water table conditions at the site are now being monitored so that future flow predictions can be correlated with field data. Six automatic water-level recorders were installed on selected test wells for continuous monitoring. At specified time intervals, water levels in all of the test wells are manually recorded by means of drop lines. Well borings have been analyzed and the coordinates of all the test wells in the system have been determined.

Another hydrologic study is underway to assess the feasibility and potential of a winter spray operation. The first overall objective is to study the hydrologic balance of both natural and wastewater added to the subwatershed for the winter months. Continuing investigations will monitor the same parameters for an entire water year to determine water quality for both surface runoff and infiltration.

The 10-acre subwatershed is located in the southwest portion of the spray region and drains into Felton Creek. Normal drainage is probably through the subsurface with some runoff directly into the stream during both periods. Approximately 4 inches of wastewater is applied to the area per week on an intermittant schedule that started in January, 1975. This research project should determine the impact of ice accumulation, infiltration characteristics beneath the spray area, runoff response, and the fate of nutrients in the runoff and infiltrated water. The integrated data computed from these hydrologic studies will provide integrated data on the water quantity and quality balance at the spray irrigation site.

CROP MANAGEMENT[14]

The objectives of this research program are as follows:

- To compare annual crops with perennial forage crops that produce the high yields needed to feed livestock over several years without having to be reestablished. When the crops are irrigated with high levels of sewage effluent, they can be harvested under varying time frequencies to obtain the maximum biomass per acre.
- To determine how soils and plants fix minerals and the fate of heavy metals when wastewater effluent is applied on perennial forage crops and annual crops.
- To estimate the *in vitro* digestibility as an indicator of *in vivo* digestibility to secure maximum biomass and adsorption of nutrients.

The field plots were established on 2 acres and irrigated from early May to late November with 1, 2, and 3 inches of wastewater effluent each week. Table I-4 gives the estimated soil loading per acre with an application of 1 inch of secondary effluent from the East Lansing plant. The soil was categorized in October, 1973, as a uniform Miami loam by taking 45 samples in 1-foot increments to a depth of 10 feet.

The eight perennial legumes and eight perennial grasses were established in August, 1973, by seeding with a precision planter. In one area, rye was sown in early September to serve as a winter cover crop. The annual crops—two varities of hybrid corn, one forage sorghum, and

Table I-4.—*Estimated soil loadings per acre on application of 1 inch of East Lansing sewage treatment plant secondary effluent*

Chemical parameter	Concentration in secondary effluent (mg/l)	Grams per acre inch	Pounds per acre inch	Pounds per acre per year[a]
Organic nitrogen	2.2	227	0.5	36
Nitrate nitrogen	3.07	317	0.7	50
Nitrite nitrogen	0.25	26	0.06	4.1
Ammonia nitrogen	9.70	1,261	2.77	200
Soluble phosphorus	1.1	143	0.3	23
Total phosphorus	4.9	637	1.4	101
Total carbon	150	15,450	34	2,445
Total organic carbon	30	3,090	6.8	489
Dissolved organic carbon	20	2,060	4.5	326
Suspended solids	63	6,489	14.3	1,027
Volatile solids	25	2,575	5.7	408
Chlorides	261	26,883	59.1	4,254
Iron[b]	0.81	83	0.18	13.2
Manganese	0.09	9	0.02	1.5
Zinc	0.19	20	0.04	3.1
Nickel	0.11	11	0.025	1.8
Copper	0.06	6	0.013	1.0
Mercury	0.00005	0.005	0.00001	0.0008

[a]At a rate of 2 inches per week between March and November (36 weeks).
[b]Iron is being added for chemical phosphorus removal at the East Lansing sewage treatment plant.

one sorghum sudangrass—were established in mid-May with a no-till planter after the rye was treated with Paraquat herbicide to kill the top growth (see table I-5).

Because of technical problems, the wastewater effluent was not available until July 16, 1973. Then effluent spray levels of 1, 2, and 3 inches per week were started and continued for 14 weeks until October 21, when the final plots were harvested and the soil was sampled. The untilled soil absorbed the effluent rapidly. One inch was absorbed in an hour without any runoff, even on plots that received 3 inches per week in three applications of 1 inch each on Monday, Wednesday, and Friday.

Yields of the first annual grass crop and three harvests of perennial grasses were lower than expected, probably because in the 14-week irrigation period, only approximately 27, 54, and 91 pounds of nitrogen were applied per acre at the 1-, 2-, and 3-inch levels of effluent, respectively. At least 150 pounds of nitrogen per acre are necessary for a good yield of perennial grasses and annual grass crops such as corn. Even at the high rate of effluent spray with 91 pounds of nitrogen per acre, annual and perennial grasses were deficient by about 60 pounds per acre. However, the legumes yielded well and showed no symptoms of mineral or nitrogen deficiency. Apparently the legumes obtained enough nitrogen symbiotically from the

Table I-5.—*Plants irrigated with municipal wastewater effluent for forage crop production (planted August 1973, harvested 1974)*

Perennials
Grasses
Smooth bromegrass (*Bromus inermis* Leyss) cultivar Sac (southern)
Smooth bromegrass (*Bromus inermis* Leyss) Canadian source (northern)
Orchardgrass (*Dactylis glomerata* L.) cultivar Nordstern
Tall fescue (*Festuca arundinacea* Schred.) cultivar Ky. 31
Timothy (*Phleum pratense* Leyss) cultivar Verdant
Kentucky bluegrasss (*Poa pratensis* Leyss) cultivar Park
Creeping foxtail (*Alopecurus arundinaceus* Poir) cultivar Garrison
Reed canarygrass (*Phalaris arundinacea* L.) Commercial
Legumes
Alfalfa (*Medicago sativa* L.) cultivar Saranac
Alfalfa (*Medicago sativa* L.) cultivar Agate (*Phytophthora* resistant)
Alfalfa (*Medicago sativa* L.) cultivar Vernal
Alfalfa (*Medicago sativa* L.) cultivar 520
Alfalfa (*Medicago sativa* L.) cultivar Iroquois
Alfalfa (*Medicago sativa* L.) cultivar Ramsey
Birdsfoot trefoil (*Lotus corniculatus* L.) cultivar Viking
Birdsfoot trefoil (*Lotus corniculatus* L.) cultivar Carrol
Red clover (*Trifolium pratense*) cultivar Arlington
Annuals
(planted each spring starting 1974, harvested the same year)
Corn (*Zea mays* L.) cultivar Funk G-4444
Corn (*Zea mays* L.) cultivar Mich. 560-3X
Sudangrass (*Sorghum sudanense* P. Stapf) cultivar Piper
Sorghum-sudangrass hybrid (*Sorghum bicolor* L. Moench x *S. sudanense* P. Stapf) cultivar Pioneer 908
Forage sorghum (*Sorghum bicolor* L. Moench) cultivar Pioneer 931

air to meet the requirement of around 200 pounds per acre, because the effluent was deficient in applied nitrogen.

The soil was sampled in 45 locations in 1-foot increments to a depth of 10 feet for soil profile data on pH, conductivity, extractable P, K, Ca, Mg, Na, Cl, NO_3, N, Ca, Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn, plus Kjeldahl N and total C. Samples of plants were analyzed for these elements with micro-Kjeldahl, emission spectrographic, atomic absorption, ion electrode, and colorimetric analyses. Certain elements, such as Cl, Cd, Co, Ni, and Pb, are determined in plant tissues only if spot checks show them to be a potential problem. Samples were collected in the fall of 1973 for baseline data and in 1974 after 1 year of cropping. The first year's samples have been analyzed, and the 1974 samples are being analyzed now. Plant samples have been ground up and are being analyzed for nitrogen and minerals and for *in vitro* digestibility.

In 1975, the same annual crops are again being planted. Soybeans have been added because the other legumes performed so well in 1974. The first effluent was applied in mid-April to be continued for 26 weeks. Approximately 70, 140, and 210 pounds of nitrogen are being added per acre at 1-, 2-, and 3-inch levels in 1975. This should generate differential yields of the annual and perennial grass crops.

In addition to research into design and management criteria for the successful operation of this type of wastewater treatment, the WQMP has inspired a multitude of innovative ancillary research projects. Those factors which interact to control aquatic fertility will be evaluated as well as hydroponics and high-rate fish culture. The terrestrial research will enhance food and fiber production through the use of wastewater while basic land resources are protected and improved. Another research area is the economic and social evaluation of this form of waste recycling adjacent to a large urban population. For this, the maximum public recreation potential of the WQMP will be assessed.

Chapter II

THE CITY OF TALLAHASSEE SPRAY IRRIGATION PROJECT

Tallahassee's two treatment plants, the Lake Bradford Plant (4.5 mgd) and the Dale Mabry Plant (0.5 mgd), were placed in operation during the 1940's. Their effluent was discharged to a natural drainage stream which flows into Lake Munson. Since this stream also receives most of the storm runoff water from the city, it has become heavily laden with silt during the past 30 years and shows the typical signs of accelerating eutrophication. Because no rivers flow through Tallahassee, a city located 16 miles from the coast, Lake Munson is the only receiving water within Tallahassee's major drainage basin. Therefore, it will continue to receive runoff water and any treated wastewater which is discharged to a surface stream (figure II-1).

In 1961, the city began operating a 60,000-gpd high-rate trickling filter plant to serve the municipal airport. Over a 6-month period during 1961-1962, field experiments at this plant demonstrated that the effluent could be satisfactorily disposed of on land by irrigating at the rate of 4 inches per day over 8 hours.

When Tallahassee's two plants reached their planned capacity in 1965, the new southwest wastewater treatment plant was constructed near the airport where soil and groundwater conditions were similar to the experimental irrigation plot. The high-rate trickling filter plant has a comminuter, degritter, primary clarifier, trickling filter, final clarifier, chlorine contact tank, holding pond, a wastewater irrigation field, and a surface outlet to Lake Munson. Florida state law requires that treated effluent be chlorinated before it is released into receiving waters or applied to the land by spray irrigation. Because local citizens have continued to complain about the appearance of Lake Munson, the city is in the process of developing an alternative 850-acre effluent disposal site 1.5 miles north of the lake, where land irrigation of the entire combined flow of 11 mgd has been shown to be feasible. The Bureau of Sanitary Engineering, Florida State Board of Health, permitted one mgd effluent spray irrigation system in lieu of the surface outlet. If this irrigation system proves satisfactory, permission for additional irrigation capacity is to be granted. The system has been operating continuously since the initial flow of 0.25 mgd began in the summer of 1966. Daily flows were gradually increased to 1 mgd by the summer of 1969. Plant effluent BOD and suspended solids averaged 15 to 20 ppm during this period.

Plans called for the effluent to flow through the holding pond and be applied to the irrigation fields on an "as needed" basis to control the pond water level. After 6 months operation, less than one-third of the holding pond bottom had become wetted, so none of the effluent was available for irrigation. The pond was then bypassed, and during the spring of 1967, the plant effluent was applied directly to the irrigation plots.

In 1972, the Environmental Protection Agency funded a 3-year study to be conducted by Dr. A. R. Overman of the Department of Agricultural Engineering at the University of

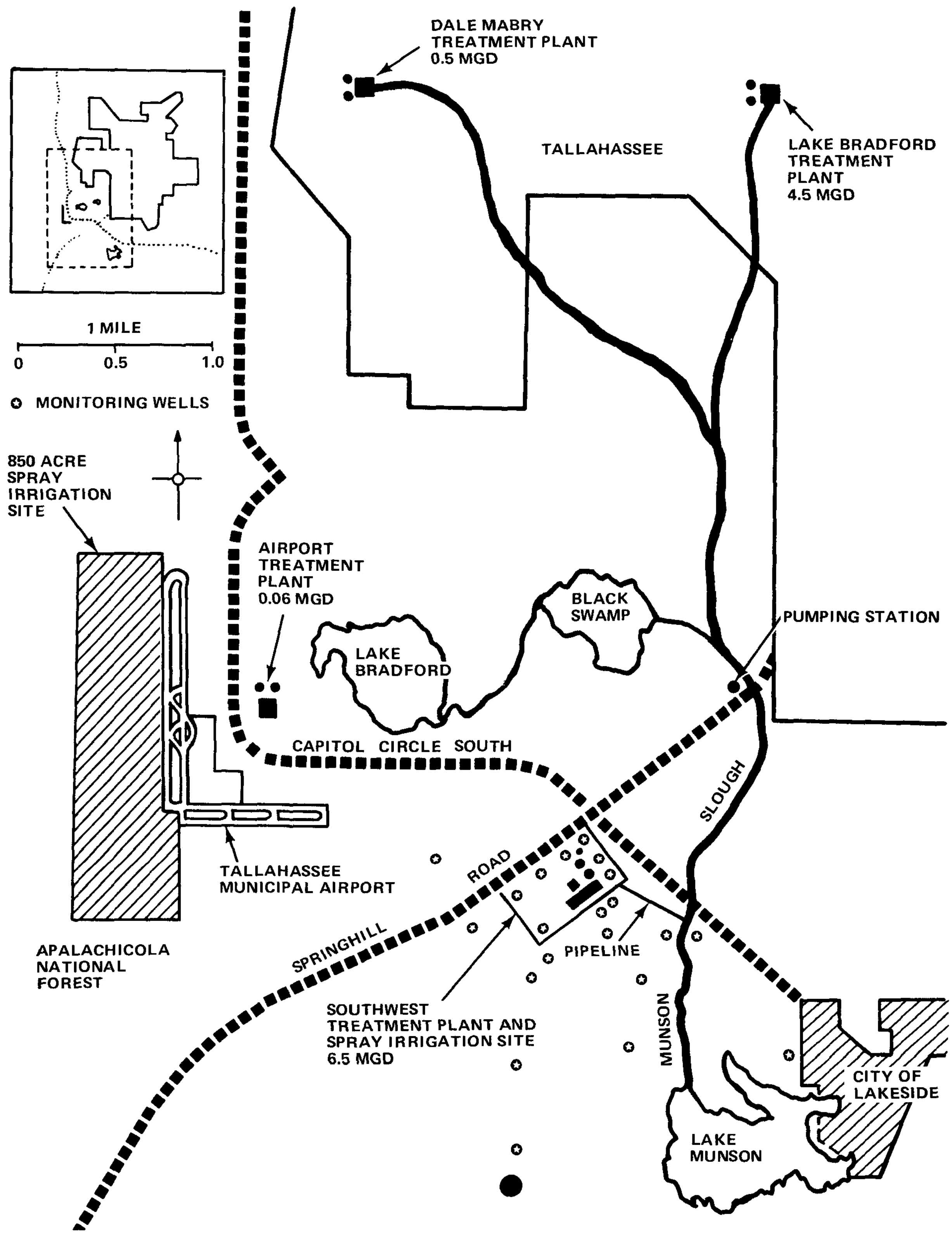


Figure II-1. Tallahassee Spray Irrigation Project.

Florida. Various crop responses are being determined as a function of the wastewater loading and the groundwater quality is being monitored. This research will provide design and operational criteria for other Florida municipalities as well as Tallahassee.

THE TALLAHASSEE FACILITY AND ITS OPERATION

Site Selection

The treatment plant is located on land which was once part of the Apalachicola National Forest. Geologically, it is part of Lake Munson Hills, a 40-square-mile area at the western edge of the Woodville Karst Plain. The 200-acre plant site is 50 to 70 feet above mean sea level, and the normal static water level is 40 feet below ground surface.

The soil is mostly lakeland fine quartz sand with a depth to water table and limestone aquifer of approximately 50 feet. This soil typically has an infiltration capacity of 3 to 4 inches per hour. Usually it has 1- to 2-percent organic matter and less than 5-percent clay. The low natural fertility of the soil is reflected in the native vegetation. Besides scrub oak and similar plants, slash pine grow rather slowly in the area. Furthermore, the soil has a poor moisture-holding capacity with an available water content of about 1 inch per foot of soil. The extensive citrus farming in central Florida demonstrates that these soils can be very productive with proper fertilization and irrigation. Their deep rooting zone and high permeability are conducive to intense production.

Sieve analyses on samples collected 1 foot below ground surface show an average effective size of 0.15 mm and a uniformity coefficient of 2.3. These characteristics provide an almost unlimited hydraulic absorption capacity, ensuring that flooding and the attendant runoff will not be a problem.

Soil samples collected as drilling cores throughout the 200-acre site show a general pattern of 20 to 25 feet of yellow quartz sand below the surface. Under that is a clay lens varying in thickness from a few feet to more than 10 feet, followed by 10 to 12 feet of white quartz sand and then limerock.

Pumping Station and Irrigation Field Layout

The pumping station that supplies the irrigation field is located near the chlorine contact chamber. It was designed to pump effluent into the wet pit from either the contact chamber or the holding pond. When the flow from the contact chamber exceeded the pump capacity, the excess spilled into the holding pond. The centrifugal pump was designed for an output of 720 gpm at 160 feet of total head driven by a 50-hp, 3-phase motor. An inline meter measures how much effluent has been pumped and automatically shuts it off at a predetermined number of gallons.

The irrigation pipe system is composed of 6- to 8-inch aluminum main lines and 2-inch aluminum lateral lines. The sprinklers are spaced on 100-foot centers, and each one delivers

45 gpm at an application rate of 0.45 inches per hour. The system was designed to operate at between 55 and 60 psi at the sprinkler head. The piping system is valved so that 16 sprinklers can be operated at one time to apply effluent at the rate of approximately 1 mgd to 4 acres. Altogether, 16 acres are under irrigation in four 4-acre tracts. One or a combination of the four plots can be sprinkled at any time. It was soon established that all 16 acres did not have to be irrigated simultaneously. Only 8 acres were necessary for the 1-mgd flow except to observe how the grass responded to municipal wastewater irrigation. To determine which grasses responded best, the four plots were seeded with Pensacola Bahia, Argentina Bahia, Centipede, and mixed wild grasses.

In the spring of 1971, a bypass line was completed from the Lake Bradford Plant to carry the overload to the Southwest Plant. A gun-type sprinkler was then installed and positioned to irrigate both undisturbed forest land and a plowed field. After 7 continuous days of irrigation at the rate of 250,000 gallons per acre per day, the forest land showed no signs of ponding. However, the plowed ground started ponding after the 2nd day. Therefore, four big sprinkler guns were installed on 400-foot centers in a rectangular plot to irrigate the forest land. Each gun delivers 1,060 gpm in a 555-foot circle. They are operated in pairs and alternated every other day. Each pair of sprinklers applies 2 million gallons daily. Neither the spray operation nor the residual field emit much odor. Nor have there been any signs of solids building up on the irrigation field surfaces.

Design Factors

At Tallahassee, the design of this spray irrigation field has demonstrated the reliability of both the equipment to move the effluent and the irrigation field to accept it without ponding or runoff. Under the initial experimental design, the aluminum farm irrigation pipe was laid on the surface so that it could be rerouted with a minimum of effort if the system failed. The aluminum pipe has proven to be unsatisfactory; the exposed lines have been bent, broken, or corroded by external mechanical damage and internal wear from abrasion. Therefore, underground cast iron pipe will be used when the irrigation field is expanded. Alternate pumps are being installed to eliminate downtime for pump repair unless both of them fail simultaneously.

Managerial procedures have evolved primarily from experience. The system was designed so that fields can be dosed alternately, but the appropriate dosing cycles had to be determined by operating the irrigation fields in accordance with their immediate purpose. For example, if crops are grown that only require mowing, the dosing periods can be much shorter than if they require harvesting. The sprinkler heads were protected from stoppages by placing a self-cleaning traveling screen with 1/4-inch openings in front of the pumps to remove suspended debris, and this problem has very seldom arisen.

CHEMICAL, PHYSICAL, AND BIOLOGICAL MONITORING

Selected chemical and biological parameters are monitored throughout the system. The wastewater is tested for pH, chlorides, orthophosphate, BOD_5, COD, TOC, nitrate nitrogen, nitrite nitrogen, Kjeldahl nitrogen, ammonia nitrogen, conductivity, and total and fecal coliform. To determine cause and effect relationships, groundwater samples from 23 monitor wells undergo the same analytical tests as the effluent samples.

Soil solution sampling tubes were also installed throughout the irrigation plots at depths ranging from 6 inches to 18 feet. The soil solution was difficult to collect when the wells had low rates of loading, but not at high rates. At 300,000 gallons per acre per day loading rates, laboratory analyses indicated that the concentration of orthophosphate dropped from 25 ppm at the surface to 0.04 ppm at a depth of 10 feet.

Most of the ammonium nitrogen was converted to nitrate nitrogen in the upper 24 inches of soil. At loading rates high enough to collect solution samples in the 18-foot sample tube, there was no clear evidence of denitrification or that the plants absorbed any appreciable amount of nitrate nitrogen as the effluent percolated downward through the soil.

While density of fecal coliform bacteria in the influent was normally in the range of 10^5-10^6 per 100 ml, the density in water from the monitoring wells was usually zero or occasionally one or two bacteria per 100 ml. Additionally, because the nearest residences were more than a mile away from the well-buffered spray irrigation site, the aerosol viral and bacterial hazard was considered to be minimal and was not monitored.

Effluent Characteristics

From a pollution standpoint, the two primary nutrients are nitrogen and phosphorus. To calculate their loading rates, the effluent is assumed to contain 25 ppm of total nitrogen (nitrate + ammonia + organic nitrogen) and 10 ppm of total phosphorus. These values convert to loading rates of 5.7 pounds of nitrogen per acre per inch and 2.3 pounds of phosphorus per acre per inch, respectively. Previous work[15] has shown that all nitrogen is converted microbially to nitrate within the first 1 or 2 feet of well-drained soil. While microbial denitrification takes place, the extent of denitrification has not been determined under effluent irrigation. Loading rates for effluent containing the nitrogen and phosphorus concentrations noted above are shown in table II-1.

Table II-1.—*Nitrogen and phosphorus loading rates*

Irrigation rate (inches/week)	Nitrogen applied (pounds/acre/year)	Phosphorus applied (pounds/acre/year)
1	300	120
2	600	240
3	900	360
4	1,200	480

NITROGEN UPTAKE BY SELECTED GRASSES

Coastal Bermuda Grass—Rye Grass

According to Burton's data,[16] presented in table II-2, crop yields of up to 10 tons of coastal bermuda grass per acre can reasonably be expected to remove 450 pounds of nitrogen per acre. Nitrogen uptake by rye grass can be estimated from Overman's work[15] presented in table II-3. Burton also reported similar results.[16] Therefore, based on crop yields of 3 tons per acre, the removal of approximately 150 pounds of nitrogen per acre appears feasible. A crop rotation schedule of coastal bermuda grass in the summer and rye grass in the winter can potentially remove about 600 pounds of nitrogen per acre per year. Assuming an irrigation rate of 3 inches per week and 25 ppm nitrogen, about 900 pounds of nitrogen would be applied to the soil. The combination would have a 67-percent recovery efficiency.

Nitrogen uptake data for rye are presented in tables II-2 and II-3. Assuming a crop yield of 2 tons per acre, a nitrogen uptake of approximately 200 pounds per acre per year could be expected. Therefore, the coastal bermuda grass–rye grass combination could be expected to utilize about 650 pounds of nitrogen per acre per year. With a nitrogen loading rate of 900 pounds per acre per year, the recovery efficiency would be 72 percent.

Table II-2.—*The uptake of nitrogen by selected grasses*[a]

Nitrogen applied (pounds/acre)	Dry weight of crop (tons/acre)	Nitrogen content (percent)	Nitrogen harvested (pounds/acre)
Coastal bermuda grass[b]			
300	9.6	1.34	259
600	12.2	1.74	424
900	12.5	1.85	466
Rye grass[b]			
400	3.5	2.16	150
Rye[b]			
400	2.8	3.39	189

[a]Adapted from G. W. Burton, 1973.
[b]For one cutting only.

Table II-3.—*The uptake of nitrogen applied to the soil in wastewater by rye and rye grass*[a]

Irrigation rate (in./week)	Nitrogen applied (lb/acre)	Rye Grass[b] Dry weight of crop (ton/acre)	Rye Grass[b] Nitrogen content (percent)	Rye Grass[b] Nitrogen harvested (lb/acre)	Rye[b] Dry weight of crop (ton/acre)	Rye[b] Nitrogen content (percent)	Rye[b] Nitrogen harvested (lb/acre)
0.25	12	1.06	1.97	47	0.60	4.21	57
0.50	25	0.87	2.03	39	0.69	4.61	71
1.00	50	0.93	2.35	49	0.90	4.62	93
2.00	100	1.03	1.75	64	1.00	4.79	107

[a]Adapted from G. W. Burton, 1973.
[b]For one cutting only.

Residual Nitrogen

With a crop rotation of either coastal bermuda grass and rye grass or coastal bermuda grass and rye, efficiency of nitrogen recovery would be approximately 70 percent, leaving about 7.5 ppm of residual nitrogen. Some of this remains in the root system of the plants and is released when the roots decay. Carbon is also released during microbial decomposition. It appears likely that some carbon moves down to the water table where it can be metabolized by denitrifying bacteria to convert nitrate ions to nitrogen gas, which then escapes. If 10 percent of the original nitrogen was lost by this process, then approximately 2.5 ppm would be denitrified. Under these conditions, no more than 5-ppm nitrate nitrogen would remain in groundwater. The degree of denitrification under these conditions at Tallahassee is not yet known.

PHOSPHORUS UPTAKE BY SELECTED GRASSES

Coastal Bermuda Grass—Rye Grass

Phosphorus uptake by coastal bermuda grass has been reported by Adams et al. and some of their data are presented in table II-4.[17] Assuming a crop yield of 10 tons per acre with a phosphorus content of 0.25 percent, approximately 50 pounds of phosphorus would be removed per acre per year. Parks and Fisher[18] reported the phosphorus content of rye grass to be approximately 0.25 percent. With crop yields of 3.5 tons per acre, about 18 pounds of phosphorus would be removed per acre per year. Therefore, the crop combination of coastal bermuda grass and rye grass would remove about 68 pounds of phosphorus per acre per year.

Table II-4.—*The uptake of phosphorus by coastal bermuda grass*[a]

Phosphorus applied (pounds/acre)	Phosphorus crop content (percent)	Phosphorus harvested (pounds/acre)
0	0.20	7
21	0.21	16
42	0.22	25
84	0.25	36

[a]Adapted from Adams et al., 1967.

Since an irrigation rate of 3 inches per week of wastewater with a 10-ppm phosphorus concentration would apply 360 pounds per acre per year, this combination would have a recovery efficiency of 19 percent.

Coastal Bermuda Grass and Rye

The phosphorus uptake by rye is calculated to be approximately 14 pounds per acre per year based on a crop yield of 2.8 tons per acre (table II-2) with a phosphorus content of 0.25 percent. The crop rotation combination of coastal bermuda grass and rye would utilize approximately 64 pounds per acre per year of the 360 pounds applied by spraying. This is equivalent to an uptake efficiency for this combination of 18 percent.

Residual Phosphorus

Whereas nitrate is highly mobile in soil, phosphorus is readily fixed as precipitates of aluminum, iron, and calcium. The fixation capacity of lakeland fine sand appears adequate for an estimated 75-year life span at the Tallahassee site.

If 360 pounds of phosphorus are applied to each acre of soil every year, and only 20 percent of it is removed with the crops, a residual phosphorus loading of 228 pounds per acre would be added to the soil each year. The fixation capacity of 23,250 pounds of phosphorus per acre to a 50-foot depth has been calculated on the assumption that the soil has a bulk density of 1.70 gm/cm^3 and can adsorb 100 ug of phosphorus per gm. Fiskell[19] has shown that for every application of 100 ug of phosphorus per gm of soil, (1) this same amount is fixed, and (2) the solution would concentrate 1 ppm. Other values are shown in table II-5.

Field measurements of phosphorus movement in lakeland fine sand showed that of 3,200 pounds of phosphorus per acre applied over a 6-year period, all of it remained in the upper 4 feet of soil.[19] This would be equivalent to 40,000 pounds of phosphorus per acre per 50 feet, which corresponds to the range shown in table II-5. Finally, it does not appear likely that the fixation of phosphorus would cause soil clogging. For example, fixation levels of 100-, 200-, and 300-ug phosphorus per gm of soil have corresponded to mass increases of only 0.01, 0.02, and 0.03 percent.

Table II-5.—*Phosphorus fixation by lakeland sand*[a]

Solution phosphorus (ppm)	Adsorbed phosphorus (ug/gm soil)	Phosphorus capacity (pounds/acre/50 feet)	Life of site[b] (years)
1	100	23,000	75
5	200	46,000	150
15	300	69,000	225

[a]Adapted from J. G. A. Fiskell and R. Ballard, 1973.
[b]Assuming 3 inches/week, 10-ppm phosphorus, and residual phosphorus of 288 pounds/acre/year.

CROP MANAGEMENT

Cover crops for the fields were planned for year-round yields, a factor that is considerably more important in the northern than in the southern regions of the state. Forage crops are commonly grown year-round in the southeastern states. At Tallahassee, a practical combination is coastal bermuda grass (summer) and rye grass or rye (winter). Both of them have shown excellent growth and production under proper fertilization and irrigation. They have the best uptake of nitrogen among all crops in common use today. Extensive information is available on their management and utilization.

Overman's study[15] indicates that coastal bermuda grass interseeded with winter rye will utilize 600 pounds of nitrogen per acre per year. With 25 ppm as the concentration of total nitrogen, 2 inches per week of effluent are required. This nitrogen will be removed from the site when the crop is harvested. The phosphorus is expected to have minimal agricultural use. However, the soils exhibit very high phosphorus fixation capacities. Therefore, this mechanism will probably remove almost all of the phosphorus.

Cropping Practices

To maximize crop yields from grass, it is very important to establish a level sod. This enables the harvester to clip closely at fast ground speeds without gouging the sod. A cutting height of approximately 4 inches is recommended for both summer and winter crops. To avoid damage to equipment, all tree roots and debris should be cleared from the land before the grass is established. The land should also be disked thoroughly.

Grass should be planted on the site before any effluent is applied. Otherwise, native grasses will grow and inhibit the establishment of a uniform sod. This is particularly true for the summer season. Once established, either coastal bermuda grass, rye grass, or rye will provide effective competition against weeds.

The summer coastal bermuda grass crop will have a growing season from May until November. Either rye grass or rye can be overseeded for a winter crop and will have a growing season from November until May. The coastal bermuda grass then will regenerate in May following the last winter harvest.

A cutting frequency of 6 to 8 weeks is recommended. This should provide a satisfactory balance between high yields on the one hand and lodging on the other. The quality of forage should also be adequate with this practice.

Irrigation Management

Experience has shown that to irrigate at a rate of 3 inches per week, one continual application is more suitable than split applications, as the following analysis demonstrates.

Experiments at Tallahassee have shown that lakeland sand drains to a water tension of 60 to 70 cm. This corresponds to a water content of about 0.10. From experiments by Overman and West,[20] it may be deduced that at an irrigation itensity of 0.5 inches per hour, the water content would rise to approximately 0.25. Hence, during the 6-hour irrigation period, the 3 inches of effluent will be distributed over a soil depth of approximately 12 inches (3 inches/0.25) and will gradually redistribute over a depth of 30 inches (3 inches/0.10), which is still within the root zone of these forage crops. This should allow adequate time for nutrient uptake in the root zone.

There are advantages to using one application each week. Less effort is required to rotate the valves. Problems with plant disease and lodging are reduced by minimizing the time for wetting the crops. Finally, harvesting operations are .made smoother with fewer irrigations, and field drying is also facilitated.

Chapter III

THE FLUSHING MEADOWS PROJECT

The Salt River Valley in central Arizona is an irrigated agricultural area undergoing rapid urbanization. An acre of urban land does not use much less water than an acre of agricultural land. However, whereas the agriculture is essentially consumptive, about 50 percent of the water for urban use is returned as sewage. Approximately two-thirds of the water for irrigation and municipal supplies comes from surface reservoirs on the Salt and Verde Rivers. The remaining one-third is supplied from groundwater, essentially a nonrenewable resource. While this groundwater level is presently dropping at a rate of about 10 feet per year, the depletion could be reduced if the groundwater could be recharged with renovated wastewater from the sewage effluent.

The main sewage treatment plants in the valley are the Phoenix 91st Avenue and 23rd Avenue plants. Both are activated sludge plants that discharge their effluent into the Salt River bed. Their combined flow is presently about 80 mgd. Each year, the flow increases by about 5 to 6 mgd, mainly due to population growth. Thus, a flow of about 240 mgd or about 270,000 acre feet per year can be expected by the year 2000. At an application rate of 4.5 feet per acre per year, this source could irrigate some 60,000 acres of agricultural land. In other words, at the current rate more water will be available for irrigation than agricultural land will require to absorb it. The remaining municipal effluent can be reclaimed for other purposes, such as industry and recreation.

To treat the effluent for unrestricted irrigation and recreation on a large scale necessitates expanding the system beyond the present conventional activated sludge process. According to Arizona standards,[21] tertiary treatment is required to decrease the BOD_5 and suspended solids content to less than 10 ppm, and disinfectants must be applied as needed to keep the fecal coliform density below 200 per 100 ml. Some of the nitrogen should also be removed from the municipal effluent for large scale irrigation to avoid undesirable effects on the crop quality or harvesting schedule. The nitrogen and phosphorus must be removed if the effluent is used for recreational lakes. In a densely populated region such as the Salt River Valley, large scale reuse of the effluent requires that it be treated to be aesthetically acceptable.

Because the hydrogeologic conditions in the Salt River bed are favorable for groundwater recharge by surface spreading, high-rate infiltration from basins in the river bed can produce a renovated effluent of the desired quality to be pumped out of the ground. To investigate the feasibility of renovating the effluent in this manner, a pilot project was constructed in 1967 as a cooperative effort between the U.S. Water Conservation Laboratory, the Salt River Project, and the city of Phoenix. For the first 3 years, the project was partially supported by a grant from the Environmental Protection Agency.

FLUSHING MEADOWS FACILITY AND ITS OPERATION

Description of Project

The pilot Flushing Meadows Project (FMP) is located in the Salt River bed about 1.5 miles downstream from the 91st Avenue sewage treatment plant. Secondary effluent is pumped from the effluent channel into six parallel, horizontal basins that are each 20 feet by 700 feet and 20 feet apart (see figure III-1). Usually, 1 foot of water is held in the basins by an overflow structure at their lower end. The infiltration rate is measured from the difference between the inflow and outflow rates by critical depth flumes at each end of the basins.[22] The infiltration rate for the 2-acre system is approximately 0.5 mgd.

Most of the soil in the basins is fine loamy sand to a depth of about 3 feet, then coarse sand and gravel layers extend to about 250 feet, where a clay layer forms the lower boundary

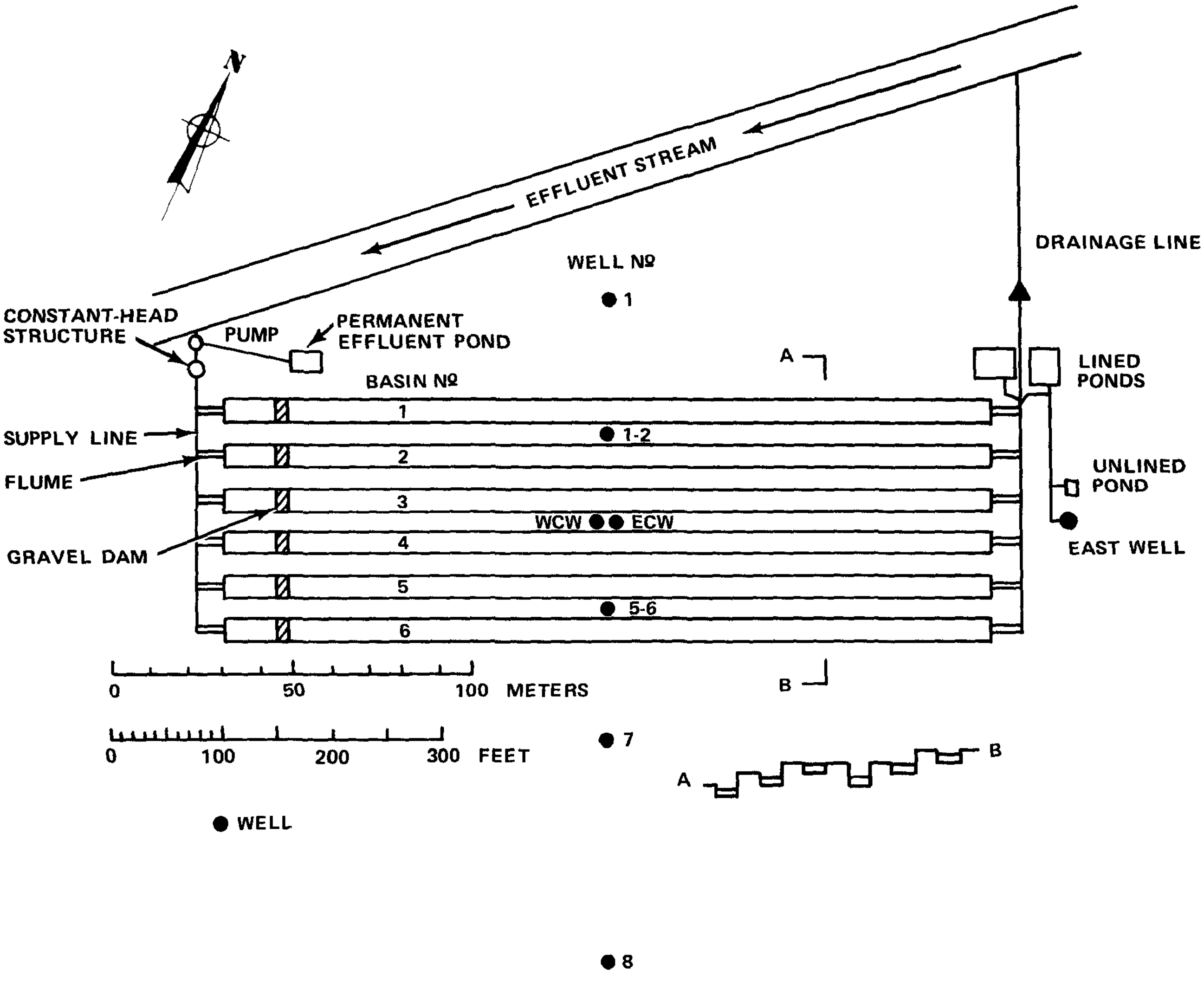


Figure III-1. Flushing Meadows Project schematic.

of the aquifer.[23,24] The static water table is at a depth of about 10 feet. Observation wells for sampling groundwater and renovated sewage water were installed in a line midway across the basin area (figure III-1). All of the wells draw water from a depth of 20 feet except the East Center Well and the West Center Well, which draw water from a depth of 30 and 100 feet, respectively.

Infiltration Rates

The infiltration rates in the basins generally decreased during flooding, but the rate was restored during periods of drying.[23] Maximum long-term infiltration or "hydraulic loading" was obtained with flooding periods of about 20 days, alternated with drying periods of about 10 days in the summer and 20 days in the winter. With this schedule, from 300 to 400 feet of water per year have been infiltrated from an average depth of 1 foot. At these rates, 3 to 4 acres of infiltration basin are required for each mgd of effluent.

Infiltration rates were higher in fully vegetated basins and lower in a gravel-covered basin than in a bare soil basin.[23] However, since the basins were flooded with a few inches of water for a few days in the spring and early summer to allow the vegetation to develop, less water was infiltrated in these basins than in the bare soil basin, where greater water depths and longer flooding periods were maintained during the entire year. Thus, maximum hydraulic loading is probably obtained in nonvegetated basins with water depths of several feet. If the suspended solids content of the effluent can be kept below 20 ppm, little or no sludge accumulates on the bottom of the basins, and they can be operated for several years without having to be cleaned. On the other hand, annual or more frequent removal of accumulated solids is necessary if the effluent has more than 20 ppm of suspended solids.[25]

WATER QUALITY IMPROVEMENT

Nitrogen

The average nitrogen content of the effluent is about 30 ppm, almost all of it in the ammonium form. Since the annual infiltration is about 300 feet, the nitrogen load of the system is in the order of 30,000 pounds per acre per year, much more than the few hundred pounds per acre that can be removed from the soil each year by growing and harvesting crops. These higher loads of nitrogen must be removed by biodenitrification in the soil. Therefore, the system must be designed and managed to bring nitrate and organic carbon together under anaerobic conditions. To do this, the flooding and drying periods of the basins must be properly scheduled.

The effect of the flooding schedule on the form and concentration of the nitrogen in the renovated water is shown in figure III-2. It applies to the renovated water from the East Center Well which is located in the center of the basin area (figure III-1) and obtains water from a depth of 30 feet. The renovated water from this well is mainly effluent that has been infiltrated in basins 3 and 4. This water travels underground for about 40 feet over 5 to 10 days.

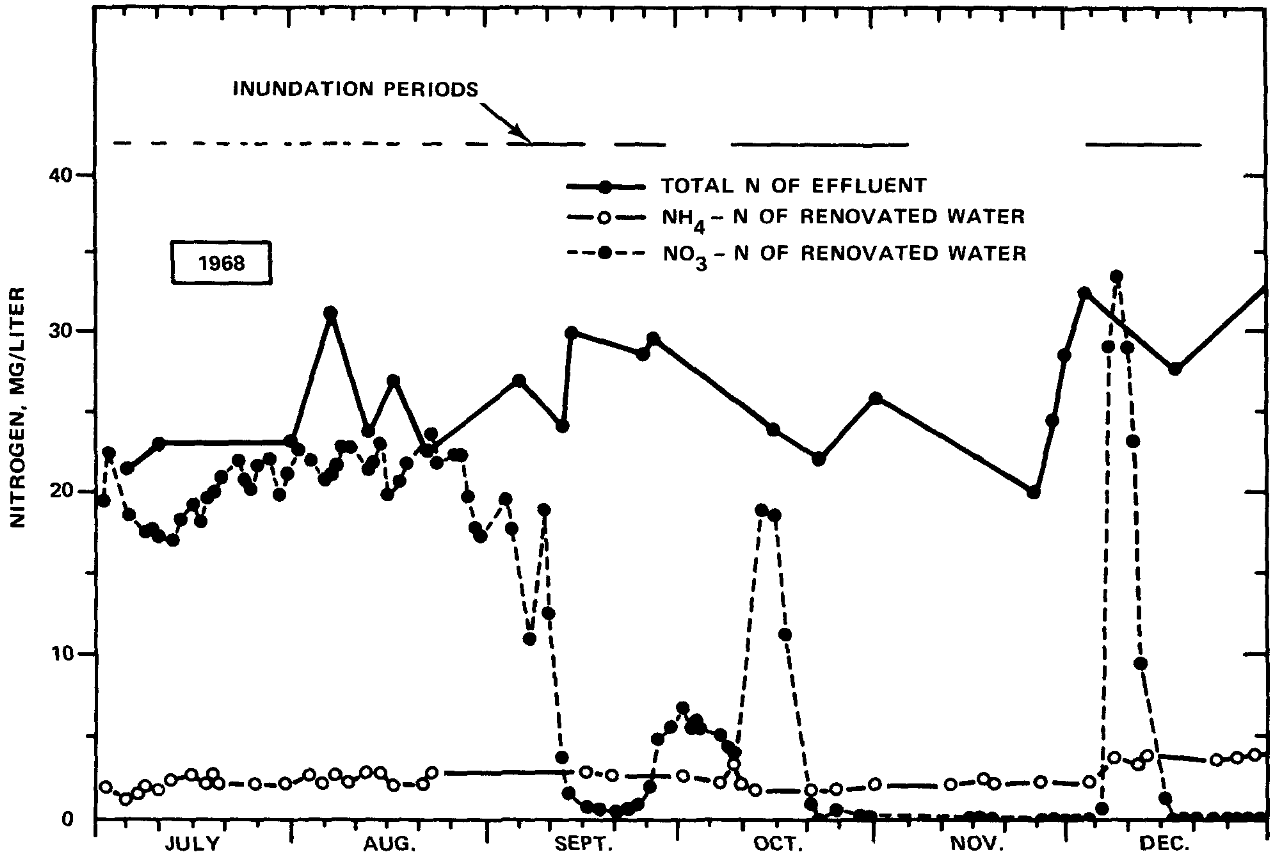


Figure III-2. Flooding impact in nitrogen levels in secondary sewage effluent and renovated water.

With short, frequent inundations, from 2 to 3 days of flooding and 3 to 5 days of drying, in July and August, almost all of the nitrogen in the effluent was converted to nitrate in the renovated water. With flooding and drying periods of several weeks each, such as from September until January, the ammonium level in the renovated water was not immediately affected; but the nitrate level was almost zero except for a peak from 5 to 10 days after the start of a new flooding period. The nitrate peaks in October and December are recorded in figure III-2. The low nitrate level in the renovated water during 3-week flooding periods occurs because the oxygen is depleted in the soil and prevents nitrification. Thus, the nitrogen stays in the ammonium form which can be adsorbed by the cation exchange complex of clay and organic matter in the soil. This explains the low nitrate and ammonium levels in the renovated water between October 20 and December 7 and after December 17 (figure III-2). When the flooding is stopped, drainage and drying below the basins allow oxygen to enter the soil. Then the previously adsorbed ammonium nitrifies. When flooding is resumed, the new water pushes the nitrate-enriched capillary water down into the soil. As it infiltrates, a nitrate peak occurs at the intake of the observation well 5 to 10 days after the start of a new flooding period.

During a long flooding period, not all of the ammonium adsorbed on the clay and organic matter is leached out in the nitrate peak when flooding is resumed because part of what was nitrified from the adsorbed ammonium during drying is again denitrified. This can take place during the dry period and after flooding is started because the nitrate will then move down into the anaerobic zones with the newly infiltrating effluent. From the outlying observation wells where the nitrate peaks are more dispersed, the overall nitrogen removal for the 2- to 3-week flooding and drying periods was estimated to be about 30 percent. Figure III-2 shows, however, that after the nitrate peak passes, the total nitrogen level in the renovated water is nearly 90 percent less than that in the effluent. The 30-percent overall nitrogen removal agrees with the results of laboratory studies.[26]

When long flooding and drying periods stimulate nitrogen removal by denitrification, care has to be taken that more ammonium is not adsorbed by the soil during flooding than can be nitrified during drying.[27] If all the adsorbed ammonium is not nitrified during the drying cycle, the cation exchange complex in the soil may become saturated with ammonium during the subsequent flooding. This further reduces the adsorption of ammonium. Consequently, its percentage will increase in the renovated water. When this is observed, a sequence of short flooding periods, 2 days wet and 5 days dry for example, should be used to convert adsorbed ammonium in the soil to the nitrate form. Some of these nitrates can then be denitrified, particularly if a crop is grown. When the capacity of the soil to adsorb ammonium is restored, longer flooding and drying periods can be used again to maximize nitrogen removal.

Nearly all of the nitrogen in the effluent can be converted to the nitrate form during short flooding periods when the effluent is used for irrigation. Normally, several inches of water are applied every 2 or 3 weeks. With such an application schedule, aerobic conditions prevail in the soil profile, and the nitrogen in the effluent is converted to the nitrate form. Because the water moving downward from a root zone of an irrigated crop has a salt concentration several times that of the irrigation water,[28] nitrate-nitrogen concentrations can be higher in the deep percolation below sewage-irrigated fields, and can be higher than the total nitrogen concentration in the sewage effluent itself. In fact, increased nitrate levels in the groundwater below sewage irrigation fields are commonly observed.[29,30]

Phosphate

The concentration of phosphorus measured as orthophosphate in the effluent was about 15 ppm in 1969. It decreased to around 10 ppm in 1970 and remained the same in 1971 and 1972. Perhaps it stabilized because more low phosphate detergents were used. The renovated water from the East Center Well contained about 50 percent less phosphate; and Well 1, 100 feet north of the basin area, had about 80 percent (90 percent in 1972) less phosphate than the effluent. The renovated water from Well 7, 100 feet south of the basins, had somewhat more phosphorus than Well 1. This may have been because Well 7 is much more permeable and hence has much coarser aquifer material than Well 1.[24]

The phosphate removal has been fairly constant over the more than 5 years the project has operated, while a total of about 1,400 feet of effluent were applied. Most of the phosphate is probably removed when the calcium phosphate compounds precipitate in the soil and underlying sands and gravels.

Fluoride

Normally, 4 to 5 ppm of fluoride are present in the effluent. About 50 percent of the fluoride is removed from the renovated water from the East Center Well and 70 percent from Well 1. This parallels the phosphate removal and suggests that fluorapatities are formed in the soil.

Boron

The boron concentration of the effluent has increased from about 0.4 ppm in 1968 to about 0.8 ppm in 1971 and 1972. Boron is not removed as the effluent moves through the sand and gravel layers of the Salt River bed. Instead, it concentrates in excess of 0.5 ppm in irrigation water and could affect the yield of some of the more boron-sensitive crops in sandy soils.[31]

Salts and pH

The total salt content of the effluent and of the renovated water is usually in the 1,000- to 1,200-ppm range. Evaporation from the basins would cause the salt concentration of the renovated water to be about 2 percent higher than that of the effluent. The pH of the effluent is generally around 8, decreasing to about 7 as it becomes renovated water.

Oxygen Demand

The BOD_5 of the renovated water is usually less than 0.5 ppm, compared with a range of 10 to 20 ppm for the effluent. The total organic carbon content of the effluent ranges from 10 to 30 ppm, and that of the renovated water is from 2 to 7 ppm. Thus, while the suspended solids and biodegradable carbon are essentially all removed as the effluent moves through the soil, some organic carbon still remains in the renovated water.

Fecal Coliform Bacteria

The fecal coliform density in the effluent is normally in the range of 10^5 to 10^6 per 100 ml. This is usually reduced to about 0 to 10 per 100 ml in the renovated water from the East Center Well although, occasionally, densities of several hundred per 100 ml have been observed, particularly when newly infiltrated water reached the well when a long flooding period began after a long drying period. The coliform density decreased as the renovated water traveled further underground. No fecal coliforms have been detected after 300 feet of lateral movement below the water table. Almost all of the coliform bacteria were removed in the first 3 feet of soil.

To renovate the present flow of about 100 mgd from the two Phoenix treatment plants, about 375 acres of infiltration basins would be required, and this would have to be expanded to about 900 acres if the projected 240-mgd flow were renovated in the year 2000. Infiltration basins could be located along both sides of the Salt River bed, and the renovated water could be pumped from wells in the center (figure III-3). This system should be designed to avoid spreading the renovated water into the aquifer outside the Salt River bed, to ensure a minimum underground travel time of several weeks and a distance of several hundred feet, and to keep the water table from rising to more than about 5 feet below the bottom of the basins during infiltration.[24] The preceding data indicate that such a system would produce renovated water of more than sufficient quality to permit unrestricted irrigation and recreation.

The hydraulic properties of the aquifer were evaluated with an electric analog by measuring water levels in the observation wells after infiltration.[24] On the basis of these data, water table profiles and underground detection times were projected for the system (figure III-3) with different model layouts of infiltration basins and wells.[24]

The total cost to filter the effluent underground and the renovated water out of the Salt River bed was estimated at about $5 per acre foot,[32] or about $15 per million gallons in May 1973, and today's cost may be 50 percent higher. Nevertheless, this is still much less than the cost of equivalent tertiary treatment at a conventional sewage plant.

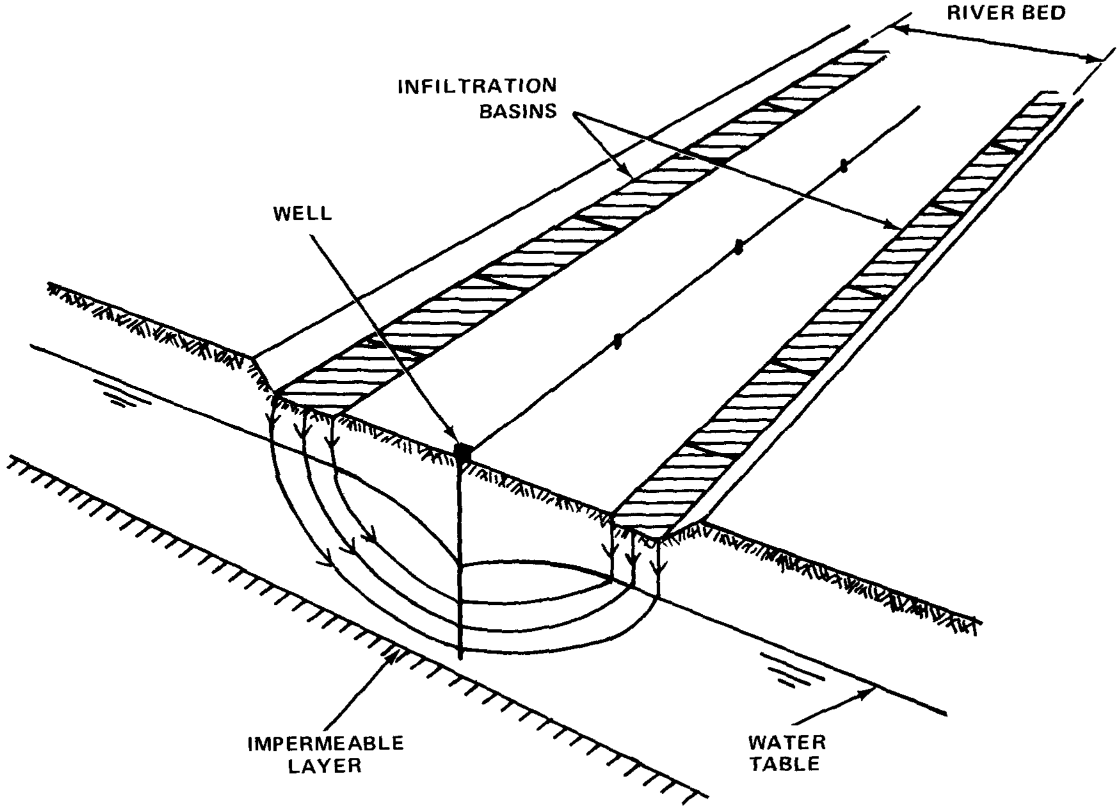


Figure III-3. Infiltration basins system on both sides of river bed with center wells for pumping renovated water.

Chapter IV

THE PENNSYLVANIA STATE UNIVERSITY WASTEWATER RENOVATION AND CONSERVATION PROJECT

The Pennsylvania State University Wastewater Renovation and Conservation Project (WRCP) was initiated in 1962 to evaluate alternative methods of preventing further eutrophication of a stream that received effluent from a sewage treatment plant. A group of scientists weighed a number of alternatives, including the feasibility, possible environmental impact, and economics of applying treated municipal wastewater on the land by spray irrigation. Other possible ways to protect the stream were to modify the existing sewage treatment plant to remove more phosphorus and nitrogen, to dispose of the effluent in deep wells, or to construct a new outfall to Bald Eagle Creek 10 miles away for an estimated cost of $10 million. Instead, wastewater renovation was combined with conservation, and the term "Living Filter" was coined to describe the concept of renovating and reusing municipal wastewater by land application. The experts involved in planning the system included agricultural, civil, and sanitary engineers, as well as agronomists, biochemists, ecologists, foresters, geologists, hydrologists, limnologists, microbiologists, and zoologists.

Initially, approximately 0.5 of the 3.7-mgd flow of the plant was diverted to irrigate and fertilize crops and woodlots. In 1968, plans were initiated to apply the entire plant flow of approximately 4 mgd to the land. After a 4-year delay, the living filter system was expanded to approximately 500 additional acres in the gameland area. However, the capacity of the system was reduced to 3 mgd to stay within the allocated budget because construction costs increased after this expansion was proposed in 1968. Presently, most of the wastewater pumping plant and the 18-inch steel force main to the gameland have been completed. The proposed solid set irrigation system is projected to be in operation by the end of 1975 or the spring of 1976.

THE PENNSYLVANIA STATE UNIVERSITY FACILITY AND ITS OPERATION

The sewage treatment plant located on the eastern edge of the campus serves the university and much of the borough of State College. The wastewater undergoes primary treatment and either trickling filter or activated sludge secondary treatment. After secondary treatment, the flows are combined before chlorination. The average concentrations as well as the minimum and maximum values for selected chemical parameters are reported for 1971 in table IV-1.[33] The last column in the table shows the value of applying 2 inches of this wastewater per week as fertilizer.

The chlorinated secondary effluent is pumped through a 6-inch asbestos-cement force main at a rate of 350 gpm (0.5 mgd) to either the agronomy and forestry areas approximately 2.5 miles away or the gameland area 2 miles farther away. Since the agronomy and gameland spray areas are at ground elevations 180 feet and 280 feet higher than the sewage treatment plant, the effluent is pumped at 226 psi and delivered to the farthest distribution head at approximately 40 psi, with correspondingly greater pressures at locations closer to the pumping station (figure IV-1).

Table IV-1.—*Chemical composition of sewage effluent applied during 1971*[33]

Constituent	Range		Average (mg/l)	Total amount applied[a] (pounds/acre)
	Minimum (mg/l)	Maximum (mg/l)		
pH	7.4	8.9	8.1	–
MBAS[b]	0.03	0.88	0.37	5
Nitrate-N	2.6	17.5	8.6	128
Organic-N	0.0	7.0	2.4	36
NH_4-N	0.0	5.0	0.9	13
Phosphorus	0.250	4.750	2.651	39
Calcium	23.1	27.8	25.2	375
Magnesium	9.1	15.1	12.9	192
Sodium	18.8	35.9	28.1	419
Boron	0.14	0.27	0.21	3
Manganese	0.01	0.04	0.02	0.2

[a]Amount applied on areas which received 2 inches of effluent per week.

[b]Methylene blue active substance (detergent residue) values are for 1970; constituent not included in analyses in 1971.

Approximately 60 acres of crop and forest land with various kinds of soil are irrigated with the wastewater. In the agronomy-forestry area, the soil layer ranges in depth from 5 to 80 feet over a dolomite bedrock. The clay-loam is less permeable than other nearby soils. In the forest, the mulch layer and undercover plants were not disturbed. The soil in the gameland area is a deeper, sandy loam. Here, the soil overlay ranges from 20 to 160 feet above beds of sandstone, dolomite, and quartzite. The depth of the groundwater varies from about 100 to 350 feet.

The solid set sprinkler irrigation system has a flexible design that spaces the sprinklers from 40 feet by 60 feet to 80 feet by 100 feet. After some experimentation with application levels as high as 6 inches per week, most of the spray irrigation has been applied at a level of 2 inches per week in one continuous 12-hour period, with 6.5 days between sprayings. This

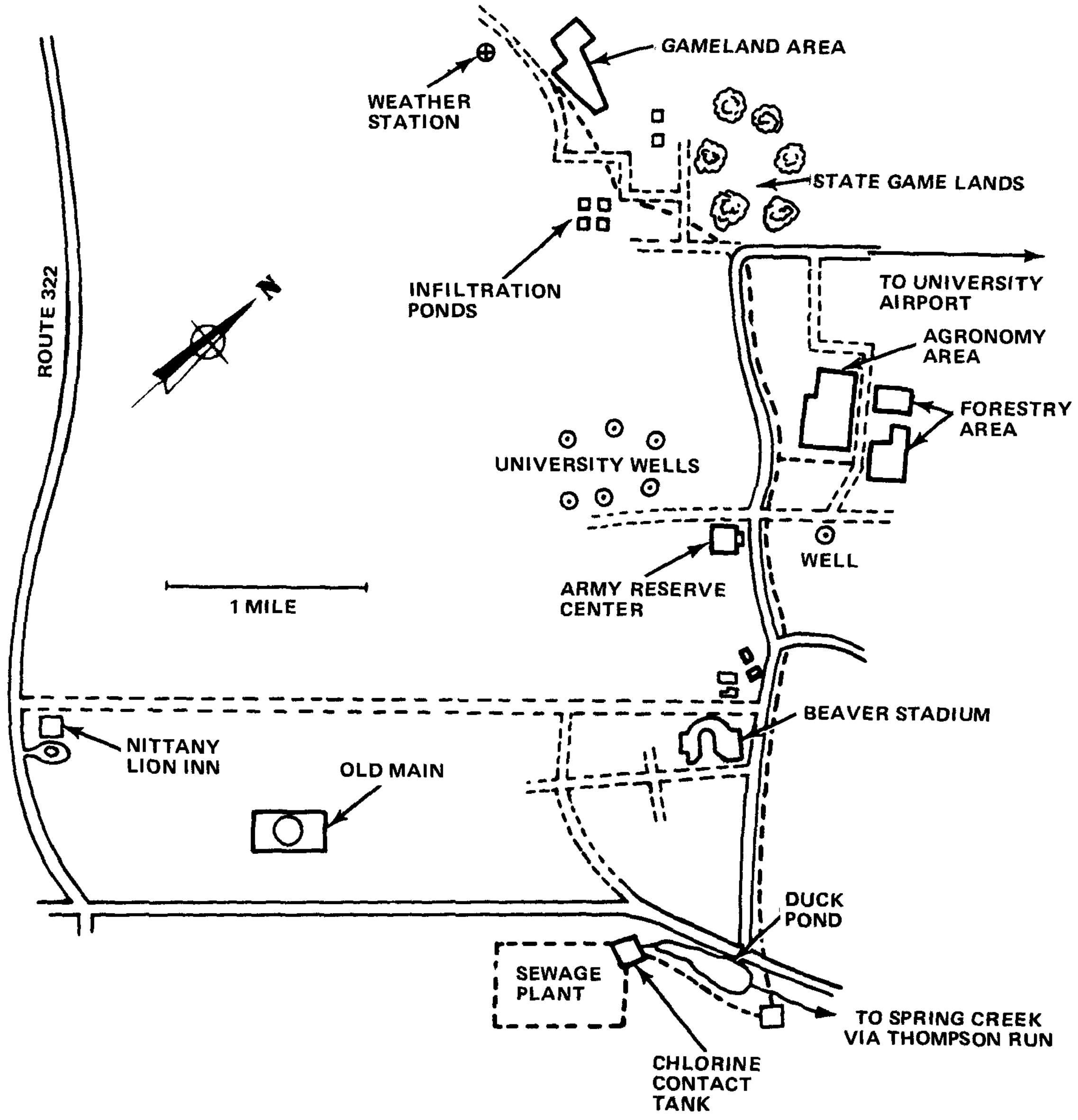


Figure IV-1. The Pennsylvania State University Wastewater Renovation and Conservation Research Project.

application level was maintained because the flow remained well below the infiltration capacity of the soil, thus permitting good renovation.

The spray irrigation areas are surrounded by a buffer zone, but the buffer distance varies and no attempt has been made to maintain any minimum buffer zone. In the gameland area, some residences and a store are less than 300 feet from a spray area. Additionally, a new community called "Toftree" is located along the gameland property line and in general proximity to the spray areas that will be used when the expanded spray irrigation system becomes operational in early 1976. Opinions have been expressed that aerosol pollution hazards are minimal or absent.[1]

MONITORING

The chemical quality of a composite of the chlorinated, secondary treated wastewater was analyzed as it was pumped through the sprinklers during each irrigation sequence. The most consistently monitored chemical parameters and their average concentrations measured for 1971 are presented in table IV-1, along with the range between minimum and maximum values.

As the wastewater percolated through the soil, changes in its quality were measured by taking samples from suction lysimeters 6 inches to 15 feet deep and from shallow monitoring wells 6 to 50 feet deep. In addition, deep wells (150 to 300 feet) were installed to monitor changes in the groundwater aquifer that supplies potable water to the university.

SCOPE OF THE RESEARCH

Crop Responses to Wastewater Effluent

At Penn State, several factors made the perennial grasses the most suitable crops for lands receiving wastewater effluent. In general, they have fibrous root systems and form sod that helps control erosion but still allows a high rate of infiltration. The grasses are tolerant of a wide range of ecological conditions. They have a high uptake of nutrients over a long period of growth. In 6 years, 2,127 pounds of nitrogen were applied to the reed canary grass in 536 inches of sewage effluent and sludge. Of this, 2,071 pounds were removed in the harvested crop, a 93-percent renovation efficiency. The average concentration of nitrate nitrogen was 3.5 ppm in the percolate at the 4-foot depth in the effluent-irrigated areas and 0.2 ppm in the control areas. During the same period, 797 pounds of phosphorus were applied in the wastewater, and 279 pounds were removed when the crop was harvested. The overall crop renovation efficiency was 35 percent for phosphorus. Individual annual renovation efficiencies varied from 24 to 63 percent for phosphorus removal by crops.[34]

Forest Responses to Wastewater Effluent

The forests consisted of a red pine plantation (*Pinus resinosa*) and a sparse white spruce plantation (*Picea glauca*) as well as mixed hardwood. The spray application rate was 0.25 inch per hour, and the level ranged from 1 to 6 inches per week in spraying sequences that varied from 23 weeks during the growing season to 1 full year. The forested areas were highly efficient in removing phosphorus. For all application levels, the forest biosystem decreased the phosphorus concentrations more than 90 percent at the 2-foot depth. However, the forest biosystem was not as consistently efficient in reducing the nitrogen concentrations. A 6-year average of the mean annual concentration of nitrate nitrogen was collected at the 48-inch soil depth. Where varying total depths of wastewater were received, the soil measured from 0.2 to 0.6 ppm in the control areas and from 3.9 to 24.4 ppm of nitrate nitrogen in areas that received 2 inches of effluent per week. The difference was due in part to the organic character of the forest mulch, which promotes a higher degree of denitrification.

The growth of the trees varied considerably, depending on the species and the level of application of the effluent. The white spruce and the young hardwoods grew the most when they were irrigated at the level of 2 inches per week. In general, hardwood forests are not as efficient as agronomic crops in removing the nutrients. For example, a corn silage crop removed 145 percent of the nitrogen applied in the sewage effluent. In contrast, the trees removed only 39 percent, and most of it was returned to the soil in falling leaves. The silage corn crop also removed 143 percent of the phosphorus from the sewage effluent,[34,35] while the hardwoods removed only 19 percent.

Wildlife Response to Wastewater Effluent

The leader deer technique was initiated to determine the animal's preference for or avoidance of irrigated areas. The deer grazed on irrigated sites as readily as on the control sites. In winter, wild deer rested and grazed within the ice-covered areas that had been irrigated. Moreover, in the irrigated areas the winter carrying capacity for rabbits appeared to be much greater than in the control areas, presumably because of improved living conditions in "caves" under ice-covered brush. Here they could also eat the terminal branches of the bent-over brush. Rabbits trapped in the irrigated areas were larger and healthier than those taken in the control areas.[36]

Chapter V

THE CITY OF BOULDER COLORADO PROJECT

Although Boulder has two existing secondary (trickling filter) plants with adequate capacity to handle projected 1985 flows, the existing plants cannot provide treatment sufficient to meet pending discharge requirements. The regional water quality management plan for the area including Boulder calls for secondary treatment plus nitrification of ammonia to a concentration less than 4.3 mg/l. In addition, Boulder wished to consider higher levels of treatment than required by the state and federal regulations and asked that treatment systems be evaluated which would be capable of providing an effluent with the following characteristics:

- BOD 5.0 mg/l
- Total nitrogen 5.0 mg/l
- Total phosphorus 0.1 mg/l

Boulder also requested that other treatment systems providing effluents of lesser quality be evaluated. Thus, the resulting study considers a wide range of land treatment and Advanced Wastewater Treatment (AWT) systems.

The design flow conditions for the Boulder Colorado Project (BCP) were:

Year	Design daily, mgd	Average daily, mgd	Peak rate, mgd
1975	17.0	13.0	29.8
1985	20.0	15.3	35.0
1995	27.5	21.0	46.8

ADVANCED WASTEWATER TREATMENT CONSIDERATIONS

There are three AWT alternatives which have been examined. They are shown in table V-1 and described in the following paragraphs.

Table V-1.—*Alternatives—Boulder, Colorado*

AWT-I processes	AWT-II processes	AWT-III processes
[a]Pretreatment	[a]Pretreatment	[a]Pretreatment
[a]Primary clarification	[a]Primary clarification	[a]Primary clarification
Oxygen-activated sludge	[a]Trickling filters	[a]Trickling filters
[a]Secondary clarification	[a]Secondary clarification	[a]Secondary clarification
Flow equalization	Flow equalization	Nitrification
Lime clarification (2 stage)	Nitrification	Disinfection
Filtration	Denitrification	
Activated carbon	Lime clarification (1 stage)	
Selective ion exchange	Filtration	
Disinfection	Disinfection	

Effluent quality (maximum values, mg/l)

	AWT-I	AWT-II	AWT-III
BOD	3	10	20
SS	1	5	20
NH_3-N	1	3	3
NO_3-N	1	3	23
Total N	2	6	26
Total P	0.1	1	20
TDS	500-600	500	400

[a]Existing treatment units.

Alternative AWT-I provides the highest degree of treatment of the AWT alternatives. The existing pretreatment process, primary clarifiers, and final clarifiers would be used. A pure oxygen-activated sludge system is used in lieu of the existing trickling filters to maximize the reduction of soluble BOD. Phosphorus removal would be accomplished by two-stage lime clarification, and suspended solids removal would be accomplished by mixed-media filtration.

Carbon adsorption follows. Nitrogen removal would be accomplished by the selective ion exchange process, with ammonium salts being recovered from the regenerate stream. Disinfection would be accomplished by ozone generated from oxygen-enriched air from the oxygen generation system required for the activated sludge process. Organic sludges would be applied to the land while lime sludges would be recalcined and reused.

AWT-II utilizes the existing primary and secondary treatment process with minor modifications to improve performance and hydraulic capacity. Flow equalization would be provided prior to biological nitrification, followed by denitrification. Nitrification would be accomplished by a pure oxygen-activated sludge system, followed by an anaerobic filter for denitrification. Phosphorus removal would be accomplished by single-stage lime clarification, followed by mixed-media filtration for further suspended solids removal. Disinfection would be accomplished by ozone generated from oxygen-enriched air supplied by the onsite oxygen generation system required for nitrification. Organic and chemical sludges would be disposed of on the land.

AWT-III uses the existing primary and secondary treatment system with minor modifications to improve performance and hydraulic capacity. Nitrification would be accomplished by a pure oxygen-activated sludge system, and disinfection would be by ozone produced from oxygen-enriched air supplied from the onsite oxygen generation equipment. The organic sludges would be disposed of on the land.

AWT-I and II would exceed the pending discharge standards, while AWT-III closely corresponds to these standards.

Table V-2 summarizes the cost projections (July 1974 basis) for the AWT alternatives. These estimates are based on construction of all AWT processes to a capacity of 20-mgd raw sewage flow in 1975 with an expansion of 27.5 mgd (the 1955 design flow) in 1985.

LAND TREATMENT CONSIDERATIONS

The eastern part of Boulder County is a semi-arid area with insufficient precipitation for peak crop growth and a limited supply of surface water. In addition, there are extensive irrigation systems in the area and much of the wastewater discharge is diverted. Flooding (rather than spray irrigation) is the present method of irrigation and is the technique used in evaluating the potential land treatment systems. Water rights involved in new diversions of wastewaters are complex on the eastern slopes of the Rockies but, for the purposes of this publication, it is not necessary to discuss the details of the water rights in the Boulder area. The reader is cautioned that, in many parts of the country, the evaluation of water rights can be an important aspect and competent legal advice should be sought.

Alternate Irrigation Systems

The alternatives of irrigation, high-rate irrigation, and infiltration-percolation (as defined in table V-3) were considered. All have been used for treatment of municipal wastewater, both in this country and elsewhere. The objectives and characteristics of each of the processes are distinctly different. The quality of the water returned to the stream or groundwater will

Table V-2.—*Cost of AWT Alternatives (BCP)*

	1975 expansion to 20 mgd	1985 expansion to 27.5 mgd
AWT-I		
Total capital costs[a]	$28,975,000	$17,181,000
Maximum annual O & M costs	1,893,000	2,474,000
All costs, present value	$53,334,000	
AWT-II		
Total capital costs	$18,500,000	$11,777,000
Maximum annual O & M costs	1,404,000	2,004,000
All costs, present value	$37,187,000	
AWT-III		
Total capital costs	$10,415,000	$ 7,292,000
Maximum annual O & M costs	821,000	1,232,000
All costs, present value	$21,752,000	

[a]Includes 20 percent construction contingency, 12 percent for construction financing, and 15 percent for engineering, legal, and administrative fees (cost on July 1974 basis).

differ within a process depending on loading rate, soil characteristics, crop type, and operation. The loading rate should be considered carefully since it influences the quality of return flows. Loading rates and land area requirements overlap for the different processes, making clear distinction difficult. The irrigation alternative is compatible with existing irrigation practices in the Boulder area and effluent could be supplied to existing private irrigation ditches. The high-rate process conflicts with local practices because the disposal of effluent takes priority over crop production. It was concluded that the city would have to own the land to make the high-rate system practical. Table V-4 summarizes the effluent quality projected for each of these systems when applied in the Boulder area in accordance with the criteria discussed herein. All of the land treatment processes produce an effluent quality which exceeds pending discharge standards.

Table V-3.—*Characteristics of land application processes considered for the BCP*

	Annual loading	Land area requirement for 1 mgd flow	Objective	Suitable soils	Dispersal of applied water	Impact on quality of applied water
Irrigation	<1 to >5 ft/yr	<225 to >1,100 acres plus buffer areas, etc.	Maximize agricultural production.	Suitable for irrigated agriculture.	Most to evapotranspiration. Some to groundwater; little or no runoff.	BOD and SS removed. Most nutrients consumed in crop or fixed. TDS greatly increased.
High rate irrigation	1 to >10 ft/yr	<110 to 1,100 acres plus buffer areas, etc.	Maximize water and treatment by evapotranspiration and percolation with crop production as a side benefit.	More permeable soils suitable for irrigated agriculture; many use soils marginal because of coarse texture.	Evapotranspiration and groundwater; little or no runoff.	BOD and SS removed. Nutrients reduced. TDS substantially increased.
Infiltration-percolation	11 to 500 ft/yr	2 to 100 acres plus buffer areas, etc.	Recharge water or filter water; crop may be grown with little or no benefit.	Highly permeable sands and gravels.	To groundwater, some evapotranspiration; no runoff.	BOD and SS reduced. Little change in TDS.

Table V-4.—*Effluent quality associated with land treatment alternatives*

	Maximum values, mg/l		
	Irrigation	High-rate irrigation	Infiltration-percolation
BOD	1	1	5
SS	1	1	5
NH_3-N	0.5	0.5	1
NO_3-N	4.5	4.5	9
Total N	5	5	10
Total P	0.1	0.2	2
TDS	2,000	860	770
Pretreatment	Aerated lagoon treatment of existing effluent	Existing treatment only	Existing treatment only

General Design Criteria

The criteria used to establish potential areas for the various land application processes were:

- Site should not endanger rare and endangered plant or animal species.
- The site should not conflict with present land use and should reinforce the adopted land use plans.
- Presently irrigated areas should be used as much as possible to minimize the water rights problem.
- The site should minimize the socio-economic impact on the community and the traveling public. The number of dwellings, other buildings, and miles of road on the site should be considered.
- Emphasis should be given to the use of greenbelt lands when practical.
- Preference should be given to soil groups which are most suitable for the various land application processes as shown in table V-5.

Table V-5.—*Soil suitability for land application processes*

Soil group	Irrigation	High-rate irrigation	Infiltration-percolation
1	Very suitable	Maximum	Moderate
2	Very suitable	High	Moderate for high permeability
3	Suitable	Moderate	Very low
4	Low suitability	Low	Maximum for high permeability soil
5	Unsuitable	Unsuitable	Unsuitable

Soil suitability for the irrigation and high-rate irrigation processes is very similar, as shown in table V-5. A considerable area of the most suitable soils, Groups 1 and 2, are available in the study area. The soil most suitable for the irrigation and high-rate irrigation processes also has the highest capacity for adsorption and removal of various pollutants, including nutrients, heavy metals, etc. The least suitable group (4) and unsuitable group (5) soils coincide with grassland and other uncultivated areas.

The infiltration-percolation process requires highly permeable soil and surficial geology capable of transmitting large volumes of water. This material will not provide the degree of treatment possible with the irrigation and high-rate irrigation processes. Soil which is suitable for irrigation or high-rate irrigation will not be suitable for infiltration-percolation and vice versa. The material most suitable for the infiltration-percolation process is the coarse-textured, most permeable portions of alluvial material characteristics of Class 4 soil.

Site Evaluation

The potential irrigation or high-rate irrigation sites and two potential infiltration-percolation sites were identified and evaluated by the following criteria:

- Loading rate—Detailed soil information from the Soil Conservation Service was used to evaluate soils on the potential sites. The following design and evaluation criteria were used:
  - Well-drained or easily drainable soil
  - Intermittent application to provide ample opportunity for soil aeration
  - Soil profile depths of 5 feet or more
  - High absorptive capacity for pollutant removal
  - Choice crop suitability and/or high denitrification rates to maximize nutrient removal
  - Maximum loading rate for high-rate irrigation of 7 feet during April/October season loading rate (This rate is reduced proportionately by shallow root depth, rock in the soil, and low permeability.)
  - Infiltration-percolation process loading rates proportional to 12.5 percent of the permeability
  - Gross area based on the net area required plus areas for roads, buffers, operation, and unsuitable land (as a percent of total area)
- Area considered—Only sites within the study area and within the Northern Colorado Water Conservancy District boundary were considered. Preference was given to sites entirely within Boulder County.
- Power requirements—To reduce the power requirements, the differential elevation between the treatment plant and the potential site should be minimized.
- Buffer areas—Buffer width requirements are dependent on the irrigation method and degree of pretreatment prior to application. The buffer width required for surface (flooding) irrigation methods selected for this study may be less than 50 feet.
- Slopes—Land slopes greater than 15 percent were considered unsuitable for any wastewater application. Slopes greater than 6 percent were considered unsuitable for surface (flooding) irrigation methods.

- Site treatment capacity—To foster economics of scale and to obviate additional water rights analyses, only sites capable of treating the 1995 design flows on a contiguous area were considered.

- Storage—Because of the requirement for winter storage of effluent, the site selected should be in proximity to a suitable storage location. The storage of secondary effluent also will require storage rights, so existing storage facilities were considered.

- Site area—The costs for development of an irrigation site are proportional to the area required for treatment. Thus, sites with the highest treatment capacity per unit area were given preference.

- Water rights—In order to minimize problems regarding the water rights, preference was given to sites within the Boulder Creek watershed and to sites where ditches terminated within site boundaries.

Areal Requirements

In the Boulder area, the average annual effective precipitation is 10 inches/year. The potential evapotranspiration (ET) was determined for several types of crops and is shown in table V-6. Based on the assumed cropping pattern shown in table V-6, a mean evapotranspiration of 25.8 inches per year was determined. Using a 70-percent irrigation efficiency (consistent with irrigation design procedures and local practices), a requirement of 22.6 inches per year was determined for the irrigation alternate which maximizes crop production. This is equivalent to about 590 acres/mg treated for the irrigation alternate.

The allowable hydraulic loading for the high-rate irrigation process is dependent only upon the soil's capacity for transmitting water and not on crop irrigation requirements. The maximum hydraulic loading is the sum of soil moisture depletion plus that quantity which can be transmitted through the root zone. The soil moisture depletion was determined to be 12.3 inches for the season. The soils in the potential sites were classified using the hydraulic loading criteria shown in table V-7. The best site had an allowable average loading rate of 6 feet per year, which is equivalent to an irrigated area requirement of 186 acres/mg.

The loading rate for the infiltration-percolation process is dependent on the soil and surficial geology for infiltration and treatment. As loading rates increase, the treatment provided will generally decrease; thus, a balance between treatment and loading rates is important. A soil classification for high loading rates was developed from detailed soil maps. Weighted average loading rates for the sites were estimated at 30 feet per year.

Irrigation Season

Climate is a constraint on the timing of effluent application on land. Soil temperature data indicated that the soil in the study area may be frozen during parts of some years from November through March. For the irrigation and high-rate irrigation processes, effluent would not be applied during periods of frozen ground because runoff directly to the surface waters could occur. The April through October period was used as the maximum effluent application

Table V-6.—*Crop evapotranspiration and irrigation requirements (in inches)*

Month	Study area mean effective precipitation	Mean potential ET[a]	Average supplemental irrigation requirement[b]	ET corn (silage)	ET pasture	ET alfalfa	ET spring grain
Jan.	0.2	0.2	0.0	0.1	0.3	0.4	0.1
Feb.	0.3	0.3	0.0	0.2	0.5	0.6	0.2
Mar.	0.6	0.6	0.0	0.3	1.0	1.2	0.3
Apr.	1.2	1.2	0.0	0.5	2.0	2.3	1.1
May	2.1	3.0	1.3	1.9	3.8	4.5	4.4
June	1.4	5.5	5.9	4.8	5.3	6.5	7.3
July	1.1	7.0	8.4	7.6	6.5	7.9	4.3
Aug.	1.0	4.5	5.0	4.0	5.8	6.8	1.8
Sept.	0.8	1.8	1.4	0.8	3.4	3.9	0.8
Oct.	0.7	1.1	0.6	0.5	2.0	2.3	0.5
Nov.	0.4	0.4	0.0	0.2	0.7	0.9	0.2
Dec.	0.2	0.2	0.0	0.1	0.4	0.4	0.1
Total	10.0	25.8	22.6	21.0	31.7	37.7	21.1

[a]Based on an assumed cropping pattern of 1/2 corn, 1/4 pasture, 1/8 alfalfa, and 1/8 spring grain.
[b](Mean potential ET minus mean effective precipitation) divided by 70-percent irrigation efficiency.

season. Maximum effluent loading will also be limited to the active growing season. Plant and soil microorganism activity is greater during this time, so treatment of the effluent would be most effective.

For the infiltation-percolation process, the soil is much coarser to allow higher loadings. Because of the coarse soil required to make this process successful, applications of warm effluent may keep the soil from freezing for all but the most severe portion of the winter. Applications would be made for 10 to 11 months of the year. Water would be applied for 5 days, followed by 10- to 20-day rest periods.

Alternate Land Treatment Considerations

Alternative L-I involved the irrigation process as defined in table V-3. Secondary effluent would be distributed by existing ditches to privately-owned land. Water would be applied by surface irrigation, mostly furrows, as commonly employed in the area. The irrigation ditches and all irrigated land would remain in private ownership, with the ditch company maintaining management and operation of the system. A long-term contract between the city and the ditch company would provide the basis for continuing operation of the system. Secondary effluent would be delivered directly to a winter storage reservoir, where it would be stored

Table V-7.—*Estimated maximum hydraulic loading of wastewater effluent for various soil textures (ideal conditions)*[a]

	Basic infiltration[b] 0%-4% slope	Movement through soil root zone[c]	
		in./day	in./yr
Very coarse textured sands and fine sands	1.0+	20	600
Coarse textured loamy sands and loamy fine sands	0.7-1.5	10	300
Moderately coarse textured sandy loams and fine sandy loams	0.5-1.0	4	150
Medium textured very fine sandy loams, loams, and silt loams	0.3-0.7	2	90
Moderately fine textured sandy clay loams and silty clay loams	0.2-0.4	1	40
Fine textured sandy clays, silty clays, and clays	0.1-0.2	0.5	10

[a]Proportionate reductions must be made for various problems such as percentage of rock, soil depths less than 5 feet, or restrictive layers (frangipans, claypans, etc.).
[b]Values shown are for bare soil; for good vegetative cover, increase tabled values by 25 to 50 percent; for slopes between 4 to 8 percent, reduce tabled values by 25 percent; for slopes greater than 8 percent, reduce tabled values by 50 percent.
[c]Precipitation plus effluent less evapotranspiration.

during the winter and released for irrigation during the peak demand periods. For the projected 1995 flow of 7,665 mg/year, approximately 15,000 acres (12,000 acres net irrigated) are required for this alternative. A suitable site was found.

For Alternative L-I, the city would be required to provide restitution for additional expenses incurred by the ditch company. This would include:

- Limited future development within the site area
- Increased maintenance
- Increased reservoir capacity
- Control of return flows from canals and irrigated farms
- Correction of drainage problems developed as a result of the increased water supply

Although Alternative L-I would produce the highest level of wastewater treatment possible with land application, management and operation of the system will be out of the city's direct control, thus reducing reliability.

Alternative L-II involves the high-rate irrigation process on city-owned and city-managed land. Storage of secondary effluent would be necessary during the winter months. Approximately 5,000 acres (4,060 acres net irrigated) are required for this alternative.

Alternative L-II would provide an intermediate level of treatment but may approach the level of treatment in Alternative L-I. Because management and operation of the system will be under the city's control, the reliability of operation would be improved over Alternative L-I. However, because loading rates would be higher, there is a corresponding higher risk of polluting the soil and groundwater. Salt loading may be increased with high-rate irrigation because of the increased leaching through a highly calcareous subsoil. The salt concentrations of the subsurface drainage would be lower than with the irrigation process because less total volume of water would be consumed by evapotranspiration. Effluent would be applied by surface irrigation utilizing both borders and furrows for this alternative. Automation would be provided to reduce labor requirements and improve control of the water.

Alternative L-III is the infiltration-percolation process on a site owned and managed by the city. The application season for this alternative will extend over more than 10 months, requiring minimal storage. Approximately 1,120 acres (815 net irrigated) are required for this alternative.

Secondary effluent for Alternative L-III would be applied on flood plain land which is presently partly within proposed greenbelt land. This alternative would minimize land area requirements and the necessary storage capacity, thus minimizing the environmental impacts. Secondary effluent would be applied using the basin method of surface irrigation on land adjacent to the sewage treatment plant. A lower level of treatment would be provided by this land application alternative than for Alternatives L-I and L-II. However, it would exceed the quality required for discharge into the stream. The proposed site has a high water table and would necessitate a subsurface drainage system to prevent water logging of the soil. This drainage system would collect and return to the surface water virtually all effluent applied to the site. There would be no flow of effluent outside of the site boundary within the groundwater system. Drainage water would be monitored before discharge to surface water.

Land Treatment Alternative Evaluation

ALTERNATIVE L-I. Figure V-1 presents a schematic representation of Alternative L-I which was partly described earlier. As shown in figure V-2, 65 percent of applied water is consumed by crop evapotranspiration. An estimated 27 percent of applied water would percolate to the groundwater system. Approximately one-tenth of this percolated water would be collected by subsurface drainage and discharge to surface streams. In addition to the crop consumptive use, there is an 8-percent nonbeneficial evaporation and evapotranspiration of water from reservoirs, canals, and the surface runoff collection system. This 8 percent includes water lost from the soil surface and phreatophyte vegetation adjacent to the surface water bodies.

In Alternative L-I, the effluent would be delivered from the treatment plant to storage by gravity through 43,600 feet of 66-inch buried concrete pipe. The pipe would be lined to

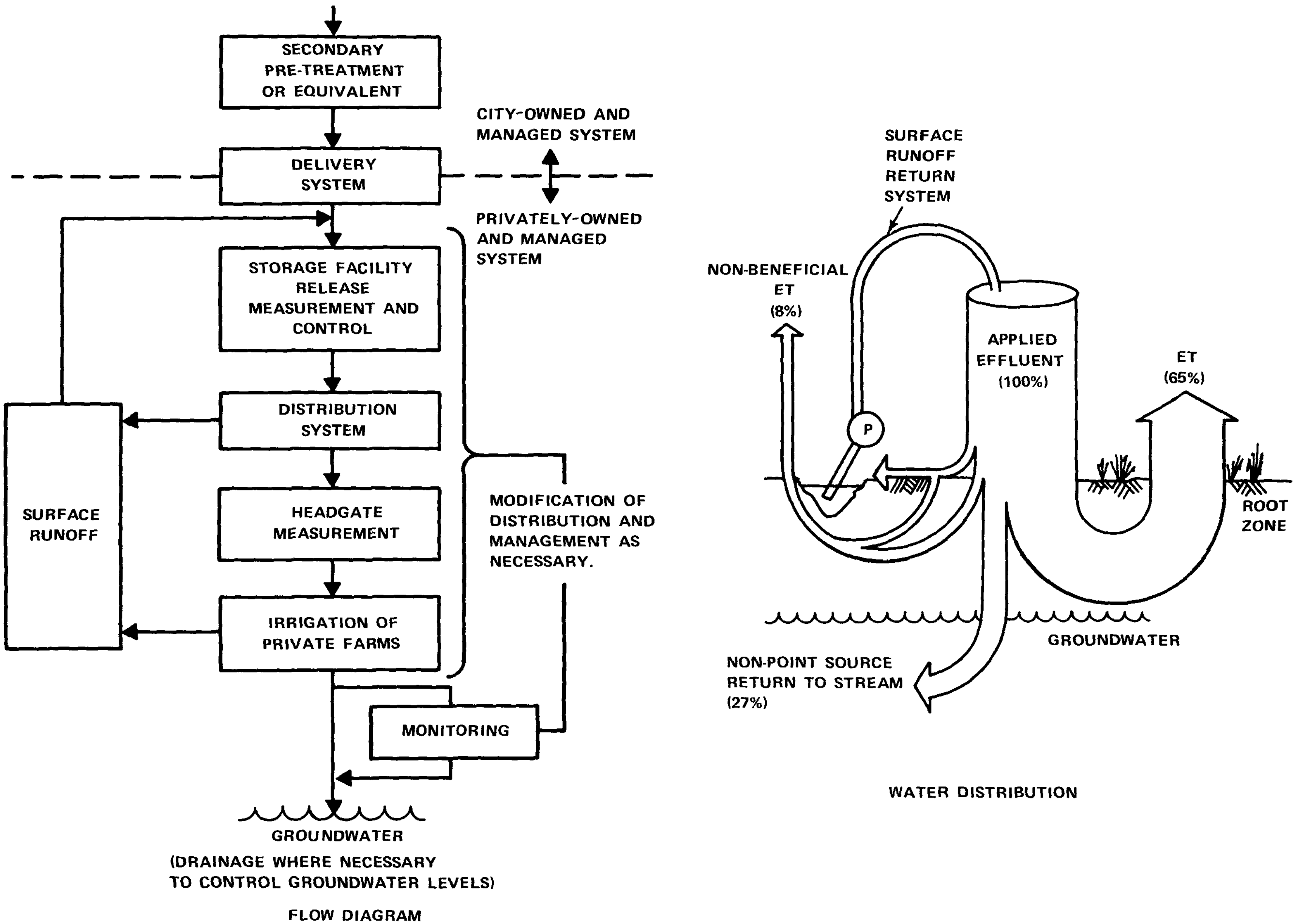


Figure V-1. Land treatment irrigation Alternative L-I – Boulder.

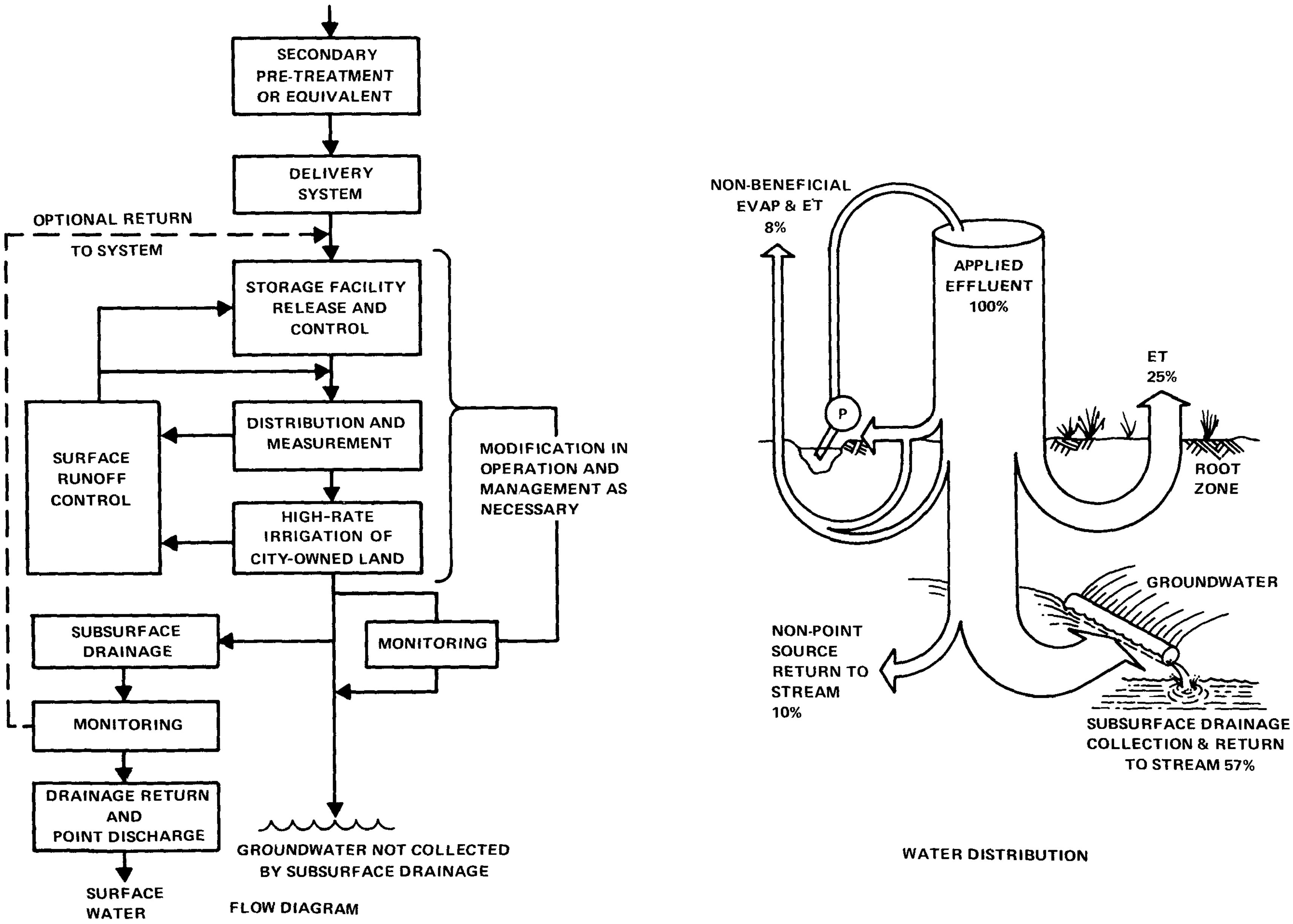


Figure V-2. Land treatment high-rate irrigation Alternative L-II – Boulder.

prevent corrosion and would be sized to carry the peak 1995 flow. A total storage capacity of 17,000 acre feet is required by 1995 and would be achieved by a combination of enlarging an existing reservoir to 12,000 acre feet and adding a new 5,000-acre foot reservoir in 1985. The effluent would be released from the reservoir(s) by pumping to the portion of the distribution system above the reservoir and by gravity flow to distribution systems below the reservoir. The existing irrigation system would be used wherever possible to distribute effluent to the farms. The effluent flow from the reservoir would be measured to meet the irrigation demands.

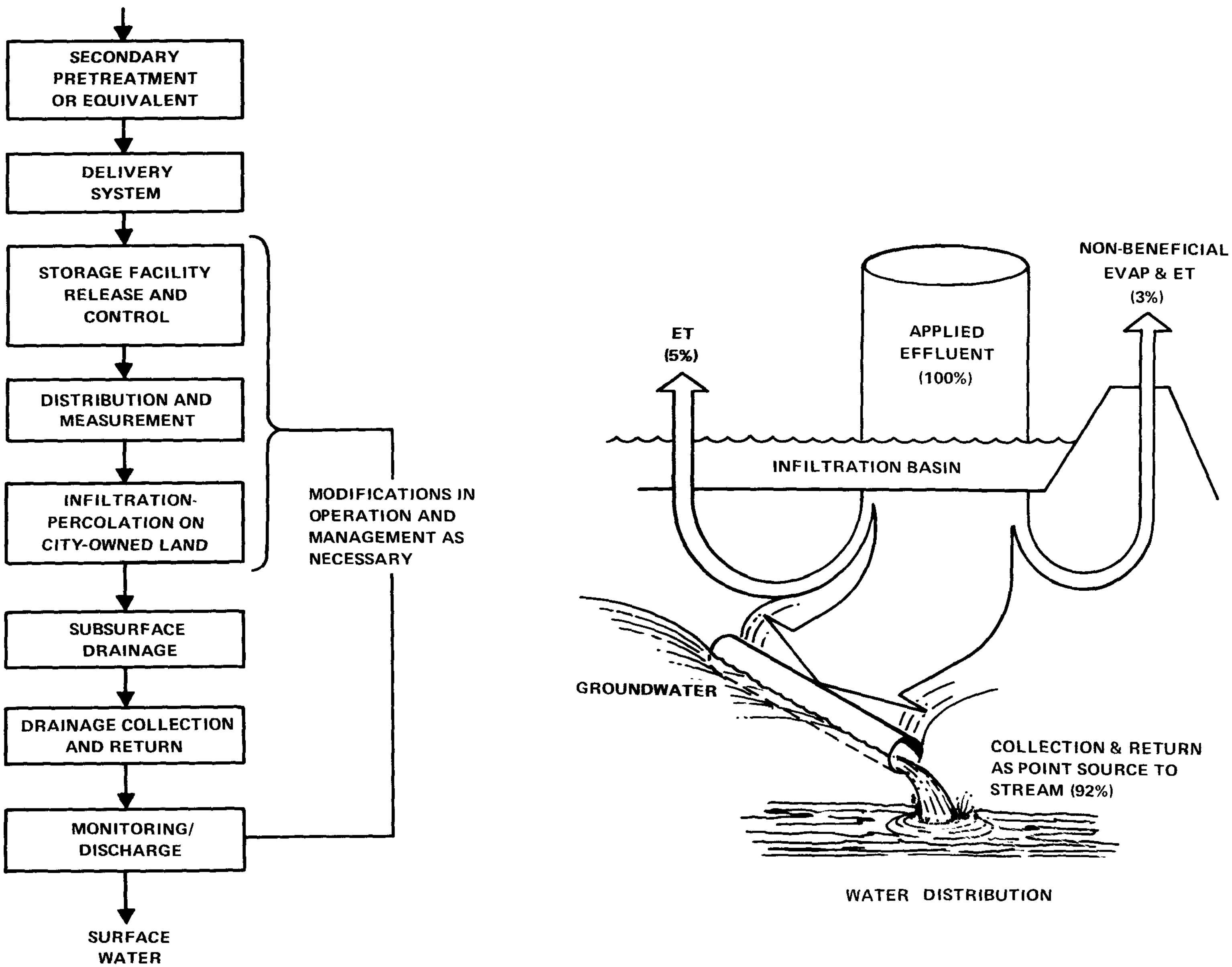
The irrigation return flow water from field runoff (including a 10-year storm runoff) and irrigation ditch operational spills would be collected and returned for reuse by a runoff collection system. The initial stage return flow would be collected by about 14 miles of 1- to 3-cfs unlined ditches. These ditches would drain into sumps and the effluent would then be pumped through concrete pipe to the reservoir and various canals for recycling. Additional ditches and return pumps would be required by 1985. It was estimated that the improved water supply would result in the requirement for subsurface drainage of about 10 percent of the total area. The drains would be 3- to 6-inch corrugated polyethylene agricultural drains at a depth of 8 feet and spaced at 200 feet. Larger collector drains would collect this drain water and discharge it into Boulder and Dry Creeks.

For the 1985 flows (step 1 development), a total area of 10,000 acres, with approximately 8,400 irrigated acres, will be required. The total area required for step 2 at the 1995 level of development will consist of 15,000 acres, with approximately 12,100 acres irrigated.

ALTERNATIVE L-II. Figure V-2 summarizes this alternative. Because of the higher application rates, a much larger portion of the applied wastewater returns to the streams rather than being lost to the atmosphere. As in Alternative L-I, the wastewater would be delivered to the storage facility by gravity. Storage would again be provided by expanding an existing reservoir and adding a new reservoir in the future. The existing distribution ditch capacity would be inadequate for this alternative and would be enlarged. Many of the irrigation sublaterals, structures, and on-farm systems would be enlarged and rehabilitated to create greater capacity and reliability for the higher irrigation rates. Considerable site preparation would be required to effectively control flows and ensure reliability. Surface runoff would be collected in 2- to 3-cfs capacity unlined ditches and recycled to the irrigation system in a manner similar to Alternative L-I.

Subsurface drainage would require approximately 436,000 feet of 4-inch-diameter corrugated plastic pipe, at a depth of 8 feet and spaced at 300 foot intervals, to drain the step 1 area adequately for 1985 flows. The subdrainage would be collected by collector drains 8 feet deep. The collector drains would feed three sumps which vary in capacity from 3.5 to 9.5 acre feet. Step 2 construction (for 1995 flows) will require an addition of 145,000 feet of subdrainage lines and additional subdrainage collection lines. Once the subdrainage water is collected, a network of pumps and pipelines would deliver this drainage water back to Boulder Creek and discharge it at a point near the existing treatment plant.

ALTERNATIVE L-III. Alternative L-III, the components of which are shown in figure V-3, would require the least land area of any land application system considered. This alternative consists of the application of the infiltration-percolation process to a city-owned site located on alluvial material adjacent to Boulder Creek. Application would be made throughout the year except during extremely cold weather, as noted earlier. A storage reservoir with a storage capacity of 1.2 months average winter flow will be required. Loading rates for this alternative would approach 30 feet per year.



FLOW DIAGRAM

Figure V-3. Land treatment infiltration-percolation Alternative L-III – Boulder.

A water balance (see figure V-3) for this alternative indicates that 92 percent of the applied water would be returned to the surface stream via the subsurface drainage system. Five percent of applied water would be beneficially used in growing crops. Three percent would be lost to nonbeneficial evaporation from water surfaces and evapotranspiration from phreatophytes.

In this alternative, the effluent would be delivered to the reservoir with a low lift pump through 2,000 feet of pipe. The storage reservoir would consist of two cells totaling 135 acres of surface with an average depth of 18 feet. A total storage volume of 2,400 acre feet would be available. This is a storage capacity of 1.9 months in 1975 and 1.2 months in 1995. The effluent would be pumped to a buried distribution system which would distribute the water to the infiltration basins.

The infiltration basins would be leveled to a flat bottom and will range in size from a few acres to over 30 acres. On the steeper slopes, the basins may be as narrow as 200 feet, while for the flatter slopes the width would be as wide as 600 feet. Lengths would range from 500 feet to 3,000 feet, with 2,000 to 2,500 feet being an average length. Berms with a total width of about 50 feet and height of 3 feet would be provided between basins. Effluent would be applied on the surface at a depth of approximately 1 foot for a time period of several days, followed by several days rest period. The water would infiltrate the surface and move to the groundwater through permeable sand and gravel.

Corrugated polyethylene drainage pipe would be used to collect subsurface drainage. The spacing for the drainage tiles would be approximately 95 feet and they would be buried to a depth of 12 feet. Because of the high loading rates and the rapid percolation to the groundwater with this alternative, drainage tiles up to 15 inches in diameter are required to the 95-foot spacings to carry away the subsurface drainage water. The gravity subdrainage collector system would collect the tile drainage and deliver it to pump stations or directly to Boulder Creek.

Cost of Land Treatment Alternatives

A number of assumptions were made in making the economic evaluation:

- A 20-year planning period beginning in 1975 was selected for economic comparison purposes. Capital costs were amortized over a 20-year period at a 7-percent interest rate as required for Environmental Protection Agency facilities plans.
- As with the AWT alternatives, expansion or phasing of the proposed treatment facility would be accomplished in two steps. For comparison purposes, the initial step was assumed to begin operation in 1975 and the second step in 1985. The first step of the expansion program would be able to provide adequate treatment until approximately 1985 and the second step to 1995. Because of the implementation time required, none of the alternative plans could actually be implemented by 1975 (as discussed later).
- All construction costs presented are adjusted to reflect the construction cost in the Denver metropolitan area in July 1974.
- Operation and maintenance costs also have been adjusted to reflect July 1974 costs.

- All construction costs include a 20-percent construction contingency allowance and 12-percent allowance for interim financing during construction, which is expected to last at least 2 years.

- Engineering, legal, and administrative fees are estimated to equal 15 percent of the total construction cost.

- In Alternative L-I, it was assumed that the city would purchase the development rights for the privately-owned land at a cost of $1,500 per acre. In Alternatives L-II and L-III, it was assumed the city would purchase the land at a cost of $2,500 per acre.

- In Alternative L-I, the income was assumed to be $4.50 per acre foot of water based on existing irrigation water costs. In Alternative L-II, the income was estimated at $100 per acre based on typical lease rates of $50 per acre plus the value of the nutrients in the effluent estimated at $50 per acre. In Alternative L-III, the income was estimated at $50 per acre.

Tables V-8, V-9, and V-10 summarize the estimated costs of each of the land treatment alternatives. Table V-11 compares the costs for the irrigation system in Boulder. The marked effect of local conditions upon system costs is apparent from this table. Boulder represents the favorable end of the spectrum in many regards.

Land Treatment Implementation Considerations

Alternatives L-I and L-II would necessitate a relocation of a state highway, which would require extensive public hearings and approval of the Federal Highway Administration. In addition, a special-use permit would be required for implementation, also involving extensive public hearings. Detailed field studies of soil and surface geology and water rights would also be required. It was estimated that 4.5 to 5.5 years would be required to completely implement the land treatment alternatives.

The implementation of Alternative L-I would affect farmers living on the site for the following reasons:

- Crop productivity per acre would increase due to an improved water supply.

- The reliability of the water supply would also increase, facilitating crop planning and minimizing the dependence on precipitation.

- The gross agricultural productivity of the site would increase due to additional land brought under irrigation.

If this plan were implemented, the production of root crops like sugar beets and onions would be terminated. Farmers who are acclimated to growing these types of crops may resist changing to forage crop production, irrespective of economics.

Table V-8.—*Costs of Alternative L-I*

Cost item	Step 1	Step 2
Construction costs		
Pretreatment	$ 1,325,000	$ 680,000
Flow equalization	890,000	615,000
Delivery	5,302,000	–
Storage	2,496,000	1,686,800
Distribution	621,500	1,131,200
Runoff collection/return	846,200	310,900
Drainage collection	562,000	228,000
Site preparation	10,000	2,000
Organic sludge disposal	3,127,000	726,000
Subtotal	$15,179,700	$ 5,378,900
Administrative and engineering	$ 2,376,300	$ 807,100
Land	15,000,000	7,500,000
Legal and administrative	667,000	333,000
Total capital costs	33,123,000	14,020,000
Maximum annual O & M costs	903,000	1,139,000
Annual income	(77,000)	(106,000)

Present worth of all costs = $40,637,000

Table V-9.—*Costs of Alternative L-II*

Cost item	Step 1	Step 2
Construction costs		
Pretreatment	$ –	$1,110,000
Flow equalization	890,000	615,000
Delivery	5,250,000	–
Storage	814,000	349,000
Distribution	603,400	148,500
Irrigation	819,000	267,500
Runoff collection/return	372,500	20,000
Drainage collection	3,011,300	801,600
Drainage return	2,110,200	–
Site preparation	211,000	66,000
Organic sludge disposal	3,127,000	726,000
Subtotal	$17,209,200	$4,104,500
Administrative and engineering	$ 2,581,800	$ 615,500
Land	12,500,000	–
Legal and administrative	1,800,000	–
Total capital costs	34,091,000	4,720,000
Maximum annual O & M costs	881,000	1,037,000
Annual income	(500,000)	(470,000)

Present worth of all costs = $35,099,000

Table V-10.—*Costs of Alternative L-III*

Cost item	Step 1	Step 2
Construction costs		
Pretreatment	$ –	$1,110,000
Flow equalization	890,000	615,000
Delivery	244,600	–
Storage	1,261,000	–
Distribution	2,249,000	841,000
Irrigation	1,935,600	668,600
Drainage collection	3,549,600	1,305,300
Drainage return	1,507,000	87,600
Site preparation	82,700	26,900
Organic sludge disposal	3,127,000	726,000
Subtotal	$14,846,500	$5,380,400
Administrative and engineering	$ 2,226,500	$ 807,600
Land	2,785,000	–
Legal and administrative	1,000,000	–
Total capital costs	20,868,000	6,188,000
Maximum annual O & M costs	732,000	858,000
Annual income	(41,000)	(41,990)
Present worth of all costs = $27,277,000		

Table V-11.—*Comparison of irrigation system costs*

	Costs/irrigated acre	
	Alternative L-I[b]	Alternative L-II[c]
Distribution	$ 146	$ 185
Surface runoff collection/return	96	97
Subsurface drainage and return	66	1,458
Site preparation	1	68
Irrigation system	—[a]	268
Total	$ 309	$ 2,076
Costs per mgd of capacity	$134,836	$306,493

[a]Uses existing, privately-owned systems.
[b]12,000 irrigated acres, 27.5-mgd capacity.
[c]4,060 irrigated acres, 27.5-mgd capacity.

For reasons similar to those mentioned above, the adoption of Alternative L-II would increase the agricultural productivity of the affected land; however, crop diversity will be limited to forage crops. The economic value of the crops grown on the site would be as high or higher than present due to higher yields per acre and high marketability.

Comparison of Treatment Alternatives

LAND REQUIREMENTS. Alternative L-I would restrict development on 15,000 acres of privately-owned land; Alternative L-II would require 5,000 acres of city-owned land; and Alternative L-III would require 1,120 acres of city-owned land. The AWT alternatives would all be placed on the existing 80-acre treatment plant site.

EFFLUENT QUALITY. Tables V-1 and V-4 present effluent quality data. None of the land treatment and AWT alternatives produce precisely the same effluent quality. All alternatives except AWT-III produce an effluent quality which exceeds the pending discharge requirements. AWT-III would meet the pending requirements which call for nitrification of ammonia. As noted earlier, Boulder wished to evaluate alternatives that would provide a very high degree of treatment even if not required to do so.

TREATMENT RELIABILITY. Alternative L-I would be moderately reliable due to the fact that the irrigation system would not be directly controlled by the city. Alternative L-II would have better reliability because the city would own and control operation of the irrigation system. The reliability of both Alternatives L-I and L-II are affected by potential stormwater runoff during storms which exceed the design capacity of the surface runoff collection system (10-year storm runoff). Alternative L-III would have good reliability but would suffer from lower nitrogen removals in the winter. Alternative AWT-I is the most reliable system since it uses combined biological and physical-chemical treatment. AWT-II and AWT-III are less reliable than AWT-I since they depend on biological processes for nitrogen removal.

IMPLEMENTATION. The land treatment alternatives would require more time to implement due to the delays associated with major land purchases and obtaining the necessary use permits and other approvals. It was concluded that 4.5 to 5.5 years would be required to implement the land treatment alternatives, while 3 to 4 years would be required for the AWT alternatives.

WATER RIGHTS. The water rights implications of the land treatment Alternatives L-I and L-II were greater than for the AWT alternatives or L-III and may require court action.

ENVIRONMENTAL IMPACTS. In the Boulder area climate, fog formation is possible in the vicinity of the storage reservoirs associated with the land treatment alternatives, with resulting travel hazards on adjacent roads. The higher application rates associated with Alternative L-II could cause fog over the entire irrigation site in spring and fall. The furnaces associated with the AWT alternatives are potential sources of pollutants but are controllable.

No significant effects on soils were projected for any of the alternatives. Alternatives L-I and L-II could benefit soil tilth and fertility. Some buildup of heavy metals may occur with L-II, but not to toxic levels due to the calcarious nature of the soil.

Alternative L-I would have a potential for health risks since people would continue to reside on the irrigation site. The storage reservoirs would provide a favorable environment for insect vectors.

The land treatment alternatives would inundate 150 to 400 acres of productive agricultural land in the storage reservoirs. The diversity of vegetation would be reduced by Alternatives L-II and L-III. The AWT alternatives would not significantly affect vegetation.

Alternative L-I would displace only 3 to 4 families in the reservoir site, while Alternative L-II would displace 75 families who would also lose both their source of employment and their homes. A highly negative public reaction to the land treatment alternatives (particularly L-II) was anticipated. It was also expected that people living adjacent to the treatment plant site would oppose the major expansion associated with AWT-I and AWT-II.

Alternatives L-I and L-II would require relocation of a state highway.

RESOURCE COMMITMENTS. It is very difficult to generalize on the relative power consumptions of land treatment and AWT. The estimated electrical energy requirements are shown in table V-12. The power requirements for land treatment are composed of the following:

- Pretreatment
- Those required to transport the wastewater to the storage facility (zero for Alternatives L-I and L-II)

Table V-12.—*Electrical resource commitments of alternatives*

	Electrical energy	
Alternative	10^6 Kwh/year	Kwh/mg
L-I	8.6	1,122
L-II	19.0	2,479
L-III	6.7	874
AWT-I	19.0	2,479
AWT-II	13.5	1,761
AWT-III	9.0	1,174

- Distribution of the effluent to the irrigation system (very low for Boulder due to flooding system used for irrigation and gravity flow to portions of the system)
- Return of collected surface runoff to irrigation system
- Power required to transport the treated effluent from its point of collection to the discharge point.

ECONOMICS. Table V-13 summarizes the costs of each of the alternatives. Other related economic factors are that Alternative L-II would reduce the tax base by 5,000 acres and Alternative L-III by 1,120 acres. Crop values are not expected to change significantly with the land treatment alternatives although crop diversity will be lessened.

CURRENT STATUS. EPA has indicated to the city that the cost of alternatives which exceed the required degree of treatment would not be fully grant-eligible. Only the portion of the costs required to meet discharge standards would be grant-eligible. The added economic burden of providing higher degrees of treatment than required has apparently deterred selection of land treatment alternatives and AWT-I and II. Had very high degrees of treatment been required, the land treatment alternatives would have been more cost-effective under the conditions in Boulder than the AWT alternatives.

Since this study was made, the nitrification requirement has been dropped (at least temporarily) and the City of Boulder has conducted a more detailed facilities plan based on meeting secondary standards (30 mg/l BOD and SS) by options such as infiltration-percolation, land application (similar to L-2), activated sludge (either before or after the trickling filters), lagoons, chemical coagulation, and mixed media filtration. Based on this study, the City Council has approved a facilities plan based on lagoon treatment of the trickling filter effluent with the option of adopting the infiltration-percolation approach should EPA rule it fully grant-eligible.

Table V-13.—*Cost comparison summary*

Alternative	Capital costs	O & M costs[a]	Present worth of all costs
L-I	$47,143,000	$1,139,000	$40,637,000
L-II	$38,811,000	$1,037,000	$35,099,000
L-III	$27,056,000	$ 858,000	$27,277,000
AWT-I	$46,156,000	$2,474,000	$53,334,000
AWT-II	$30,277,000	$2,004,000	$37,187,000
AWT-III	$17,707,000	$1,232,000	$21,752,000

[a]For 1995 flows.

COST COMPARISON SUMMARY

The preceding example is a good illustration of the effect that local conditions can have on the relative costs of AWT and land treatment. For high degrees of treatment, land treatment offered economic savings over AWT in Boulder, Colorado. In order to make some general observations on the relative economic merits of AWT and land treatment, generalized cost curves were prepared. (For detailed estimates, the EPA document, *Cost of Land Application Systems,* should be used.) The following curves were prepared to reflect the general nature of the effects of conditions ranging from relatively favorable to relatively unfavorable on land treatment costs. Table V-14 summarizes the basic assumptions made. These curves are for sprinkler systems since the flooding system is not as widely applicable. There are obvious exceptions to any set of generalized conditions, and this is true for the conditions in table V-14. For example, at Boulder there was one alternative where an existing irrigation system could be used with virtually no modification so that the costs of the irrigation system and site preparation would be reduced even further below those shown for favorable conditions. However, these are unusually favorable circumstances. The total of $960 per acre shown for very favorable conditions (table V-14) is approximately the costs experienced at Muskegon, Michigan, where conditions are favorable (flat, sandy soils, center pivot irrigation). There will be cases where conditions may be even more favorable than shown in table V-14 as very favorable, and also even more unfavorable than those shown as unfavorable (i.e., subsurface drainage costs for the high-rate system in Boulder were $1,458/acre as opposed to the $1,000 shown as unfavorable in table V-14). However, the range of conditions shown in table V-14 does reflect a range of costs that spans circumstances which would be described as favorable to unfavorable in many cases.

Tables V-15, V-16, and V-17 show the development of cost estimates for various capacity systems under the range of conditions described in table V-14. These costs do not include pretreatment costs, the costs to deliver wastewater to the irrigation site, or revenue from (or costs to dispose of) crops. The purpose of this section is to compare costs of land treatment with AWT techniques; thus, inclusion of costs to transport wastewater to the land treatment

Table V-14.—*Examples of impact of conditions on land treatment costs per acre (1974)*

Item	Unfavorable conditions	Moderately favorable conditions	Very favorable conditions
Land preparation	Extensive earthwork and clearing—$350	$ 150	Little earthwork and clearing—$50
Surface runoff control	Rolling topography and intense storms—$1,000	$ 500	Relatively level site and moderate rain—$200
Subsurface drainage	Extensive underdrain system needed—$1,000	$ 400	None required
Irrigation system			
Pumping station and distribution main	$ 700	$ 500	$ 400
Laterals and sprinklers	Solid set—$2,000	Solid set—$1,400	Center pivot—$300
Land costs	$2,000	$1,000	$ 500
Relocation costs	$ 50	$ 30	$ 10
Totals	$7,100	$4,030	$1,460

site (which are totally site specific in any case) would be unfavorably biased against land treatment. As noted earlier, the irrigated areal requirements can vary from 100 to 500 acres/mg. Because total costs are related to the area required, costs are shown for a range of areal requirements for each flow condition. It was assumed that total areal requirements were 130 percent of the irrigated area to provide for buffer zones and to account for unusable areas within the irrigation site. Land costs were assumed to be $500, $1,000, and $2,000 per acre for the very favorable, moderately favorable, and unfavorable conditions, respectively. Storage for 5 months flow was assumed. Engineering, legal, and contingency costs were applied to the nonland costs only. Capital costs were amortized at 7 percent for 20 years.

In order to span a range of AWT alternatives, two levels of treatment were assumed. "AWT-minimum" would consist of coagulation, sedimentation, and filtration. This would reduce phosphorus, BOD, suspended solids, and coliform to levels comparable to that achieved by a land treatment system where nitrogen removal is not of concern.

"AWT-maximum" adds biological nitrogen removal and activated carbon adsorption and regeneration to the AWT-minimum approach. As with land treatment, secondary treatment and raw sewage transport costs are not included. It was assumed that the chemical sludges would be lime sludges which would be dewatered and recalcined. It is probable that AWT costs can be reduced if dewatering and burial of lime sludges near the plant site are practical for a given locale. Recalcining costs are included, however, to ensure an adequately high AWT cost estimate. AWT costs are also expressed in 1974 cost levels. Table V-18 summarizes the AWT cost estimates which include costs for engineering and legal fees, and contingencies.

The AWT costs and land treatment costs are plotted in figures V-4, V-5, and V-6. Although such generalized costs have limitations, they do indicate general trends in the relative costs of AWT and land treatment. Increases in the degree of treatment required and decreases in plant size improve the competitive economic position of land treatment with conventional AWT processes.

Table V-15.—*Illustrative estimated costs for a spray irrigation system—very favorable conditions*

	Costs, thousands of dollars								
	1 mgd			10 mgd			50 mgd		
	100[a]	200	500	100	200	500	100	200	500
Capital costs									
Total land purchase[b]	65.0	130.0	325.0	650	1,300	3,250	3,250	6,500	16,250
Land preparation[c]	5.0	10.0	25.0	50	100	250	250	500	1,250
Surface runoff control[c]	20.0	40.0	100.0	200	400	1,000	1,000	2,000	5,000
Subsurface drainage[c]	0	0	0	0	0	0	0	0	0
Irrigation system[c]	70.0	140.0	350.0	700	1,400	3,500	3,500	7,000	17,500
Relocation costs	1.3	2.6	6.5	13	26	65	65	130	325
Storage lagoon	180.0	180.0	180.0	900	900	900	3,000	3,000	3,000
Subtotal	341.3	502.6	986.5	2,513	4,126	8,965	11,065	19,130	48,325
Plus 25% for legal, engr., contingencies (non land costs only)									
Total capital costs	410	595	1,152	2,978	4,832	10,394	13,019	22,288	50,094
Annual costs									
Amortization (20 yrs @ 7%)	38.7	56.1	108.6	280.9	455.8	980	1,228	2,102	4,725
Labor, operating	10	13	18	20	30	40	75	100	140
Power	7	7	9	50	60	70	240	270	300
Maintenance	25	30	40	160	200	300	480	550	750
Total annual costs	80.7	106.1	175.6	510.9	745.8	1,390	2,023	3,022	5,915
Total, ¢/1,000 gals	22.1	29.0	48.1	14.0	20.4	38.0	11.1	16.5	32.4

Note: Costs not included in the above: secondary treatment, facilities to pump and transport wastewater to irrigation site, disposal of crop (cost or revenue).

[a]Irrigated land area requirements, acres/mg.

[b]Total land purchased = 130 percent x irrigated land ($500/acre used).

[c]Applies to irrigated land only.

Table V-16.—*Illustrative estimated costs for a spray irrigation system—moderately favorable conditions*

	Cost, thousands of dollars								
	1 mgd			10 mgd			50 mgd		
	100[a]	200	500	100	200	500	100	200	500
Capital costs									
Total land purchase[b]	130	260	650	1,300	2,600	6,500	6,500	13,000	32,500
Land preparation[c]	15	30	75	150	300	750	750	1,500	3,750
Surface runoff control[c]	50	100	250	500	1,000	2,500	2,500	5,000	12,500
Subsurface drainage[c]	40	80	200	400	800	2,000	2,000	4,000	10,000
Irrigation system[c]	195	390	975	1,950	3,900	9,750	9,750	19,500	48,750
Relocation costs	3	6	15	30	60	150	150	300	750
Storage lagoon	200	200	200	950	950	950	3,200	3,200	3,200
Subtotal	633	1,066	2,365	5,280	9,610	22,600	24,850	46,500	111,450
Plus 25% for legal, engr., contingencies (non land costs only)									
Total capital costs	791	1,332	2,956	6,600	12,012	28,250	31,062	56,187	139,312
Annual costs									
Amortization (20 yrs @ 7%)	74	126	279	623	1,134	2,665	2,931	5,300	13,142
Labor, operating	10	13	18	20	30	40	75	100	140
Power	7	7	9	50	60	70	240	270	300
Maintenance	20	25	30	130	160	240	380	450	600
Total annual costs	111	171	336	823	1,384	3,015	3,626	6,120	14,182
Total, ¢/1,000 gals	30.3	46.9	92.0	22.5	37.9	82.6	19.8	33.6	77.7

Note: Costs not included in the above: secondary treatment, facilities to pump and transport wastewater to irrigation site, disposal of crop (cost or revenue).

[a]Irrigated land area requirements, acres/mg.

[b]Total land purchased = 130 percent x irrigated land.

[c]Applies to irrigated land only.

Table V-17.—*Illustrative estimated costs for a spray irrigation system—unfavorable conditions*

	Costs, thousands of dollars								
	1 mgd			10 mgd			50 mgd		
	100[a]	200	500	100	200	500	100	200	500
Capital costs									
Total land purchase[b]	260	520	1,300	2,600	5,200	13,000	13,000	26,000	65,000
Land preparation[c]	35	70	175	350	700	1,750	1,750	3,500	8,750
Surface runoff control[c]	100	200	500	1,000	2,000	5,000	5,000	10,000	25,000
Subsurface drainage[c]	100	200	500	1,000	2,000	5,000	5,000	10,000	25,000
Irrigation system[c]	270	540	1,350	2,700	5,400	13,500	13,500	27,000	67,500
Relocation costs	5	10	25	50	100	250	250	500	1,250
Storage lagoon	220	220	220	1,050	1,050	1,050	3,500	3,500	3,500
Subtotal	990	1,760	4,070	8,750	16,450	39,550	42,000	80,500	196,000
Plus 25% for legal, engr., contingencies (non land costs only)									
Total capital costs	1,238	2,200	5,088	10,938	20,563	49,438	52,500	100,625	245,000
Annual costs									
Amortization (20 yrs @ 7%)	116	208	479	1,032	1,939	4,664	4,952	9,492	23,113
Labor, operating	10	13	18	20	30	40	75	100	140
Power	7	7	9	50	60	70	240	270	300
Maintenance	20	25	30	130	160	240	380	450	600
Total annual costs	153	253	536	1,232	2,189	5,014	5,647	10,312	24,153
Total, ¢/1,000 gals	41.9	69.3	146.4	33.9	59.9	137.3	30.9	56.4	132.3

Note: Costs not included in the above: secondary treatment, facilities to pump and transport wastewater to irrigation site, disposal of crop (cost or revenue).

[a]Irrigated land area requirements, acres/mg.

[b]Total land purchased = 130 percent x irrigated land.

[c]Applies to irrigated land only.

Table V-18.—*AWT system costs*

	1 mgd		10 mgd		50 mgd	
	Capital[a]	O & M[b]	Capital	O & M	Capital	O & M
AWT minimum						
Coagulation-sedimentation	0.23	0.016	0.65	0.11	2.4	0.38
Filtration	0.32	0.026	1.30	0.12	3.0	0.34
Sludge handling	1.80	0.040	3.20	0.17	6.5	0.50
Total	2.35	0.082	5.15	0.40	11.9	1.22
¢/1,000 gals[b]	82.9		24.2		12.8	
AWT maximum						
Coagulation-sedimentation	0.23	0.016	0.65	0.11	2.4	0.38
Filtration	0.32	0.026	1.30	0.12	3.0	0.34
Sludge handling	1.80	0.040	3.20	0.17	6.5	0.50
Nitrif.-denitrif.	0.75	0.090	3.00	0.34	11.5	1.20
Act. carbon	1.00	0.020	3.50	0.07	12.0	0.30
Total	4.10	0.192	11.65	0.81	35.4	2.72
¢/1,000 gals	158.0		52.2		33.1	

[a] $ x 10^6.
[b] $ x 10^6 per year.
[c] Capital costs amortized, 20 years at 7%.

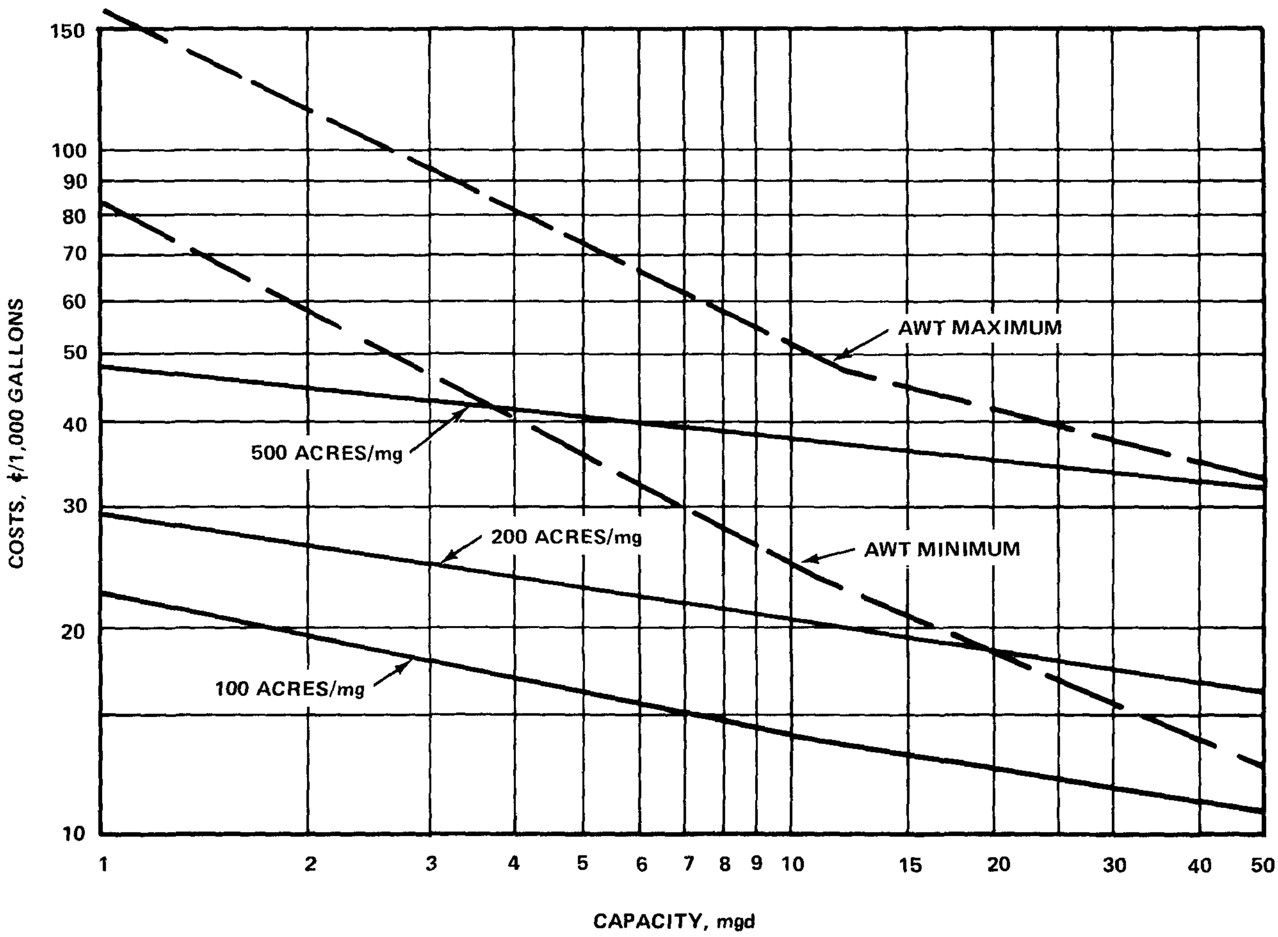


Figure V-4. AWT cost comparison—very favorable conditions for land treatment.

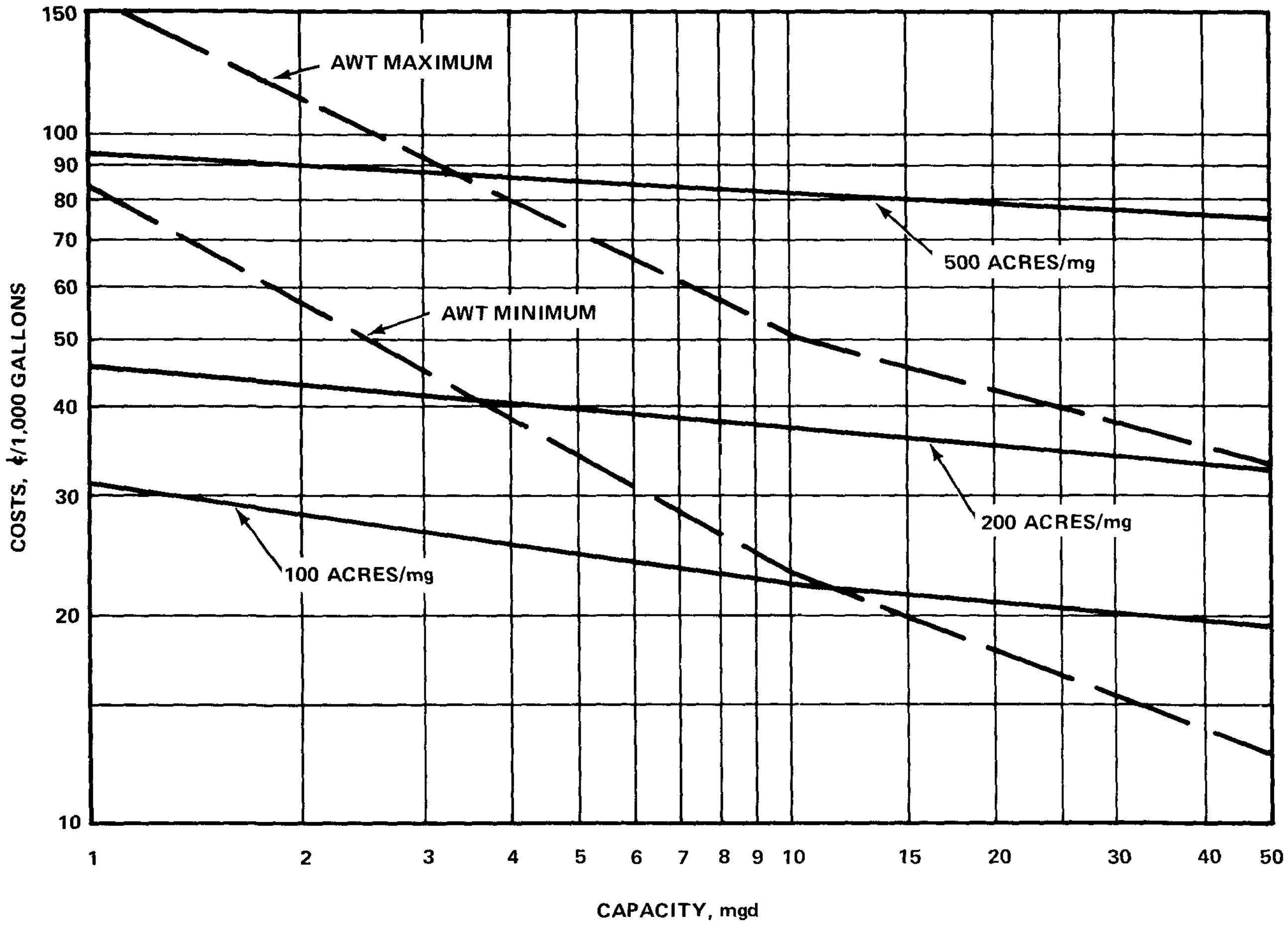


Figure V-5. AWT cost comparison—moderately favorable conditions for land treatment.

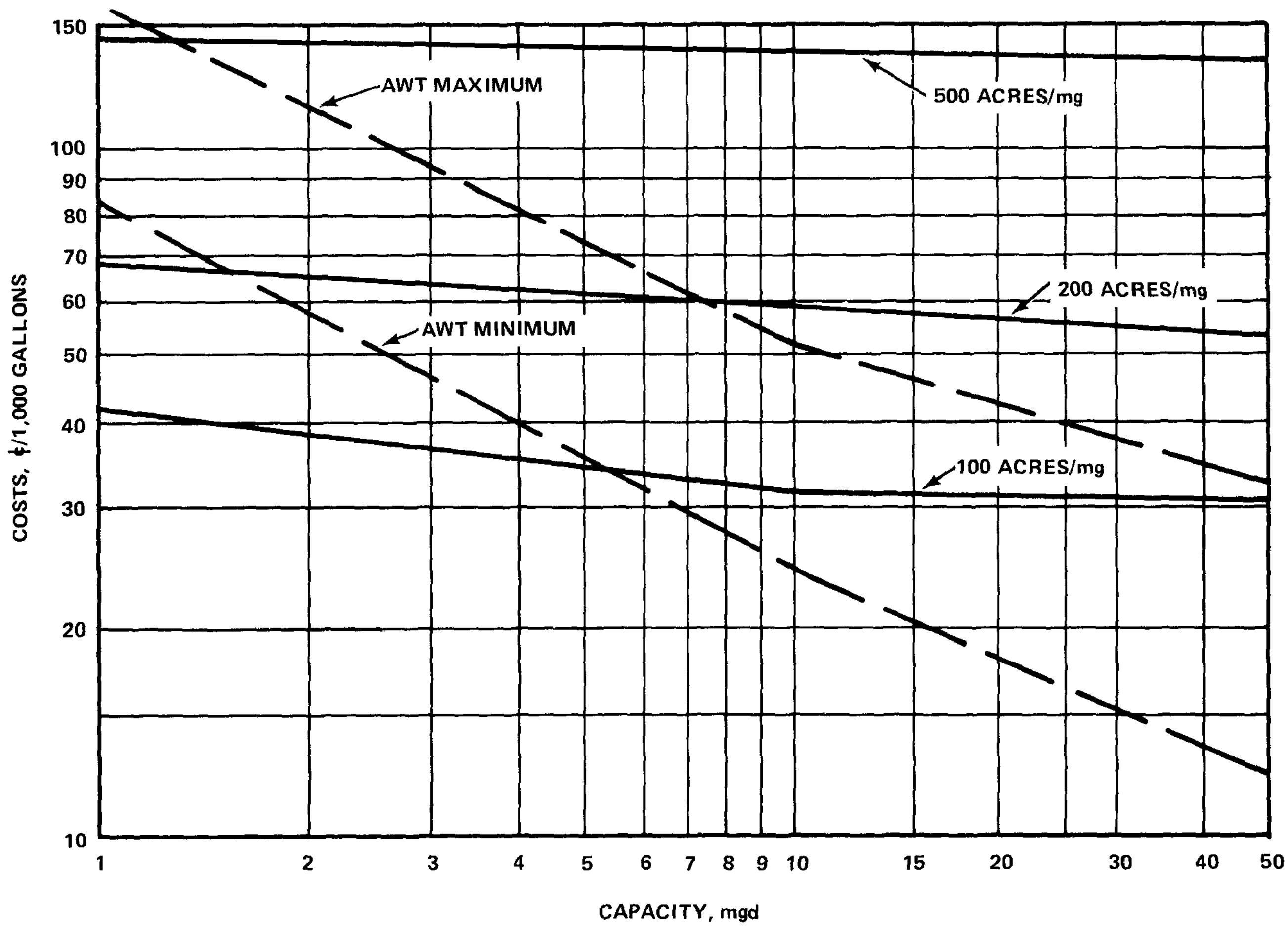


Figure V-6. AWT cost comparison—unfavorable conditions for land treatment.

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