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PHOSPHORUS REMOVAL IN A PILOT SCALE TRICKLING FILTER SYSTEM BY --ETC(U)
JAN 78 R D MILLER, R S RYCZAK, A OSTROFSKY

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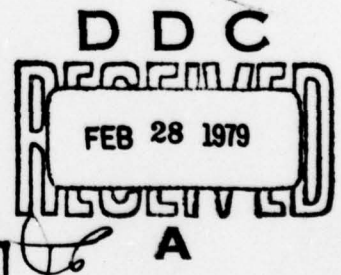
PHOSPHORUS REMOVAL IN A PILOT SCALE TRICKLING FILTER SYSTEM
BY LOW LEVEL LIME ADDITION TO RAW WASTEWATER

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2.46 cu m/day

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cont. → trickling filter system. Lime was added to a rapid mix tank prior to primary clarification at pH levels of 9.0, 9.5 and 9.8 entering the clarifier. Phosphorus precipitation, solid-liquid separation of the insolubilized phosphorus, nutrient levels entering the trickling filter, biological treatment efficiency, sludge production and sludge characteristics were all monitored. Ferric chloride and polyelectrolytes were tested for their effectiveness as flocculating aids in the solid-liquid separation of the insolubilized phosphorus. Results indicate that low level lime addition to raw wastewater in a trickling filter system can provide an effective simple-to-operate, cost-effective method of upgrading a plant to successfully comply with effluent limitations. ↗

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INTRODUCTION

Accelerated eutrophication is causing serious deterioration of much of the nation's fresh surface water resources. Many surface water supplies have already deteriorated, creating water supply and treatment problems. Aquatic biota and water recreation are adversely affected by accelerated eutrophication. Increased restrictions on water uses due to quality deterioration are attributed to the availability of critical nutrients which stimulate excessive algae and plant growth. Phosphorus has long been identified as one limiting nutrient. Man's wastewaters are primary sources of phosphorus in many surface water supplies; hence, control of wastewater discharges can be a key to controlling accelerated eutrophication. Research indicates that phosphorus is usually the limiting nutrient and the nutrient most amenable to removal by wastewater treatment systems.¹

Identification of phosphorus as a limiting nutrient, plus high phosphorus concentrations in wastewaters, have resulted in wastewater discharge limitations for phosphorus. Discharge limitations are embodied in the National Pollutant Discharge Elimination System (NPDES) within Public Law 92-500² and apply to all categories of wastewaters. Department of the Army installations must apply for and receive discharge permits for all wastewater discharges. In many cases, existing NPDES permits impose phosphorus limitations on Army produced wastewaters. It is anticipated that future NPDES permits will contain phosphorus limitations for a greater number of wastewater discharges than at present.

This report describes phosphorus removal studies undertaken to provide advanced wastewater treatment (AWT) technology applicable to US Army wastewater treatment facilities. A detailed review of phosphorus removal technology was conducted prior to initiating these studies and has been previously published.³ The review showed that technology provided must be capable of meeting current and future NPDES permit limitations. Although AWT technology exists, new approaches need investigation to more efficiently meet new requirements. Application of some AWT technology by actual facility design is currently underway; however, application of AWT technology in meeting US Army NPDES permit limitations is not yet well established. The review pointed out that Army wastewater treatment systems have special characteristics such as types of processes and flows, and that normal AWT technology may not apply or may need modification before it can be applied.

This research effort was directed primarily toward upgrading existing Army wastewater treatment facilities to meet NPDES permit limitations, as opposed to research directed toward completely replacing existing facilities. Considerations in research for design upgrade included maximum use of existing equipment and facilities, simplicity of operation and maintenance, and minimum laboratory support. Research objectives included

identification and assessment of a process with potential wide application to existing Army wastewater treatment systems and compatibility with other treatment unit processes.

RESEARCH APPROACH

In order to assess the impact of Public Law 92-500 on Army installations, a comprehensive review of NPDES permit limitations was conducted in early 1976 for many Army wastewater discharges. Of 78 installations reviewed, 49 had been issued NPDES permits for 64 wastewater discharges. Since Public Law 92-500 places limitations on wastewater discharges, but does not dictate methods of obtaining those limitations, the Army has alternatives of meeting stringent limitations by AWT wastewater treatment plus land application or connection to area wide systems. Of the 78 installations reviewed, 19 installations had all wastewater discharges connected to municipal/area wide systems. Feasibility studies for land application had been conducted at 14 installations, but pursuit of land application as a means of meeting NPDES permit limitations had ceased at most of those installations for a variety of reasons. Of the alternatives for stringent limitations, AWT would be necessary in most cases.

Of the 64 NPDES permits reviewed, 37 required only secondary treatment while 27 contained more stringent limitations. AWT was the only alternative in most cases. More specific data on the 27 permits containing stringent limitations (AWT requirements) are presented in Table 1. Phosphorus removal was indicated for more than one-third of those wastewaters having AWT requirements. The wastewater discharge limitations for phosphorus showed a range (as P) of 0.2 to 2.0 mg/l with a mode of 1.0 mg/l. Data are for NPDES permits after 1 July 1977 and prior to 1980. New NPDES permits will be issued for the 1980's.

Army wastewater treatment systems consist primarily of trickling filters as secondary treatment processes, a few activated sludge systems and several extended aeration package plants. The Army has unique situations in which treatment plants are often flow underloaded due to decreases in size of the Army population during peacetime. Also, consolidation of activities from several installations to only one installation, summer training of Reserve and National Guard troops, and maneuvers of troops can cause drastic seasonal changes in loadings on treatment plants. Drastic diurnal changes in loadings can be caused by civilian work forces that contribute wastes during normal working hours but not at other times. In addition, post staffing of Army treatment plants (most plants are 0.1 to 5.0 mgd) has dictated the need for simplicity of operation and maintenance. Therefore, AWT techniques applied to municipal wastewater treatment systems may not be applicable to Army treatment systems.

TABLE 1. WASTEWATER DISCHARGE PERMITS REQUIRING ADVANCED TREATMENT
(64 PERMITS REVIEWED)

P	NH ₃ -N	Total N	BOD	SS	Total
2	-	-	-	-	2
-	2	-	-	-	2
4	4	4	4	4	4
1	1	-	1	1	1
-	5	-	5	-	5
2	2	-	2	-	2
2	-	-	2	2	2
-	1	-	1	1	1
-	-	-	8	8	8
—	—	—	—	—	—
Total 11	15	4	23	16	27

Technology assessment included a literature review of state-of-the-art of phosphorus removal technology.^{3,4} Recommendations were made concerning process selection, applicability and research needs for Army installations.³ A summary of pertinent phosphorus removal technology is presented herein; the reader is referred to references 3 and 4 for more details.

Domestic sewage contains roughly 5 to 20 mg/l phosphorus (as P). About 50 percent of this will be in the ortho form, 40 percent in an inorganic condensed form and 10 percent organically bound. Detergents contribute 20 to 70 percent of the phosphorus in domestic wastewater. The inorganic condensed and organic forms are partially converted to the ortho form as the phosphorus moves through a treatment plant.

Biological removal of phosphorus occurs in trickling filters and activated sludge plants through microbial action. Microorganisms adsorb the phosphorus (usually in the ortho form) and incorporate it into new cell mass. The cell mass is removed and treated by solid waste disposal techniques. Overall phosphorus removal depends on the phosphorus capacity of the cells, the rate of uptake, the rate of cell growth and cell wastage. Expected removals across a trickling filter are 20 to 30 percent while an activated sludge plant can expect to remove 30 to 50 percent.

Phosphorus can be removed from a wastestream and incorporated into a sludge by chemical precipitation. The use of lime, alum, sodium aluminate and iron salts to precipitate phosphorus is common practice in wastewater treatment. The chemicals are used in full scale plants in several different flow schemes. Expected effluent concentrations from a chemical-physical process are from 0.5 to 2.0 mg/l total phosphorus (as P).

Chemical-physical techniques are most successful with the orthoform. Phosphorus removal using lime is a function of pH and alkalinity. Alum, aluminate and iron salt dosages depend on phosphorus concentrations and alkalinity. Successful lime treatment is accomplished at pH levels greater than 9.0. Alum is most successful at pH levels of 5.7 to 6.3. Ferrous salts are successful near the pH of 8.0 while ferric salts are more effective in the pH range of 4.0 to 5.0. Control of a lime feed system requires only pH monitoring, while alum and iron doses should be made in a proportion to the influent phosphorus concentration. Consequently, a lime precipitation scheme is the simplest of the three chemical schemes commonly used. Alum and iron salts could be dosed at one set level, or based on daily jar tests. However, fluctuating phosphorus levels result in significant chemical wastage in such a control scheme.

Although physical-chemical treatment to remove phosphorus can be operated as a separate system, the usual method is to combine chemical treatment with a biological system. Chemical-biological removal is accomplished with the same chemicals used in purely chemical-physical removal. The chemicals can be added to raw, degrittied sewage; to the primary effluent; to the aeration tank or trickling filter; to the secondary clarifier influent or effluent. The choice of chemical and point of addition depend on effluent standards, alkalinity, pH, sludge dewatering, sludge disposal, chemical costs and chemical availability. A chemical-biological process can produce effluent phosphorus levels of 1.0 mg/l total phosphorus (as P) consistently. Should effluent levels of 1.0 mg/l or less be required, a filtration step following the secondary clarifier, or tertiary clarifier, can be added to produce phosphorus levels as low as 0.2 mg/l total phosphorus (as P).

The addition of a chemical precipitation process will increase overall sludge production. Sludge handling, dewatering and disposal properties will also change. These properties depend on the chemical used and the point of chemical application. Sludge dewatering and disposal can contribute 30 percent of initial capital costs and up to 50 percent of annual operating costs in a secondary plant. Consequently, process selection efforts must consider the amount and nature of additional solids produced for each scheme considered.

From combined reviews of the literature, Army NPDES permits, and existing Army wastewater treatment facilities, it was concluded that phosphorus removal in Army wastewater treatment plants should be limited to chemical precipitation techniques using lime, iron salts, or aluminum salts plus adjunct materials for effective solid-liquid separation. Further, it was concluded that lime addition to pH levels below 10.0 (i.e., low level lime addition) should be a prime candidate for phosphorus removal due to the simplicity of process control, reliability, economic desirability and potential effectiveness.

Low level lime addition has recently been applied prior to activated sludge aeration basins with favorable results.⁴ The point of addition is to the raw, degrittied sewage and the pH is elevated to 9.5 to 10.0. Review of the literature yielded no applications or studies of low level lime addition prior to a trickling filter. Lime addition has traditionally been associated with higher pH levels and a recarbonation requirement. Activated sludge aeration basins contain enough buffering capacity due to microbial activity to reduce the elevated pH to a reasonable level for biological treatment, normally below pH 8.5. The buffering capacity of trickling filters is generally regarded as too little for much pH adjustment. Subsequently, lime addition has not been previously attempted for use in trickling filter systems except as a tertiary process employing higher pH levels and a recarbonation requirement.

PURPOSE

The purpose of this study was to evaluate phosphorus removal in a trickling filter system by low level lime addition to raw wastewater. Phosphorus removal, trickling filter performance, recarbonation requirement, and need for adjunct materials for floc formation and solid-liquid separation were evaluated. Characteristics of the low level lime addition process such as ease of process control, reliability, and effectiveness were to be verified. Adjunct materials including polyelectrolytes, clay and ferric chloride were tested as aids in solid-liquid separation. The main criterion for phosphorus removal was that 2.0 mg/l total phosphorus (as P) in the wastewater effluent would indicate an effective process, while 1.0 mg/l would indicate a highly effective process.

MATERIALS AND METHODS

Laboratory studies were used to initially evaluate phosphorus precipitation by lime. The pH level at which phosphorus became insolubilized, and the lime dose required, were primary factors to be observed. Laboratory studies were followed by pilot-scale evaluations. Pilot-scale studies were conducted only on selected laboratory tests. The use of adjunct material for effective solid-liquid separation was also evaluated at the laboratory level, and only briefly tested at the pilot-scale level.

Laboratory Studies

Laboratory studies were conducted on primary clarifier influent to determine pH and lime doses to be evaluated at the pilot scale. During pilot studies, laboratory investigations continued with studies of coagulant and flocculant aids. Two high molecular weight anionic polymers were evaluated for solid-liquid separation. Ferric chloride was tested for both solid-liquid separation and pH reduction. Three clays (sodium

saturated montmorillonite, calcium saturated montmorillonite and Kaolinite) were studied as weighting agents to assist in solid-liquid separation. Laboratory studies were also done under elevated condensed phosphate levels and, separately, under elevated alkalinity levels.

Laboratory studies were conducted with a Phipps and Bird jar test apparatus which allowed six samples to be stirred in identical fashion. The speed of the stirring paddles could be controlled at a constant rate anywhere between 10 to 100 rpm. Sample sizes of 1000 ml were used and were placed in 2000 ml beakers. Chemical addition of lime, polymers and clay for various studies were made from stock slurries. Jar test procedures included a 3-minute rapid mix at 100 rpm, 20 minutes of flocculation at 20 rpm followed by 20 minutes of quiescent settling. Studies without flocculation used a 10-minute rapid mix followed by 30 minutes of quiescent settling.

Pilot Studies

Lime dosing prior to primary sedimentation was evaluated at pilot scale by adjusting pH levels to 9.0, 9.5 and 9.8. Figure 1 summarizes the operating conditions of pilot scale evaluations. A relatively constant flow of 1200 gpd was applied to the primary clarifier for all phases of the study. Primary clarifier detention time was approximately 75 minutes with a 200 gpd/sq ft overflow rate. An average of 800 gpd of primary effluent was applied continuously to the trickling filter for a surface loading rate of 350 gpd/sq ft or 15.5 million gallons per acre per day. Filter recycle averaged 400 gpd. The secondary clarifier received 700 gpd of trickling filter effluent for a detention time of 60 minutes and a 200 gpd/sq ft surface overflow rate. Clarifier solids were wasted daily. System performance was evaluated for 6 weeks at the 9.0 pH level. Two weeks acclimatization preceded 6 weeks of evaluation at the 9.5 pH level. Three weeks of operation at pH 9.8 was followed by 1 week of clay addition and 1 week of sludge recycle. An iron salt was evaluated as a flocculant aid both with and without flocculation in the primary sedimentation basin. All adjunct material studies were conducted at a 9.5 pH level.

Pilot studies used domestic wastewater from the Fort Detrick housing area. The wastewater was shredded by a grinder pump and pumped into a 250 gallon equalization tank which was periodically replenished through a float level switch control. This enabled an essentially constant flow of partially settled wastewater to be pumped to the primary clarifier. Primary effluent was collected in a wet well and pumped to the filter to provide a constant hydraulic load. The wastewater was sprayed continuously over the 2-inch irregular stone media onto 2.25 square feet of filter surface. Effective media depth was 4 feet. Effluent was collected at the bottom of the filter in a wet well and pumped to the secondary clarifier.

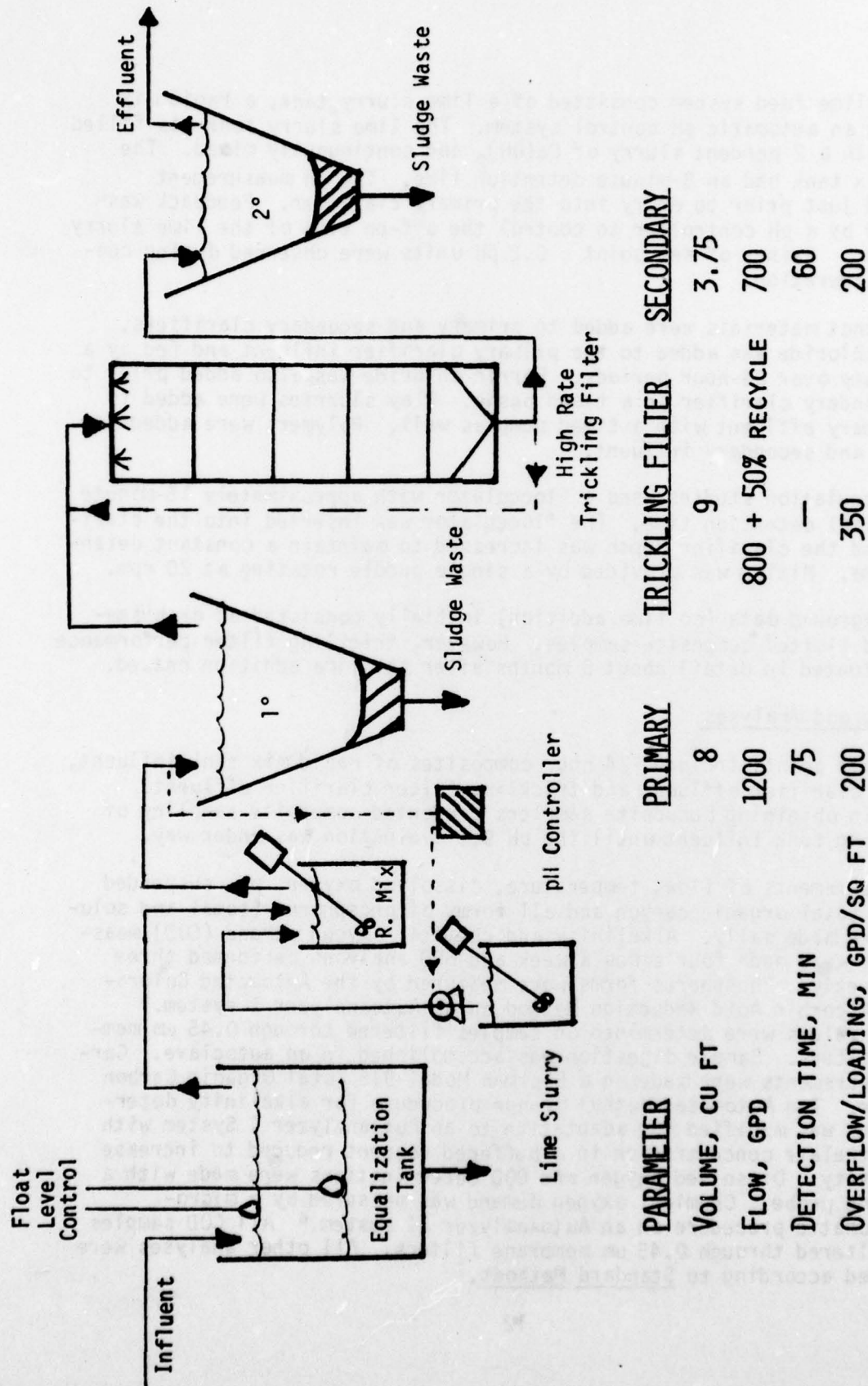


Figure 1. Experimental Conditions.

The lime feed system consisted of a lime slurry tank, a rapid mix tank and an automatic pH control system. The lime slurry tank was filled daily with a 2 percent slurry of Ca(OH)_2 and continuously mixed. The rapid mix tank had an 8-minute detention time. The pH measurement occurred just prior to entry into the primary clarifier. Feedback was employed by a pH controller to control the off-on time of the lime slurry feed pump. Swings of set point ± 0.2 pH units were observed during controller operation.

Adjunct materials were added to primary and secondary clarifiers. Ferric chloride was added to the primary clarifier influent and fed by a timed pump over 24-hour periods. Ferric chloride was also added prior to the secondary clarifier on a timed basis. Clay slurries were added to the primary effluent with a timed pump as well. Polymers were added to primary and secondary influent.

Flocculation studies used a flocculator with approximately 15-minute theoretical detention time. The flocculator was inserted into the clarifier, and the clarifier depth was increased to maintain a constant detention time. Mixing was provided by a single paddle rotating at 20 rpm.

Background data (no lime addition) initially consisted of grab samples and limited composite samples. However, trickling filter performance was evaluated in detail about 8 months after the lime addition ceased.

Sampling and Analyses

Sample points included 24 hour composites of rapid mix tank influent, primary clarifier effluent and trickling filter clarifier effluent. Delays in obtaining composite samplers prevented composite sampling of the mixing tank influent until the pH 9.5 evaluation was under way.

Measurements of flow, temperature, dissolved oxygen, pH, suspended solids, total organic carbon and all forms of phosphorus (total and soluble) were made daily. Alkalinity and chemical oxygen demand (COD) measurements were made four times a week and BOD analyses performed three times weekly. Phosphorus forms were measured by the Automated Colorimetric Ascorbic Acid Reduction Method on an Autoanalyzer I system.⁵ Soluble values were determined on samples filtered through $0.45 \mu\text{m}$ membrane filters. Sample digestion was accomplished in an autoclave. Carbon measurements were made on a Beckman Model 915 Total Organic Carbon Analyzer. The Automated Methyl Orange procedure for alkalinity determinations was modified for adaptation to an Autoanalyzer I System with acid phthalate concentration in a buffered reagent reduced to increase sensitivity. Dissolved oxygen and BOD determinations were made with a meter and probe. Chemical oxygen demand was measured by a micro-semiautomatic procedure on an Autoanalyzer II system.⁶ All COD samples were filtered through $0.45 \mu\text{m}$ membrane filters. All other analyses were performed according to Standard Methods.⁷

RESULTS AND DISCUSSION

The pH levels selected for trickling filter performance evaluation were based on preliminary jar tests using lime for phosphorus removal. A total of eight preliminary jar tests were run over a period of about 1 month on separate primary influent grab samples. Figure 2 shows a typical jar test result. Lime was added to give the indicated pH, and the jar tests were conducted as explained previously in the "Materials and Methods" section using no flocculation. Soluble phosphorus was reduced to about 1.0 mg/l at pH 9.5 and less than 1.0 mg/l at pH 10.0. These levels of soluble phosphorus reduction were considered to be highly effective for obtaining total phosphorus levels of 1.0 mg/l (as P) after biological treatment. The biological treatment process was expected to remove about 0.5 to 1.0 mg/l total phosphorus (as P) due to biological synthesis as explained in an earlier section. Soluble phosphorus was reduced only to about 3.0 mg/l at pH 9.0. However, additional phosphorus reduction through biological synthesis and the capability for precipitation after the biological process made pH 9.0 a potentially effective pH level. Therefore, the pH levels selected for evaluation at pilot scale became pH 7.1 (neutral), pH 9.0, pH 9.5, and pH 9.8.

Figure 2 shows that the insolubilized phosphorus (unfiltered minus filtered phosphorus) did not settle well. For the treatment process to be successful, the insolubilized phosphorus would have to be removed prior to the biological process. The best method to remove the insolubilized phosphorus appeared to be through the use of flocculation and/or coagulant aids such as polymers, salts of aluminum and iron, and weighting agents such as clay. Laboratory studies were continued in an effort to evaluate the effectiveness of flocculation and coagulant aids for solid-liquid separation. Pilot studies were begun using lime alone to evaluate phosphorus removal and trickling filter performance at the selected pH levels. Additional pilot studies were conducted later based on outcome of laboratory studies for effective solid-liquid separation.

Results of all pilot studies are listed in the Appendix. The pilot trickling filter system was operated without chemical addition, with lime addition to pH 9.0, 9.5 and 9.8, and with lime addition plus flocculation and coagulant aids for solid-liquid separation. Coagulant aids tested at pilot level included ferric chloride and polymer with and without flocculation in the primary sedimentation basin and secondary sedimentation basin. Analyses included total, ortho, and hydrolyzable phosphorus. Organic phosphorus can be calculated as total phosphorus minus ortho and hydrolyzable phosphorus. Both filtered and unfiltered phosphorus analyses were conducted. Chemical oxygen demand, total organic carbon, and biochemical oxygen demand analyses were conducted to evaluate trickling filter performance by organic carbon removal. Alkalinity, pH, suspended solids, settleability, temperature and flow were measured to evaluate the effects of phosphorus removal and trickling filter performance.

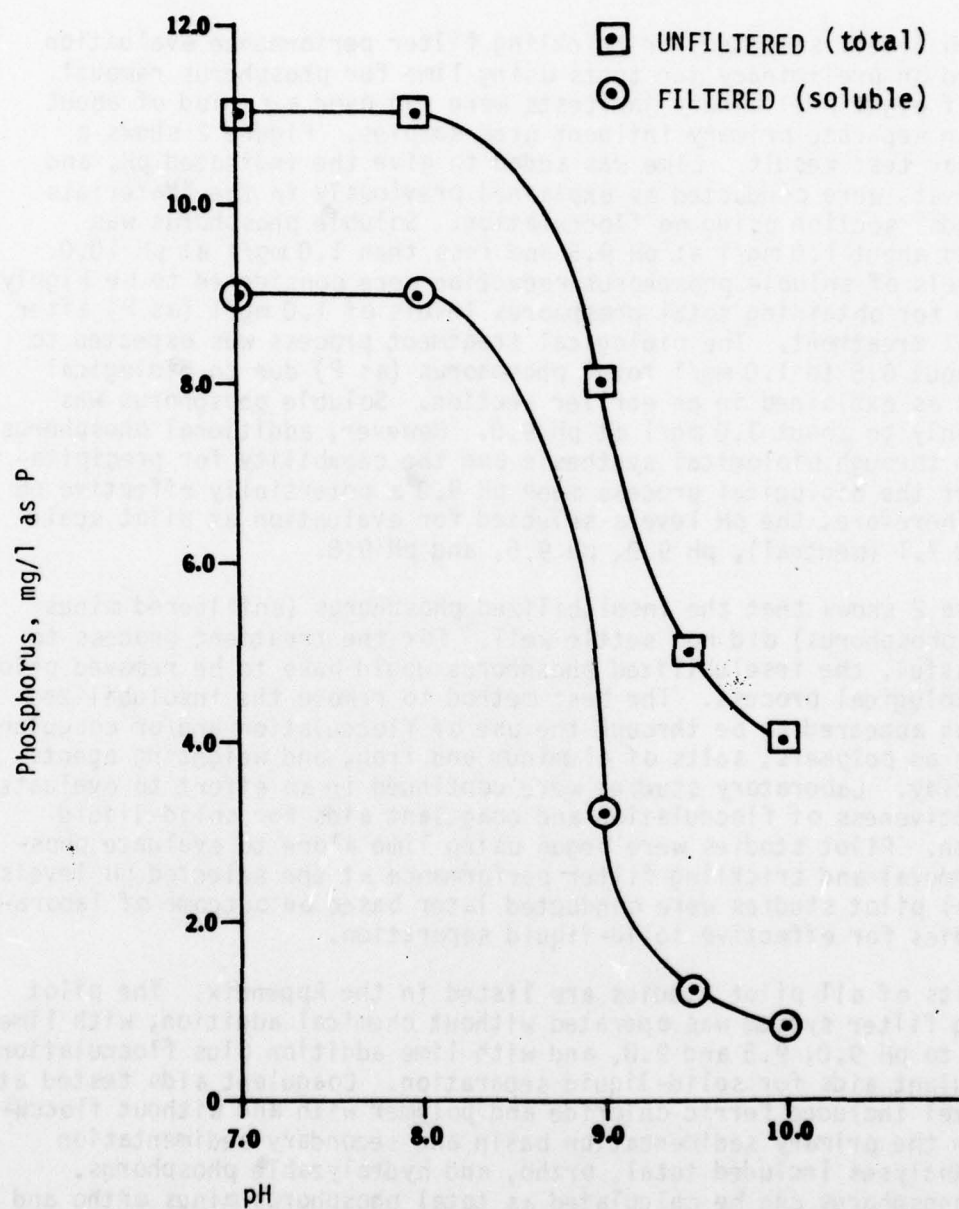


Figure 2. Typical Jar Test Result, Lime Addition to Primary Influent.

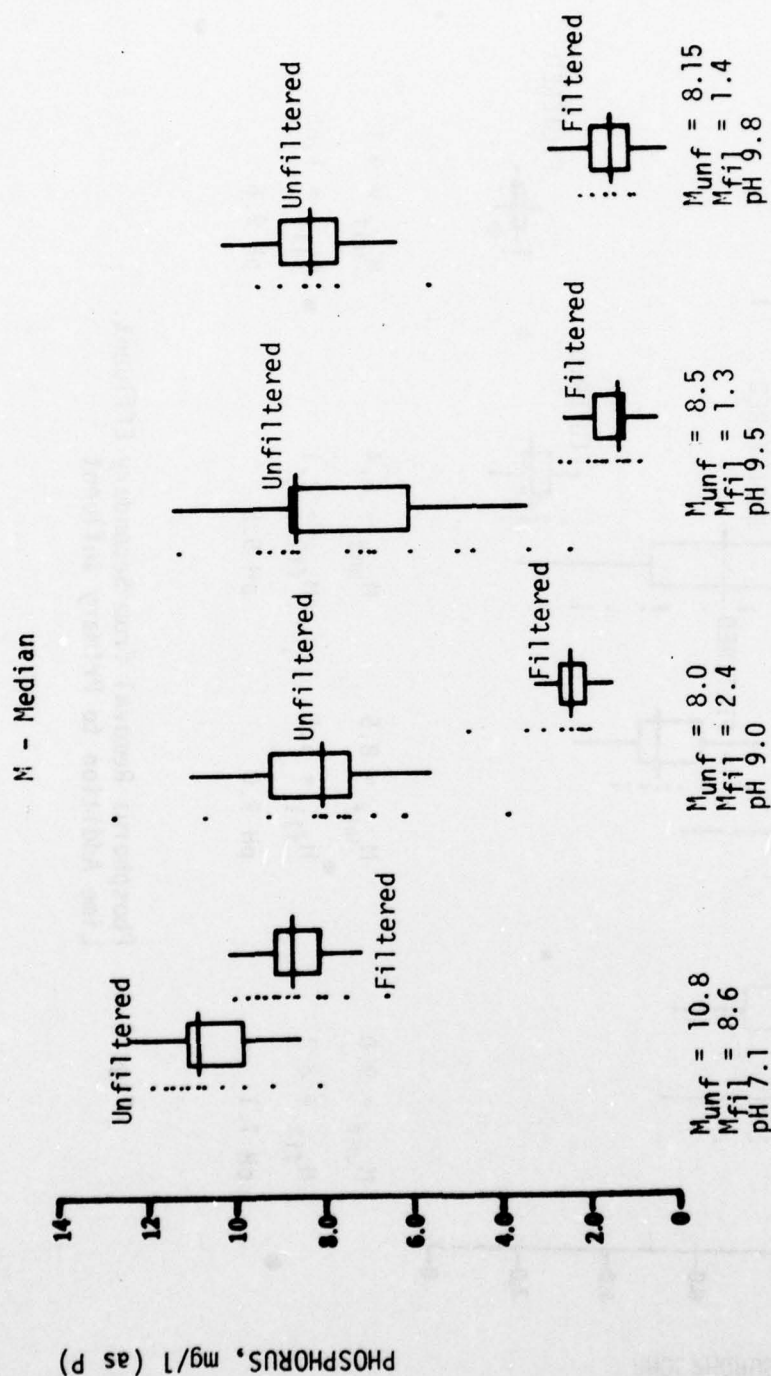


Figure 3. Phosphorus Removal from Primary Effluent Using Lime Addition to Primary Influent

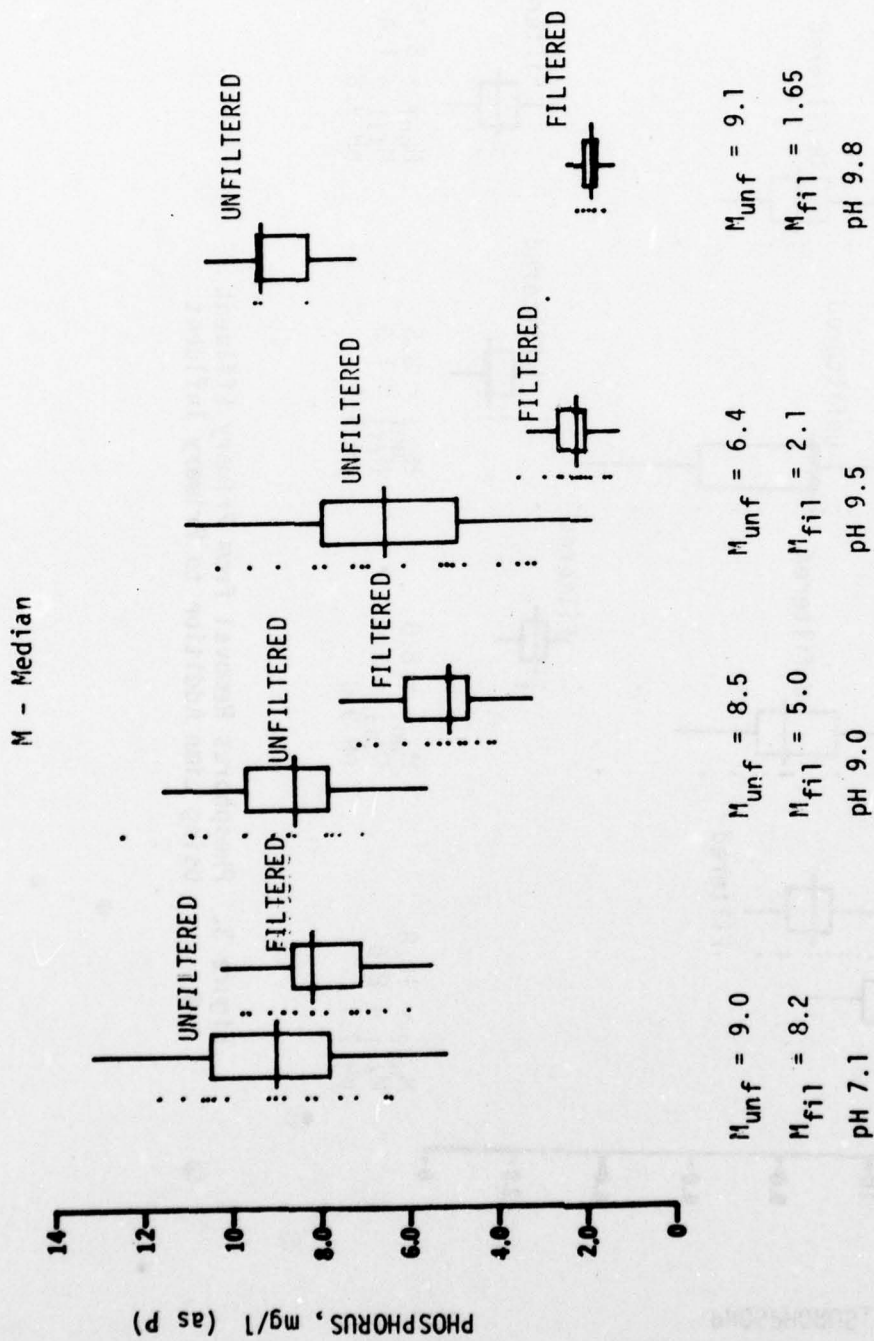


Figure 4. Phosphorus Removal from Secondary Effluent,
Lime Addition to Primary Influent

TABLE 2. HYPOTHETICAL PHOSPHORUS REMOVAL SYSTEM

Process/Location	Chemical Added	pH	Phosphorus Level, mg/l
Raw wastewater		7.0	10.0
Rapid mix ^a Flocculation ^a	Lime Coagulant aid	9.5	
Primary sedimentation			1.5-2.0
Biological process (Trickling filter, activated sludge, or rotating biological contactors)		7.5-8.5	0.5-1.5
Rapid mix ^a Flocculation ^a	Coagulant aid	7.2-8.0	
Secondary sedimentation			0.2-0.8
Filtration ^a			0.1-0.3

a. Processes not currently part of secondary treatment plants.

phosphorus concentrations when flocculation was used. No noticeable reductions occurred in the absence of flocculation. Clays were also tested for their effect in solid-liquid separation. Clays tested included Kaolinite and montmorillonite (bentonite). Bentonite produced 70 to 90 percent phosphorus reductions at clay dosages of 500 to 1000 mg/l, while Kaolinite showed no noticeable reductions. The use of clays and polymers gave results similar to the use of clay alone. Clay dosages up to 200 mg/l showed no improvement in total phosphorus removal. The high dosages of clays required for effective solid-liquid separation were considered unreasonable for plant operations due to the solids produced.

Ferric chloride was evaluated as a coagulant aid to improve solid-liquid separation. Laboratory studies were conducted at iron doses of 2.0, 5.0 and 10 mg/l (as Fe). Jar tests were conducted using flocculation and using no flocculation. Figure 5 shows the results of ferric chloride addition as a coagulant aid using flocculation. The wastewater used in the jar tests was primary influent grab sample that had been treated to the indicated pH using lime. Total phosphorus was reduced to less than 1.0 mg/l at iron doses of 5 mg/l or greater when added to lime treated primary effluent at pH 9.7. Figure 6 shows the results of ferric

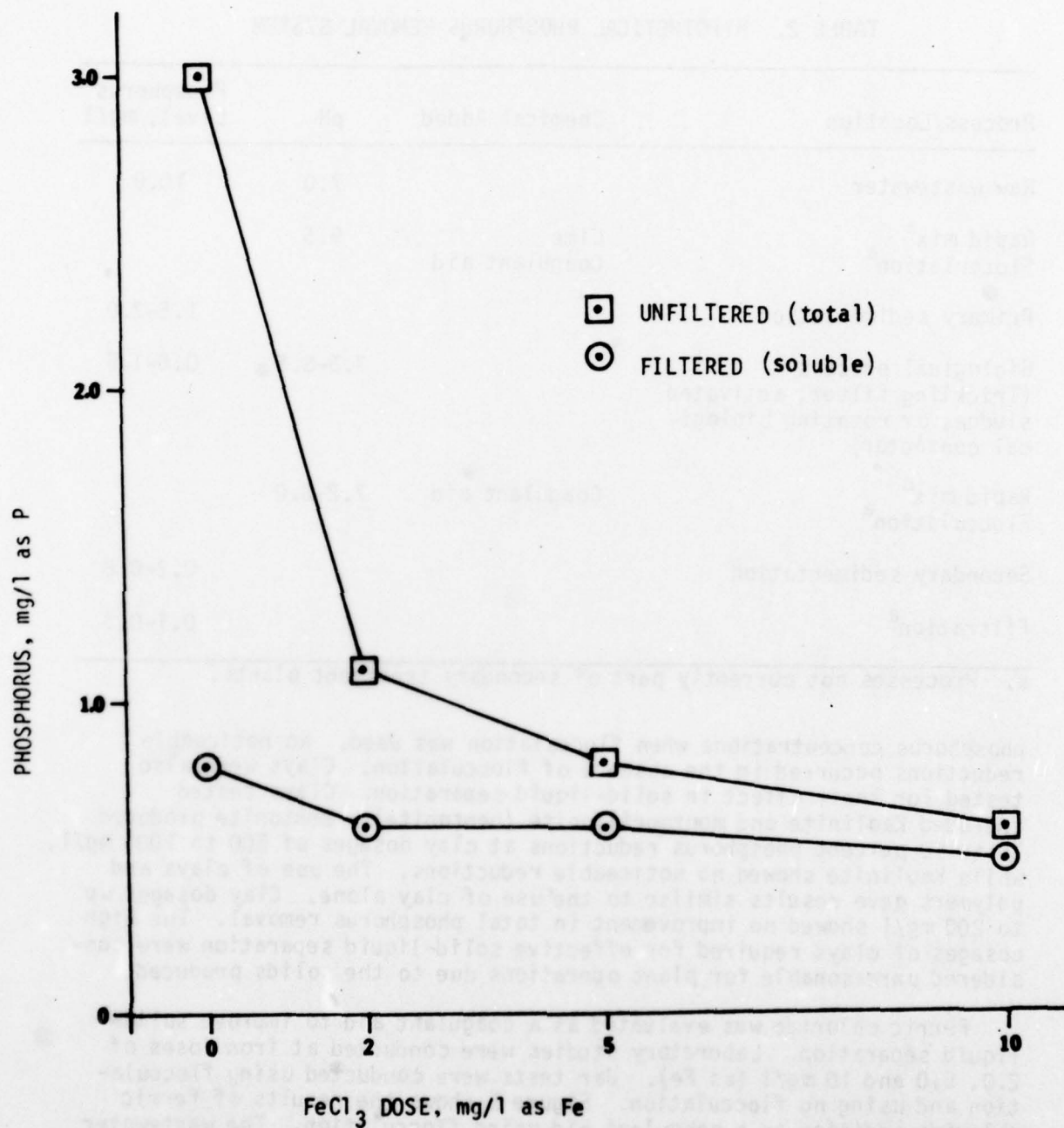


Figure 5. Jar Test Using Ferric Chloride as Coagulant Aid, pH 9.7, Primary Influent.

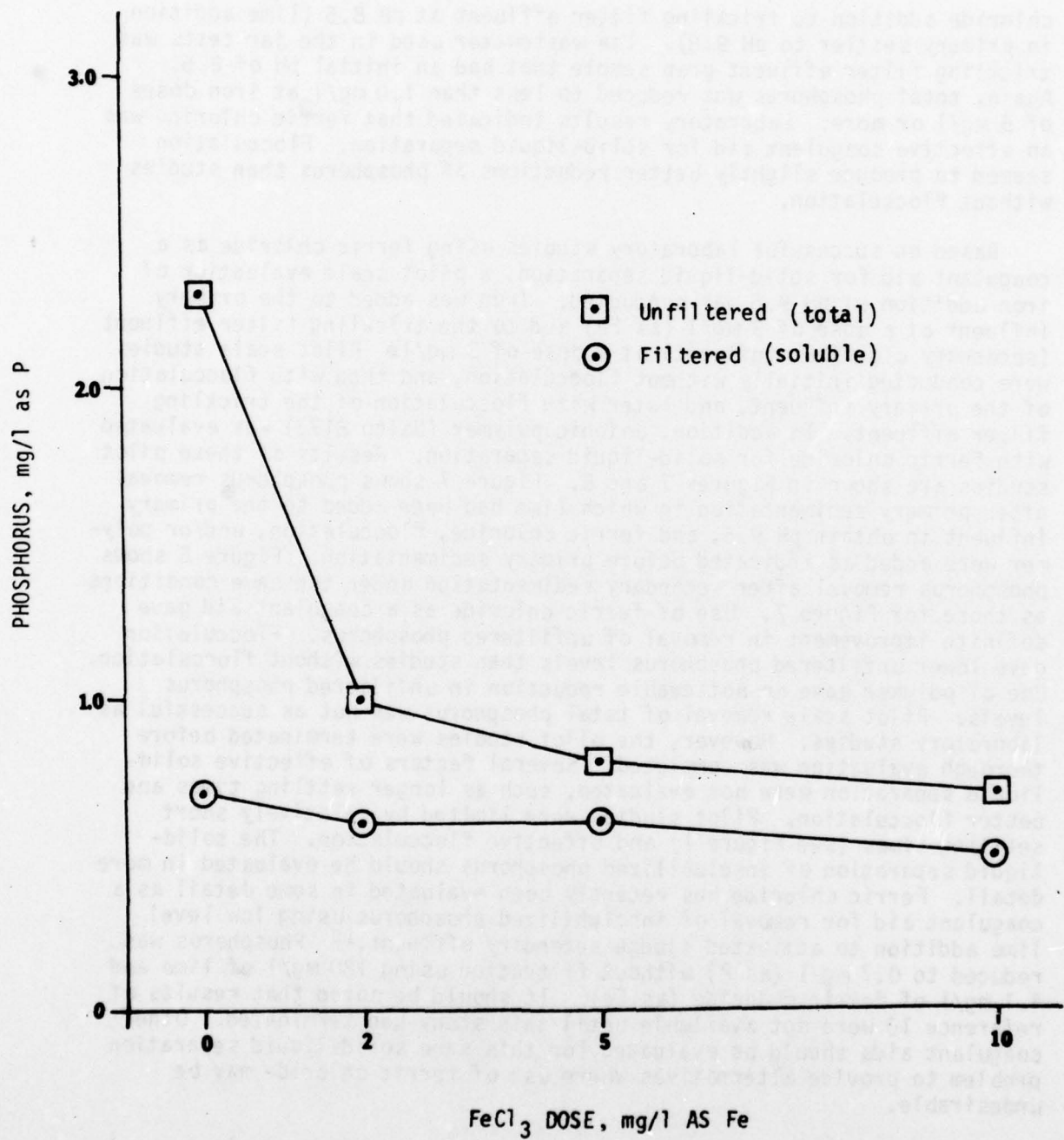


Figure 6. Jar Test Using Ferric Chloride as Coagulant Aid, pH 8.5, Trickling Filter Effluent.

chloride addition to trickling filter effluent at pH 8.5 (lime addition in primary settler to pH 9.8). The wastewater used in the jar tests was trickling filter effluent grab sample that had an initial pH of 8.5. Again, total phosphorus was reduced to less than 1.0 mg/l at iron doses of 5 mg/l or more. Laboratory results indicated that ferric chloride was an effective coagulant aid for solid-liquid separation. Flocculation seemed to produce slightly better reductions of phosphorus than studies without flocculation.

Based on successful laboratory studies using ferric chloride as a coagulant aid for solid-liquid separation, a pilot scale evaluation of iron addition at pH 9.5 was conducted. Iron was added to the primary influent at a dose of 5 mg/l (as Fe) and to the trickling filter effluent (secondary clarifier influent) at a dose of 3 mg/l. Pilot scale studies were conducted initially without flocculation, and then with flocculation of the primary influent, and later with flocculation of the trickling filter effluent. In addition, anionic polymer (Nalco 8173) was evaluated with ferric chloride for solid-liquid separation. Results of these pilot studies are shown in Figures 7 and 8. Figure 7 shows phosphorus removal after primary sedimentation in which lime had been added to the primary influent to obtain pH 9.5, and ferric chloride, flocculation, and/or polymer were added as indicated before primary sedimentation. Figure 8 shows phosphorus removal after secondary sedimentation under the same conditions as those for Figure 7. Use of ferric chloride as a coagulant aid gave definite improvement in removal of unfiltered phosphorus. Flocculation gave lower unfiltered phosphorus levels than studies without flocculation. Use of polymer gave no noticeable reduction in unfiltered phosphorus levels. Pilot scale removal of total phosphorus was not as successful as laboratory studies. However, the pilot studies were terminated before thorough evaluation was completed. Several factors of effective solid-liquid separation were not evaluated, such as longer settling times and better flocculation. Pilot studies were limited by relatively short settling times (see Figure 1) and effective flocculation. The solid-liquid separation of insolubilized phosphorus should be evaluated in more detail. Ferric chloride has recently been evaluated in some detail as a coagulant aid for removal of insolubilized phosphorus using low level lime addition to activated sludge secondary effluent.¹⁰ Phosphorus was reduced to 0.7 mg/l (as P) without filtration using 180 mg/l of lime and 4.1 mg/l of ferric chloride (as Fe). It should be noted that results of reference 10 were not available until this study had terminated. Other coagulant aids should be evaluated for this same solid-liquid separation problem to provide alternatives where use of ferric chloride may be undesirable.

The effect of elevated pH on trickling filter performance is shown in Figures 9, 10 and 11. It appeared that no deterioration in trickling filter performance occurred at pH 9.0 and 9.5 and that a slight reduction in performance occurred at pH 9.8. Organic removal efficiencies were within ranges expected of a high rate filter under the loading applied.

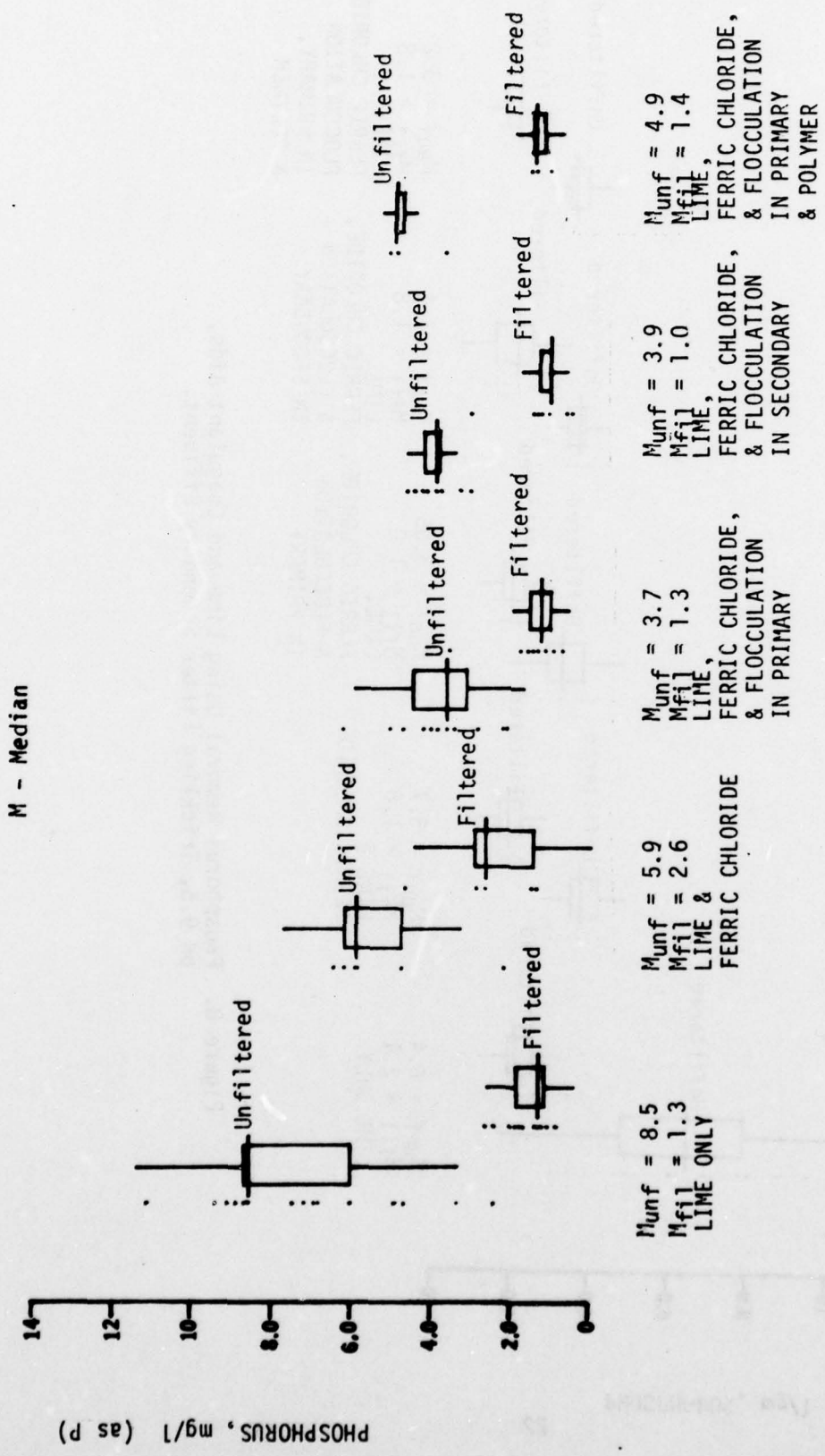


Figure 7. Phosphorus Removal Using Lime and Coagulant Aids, pH 9.5, Primary Effluent.

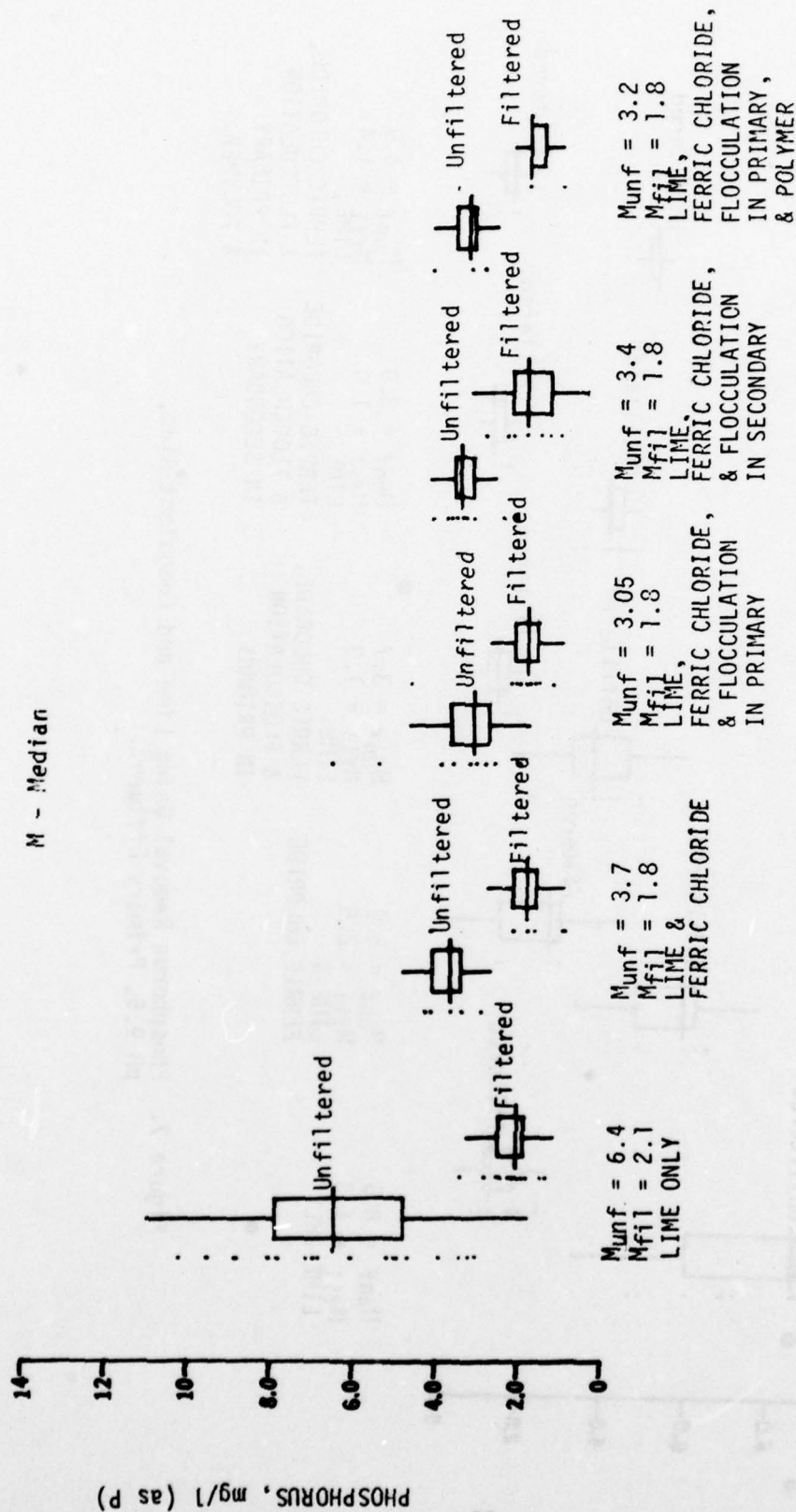


Figure 8. Phosphorus Removal Using Lime and Coagulant Aids, pH 9.5, Trickling Filter Secondary Effluent.

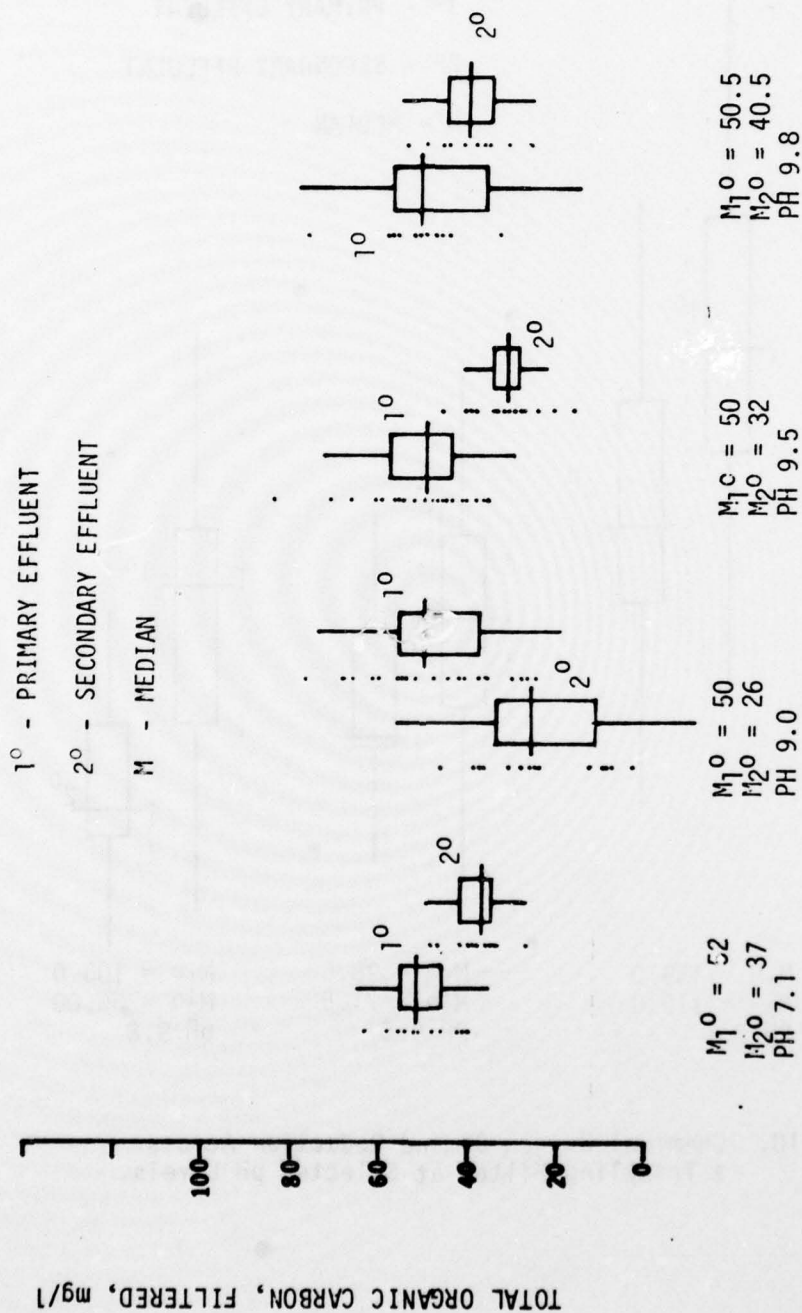


Figure 9. Total Organic Carbon Removal Across a Trickling Filter at Selected pH Levels.

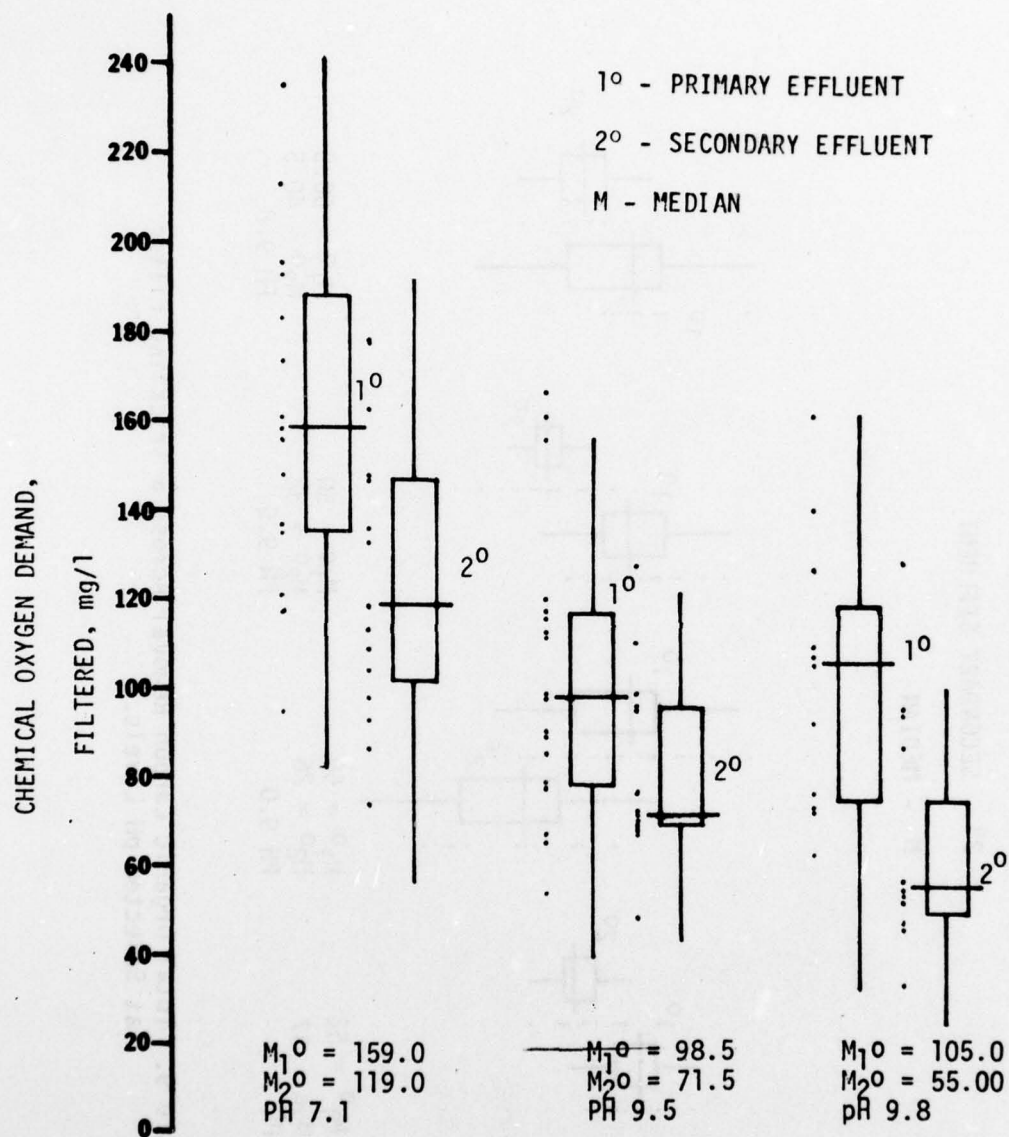


Figure 10. Chemical Oxygen Demand Reduction Across a Trickling Filter at Selected pH Levels.

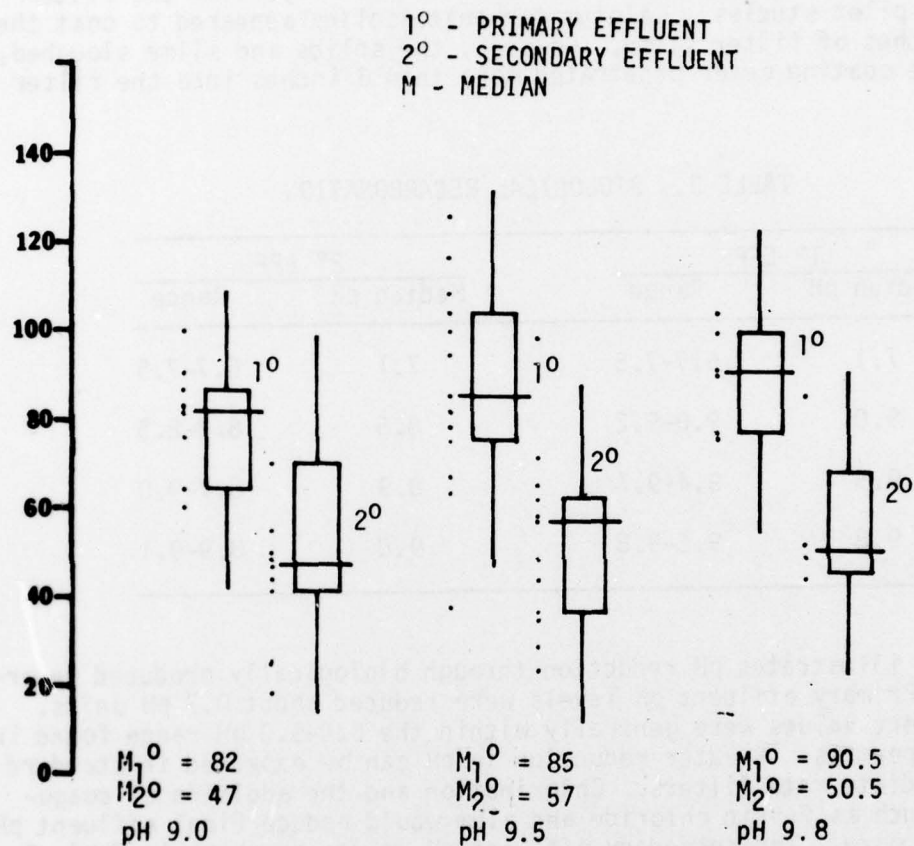


Figure 11. Biochemical Oxygen Demand,
5-Day, Filtered, mg/l.

In addition to the organic reduction data, pH reduction across the filter (see Table 3) indicated continuously active biological activity. Visual observation of the trickling filter (which was made of plexiglass) revealed that biological slime was present in all layers of the filter during the pilot studies. Calcium carbonate solids appeared to coat the top few inches of filter slime. However, the solids and slime sloughed, so that the coating never penetrated more than 6 inches into the filter bed.

TABLE 3. BIOLOGICAL RECARBONATION

1° EFF		2° EFF	
Median pH	Range	Median pH	Range
7.1	6.7-7.5	7.1	6.7-7.5
9.0	9.0-9.2	8.5	8.2-8.5
9.5	9.4-9.7	8.9	8.7-9.0
9.8	9.6-9.8	9.0	8.9-9.1

Table 3 illustrates pH reduction through biologically produced recarbonation. Primary effluent pH levels were reduced about 0.7 pH units. Final effluent values were generally within the 6.0-9.0 pH range found in most NPDES permits. Greater reduction in pH can be expected in standard and intermediate rate filters. Chlorination and the addition of coagulant aids such as ferric chloride and alum would reduce final effluent pH values even more. The secondary effluent pH values as shown in Table 3 and effluent alkalinity values shown in Table 4 resulting from lime addition are ideal for biological nitrification.⁸

An acclimation period of 1 to 2 weeks was used before data collection started at pH 9.5 and 9.8. It is believed that the fixed film microorganisms were able to adjust to elevated pH levels through population shifts and recarbonation produced by the biomass. Recarbonation across the filter was previously explained by data contained in Table 3. It is hypothesized that microorganisms in the fixed film were exposed to pH levels much lower than wastewater pH values. Thus, carbon dioxide and pH gradients would exist in liquid films adjacent to the fixed biomass. This hypothesis would explain both observed trickling filter performance at elevated pH levels and the recarbonation of the wastewater.

TABLE 4. LIME DOSE REQUIRED TO REACH THE INDICATED pH,
AND THE RESULTING ALKALINITY

pH	Lime Dose, mg/l as $\text{Ca}(\text{OH})_2$	Soluble ^a Alkalinity, mg/l as CaCO_3		
		1° INF	1° EFF	2° EFF
7.1	NA ^b	ND ^c	143	142
9.0	82	ND	225	228
9.5	140	158	200	210
9.8	144	145	217	235

a. Filtered through 0.45 μm membrane filter.

b. Not applicable.

c. No data.

The lime dose required to reach successively higher pH levels obviously increased as shown in Table 4. There was no correlation between influent wastewater alkalinity and lime dose required to reach a given pH level for alkalinity values encountered, 100-200 mg/l as CaCO_3 . Laboratory studies wherein the initial alkalinity was increased by 150 mg/l also showed no correlation between alkalinity and lime dose required to reach a given pH level. Table 4 shows no significant change in alkalinity values across the trickling filter for initial pH levels of 7.2 and 9.0; whereas there was an obvious increase for pH levels of 9.5 and 9.8. Calcium carbonate and calcium hydroxyapatite solubility data may explain these observations. Biological recarbonation reduced pH levels across the trickling filter system, and the calcium salts became more soluble at lower pH levels (8.5-9.0). Carbonate and phosphate ions were subsequently released, resulting in increased soluble alkalinity. Table 4 also shows pH 9.5 to be the minimum solubility point for calcium carbonate as reported elsewhere,⁴ since soluble alkalinity was lowest at that pH level.

The solid-liquid separation problem mentioned earlier is examined in greater detail by data in Table 5. Since primary influent suspended solids averaged 95 mg/l, it is apparent from Table 5 that solids were produced by lime addition at all elevated pH levels. A mass balance for suspended solids showed that 110 mg/l were produced at pH 9.0 and 140 mg/l produced at pH 9.5. Primary clarifier solids concentrations were 4.2 percent at pH 9.0 and 5.8 percent at pH 9.5 with 45 percent volatile solids at each pH level.

TABLE 5. SOLIDS-LIQUID SEPARATION, LIME ADDITION ONLY

pH	Suspended Solids, mg/l		Settleability, ml/l	
	1° EFF	2° EFF	1° EFF	2° EFF
7.1	68	50	≤ 0.2	≤ 0.2
9.0	122	69	≤ 0.2	≤ 0.2
9.5	151	100	≤ 0.2	≤ 0.2

SUMMARY AND CONCLUSIONS

The low level lime addition process for phosphorus removal consists of lime addition to raw wastewater to obtain a pH of about 9.5 to 10. Phosphorus is precipitated at that pH level and settled out in the primary clarifier. Microbial activity of the activated sludge process provides sufficient buffering capacity to lower the pH to near neutral, thus making recarbonation unnecessary. In the study undertaken, laboratory and pilot tests were conducted to evaluate phosphorus precipitation within pH ranges of the low level lime addition process; pilot tests were conducted at pH 9.0, 9.5, 9.8 and neutral. Pilot tests consisted of lime addition to raw wastewater within a trickling filter system. Coagulant aids were evaluated at the pH 9.5 level by addition to both primary and secondary clarifiers to assist in solid-liquid separation. Phosphorus reductions to less than 2.0 mg/l (as P) were considered effective. The following conclusions can be made relative to the system studied:

1. Phosphorus was effectively insolubilized at pH 9.5.
2. Trickling filter performance was not adversely affected by the elevated pH of 9.5.
3. Recarbonation was not necessary due to sufficient buffering capacity of the trickling filter biomass.
4. Total phosphorus was not effectively removed at pH 9.5 by lime addition alone.
5. Use of coagulant aid(s) appeared favorable for producing effective phosphorus removal at pH 9.5.

RECOMMENDATIONS

1. A full-scale project should be undertaken to demonstrate the feasibility of phosphorus removal by low lime addition to raw wastewater in a trickling filter system.
2. The solid-liquid separation of insolubilized phosphorus should be studied in more detail to determine an optimum removal process.

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LIST OF ABBREVIATIONS

NPDES	National Pollutant Discharge Elimination System
AWT	advanced wastewater treatment
BOD	biochemical oxygen demand
SS	suspended solids
P	phosphorus
NH ₃ -N	ammonia nitrogen
N	nitrogen
COD	chemical oxygen demand
mg/l	milligrams per liter
INF	influent
EFF	effluent
1°	primary
2°	secondary
μm	micrometer
ml/l	milliliter per liter
NA	not applicable
ND	no data

APPENDIX

SUMMARY OF DATA

Condition #1, No Chemical Addition, 13 Jan - 19 Apr 1976,
Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1244	1065-1388	100	55
Temperature, °C	18	15-20.5	1.3	56
pH	7.46	6.94-7.98	--	55
Phosphorus, mg/l (as P)				
Total Unfiltered	--	--	--	-
Total Filtered	--	--	--	-
Ortho Unfiltered	--	--	--	-
Ortho Filtered	--	--	--	-
Hydrolyzable Unfiltered	--	--	--	-
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	132	84-172	32	43
Suspended Solids, mg/l	55	27-106	22	57
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	110	56-148	30	28
Filtered	60	23-103	22	31
Chemical Oxygen Demand Filtered, mg/l	--	--	--	-
Total Organic Carbon, Filtered, mg/l	45	31-77	10	29
Settleability, ml/l	0.2	0.1-3.0	0.5	55

Condition #2, No Chemical Addition, 19 Jan - 17 Feb 1978,
Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1223	1150-1330	39	20
Temperature, °C	14.3	12.9-16	0.86	20
pH	7.05	6.9-7.2	--	20
Phosphorus, mg/l (as P)				
Total Unfiltered	11.1	9.8-12.5	0.83	15
Total Filtered	9.3	7.5-11.3	1.02	15
Ortho Unfiltered	7.5	4.5-9.9	1.4	15
Ortho Filtered	6.7	5.1-8.8	1.2	15
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	166	135-188	16	12
Filtered	--	--	--	--
Suspended Solids, mg/l	101	58-154	32	14
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Chemical Oxygen Demand Filtered, mg/l	179	126-281	39	15
Total Organic Carbon, Filtered, mg/l	58	43-66	7	14
Settleability, ml/l	--	--	--	--

Condition #2, No Chemical Addition, 19 Jan - 17 Feb 1978,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1223	1150-1330	39	20
Temperature, °C	14.3	12.9-16	0.86	20
pH	7.05	6.9-7.2	--	20
Phosphorus, mg/l (as P)				
Total Unfiltered	10.4	8.1-11.8	1.1	15
Total Filtered	8.6	6.5-10	0.91	15
Ortho Unfiltered	7.5	5.3-10.5	1.6	15
Ortho Filtered	6.6	4.2-9.5	1.6	15
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	168	150-186	10	13
Filtered	--	--	--	--
Suspended Solids, mg/l	77	46-115	20	15
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Chemical Oxygen Demand Filtered, mg/l	162	121-236	38	15
Total Organic Carbon, Filtered, mg/l	51	41-63	7	13
Settleability, ml/l	--	--	--	--

Condition #2, No Chemical Addition, 19 Jan - 17 Feb 1978,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	665	608-773	44	20
Temperature, °C	14.3	12.9-16	0.86	20
pH	7.05	6.9-7.2	--	20
Phosphorus, mg/l (as P)				
Total Unfiltered	9.0	6.4-11.6	1.7	15
Total Filtered	7.9	6.0-9.7	1.2	15
Ortho Unfiltered	7.7	4.6-10.9	1.8	15
Ortho Filtered	6.9	3.9-9.7	1.7	15
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	172	153-193	14	13
Filtered	--	--	--	--
Suspended Solids, mg/l	60	28-84	15	15
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Chemical Oxygen Demand Filtered, mg/l	123	74-162	30	15
Total Organic Carbon, Filtered, mg/l	38	27-48	7	14
Settleability, ml/l	--	--	--	--

Condition #3, Lime Addition to pH 9.0, 15 Nov - 27 Dec 1976,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	987	894-1259	121	27
Temperature, °C	15.6	13.8-19.5	1.3	25
pH	8.85	8.48-9.22	--	25
Phosphorus, mg/l (as P)				
Total Unfiltered	8.6	3.8-10.6	3.0	13
Total Filtered	2.6	2.0-4.7	0.7	13
Ortho Unfiltered	4.5	3.3-7.7	1.1	13
Ortho Filtered	2.1	1.6-3.4	0.5	13
Hydrolyzable Unfiltered	3.1	0.5-7.3	1.6	13
Hydrolyzable Filtered	0.3	0.0-1.7	0.2	13
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	208	157-262	32	24
Suspended Solids, mg/l	122	56-191	34	26
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	147	68-186	33	10
Filtered	74	32-100	19	10
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	48	25-77	14	22
Settleability, ml/l	0.23	0.1-1.0	0.20	26

Condition #3, Lime Addition to pH 9.0, 15 Nov - 27 Dec 1976,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	682	560-867	66	27
Temperature, °C	14.6	11.4-19.5	1.8	26
pH	7.8	7.1-8.5	--	25
Phosphorus, mg/l (as P)				
Total Unfiltered	9.0	7.0-12.4	1.5	13
Total Filtered	5.3	4.1-7.0	1.1	13
Ortho Unfiltered	5.8	4.1-8.0	1.0	13
Ortho Filtered	4.3	3.3-6.6	0.9	13
Hydrolyzable Unfiltered	2.2	0.0-4.8	1.4	12
Hydrolyzable Filtered	0.2	0.0-0.8	0.4	12
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	219	156-300	31	24
Suspended Solids, mg/l	69	35-124	20	24
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	95	57-126	25	9
Filtered	44	19-70	15	9
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	25	3-46	13	15
Settleability, ml/l	0.22	0.1-0.8	0.17	25

Condition #4, Lime Addition to pH 9.5, 7 Jan - 28 Feb 1977,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1035	925-1191	74	26
Temperature, °C	14.7	12.4-15.9	0.9	22
pH	9.4	9.1-9.6	--	22
Phosphorus, mg/l (as P)				
Total Unfiltered	7.4	2.4-11.2	2.4	21
Total Filtered	1.5	1.0-2.6	0.5	19
Ortho Unfiltered	3.9	2.2-7.8	1.6	21
Ortho Filtered	1.0	0.6-1.9	0.4	20
Hydrolyzable Unfiltered	2.5	0.3-4.8	1.5	19
Hydrolyzable Filtered	0.3	0-1	0.3	20
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	215	138-255	30	18
Suspended Solids, mg/l	133	75-170	25	25
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	156	90-230	35	13
Filtered	87	38-125	24	13
Chemical Oxygen Demand Filtered, mg/l	104	54-161	33	18
Total Organic Carbon, Filtered, mg/l	51	36-84	11	24
Settleability, ml/l	0.11	0.1-0.2	0.03	25

Condition #4, Lime Addition to pH 9.5, 7 Jan - 28 Feb 1977,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	691	566-874	75	25
Temperature, °C	14.6	12.1-17.1	1.3	22
pH	8.7	8.2-9.2	--	23
Phosphorus, mg/l (as P)				
Total Unfiltered	6.2	3.0-10.2	2.1	20
Total Filtered	2.1	1.3-2.8	0.5	21
Ortho Unfiltered	4.5	2.6-7.9	1.7	20
Ortho Filtered	1.8	0.7-8.2	0.6	21
Hydrolyzable Unfiltered	1.7	0.6-3.0	1.0	20
Hydrolyzable Filtered	0.1	0.0-0.5	0.2	20
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	252	235-255	11	7
Suspended Solids, mg/l	96	66-152	19	21
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	104	61-139	25	13
Filtered	53	24-71	20	13
Chemical Oxygen Demand Filtered, mg/l	81	48-127	22	12
Total Organic Carbon, Filtered, mg/l	33	17-46	7	21
Settleability, ml/l	0.2	0.1-1.7	0.4	25

Condition #5, Lime Addition to pH 9.8, 1 Mar - 18 Mar 1977
Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	--	--	--	--
Temperature, °C	16	13.8-16.9	1.0	12
pH	7.1	6.8-7.5	--	12
Phosphorus, mg/l (as P)				
Total Unfiltered	11.2	9.3-12.6	1.2	6
Total Filtered	8.5	4.5-10.5	2.1	6
Ortho Unfiltered	8.3	7.4-11.0	1.3	6
Ortho Filtered	6.8	3.7-7.8	1.5	6
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Suspended Solids, mg/l	86	66-111	19	12
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	204	158-249	41	6
Filtered	102	71-130	24	6
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	53	30-97	18	10
Settleability, ml/l	--	--	--	--

Condition #5, Lime Addition to pH 9.8, 1 Mar - 18 Mar 1977,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1100	995-1191	62	14
Temperature, °C	15	13.8-16.7	0.8	14
pH	9.7	9.5-9.8	--	14
Phosphorus, mg/l (as P)				
Total Unfiltered	7.9	5.5-9.4	1.3	6
Total Filtered	1.4	0.9-2.1	0.5	6
Ortho Unfiltered	3.3	2.2-3.8	0.7	6
Ortho Filtered	0.8	0.6-1.3	0.3	6
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	216	175-252	31	12
Suspended Solids, mg/l	127	102-176	21	14
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	171	130-235	36	6
Filtered	106	77-176	35	6
Chemical Oxygen Demand Filtered, mg/l	99	62-161	32	12
Total Organic Carbon, Filtered, mg/l	52	34-77	10	12
Settleability, ml/l	0.12	0.1-0.2	0.02	14

Condition #5, Lime Addition to pH 9.8, 1 Mar - 18 Mar 1977,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	757	658-878	71	14
Temperature, °C	16	15.1-17.6	0.8	12
pH	8.7	8.3-9.0	--	13
Phosphorus, mg/l (as P)				
Total Unfiltered	7.9	2.7-9.2	2.6	6
Total Filtered	1.7	1.4-2.0	0.2	6
Ortho Unfiltered	3.0	2.7-4.7	0.8	6
Ortho Filtered	1.2	1.0-1.7	0.5	6
Hydrolyzable Unfiltered	--	--	--	--
Hydrolyzable Filtered	--	--	--	--
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	249	128-280	45	12
Suspended Solids, mg/l	108	86-138	15	14
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	113	85-147	27	4
Filtered	58	44-85	19	4
Chemical Oxygen Demand Filtered, mg/l	70	33-128	29	12
Total Organic Carbon, Filtered, mg/l	41	27-54	8	12
Settleability, ml/l	0.14	0.1-0.3	0.07	13

Condition #6, Lime Addition to pH 9.5 Plus Ferric Chloride,
15 Apr - 24 Apr 1977, Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1286	1135-1306	145	6
Temperature, °C	18.4	16.8-20	1.1	6
pH	7.2	7.1-7.3	0.1	6
Phosphorus, mg/l (as P)				
Total Unfiltered	13.7	12.8-15.2	0.9	5
Total Filtered	9.8	5.3-12.2	2.9	5
Ortho Unfiltered	11.1	9.5-12.5	1.3	5
Ortho Filtered	8.7	5.3-11.6	2.6	5
Hydrolyzable Unfiltered	0.9	0.5-1.8	0.7	5
Hydrolyzable Filtered	0.3	0.0-1.1	0.5	4
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	174	157-214	17.6	8
Suspended Solids, mg/l	116	60-165	35	6
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	195	162-212	29	3
Filtered	72	58-91	17	3
Chemical Oxygen Demand Filtered, mg/l	94	67-177	42	7
Total Organic Carbon, Filtered, mg/l	46	41-53	4	5
Settleability, ml/l	--	--	--	--

Condition #6, Lime Addition to pH 9.5 Plus Ferric Chloride,
15 Apr - 24 Apr 1977, Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	--	--	--	-
Temperature, °C	18.2	16.7-19.9	1.2	5
pH	9.1	8.8-9.3	0.2	5
Phosphorus, mg/l (as P)				
Total Unfiltered	5.1	2.2-6.0	1.7	5
Total Filtered	2.5	1.3-4.6	1.3	5
Ortho Unfiltered	3.3	2.2-4.5	0.9	5
Ortho Filtered	1.7	0.8-3.1	0.9	5
Hydrolyzable Unfiltered	1.5	0.0-3.5	1.6	5
Hydrolyzable Filtered	0.5	0.0-1.3	0.5	5
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	210	172-235	22.3	7
Suspended Solids, mg/l	118	93-154	23	5
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	107	85-134	25	3
Filtered	52	38-63	13	3
Chemical Oxygen Demand Filtered, mg/l	105	73-144	30	7
Total Organic Carbon, Filtered, mg/l	41	37-50	5	6
Settleability, ml/l	0.1	0.1-0.1	0	5

Condition #6, Lime Addition to pH 9.5 Plus Ferric Chloride,
15 Apr - 24 Apr 1977, Trickling Filter
Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	787	696-1000	131	5
Temperature, °C	19.8	18.2-21.3	1.2	5
pH	8.3	7.8-8.5	3	5
Phosphorus, mg/l (as P)				
Total Unfiltered	3.7	2.9-4.2	0.5	5
Total Filtered	1.6	0.9-2.2	0.5	4
Ortho Unfiltered	2.1	1.7-3.2	0.6	5
Ortho Filtered	1.3	0.9-1.8	0.4	5
Hydrolyzable Unfiltered	0.7	0.0-1.7	0.6	5
Hydrolyzable Filtered	0.1	0.0-0.3	0.2	4
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	220	192-252	24.5	6
Suspended Solids, mg/l	93	78-109	11	5
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	52	41-62	11	3
Filtered	20	15-22	4	3
Chemical Oxygen Demand Filtered, mg/l	96	47-151	39	5
Total Organic Carbon, Filtered, mg/l	25	24-29	2	6
Settleability, ml/l	0.3	0.1-0.5	0.2	5

Condition #7, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 25 Apr - 10 May 1977,
Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1302	1261-1331	25	11
Temperature, °C	19.8	18.5-20.5	0.6	10
pH	7.3	6.7-7.9	--	10
Phosphorus, mg/l (as P)				
Total Unfiltered	11.7	6.2-15.2	2.5	12
Total Filtered	9.8	5.1-12.2	2.4	12
Ortho Unfiltered	10.2	5.5-13.3	3.0	12
Ortho Filtered	9.1	4.5-12.0	2.7	12
Hydrolyzable Unfiltered	0.8	0.0-2.9	0.9	12
Hydrolyzable Filtered	0.5	0.0-2.5	0.8	11
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	171	165-231	26	11
Suspended Solids, mg/l	93	62-123	20	11
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	213	182-224	21	6
Filtered	115	90-146	22	6
Chemical Oxygen Demand Filtered, mg/l	132	82-200	35	12
Total Organic Carbon, Filtered, mg/l	48	37-61	7	11
Settleability, ml/l	--	--	--	--

Condition #7, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 25 Apr - 10 May 1977,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	--	--	--	--
Temperature, °C	18.8	17.5-20.0	1.4	10
pH	9.1	8.9-9.2	--	10
Phosphorus, mg/l (as P)				
Total Unfiltered	3.8	2.2-6.2	1.2	12
Total Filtered	1.4	0.7-3.5	0.7	12
Ortho Unfiltered	2.3	1.6-3.4	0.6	12
Ortho Filtered	1.0	0.6-3.3	0.8	12
Hydrolyzable Unfiltered	1.3	0.3-2.8	0.7	10
Hydrolyzable Filtered	0.2	0.0-0.5	0.2	11
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	195	180-214	27	11
Suspended Solids, mg/l	78	62-143	24	11
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	132	103-170	22	6
Filtered	100	81-127	19	6
Chemical Oxygen Demand Filtered, mg/l	116	68-177	29	12
Total Organic Carbon, Filtered, mg/l	44	35-51	6	11
Settleability, ml/l	0.5	0.2-0.8	0.2	9

Condition #7, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 25 Apr - 10 May 1977,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	892	830-1089	72	11
Temperature, °C	19.8	17.5-21.9	1.6	10
pH	8.2	7.8-8.5	--	9
Phosphorus, mg/l (as P)				
Total Unfiltered	3.5	2.0-5.4	1.3	12
Total Filtered	1.9	1.2-4.6	0.9	12
Ortho Unfiltered	2.3	1.1-4.7	1.1	12
Ortho Filtered	1.6	0.9-2.6	0.5	12
Hydrolyzable Unfiltered	0.7	0.0-1.3	0.5	12
Hydrolyzable Filtered	0.3	0.0-0.8	0.3	11
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	203	117-222	30	11
Suspended Solids, mg/l	62	40-93	17	11
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	70	54-112	23	6
Filtered	41	19-78	20	6
Chemical Oxygen Demand Filtered, mg/l	76	53-98	14	12
Total Organic Carbon, Filtered, mg/l	27	24-35	3	11
Settleability, ml/l	0.6	0.2-0.8	0.2	10

Condition #8, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 16 May - 1 Jun 1977,
Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1336	1033-1433	115	10
Temperature, °C	20.8	19.9-21.9	0.6	10
pH	6.8	6.7-6.9	--	9
Phosphorus, mg/l (as P)				
Total Unfiltered	11.3	8.6-13.4	1.7	9
Total Filtered	8.8	5.8-11	1.8	9
Ortho Unfiltered	8.7	6.0-12.2	2.3	9
Ortho Filtered	7.7	5.7-10.3	1.8	9
Hydrolyzable Unfiltered	1.8	1.0-3.9	0.9	9
Hydrolyzable Filtered	0.9	0.1-2.4	0.7	8
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	162	147-182	14	11
Suspended Solids, mg/l	106	78-128	14	10
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	221	174-279	41	6
Filtered	113	87-161	26	6
Chemical Oxygen Demand Filtered, mg/l	178	120-299	49	11
Total Organic Carbon, Filtered, mg/l	41	28-57	11	7
Settleability, ml/l	--	--	--	--

Condition #8, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 16 May - 1 Jun 1977,
Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	--	--	--	--
Temperature, °C	20.3	18.6-21.8	1.0	8
pH	9.1	9.0-9.2	--	7
Phosphorus, mg/l (as P)				
Total Unfiltered	3.9	3.0-4.6	0.5	9
Total Filtered	1.2	0.5-3.0	0.7	9
Ortho Unfiltered	2.2	1.6-3.8	0.7	9
Ortho Filtered	0.8	0.5-2.6	0.7	9
Hydrolyzable Unfiltered	1.4	0.5-2.0	0.5	8
Hydrolyzable Filtered	0.2	0.0-0.4	0.2	8
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	196	162-222	21	9
Suspended Solids, mg/l	70	42-96	19	8
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	151	118-218	39	6
Filtered	111	68-143	29	6
Chemical Oxygen Demand Filtered, mg/l	141	117-210	29	9
Total Organic Carbon, Filtered, mg/l	35	25-45	11	6
Settleability, ml/l	0.1	0.1-0.2	0.05	8

Condition #8, Lime Addition to pH 9.5 Plus Ferric Chloride
and Flocculation, 16 May - 1 Jun 1977,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	916	855-977	48	8
Temperature, °C	21.2	19.5-22.7	1.0	8
pH	8.0	7.7-8.3	--	8
Phosphorus, mg/l (as P)				
Total Unfiltered	3.2	2.1-4.1	0.6	9
Total Filtered	1.8	1.0-2.8	0.6	9
Ortho Unfiltered	2.2	1.4-3.6	0.7	9
Ortho Filtered	1.5	0.7-2.2	0.5	9
Hydrolyzable Unfiltered	0.8	0.4-1.1	0.2	8
Hydrolyzable Filtered	0.3	0.0-1.0	0.3	9
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	210	165-228	21	8
Suspended Solids, mg/l	54	26-79	16	8
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	88	46-114	26	5
Filtered	53	41-64	13	5
Chemical Oxygen Demand Filtered, mg/l	112	76-211	45	9
Total Organic Carbon, Filtered, mg/l	22	2-45	16	7
Settleability, ml/l	0.7	0.4-1.0	0.3	8

Condition #9, Lime Addition to pH 9.5 Plus Ferric Chloride,
Plus Polymer, 2-17 Jun 1977, Primary Influent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	1353	1312-1467	49	10
Temperature, °C	21	20-22.3	1.2	10
pH	6.8	6.6-7.0	--	10
Phosphorus, mg/l (as P)				
Total Unfiltered	13	11.2-15.4	2.2	3
Total Filtered	9	7.4-10.2	1.5	3
Ortho Unfiltered	11.1	8.1-15.4	3.8	3
Ortho Filtered	8.8	7.0-10.2	1.6	3
Hydrolyzable Unfiltered	2.7	2.3-3.1	0.6	2
Hydrolyzable Filtered	3.5	0.1-10.2	5.8	3
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Suspended Solids, mg/l	116	75-192	32	11
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	249	226-267	17	4
Filtered	118	96-134	19	4
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	50	42-60	5.7	10
Settleability, ml/l	--	--	--	--

Condition #9, Lime Addition to pH 9.5 Plus Ferric Chloride,
Plus Polymer, 2-17 Jun 1977, Primary Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	--	--	--	--
Temperature, °C	21	19.1-22.8	1.9	3
pH	9.2	8.9-9.4	--	10
Phosphorus, mg/l (as P)				
Total Unfiltered	4.5	3.7-5.0	0.7	3
Total Filtered	1.3	1.0-1.5	0.3	3
Ortho Unfiltered	2.7	2.3-3.0	0.4	3
Ortho Filtered	0.7	0.6-0.9	0.2	3
Hydrolyzable Unfiltered	1.4	0.5-2.6	1.1	3
Hydrolyzable Filtered	0.3	0.1-0.4	0.2	3
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Suspended Solids, mg/l	82	58-128	22	10
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	157	120-191	30	4
Filtered	107	76-150	35	4
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	46	37-52	4.6	10
Settleability, ml/l	0.4	0.1-2.5	0.8	9

Condition #9, Lime Addition to pH 9.5 Plus Ferric Chloride,
Plus Polymer, 2-17 Jun 1977,
Trickling Filter Secondary Clarifier Effluent

	Average	Range	Std. Dev.	No. Observ.
Flow, gpd	860	811-957	84	3
Temperature, °C	20	18.5-21.5	1.1	10
pH	8.1	7.5-8.7	--	3
Phosphorus, mg/l (as P)				
Total Unfiltered	3.4	2.9-4.1	0.6	3
Total Filtered	1.5	1.0-1.8	0.5	3
Ortho Unfiltered	2.7	1.7-3.7	1.0	3
Ortho Filtered	1.2	0.7-1.4	0.4	3
Hydrolyzable Unfiltered	0.4	0.1-0.8	0.4	3
Hydrolyzable Filtered	0.3	0.1-0.4	0.2	3
Alkalinity, mg/l (as CaCO ₃)				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Suspended Solids, mg/l	75	31-110	40	3
5-Day Biochemical Oxygen Demand, mg/l				
Unfiltered	--	--	--	--
Filtered	--	--	--	--
Chemical Oxygen Demand Filtered, mg/l	--	--	--	--
Total Organic Carbon, Filtered, mg/l	--	--	--	--
Settleability, ml/l	1.0	0.5-2.5	1.3	3

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