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Phosphate Removal from Sewage Water by Soil Columns

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ABSTRACT

Phosphate (PO_4-P) removal from secondary sewage effluent by calcareous sand columns was proportional to the infiltration rate. Phosphate concentrations in drainage from columns, packed with a mixture of sand from recharge basins and sand never previously exposed to sewage water, were below 1 ppm for over 200 days, increased, and finally leveled off at different concentrations, depending upon the infiltration rate. The equilibrium PO_4-P concentration could be increased or decreased by increasing or decreasing the infiltration rate. Evidently, PO_4-P was initially adsorbed by a reaction independent of flow velocity or retention time and, when this adsorption capacity was reached, PO_4-P was removed by a time-dependent adsorption or precipitation reaction. The rapid response to either increases or decreases in infiltration rate suggested a precipitation reaction. The PO_4-P removal continued after application of 250 m of sewage water and 60,000 kg/ha PO_4-P during 7 years of flooding. Removal of 75-80% of the PO_4-P applied in secondary sewage effluent continued when the infiltration rate was maintained below 15 cm/day. Bermudagrass (*Cynodon dactylon*) greatly increased PO_4-P concentrations in column effluent samples.

Additional Index Words: ground water recharge, waste water.

High-rate land filtration shows great promise as a waste water renovation method. Previous reports showed that most of the nitrogen, organic material, and fecal coliform bacteria could be removed by proper management of a ground water recharge system where a calcareous sand was intermittently flooded with secondary sewage effluent at infiltration rates of 15 to 50 cm/day (Bouwer et al., 1974a, 1974b; Lance et al., 1976). Orthophosphate-phosphorus in water from a well in the center of the field recharge system ranged from 30 to 70% of the total PO_4-P concentration in the secondary effluent over a 4-year period (Bouwer et al., 1974b). It was suggested that variation in PO_4-P removal might be due to differences in the application rate and PO_4-P concentration of the secondary effluent. Samples from wells 30 m from the edge of the infiltration area indicated that additional underground travel increased PO_4-P removal.

Little information is available on PO_4-P removal by other soils flooded with sewage water for long periods. John (1974) reported that PO_4-P removal by a 20-cm column of Squilax loam (a calcareous meadow soil) was 97% initially, but decreased to 81% after 77 days of intermittent flooding. Infiltration rates for this soil averaged approximately 7 cm/day. Greenberg and McGauhey (1955) found that percolation through 3 m of Hanford fine sandy loam was required to reduce PO_4-P concentrations below 1 ppm after 2 years of continuous flooding with secondary sewage effluent, whereas 0.3 m was needed for basins intermittently flooded on a 1-week flooding, 1-week drying cycle. Their infiltration rates averaged about 15 cm/day.

The objectives of this study were to determine the factors affecting PO_4-P removal by a calcareous sand flooded at high infiltration rates (15 to 50 cm/day) for several years, and to develop management practices to maximize PO_4-P removal.

PROCEDURE

Soil columns were constructed by packing loamy sand from basins used for rapid infiltration of secondary sewage effluent into polyvinyl chloride (PVC) pipe. Each 2.75-m length of 10-cm (ID) PVC pipe was filled with 6 cm of pea gravel (at the bottom) and 250 cm of loamy sand. The basins, located in the dry Salt River bed near Phoenix, Ariz., had been intermittently flooded with secondary effluent for 4 years before the sand was removed for this study (Bouwer et al., 1974a, 1974b). A total of about 350 m of effluent was applied. The columns were intermittently flooded with effluent in the laboratory during various experiments for 2 additional years before conducting the experiments described in this report. The air-dried soil containing 3% clay, 8% silt, and 89% sand was packed so that average bulk densities for each column ranged from 1.5 to 1.6 g/cm^3. Slight differences in packing resulted in a range of infiltration rates of 15 to 50 cm/day. Infiltration rates for particular columns were varied by adding and then omitting pulses of sugar (100–200 ppm dextrose) during the first 2 days of each flooding cycle. The sewage effluent was applied with a Mariotte siphon to maintain a 15-cm constant pressure head at the soil surface. Details of the flow system have been described previously (Lance and Whisler, 1972; Lance et al., 1973).

Other 2.75-m-long columns were constructed by packing 15-cm (ID) pipe with a mixture of two parts sand from the field recharge basins and one part builders' sand from a location in the Salt River bed which had not been previously flooded with sewage water. These pipes were placed in an insulated building with the tops protruding through the roof. The soil was packed in the columns to the roof level (250 cm) so that the soil surface was exposed to the atmosphere. Six of the nine columns were planted with common bermudagrass (*Cynodon dactylon*). The sewage water reservoir was placed inside the building, where the temperature was maintained at 20 to 25C. An 8- to 10-cm head was maintained by a float device which activated a solenoid-switch pump system.

All columns were flooded on a schedule of 9 days flooding alternated with 5 days drying. The flow rate and cumulative flow through the columns were measured by weighing the outflow daily, and the cumulative outflow was sampled periodically. The sewage water and column samples were analyzed for orthophosphate with a Technicon AutoAnalyzer[3]. Total PO_4-P was determined periodically after adding concentrated sulphuric acid and potassium persulfate to water samples and heating at 121C for 30 min in an autoclave. Since differences in total PO_4-P and orthophosphate were small, all data reported are for orthophosphate. Calcium was determined by EDTA titration and fluoride by the SPADNS method (APHA, 1971).

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[3]Trade names and company names are included for the benefit of the reader and do not indicate endorsement or preferential treatment of the listed product by the USDA.

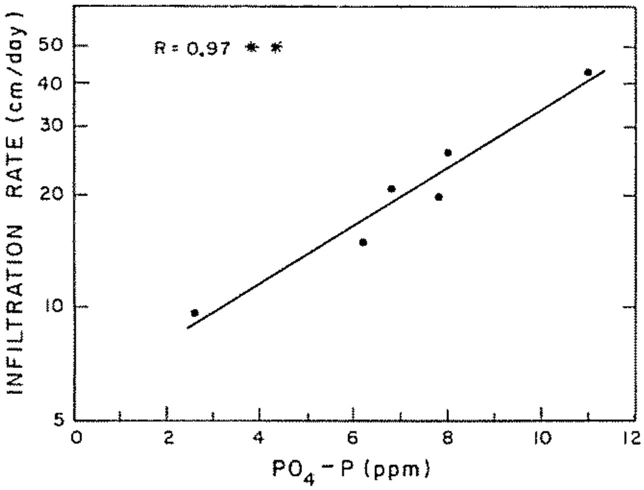

Fig. 1—Effect of infiltration rate on phosphate in water from soil columns intermittently flooded with sewage water containing 12.1 ppm PO_4-P. Data from each of six columns were averaged for 6 months of flooding on a schedule of 9 days flooding alternated with 5 days drying.

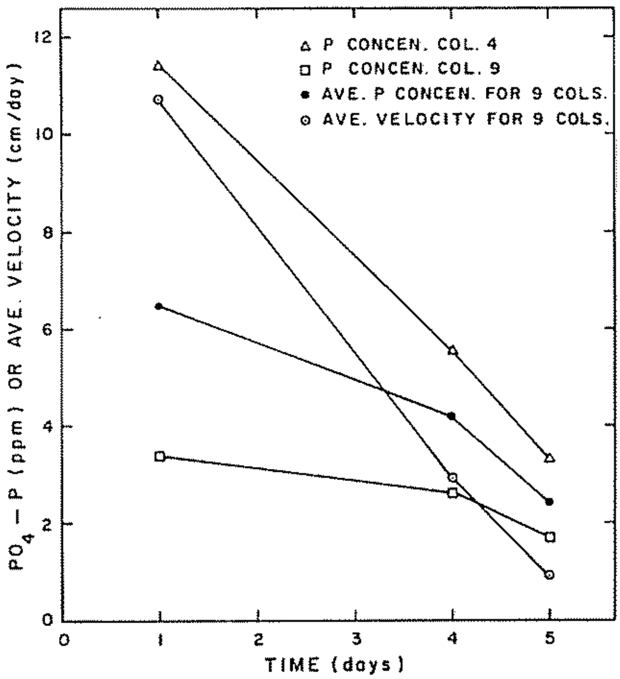

Fig. 2—Changes in phosphate concentrations and average velocity for water draining from soil columns during the drying period of a schedule of 9 days flooding alternated with 5 days drying.

RESULTS AND DISCUSSION

Phosphate Removal

Phosphate removal increased as the infiltration rate decreased (Fig. 1). The data from six columns packed with sand from the infiltration basins were averaged over a 6-month period when the mean PO_4-P content of the sewage was 12.1 ppm. The effect of flow velocity is further illustrated by the decrease in PO_4-P in the water draining from the columns for 5 days after the sewage application stopped (Fig. 2). The PO_4-P concentration in water draining from column 4, which had the highest flow velocity during the flooding period, declined rapidly as the flow velocity decreased during the drainage period. The PO_4-P concentration in drainage water from the other columns with lower velocities decreased more slowly. Average flow velocities of the different columns were similar during the drainage period when sewage was not applied, even though their flow velocities varied considerably during flooding.

Infiltration rates of laboratory columns flooded with sewage water decreased when a pulse of carbon (dextrose) was added to the sewage water, and then increased when

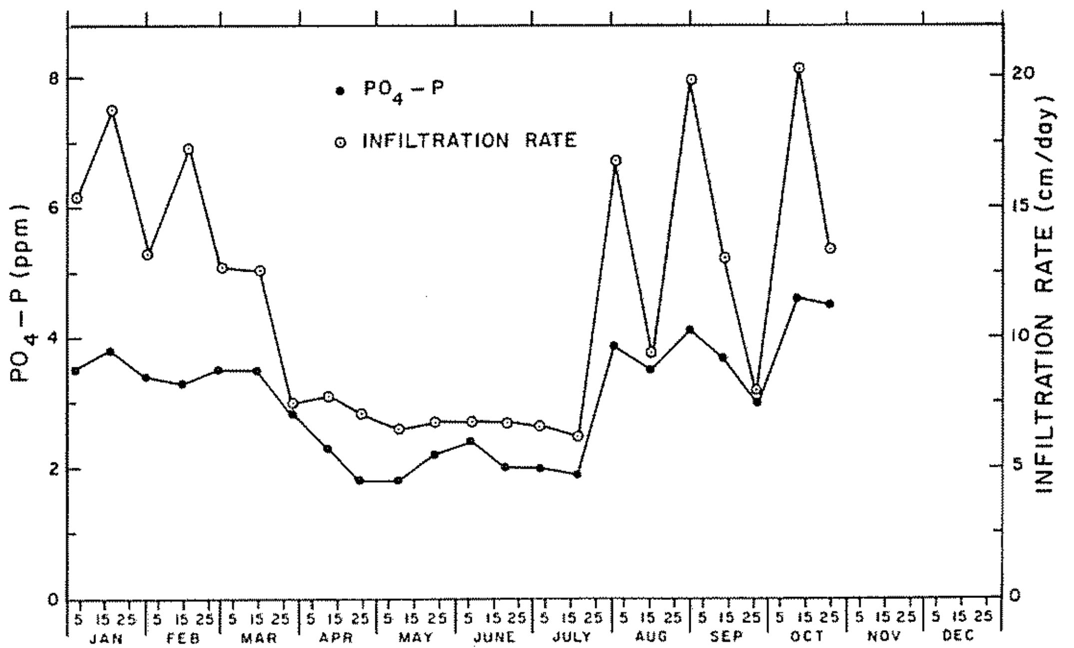

Fig. 3—Changes in phosphate concentration and infiltration rate with time for a soil column intermittently flooded with sewage water at low infiltration rates.

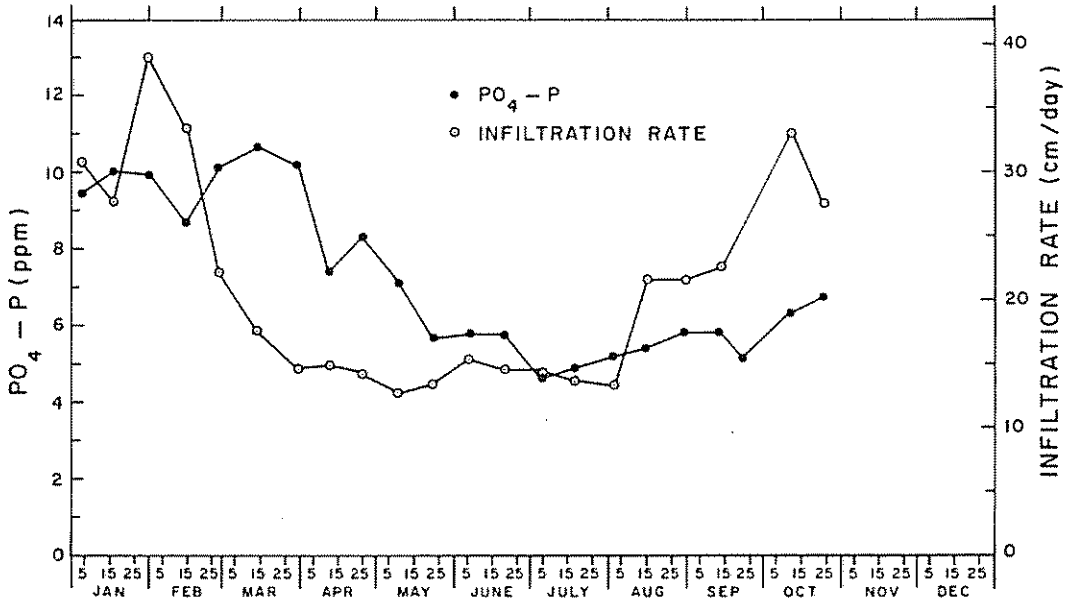

Fig. 4—Changes in phosphate concentration and infiltration rate with time for a soil column intermittently flooded with sewage water at high infiltration rates.

it was omitted. The PO_4-P in water outflow from these columns decreased to a lower equilibrium concentration when the infiltration rate decreased. When the infiltration rate returned to the higher level the equilibrium PO_4-P level also increased (Fig. 3 and 4). The column flooded at low infiltration rates (7 to 20 cm/day) responded rapidly to changes in infiltration rate (Fig. 3), while changes in PO_4-P concentrations for another column with higher infiltration rates (14 to 39 cm/day) lagged about three flooding cycles behind changes in infiltration rates (Fig. 4). The decrease in infiltration rate due to soil clogging when dextrose was added did not occur in still another soil column (for some unexplained reason), and the PO_4-P concentration did not decrease (data not shown). This showed that the decrease in the PO_4-P concentration in water from other columns was not due to a proliferation of microorganisms, and subsequent increase in microbial uptake of PO_4-P. Thus, the PO_4-P concentration seemed to be controlled by the detention time of the sewage water in the soil column, since the equilibrium PO_4-P concentration in water draining from the columns could be increased or decreased by increasing or decreasing the infiltration rate. The fact that PO_4-P removal could be increased by decreasing the infiltration rate after the soil has equilibrated with the sewage water at the higher rate suggested that this removal was more than a simple adsorption reaction.

Phosphate concentrations in water from columns packed with a mixture of two parts recharge basin sand and one part builders' sand, which had not been flooded with sewage water previously, were low (0.5 to 1.0 ppm) for > 200 days of flooding on a schedule of 9 days flooding alternated with 5 days drying. The PO_4-P concentration then increased and leveled off at equilibrium concentrations dependent upon the various infiltration rates (Fig. 5). At the high infiltration rate (22.3 cm/day), PO_4-P

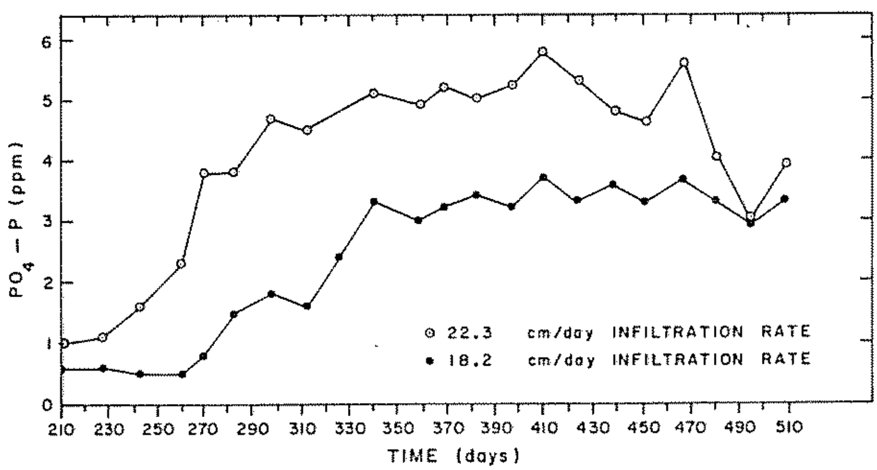

Fig. 5—Phosphate concentrations in water from soil columns containing some sand which had not been treated previously with sewage water. Flooding schedule was 9 days flooding and 5 days drying. Phosphate concentrations were below 1 ppm during the first 210 days of intermittent flooding.

concentrations increased more rapidly and reached a higher equilibrium level than those concentrations from a column with a lower infiltration rate (18.2 cm/day). The PO_4-P concentration from all columns decreased after about 460 days, due to a decrease in the PO_4-P concentration of the incoming sewage water. Phosphate removal was 90 to 95% for all columns for the first 200 days of intermittent flooding. Phosphate removal was 73 and 58% for the 18.2 and 22.3 cm/day infiltration rates, respectively, after the equilibrium levels were reached in water from the columns. (Based on 300- to 360-day period when PO_4-P of incoming sewage averaged 12.1 ppm.) About 35 m of sewage water was applied before the PO_4-P in the column effluent started to increase after 230 to 270 days. The beginning of the increase in PO_4-P depended upon the infiltration rate, which limited the total amount of sewage water applied.

Thus, the initial adsorption of PO_4-P by a soil mixture containing sand which had not been treated previously with sewage was not dependent upon the retention time. After the soil's initial adsorption capacity was saturated, PO_4-P continued to be removed by some time-dependent adsorption or precipitation reaction. During this latter phase of the experiment, these columns demonstrated a relationship between PO_4-P removal and infiltration rate similar to that of the columns packed with river bed sand that had been flooded previously with sewage water for several years.

Magdoff et al. (1974) reported a similar pattern of changes in PO_4-P concentrations with time in water from columns flooded with septic tank effluent. However, PO_4-P concentrations in water from their columns started to increase after only 20 days of flooding with 8 cm/day of effluent containing about 20 ppm PO_4-P. Their data also seem to show that columns with lower flood velocities removed more PO_4-P than similar columns with higher

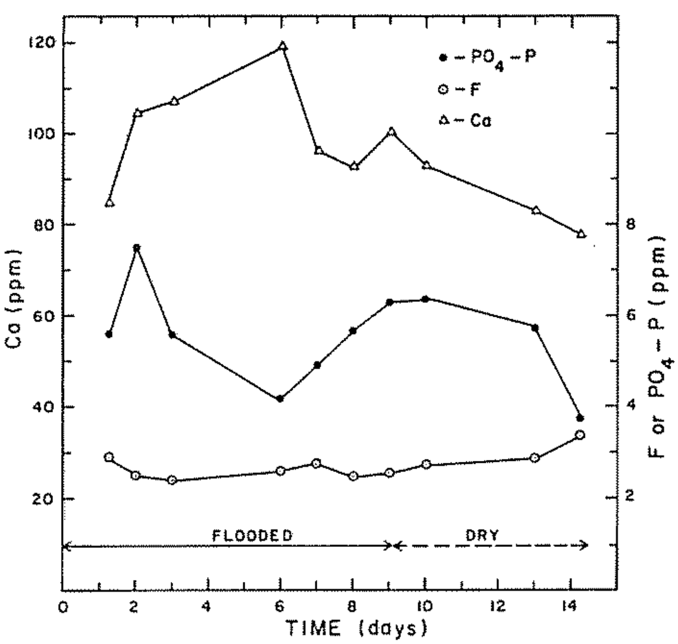

Fig. 6—Phosphate, Ca, and F concentrations in water draining from a soil column flooded with sewage water on a cycle of 9 days flooding followed by 5 days drying.

Table 1—Fluoride concentrations in outflow from soil columns flooded with sewage water containing 4.0 ppm F

Cycle	Column 1	2	3	4	5	6	7	8
	ppm							
1	2.2	2.4	2.6	2.4	2.4	2.7	2.5	2.7
2	2.2	2.3	2.5	2.5	2.6	2.6	2.4	2.6
3	2.5	2.5	2.5	2.6	2.7	2.6	2.4	2.5
Avg.	2.3	2.4	2.5	2.5	2.6	2.6	2.4	2.6
Avg. infiltration rate, cm/day	14	21	15	28	18	20	14	22

velocities, although they attributed differences in P removal to differences in Ca concentrations in the water moving through the column.

Comparisons with Other Ions

To study the PO_4-P removal reactions, fluctuations in phosphate concentrations of column effluent during the flooding and drying cycles were compared with corresponding changes in concentrations of other ions. The dip in PO_4-P concentration during the middle of the flooding period coincided with a peak in the Ca concentration (Fig. 6). A 2–3 ppm difference between the high and low PO_4-P concentrations during each flooding period was observed for columns that contained some soil which had not been previously flooded with sewage. A similar pattern of PO_4-P concentrations was observed in columns containing soils which had been flooded for several years, but the PO_4-P concentrations varied only 0.5 to 1 ppm. The Ca content of the sewage water was 55 ± 3 ppm, whereas that of the water samples from the columns was always higher, with the peak Ca concentrations in column samples usually more than twice that of the sewage samples. However, these analyses were for total Ca, and do not show how much Ca was present as Ca^{2+}.

Field observations indicated that PO_4-P removal might parallel F removal (Bouwer et al., 1974b). However, this did not apply for the soil columns in the present study; the F concentration varied only slightly during the flooding period. Also, F concentrations varied only slightly as infiltration rates increased (Table 1).

The dip in the PO_4-P concentration also corresponded exactly with the nitrate (NO_3-N) peak, which was measured near the beginning of each flooding period (Fig. 7), The NO_3-N was due to leaching of nitrate formed during the previous dry periods and, thus, can be used as tracer to indicate when the water applied at the beginning of the flooding period breaks through the outlet of the column. The lowest PO_4-P concentrations measured during the flooding period were in water which has been applied at the beginning of the flooding period. This would indicate that drying the soil restores some of its PO_4-P adsorption capacity. Regeneration of P sorption sites by alternate wetting and drying treatments has been reported for a number of soils (B. G. Ellis and A. E. Erickson. 1969. Mimeo Rep., Michigan State Univ., E. Lansing, Mich.; Sawhney and Hill, 1975). Therefore, decrease in the PO_4-P concentration could have been due to the Ca peak, or to some effect of drying, or to a combination of both factors.

Concentrations of Fe and Al ions were not measured in water from the columns. However, the pH of the sewage water was 7.5 to 8, and the pH of water samples taken from various column depths ranged from 7.3 to 7.5. It seems unlikely that Fe and Al compounds would significantly affect PO_4-P removal when a calcareous sand (4–6% $CaCO_3$ equivalent) was flooded with alkaline sewage water.

Phosphate Removal Mechanisms

These data indicate that PO_4-P probably was removed by adsorption when the soil was initially flooded with sewage water. After the soil adsorption capacity was saturated, removal continued by precipitation, probably as some form of calcium phosphate. Cole et al. (1953) reported that PO_4-P was adsorbed by $CaCO_3$ when low concentrations ($< 3 \times 10^{-4} M$) of PO_4-P were added to $CaCO_3$ suspensions. Dicalcium phosphate, or a similar compound, was precipitated at higher PO_4-P concentrations. Percolation studies showed a rapid initial sorption, followed by a secondary reaction which appeared 1 hour later and continued for several hours. They suggested that time was needed for a certain degree of nucleation before the precipitation rate became appreciable. Griffin and Jurinak (1973) concluded that the interaction of PO_4-P with a calcite surface is a heterogenous nucleation process. Enfield (1974) reported a rapid initial sorption, followed by a linear increase in the amount of PO_4-P sorbed with time between 10 and 300 hours, when samples of Chigley gravelly sandy loam were equilibrated with 100 ppm PO_4-P. The detention time in our soil columns ranged from about 40 to 160 hours. Thus, formation of nuclei could occur with time, and could account for the increased PO_4-P removal from sewage water as the detention time increased. This would be consistent with field data which showed that the PO_4-P concentration declined as the water moved laterally away from the recharge site.

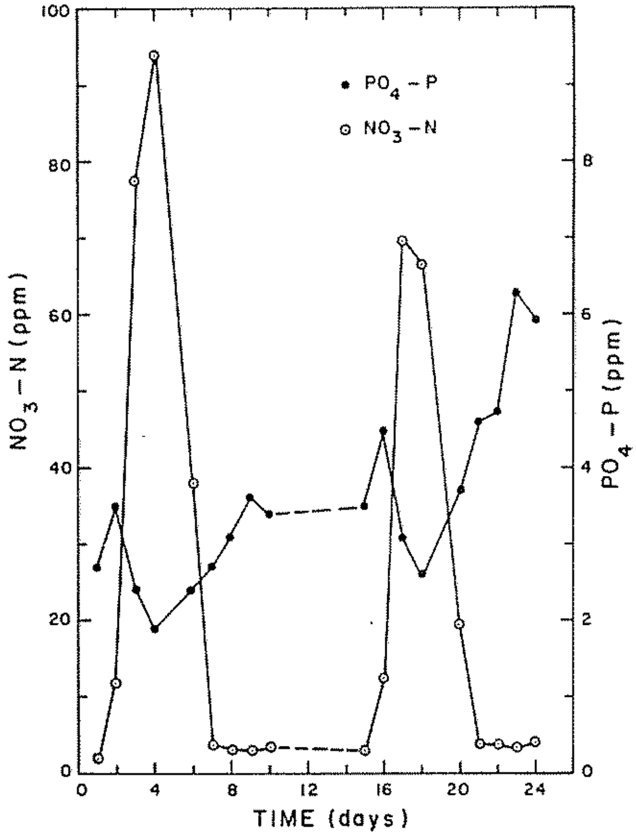

Fig. 7—Nitrate and phosphate concentrations in water from a soil column flooded on a schedule of 9 days flooding alternated with 5 days drying. The dashed line indicates the dry period.

Monitoring salt concentrations showed that this effect was not due to dilution (Bouwer et al., 1974b).

Adsorption of PO_4-P on $CaCO_3$, followed by precipitation of calcium phosphates after saturation of the adsorption capacity, is a model which would fit our data. How-

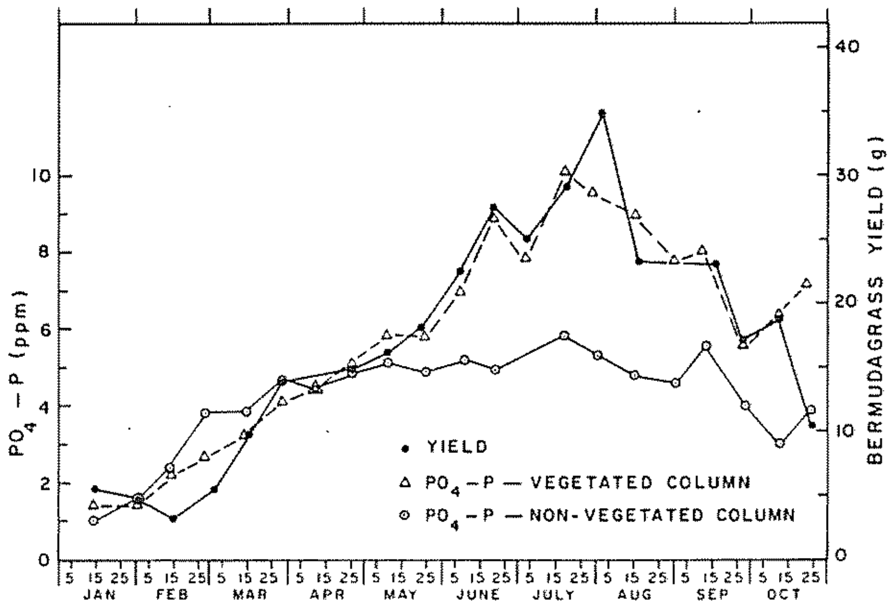

Fig. 8—Yield of Bermudagrass and phosphate concentrations in water from soil columns intermittently flooded with sewage water.

ever, more work on the nature of the phosphate compounds retained in the soil would be needed to test this model. It does seem clear that only precipitation of some form of calcium phosphates could account for the continued retention of several thousand kg/ha of PO_4-P per year in this soil. The PO_4-P precipitation may continue indefinitely, since approximately 250 m of sewage water and 60,000 kg/ha of PO_4-P have already been applied during 7 years of operation (field and laboratory) without exhausting the phosphate removal capacity. Apparently, the soil provides enough Ca to continue PO_4-P precipitation, since the water from the columns always contained 15 to 65 ppm more Ca than did the sewage water.

Effect of Vegetation

Bermudagrass greatly influenced the movement of PO_4-P through the soil columns. Phosphate concentrations in water from vegetated and nonvegetated columns with similar infiltration rates were nearly identical, until spring when the grass began to grow (Fig. 8). Then, PO_4-P concentrations in the effluent from vegetated columns increased rapidly. When plant yield of dry matter and PO_4-P concentration in column effluent were plotted vs. time, the curves were almost identical in shape. The plant roots evidently kept phosphate in solution. This might have been due to competition of organic ions with PO_4-P for adsorption sites, Ca chelation which reduced precipitation of calcium phosphates, Ca uptake by plants, a pH reduction in the rhizosphere, or a combination of these factors.

SUMMARY AND CONCLUSIONS

Phosphate removal from secondary sewage effluent by soil columns increased as the infiltration rate decreased. Phosphate concentrations in the effluent from columns packed with a mixture of sand which had never been treated with sewage, and recharge basin sand which had been flooded with sewage water for several years, were below 1 ppm for over 200 days, on a 9-day flooding and 5-day drying cycle. Then, PO_4-P concentrations increased and leveled off at different concentrations, depending upon the infiltration rate of the column. These concentrations remained relatively stable as long as the PO_4-P concentration in the incoming sewage water remained constant. After the PO_4-P level in water from a column was established, it could be increased or lowered by increasing or decreasing the infiltration rate.

These results indicated that when sand was initially flooded with sewage water, PO_4-P was adsorbed by a reaction independent of flow velocity or detention time. This adsorption capacity became saturated, and then PO_4-P was removed by an adsorption or precipitation reaction which was dependent on the detention time. The immediate response of some columns to changes in infiltration rate or flow velocity suggested a precipitation reaction.

Bermudagrass greatly increased the PO_4-P concentration in the column effluent. When dry matter yield and PO_4-P concentration were plotted vs. time, the two curves were almost identical in shape. The plant root exudates evidently kept phosphate in solution.

These results indicate that tremendous quantities of PO_4-P can be stored in a calcareous sand. Initially, about 90% of the PO_4-P could be removed from sewage water containing 12 ppm PO_4-P. After the initial absorption capacity is saturated, 75 to 80% of the applied PO_4-P can be removed by maintaining infiltration rates below 15 cm/day. Thus, these and previous experiments (Lance et al., 1976) showed that most of the N, P, organic C, and fecal bacteria were removed from sewage water when the soil was flooded intermittently at carefully controlled infiltration rates. The 15 cm/day infiltration rate results in the application of 35 m/year of sewage water, when alternating 9-day flooding periods with 5-day drying periods.

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