EFFECT OF ILLUVIATED DEPOSITS ON INFILTRATION RATES AND DENITRIFICATION DURING SEWAGE EFFLUENT RECHARGE

by

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A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

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STATEMENT BY AUTHOR

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ACKNOWLEDGMENTS

The author wishes to express his extreme gratitude, appreciation, and thanks to Dr. L. G. Wilson for his unending help, guidance, and support throughout his graduate career and preparation of this thesis.

Thanks are also extended to Professor Sol Resnick, Director of the Water Resources Research Center, for his financial support and to all the personnel at the Center for their help during preparation of this thesis; with special thanks to Nancy Svacha and Maureen Rigo for their help in typing and data analysis.

The author also wishes to express his thanks to the Pima County and City of Tucson Departments of Sanitation for their cooperation and assistance during the preliminary and operational phases of this project. Thanks are also extended to Dr. A. W. Warrick for supplying the tensiometers used during this study and to Dr. D. B. Marx for performing portions of the statistical analyses.

The author wishes to express his gratitude to Dr. M. J. Zwolinski, Dr. G. S. Lehman, and Dr. P. F. Ffolliott of the School of Renewable Natural Resources, for their guidance during this study and for serving on my committee.

Special thanks go to my father, my brother, Ron, John Eichelberger, and Bruce Merriman for their aid in the construction and initiation of this project, with very special thanks to Bruce for his moral support throughout this study.

Last but not least, my sincerest gratitude and appreciation to my wife, Paula, just for being there.

The work upon which this thesis is based was supported by funds provided by the U. S. Department of the Interior, Office of Water Research and Technology, as authorized under the Water Resources Act of 1964.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF TABLES

Table Page

ABSTRACT

A column study was conducted to determine the interrelationships among nitrogen transformations, infiltration rates, and development of a black layer during sewage effluent recharge. Columns were packed with river sand and continuously flooded with sewage effluent for 28 days during the first trial, designated run 1. Run 2 lasted for 64 days and gravel was used in place of sand. For both runs infiltration rates and manometer readings were recorded daily and samples of the inflow and outflow were collected and analyzed for the various nitrogen compounds.

Infiltration rates decreased rapidly upon application of the sewage, mainly due to clogging of the surface by suspended solids. A black layer developed within a few days, the thickness of which was inversely related to the infiltration rate. There was an average reduction in total nitrogen of 62.9% during run 1 and 15.9% during run 2.

Black layer development was not a cause of reduced infiltration rates, but lower infiltration rates appeared to be an indirect cause of a thicker black layer within a given soil type. Total nitrogen reduction was apparently not related to black layer development. However, the percent of total nitrogen removal was greater for lower infiltration rates.

INTRODUCTION

Ephemeral stream channels are used by some southwestern communities for disposal of sewage effluent. One community that disposes of its sewage in this manner is Tucson, Arizona. Since 1955, the principal drainage tributary of the Tucson Basin, the Santa Cruz River, has been receiving discharged secondary effluent from the City of Tucson sewage treatment plant (Wilson, Herbert, and Ramsey, 1975). In fiscal year 1973-1974, 31,460 acre-feet of effluent was released into the ephemeral stream channel (Dye, 1974). Davidson (1973) estimated that more than 90% of the effluent released into the channel is being recharged and is affecting both ground water levels and water quality. In addition, Cluff, DeCook, and Matlock (1971) observed that water levels in the vicinity of the Santa Cruz River have begun to rise, and that the nitrate content of ground water in the recharge area has increased steadily. Because the current supply of ground water is being depleted about five times faster than it is being replenished (Arizona Water Commission, 1975), strong consideration has been given to ground-water recharge of sewage effluent from proposed county treatment facilities (Ehrich, Kluesener, and Harper, 1973). In effect, the recycling system would be similar to the method the city has used for effluent disposal since 1955 and would reduce the present overdraft by replacing a portion of the used water with treated effluent.

Unfortunately, there is a potential danger of ground water contamination when recharging sewage effluent (Hughes, 1975), since the fate of microorganisms and certain chemical constituents during recharge is not fully understood (Schaub et al., 1975).

Recently, there has been great concern about nitrates, enteric viruses, and organic toxins reaching the ground water system during rapid infiltration of sewage (Sorber, Schaub, and Guter, 1972). The main consideration of the study reported herein is the fate of nitrates in the recharging effluent. As mentioned earlier, Cluff et al. (1971) observed an increase in nitrate content of the ground water along the Santa Cruz River. However, Wilson et al. (1975) indicated that the overall quality of ground water in the area of recharge may be better than that of the ground water upstream of the Tucson sewage treatment plant, and observed during a one-year study that recharge of sewage effluent in the river did not contribute nitrate to local ground-water supplies.

In a study of land application of waste water, Schaub et al. (1975) observed a black asphaltic-appearing layer at a depth of about 18 inches (approximately 46 cm). Sebenik, Cluff, and DeCook (1972) observed a similar black, odoriferous layer in the upper soil water interphase layer of the Santa Cruz River. Thomas, Schwartz, and Bendixen (1966) reported that the black, ferrous sulfide layer that develops under sewage spreading is an indicator of reducing conditions. Since reducing conditions are necessary for denitrification of nitrates, the fate of nitrate in recharging sewage may be related to the formation of the black layer found in the deposits along the Santa Cruz River.

McGauhey and Krone (1967) summarized existing information on mechanisms of soil clogging, and indicated that there may be a relationship between reduced infiltration rates and the development of a black, ferrous sulfide layer. Mitchell and Nevo (1964), however, suggested that reduced infiltration rates are due to a build-up of bacterial polysaccharides rather than the black layer, and Rice (1974) concluded that the principal cause of clogging is deposition of suspended solids on the soil surface.

Obviously, the interrelationships between the various water quality changes and sewage effluent recharge are not fully understood. The objective of this study was to determine the interrelationships among nitrogen transformations, infiltration rates, and development of the black layer found in the Santa Cruz River downstream of the Tucson sewage treatment plant.

LITERATURE REVIEW

Influence of Sewage Effluent Recharge on Infiltration Rates

Ponding of sewage effluent during intermittent flooding may occur as a result of a reduction in infiltration rates (Thomas et al., 1966; Rice, 1974; Lance and Whisler, 1975). An understanding of the soil clogging process affecting the infiltration rate reduction is necessary for the design and operation of recharge systems (Rice, 1974). McGauhey and Krone (1967) classified the three factors that result in soil clogging as chemical, biological, and physical.

Chemical clogging is mainly due to the chemical interaction between dissolved salts in the recharging water and the soil. The reactions result in decreased pore diameters and, consequently, lower permeability. Chemical clogging seldom occurs unless there is a high concentration of sodium in the percolating water. Soils affected by chemical clogging usually have a low permeability and are normally not suited for sewage effluent recharge (Rice, 1974).

Biological clogging has been attributed to microbial activity and accumulation of microorganisms and microbial slimes in the soil (Allison, 1947). Studies by Allison revealed that the clogging mechanism is the third of three phases which contribute to changes in the percolation rate during prolonged water spreading (Figure 1). Phases I and II are caused by soil slaking and dissolving of entrapped air, respectively. Biological clogging is generally associated with anaerobic conditions and usually

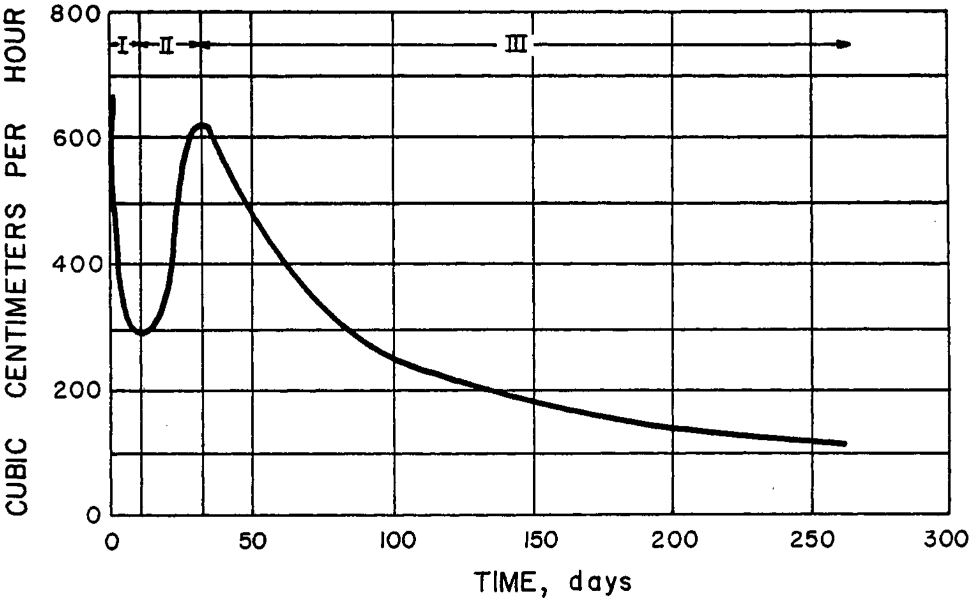


Figure 1. Typical Percolation Rate Curve for Prolonged Water Spreading on a Soil Core Occurring in Three Phases. -- After McGauhey and Krone (1967).

occurs at the soil surface, but can occur at any depth (Jones, 1965). Evidence obtained by Mitchell and Nevo (1964) suggests that the major factor causing clogging in sand is the production of polysaccharides by anaerobic bacteria and Lance and Whisler (1972) associated a decrease in infiltration rates with nitrogen production during denitrification.

Rice (1974) reported that the main cause of physical clogging is the deposition of suspended solids on the soil surface. He observed that, as more suspended solids were deposited, the layer became more compact and less permeable, thus accelerating the clogging process. Upon drying of the surface seal, cracking occurred and infiltration was restored to nearly its original rate. During the drying stage, air entering the pores could become entrapped and cause some physical clogging upon reflooding.

Thomas et al. (1966) observed a three-phase decrease in infiltration rates during intermittent spreading of sewage effluent. Phase I consisted of a slow reduction of infiltration over an extended period of time under aerobic conditions. Phase II was a brief period of rapid reduction under anaerobic conditions, and Phase III comprised a further gradual decline under continued anaerobic conditions. They concluded that anaerobic microbial transformations contributed significantly to soil clogging in Phase II.

Results of a study by Lance and Whisler (1975) indicated that, as the carbon content of applied sewage increased, clogging because of entrapped gases increased up to a point and leveled off. The point at which clogging leveled off was probably the point at which the nitrifying bacteria could no longer use all the applied carbon for energy production. They concluded that suspended solids increased resistance to flow at the soil surface, while dissolved organic carbon increases resistance below the surface in the region of gas production and that clogging by suspended solids seemed to be a more serious problem than clogging from increased dissolved carbon content of secondary sewage effluent.

Black Layer Development during Infiltration of Sewage

Laverty, Stone, and Meyerson (1961) conducted a study on the feasibility of reclaiming Los Angeles Hyperian Treatment Plant effluent for injection into recharge wells. During that study, a black, mucky, anaerobic mat was observed upon dry raking of the spreading basins. The sulfide-type mat oxidized rapidly on exposure to the sun and air and disappeared completely within a day or two. During intermittent spreading of sewage, formation of the mat did not occur.

According to Ford and Calvert (1966), as reported by Parr (1969), formation of an insoluble, black, ferrous sulfide layer can markedly decrease the hydraulic conductivity in some poorly drained soils. Experiments by Winneberger et al. (1960) revealed that a black layer found at the surface of a flooded soil was due to ferrous sulfide, which was precipitated by anaerobic degradation of sulfates. The ferrous sulfide was observed to penetrate downward a short distance into the soils according to the laws that govern the movement of particles in a porous medium. An organic mat associated with the black layer was found to be confined to a thin layer at the surface.

Ignatieff (1941) reported that well-drained soils contained very little, if any, ferrous iron, whereas water-logged soils had large quantities of ferrous iron after an initial two or three day lag. He attributed the high levels to biological processes. Connel and Patrick (1969) discovered that, in the absence of sufficient iron for precipitation of ferrous sulfide in rice paddies, hydrogen sulfide is formed and has a detrimental effect on the rice plants. They also noted that the addition of nitrate was effective in inhibiting sulfate reduction for several days until the nitrate has been reduced. In other words, the nitrate supplied the oxygen for microbial activity.

In a study of biological clogging by Mitchell and Nevo (1964), a clogged layer in permeameters treated with casein and sulfur occurred at a depth greater than 4 cm in the same section where the black layer of ferrous sulfide was found. Apparently, microorganisms utilizing organic matter released H_2S, which is soluble in water. The H_2S moved down the profile where it reacted with iron in the sand, forming the black, ferrous sulfide layer. They concluded that formation of ferrous sulfide is an indicator of the reducing conditions which result in biological clogging. Thomas et al. (1966) also concluded that ferrous sulfide is an indicator of reducing conditions, but not a primary cause of clogging. Unfortunately, the individual steps responsible for the development of the ferrous sulfide layer have not yet been characterized (Alexander, 1961).

More recently, Schaub et al. (1975) observed a black, asphaltic-appearing layer at a depth of 18 to 24 inches (approximately 46 to 61 cm) in a rapid infiltration bed. This layer disappeared when the bed was allowed to dry. They found high concentrations of organic carbon and heavy metals associated with the black layer. The high levels also disappeared after prolonged cessation of waste water application. They did not attempt to determine if the carbon and/or heavy metal constituents were the cause or effect of reduced permeability.

Nitrogen Transformations during Sewage Effluent Recharge

Lance (1972) outlined the reactions responsible for nitrogen removal during infiltration of secondary sewage effluent, as shown in Figure 2. The most important reactions during effluent recharge in an ephemeral stream channel are nitrification, denitrification, and absorption by clays. Ammonification may also play a role during the recharge process.

Nitrification is a microbiological process whereby ammonia is oxidized by an autotrophic, nitrifying bacteria. The *Nitrosomonas* group converts ammonia under aerobic conditions to nitrites and derives energy from the reaction. The nitrites are further oxidized to nitrate by the *Nitrobacter* group of nitrifying bacteria. The soluble nitrates are then carried away by percolating water if aerobic conditions persist (Sawyer and McCarty, 1967).

Denitrification is a microbiological process in which nitrates are reduced to free nitrogen gas and released to the atmosphere. The denitrifying bacteria require a source of organic carbon to provide energy for the reduction of nitrate and the process will only take place under anaerobic conditions (Bouwer, 1974).

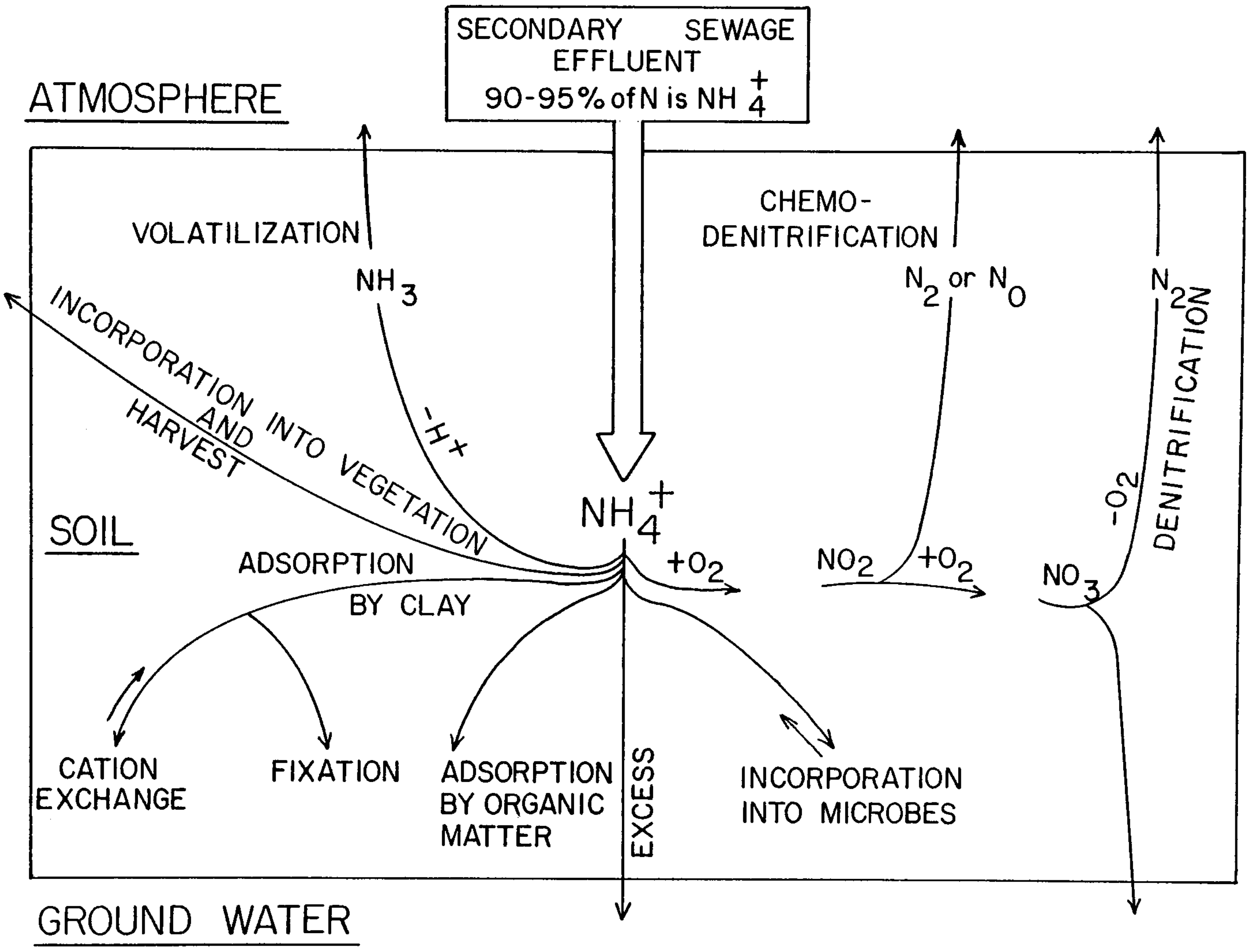


Figure 2. Reactions Responsible for Nitrogen Removal. -- After Lance (1972).

Under anaerobic conditions, ammonia cannot be oxidized to nitrate and is carried into the soil system by the infiltrating sewage. When the positively charged ammonium cation comes in contact with a negatively charged clay micelle, the ammonium cation is adsorbed by the clay particle. The amount of ammonia that can be adsorbed depends on the cation exchange capacity of the soil, and the amount of other cations (e.g., calcium, magnesium, and sodium) already on the exchange sites. As long as anaerobic conditions persist, ammonia will remain immobilized. However, if conditions become aerobic, the ammonia will be oxidized to the more soluble nitrate form and be removed from the clay complex by infiltrating water (Lance, 1975).

Ammonification or nitrogen mineralization is the microbial decomposition of organic nitrogen to ammonium. Ammonification is less sensitive to environmental changes than nitrification or denitrification and can occur under aerobic or anaerobic conditions. In general, the mineralization process becomes more rapid as temperature increases (Alexander, 1961).

Due to the health hazards associated with nitrates in drinking water (Winton, Tardiff, and McCabe, 1971), removal of nitrogen in recharging sewage effluent has been given considerable attention. Bouwer (1974) describes management practices associated with intermittent flooding of recharge basins which affect the nitrogen transformations and the amount of nitrogen removed.

The majority of the nitrogen in secondary treated sewage is in the ammonia form (ammonium NH_4^+). In order for denitrification, a prime reaction for nitrogen removal in recharging effluent, to take place, the ammonia must first be oxidized to nitrate. This means that the nitrogen has to pass through both an oxidized environment for nitrification and a reduced zone for denitrification within the same soil profile (Lance, 1975).

Lance and Whisler (1972) determined that alternate flooding and drying cycles allowed enough oxygen to enter the soil for nitrification and provided the reducing conditions required for denitrification. The optimum schedule of flooding and drying was found to depend upon the soil and waste water used. However, the problem with their approach was that the nitrate formed during the dry period was leached through the soil in a concentrated peak upon reapplication of the sewage. Low concentrations of organic carbon in the recharging sewage left the denitrifying bacteria without a large enough energy source for complete denitrification.

During their study, Lance and Whisler (1972) observed an average net nitrogen removal of 30% when laboratory soil columns were managed for maximum infiltration during intermittent flooding with secondary sewage effluent. They were able to increase removal by three different methods: 1) adding a carbon source, 2) recycling high nitrate water through the columns, and 3) reducing the infiltration rate. The results indicated that recharge systems can be managed to provide substantial nitrogen removal during sewage effluent recharge.

Use of Soil Columns as a Research Tool

Experiments with sand-filled columns were conducted as early as 1856 when Henry Darcy derived his formula for flow through porous media

(Davis and DeWiest, 1967). Among other applications, Darcy's law is now used in conjunction with data obtained from permeameters to estimate soil hydraulic conductivity.

Since Darcy's time, soil columns have been used extensively to study the effects of various treatments on soil leachates. For example, MacIntire and Mooers (1921) designed a soil column which was inserted into the ground to more closely represent field conditions when studying soil leaching. Subsequently, other workers have used different column designs to study leaching of salts and soil infiltration rates.

In recent years, soil columns have been used widely in determining hydraulic conductivity and infiltration rates of different materials applied with sewage effluent. Water quality changes using different application rates and cycling procedures have also been studied (Mitchell and Nevo, 1964; Lance and Whisler, 1972; Rice, 1974).

When using soil columns to simulate field conditions, at least three major problem areas should be recognized and treated: soil sample, wall effect, and air entrapment.

The first problem is obtaining an undisturbed soil sample which is representative of the area of interest. In most cases, this is very time-consuming and difficult, if not impossible. Consequently, methods have been developed in which thoroughly mixed material from the study area can be packed uniformly in the columns.

Jackson, Reginato, and Reeves (1962) developed a mechanized device for packing soil columns which enables uniform dense packing of the soil. In addition, Ripple, James, and Rubin (1974) developed a method of impact packing which reduces radial segregation of soil particles, and Wilson (personal communication, 1975) has described a method of packing in which a tremi is used to achieve uniform soil density. Use of a tremi allows the soil to be added directly at the surface and eliminates separation of various aggregate sizes during the fall from the top of the column to the soil surface.

Although exact field conditions are not duplicated, proper packing of soil columns enables the researcher to use several columns and be reasonably sure that differences are minimal.

Obtaining a representative sample of the study area is somewhat simplified by the use of properly packed columns. By thorough mixing of randomly collected samples, a soil resembling some sort of "average" condition is produced and then uniformly packed in the soil columns. This uniform packing of an "average" soil nearly eliminates any stratification and will not, in most cases, exactly duplicate field conditions. However, it does eliminate the impossible task of locating several identical representative core samples and provides the researcher with the means to obtain an indication of what may happen in a field situation.

The second major problem associated with the use of soil columns is wall effect. When soil is packed in a column it is bounded by a smooth surface, rather than by the granular material that would normally interlock with the sample in the field. Therefore, the porosity near the wall is greater than that of the rest of the column. Thus, infiltration rates near the wall of the column are normally greater (Ripple et al., 1974).

Dudgeon (1967) disputed the argument that wall effects can be neglected if the ratio of particle size to column diameter is less than 1:10. However, Worcester, McIntosh, and Wilson (1968) concluded that boundary flow may be ignored if only gross trends are desired.

The third major problem to be considered when using soil columns is that of air entrapment. When a soil column is flooded from the top, air has difficulty escaping through the outlet at the bottom and is commonly compressed and trapped in the pore spaces. Until this air is dissolved by the water or through the surface, it can greatly reduce infiltration rates (McGauhey and Krone, 1967).

Two techniques have been used to minimize this initial air entrapment. The simplest method is flooding from the bottom of the column, which forces the air out through the soil surface. Another, probably more reliable, method is to displace the air in the soil with a soluble gas such as CO_2 before flooding. The CO_2 is removed from the pore spaces when it is dissolved by the percolating water (Lance and Whisler, 1972).

Since soil samples used in soil columns are removed from the natural surroundings, any treatment on the samples will not exactly duplicate a similar treatment in the field. However, treatments using soil columns can be done on a much smaller scale under controlled conditions, making the use of columns much more convenient and economical than a large-scale field test.

Although soil columns do not duplicate field conditions, when the problems are recognized and properly handled, they are a useful tool for giving an indication of what might take place in the field. They make an ideal first step in studies which will eventually incorporate the use of field plots.

MATERIALS AND METHODS

The interrelationships among infiltration rates, nitrogen transformations, and black layer development were tested by percolating sewage effluent through three, clear acrylic columns filled with deposits from the Santa Cruz River. An additional column was flooded with tap water to serve as a control.

Infiltration rates were determined by measuring the daily flow rates. Samples of the sewage, tap water, and outflow from each column were collected and analyzed to determine the nitrogen transformations. Finally, the black layer development was characterized by visual observations and manometer readings from tensiometers installed at various depths in the profile.

Materials

Column Construction

Four, clear acrylic columns, 122 cm long by 10.17 cm in diameter, were used for this investigation. A plexiglass bottom was attached to each column with ethylene dichloride and further sealed with epoxy. A 0.95 cm hole was drilled in the center of the bottom and a quick disconnect was sealed in the orifice with epoxy. The quick disconnect allowed removal of polyethylene drain hoses during flow measurements.

All four columns were mounted in an enclosed wooden frame (Figure 3). Each column extended through the top of the frame a few

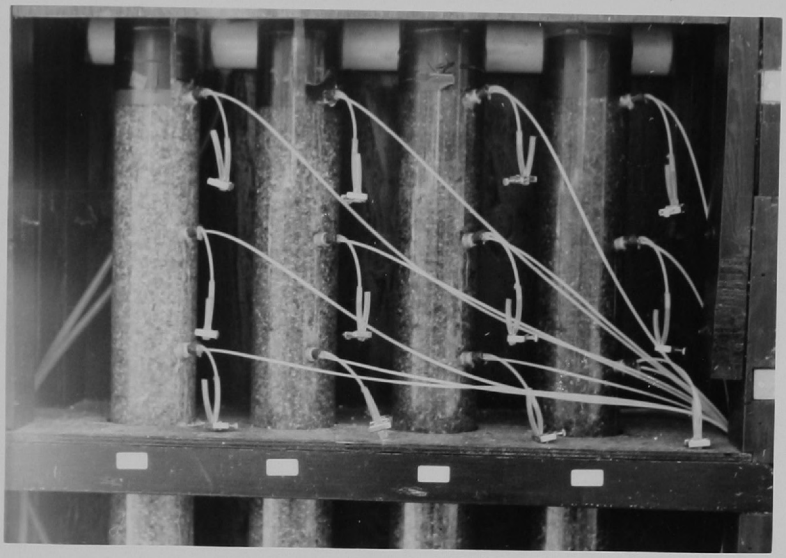


Figure 3. Soil Columns.

centimeters to simulate field conditions. The outside of the wooden housing was painted white to minimize heat absorption and the inside was painted black to minimize light reflection and algae growth. One side of the frame was hinged to allow access and observation of the soil columns.

Two plastic pipe, constant head manifolds were constructed to supply the control column with tap water and the remaining three columns with sewage. The manifolds were mounted in the rear upper corner of the wooden enclosure, just below the top of the columns. The water supply was fed from the manifolds through a polyethylene tube to an epoxied connector 115 cm from the bottom of each column.

A pilot study was conducted using a single column to determine if the black layer would develop in a soil column flooded with sewage effluent. The layer first appeared at the top of the river sand in the column and then extended to about 20 cm below the surface. From these data, it was decided that tensiometers should be located at 2, 20, and 35 cm below the soil surface. The top, middle, and bottom tensiometers would allow pressure readings near the surface of, within, and below the black layer, respectively. Each 1.5 x 7.3 cm tensiometer was epoxied into place with the porous cup located in the center of the column at a slightly downward incline (Figure 4). The incline was to aid in removing air from the manometer lines.

A manometer board was constructed with a cover and mounted on one end of the wooden enclosure. Each tensiometer was equipped with a filling and air removal tube and a 0.16 cm polyethylene manometer tube

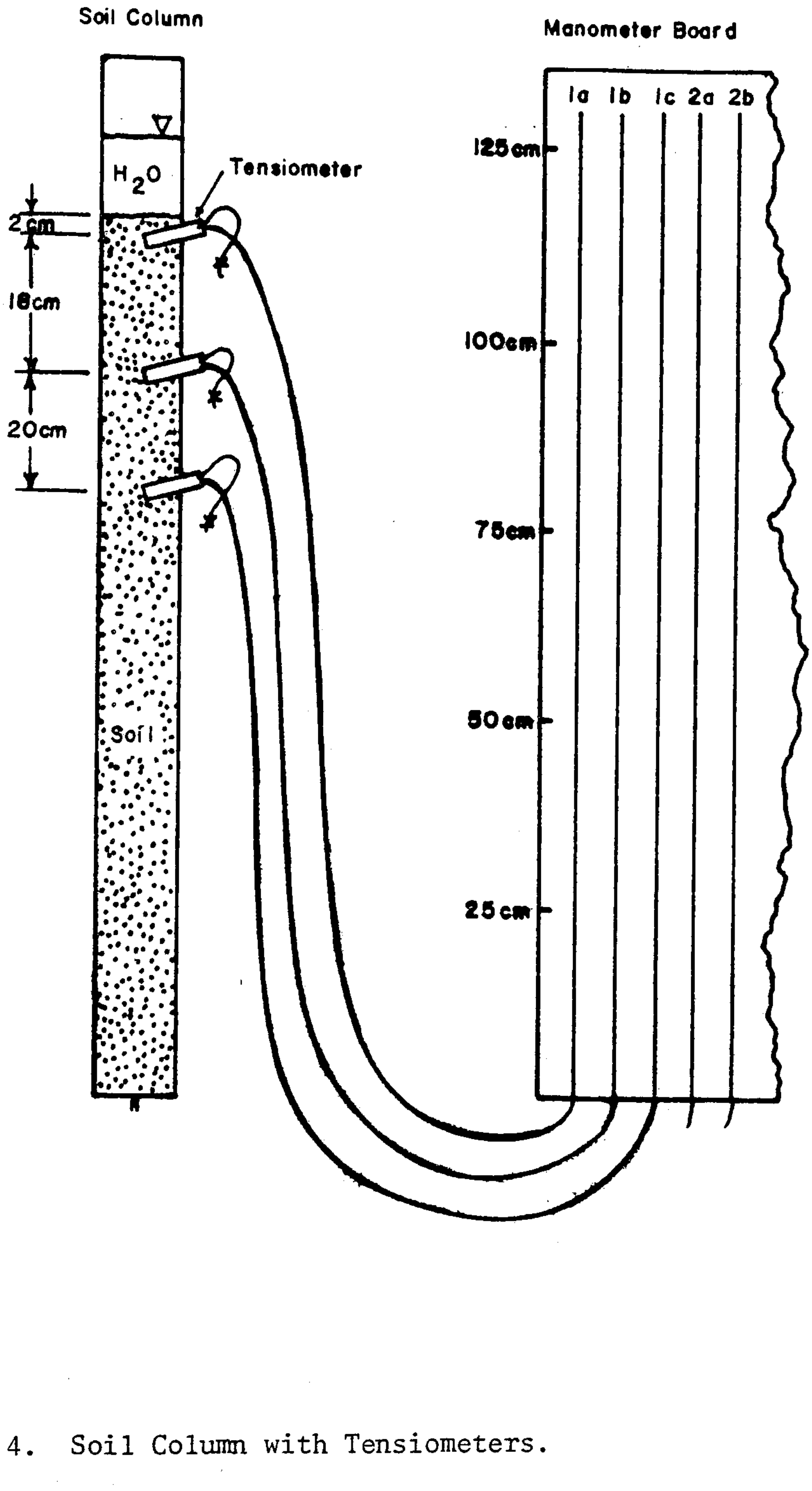


Figure 4. Soil Column with Tensiometers.

(Figure 4). The manometer tubes were stapled to the manometer board and labeled. All connections were sealed with epoxy.

Soils

Two separate experiments were run during this investigation. For the first run, a mixture of river sand was used from randomly selected locations along the Santa Cruz River. As the first experiment proceeded, the flow rates of the columns flooded with sewage rapidly decreased to zero. Consequently, a second run was made using a fine pea gravel in place of the river sand. It was hoped that flow rates through the gravel would remain high enough to allow sampling throughout an extended period of time.

Soil analyses were made using the procedure outlined in "Methods of Soil Analysis" (1965). Eight-inch Tyler Standard Screens were used to separate sand and gravel fractions and the pipette method was used to determine the silt and clay fractions. The results are presented in Table 1.

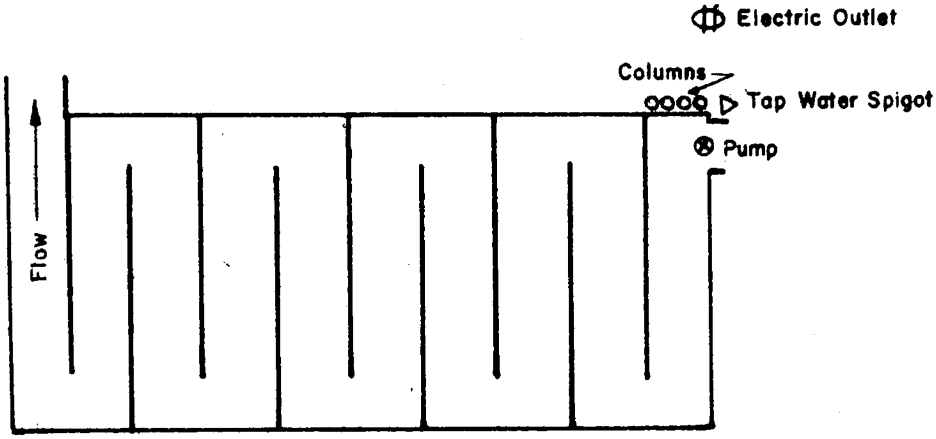
Water Supply

The experimental apparatus was set up beside the chlorine contact chamber of Plant No. 1 at the City of Tucson Sewage Treatment Plant. The location not only provided a continuous supply of secondary sewage effluent, but there was a supply of tap water and electricity as well (Figure 5).

A small submersible pump installed several feet upstream of the chlorination point fed a continuous supply of effluent to one of the

Table 1. Soil Textural Analysis of Santa Cruz River Sand and Small Pea Gravel.

Sieve Size (mm)	Description	Run 1 (%)	Run 2 (%)
> 6.350	Medium gravel	1.4	0.00
3.962 - 6.350	Fine gravel	1.8	24.50
1.981 - 3.962	Very fine gravel	17.9	73.30
0.991 - 1.981	Very coarse sand	17.7	1.30
0.459 - 0.991	Coarse sand	25.1	0.30
0.246 - 0.459	Medium sand	20.6	0.10
0.124 - 0.246	Fine sand	10.0	0.07
0.061 - 0.124	Very fine sand	2.8	0.07
0.002 - 0.061	Silt	0.5	0.02
< 0.002	Clay	1.8	0.01



CHLORINE CONTACT CHAMBER
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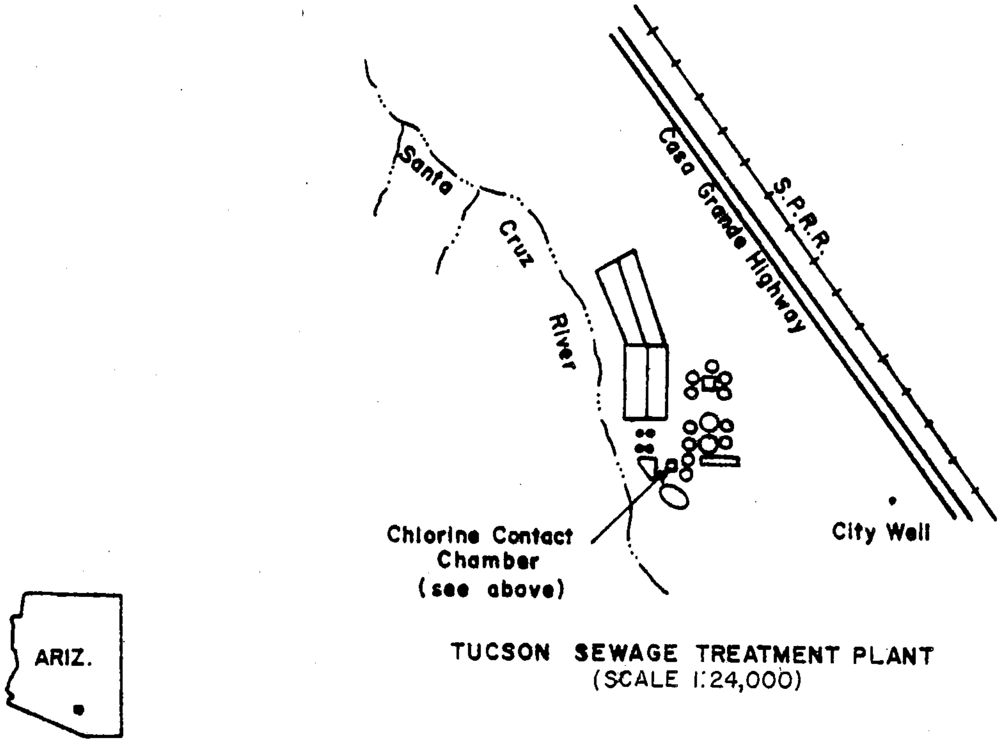

TUCSON SEWAGE TREATMENT PLANT
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Figure 5. Column Location.

manifolds. The pump provided unchlorinated sewage in excess of that which percolated through the columns. The excess was allowed to overflow and returned to the chlorine contact chamber. By continuous pumping, a fresh supply of sewage was maintained at a constant head for all of the columns being treated with sewage.

A constant head of tap water was maintained for the control column by attaching the second manifold to a fresh water spigot via a small diameter hose. The spigot was run continuously and the overflow was allowed to drain into the chlorine contact chamber. A city well located near the treatment plant supplied the facility with its water (Figure 5).

Both the sewage and tap water were analyzed at the Water Resources Research Center laboratory for their various chemical constituents on several separate occasions. The average values are presented in Table 2.

Methods

Experimental Design

Only four clear acrylic soil columns were available for this study. Since very few changes were expected to take place in a control column, it was decided that three columns would be used for treatment and the remaining column would serve as a control. Using three of the columns for treatment provided the best possible chance of detecting any changes while still maintaining a control (Marx, personal communication, 1975).

Table 2. Average Values of Various Chemical Constituents in the Tap Water and Sewage Effluent.

Constituent	Tap Water	Sewage
pH	7.5	7.6
EC (mmhos)	1.04	1.02
Cl (mg/l)	108.3	85.3
Na (mg/l)	144.9	113.0
K (mg/l)	3.1	10.2
Ca (mg/l)	90.7	40.8
Mg (mg/l)	15.5	6.9
CO_3 (mg/l)	0.0	0.0
HCO_3 (mg/l)	283.0	301.5
Hard* (mg/l)	282.4	130.8
NH_4-N (mg/l)	0.0	18.38
KJN** (mg/l)	0.0	20.9
NO_2 + NO_3-N (mg/l)	10.3	1.75
Total N*** (mg/l)	10.3	22.6

*Hardness (in mg/l) is CaCO = M^{++} (in mg/l) x 50/eq. wt. of M^{++}, where M^{++} represents any divalent metallic ion (Sawyer and McCarty, 1967).

**KJN is the sum of NH_4-N + Org-N.

***Total N is the sum of NH_4-N + Org-N + NO_2 + NO_3-N.

The two main treatment effects that were analyzed statistically are the difference in total nitrogen reduction between the treated columns and the control, and the difference between infiltration rates in the treated columns and the control. The differences in total nitrogen were tested with a student T test using the assumption that the average total nitrogen reduction in the control column was zero. A least squares curve fitting method of non-linear regression was used to test the differences in infiltration rates. The infiltration rates were assumed to follow a negative exponential relationship with time. In the following function,

$$y = \alpha + e^{-\gamma t+\beta}$$

y equals the infiltration rate, t is time in hours, α represents the lower asymptote, $\alpha + e^{\beta}$ is the y intercept, and γ represents the degree of descent of the curve. The parameters α, γ, and β were estimated by the non-linear least squares analysis. Upon testing with an F distribution, it was found that the three treated columns could be represented by a common curve. The reduction in infiltration rates for the treated columns was then tested by using an F test to determine if the common treatment curve differed from the control curve (Marx, personal communication, 1976).

Soil Packing

For both runs, all four columns were packed as uniformly as possible by filling through a long plastic pipe (tremi) and evenly tapping the sides with a rubber mallet. The soil was air-dried and sifted for thorough mixing and removal of large stones. Buckets of the dry soil were weighed and then scooped into a funnel attached to the upper end of the tremi. When each column was filled to the same height, the buckets were reweighed to determine the mass of the soil added to each column. The bulk density and porosity were then determined, assuming a particle density of 2.65 g/cc. The results are presented in Table 3.

Table 3. Porosity and Bulk Density of Soil Used in Run 1 and Run 2.

	Run 1		Run 2	
Column No.	P_B (g/cc)	Porosity (%)	P_B (g/cc)	Porosity (%)
1	1.66	37.4	1.56	41.2
2	1.68	36.6	1.60	39.5
3	1.66	37.4	1.58	39.9
4	1.64	38.1	1.58	40.5

For run 1, the bottom two centimeters of each column were filled with six millimeter gravel before filling with river sand. In run 2, approximately two centimeters of glass wool were placed in the bottom of each column before filling with pea gravel.

Application of Tap Water

At the beginning of each run, all columns were simultaneously flooded with tap water through the outlet at the bottom. Flooding from the bottom allowed the majority of the air between soil particles to escape through the surface. However, a small amount probably remained within small pockets and dead spaces. During the second run, all four columns were continuously flooded through the top immediately after they were completely filled from the bottom. The tap water was allowed to percolate through the soil until a characteristic curve, described by Allison (1947), began to develop. At the point at which it was felt that most of the entrapped air was dissolved, columns 2, 3, and 4 were switched over to sewage and column 1 remained flooded with tap water.

Mechanical problems during the initial flooding of the columns in run 1 allowed the soil columns to partially drain before they could be flooded at the top. Consequently, air re-entered the pores and the flow rates at the beginning of run 1 were more erratic than run 2.

In addition to dissolving the entrapped air, flooding with tap water for the first few days allowed determination of the differences in flow rates between columns. Differences in tensiometer response were also observed during this period. The hydraulic conductivity of each column was determined from the flow rates and values of total hydraulic head obtained at the end of the tap water cycle.

Application of Sewage

After the hydraulic properties of the soil columns were characterized with tap water, in both runs, sewage was applied to columns 2, 3, and 4 without allowing them to drain. This was accomplished by replacing the tap water hose connected to the inlet of the three column manifold with the sewage hose connected to the submersible pump. Sewage was applied continuously for 28 days for the first run and for 64 days during the second run. All columns were allowed to drain and dry overnight at the end of each run. They were reflooded and water samples were taken in an attempt to observe a high nitrate peak similar to that reported by Lance and Whisler (1972). In addition to the first drying period during run 2, the columns were allowed to dry a second time. The second drying period lasted several days before the columns were reflooded and sampled.

Measurement of Flow Rates

Daily flow measurements were taken for each column. A graduated cylinder was placed under the drain of the column being measured and the amount of time required to fill the cylinder was measured with a stop watch. The procedure was repeated two or three times and an average flow rate was recorded for each column. Air temperature, temperature of inflow and outflow of sewage and tap water, and the time of the measurements were also recorded. Daily flow rates were later plotted for both runs.

Total flow volumes through each column were estimated by averaging the flow rate between two readings and multiplying by the time elapsed between those readings. These values were later used for determining the amount of nitrogen applied and removed by the infiltrating water.

Manometer Readings

Initially, the tensiometers and manometers were filled with boiled deionized water. Boiling removed dissolved air from the water and minimized air bubbles in the lines. The tensiometers were allowed to equilibrate with the soil before the water level in the manometers was recorded.

On occasion, the lines were flushed with a large syringe to remove air bubbles. For a short period of time, the lines of several manometers were flushed daily to remove deposits left by a small, persistent insect.

The level of the meniscus in each manometer was recorded daily at about the same time the flow measurements were made. Since the zero point on the manometer board corresponded to the reference level, the observed values represented total hydraulic head in inches of water. These values were later plotted for each period.

Water Sampling and Analysis

Samples of the applied sewage and tap water and the outflow from each column were collected at random time intervals. At the beginning of each run, flow rates were high enough to assume that a grab sample of the sewage being applied was from nearly the same source as that which was percolating through the columns. However, as flow rates decreased, it became necessary to take composite samples of the sewage being applied. Composite samples of the inflow were taken by disconnecting the inlet hose, allowing the manifold to drain, and then, as the top of the columns drained, collecting a portion of the sewage which had been standing in them during the collection period. Care was taken not to drain columns below the soil surface to avoid air entry into the soil.

Two bottles were filled for each sample collected. Mercuric chloride was added to one sample bottle to inhibit the nitrifying bacteria and fix the nitrogen species. The second sample bottle contained no additives and was used to collect a sample for other determinations. When extended periods of time were required to collect outflow samples, the mercuric chloride was first placed in the collection bottle and the effluent was allowed to drain into the pretreated bottle. In this way, the samples were fixed on contact. All samples were immediately transported to the Water Resources Research Center field laboratory, where they were promptly analyzed or refrigerated.

The untreated samples were tested for pH with a Beckman model 407A specific ion meter. They were also tested for chloride using the mercuric nitrate method (Standard Methods for Examination of Water and Wastewater, 1971). Specific conductance was tested with an Industrial Instruments Solu Bridge. The samples preserved with mercuric chloride were used to determine the various nitrogen compounds. Organic plus ammonia nitrogen were determined using the Kjeldahl method (Standard Methods, 1971) and ammonia and nitrate plus nitrite were determined by Bremner's steam distillation technique ("Methods of Soil Analysis," 1965).

Several samples were also analyzed for Ca^{++}, Mg^{++}, Na^{+}, K, CO_3, and $HCO_3^{=}$ (Table 2). Techniques from Standard Methods (1971) were employed in each analysis.

Field Investigations

Before the column study was begun, several observations were made in and along the Santa Cruz River. Three 2.5-cm well points were installed in the river at the Ruthrauff Road crossing. They were hand-driven to depths of 1, 2, and 3 feet (about 30, 61, and 91 cm). The water level in the one- and two-foot well points rose to within a few millimeters of the surface of the river. The third well point was dry and apparently extended into an unsaturated zone. The results seem to indicate the presence of a shallow, perched water table.

A two-meter deep trench was hand-dug adjacent and perpendicular to the river several hundred meters below the outfall of the Ina Road sewage lagoons. The trench was later extended to about seven meters long and five meters deep with a backhoe. Three distinct black layers were observed at depths of 15 to 25 centimeters, 46 to 61 centimeters, and from one meter to more than five meters. The upper two layers extended out about two meters from the river like fingers where they tapered off and disappeared. Both of the upper layers had a thin clay lense within them. In each case, the black coloring was both above and below the clay.

The bottom of the lower layer was never reached, and it may extend as far as the water table but there is no evidence to support this speculation. However, the depth to the top of the lower layer increased as the distance from the river's edge increased. There were only a few locations close to the river that were saturated. The rest of the black layer was moist but not saturated.

RESULTS

Black Layer Development

During the 12-hour period of tap water application on the river sand (run 1), there was no black layer visible in any of the four columns. Continued application of tap water to the control column did not result in any visible black deposits. The three columns treated with sewage during the first run began to develop a black layer in the sludge overlying the sand after four days. At the beginning of the fifth day of sewage application, the layer had migrated 3.2, 3.5, and 3.8 cm into the sand of columns 2, 3, and 4, respectively. The black deposits continued to spread downward throughout the remainder of the experiment. On the last day of continuous flooding, the thickness of the layer was about 5.4, 10.2, and 13.5 cm in columns 2, 3, and 4, respectively. Upon drying of the columns, the black layer gradually disappeared for about two days until there were only minor traces remaining.

In the second run, after seven days of flooding the gravel with tap water, there were no traces of black deposits in any of the columns. Again, continued application of tap water in the control column did not result in any visible black deposits. Six days after the treatment columns were flooded with sewage, the black layer began to develop at the surface of the gravel in columns 3 and 4. On the seventh day, all three treated columns had several centimeters of black deposits at the surface and points and pockets of black throughout the remainder of each column.

Within a few more days, all three columns had turned almost completely black with column 3 being the darkest in color and column 2 the lightest. The black deposits persisted until the bottom orifices were freed from obstructions, at which time the flow rate increased markedly in the treated columns and the lower portion of the black layer became slightly lighter.

Reduction in Infiltration Rates

Hydraulic conductivity values for the columns in both runs are presented in Table 4. As would be expected, the hydraulic conductivity of the gravel in run 2 was much higher than that of the sand in run 1. Variation among columns for each run was minimal; however, the slight differences can probably be attributed to variations in packing.

Table 4. Hydraulic Conductivity Values for Each Column for Both Runs.

Column No.	Hydraulic Conductivity, K (cm/min)	
	Run 1	Run 2
1	.35	3.96
2	.49	2.87
3	.28	3.16
4	.31	3.07

During the initial flooding with tap water in run 1, column 2 had the highest hydraulic conductivity and flow rate; column 1, the control column, was second highest; column 4 was third highest; and column 3 had the lowest hydraulic conductivity and flow rate. Almost immediately after sewage was applied to columns 2, 3, and 4, the flow rates dropped considerably and after about a day the rates leveled off and asymptotically approached zero for the remainder of the experiment (Figure 6). During this time, the manometers showed negative pressure heads in the treated columns (Appendix A). The flow rate in the control column began to follow a characteristic curve as described by Allison (1947) (Figure 1), but for some unexplained reason, after a week the flow gradually increased for about ten days before it began dropping off again.

An important observation is that column 2 initially had a higher flow rate than the control column, but upon application of sewage the rate dropped markedly below that of the control. Statistical analysis by a curve-fitting method of non-linear regression (Marx, personal communication, 1976) revealed that there was no significant difference among columns during the characterization period, but after application of sewage there was a highly significant difference between the treated columns and the control at the .05 level of confidence.

During the initial flooding with tap water in run 2, column 1, the control column, had the highest hydraulic conductivity and, therefore, a higher flow rate than columns 2, 3, and 4. Upon application of sewage, the flow rate in the treated columns again dropped considerably, while the control column continued to follow a characterized curve. After about a week, the flow rate in the treated columns decreased to

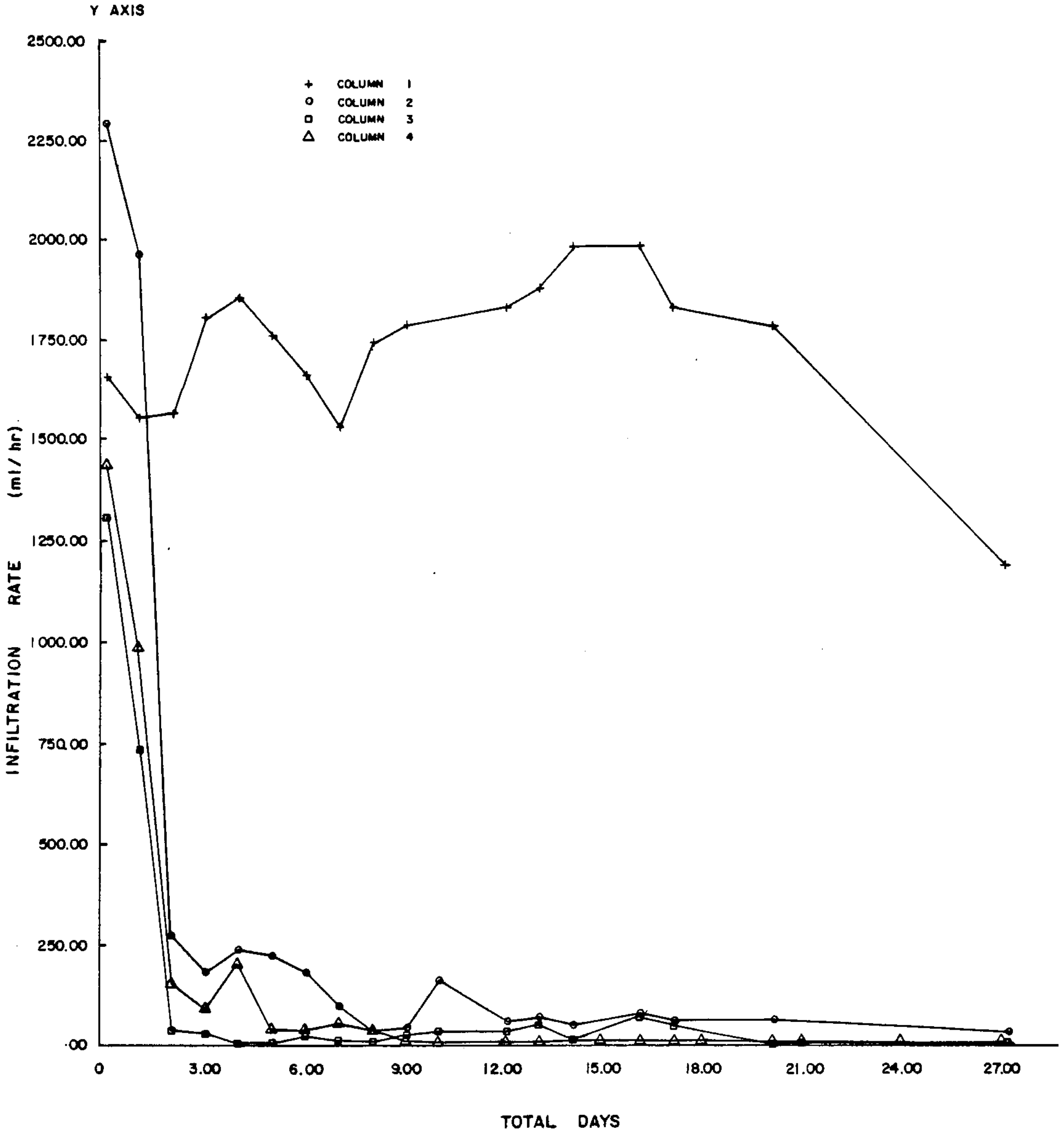

Figure 6. Infiltration Rates for 28 Days of Continuous Flooding during Run 1.

almost zero. The flow rate remained extremely low for about three more weeks and the manometer readings (Appendix B) gradually changed from negative pressure heads to higher and higher positive heads. Eventually, the columns were probably saturated throughout, i.e., a perched water table developed above the base of the column. After a total of about 47 days from the start of the experiment, clogging in the column outlets was discovered and alleviated. Upon unclogging of the columns, the daily flow rates varied considerably; however, the average rate of the treated columns was considerably lower than that of the control column (Figure 7) and the level of the manometers began to drop off again. A statistical analysis using a curve-fitting method of non-linear regression (Marx, personal communication, 1976) revealed that there was a significant difference in flow between the control column and the treated columns after sewage application.

The initial decrease in flow for both runs was due mainly to surface clogging, which was also observed by Rice (1974). During the second run, the clogging of the outlets gradually overshadowed the surface clogging. Clogging of the outlets remained the predominant factor of reduced flow rates until the clogging was alleviated, at which time surface clogging again became the predominate factor.

Nitrogen Transformations

A sample of the tap water flowing into and out of the columns was taken during the initial characterization period of both runs. The high nitrate tap water lost no nitrogen during the infiltration process. The results of continued sampling of the inflowing tap water and control

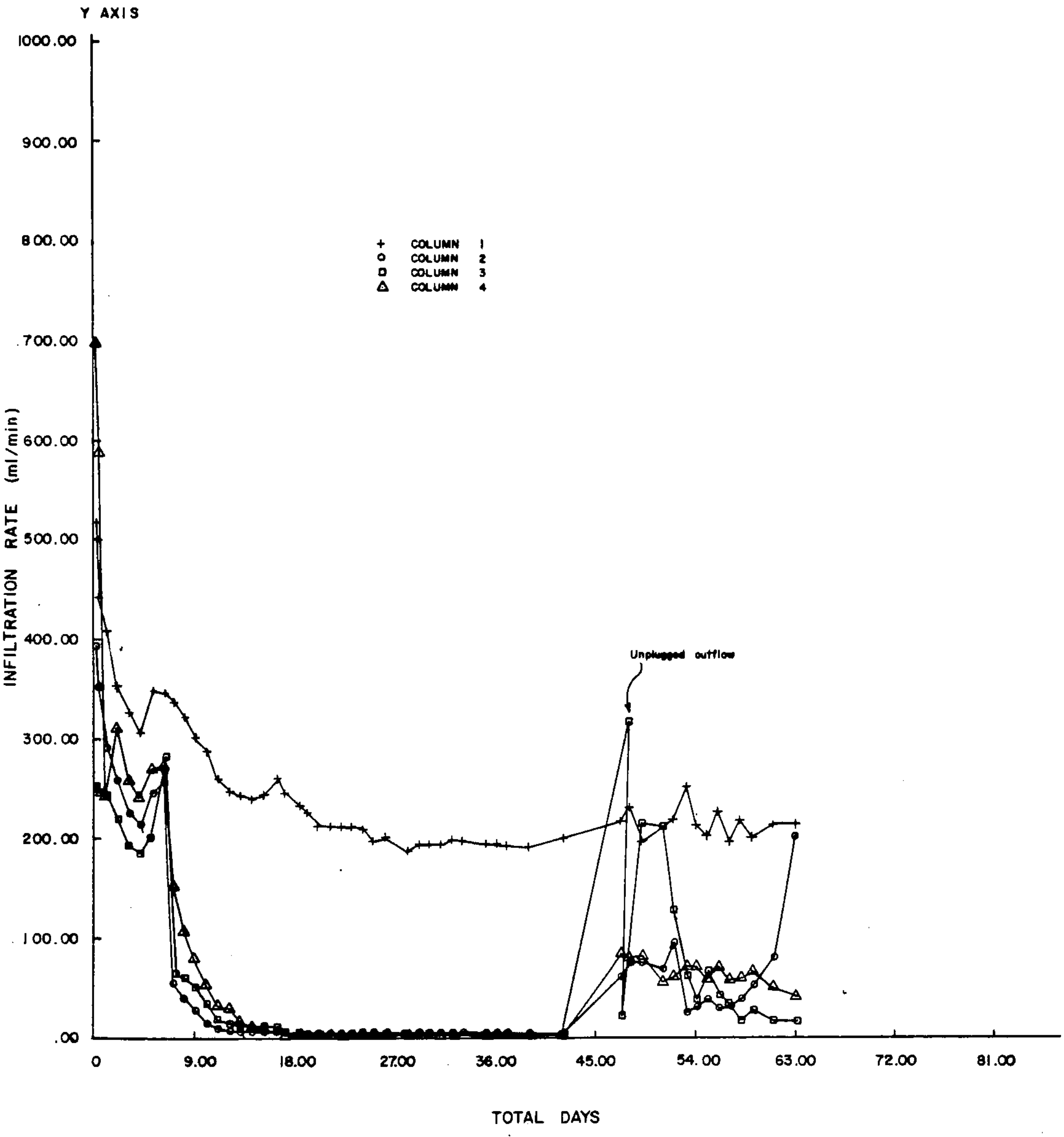

Figure 7. Infiltration Rates for 64 Days of Continuous Flooding during Run 2.

column outflow during both runs was similar to the results obtained in the characterization period (Table 5).

During the first run, four sets of water samples were taken at random time intervals while the treatment columns were being continuously flooded with sewage effluent. An additional set of samples was taken after the columns had been allowed to dry for 24 hours and reflooded (Table 5).

The nitrogen analyses for run 1 are presented in Table 5. All values are reported in mg/l of nitrogen. The tap water had a much higher nitrate content than the sewage and after the characterization period time was allowed for displacement of the tap water with sewage before sampling was continued. Most of the nitrogen in the sewage and the outflow of the treated columns was in the ammonia form with the column outflow being consistently lower than the sewage. Column 3 had very low values of ammonia compared to columns 2 and 4. The last set of samples was taken after the surface of the columns had been allowed to dry for 24 hours. Continuous flow to the columns was stopped after the January 30th sampling, but flow rates were so low that the columns remained flooded for several days. The remaining water was finally siphoned to allow some drying. Due to time limitations, a longer drying period was not possible.

Reductions in total nitrogen were estimated by plotting total nitrogen in the inflow and outflow of each column against total flow for each column (Figures 8 through 10) and integrating the area under the curves with a planimeter. Columns 2, 3, and 4 showed a 42.7, 86.3, and

Table 5. Nitrogen Analyses for Run 1.

Date	Sample	NH_4-N (mg/l)	NO_2 + NO_2-N (mg/l)	Kjeldahl N (mg/l)	Total N* (mg/l)
1-13-76	Tap water	0.00	10.36	0.00	10.36
	Sewage	22.26	0.56	24.50	25.06
	Column 1	0.34	10.36	0.00	10.36
	Column 2	0.00	0.00	1.40	1.40
	Column 3	0.28	2.52	1.26	3.78
	Column 4	0.28	2.52	1.26	3.78
1-17-76	Tap water	0.00	10.64	0.00	10.64
	Sewage	20.58	0.56	23.38	23.94
	Column 1	0.00	10.42	0.00	10.42
	Column 2	15.68	0.56	18.06	18.62
	Column 3	0.00	0.56	1.40	1.96
	Column 4	10.78	0.42	13.02	13.44
1-24-76	Tap water	0.00	10.36	0.00	10.36
	Sewage	18.62	0.42	22.82	23.24
	Column 1	0.00	10.92	0.00	10.92
	Column 2	17.92	0.42	21.84	22.26
	Column 3	0.56	2.80	2.94	5.74
	Column 4	11.00	0.50	13.44	13.94
1-30-76	Tap water	0.00	10.44	0.00	10.74
	Sewage	14.86	1.50	18.37	19.87
	Column 1	0.00	9.93	0.00	9.93
	Column 2	14.86	0.86	18.90	19.76
	Column 3	0.56	3.24	1.34	4.58
	Column 4	9.40	1.14	13.30	14.44
2-9-76	(24-hour drying period)				
2-10-76	Tap water	0.00	8.40	0.00	8.40
	Sewage	17.36	9.38	20.72	30.10
	Column 1	0.00	10.36	0.00	10.36
	Column 2	16.38	0.70	21.00	21.70
	Column 3	5.18	0.70	6.16	6.86
	Column 4	13.55	0.84	16.66	17.50

*Total N is the sum of NH_4-N + Org-N + NO_2 + NO_3-N.

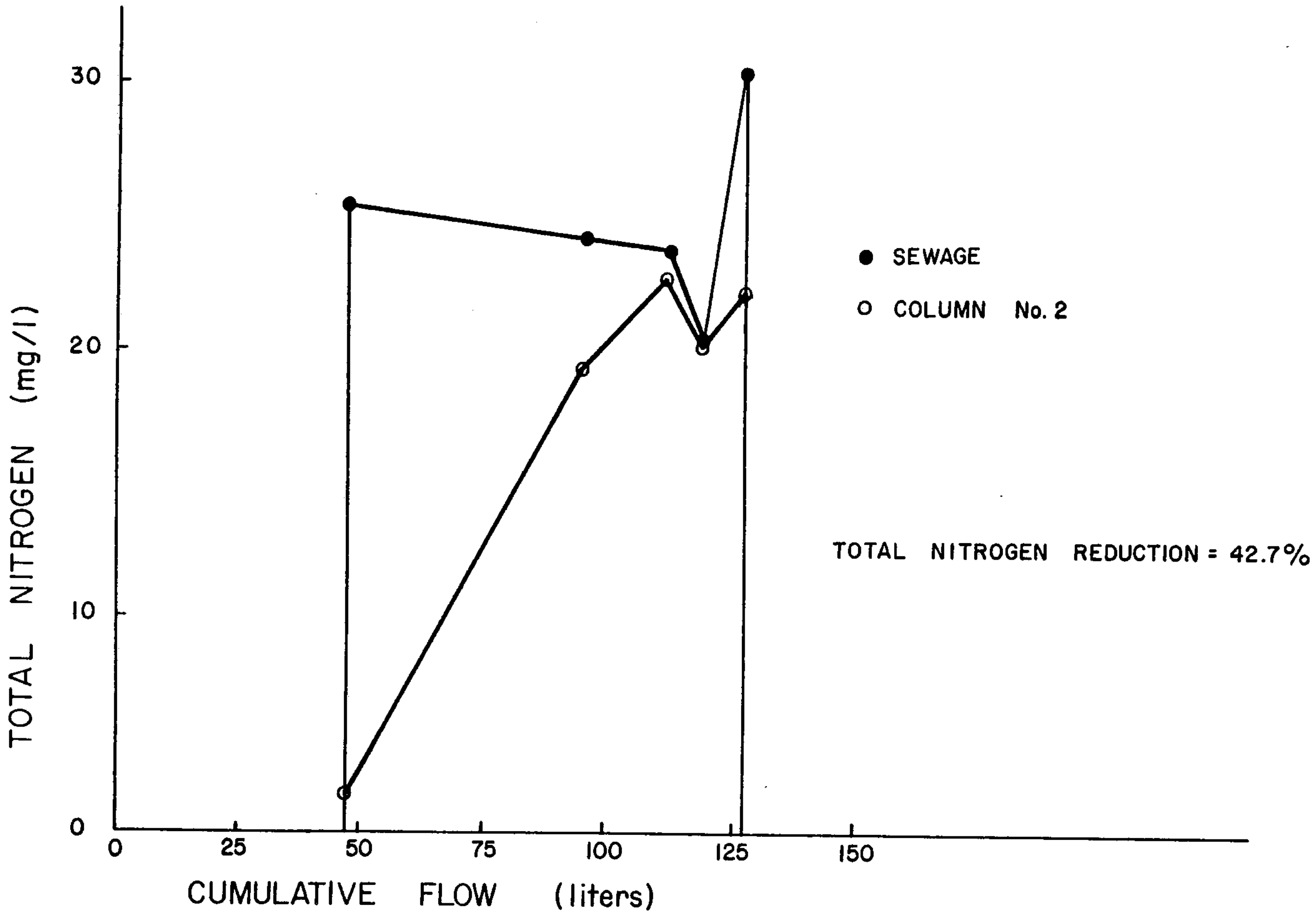

Figure 8. Total N Reduction for Column 2, Run 1.

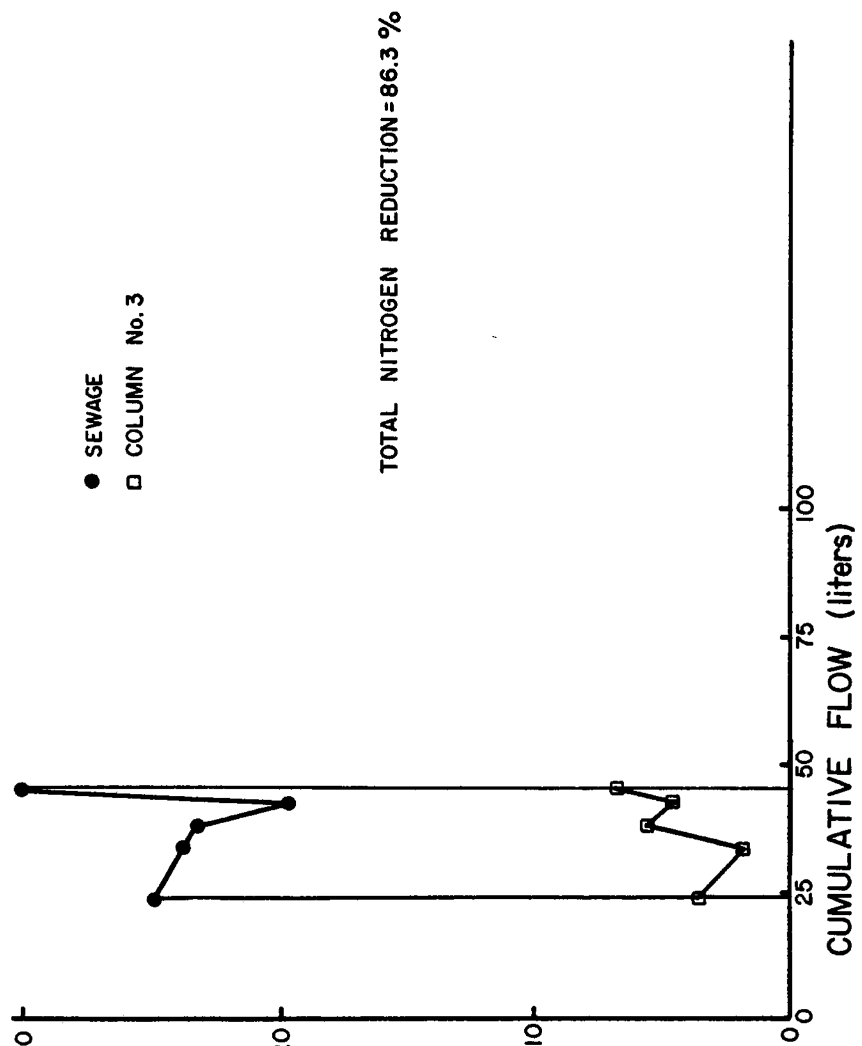

Figure 9. Total N Reduction for Column 3, Run 1.

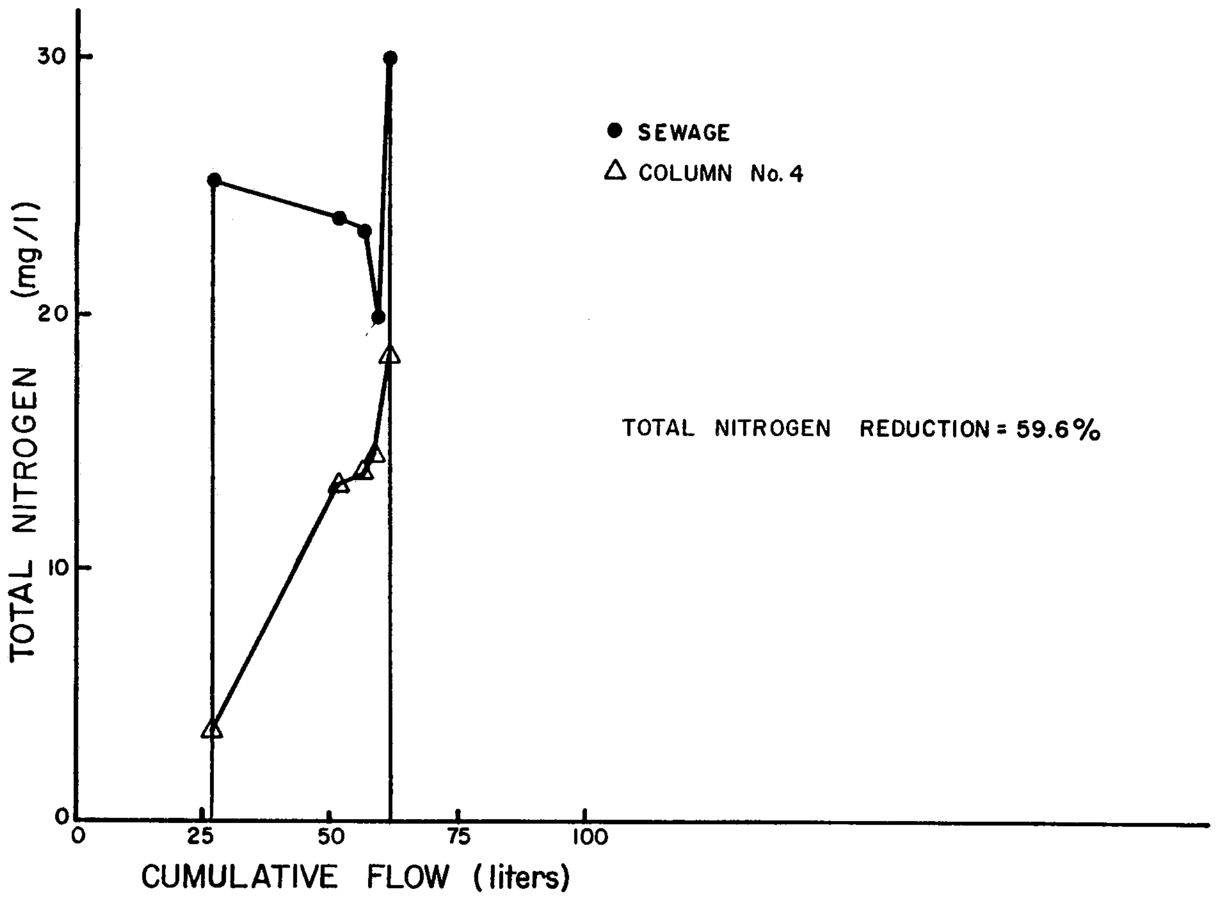

Figure 10. Total N Reduction for Column 4, Run 1.

59.6 percent reduction, respectively, with the average reduction being 62.9 percent. The reduction in total nitrogen as determined by Student T test was significant at the .05 confidence level, but not at the .01 level.

Figures 8 through 10 represent the percent reduction in total nitrogen for run 1. They also show that the nitrogen losses were greater near the beginning of the run.

During the second run, nine sets of samples were collected in the period that the columns were continually flooded with sewage. Another set of samples was taken after a 24-hour drying period (Table 6). A 16.4, 16.2, and 15.0 percent reduction in total nitrogen was observed in columns 2, 3, and 4, respectively, with an average of 15.9 percent reduction (Figures 11 through 13). The reduction was highly significant at the .01 confidence level, as determined by a Student T test.

The difference in the significance level of total nitrogen reduction for run 1 and run 2 can be attributed to the variability among columns during run 1 and the consistency during run 2. The exact cause of the variability in run 1 is not known, but may be a result of differences in packing.

Table 6 represents the nitrogen analyses for run 2. Again, the results are reported in mg/1 of nitrogen. The trends are similar to those presented in Table 5 for run 1 except that the values for columns 2, 3, and 4 were much closer to each other than they were for run 1.

For two sets of samples taken during the period of continuous flooding, the ammonia concentration flowing out of the columns was higher

Table 6. Nitrogen Analyses for Run 2.

Date	Sample	NH_4-N (mg/l)	NO_3 + NO_2-N (mg/l)	KJN (mg/l)	Total N (mg/l)
3-25-76	Sewage	--	--	--	--
	Tap water	0.00	10.36	0.00	10.36
	Column 1	0.00	10.36	0.00	10.36
	Column 2	0.00	10.36	0.00	10.36
	Column 3	0.00	10.36	0.00	10.36
	Column 4	0.00	10.36	0.00	10.36
3-26-76	Sewage	19.60	1.82	22.26	24.08
	Tap water	0.00	10.08	0.00	10.08
	Column 1	0.00	10.28	0.00	10.28
	Column 2	12.62	1.40	15.98	17.38
	Column 3	13.72	1.26	15.26	16.52
	Column 4	15.82	1.18	16.80	17.98
3-29-76	Sewage	17.64	3.64	19.94	23.58
	Tap water	0.00	10.56	0.00	10.56
	Column 1	0.00	10.50	0.00	10.50
	Column 2	16.38	0.90	19.74	20.64
	Column 3	16.10	1.54	18.20	19.74
	Column 4	15.68	1.06	18.62	19.68
4-5-76	Sewage	15.96	2.80	18.26	21.06
	Tap water	0.00	9.94	0.00	9.94
	Column 1	0.00	10.36	0.00	10.36
	Column 2	17.08	0.56	20.30	20.86
	Column 3	19.60	0.56	22.65	23.21
	Column 4	20.02	0.64	23.41	24.05
4-21-76	Sewage	14.00	1.12	16.80	17.92
	Tap water	0.00	10.36	0.00	10.36
	Column 1	0.00	10.44	0.00	10.44
	Column 2	16.46	0.50	19.32	19.82
	Column 3	17.89	0.42	20.66	21.08
	Column 4	18.87	0.56	25.20	25.76
5-1-76	Sewage	15.32	0.50	21.42	21.92
	Tap water	0.00	10.53	0.00	10.53
	Column 1	0.00	10.53	0.00	10.53
	Column 2	8.45	0.45	11.06	11.51
	Column 3	14.20	0.58	17.05	17.63
	Column 4	11.46	0.75	17.42	18.17

Table 6. Nitrogen Analyses for Run 2. -- Continued.

Date	Sample	NH_4-N (mg/l)	NO_3 + NO_2-N (mg/l)	KJN (mg/l)	Total N (mg/l)
5-6-76	Sewage	14.84	0.42	27.13	27.55
	Tap water	--	--	--	--
	Column 1	--	--	--	--
	Column 2	6.02	0.28	9.24	9.52
	Column 3	12.68	0.87	14.31	15.18
	Column 4	13.72	0.56	17.70	18.26
5-6-76	Sewage	--	--	--	--
	Tap water	--	--	--	--
	Column 1	0.00	10.47	0.00	10.47
	Column 2	14.70	1.46	16.60	18.06
	Column 3	17.22	0.42	19.74	20.16
	Column 4	17.08	0.48	18.90	19.38
5-13-76	Sewage	17.64	0.90	22.43	23.33
	Tap water	0.00	10.67	0.00	10.67
	Column 1	0.00	10.39	0.00	10.39
	Column 2	17.64	0.70	20.55	21.25
	Column 3	17.19	0.70	19.54	20.24
	Column 4	16.52	0.50	19.07	19.57
5-21-76	Sewage	18.06	0.87	21.59	22.46
	Tap water	0.00	10.64	0.00	10.64
	Column 1	0.00	10.78	0.00	10.78
	Column 2	16.24	0.59	19.26	19.85
	Column 3	16.52	0.59	18.87	19.46
	Column 4	16.10	0.73	18.51	19.24
	(24-hour drying period)				
5-28-76	Sewage	17.92	1.29	23.02	24.31
	Tap water	0.00	10.92	0.00	10.92
	Column 1	0.00	10.78	0.00	10.78
	Column 2	19.88	1.29	24.64	25.93
	Column 3	22.96	1.29	27.72	29.01
	Column 4	23.52	1.06	29.68	30.74
	(1-week drying period)				

Table 6. Nitrogen Analyses for Run 2. -- Continued.

Date	Sample	NH_4-N (mg/l)	NO_3 + NO_2-N (mg/l)	KJN (mg/l)	Total N (mg/l)
6-7-76	Sewage	17.78	0.56	19.82	20.32
	Tap water	0.00	11.20	0.00	11.20
	Column 1	0.00	10.92	0.00	10.92
	Column 2	16.30	29.68	17.58	47.26
	Column 3	14.76	9.02	18.06	27.08
	Column 4	22.82	29.68	24.30	53.98
6-7-76	Sewage	22.40	0.98	25.20	26.18
	Tap water	--	--	--	--
	Column 1	0.00	11.06	0.00	11.06
	Column 2	23.13	1.12	24.14	25.26
	Column 3	22.68	1.06	25.59	26.65
	Column 4	22.12	1.15	25.34	26.49
6-8-76	Sewage	16.52	1.12	20.92	22.04
	Tap water	--	--	--	--
	Column 1	0.00	10.78	0.00	10.78
	Column 2	17.25	1.68	19.40	21.08
	Column 3	16.91	0.67	19.82	20.49
	Column 4	17.25	0.67	20.47	21.41

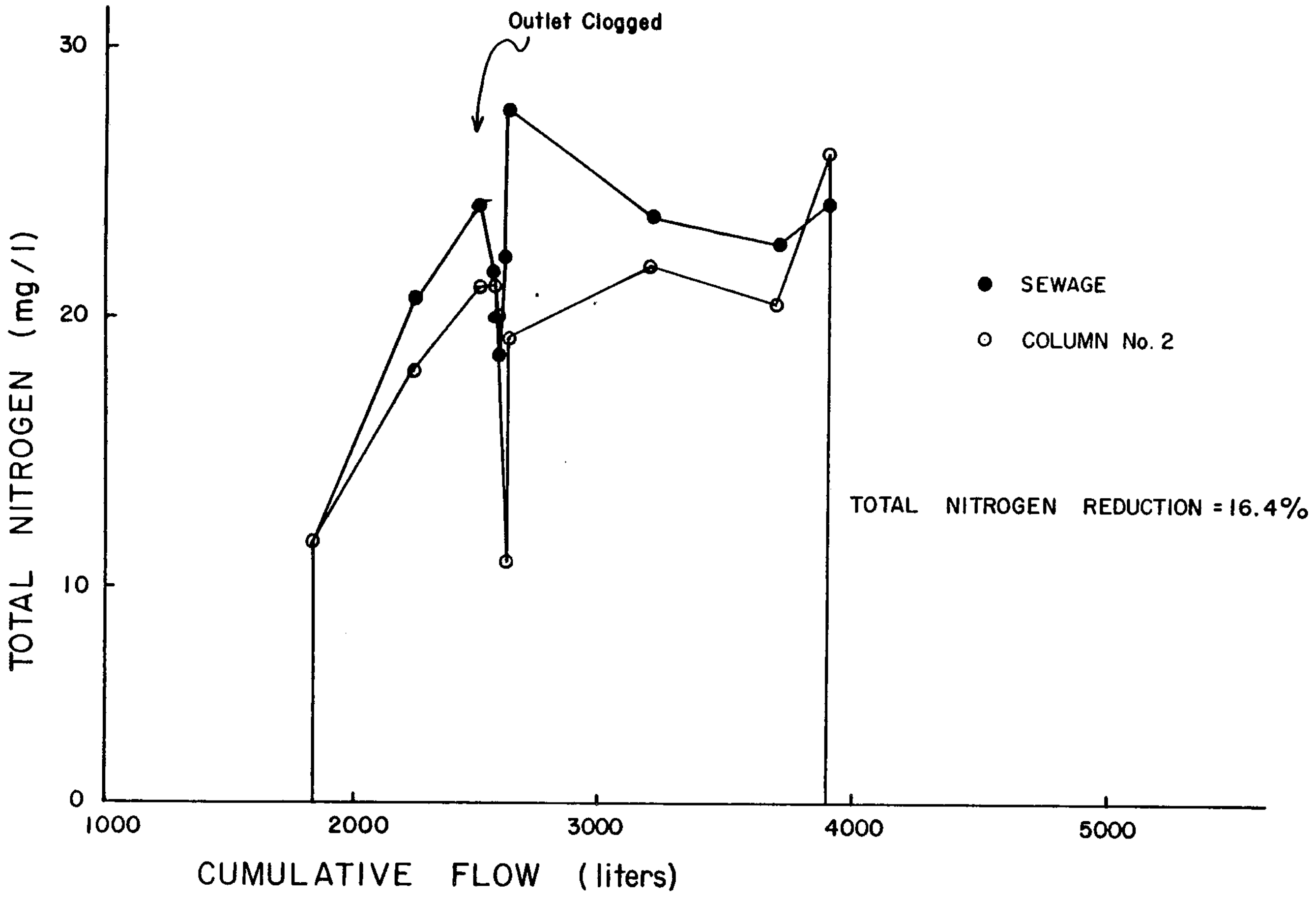

Figure 11. Total N Reduction for Column 2, Run 2.

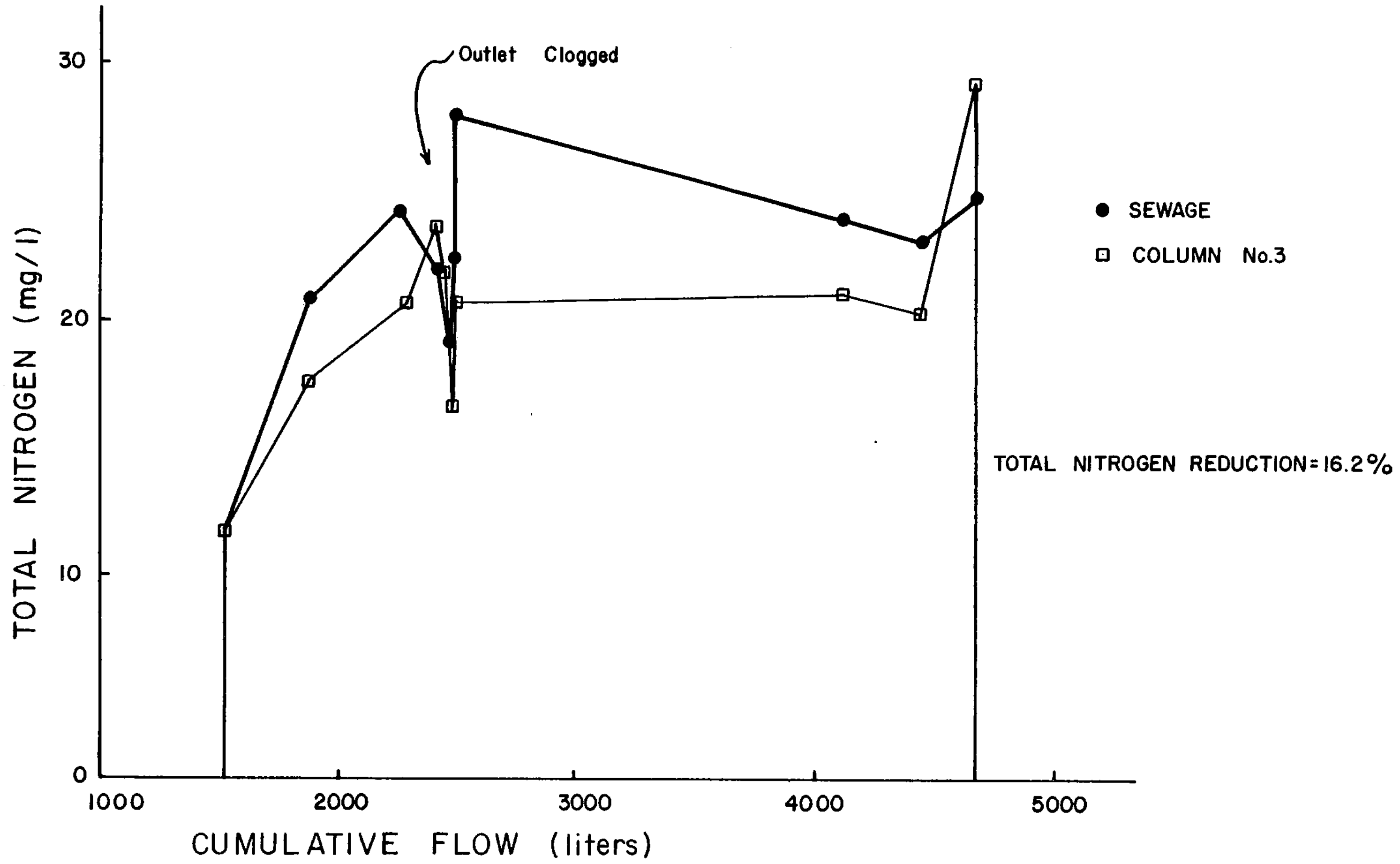

Figure 12. Total N Reduction for Column 3, Run 2.

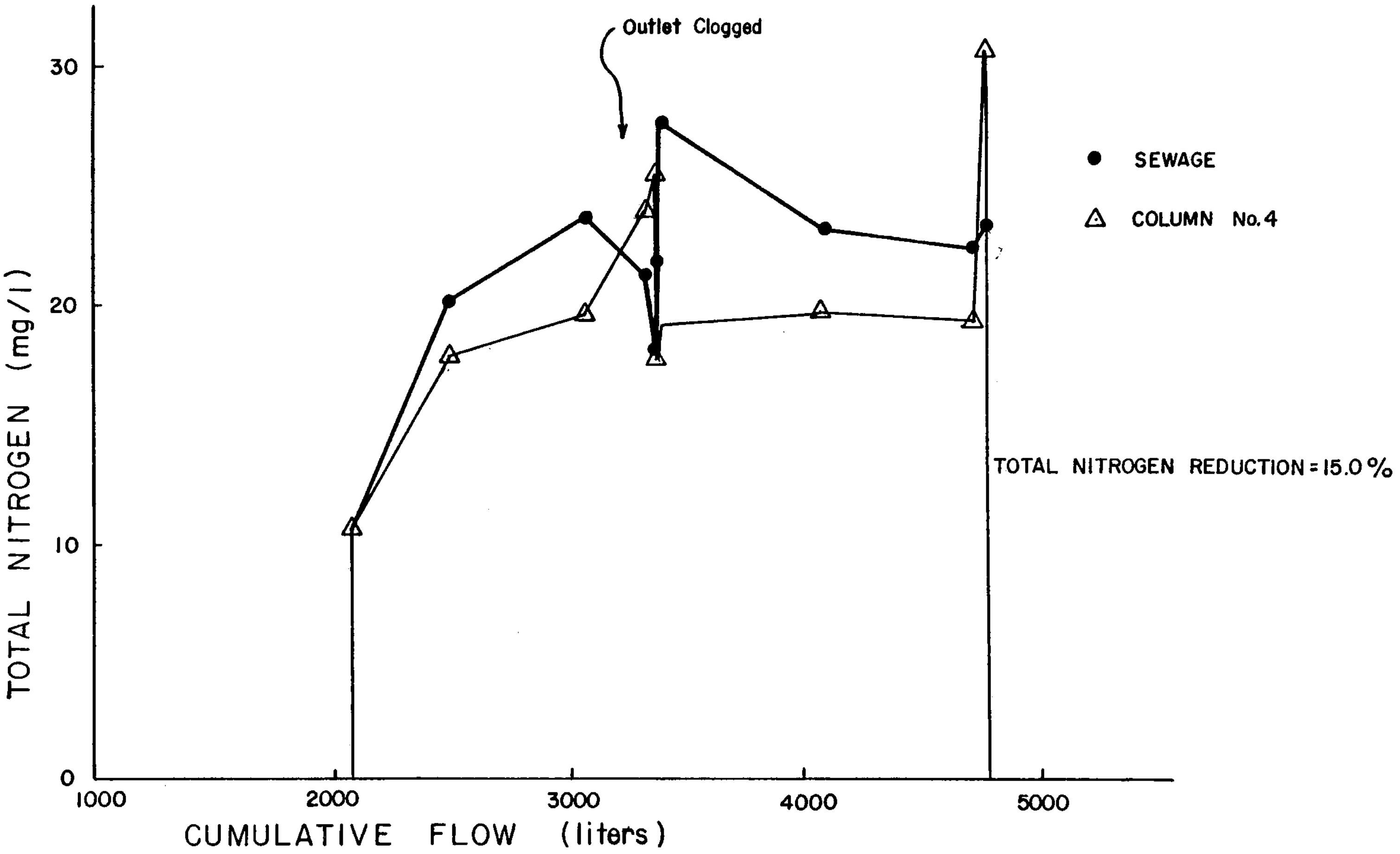

Figure 13. Total N Reduction for Column 4, Run 2.

than that flowing in (4-5-76 and 4-21-76, Table 6). Obstruction of the outlets caused the flow rates to be very low when these two samples were taken. Consequently, the long detention times probably allowed ammonification of organic nitrogen which could account for the higher ammonia concentrations in the outflow.

A sudden jump in the concentration of ammonia flowing through the columns was observed after the column outlets were unclogged (5-6-76, Table 5). Ammonification of organic nitrogen in the stagnant water-filled pores may have created more ammonia than could be adsorbed by the clay and organic matter, and since the columns were anaerobic, nitrification was prevented. When the outlets were unclogged, these pores could again transmit water and the excess ammonia was flushed from the columns.

The last three sets of samples were taken after an extended drying period. The first of these three sets of samples was taken immediately after reflooding and was high in nitrate. The two remaining sets of samples were taken at 8 and 24 hours after reflooding and the nitrate content had decreased to the levels previously obtained. These results are similar to those obtained in studies by Lance and Whisler (1975) in which a high nitrate peak was observed after several days of drying. The samples taken after a 24-hour drying period on May 28th had slightly higher nitrate values but there was no high nitrate peak.

Figures 11 through 13 represent the reductions in total nitrogen for run 2. The greatest reductions were during the periods when the outlets were not clogged.

DISCUSSION

Relationship between Black Layer Development and Infiltration Rates

During both runs, the infiltration rate dropped immediately upon application of sewage and the black layer did not appear until several days later. Therefore, the black layer is not a cause of reduced infiltration rates. However, there was some correlation between the infiltration rate and the thickness of the black layer. Observations during both runs revealed that, in general, the faster the flow, the thinner the black layer and vice versa. Winneberger et al. (1960) reported that ferrous sulfide deposits penetrated downward according to the laws that govern the movement of particles in a porous medium, and McGauhey and Krone (1967) stated that the removal rate of particles by a porous medium during the infiltration process increased as the accumulated solids increased. So, it seems reasonable to assume that, for higher infiltration rates, there would be a more rapid accumulation of fine particles closer to the surface, which would result in a thinner black layer. One obvious problem with this theory is that run 2 had much higher flow rates and thicker black deposits than run 1. However, the clogging of the outlets during run 2 caused the gravel to become saturated, similar to a perched water table condition in the field. The saturated conditions eliminated most of the oxygen and, consequently, the black layer developed throughout the length of the columns. Had the water table conditions not developed, the black layer may have developed in a manner similar to that in run 1. However, the larger pores in the gravel would probably have allowed deeper penetration of the fines before they could begin to accumulate and increase the removal rate. In fact, during the short period after the black layer began to build up and before the water table conditions developed, the black layer was thicker than it was during the same period in run 1.

The above interpretation of Winneberger's theory depends on downward filtration of ferrous sulfide precipitated at the surface. However, observations of the black layer during its development seem to indicate that the iron in the soil combines with sulfates dissolved in the percolating sewage upon development of anaerobic conditions. Evidence to support this observation was reported by Mitchell and Nevo (1964). They stated that microorganisms utilizing organic matter released H_2S, which moved down the profile where it reacted with iron in the sand, forming a black, ferrous sulfide layer. Since observations during this study do not coincide with the findings of Winneberger et al. (1960), another plausible explanation will be presented here.

The suspended solids in the percolating sewage could have been filtered out by filtering processes similar to those described above. After the initial deposition, the infiltration rate decreased, which was the case for both runs, and particles continued to be deposited on the surface. An interface between the bottom of the deposited material and the underlying soil created a barrier to water movement and water table conditions developed above the interface, thus creating anaerobic conditions and the black layer. Sakthivadivel (1966) found that gradually reducing the flow rate loosened bridged particles and allowed them to move down in a porous filter. So the downward extension of the black layer may be due to a downward migration of the interface as the filtered particles break loose and find their way through the underlying pores. Unfortunately, the manometer data for run 1 (Appendix A) do not support the theory that a water table exists above the interface. However, the finer material in the upper layer may hold enough water to create anaerobic conditions while at the same time exerting a suction on the tensiometer within the layer. Some evidence to support either of the above speculations was obtained during the field investigations. Well points installed within the Santa Cruz River revealed a shallow water table. Although the distribution of the black layer within the soil profile at the location of the well points is not known, the black layer was observed at the surface and could have formed in the saturated zone. Although this is all speculation, it could support the water table theory. In addition, while an observation pit was being dug adjacent to the river, a large, black clump of clay was exposed in an area surrounded by normal-colored sand. This observation seems to indicate that the clay held enough water to create anaerobic conditions and, therefore, the black layer, but the surrounding sand did not. A more detailed study, possibly using a combination of tensiometers and redox probes, is needed to determine what mechanism is responsible for creating the anaerobic conditions under which the black layer is developed.

Development of the black layer under water table conditions may be a very important process during ground-water recharge of sewage effluent in natural drainage channels. In addition to being an indicator of the conditions required for denitrification, the black layer may be a source of organic carbon and/or a sink for heavy metals and possibly other contaminants as well (Schaub et al., 1975). More studies should be conducted to determine this relationship.

Relationship between Black Layer Development and Nitrogen Transformations

There was no apparent relationship between the thickness of the black layer and the amount of total nitrogen removed. However, there was a large difference between the amount of nitrogen removed in run 1 and the amount removed in run 2. On a percentage basis, the river sand had a greater average removal than the gravel. Since the river sand had a higher clay content, which is normally associated with a higher cation exchange capacity, a higher percentage of ammonia was adsorbed in the first run than the second and, because there was no correlation between the thickness of the black layer and the nitrogen transformations within each run, it can be assumed that the differences in the black layer are not responsible for the differences in the amount of total nitrogen removed.

Figure 14 shows the total nitrogen in the sewage and the outflow of the treated columns throughout run 2. The reduction in total nitrogen between the sewage and the three columns appears to have been by denitrification and/or adsorption of ammonia by the clays. The high nitrate peak observed after an extended period of drying in run 2 (Figure 15) was not observed after the short drying period in run 1 and a

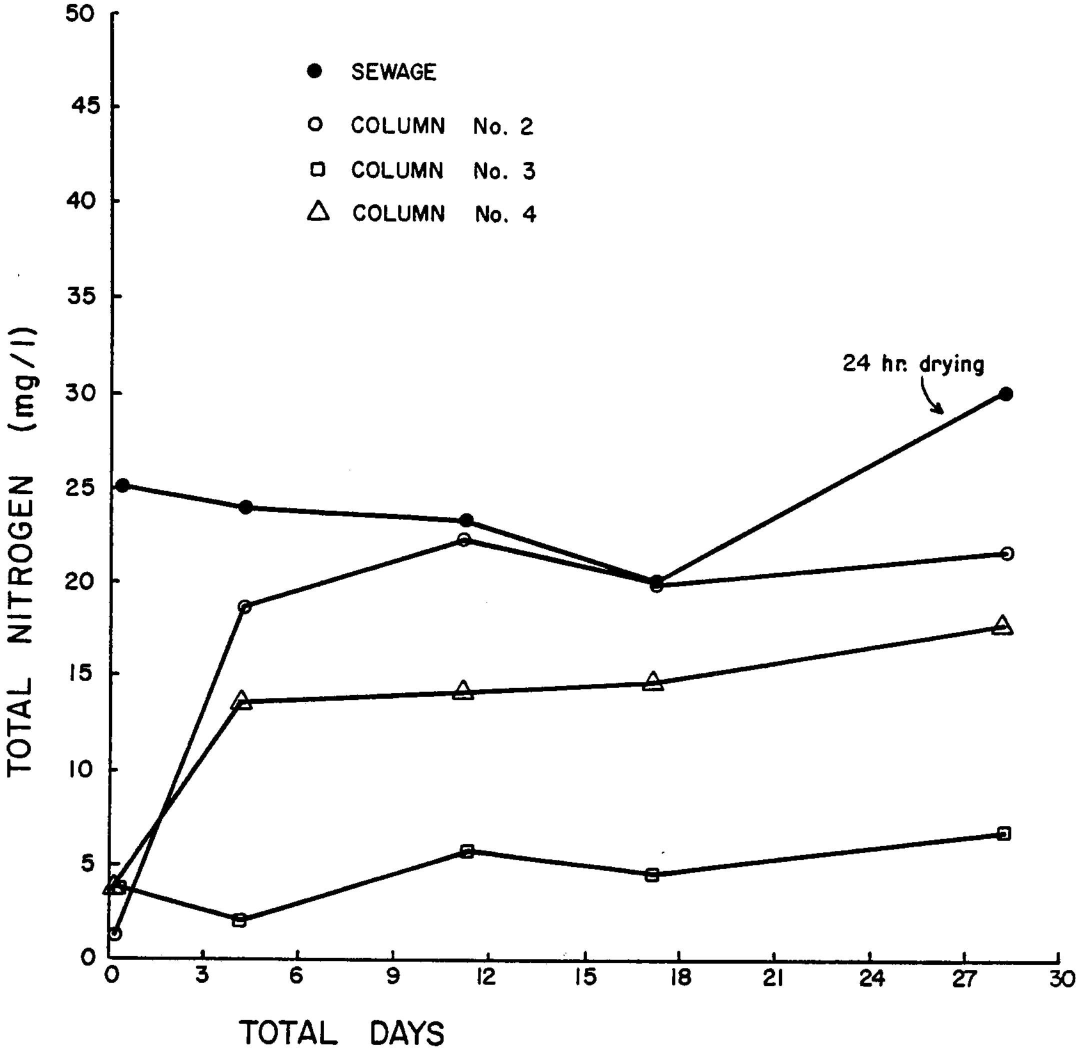

Figure 14. Total N for the Sewage and Treated Columns (Run 1).

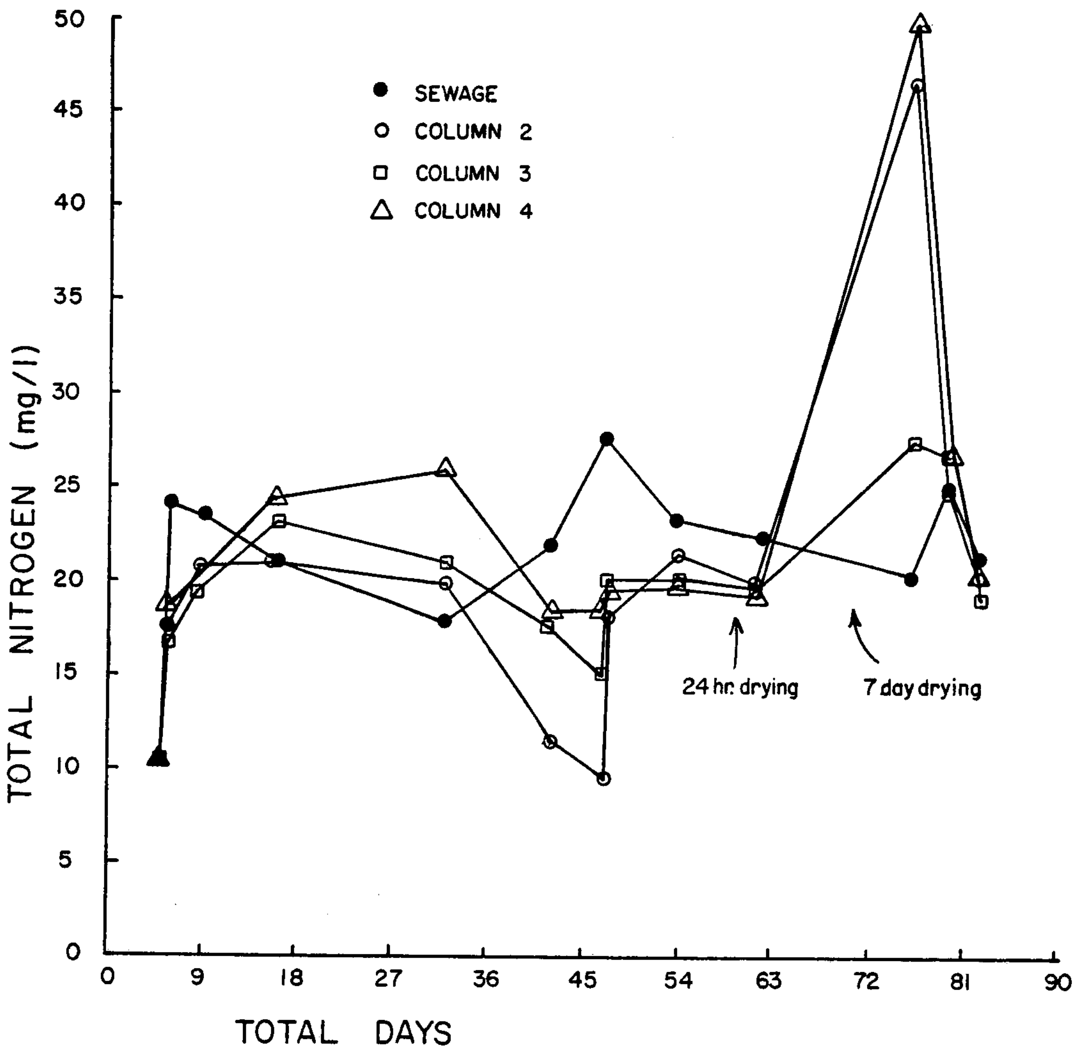

Figure 15. Total N for the Sewage and Treated Columns (Run 2).

longer drying period would have been required to determine the extent of removal by adsorption.

Figure 15 shows the total nitrogen in the sewage and the outflow of the treated columns for run 2. Since the clay fraction of the gravel was so low, very little adsorption of ammonia was expected. However, the first set of samples taken after the nine-day drying period was high in nitrates. This high nitrate peak was similar to that observed by Lance and Whisler (1975). They attributed the high nitrate peak to nitrification of adsorbed ammonia subsequent to column aeration. Possibly, ammonia was adsorbed by organic matter that had been filtered out by the gravel. Upon drying, the ammonia was exposed to the soil atmosphere and nitrified. Reflooding washed the nitrated through the column.

The nitrogen data (Table 6) indicates that the majority of the nitrogen removed was due to removal of organic nitrogen. The organic nitrogen may have been filtered out and a portion of it may have been mineralized. However, the extent of mineralization is unknown. Adsorption of, or nitrification of, ammonia and subsequent denitrification may also have taken place.

Although run 2 had a lower percentage of total nitrogen removed, the flow rate was much higher. Consequently, a much larger volume of nitrogen was removed during the second run. For run 1, there was an average of 24 pounds/acre/day (27 kilograms/hectare/day) removed, while about 141 pounds/acre/day (158 kilograms/hectare/day) were removed during run 2. Unfortunately, the total volume of nitrogen passing through the columns was also much greater for run 2.

Bouwer (1974) demonstrated that recharge basins could be managed to achieve a 30 percent removal of nitrogen and Lance and Whisler (1975) showed that even higher removal rates could be attained by increasing the carbon content or decreasing the flow rate. Higher removal rates could probably have been achieved in this study if the ammonia in the sewage had been nitrified before it entered the black layer. Schaub et al. (1975) found high concentrations of organic carbon in the black layer, which would seem to indicate that a carbon source is not a limiting factor for denitrification, provided the ammonia is first nitrified and the nitrate remains in contact with the bacteria for a long enough time. However, this remains to be proven.

If the detention time within the black layer were a limiting factor, recharge basins used for reclaiming sewage effluent might be managed to obtain the thickest possible black layer, which would give the longest possible contact time during recharge. However, high infiltration rates and nitrifying conditions must also be maintained. Although these mechanisms may not seem to be compatible, studies on the subject might be warranted because nitrogen removal during recharge of waste water is of such great import.

Relationship between Infiltration Rates and Nitrogen Transformations

There seems to be some correlation between the rate of flow and the amount of nitrogen removed. As was discussed in previous sections, when the outlets became almost completely clogged during run 2, the ammonia concentration of the outflow was greater than the inflowing sewage. This phenomenon is probably not indicative of what would happen during normal free flow conditions. In fact, there was a greater percent removal during the first run which had the slower infiltration rates. These results are similar to results of experiments by Lance and Whisler (1973), where they observed a greater percent removal of nitrogen at lower infiltration rates. However, the different infiltration rates in Lance and Whisler's study were obtained by packing the soil to different densities rather than using different soil types.

SUMMARY AND CONCLUSIONS

Two separate column studies were conducted at the City of Tucson Sewage Treatment Plant to determine the interrelationships among nitrogen transformations, infiltration rates, and development of a black layer during sewage effluent recharge. Four clear acrylic columns were uniformly packed with river sand for the first study (run 1) and the sand was replaced with gravel for the second study (run 2). Sewage effluent was continuously applied to three of the columns for 28 and 64 days during the first and second runs, respectively. The remaining column was continuously flooded with tap water and served as a control in both cases. Infiltration rates and manometer readings were recorded daily and random samples of the inflow and outflow of each column were collected and analyzed for the various nitrogen compounds.

Infiltration rates decreased rapidly upon application of the sewage and within a few days a black layer began to develop. The thickness of the black layer was inversely related to the infiltration rate, but was not a cause of reduced flow. The major cause of the initital reduction in flow rate was clogging of the surface by suspended solids. Clogging of the outlets during run 2 created water table conditions throughout the length of the treated columns which created anaerobic conditions and, consequently, the black layer. There was an average reduction in total nitrogen of 62.9 percent for the first run and 15.9 percent for the second run. The mechanisms of removal for run 1 were predominately adsorption and denitrification, whereas the predominate removal mechanism in run 2 was filtering of organic nitrogen with adsorption and denitrification also playing an important role.

Development of the black layer was not a cause of reduced infiltration rates. However, lower infiltration rates appeared to be an indirect cause of a thicker black layer within a given soil type. There was no apparent relationship between black layer development and reduction in total nitrogen, but the majority of the nitrogen was in the wrong form for denitrification, which makes this part of the results inconclusive. The percent of total nitrogen removal was greater for lower infiltration rates.

APPENDIX A

MANOMETER READINGS FOR RUN 1

		Tensiometer (Inches of Total Hydraulic Head)											
Date	Time	1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c
1-13-76	0815	-26.35	-20.75	-17.05	-24.40	-19.15	-16.30	-25.70	-20.70	-19.20	-22.00	-20.25	-20.60
	1200	3.75	6.10	7.80	4.70	6.60	9.50	4.85	7.90	10.40	3.20	8.20	10.00
	1540	4.22	6.10	7.80	4.40	6.05	9.08	5.00	7.90	10.35	2.95	8.40	10.20
1-14-76	0705	3.90	3.70	5.50	-11.40	-12.50	-11.30	-11.50	-11.90	-12.60	- 4.40	- 2.30	- 2.60
	1505	4.00	4.50	7.00	3.10	- 2.00	0.06	- 9.30	- 9.30	- 9.30	- 1.20	2.70	5.30
1-15-76	1056	4.00	5.20	8.40	2.70	- 3.40	- 3.20	-17.10	-17.80	-18.30	-18.20	-16.50	-18.20
1-16-76	0730	4.00	4.20	7.60	9.50	- 8.80	- 8.10	-23.20	-24.60	-25.20	-22.50	-22.70	-24.10
1-17-76	1410	4.00	4.40	8.30	- 5.70	-10.80	- 9.30	-16.30	-17.10	-16.90	-22.50	-21.70	-21.00
1-18-76	1215	4.00	4.00	8.10	- 7.40	-11.60	- 9.90	-17.50	-19.70	-18.00	-18.20	-15.30	-12.20
1-19-76	0710	4.00	2.90	7.10	-13.10	-18.40	-16.40	-26.00	-28.30	-26.60	-16.60	-15.80	-14.70
	1300	4.00	3.40	7.60	-10.00	-13.90	-12.10	-18.50	-19.40	-17.60	-16.80	-15.30	-11.90
1-20-76	0730	4.10	2.20	5.90	-16.10	-20.20	-18.00	-19.60	-21.40	-19.90	-16.30	-15.30	-13.00
	1555	4.10	2.00	5.60	- 7.80	- 4.90	-10.40	-16.00	-19.20	-17.50	-15.90	-15.10	-12.50
1-21-76	1705	4.40	1.00	3.10	-15.70	-17.70	-16.20	-17.90	-18.90	-17.00	-14.70	-14.10	-11.20
1-22-76	1545	4.20	0.70	1.40	-15.80	-17.80	-16.00	-16.70	-18.20	-16.50	-14.60	-13.40	- 9.60
1-23-76	1145	4.20	0.70	-	-	-	-	-	-	-	-	-	-
1-24-76	1315	4.10	1.00	-	-	-	-	-	-	-	-	-	-

APPENDIX B

MANOMETER READINGS FOR RUN 2

		Tensiometer (Inches of Total Hydraulic Head)											
Date	Time	1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c
3-23-76	0730	4.5	10.9	16.5	5.0	11.6	17.2	4.9	11.2	17.1	4.7	7.5	7.2
	1420	4.5	10.8	16.5	4.9	11.5	17.2	5.0	11.6	17.0	4.9	8.0	7.5
3-24-76	0705	4.5	11.0	16.6	5.0	11.5	17.2	5.0	11.6	17.2	4.8	7.7	7.2
3-25-76	1100	4.5	10.7	16.5	5.1	11.7	17.5	5.0	11.7	17.3	4.8	7.8	7.3
3-26-76	1240	4.5	10.7	16.5	5.0	11.5	17.2	4.9	11.3	16.7	4.7	7.6	7.2
	1340	4.3	10.5	16.6	4.7	11.4	16.9	4.8	11.2	16.6	4.7	7.8	7.4
	1440	4.5	11.2	16.8	5.0	11.8	17.5	4.9	11.6	17.2	4.7	7.6	7.1
3-27-76	0810	4.5	11.0	16.6	3.7	10.3	16.3	3.9	10.3	16.2	3.6	6.1	11.2
3-28-76	0815	4.5	11.1	16.7	1.1	7.2	13.3	1.3	6.1	12.0	1.5	2.2	6.8
3-29-76	0705	4.5	11.1	16.7	0.3	6.1	12.1	-0.9	2.3	8.2	0.3	-1.1	3.2
	1525	4.5	11.1	16.7	-0.7	5.0	11.0	-2.5	0.6	6.7	-1.3	-6.8	-2.7
3-30-76	0730	4.5	11.1	16.8	0.0	6.2	12.1	-2.0	0.5	6.3	-0.8	-4.5	0.0
3-31-76	0715	4.6	11.2	16.9	-0.5	6.0	11.9	-1.9	1.4	7.3	-2.8	-7.3	-2.3
4-1-76	0720	4.7	11.4	17.1	0.1	6.7	12.7	-1.6	2.0	7.9	-2.5	-5.9	-0.6
4-2-76	0730	4.7	11.4	17.1	1.7	8.5	14.3	-1.2	2.9	8.8	-3.4	-4.9	0.7
4-3-76	0900	4.8	11.6	17.2	1.8	8.5	14.5	-1.1	3.6	9.5	-5.4	-4.2	1.6
4-4-76	1135	5.1	11.6	17.4	1.2	7.9	13.9	-0.9	3.2	9.1	-6.0	-4.4	1.4
4-5-76	1330	4.7	11.4	17.1	2.0	8.8	14.9	-2.3	1.9	8.0	-7.4	-4.1	1.9
4-6-76	0718	4.8	11.5	17.2	2.5	9.3	15.3	-1.4	3.8	9.7	-1.2	3.8	9.8
4-7-76	1620	4.9	11.7	17.3	2.7	9.6	15.6	0.0	6.2	12.2	-1.8	4.3	10.3
4-8-76	0725	4.9	11.7	17.3	3.3	10.1	16.1	0.2	6.4	12.2	-0.9	5.5	11.6
4-9-76	0715	4.9	11.7	17.4	3.0	9.9	15.8	2.2	8.9	14.8	0.3	7.0	13.1
4-10-76	0725	4.9	11.7	17.4	2.6	9.5	15.4	1.2	7.8	13.8	-0.6	6.0	12.0
4-11-76	0855	4.9	11.7	17.4	2.2	9.1	15.0	0.2	6.8	12.7	-1.4	5.2	11.2
4-12-76	0700	5.0	11.8	17.4	2.4	9.3	15.3	-1.5	4.6	10.5	1.3	7.7	13.7
4-13-76	0703	5.0	11.7	17.5	2.3	9.1	15.1	-1.1	4.8	10.7	0.1	6.0	12.1
4-14-76	0710	5.0	11.7	17.5	2.1	9.0	15.0	-1.1	4.9	10.8	-1.0	4.6	10.7

Date	Time	Tensiometer (Inches of Total Hydraulic Head)											
		1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c
4-15-76	0706	4.9	11.7	17.5	2.5	9.3	15.3	-1.1	5.2	11.0	-1.4	4.3	10.3
	1515	5.0	11.8	17.4	5.0	11.8	17.9	4.7	10.5	16.8	4.6	10.4	16.4
4-17-76	0855	4.9	11.7	17.6	5.0	11.9	17.9	4.7	10.8	16.9	4.7	11.0	17.1
4-18-76	0756	5.0	11.8	17.4	5.0	11.9	17.9	4.7	11.0	17.0	4.7	11.2	17.2
4-19-76	0710	5.0	11.7	17.5	5.1	11.9	17.9	4.6	10.7	16.7	4.6	11.1	17.1
4-20-76	0711	4.9	11.7	17.6	5.0	11.9	17.9	4.7	10.9	16.9	4.6	11.2	17.1
4-21-76	0659	5.0	11.7	17.4	5.1	11.9	17.9	4.7	11.0	17.0	4.8	11.4	17.4
4-22-76	0714	5.0	11.8	17.5	5.1	11.9	17.9	4.7	11.3	17.2	4.8	11.5	17.5
4-24-76	0921	5.0	11.8	17.5	5.3	12.1	18.1	5.1	11.7	17.7	5.0	12.0	18.0
4-25-76	0857	5.0	11.8	17.5	5.1	12.0	18.0	5.0	11.7	17.7	5.1	12.0	18.0
4-26-76	0704	5.0	11.8	17.5	5.2	12.0	18.0	5.0	11.7	17.7	5.1	12.0	18.0
4-28-76	0700	6.2	11.9	17.6	5.2	12.2	18.0	5.0	11.7	17.7	5.1	12.0	18.0
5-1-76	0920	5.3	11.9	17.7	4.8	11.7	17.6	4.6	11.6	17.3	4.6	11.6	17.8
5-6-76	1340	5.2	11.8	17.6	5.0	11.3	17.3	4.3	9.4	15.3	3.2	2.9	7.7
5-7-76	0720	5.1	11.8	17.5	4.3	10.5	16.5	-0.2	-0.4	-5.4	2.0	2.1	7.4
5-8-76	0957	5.1	11.8	17.6	3.6	10.2	16.1	-0.7	-3.8	-0.2	0.3	0.4	5.8
5-10-76	0750	5.1	11.9	17.6	2.4	8.9	14.8	-7.2	-16.4	-15.0	-1.7	-2.0	3.6
5-11-76	0724	5.1	11.9	17.6	0.3	6.3	12.3	-2.2	-5.0	-5.2	-4.2	-6.1	-0.2
5-12-76	1200	5.1	11.8	17.6	2.6	2.0	2.0	-2.0	-6.1	-6.2	-4.5	-8.0	-2.5
5-13-76	0746	5.1	11.8	17.6	2.1	2.2	2.2	-2.6	-5.0	-5.1	-5.0	-9.6	-4.2
5-14-76	0735	5.0	11.8	17.6	0.6	0.2	0.3	-3.1	-5.3	-5.5	-2.4	-9.5	-3.9
5-15-76	0824	4.9	11.8	17.6	-0.4	-0.7	-0.6	-8.5	-15.2	-15.2	-5.6	-17.4	-11.7
5-17-76	-	5.1	11.8	17.6	-0.6	-1.0	-1.0	-10.0	-15.7	-15.7	-7.8	-19.0	-13.6
5-18-76	0730	5.1	11.8	17.6	-0.8	-1.3	-1.3	-4.9	-8.9	-9.1	-6.5	-14.2	-9.0
5-20-76	0720	5.1	11.8	17.6	-2.0	-3.2	-3.0	-4.6	-5.6	-5.7	-9.0	-19.4	-13.9
5-21-76	0730	5.1	11.7	17.6	-3.2	-4.9	-4.8	-4.5	-6.1	-6.1	-7.2	-13.5	-7.9
5-22-76	0827	4.9	11.8	17.6	-6.0	-9.2	-9.1	-6.2	-7.1	-7.5	-8.9	-19.3	-13.6
5-25-76	1610	5.1	11.9	17.7	-7.9	-14.3	-14.5	-6.0	-7.1	-7.2	-9.7	-26.4	-21.6

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