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

by

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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 (Huges, 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 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 infilitration rates are due to a building 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.

MATERIALS AND METHODS

The interrelationships among infilitration 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.

Infilitration 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. The columns were mounted in an enclosed wooden frame. Each column extended through the top of the frame a few 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.

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. A monometer board was constructed with a cover and mounted on one end of the wooden enclosure.

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.

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.

A small submersible pump installed several feet upstream of the chlorination point fed a continuous supply of unchlorinated sewage effluent to one of the manifolds. By continuous pumping, a fresh supply of sewage was maintained at a constant head for all of the columns being treated with sewage. A contant 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.

METHODS

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. 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.

Daily flow measurements were taken 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.

The level of the meniscus in each manometer was recorded daily at about the same time the flow measurements were made.

Samples of the applied sewage and tap water and the outflow from each column were collected at random time intervals. All samples were immediately transported for analysis.

RESULTS

BLACK LAYER DEVELOPEMNT

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 balck 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 1. 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 1. 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 1). During this time, the manometers showed negative pressure heads in the treated columns.

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 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 characteristic curve. After about a week, the flow rate in the treated columns decreased to almost zero. The flow rate remained extremely low for about three more weeks and the manometer readings 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 2) and the level of the manometers began to drop off again. A statistical analysis 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 predominant factor.

NITROGEN TRANSFORMATIONS

The complete data from the nitrogen analyses will not be presented here due to space limitations but a discussion of the results will be included in a later section.

There were no changes in the nitrogen species for the control columns during either run. Total nitrogen in run 1 was reduced by 42.7, 86.3 and 59.6 percent in columns 2, 3, and 4 respectively, with the average reduction being 62.9 percent. The reduction in total nitrogen as determined by a Student T test was signigicant at the .05 conficence level, but not at the .01 level.

During the second run, columns 2, 3, and 4 showed a 16.4, 16.2 and 15.0 percent reduction in total nitrogen, respectively, with an average of 15.9 percent. The reduction was highly significant at the .01 confidence level.

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 increases 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 coicide with the findings of Winnegerger 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 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 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 3 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 dentrification and/or adsorption of ammonia by the clays. The high nitrate peak observed after an extended period of drying in run 2 (Figure 4) was not observed after the short drying period in run 1 and a longer drying period would have been required to determine the extent of removal by adsorption.

Figure 4 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 nitrates through the columns.

The nitrogen data 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. 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 efluent 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 soilds. 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 means this part if the results is inconclusive. The percent of total nitrogen removal was greater for lower infiltration rates.

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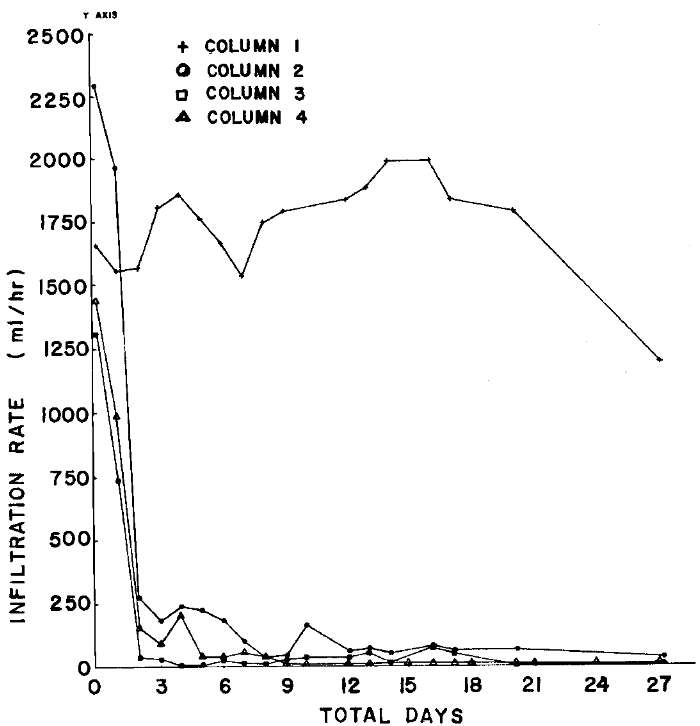

Figure 1. Infiltration Rates for 28 Days of Continuous Flooding during Run 1.

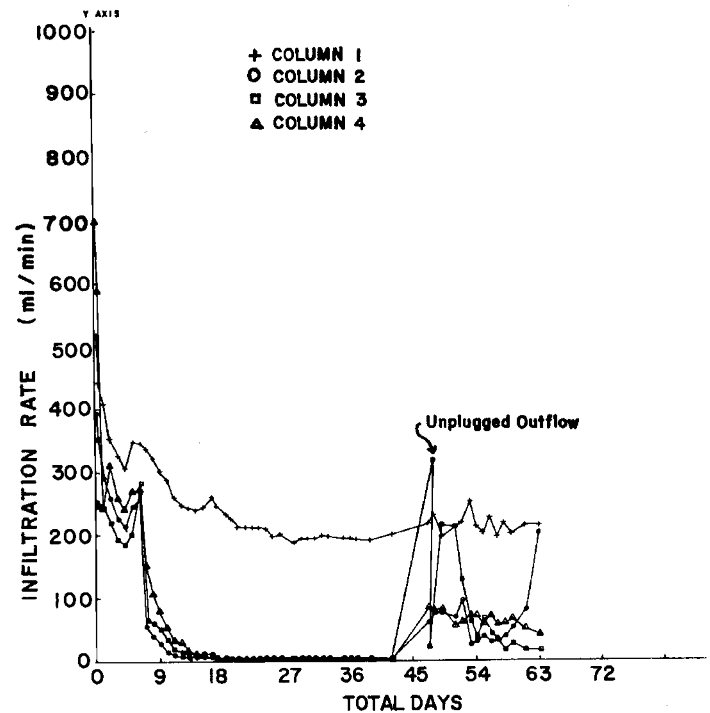

Figure 2. Infiltration Rates for 64 Days of Continuous Flooding during Run 2.

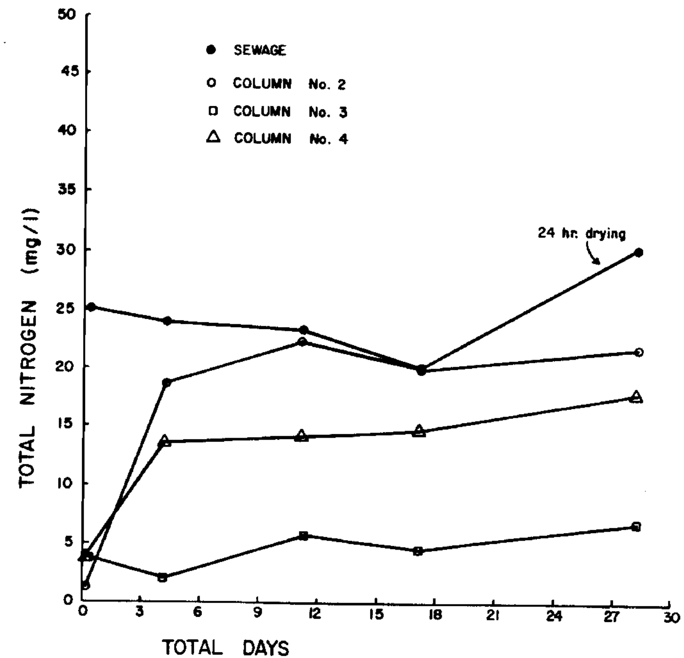

Figure 3. Total N for the Sewage and Treated Columns (Run 1).

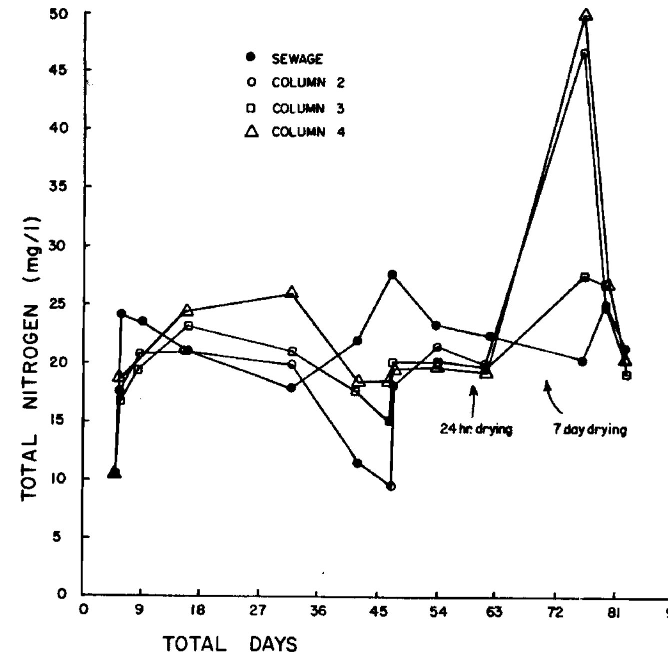

Figure 4. Total N for the Sewage and Treated Columns (Run 2).