United States
Environmental Protection
Agency

Research and Development

Robert S. Kerr Environmental
Research Laboratory
Ada, OK 74820

EPA/600/S2-85/016 Apr. 1985

EPA

Project Summary

Optimization of Nitrogen Removal by Rapid Infiltration

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The objective of this research field study was to evaluate the operational methods for optimization of nitrogen removal in the rapid-infiltration process. Previous studies (1,2) at the same site had showed a high degree of biological nitrification but essentially no nitrogen removal through denitrification. A further objective of the study was to evaluate the efficacy of removal of other pollutional constituents under the operational conditions necessary for enhanced nitrogen removal.

The rapid infiltration field site consisted of three basins with surface areas of 0.35, 0.19 and 0.22 hectares (0.87, 0.47 and 0.54 acres). The beds had approximately 3 meters (10 feet) of granular earth materials overlying an impermeable shale strata. The basins had underdrain pipes installed just above the shale base. Primary effluent from the City of Boulder wastewater treatment plant was applied to the basins utilizing hydraulic loading rates ranging from 4.4 to 42 meters/year (15 to 140 ft./yr.). Three types of loading sequences were used: flood loading every three and one-half days, flood loading daily, and sprinkler system loading based on soil moisture sensors and computer analysis and control. The influent and effluent quality variations were measured over a three-year period and the performance of the system was related to the operational parameters. The quality parameters utilized were nitrogen (total, organic, Kjeldahl, ammonia and nitrite/nitrate), biochemical oxygen demand, total organic carbon, suspended solids, total and fecal coliforms, phosphorus, and pH. Total nitrogen removals were increased substantially over the previous studies. Under optimum conditions, sustained removals above seventy-five percent were achieved with values for individual weeks in the mid eighty percent range. Increased denitrification resulted from maintaining saturated soil conditions for long periods, using low infiltration rates and reduced hydraulic loadings. The removal of phosphates was shown to be directly related to a critical phosphorus mass loading of 3.0 Kg/Ha-d (0.3 gm/m^2-d) that represented the mineralization rate for the soil chemistry of the field system. Sustained removals greater than ninety-five percent were achieved. BOD and TOC removals were high throughout the study with most BOD values above ninety percent.

The project report is published in two volumes based on each of the two loading modes, the manual loading and the automated loading system with computer control.

This Project Summary was developed by EPA's Robert S. Kerr Environmental Research Laboratory, Ada, OK, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The high-rate land treatment process utilizing rapid-infiltration beds is an economically attractive, low energy consuming process providing a high degree of pollutant removal for municipal wastewaters. When rapid-infiltration beds are designed with direct discharge to the groundwater, nitrogen removal through soil adsorption, biological nitrification and denitrification becomes one of the key parameters in the design and operation of the process. In the earlier studies at the same site, it was found that nearly complete ammonia conversion to nitrate was accomplished when applying either primary or secondary effluent but that the removal of nitrogen from the wastewater denitrification was relatively low, in the range of fifteen percent. Evaluations have been made on several rapid-infiltration sites located in different regions of the country and the results have been reported in the literature. In general, nitrogen removals in the range of thirty to seventy percent have been attained.

This research was focused on evaluation of the operational conditions that influence conversion and removal of the nitrogen forms in the treatment of primary wastewaters. In addition, the treatment efficiencies for biochemical oxygen demand (BOD), total organic carbon (TOC), suspended solids, coliform bacteria and phosphorus were evaluated under a range of operating conditions.

Conclusions

Rapid-infiltration treatment utilizing flood loading was shown to be capable of removing seventy-five percent of the total nitrogen from wastewater, continuously producing an effluent with a concentration of less than ten mg/l of N. In addition, under reduced loading conditions, effluent total nitrogen levels of 7 mg/l, phosphorus of 0.5 mg/l and BOD of 5 mg/l were attained.

Nitrogen removal was enhanced by creating reducing conditions in the soil system. Maintaining a saturated soil moisture condition with long periods of continuous flooding of the basins produced the highest nitrogen reductions. In addition, it was found that low infiltration rates improved removals by increasing the contact time of the water with the soil and by extending the periods of saturation of the upper portion of the soil. Lowering the mass loading rate and the hydraulic loading of the system reduced the ammonia leakage from the system.

The extent of phosphorus removal was found to be correlated to a distinct maximum mass loading of 3.0 Kg/Ha-d (0.3 gm/m^2-d). It was concluded that this value represented the mineralization rate for the soils employed in the study. When loadings exceeded this level, the mineralization reaction was not capable of regenerating the sites for the phosphorus adsorption at a fast enough rate to maintain a balance between the two reactions and the treatment efficiency declined rapidly.

BOD reductions were high for all loading conditions studied. A large portion of the BOD was removed in the solids mat produced at the surface of the beds by the accumulation of the solids present in the primary effluent. BOD removals were improved at lower hydraulic loading rates.

The rapid-infiltration basins provided major reductions in coliform bacterial densities. However, the removals were not sufficient to meet some environmental water quality standards and disinfection processes may be a required part of the process for discharging of the effluent into a stream.

Weather-dependent operational problems with the flood loaded beds were minimal throughout the year. The use of primary effluent did not create odor problems. Operation of the sprinkler loading system was not possible when the ambient air temperature dropped below freezing.

Several different loading rates and patterns were evaluated. The results for the best conditions are based on the four-weeks' result in the maximum removals. Optimum four-week nitrogen removals were found to be seventy-seven percent for the flood loaded beds utilizing the conditions of daily application of 4.67 cm/day. Nearly the same optimum removal, seventy-six percent, was achieved with loading twice per week at a rate of 10.3 cm/day. In both cases, reducing conditions were maintained by keeping the beds flooded over for several weeks during the loading sequence. Nitrogen removals were somewhat less for the sprinkler loaded system with a maximum four-week value of sixty-five percent at a loading rate of 3.84 cm/day. Phosphorus, BOD, and suspended solids removals were all greater when the sprinkler loading system was utilized.

Several conditions can be defined for the rapid-infiltration system studied that resulted in an optimum operational range. The optimization can be defined in terms of an operating range that will produce the best combination of removals for four constituents: BOD, phosphorus, ammonia and nitrate. The effluent requirements for a rapid-infiltration system may require removal of some or all of these constituents.

Enhanced BOD removals were found to result primarily from lowering the hydraulic loading rate of the system. Phosphorus removals were found to be high when the mass loading rates on the long and short term were less than the mineralization rate of the soil material. In this study the value was found to be 3.0 Kg/Ha-d (0.3 gm/m^2-d). With an influent wastewater phosphorus concentration of approximately 7.5 mg/l, the hydraulic loading rate should not exceed about 4 cm/day (50 ft/yr, 1 gpd/ft^2). Ammonia leakage was also found to be reduced at low mass application rates. A value of 4 cm/day for the hydraulic loading rate was also found to be advantageous for improved nitrogen removal operating conditions.

While lowering the loading rates enhanced the removals of these three parameters, there are two factors that provide the lower limit of hydraulic loading that can be used for an optimum system. One of these is system cost, but more importantly from the standpoint of performance is that nitrate removals require a high enough loading rate to produce saturated soil conditions. This is governed by the grain size distribution of the soil and the infiltration rate through the solids mat that forms at the surface of the beds. In this research, it was found that it required approximately 1000 Kg/Ha (10 mg/cm^2. 0.022 lb/ft^2) of wastewater suspended solids captured at the surface to produce an infiltration rate low enough for the continuous flooding of the bed surfaces to create reducing conditions. This would require that the beds be loaded for more than seven weeks at a rate of 4 cm/day after each drying period before reducing conditions could be fully reestablished. It was difficult to attain these conditions during the low loading rate phase of the flood loading studies on bed 1 and the sprinkler loading phase for beds 2 and 3. Two approaches could be used to improve the system operation. Resting periods, without scarification, should be short to prevent drying out of the solids mat on the surface of the beds. New designs should use tighter, more organic soils with high cation exchange capacities in order to reduce infiltration rates and enhance the adsorption capacity for ammonia and allow somewhat higher hydraulic loading rates while maintaining saturated conditions. Shallow scarification should be used only when the percolation rate of the beds cannot be restored by resting. Compaction of the soil to a prescribed Proctor density could be used after the scarification operation.

Recommendations

The nitrogen and phosphorus removal mechanisms in land treatment systems are dependent on the adsorption capacity of the soil for these constituents and by the regeneration rate of the sorption sites by biological reactions for nitrogen and chemical precipitation reactions for phosphorus. Studies relating the properties of different soils with removal effectiveness over a range of loading conditions would provide a greater understanding of the mechanisms of the treatment process and provide direction for the selection of the land treatment location for the design engineer.

Nitrogen removal effectiveness has been shown to be related to maintaining saturated soil moisture conditions that produced the reducing environment. Further development of the operational parameters for creating optimal soil moisture conditions, particularly with the sprinkler loading method, would be useful.

Most rapid infiltration systems have been designed with the concept that the effluent percolates to a ground water aquifer. The alternate system utilizing beds designed with underdrain pipes and discharge to a surface stream, such as the system used in this research project, can be designed to be a highly effective means of providing advanced wastewater treatment with a high degree of reliability while requiring low energy consumption and ease of operation. The underdrained system concept should be developed further as a contained system for small communities or cluster home developments.

Facilities

The rapid-infiltration system utilized in this field investigation was located on the site of the 75th Street wastewater treatment plant in Boulder, Colorado. The 75th Street plant is a trickling filter plant situated on the south bank of Boulder Creek. Construction of the rapid-infiltration site was accomplished in the spring of 1976. The site consisted of three basins, designated one, two, and three, moving from south to north. The configuration of the beds is shown in Figure 1. The earth materials in the beds were approximately three-meters (10-ft) deep and the base material was an impermeable shale strata. Earth berms, approximately 0.8 meters (2.5 ft) high, separated the basins, while a clay dike surrounding the entire basin area isolated the system from groundwater interference.

The rapid-infiltration site was located in the Piedmont section of Boulder County. These deposits were composed of loose sand, loose gravel, and clayey sand underlain by bedrock of oceanic origin. Each of the beds originally had approximately 75 cm (2.5 feet) of finer textured material at the surface overlying coarse sand and gravel in the lower portion of the system. Prior to this study, 60 cm (2 ft) of the finer material was removed from beds two and three so that 15 cm (0.5 ft) of finer textured materials remained. All of the beds had twelve or more percent clay and two and one-half percent or more organic matter in the surface layer.

Primary effluent wastewater was pumped through a 0.35 meter (14 in.) delivery pipe to the rapid-infiltration site. Two methods of bed loading were used. From December, 1980 to January, 1983, the beds were flood loaded. During the summer of 1982, a fixed sprinkler distribution system was installed on beds two and three and this loading method was initiated in January 1983. The system consisted of a network of 10 cm (4 in.) diameter aluminum irrigation pipes with

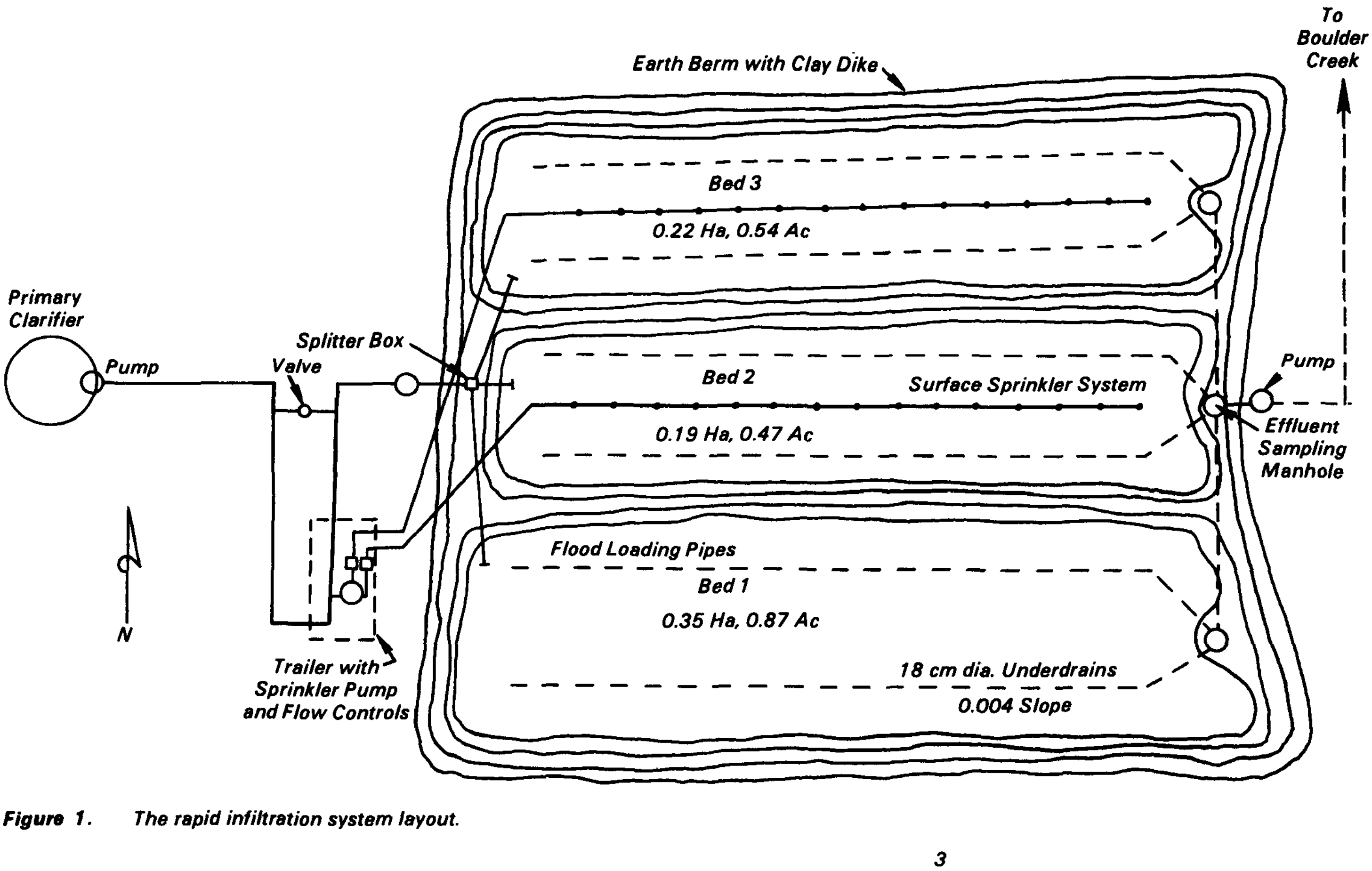

Figure 1. The rapid infiltration system layout.

risers installed at 6.2 meter (20 ft) intervals. Rotating sprinkler nozzles were installed at the top of the risers with each nozzle having a 4.4 mm (11/64 in.) orifice. There were 13 rotating nozzles per bed. The spray loading system was designed to operate at a gage pressure of 2585 mm of Hg (50 psi). The pipeline from the primary clarifier to the beds was modified so that it passed through a trailer in an inverted "U" shaped loop. A tee was installed in the pipe so that the flow could be directed to the flood loading of the beds or diverted to a separate pump and valving system that would allow the sprinkler systems to be operated.

The primary purpose of the sprinkler system was to use a computer-operated loading pattern based on sensing instruments at the site to control the moisture content of the soil in order to optimize the conditions for the nitrifying and denitrifying bacteria in the soil. Each bed had three sets of electrodes at 5 cm and 30 cm depths that measured soil temperature. Three moisture-content probes were also installed in each bed at the 5 cm depth. The temperature and moisture content data were measured on computer command and sent by telephone to the control computer located in the Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma. The computer was programmed to analyze the data and relay a signal back to the control trailer at the Boulder site if the spray pumps were to be turned on based on the sensing of soil moisture contents. The system was programmed to be inoperable when the temperature was below $-5°C$ or when the wind velocity exceeded 56 Km/hr (35 m.p.h.). It was also possible to operate the sprinkler system manually at the site.

After the wastewater passed through the soil materials in the beds, it was collected in an underdrain system consisting of two perforated 18 cm (7 in) diameter pipes running the length of each bed at a soil depth of 2.5 to 3.2 meters (8 to 10 ft), just above the shale layer at the bottom of the beds. The line from each of the beds had V-notch weirs installed in the effluent sampling manhole for flow rate measurements.

For the first two years of the study, the influent pipe led directly to an in-line, totalizing, propeller flow meter and then to a distribution spitter box. Lift plate gates were used to divert the flow to bed 1, bed 2, or bed 3 during flood loading. In the third year of the study, a section of the influent pipe was removed, reducers were attached to each end of the remaining pipe and a pipe was installed in a 'U' shape, through the control trailer and back to the original pipe. The pipe had a tee connection to a 7 cm (3 in) diameter pipe which led to a shutoff valve and the sprinkler pump. The pump discharge branched into two pipes each having a pressure actuated, rate of flow controller. Each of the two pipes exiting the control trailer was connected to a 10 cm (4 in) diameter aluminum irrigation pipe that led to the west edge of beds 2 and 3 and continued down the center of the beds to the east end. The ends of the irrigation pipes were capped and 2 cm (0.75 in) diameter risers were installed at 6.2 meter (20 ft) intervals. Rotating sprinkler heads at the top of the risers had an application radius of approximately 12.3 meters (40 ft).

Operation

Two effluent samples, acidified and unacidified, were taken at the outlet streams of the individual beds in the effluent manhole on intervals of 3, 7, 10, 24, 34, 48 and 72 hours after loading was initiated and effluent flows were measured at each time. The acidified aliquots were used for the analysis of ammonia, total Kjeldahl nitrogen, nitrate, phosphorus, and TOC. The unacidified volumes, taken at effluent peak flow, were for pH, BOD and suspended solids analyses. Special grab samples of influent and effluent flows were obtained using sterilized bottles for the coliform tests and using nitric acid acidified bottles for the calcium, magnesium, and sodium series. All chemical analyses were accomplished using methods from *Standard Methods for the Examination of Water and Wastewater* (3), or *Methods for Chemical Analysis of Water and Wastes* (4), using blanks and spikes for quality control.

Nitrogen removal involved biological nitrification and denitrification processes and for this reason, wastewater treatment plant primary effluent was used as the influent to the process to provide an adequate carbon source for the biological growth. Another reason for the use of primary effluent was to demonstrate that rapid infiltration was an effective and reliable means of achieving high removal efficiencies for BOD, suspended solids, phosphorus and other pollutional parameters while operating in a mode intended for optimum nitrogen removals.

The research was conducted as a field study using several different loading rates, loading-resting patterns and two application techniques: flood loading and sprinkler loading. At times, the combination of these parameters did not result in optimum conditions. For this reason, the time-concentration curves are presented to illustrate the effect of the variables. The average removal percentages are used to summarize the treatment achieved by the rapid-infiltration process and values for the best four-week period during the study are shown and give an indication of the performance that could be expected for a system operating continuously at near optimum conditions. Individual weekly removal percentages displayed some degree of variability, due to the changing nature of the pollutional strength of the influent stream, which is typical of a field study. For this reason, longer term four-week trends in removal percentages are more significant.

During the study, the Boulder wastewater treatment plant was involved in a major construction project. Relocation of the rapid-infiltration influent pipe was necessary and this caused some downtime for the beds which was not a planned part of the research. The inactive period for beds 2 and 3 during weeks 118-135 was caused by the construction project.

Three different modes of wastewater application were used during the study. Initially, the beds had a target value for flood loaded of approximately 40 cm (16 in.) of primary effluent on three and one-half day intervals. This pattern was followed for the first 78 weeks of the study, encompassing the period from December of 1980 through March of 1982. The second loading sequence, which involved only bed 1, utilized a lower loading rate of approximately 5 cm (2 in) of flooding application each day. This was used from April, 1982 through February of 1983. The third mode, the sprinkler distribution system was ready for use on beds 2 and 3 after January, 1983, and it was necessary to discontinue the research operation of bed 1 because the overflow of the sprinkler pumping system was directed to bed 1 and made it impossible to maintain a consistent and measured loading amount. The sprinkler system operated from January through December of 1983, although it was interrupted from March through June by the construction in the treatment plant. The average loading rates and loading patterns are summarized in Table 1. The loading rate for the 3.5-day pattern averaged 123 ft/yr based on the weeks that loading actually occurred. Resting of the beds was necessary and occupied 28 percent of the weeks of this portion of the study. The overall average loading rate over time including resting periods is given in Table 1. No intentional resting periods were utilized with the 1-day or sprinkler-system patterns. Downtime periods caused by construction in the wastewater treatment plant were not included in the calculation of loading rates.

Results

The average concentrations for the rapid-infiltration bed influents and effluents, as well as removal percentages for the total period of each loading mode, are given in Table 2. Some of the measured chemical constituents of the wastewater including pH, sodium, and magnesium were essentially unchanged during the rapid-infiltration process. The slight increase in calcium probably resulted from dissolving of calcium carbonate deposits in the bed material.

Coliform removals were significant, but relatively high concentrations remained in the process effluents. The results of this study show that the long-term use of underdrained rapid-infiltration beds may require disinfection of the effluent prior to discharge into a surface receiving water.

The values shown in Table 2 include periods of study when the variables tested were not at optimum. In order to judge a more optimized system performance, Table 3 has been constructed with a summary of the removal percentages for the important parameters shown and with the efficiencies obtained under the best condition studied based on four continuous weeks of operation.

The first ten weeks of the study were not included in the selection of the best four weeks of operation because the beds had been rested for more than a year and loading during this period did not represent normal operation.

The use of rapid-infiltration beds to remove nitrogen from wastewater involves the creation of aerobic conditions for nitrification, and reducing conditions for denitrification simultaneously or sequentially in such a manner as to prevent pulses of ammonia or nitrate from being released in the effluent during any portion of the loading and infiltration cycle.

The beds, which had been standing idle for a year, were scarified prior to any wastewater application. For the first ten weeks of loading, the influent percolated through the beds very rapidly. Infiltration rates were high (>50 cm/d) and the bed

Table 1. Loading Depths

Operating Mode		1 flood (3½ day)	2 flood (1 day)	3 sprinkler
Loading rate, including resting	cm/d	7.42	4.67	3.84
	ft/yr	88.6	56	46
	gal/d-ft²	1.8	1.15	0.95

Table 2. Average Constituent Concentration and Removals

Constituent	Bed influent	Bed effluent	% removal
Mode 1 (3½ day)			
Nitrogen			
Ammonia-N	16.5 mg/l	6.5 mg/l	60
Nitrate-N	0.27 mg/l	1.85 mg/l	—
Organic-N	7.05 mg/l	0.85 mg/l	88
Total-N	23.82 mg/l	9.20 mg/l	61
T. Phosphorus-P	7.65 mg/l	1.33 mg/l	83
BOD-5	101 mg/l	8.8 mg/l	91
TOC	67.3 mg/l	10.2 mg/l	85
Suspended solids	51.2 mg/l	14.7 mg/l	71
Coliforms/100 ml			
Total	58.5×10^6	1.6×10^5	97
Fecal	13.4×10^5	0.65×10^5	95
pH	6.85	6.85	—
Calcium	41.6 mg/l	58.6 mg/l	−41
Magnesium	21.5 mg/l	21.5 mg/l	0
Sodium	56.6 mg/l	53.0 mg/l	6
Mode 2 (1 day)			
Nitrogen			
Ammonia-N	13.75 mg/l	3.23 mg/l	77
Nitrate-N	0.36 mg/l	4.58 mg/l	—
Organic-N	8.40 mg/l	1.06 mg/l	87
Total-N	22.51 mg/l	8.87 mg/l	61
T. Phosphorus-P	8.94 mg/l	0.53 mg/l	94
BOD-5	54.5 mg/l	3.8 mg/l	93
TOC	53.1 mg/l	6.7 mg/l	87
Suspended solids	53.9 mg/l	10.2 mg/l	81
Coliforms/100 ml			
Total	—	—	—
Fecal	14.3×10^5	0.93×10^5	94
Mode 3 (sprinkler)			
Nitrogen			
Ammonia-N	17.85 mg/l	1.28 mg/l	93
Nitrate-N	0.13 mg/l	10.50 mg/l	—
Organic-N	6.76 mg/l	0.64 mg/l	91
Total-N	24.74 mg/l	12.42 mg/l	50
T. Phosphorus-P	7.13 mg/l	0.55 mg/l	92
BOD-5	80.4 mg/l	2.2 mg/l	97
TOC	54.8 mg/l	5.0 mg/l	91
Suspended solids	53.5 mg/l	6.0 mg/l	89
Coliforms/100 ml			
Total	—	—	—
Fecal	—	—	—

Table 3. Comparison of Three Loading Modes Average and Best 4-Week Results

Operating Mode	1 flood (3½ d) % removal		2 flood (1 d) % removal		3 sprinkler % removal	
	avg.	4-week	avg.	4-week	avg.	4-week
Total Nitrogen	61	76	61	77	50	65
Total Phosphorus	83	87	94	97	92	98
BOD-5	91	91	93	96	97	99.5
TOC	85	85	87	91	91	96
Suspended solids	71	73	81	89	89	98

effluents were highly nitrified but with less than forty percent nitrogen removal. These results are shown as the beginning of the time-history curves of Figure 2. The results shown in the figure are for bed 1 for the first 120 weeks of flood loading and for bed 2 with manually controlled sprinkler loading during weeks 109-117, followed by an inactive period caused by inplant construction during weeks 118-135 and then for bed 2 with computer-controlled loading for the remaining sprinkler loading period. The results of the other beds were similar. The top curve on each graph shows the loading rate as a function of the week of loading. The next curve shows the infiltration rate, and the third curve relates the total nitrogen concentration of the influent and effluent (solid dark lines) and the ammonia nitrogen concentration of the influent and effluent (lighter solid lines) and the nitrate nitrogen concentration of the effluent (dashed lines). Nitrites were included in the nitrate measurements. Organic nitrogen and influent nitrate nitrogen are not shown on the curves except that they are included in the total nitrogen values. The bottom curves show the percent removal of total nitrogen.

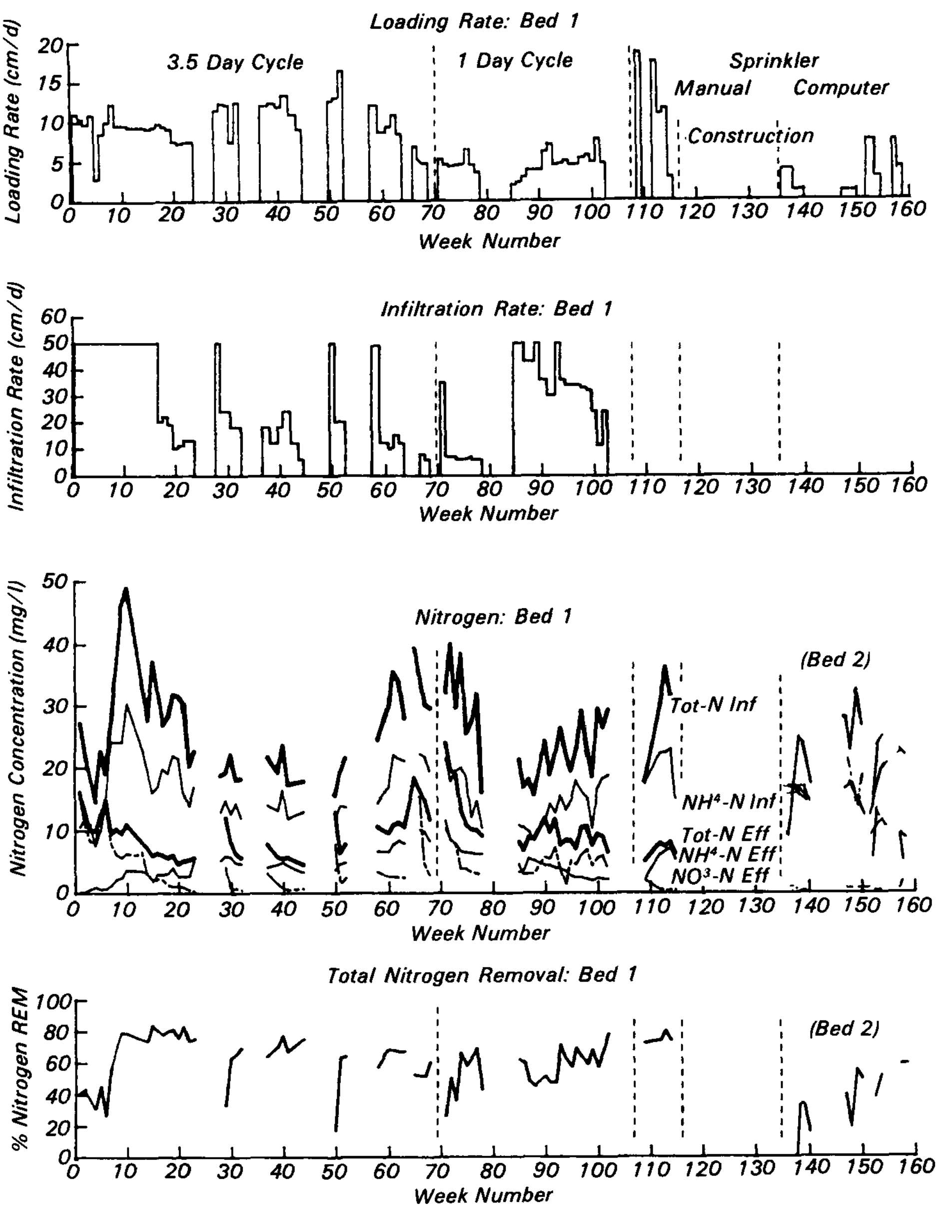

Figure 2. *Nitrogen analysis.*

Soon after the fifteenth week of loading, the infiltration rate dropped rapidly with each loading. This was caused by a buildup of a solids mat on the surface of the beds. The mat consisted of solids strained from the wastewater during the infiltration periods. The reduced infiltration rate caused the beds to be flooded over a large portion of the three and one-half days between loadings. When the infiltration rate dropped below 20 cm/day (5 gpm/ft^2), the beds were flooded over continuously between loadings. As soon as this happened, the nitrate level in the effluent dropped and the ammonia concentration began to increase. The beds were rested and scarified after 23 weeks of loading. At that time the nitrogen removal was still high, averaging better than seventy percent, but the water was flowing over the top of the side berms of the beds near the end of each loading period.

After resting and scarification, a nitrate flush occurred with the first loading. With further loadings, the infiltration rate decreased and the beds became flooded over again and the nitrogen removal rate was back into the seventy percent range. This pattern was continued using shorter periods between restings until the sixty-eighth week of the study. After the third loading sequence, the nitrate flush was nearly eliminated by using very light scarification. It was obvious from the data that the ammonia level in the effluent was continually rising and that the total nitrogen removal percentage was declining. Beds 2 and 3 were removed from the loading sequence so that the sprinkler system could be installed and bed 1 was loaded daily at a rate in the range of 5 cm (2 in.) per day. As can be seen from the curves, the ammonia level in the effluent decreased from week 71 to week 102 and the removal percentage also increased. Beginning with week 136, the computer-monitored sprinkler system was operational on beds 2 and 3. In order to prevent an overpressure in the influent pipe from the pump at the primary clarifier, it was necessary to allow an overflow stream to flood bed 1 whenever the other two beds were sprinkling. The overflow produced an unregulated flow on bed 1, which was not monitored after week 115. Several different soil moisture control points were tried, with each sequence showing improved removal, but optimum steady-state operation could not be obtained prior to the end of the field testing at week 158.

The initial loading rate of 37.6 meters/year (123.4 ft./yr.) producing a total nitrogen loading of 24.5 Kg/Ha-d (21.5 lb/ac-d), caused an overloading of the system resulting in continued increase in ammonia leakage into the effluent. When the loading was reduced to 17.0 meters/year (55.8 ft./yr.) with a total nitrogen loading of 11.1 Kg/Ha-d (9.9 lb/ac-d) beginning with week 71, the ammonia leakage showed a steady decline.

The removal of nitrate was accomplished by maintaining flooded-over conditions on the basins. This was done for periods of more than a month without adversely affecting the total nitrogen concentration in the effluent. The low infiltration rates that resulted from the formation of solids mats on the bed surfaces were necessary for the denitrification reaction to occur. The only times when poor nitrogen removals were observed were immediately after resting periods with scarification for the first three loading sequences when nitrates were released from the system due to the fact that it took several loadings to reduce the infiltration rate and establish reducing conditions. The operation with continuously saturated bed surface conditions was possible due to the field layout and the soil profile. It was possible for air to enter the lower, coarse strata of the beds from the sides and from the underdrain system.

The major factor affecting the effluent nitrogen concentration appears to be the nitrogen mass-loading rate with respect to the soil cation exchange capacity. The cation exchange capacity is usually greater for soils of higher organic content. The cation exchange capacity for the upper layer of soil in the beds of this study ranged from 15 to 24. The coarse materials in the lower portions of the beds had measured values in the range of 2 to 3. Soil organic matter, including that disked in during scarification provides the energy source for the denitrifying bacteria and this may be an important source along with the BOD of the wastewater being treated.

Phosphorus removal from wastewater was evaluated in conjunction with the operating conditions needed for nitrogen removal. Land treatment of phosphorus involves the two sequential reactions of adsorption of the phosphate ion and precipitation of a solid that is retained in the soil matrix. The precipitation usually appears to be the rate-limiting step. When a system is overloaded, the rate of precipitation becomes inadequate to continually renew the sites for the adsorption reaction, and phosphorus leakage occurs in the process effluent.

Phosphorus removals in this study are summarized in Figure 3. The lower curves in each part of the figure show that the treatment system was severely overloaded during the initial 32 weeks of the research. Long resting periods in the following weeks caused the system to completely recover by week 50. Lower loading rates and more frequent resting periods maintained efficient phosphorus removals for the remainder of the study.

Three periods were selected from the data array (weeks 15-19, 74-78 and 92-96) as steady-state condition for the points (squares) in Figure 4. A line was constructed through the points to illustrate the removal capacity of the soil in this research. The reported results of other researchers have also been shown. The curve illustrates that there was a very discernible maximum loading rate that gave high removals and there was very little tolerance for overloading. Analysis of the phosphorus removal curves for each of the beds during the period of the study showed that when the long-term (months) or short-term (days) phosphorus loading was greater than 0.3 g/m^2-d, the removal efficiency declined quite rapidly, and when the phosphorus loading was reduced below that level, the phosphorus removal improved. It was concluded that the value of 0.3 g/m^2-d represented the mineralization rate (phosphorus precipitation rate) for the soil of the beds used in this study. The other researchers points on Figure 4 show that the mineralization rate may have been quite different for the various soils encountered in the different research projects and that the value may become less with many years of operation of a system.

BOD and TOC gave similar patterns of high removal under all operating conditions for the rapid-infiltration process. The most significant parameter affecting BOD removal was the hydraulic loading rate.

The effluent suspended solids concentrations were higher than expected for an earth filtration system. Suspended solids concentrations followed the same removal pattern as that of BOD, except that the

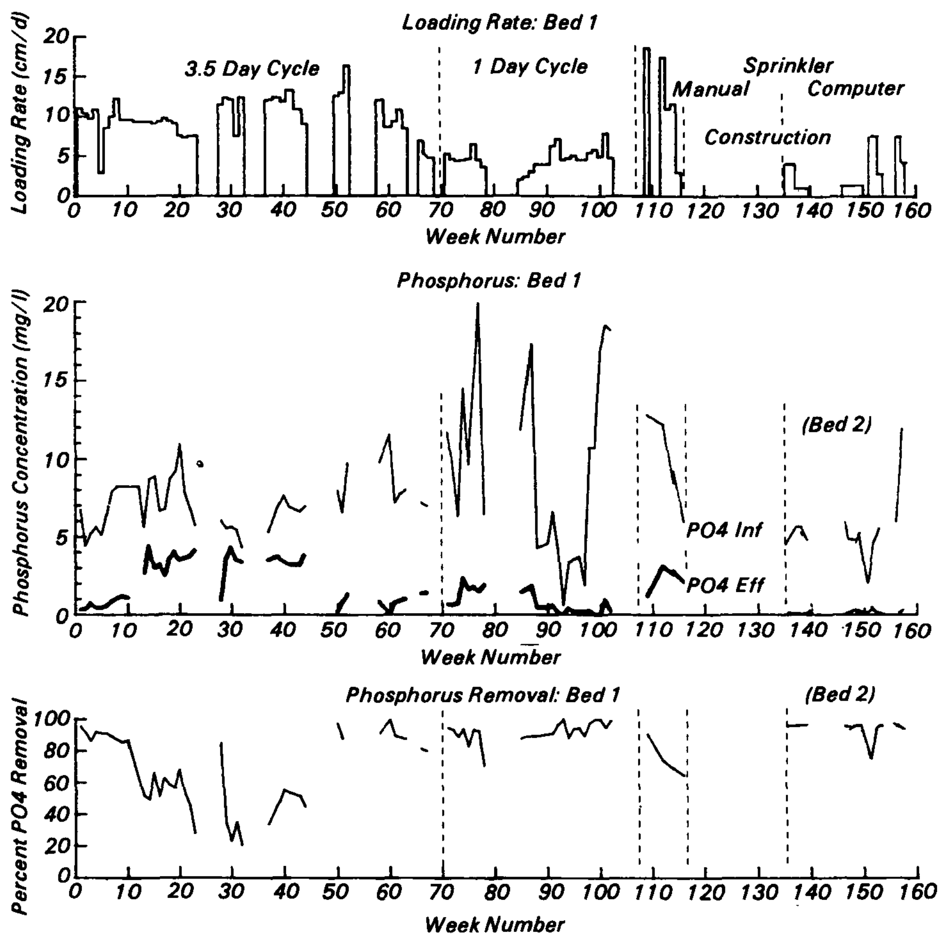

Figure 3. *Phosphorus analysis.*

influent values were lower and the effluent values were two to three mg/l greater. Inspection of the underdrain system revealed extensive biological slime growth, which was thought to be the source of the particulate matter in the effluent. For systems discharging directly to the ground water, this would not occur.

One of the major considerations in the use of rapid-infiltration beds with primary effluent is the potential of odors near the site. Odors were not a problem during the period of this research. Most of the time during the study, standing water, primary effluent, was present on the beds. Natural surface aeration was sufficient to prevent septic conditions and the ponding did not cause offensive odors.

The highly nutriated soils in the beds produced voluminous weed growth on the surface of the beds during the warmer months. Weed cutting was a necessary part of the system maintenance program at this site for aesthetic reasons. Cutting was done about every six weeks in the summer, during the period when the beds were rested. Excessive algae growth occurred when the ambient air temperature was above 33°C (90°F) for extended periods of time. This condition caused clogging of the solids mat on the beds accompanied by greatly reduced infiltration rates. When this condition became excessive, it was necessary to rest the beds, which tended to necessitate shorter, more frequent intervals between resting periods of the beds in the summer than in the winter.

Cold weather conditions had very little effect on the operation of the flood loaded beds. Temperatures as low as −23°C (−27°F) were encountered for short periods of time. Under the worst conditions, an ice layer several inches thick formed on the beds but seemed to have little effect on the overall functioning of the system. Problems were encountered with the sprinkler system during severe winter conditions. The system experienced operating problems when the ambient air temperature went below freezing. Although the wastewater was warm enough to flow through the sprinkler nozzles in the normal fashion, some of the water would wet the outside of the sprinkler head housing. When frozen, this water would prevent the sprinkler head from turning, causing it to spray in the same position throughout the loading cycle.

The thin-walled aluminum irrigation pipe was joined with connections having neoprene flap gaskets to assure that the pipe was water tight. When pressurized the pipe would drain at the joints when the pump was stopped between loadings. This prevented the freezing of the water within the pipe between loadings. This arrangement worked satisfactorily except during large snowstorms. The snow and ice surrounding the pipes would seal the joints, causing the pipes to remain full of water, in some instances causing irrigation pipe rupture. Spray loading systems must be used with care in winter weather and provisions made for cold periods when the system cannot be operated.

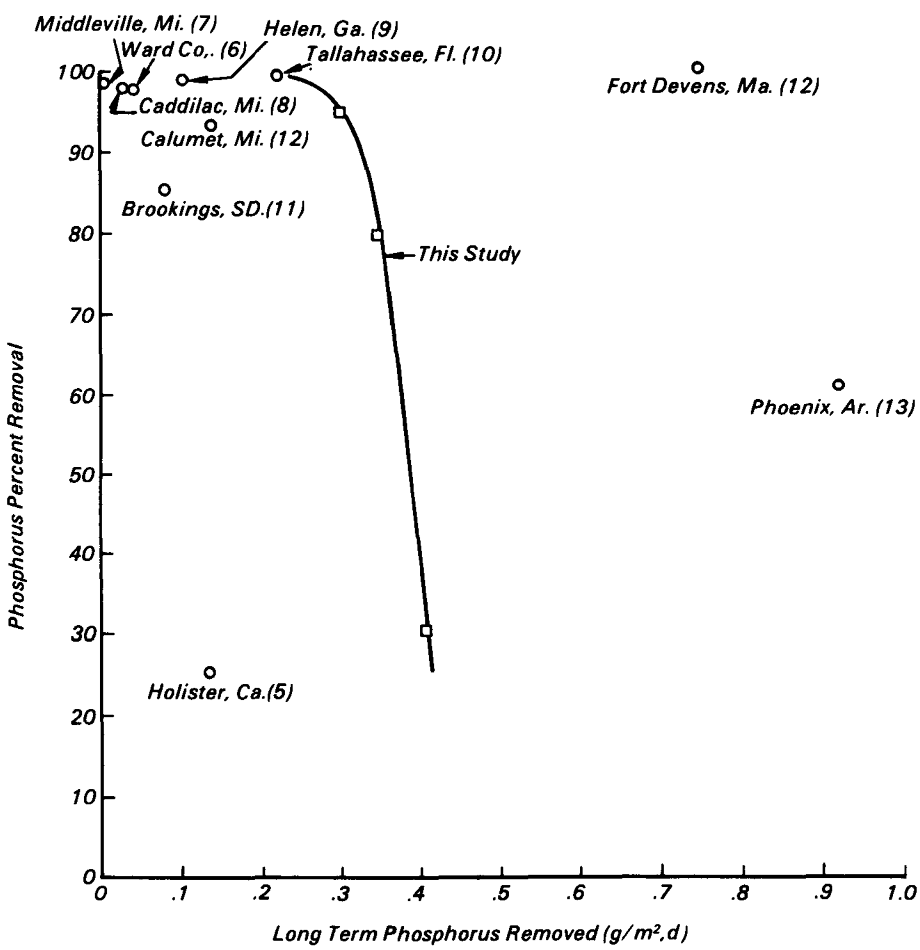

Figure 4. *Phosphorus removal comparison with other studies.*

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**Most readers would not find it necessary to purchase Volume II of this report since the environmental evaluation and supporting data of the computer-operated system are included in Volume I. Volume II contains the descriptions of the various hardware components, how they were interfaced, and computer software for operating the system.*

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