

THE OPERATION OF A COMPLETELY MIXED
ACTIVATED SLUDGE PILOT PLANT EMPLOYING
ALUM ADDITION FOR PHOSPHORUS REMOVAL

by

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I. INTRODUCTION

Excessive and undesirable algal growth can place a heavy burden on the utility of surface waters. In addition to being aesthetically displeasing, algal blooms increase the cost of water treatment and often impair the recreational value of lakes and rivers. Wastewater treatment processes are needed that will effectively reduce the nutrients currently being discharged to watercourses in order to reduce the algal growing potential of surface waters.

Of all the nutrients essential for the growth of aquatic organisms, only nitrogen and phosphorus are recognized as being growth limiting in natural aquatic systems. Control of eutrophication is reported to be effectively achieved when the level of either nutrient is less than that required to trigger an algal bloom. Concentrations of less than 0.01 mg/l and 0.3 mg/l are generally considered growth limiting for phosphorus and nitrogen, respectively.

An understanding of phosphorus and nitrogen requirements for aquatic growth has been obscured by the luxury uptake phenomenon and the ability of blue-green algae to utilize elemental nitrogen. However, it is generally agreed that control of both phosphorus and nitrogen is essential for the effective control of the eutrophication process (1).

Primary sources of phosphorus in a watershed are agricultural and urban run-off, industrial and municipal

discharges, interchange of bottom sediments, and atmospheric precipitation. Of the basic contributors, municipal wastewaters are the principal and most easily controllable source of phosphorus.

The phosphate content of treated wastewaters has risen considerably in the last few decades due primarily to the increased use of phosphates in detergents. The phosphorus content of municipal wastewater has increased from 0.55 lb/cap/yr in 1940 to 3.3 lb/cap/yr in 1968 (1). In recent years levels of 6.5 to 9.0 mg P/liter have been found typical of treated effluents throughout the United States (2). This represents considerable contrast between the current levels and the average value of 0.22 mg P/liter reported in trickling filter effluents from 12 American treatment plants in 1947 (2). A survey by G. V. Levin of Johns Hopkins University indicates that phosphorus concentrations in treatment plant effluents have now reached a plateau (2). Unless new consumer products containing significant concentrations of phosphorus are placed on the market, the phosphorus content of domestic wastewaters will not continue to increase.

Untreated municipal wastewaters normally contain 20-30 mg/l of phosphorus. The total phosphorus content may be classified in three major forms: orthophosphate, condensed or complex polyphosphate, and organic phosphate. In settled raw domestic sewage orthophosphate typically

comprises 25-30 percent of the total phosphate. Orthophosphate content increases to 80-85 percent of the total phosphate content of treated effluent from a treatment plant employing a biological process as complex polyphosphates are released from organic material and converted to soluble orthophosphate by hydrolysis (1). The soluble orthophosphate is the final breakdown product in the phosphorus cycle and is also the form of phosphorus which is most readily available to support metabolic activity.

Certain wastewater treatment schemes result in the resolubilization of phosphates in addition to the recirculation of insoluble phosphorus. The form of phosphorus is the key to efficient removals. Phosphorus is removed only when precipitated in the ortho form or as part of organic matter. An optimum method of phosphorus removal has not been agreed upon. Presently chemical methods, biological methods, and combinations of both are being studied or employed in treatment plants. Conventional biological treatment is inefficient in phosphorus removal with reductions normally being less than 20 percent (3).

A purely chemical tertiary stage is one alternative for providing nearly complete phosphorus removal. Lime or other chemicals can also be added at selected points in the treatment scheme to precipitate phosphorus. However, the reliability and completeness of phosphorus removal involves

high chemical costs (as much as \$120 per million gallons (4)) and may require the construction of additional treatment units and solids handling facilities.

The objective of this study was to successfully operate a combined chemical-biological completely mixed activated sludge pilot plant employing alum addition as part of the primary process. Of primary concern were removal efficiencies of phosphorus and total solids. Settling characteristics of the sludge, physical characteristics of floc formation, and microscopic examination of the activated sludge were also included in the study.

The pilot plant was operated and studied in conjunction with associate graduate student, D. Randolph Grubbs, who investigated nitrification and nitrogen, BOD and COD removals in the plant.

II. LITERATURE REVIEW

Conventional sewage treatment processes often fail to produce effluents that comply with current water quality criterion relative to phosphorus content. Typical plants employing both primary and secondary processes only remove 20 to 30 percent of the phosphorus present in domestic sewage. Early studies on phosphorus removal were directed toward adjusting plant operating procedures to enhance phosphorus removal in conventional biological processes. These studies were unsuccessful, but they served as a foundation for the development of chemical methods for phosphorus removal.

Sawyer (5), one of the first investigators concerned with phosphorus removal in domestic wastewater, experimented with the addition of organic carbon to achieve more efficient removals. Complete removal of 2.68 mg/l phosphorus by activated sludge was attained with the addition of enough glucose to raise the BOD to 400 mg/l. Sawyer concluded that the BOD:P ratio of the influent wastewater should exceed 100:1 for complete phosphorus removal.

Sawyer's work was based on a suspicion that low phosphorus removals from domestic wastewaters might be attributed to a nutrient imbalance with respect to bacterial requirements for respiration and cell synthesis. The imbalance was believed to consist of an excess of phosphorus and

nitrogen relative to the amount of carbon. Phosphorus concentrations exceeding metabolic requirements of bacterial sludge are largely due to the increased use of phosphate detergents in recent years. Stumm and Morgan (6) reported that the carbon:nitrogen:phosphorus ratio is normally 70:17:1 for raw domestic wastewater and 106:16:1 for bacterial sludge. Stoichiometrically, organic carbon currently controls cell synthesis in activated sludge. As a result, all of the phosphorus in domestic sewage cannot be assimilated into bacterial cells.

Roinestad and Yall (7), in an in-depth study of biological phosphorus uptake, reported that the bacterium Zoogloea ramigera was the chief phosphorus remover of the activated sludge organisms. Phosphorus was removed by the formation of volutin granules of inorganic polyphosphate within the cell wall. The authors listed the organic carbon:phosphorus:magnesium ratio as being the most critical in controlling bacterial growth.

Jenkins and Menar (8), using an activated sludge pilot plant, showed that phosphate removal was proportional to the new growth of activated sludge. In addition, they reported an average value for phosphate content of activated sludge as 2.5 percent of the volatile solids when organic loading was normal.

Several factors exert an influence on biological phosphorus removal. The most important criteria are generally

agreed to be the rate of aeration and aeration time.

The importance of aeration for phosphorus uptake was reported by Connell, et al. (9). Connell reported phosphate uptakes completed to less than 1 mg/l PO_4 in the aeration tanks with adequate aeration and a sufficiently high BOD:P ratio. Optimum aeration rates appeared to be in the range of 3 - 7 cuft/min/gal. Detention times of 4 - 6 hours appeared to be most desirable.

Sekikawa, et al. (10), in a batch laboratory study, related phosphate removal and cell growth. The researchers also discovered that further aeration after BOD had been depleted caused the release of phosphate. Sekikawa and his associates stated that the initial BOD of the wastewater influenced both the rate of phosphate removal and the final soluble phosphate concentration. High initial BOD resulted in rapid removal rates and low final soluble phosphate concentrations.

Mixed liquor suspended solids concentration has also been reported to influence biological phosphorus removal. However, there is some disagreement with respect to an optimum MLSS concentration. Levin and Shaheen (11) reported phosphorus uptake increased with increasing MLSS in the range of 1075-4270 mg/l. Feng (12), on the other hand, obtained best removals at MLSS concentrations less than 1500. Apparently, maximum uptake can occur at both high

and low MLSS. The BOD loading per 100 pounds of sludge solids was reported to provide a more controllable and reliable basis for the design and operation of an activated sludge plant. Maximum overall phosphorus removal generally occurs at a loading rate of one pound of daily five-day BOD input per two pounds of sludge solids under aeration (2).

Sufficient dissolved oxygen must be maintained in the aeration chambers to prevent resolubilization in the secondary clarifier. Dissolved oxygen levels of 2 - 5 mg/l appear to be most desirable in preventing phosphorus release. Detention time should not exceed 30 minutes in the final clarifier (2).

Activated sludge plants in several instances have achieved phosphate removals in excess of 90 percent. The Rilling plant in San Antonio, Texas has consistently averaged greater than 80 percent phosphorus removals while another plant located at the same site and treating the same wastewater averaged 35 percent removal. Connell and Vacker (13) reported that the rate of aeration and organic loading were the most critical parameters for phosphate removal in the Rilling plant.

The Back River plant in Baltimore is another activated sludge plant credited with high phosphate removal. Scalf (14) reported that phosphate removals exceeding 90 percent in the Back River plant were largely affected by suspended

solids, BOD, and phosphate and dissolved oxygen concentrations. In another study conducted by the city of Baltimore, total phosphorus removals of 82 percent were reported. Furthermore, the study concluded that neither suspended solids nor aeration detention times influenced phosphate removal (15).

High phosphate removals, as reported by the Rilling plant in San Antonio and the Back River plant in Maryland, are far in excess of the amount of phosphorus incorporated into microbial cells through cell synthesis. The occurrence of luxury biological uptake and metal precipitation are two hypotheses that have been suggested as responsible for unusually high phosphate removals.

The "luxury uptake" theory was developed by Levin and Shapiro (16) from pilot plant studies. The authors showed that cell growth was not required for uptake of phosphate in the activated sludge process. Levin and Shapiro defined "luxury uptake" as the phosphate uptake in excess of that utilized in cell synthesis. Factors controlling phosphate uptake were reported as dissolved oxygen, pH, rate of aeration, and the phosphate content of the recycled sludge. Uptake of phosphorus was increased by stripping phosphate from return sludge.

Unfortunately, phosphorus removal by "luxury uptake" is highly unpredictable and uncontrollable. Mulbarger, et al. (17) were unable to remove more than 50 percent of the

phosphorus at published conditions of "luxury uptake" in studies at the Greater Manassas Sanitary District, Prince William County, Virginia, research facility. Menar and Jenkins (18) also achieved poor performance in a pilot plant operating under the same conditions as the Rilling plant in San Antonio, Texas. The results of other plant scale studies such as the Federal Water Pollution Control Administration surveys were erratic and generally showed low phosphorus removal (1).

The calcium phosphate precipitation theory introduced by Menar and Jenkins (18) is the second hypothesis which might explain unusually high phosphate removal in activated sludge. On the basis of a pilot plant study and laboratory research, the authors concluded that the chemical precipitation of CaHPO_4 was responsible for removal of phosphorus in excess of that required for cell synthesis. Upon precipitation the CaHPO_4 becomes physically entrapped by the activated sludge to allow removal by sludge wastage. Phosphorus content on a volatile solids basis was as high as 6.8 percent in the enhanced phosphate removal system as compared to 2.3 percent generally incorporated into cellular material. Calcium levels, however, were higher in the improved phosphate removal process. The degree of phosphate precipitation was related to the pH. Highest phosphate removals were produced in plug flow conditions.

The chemical precipitation theory, like the occurrence of "luxury uptake", is not a reliable basis for design of phosphorus removal processes. Connell (19) successfully operated a segment of the Hyperion plant for high phosphorus removal by adhering to the chemical precipitation theory. Other studies, however, at Texas City, Texas and the Back River plant, Baltimore, showed chemical precipitation of phosphates to be an uncontrollable mechanism and unrelated to metallic ion concentration (13, 15).

The inadequacy of calcium phosphate precipitation and the occurrence of biological "luxury uptake" has led to the development of more controllable chemical methods for removal of phosphate in domestic wastewater. Chemical precipitation, a highly approved phosphate removal method, includes the addition of metallic salts to either the raw wastewater or to the final effluent.

Addition of metallic salts to the influent waste provides several advantages:

- 1) The method can be adapted to both trickling filtration and activated sludge.
- 2) Primary settling is improved.
- 3) BOD and suspended solids are reduced by as much as 60 and 90 percent, respectively, in the primary clarifier, reducing size requirements of aeration tanks.

Chemical addition to the final effluent provides more complete phosphorus removal but at a higher capital cost.

Precipitation of phosphates can be achieved by the addition of several metallic salts including ferric chloride, ferric sulfate, ferrous chloride, ferrous sulfate, aluminum sulfate, sodium aluminate, and lime. Removals of phosphorus are generally considered a combination of precipitation and adsorption. Wuhrman (20) attributes chemical precipitation of phosphorus by iron salts to the formation of FePO_4 . The FePO_4 is effectively removed from solution by adsorption onto hydroxide floc. Hydroxide floc also adsorbs organic phosphorus compounds and inorganic condensed phosphate. Wuhrman listed stoichiometric requirements of 1.88 mg/l Fe per mg/l phosphorus in addition to 10.0 mg/l Fe for hydroxide formation. In an earlier study Stumm (21) reported the formation of insoluble metal phosphates as accountable for phosphate removal by metallic precipitation.

Convey, Recht, and Ghassemi (22, 23) investigated the effect of pH on orthophosphate removal by alum addition. Convey reported that removal is accomplished by chemical precipitation at pH less than six and by either adsorption on aluminum hydroxide floc or incorporation in an aluminum or hydroxide group at pH exceeding six. An $\text{Al}:\text{PO}_4$ molar ratio in excess of two is required for effective removal due to the tendency of aluminum ions to hydrolyze. Complex polyphosphates were more difficult to remove because they

tended to form soluble complexes with cations. Triphosphates, for example, cannot be effectively removed by either iron or aluminum salts (2).

Recht and Ghassemi (23) concluded that both pH and cationic concentrations largely influenced the formation of large settleable flocs. The authors found the optimum pH for precipitation with aluminum to be approximately 6 and 2.5 - 4.0 for iron. A cation-to-orthophosphate molar ratio of 2:1 produced maximum removal of orthophosphate. Recht and Ghassemi also found iron slightly more efficient than aluminum in orthophosphate removal on a molar basis.

Precipitant concentration and pH also strongly influenced the removal of condensed phosphates. Optimum pH ranges for the removal of polyphosphates were approximately the same as for the removal of orthophosphate. Removal of condensed phosphates was negligible when pH varied as much as one unit from the optimum value. At optimum pH levels effective removal of triphosphate and pyrophosphate was also achieved with a 2:1 cation-to-orthophosphate equivalence molar ratio (23).

Wuhrman (20) experimented with a mixture of lime and iron for removal of phosphorus. Removal was approximately the same as that provided by addition of either lime or iron alone. However, the process was cheaper in chemical cost and in sludge handling and disposal due to reduced sludge volume.

In a laboratory study of lime application to raw wastewater, Buzzell and Sawyer (24) reported 80-90 percent removal of total phosphate and 97 percent removal of orthophosphate at a pH of 11. The formation of insoluble hydroxyapatite and calcium carbonate was responsible for phosphate precipitation by lime addition. Sludge production was one percent by volume of the raw waste.

Barth (4) investigated phosphorus removal using a 100 gallon-per-day plant in which chemicals were added directly to the aeration chamber. Sodium aluminate was found to be the most effective chemical coagulant. Removals exceeding 90 percent were obtained with the addition of aluminum in a 1:1 aluminum-to-phosphorus weight ratio.

The effectiveness of aluminum sulfate in laboratory scale treatment of primary effluent was reported by Eberhardt (11). Alum addition produced 95 percent phosphorus removal when added to a mixing chamber prior to the biological phase of the process. Best results were obtained with aluminum-to-phosphorus ratios of greater than two. Both Barth and Eberhardt estimate the chemical costs involved in their proposed processes to be approximately \$50 per million gallons.

C. P. Priesing (11) in describing 18 months of laboratory studies emphasized that phosphorus removal occurs as a result of adsorption-desorption equilibrium between the

solution and the solids. Phosphate was reported to be adsorbed during aeration and desorbed during anaerobic conditions in the clarification basin.

Recht and Ghassemi (11) conducted a detailed evaluation of lanthanum for phosphate precipitation. An initial concentration of 12 mg/l phosphorus was reduced to less than .01 mg/l phosphorus with a 1:1 lanthanum-to-phosphate molar ratio. With respect to pH requirements the lanthanum precipitation process is more flexible and controllable than the addition of other metallic ions. Equally efficient removals were obtained at a pH range of 5 to 9. In addition, almost complete removal of pyrophosphate and triphosphate was obtained with lanthanum-to-orthophosphate equivalence molar ratio of 2:1. In laboratory studies lanthanum has been found far superior to iron salts, aluminum salts, and lime for phosphate precipitation.

Several commercial processes are currently available for phosphate precipitation. The Dorr-Oliver Corporation was first to use a chemical precipitation approach for phosphorus removal on a plant scale. In the Dorr-Oliver phosphate extraction process (PEP), lime is added to the primary settling tank. As a result, the initial phosphate concentration of 20-30 mg/l is reduced to 3-6 mg/l in the effluent of the primary clarifier. The efficient primary step greatly reduces the load on the secondary, biological process. Activated sludge is then capable of removing

almost all of the remaining phosphorus. Advantages of the PEP process are low chemical costs (30-40 percent of those for tertiary precipitation) and cheaper sludge handling due to a greater proportion of easy-to-handle primary sludge (11).

The Eimco process, another chemical treatment method, utilized alum or lime for enhanced primary clarification followed by multimedia filtration and then activated carbon adsorption. Ninety-five percent removal of phosphorus was achieved with a lime dosage of 325 mg/l plus 0.25 mg/l poly-electrolyte (25).

A third phosphate precipitation process is the two stage Dow process. Phosphates are converted to insoluble phosphates in primary treatment by the addition of aluminum or iron salts. Organic polymer is added in the second step to precipitate the insoluble phosphorus. Moderately high removals of 82-92 percent have been obtained by the Dow process (26).

An alternative to chemical precipitation methods in which precipitants are added to the influent waste or to the final effluent is chemical-biological wastewater treatment. Chemical-biological treatment refers to the addition of chemicals to the aeration tank where chemical precipitation occurs. The precipitated phosphorus is then removed by wastage of activated sludge. Precipitant dosage required is much less than that needed for a separate process without biological solids. Apparently, the large active surface

area of biological floc is beneficial in removing the precipitated phosphorus. Dual use is made of the aeration chamber. The aluminum additive does not interfere with nitrification or BOD and solids removal (27). Good mixing of the mineral supplement and the wastewater is supplied by the aeration chamber in addition to sufficient residue time for reactions to occur. Chemical-biological processes are capable of producing effluent residuals of 1-2 mg/l phosphate (1).

From the preceding discussion chemical precipitation of phosphorus in domestic waters appears to be a highly efficient and practical means of reducing phosphorus concentrations in receiving waters. The chemical precipitation process if adapted to existing wastewater treatment plants and incorporated into the design of new plants would significantly reduce the "eutrophication" problem of surface waters throughout the United States.

III. MATERIALS AND METHODS

As stated in the introduction, the purpose of this research was to successfully operate a completely mixed activated sludge pilot plant employing alum addition for phosphorus removal. Removal of solids was also observed and reported.

Experimental Equipment and Procedure

The equipment used in this research was a small-scale pilot plant operated at the Stroubles Creek Wastewater Treatment Plant which treats domestic wastewater from Blacksburg, Virginia and V.P.I. and S.U. A schematic flow diagram is presented as Figure I, and Figures II and III show pertinent geometry of the units.

Flow was directed to the pilot plant through a 2-inch siphon line. During the first 24 days of the study primary effluent from the Stroubles Creek plant was used as influent to the pilot plant. Primary clarifier influent was used as the wastewater source for the pilot plant for the last 7 days of the study. Primary clarifier influent was not used as the wastewater supply for the pilot plant during the entire study because of problems with clogging of the flow control valve. A 1-inch ball valve was used to manually control the influent flow rate to the pilot plant.

The regulated influent wastewater flowed into a coagulation-flocculation unit to which alum was added. A

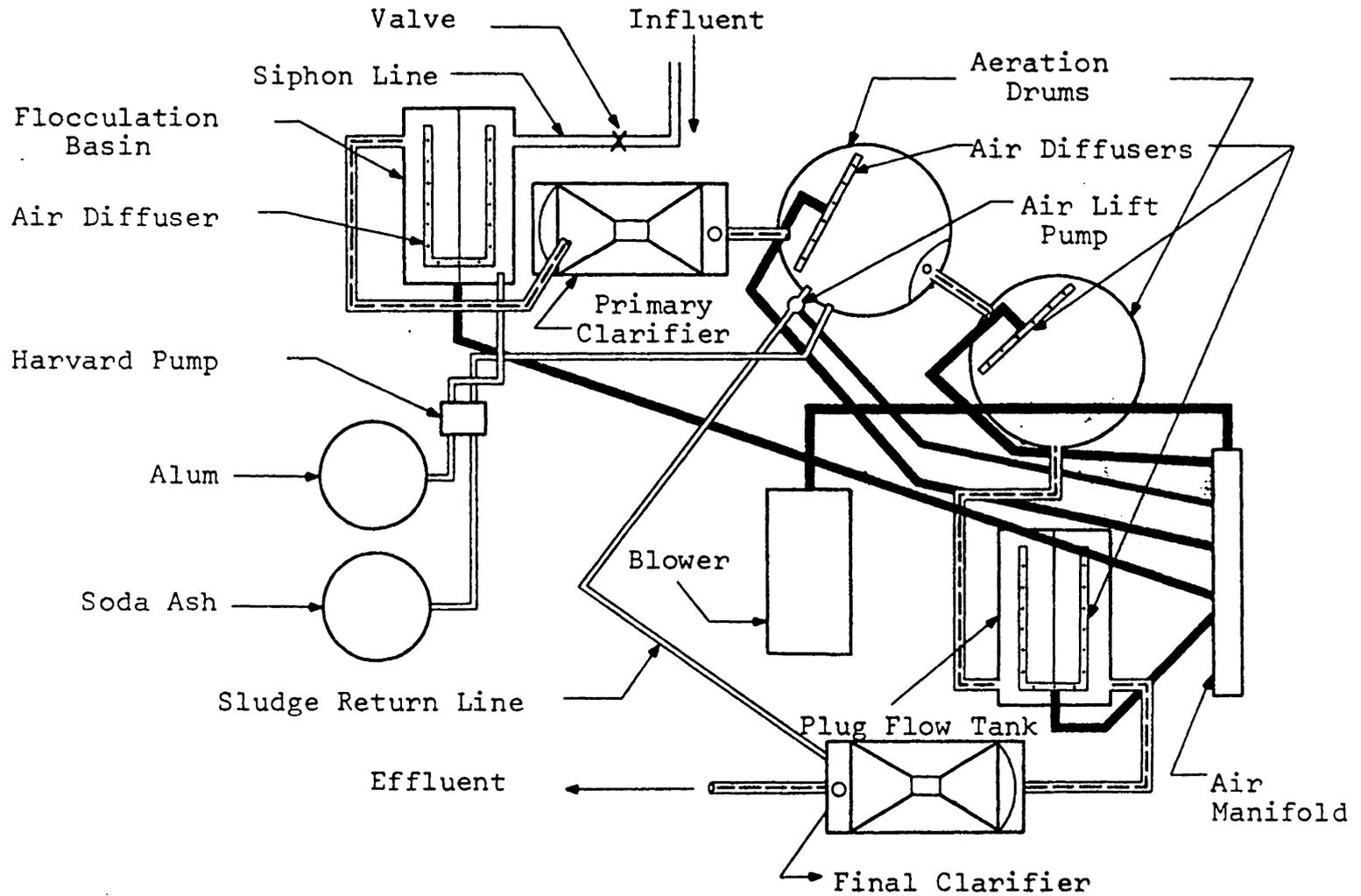


Figure I. Plan View of Pilot Plant Operation.

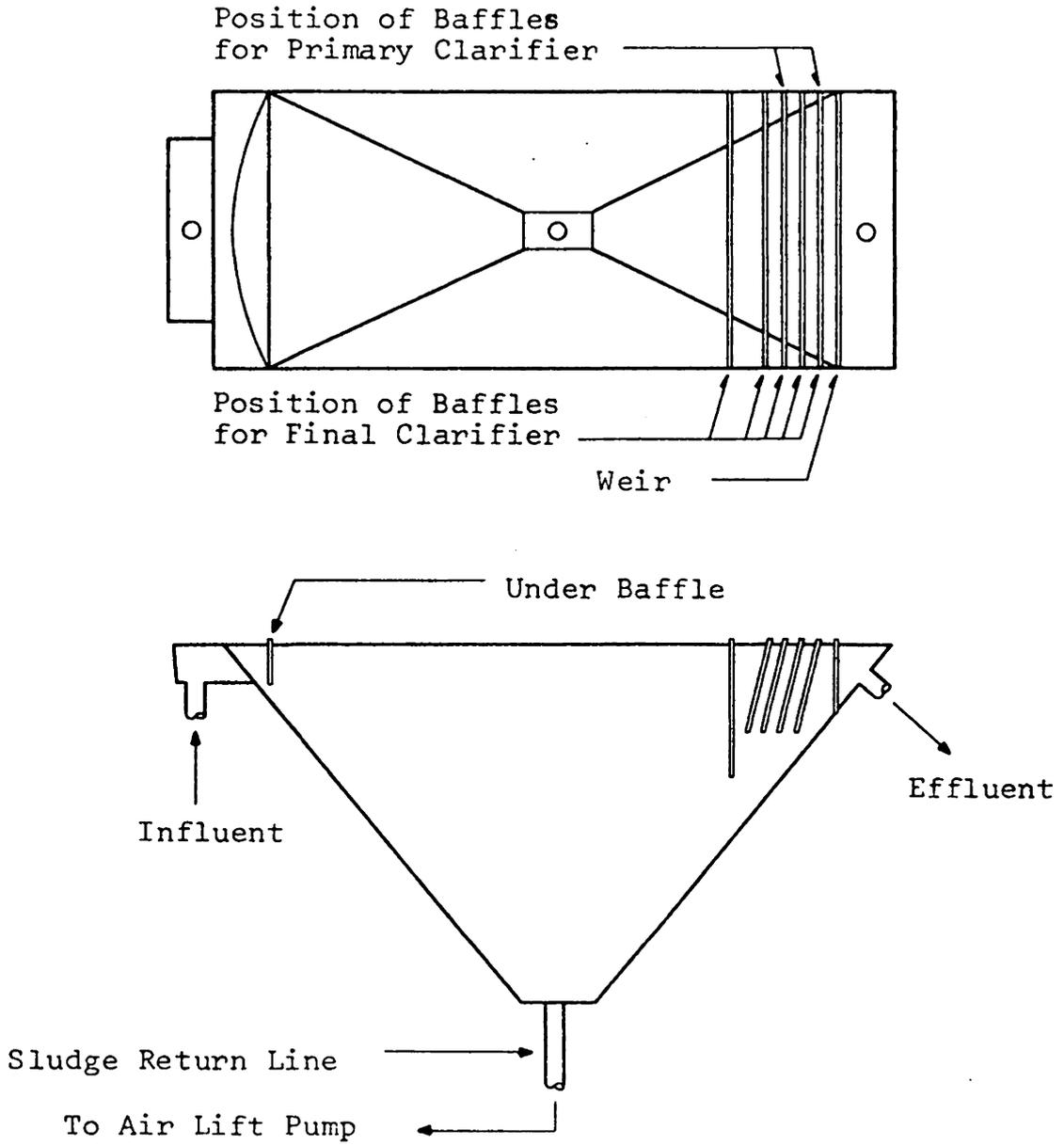


Figure II. Plan View and Elevation of Clarifiers.

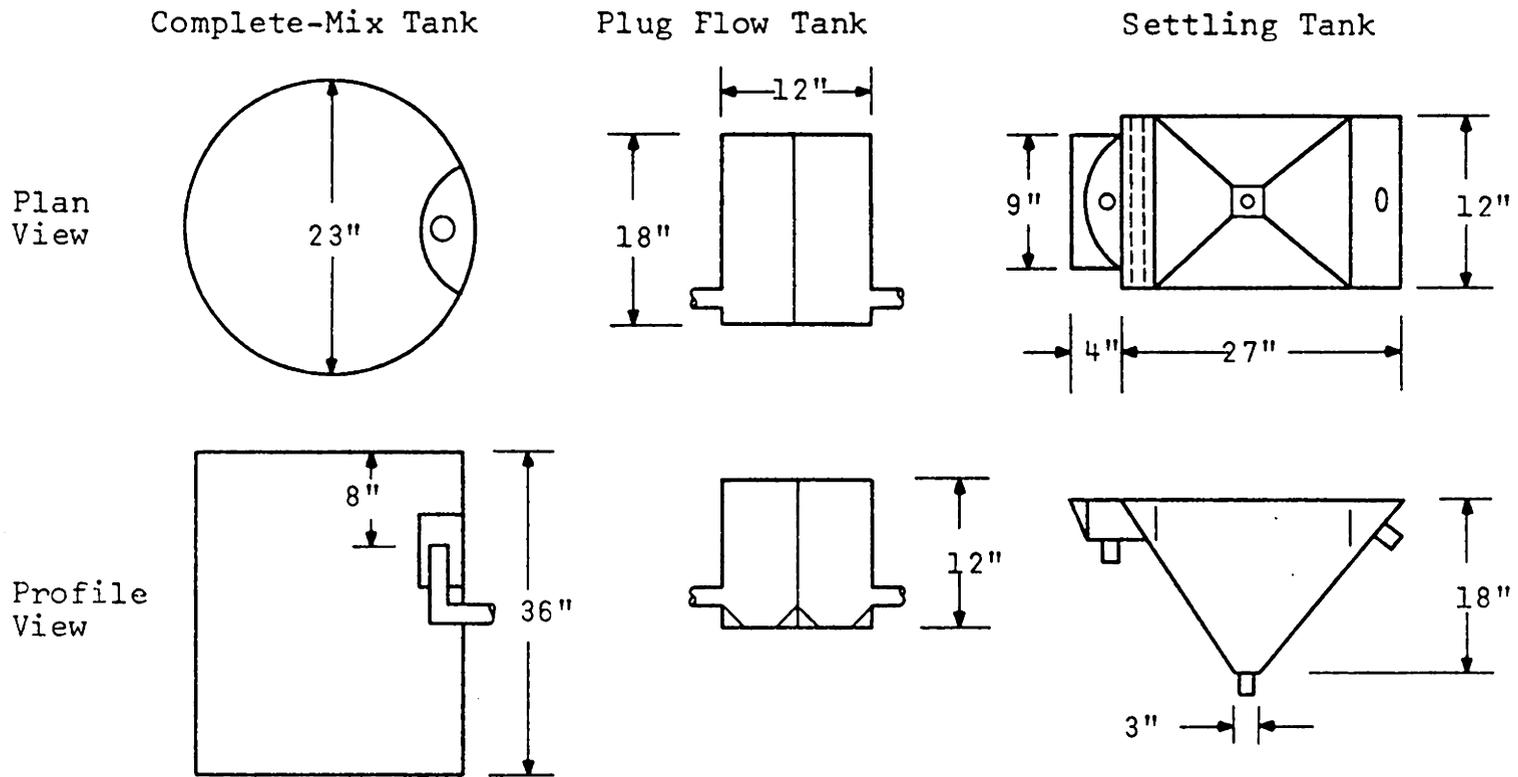


Figure III. Details of Pilot Plant Units.

desired alum dosage of 240 mg/l was pumped from a 15 liter mixing vessel by means of a Harvard peristaltic pump. A Talboy Model 102 stirrer was used to keep the alum solution well mixed. The coagulation-flocculation unit was constructed of plexiglass and had a working volume of 28 liters. Influent flow rates varied between 200 and 1000 ml per minute which yielded detention times ranging from 140 to 28 minutes in the flocculation unit. Diffused air was supplied for coagulation-flocculation by means of a model 2 MVE Sutorbilt blower equipped with a 1.5-horsepower electric motor. A manifold equipped with ball valves was used to control the air flow to the respective units. The air diffuser for the flocculation basin consisted of a 3/8-inch diameter copper tubing with 3/16-inch holes.

Effluent from the coagulation-flocculation basin flowed to the plexiglass primary sedimentation tank which had a volume of 22 liters. This provided for detention times ranging from 110 to 22 minutes depending upon the influent flow rate. Overflow rates varied from 47 gallons per day per square foot to 237 gallons per day per square foot. Two baffles were inserted at the effluent end of the tank to reduce the carry over of suspended floc. Sludge deposited in the primary settling tank was wasted manually by means of a 3/4-inch hose leading from the bottom of the tank. Primary sludge was withdrawn twice daily at approximately 9 A.M. and 5 P.M.

The primary clarifier effluent flowed into two completely mixed aeration tanks placed in series. The two cylindrical aeration tanks were constructed of metal and had a combined working volume of 324 liters. Based on influent wastewater flow rates, detention times in the aeration tanks ranged from 5.4 to 27 hours without considering the effect of recirculation. One-half inch copper tubing with 3/16-inch holes was used as air diffusers in the completely mixed tanks. The pH in the aeration tanks was regulated by the addition of soda ash to the first aeration tank. In a manner similar to that used for the addition of alum, soda ash was mixed in a 15 liter vessel by a Talboy Model 102 stirrer and pumped to the aeration tank by means of a Harvard peristaltic pump.

Effluent from the completely mixed aeration tanks passed through a 28-liter plug flow tank prior to entering the secondary clarifier. Three-eighths inch copper tubing containing 3/16-inch holes was used to diffuse air into the tank for mixing and aeration.

The secondary clarifier was identical to the primary sedimentation tank as shown in Figure II. Detention times ranged from 8.5 to 6.5 minutes when considering the effect of recirculation. Overflow rates varied from 610 gallons per day per square foot to 800 gallons per day per square foot. Four plexiglass baffles placed in a nearly vertical position were used to improve settling. Sludge return from

the settling tank back to the first completely mixed aeration tank was accomplished by means of an airlift pump. The average sludge return rate was 2400 ml per minute which gave a recirculation ratio of 12.0 to 2.4, depending upon the influent flow rate. The high return rate was used to prevent clogging of the return sludge line and because of the limitations of the airlift pump.

The samples were filtered throughout the sampling period using Number 40 Wattman filter paper to determine the effect of filtration on the performance of the plant.

The completely mixed aeration tanks were initially seeded with sludge obtained from a small package activated sludge plant operated at a rest stop on Interstate 81 between Christiansburg and Radford, Virginia.

Sampling Procedure

Grab samples were taken every other day at about the time of maximum flow through the main plant to obtain maximum strength sewage. Sampling points were plant influent, primary clarifier effluent, the second completely-mixed activated sludge tank, and the final effluent.

Methods of Analysis

All tests were run immediately after collection and included solids concentrations, pH, SVI, total carbon, and phosphates. The following methods of analysis were used.

1. Total and volatile suspended solids, SVI, phosphates, and the settleability test were run according to the procedures outlined in the 13th Edition of Standard Methods (28). Phosphates were determined by the Stannous Chloride Method. The Potassium Persulfate Digestion Procedure was used to prepare samples for total phosphate determinations.

2. Total carbon was determined by using an Oceanographic Carbon Analyser. The results were recorded on a Beckman 10-inch Potentiometric Recorder. A sample of 10 ml was used for each determination.

3. pH was determined with a Leeds and Northrup pH meter.

4. The microscopic examinations were made with an Olympus Model FH microscope.

All chemicals used in the analyses were reagent grade.

IV. RESULTS

Variation of the Indicated Parameters with Time

The completely mixed activated sludge pilot plant employing alum addition as part of the primary process was operated from June 5 to August 4. The initial three weeks of operation between June 5 and June 26 were used to acclimate the activated sludge and establish a nitrifying biomass. Data were collected between the dates of June 26 and July 25. A stable solids level had been attained at the end of the acclimation period. The activated sludge process was initially seeded on June 5 and reseeded was required on June 11 because of a mechanical malfunction. The mixed liquor suspended solids concentration was 1270 mg/l on June 26.

Primary effluent of the main plant was used as influent to the pilot plant from June 5 to July 18. Flow to the pilot plant was taken from the influent to the primary clarifier of the main plant from July 18 to August 4 to observe the effect of higher nutrient and solids loading on removal efficiencies. In addition, flow rates were increased from an average of 325 ml/min at the beginning of the study to an average of 957 ml/min for the last three testing dates. The day corresponding to the sample numbers used throughout this thesis are given in Table I. Flow rates are presented in Table II.

TABLE I
CORRELATION OF SAMPLE NUMBERS ON ALL GRAPHS
AND TABLES FOR DATA INTERPRETATION

<u>Date</u>	<u>Sample Number</u>	<u>Event</u>
06-5-72		Start of operation
06-6-72		Seed added
06-7-72		Baffles installed in primary clarifier
06-8-72		Began soda ash addition
06-11-72		Reseeded
06-26-72	1	
06-28-72	2	
06-30-72	3	
07-1-72		Baffles installed in final clarifier
07-2-72	4	
07-4-72	5	
07-6-72	6	
07-8-72	7	
07-10-72	8	
07-12-72	9	
07-14-72	10	
07-16-72	11	
07-18-72	12	
07-19-72		Switch to raw sewage as influent
07-20-72	13	
07-22-72	14	
07-25-72	15	End of alum addition
08-4-72		End of operation

TABLE II
DATE AND INFLUENT FLOW RATE
FOR RESPECTIVE SAMPLES

<u>Sample</u>	<u>Date</u>	<u>Influent Flow, ml/min</u>
1	06-26-72	190
2	06-28-72	230
3	06-30-72	330
4	07-02-72	235
5	07-04-72	170
6	07-06-72	355
7	07-08-72	340
8	07-10-72	600
9	07-12-72	425
10	07-14-72	340
11	07-16-72	230
12	07-18-72	460
13*	07-20-72	1110
14*	07-22-72	930
15*	07-24-72	830

* Denotes switch to raw sewage from Stroubles Creek Plant as influent to pilot plant.

It was originally planned to maintain a flow rate to the pilot plant of about 1500 ml/min and use a sludge wasting rate from the primary clarifier of approximately 500 ml/min. This would have given a flow rate to the secondary process of 1 liter per minute. However, this flow rate was found to be an overload for the clarification units, resulting in a carry-over of suspended solids in both the primary and secondary clarifiers. Furthermore, since the pilot plant design relied on sludge wasting by gravity flow, it was not possible to waste sludge on a continuous basis.

Detention times in the aeration tanks varied in accordance with influent flow rates and were expressed with and without the effect of recirculation as shown in Figure IV. Figure V shows detention times in the primary and secondary clarifier when recirculation was not considered. Figure VI, on the other hand, gives detention times in the final clarifier when recirculation at a rate of 2400 ml/min is taken into effect. The minimum detention time in the aeration tanks was 92 minutes and the detention time based on displacement volume in the final clarifier was 6 minutes.

Table III gives the operating parameters for the completely mixed aeration tanks. During the research period the average temperature was 23.4°C and the average pH was 7.5 for the mixed liquor. The SVI values steadily decreased from 185 at the beginning of the study period to a minimum of 69 on the final sampling date.

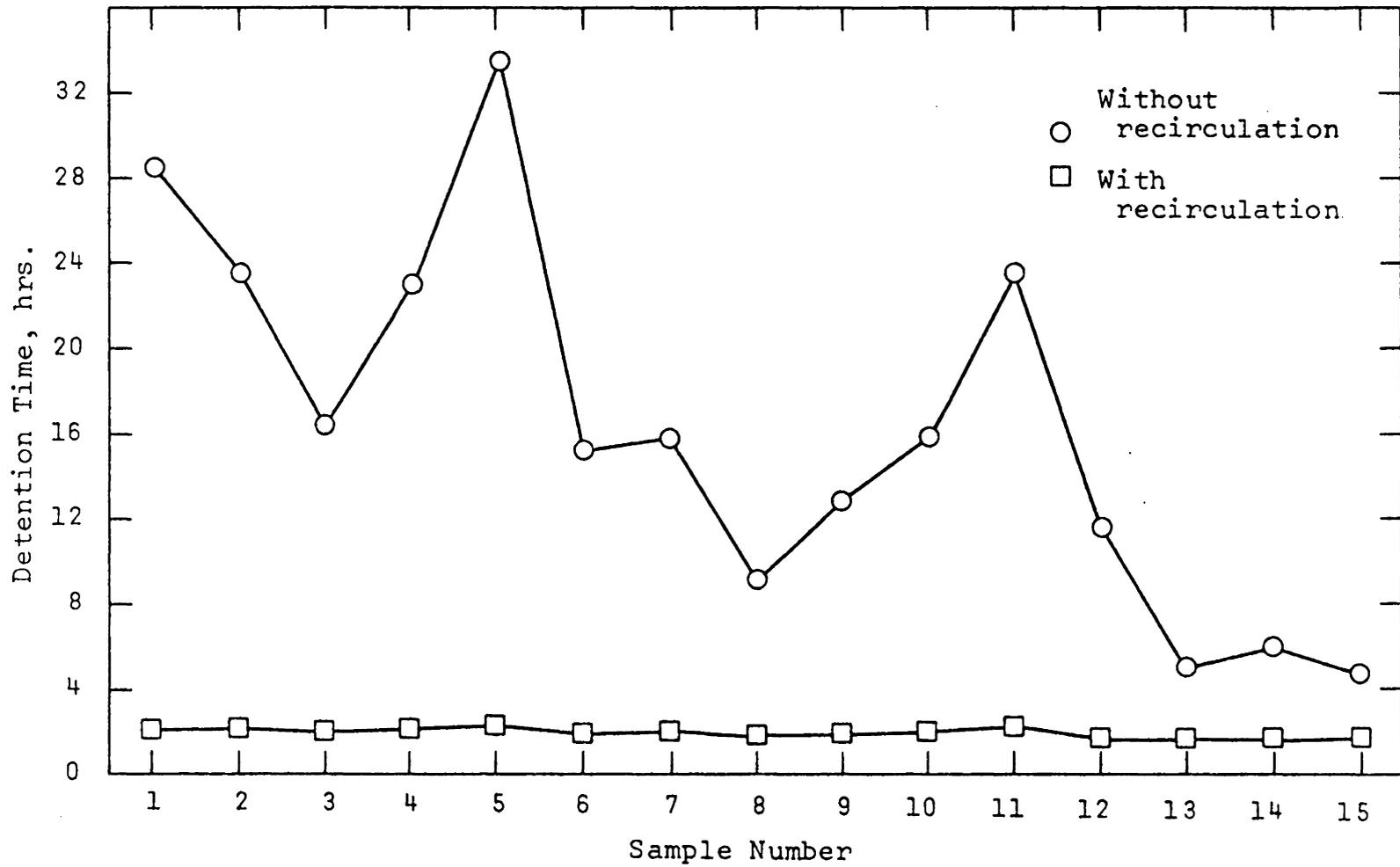


Figure IV. Variation in Detention Time with Time in the Aeration Tanks.

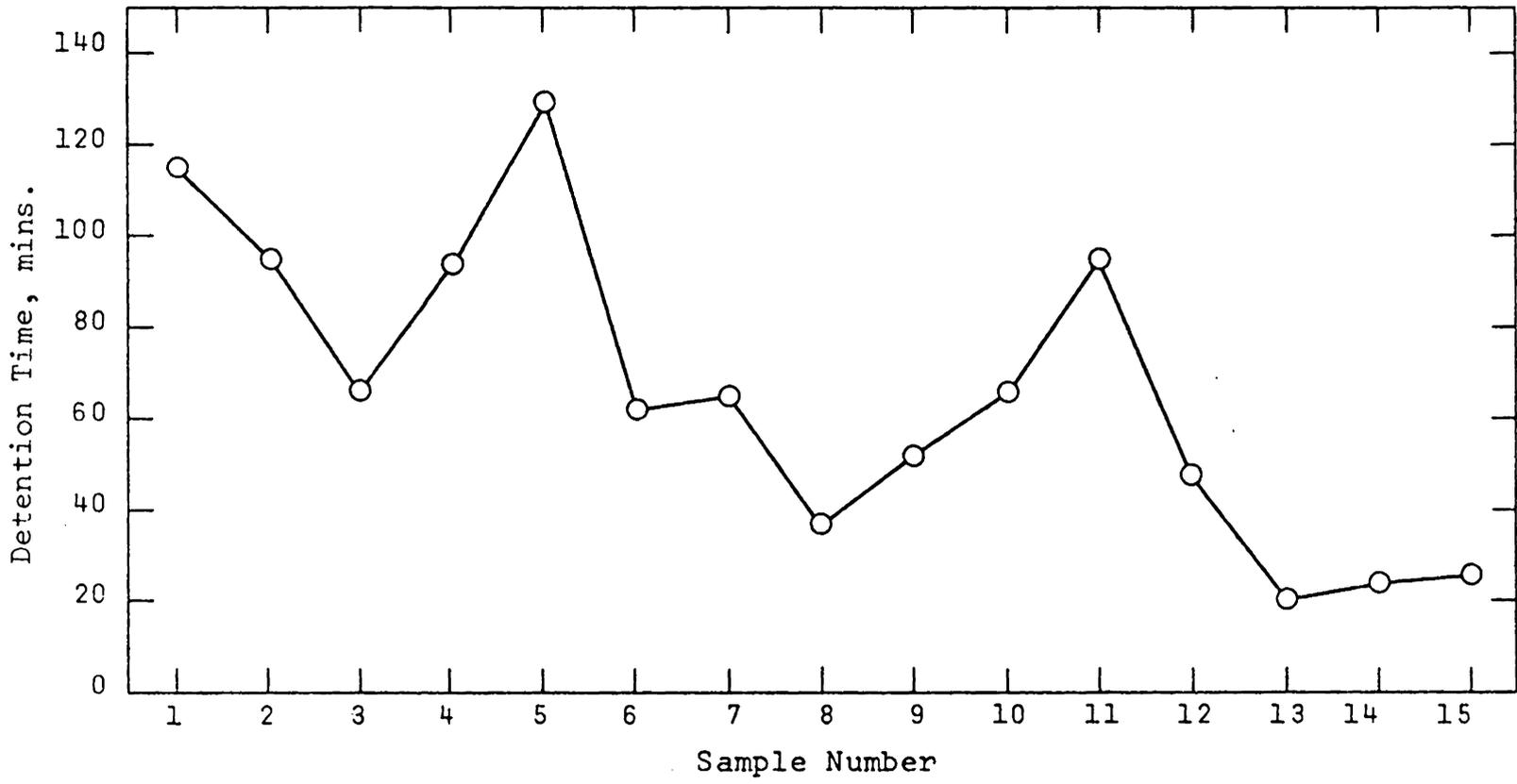


Figure V. Variation in Detention Time with Time for the Primary and Final Clarifiers without Recirculation.

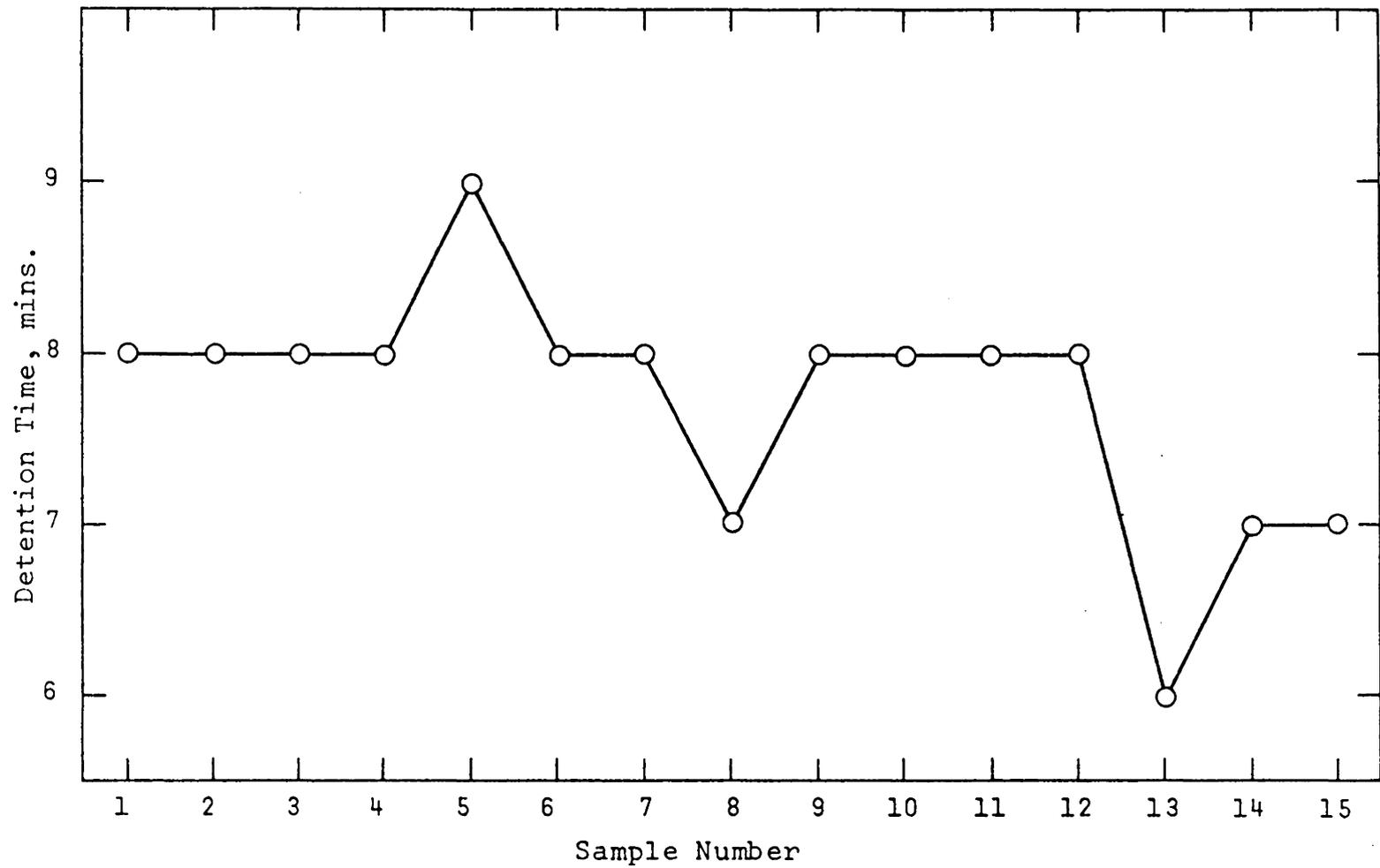


Figure VI. Variation in Detention Time with Time for the Final Clarifier with Recirculation.

TABLE III
MIXED LIQUOR DATA FOR STUDY PERIOD

<u>Sample</u>	<u>MLSS, mg/l</u>	<u>MLVSS, mg/l</u>	<u>SVI</u>	<u>pH</u>	<u>Temp., °C</u>
1	1270	630	173	8.8	-
2	1380	615	149	8.35	-
3	1120	640	188	7.3	-
4	1120	585	174	8.4	-
5	953	503	173	7.55	-
6	1015	690	128	7.6	18°
7	935	515	107	7.8	19°
8	1275	935	78	7.8	22°
9	715	435	126	7.35	24°
10	897	467	100	7.5	23.5°
11	510	340	157	7.7	26°
12	880	400	97	6.5	24°
13	980	620	112	7.3	26°
14	1145	625	87	4.7	25°
15	1440	700	69	7.35	26°

Figure VII shows how the mixed liquor suspended solids concentration varied during the study period. The MLSS concentration averaged 1040 mg/l and never exceeded 1440 mg/l.

Total carbon was determined for the primary effluent and the effluent of the completely mixed aeration tanks on July 20. Analysis revealed a 51 percent reduction in total carbon during the aeration period from an average primary effluent level of 20.2 mg/l to a concentration of 10.0 mg/l for the effluent of the second aeration tank.

The variation in BOD with time is shown in Figure VIII. BOD removal efficiency varied from 68 to 100 percent, with an average removal of 87 percent. Influent BOD values increased significantly from an average of 59 mg/l when primary effluent of the Stroubles Creek Plant was used as influent to the pilot plant to an average of 178 mg/l for the last three sampling dates for which raw sewage was used as the influent.

Figure IX shows the variation in COD during the study period. Percent removals of COD varied from 50 to 100 percent, with an average removal of 79 percent. The highest efficiency of COD removal occurred on the last three sampling dates when influent COD and BOD values were highest. Due to heavy rainfall influent samples were unusually weak in organic content between the dates of July 4 and July 14.

The total phosphate data are shown in Table IV. Influent concentration of total phosphate varied between

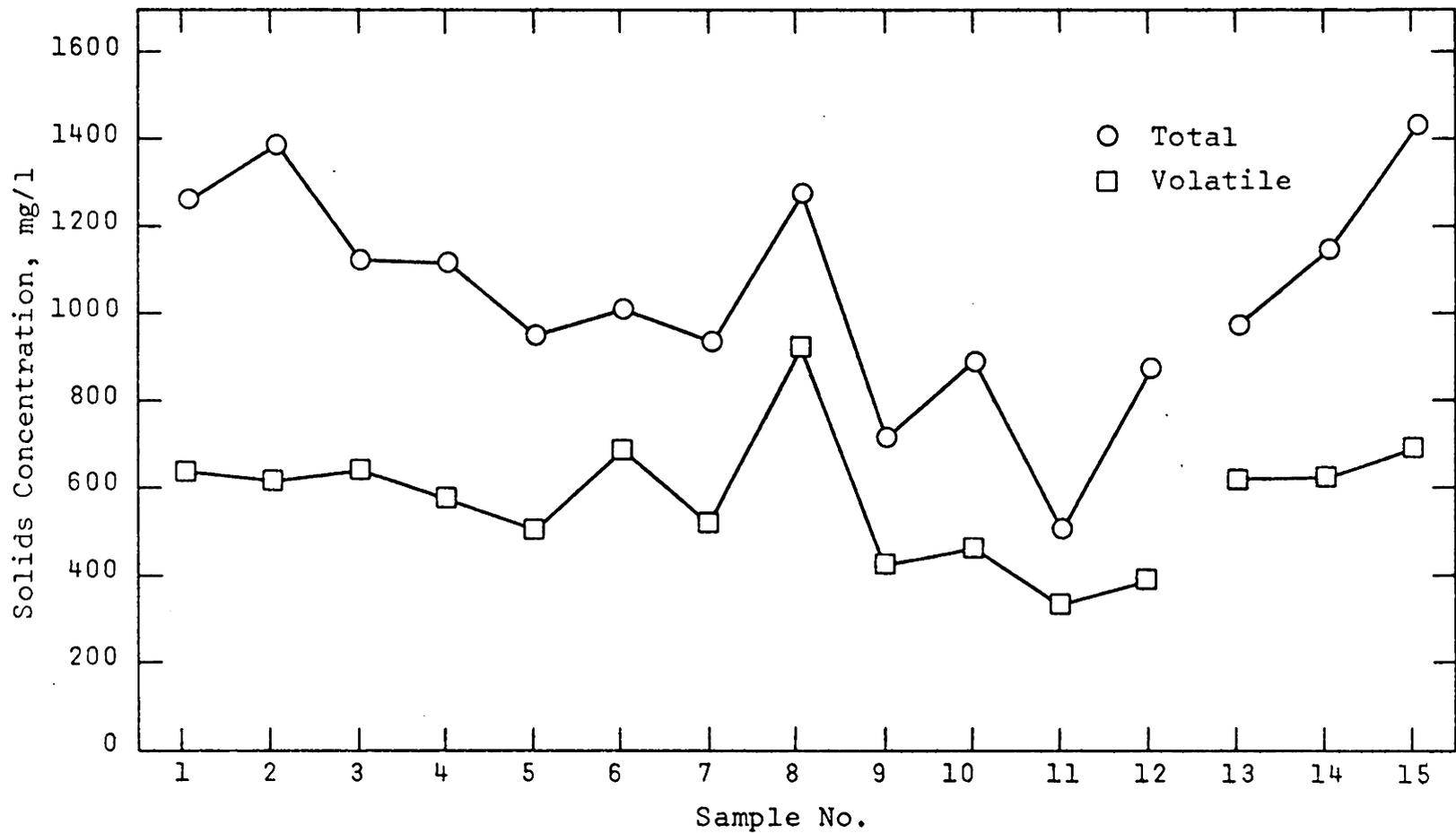


Figure VII. Variation in Solids Concentration of the Mixed Liquor with Time.

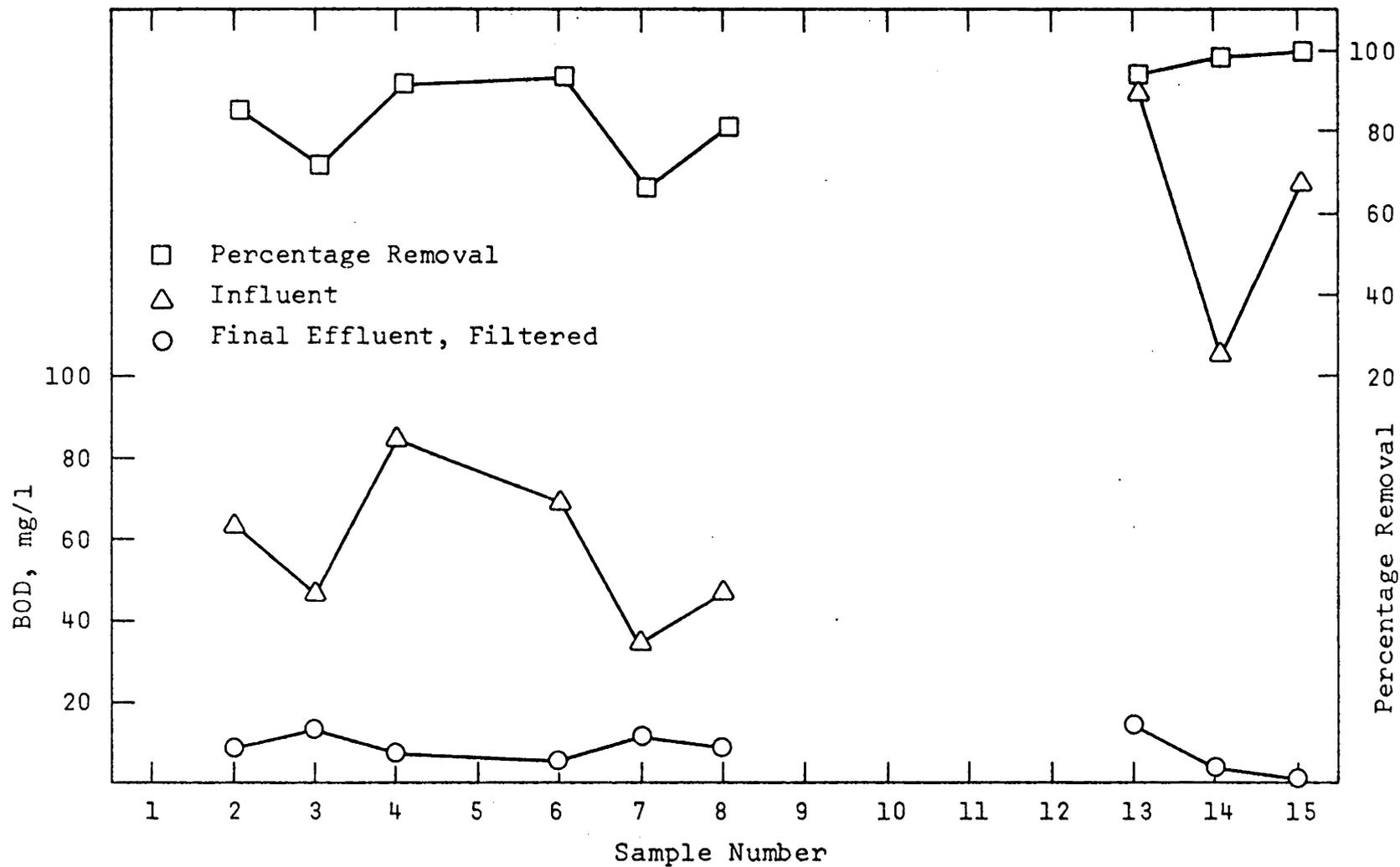


Figure VIII. Variation of BOD with Time.

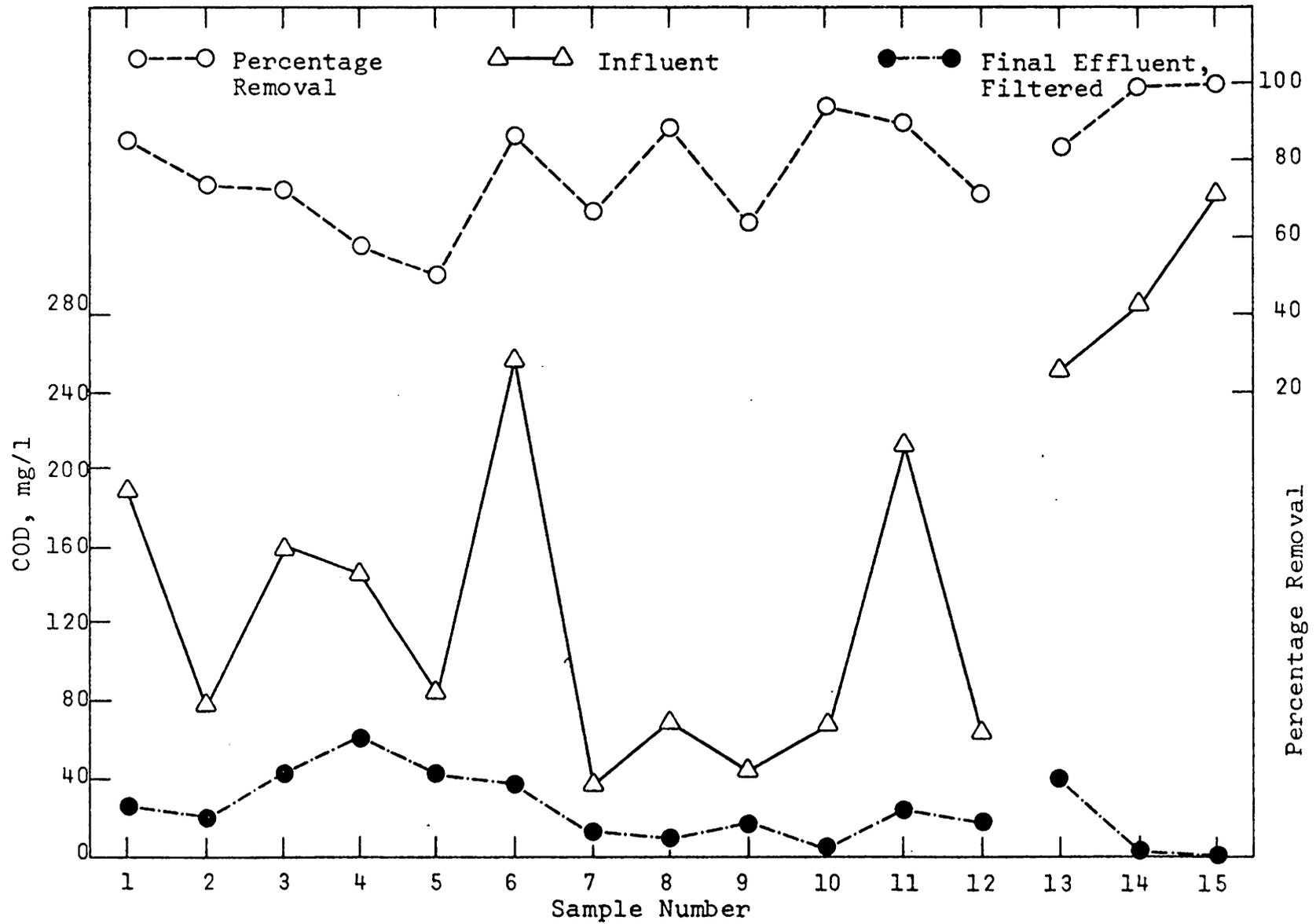


Figure IX. Variation of COD with Time.

TABLE IV

TOTAL PHOSPHATE DATA FOR STUDY PERIOD (mg/l as P)

Sample	Influent	Primary Effluent		Final Effluent		Percentage Removal
		Unfiltered	Filtered	Unfiltered	Filtered	
1	12.0	2.9	1.9	1.5	0.4	97
2	13.3	3.3	2.1	1.6	0.5	96
3	16.4	4.8	3.1	2.8	0.7	96
4	-	-	-	-	-	-
5	19.1	4.7	2.6	5.2	0.5	97
6	24.5	6.4	5.3	9.7	1.1	96
7	13.5	7.6	5.8	8.7	1.8	87
8	18.2	5.7	4.0	6.8	0.9	95
9	8.2	3.5	2.1	4.2	0.8	90
10	6.5	6.4	6.0	4.3	1.8	72
11	17.1	5.3	3.8	6.0	0.8	96
12	9.3	2.6	0.8	2.4	0.2	98
13	14.0	3.2	1.0	2.8	0.2	93
14	19.1	6.4	2.2	2.7	0.1	98
15	11.9	2.9	0.6	2.2	0.5	96

6.5 mg/l and 24.5 mg/l as P while filtered effluent values averaged about 0.7 mg/l. On the average, 68 percent of the total phosphate was precipitated in the primary process while 95 percent was removed by the complete treatment process. The lowest percent total phosphate removal of 72 percent occurred on the tenth sampling date when total phosphate concentration in the influent was also lowest. Figure X shows the variation in total phosphate concentration with time.

Orthophosphate data are presented in Figure XI. The orthophosphate content of the influent averaged 6.7 mg/l as compared to an average total phosphate content of 14.4 mg/l. The average reduction in orthophosphate content during the treatment process was 90 percent with an average orthophosphate residual in the effluent of about 0.4 mg/l. Seventy-nine percent of the orthophosphate was removed in the primary process.

The variation in condensed phosphate and organic phosphate with time is shown in Figures XII and XIII, respectively. Condensed and organic phosphate concentrations were determined on about every third sampling date. Influent concentrations were highly variable with a range of 0.7 to 5.5 mg/l for condensed phosphate and .9 to 10.9 mg/l for organic phosphate. Filtered effluent levels, however, were more consistent with an average of 0.2 mg/l for

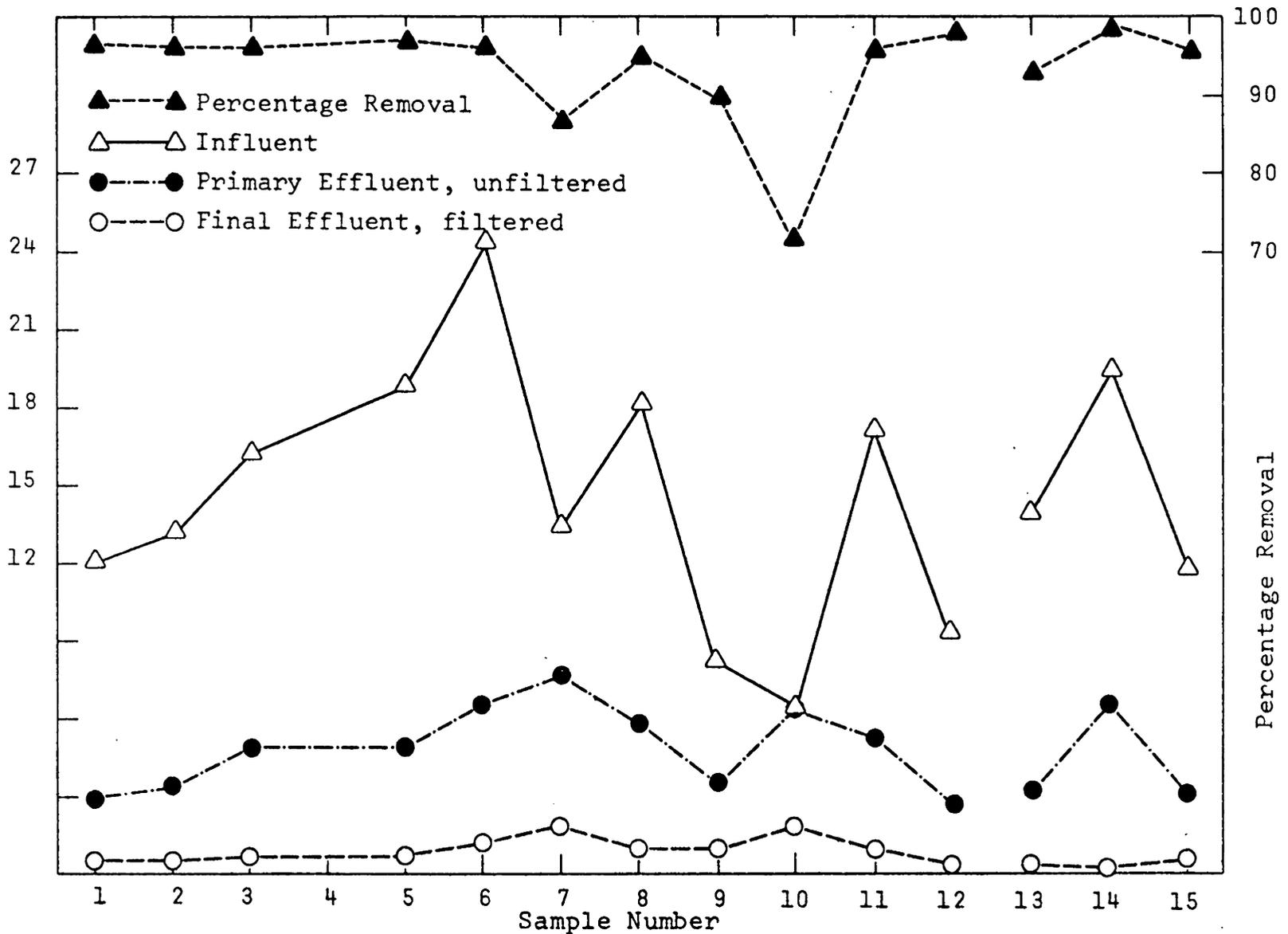


Figure X. Variation of Total Phosphate with Time.

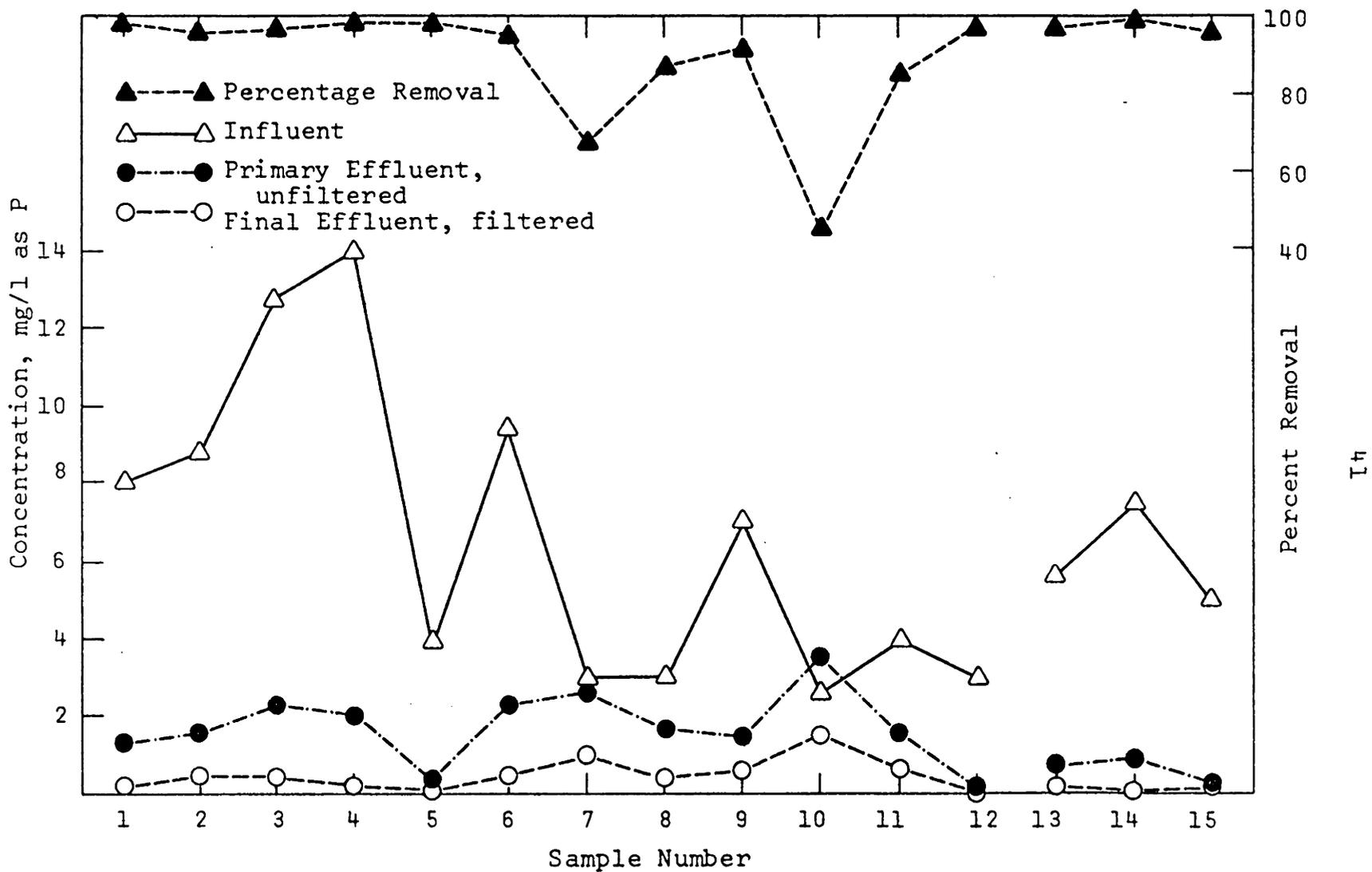


Figure XI. Variation of Orthophosphate with Time.

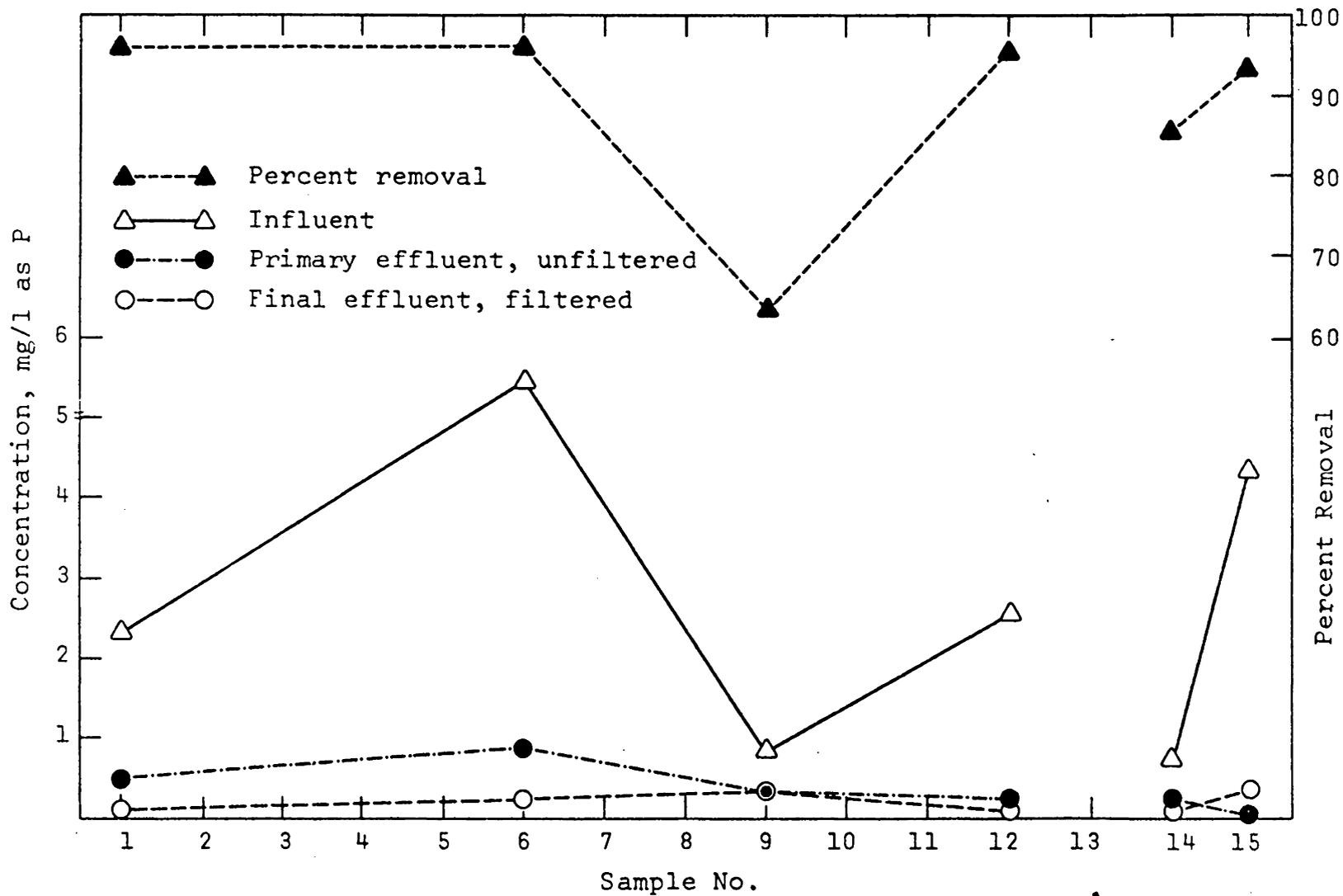


Figure XII. Variation of Condensed Phosphate with Time.

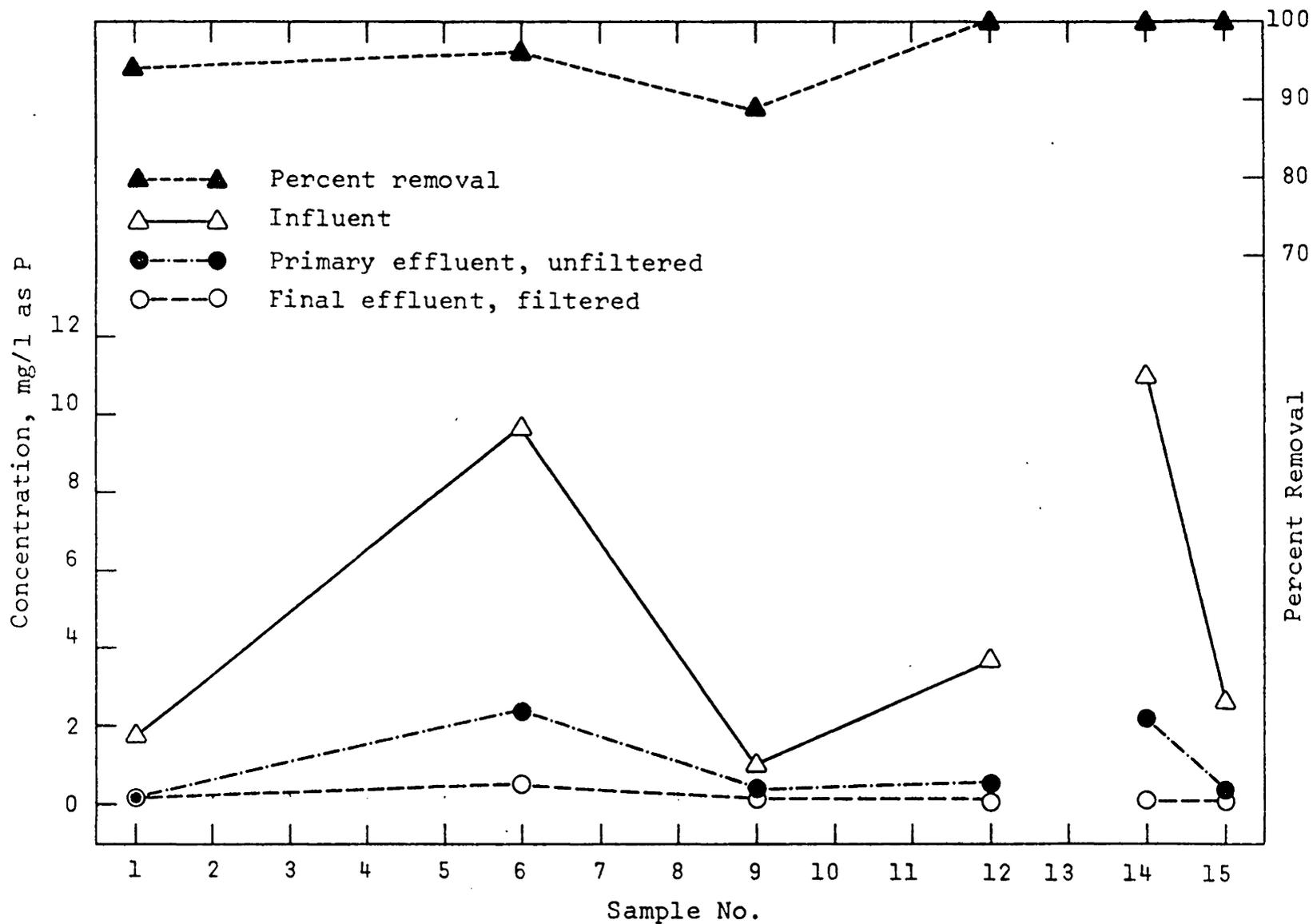


Figure XIII. Variation of Organic Phosphate with Time.

condensed phosphate and an average of 0.1 mg/l for organic phosphate. Removal efficiency averaged 88 percent for condensed phosphate while organic phosphate was reduced by 98 percent.

Removal efficiencies with and without chemical addition must be determined and compared to evaluate the merit of alum addition in removing phosphorus from wastewater. Therefore, the operation of the pilot plant was continued ten additional days after alum addition was discontinued on July 25. The analysis performed on August 4 indicated a reduction in total phosphate of 41 percent without alum addition as compared to an average removal of 95 percent for the study period in which the metallic salt was added. The influent flow rate was 860 ml/min on August 4.

The variation of organic nitrogen levels with time is shown in Figure XIV. Influent concentrations varied between 2.3 mg/l and 9.0 mg/l with effluent values averaging 1.0 mg/l. Approximately 75 percent of the organic nitrogen was removed by the pilot plant.

Figure XV shows how nitrate-nitrogen levels varied over the research period. The average influent value of 2.0 mg/l was reduced to 0.7 mg/l in the primary process. However, the level of nitrate-nitrogen in the filtered effluent rose to an average value of 8.6 mg/l indicating a high level of nitrification in the secondary process.

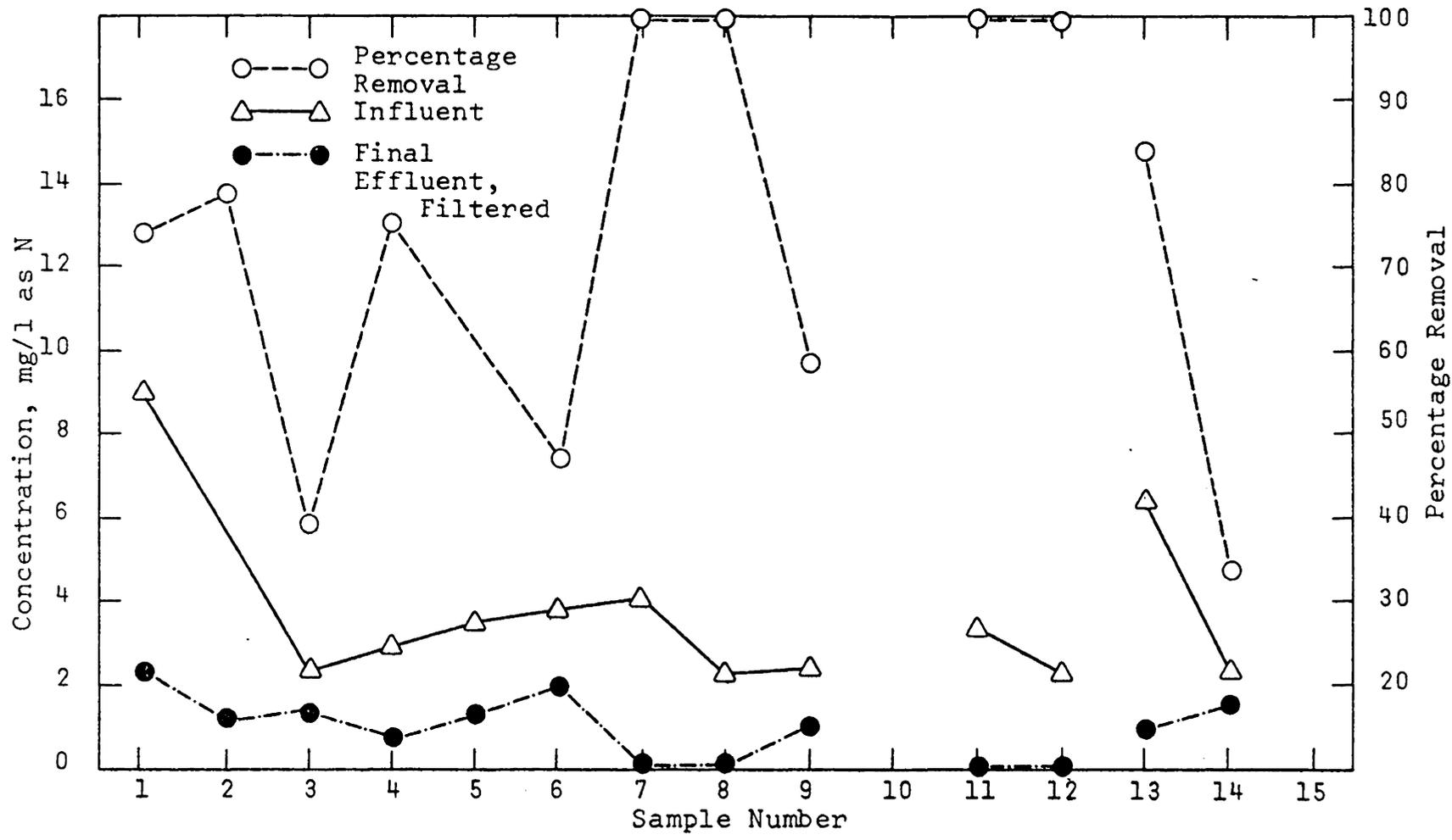


Figure XIV. Variation of Organic Nitrogen with Time.

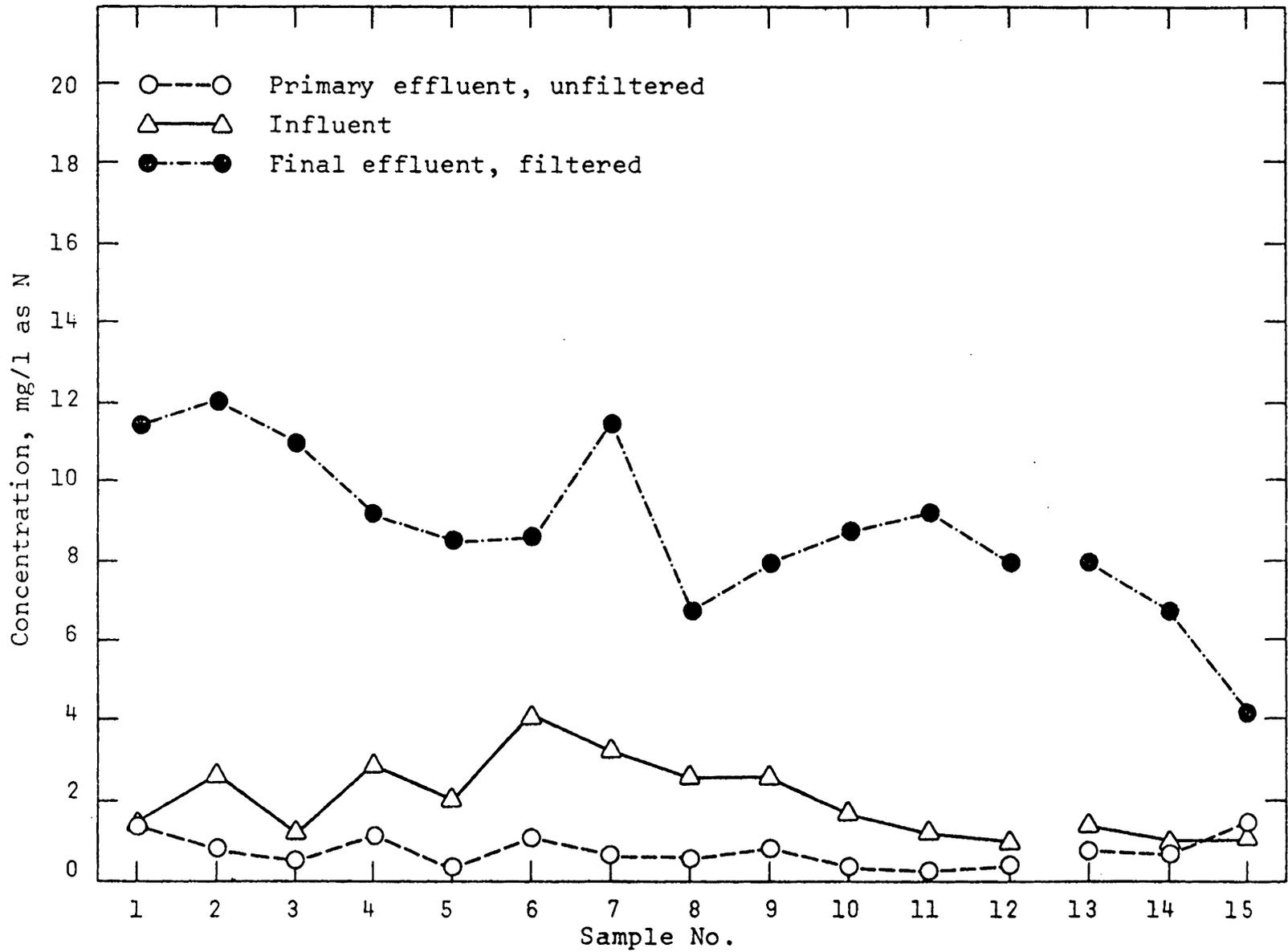


Figure XV. Variation of Nitrate-Nitrogen with Time.

The variation in ammonia-nitrogen with time is presented in Figure XVI. The ammonia-nitrogen level rose from an average influent value of 9.7 mg/l to 11.2 mg/l in the primary effluent and then was reduced to an average value of 0.8 in the final effluent. The overall reduction in ammonia-nitrogen was about 93 percent. The percent of nitrification is also presented in Figure XVI.

Table V shows the average influent, unfiltered primary effluent, filtered final effluent, and percentage removal values for BOD, COD, ammonia-nitrogen, nitrate-nitrogen, organic nitrogen, total phosphate, orthophosphate, condensed phosphate, and organic phosphate during the study period.

Sludge Settleability

SVI determinations on the mixed liquor of the aeration tanks were performed on every sampling date. Figure XVII shows the variation in SVI during the study period. The average SVI for the first five samples was 171 ml/gm and 106 ml/gm for the remaining ten samples.

Settleability tests on the mixed liquor were conducted on July 3 and July 14. The results of the two settleability tests are presented in Figure XVIII. The first test performed on July 3 is representative of the first five samples in which high SVI measurements were recorded while the result of the second test on July 14 is typical of the remaining samples which yielded lower SVI

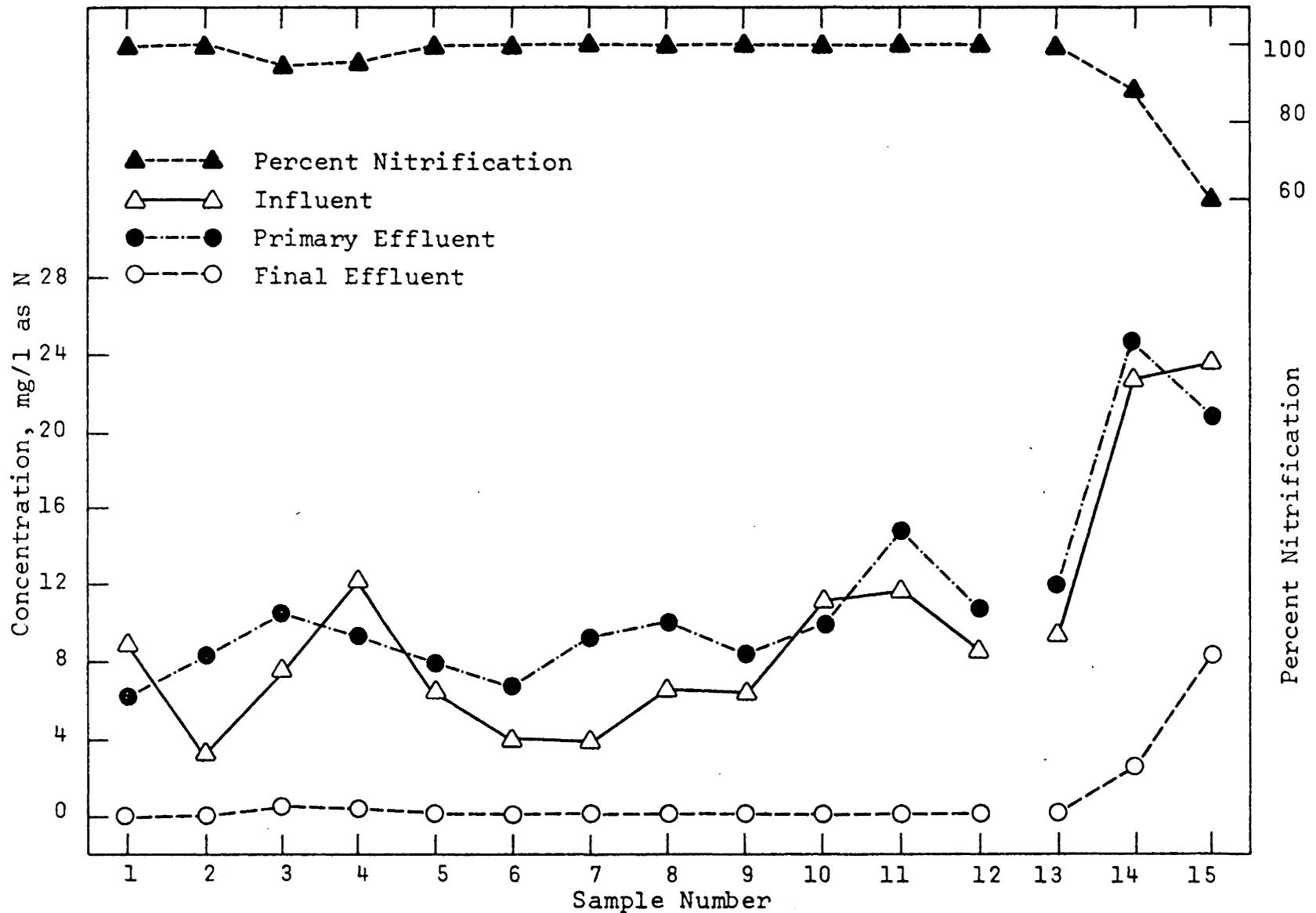


Figure XVI. Variation of Ammonia-Nitrogen with Time.

TABLE V

AVERAGE VALUES OF INDICATED PARAMETERS FOR STUDY PERIOD

<u>Parameter</u>	<u>Influent</u>	<u>Unfiltered Primary Effluent</u>	<u>Filtered Final Effluent</u>	<u>Percentage Removal</u>
BOD, mg/l	98	39	8	87
COD, mg/l	152	74	23	79
Ammonia-nitrogen mg/l as N	9.7	11.2	0.8	93
Nitrate-nitrogen mg/l as N	2.0	0.7	8.6	-
Organic nitrogen mg/l as N	3.9	2.6	1.0	75
Total phosphate mg/l as P	14.4	4.7	0.7	95
Orthophosphate mg/l as P	6.7		0.4	94
Condensed phosphate mg/l as P	2.8		0.2	93
Organic phosphate mg/l as P	4.9	0.7	0.1	98

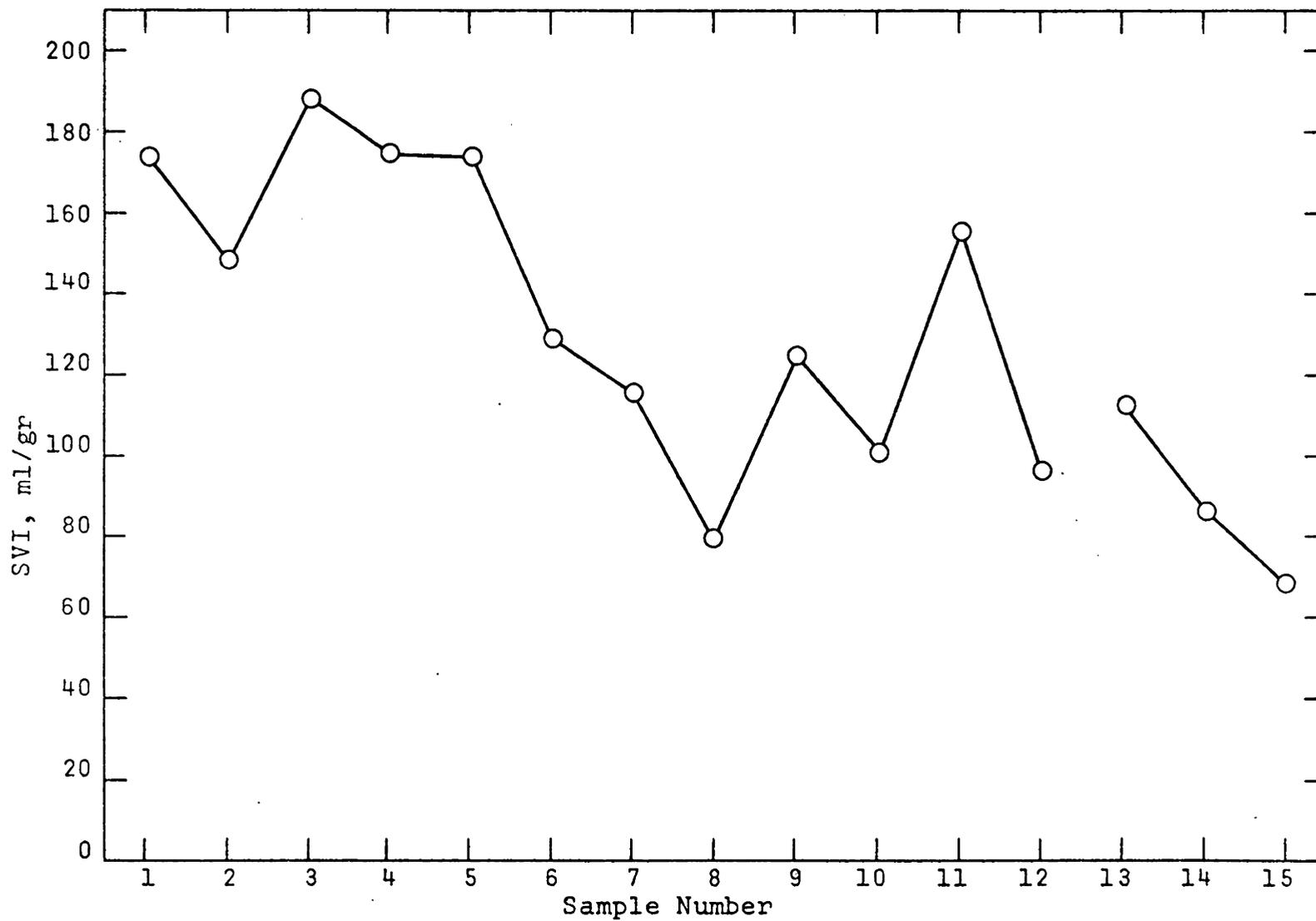


Figure XVII. Variation in SVI During the Study Period.

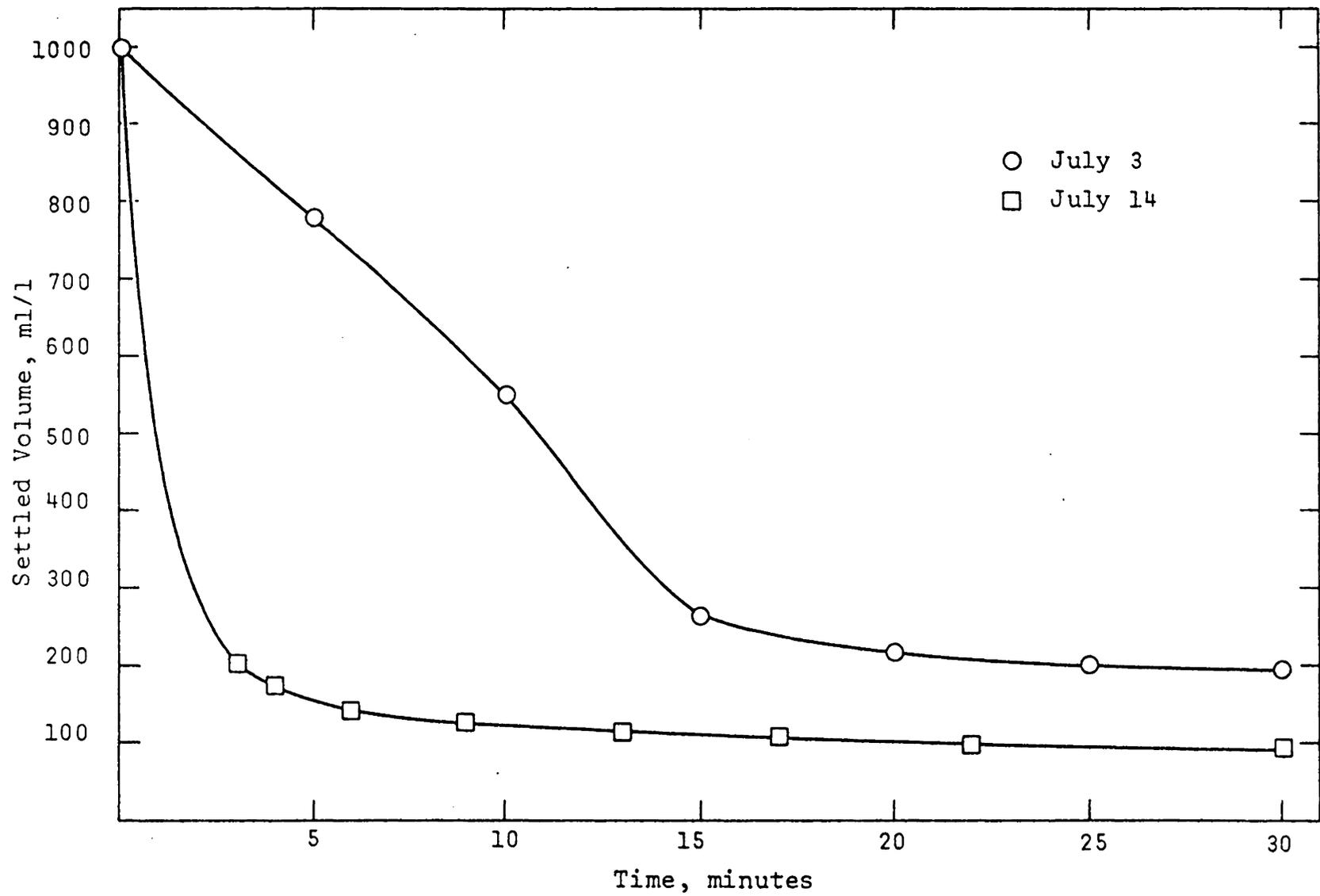


Figure XVIII. Settling Curves for the Mixed Liquor.

measurements.

The mixed liquor suspended solids concentration was about 1000 mg/l on July 3 and approximately 900 mg/l on July 14.

The total and suspended solids data for the study period are presented in Table VI. Total solids was determined for the influent sample while both total and suspended solids were reported for the primary and final effluent samples. There was an increase in average influent total solids from 410 mg/l to 702 mg/l when the switch was made from primary effluent of the main plant to raw sewage. Heavy rainfall from July 4 to July 14 is reflected in the unusually low solids levels in samples 7 through 12. The highest reductions in total solids occurred on the last three sampling dates since raw sewage was the influent to the pilot plant on those dates. Every sample showed an increase in the total solids level after aeration. Better solids removal efficiencies were observed during the final stage of the study period when the alum addition had been discontinued. This indicates that some aluminum hydroxide floc was present in the effluent.

The effect of alum addition on the amount of solids to be wasted in the primary process was also of concern. On July 22 the total solids of sludge wasted in the primary process was 602 mg/l of influent flow. As previously stated,

TABLE VI

SOLIDS DATA FOR STUDY PERIOD (mg/l)

<u>Sample</u>	<u>Influent Total</u>	<u>Primary Total</u>	<u>Effluent Suspended</u>	<u>Final Total</u>	<u>Effluent Suspended</u>
1	583	312	256	518	409
2	672	330	291	570	528
3	620	246	197	573	494
4	478	442	332	554	511
5	284	230	211	538	483
6	444	400	378	484	378
7	338	380	359	400	312
8	318	394	363	416	377
9	366	292	241	406	381
10	260	256	240	338	308
11	288	264	238	314	296
12	278	364	184	426	380
13	604	574	424	534	412
14	742	438	388	652	550
15	760	442	406	703	652

the influent flow rate on July 22 was 930 ml/min and the alum dosage was 240 mg/l. By way of comparison, sludge withdrawn on August 4 ten days after the discontinuance of alum addition contained 181 mg/l of total solids per liter of influent flow. The influent flow rate and influent total solids level was approximately the same for the two testing dates. Alum addition resulted in a 332 percent increase in solids wasted in the primary process. Solids buildup in the secondary biological process was not sufficient to allow wastage of solids from the secondary clarifier on either July 22 or August 4.

Observation of Protozoan Populations

The mixed liquor from the completely mixed aeration tanks was examined microscopically on a weekly schedule. Flagellates were the predominant predators observed at the beginning of the research period. During the middle of the sampling period, rotifers, free-swimming ciliates, and stalked ciliates were the predominant forms of predator organisms. Protozoan populations receded toward the end of the study period with rotifers and stalked ciliates being the predominant forms present.

V. DISCUSSION OF RESULTS

The principal limitations of conventional secondary wastewater treatment processes include poor phosphorus removal and a low degree of nitrification. A typical activated sludge treatment plant, principally designed to remove carbonaceous material, achieves only 20-30 percent removal of phosphorus (8) and normally less than 50 percent nitrification. The results of this pilot plant study indicated that stable, high level treatment can be achieved through the addition of metallic salts prior to primary sedimentation. The quality of the primary effluent was much better than that normally observed for conventional plants employing secondary treatment.

Results of this study indicated that, in addition to high organic removal, chemical precipitation in the primary process was responsible for 93 percent nitrification and a large reduction in the phosphorus content of the raw sewage. The average removal of phosphorus was 68 percent in the primary process and a 51 percent reduction in COD was achieved as shown in Table V. This reduced phosphorus to a level where the concentration of the element was near to being growth limiting in the activated sludge process. The low phosphorus requirements of biological systems as shown by the reported carbon:nitrogen:phosphorus ratio for bacterial sludge of 106:16:1 (6) support the merit of high

phosphorus reductions prior to biological removal. Enhanced phosphorus removal by the addition of alum in the primary process served to reduce the nutrient imbalance which exists in untreated municipal sewage.

The soluble orthophosphate concentration of the influent was reduced by 79 percent during the primary process of flocculation and sedimentation. Adsorption onto aluminum hydroxide floc or incorporation into insoluble metal phosphates was the mechanism responsible for the orthophosphate removal. The use of diffused air for agitation during the flocculation process increased the dissolved oxygen concentration in the primary clarifier and improved flocculation.

Investigation of phosphorus removal in the secondary biological process revealed that further reduction in phosphate content was accomplished by filtration of insoluble forms of phosphorus. Condensed and organic forms of phosphate remaining in the primary effluent were almost completely removed by filtration, with residual concentrations being only 0.2 mg/l and 0.1 mg/l, respectively, as shown in Table V. The reduction in orthophosphate content from an average of 1.4 mg/l in the primary effluent to 0.4 mg/l for the filtered effluent of the completely mixed aeration tanks indicates that microbial activity and/or precipitation as metallic complexes was responsible for removal of at least 1.0 mg/l.

SVI values stabilized after the fifth sampling date and averaged 106 ml/gr with a range from 69 ml/gr to 128 ml/gr for the remainder of the study period. With exception to a low pH reading for the fourteenth sampling day, pH measurements also showed little variation and averaged 7.5. The MLSS concentrations as presented in Figure VII averaged 1040 mg/l and never exceeded 1440 mg/l.

By employing chemical addition in the primary process, treatment can easily be adjusted to accommodate qualitative and quantitative shock loadings. Enhanced primary sedimentation with the use of metallic salts greatly reduces the fluctuations normally placed upon the more sensitive biological process. It is important to note that phosphorus removal by the Stroubles Creek pilot plant was not dependent upon the unpredictable luxury uptake phenomenon.

Carbon analyses indicate that low volatile solids production in the secondary biological process was attributed to low concentrations of carbonaceous material in the primary effluent. The low primary effluent carbon concentration of 20 mg/l limited cell synthesis and the consequent uptake of nutrients in the activated sludge. The 10 mg/l of organic carbon residual in the filtered effluent was thought to be mostly biologically stable substances since this level of organic material was not reflected in the biochemical oxygen demand.

Because of the extremely low yields of biological solids in the secondary process sludge wastage was not required. The low sludge yields would be very desirable in the operation of a wastewater treatment plant because sludge handling would involve a greater proportion of relatively easy-to-handle primary sludge than would be encountered with conventional biological treatment. An additional benefit of low biological solids production is that a sludge age of sufficient length to insure a nitrifying bacteria population can easily be maintained.

Although settling in the final clarifier was improved with the addition of baffles, the final effluent lacked clarity throughout the study period. The light pinpoint floc observed in the final effluent was thought to be aluminum hydroxide floc. According to Mulbarger and Shifflett (29) excessive effluent solids is usually due to failure to maintain the proper ratio of volatile solids produced to aluminum added. They reported soluble effluent aluminum concentration of 0.3 mg/l and higher as coinciding with high effluent suspended solids. In the Stroubles Creek pilot plant study, no attempt was made to regulate the alum dosage as a function of biological solids production.

Floc disintegration as a result of violent agitation or solids recycle also leads to degradation of effluent quality. Although the velocity gradient in the aeration

chamber of the pilot plant was not determined, shear values could have been great enough to break up the relatively weak aluminum hydroxide floc. Fair and Geyer (30) concluded that a velocity gradient exceeding $75 \text{ ft}/(\text{sec})(\text{ft})$ will initiate chemical floc disintegration. A practical approach to the reduction in the carry over of pinpoint floc in the effluent is to provide a period of gentle solids agitation preceding final clarification to promote reflocculation of chemical-biological solids.

Microscopic examination revealed an evolution in the protozoan populations of the activated sludge during the study period. The presence of the flagellates at the beginning of the study is generally associated with low efficiency of organic removal in the aeration units. The transition to more efficient removal of organic matter was evidenced by the predominance of free swimming ciliates in the middle of the research period. Stalked ciliates and rotifers as observed near the end of the study are associated with the high side of the treatment efficiency scale (26). Microscopic examinations indicate that the activated sludge organisms had not reached their potential for organic removal until the final phase of the study.

From the preceding discussion chemical precipitation of phosphorus in domestic wastes as a part of primary treatment appears to be a highly efficient and practical

means of reducing phosphorus concentrations in wastewater effluents. The chemical precipitation process is adaptable to existing wastewater treatment plants with a minimum amount of capital outlay required for equipment. The process can also be incorporated into the design of new plants as an effective means of upgrading wastewater quality.

VI. CONCLUSIONS

1. Enhanced primary sedimentation by the addition of alum can increase phosphorus removal from the 20-30 percent removal normally achieved in conventional activated sludge plants to 95 percent as accomplished by the Stroubles Creek pilot plant.
2. Sixty percent BOD removal and 68 percent phosphorus removal as achieved in primary treatment greatly reduce the burden on the secondary biological process. Such high removals of organic and nutrient loading in the primary process contribute to the stability of the system and insure a consistently high level of treatment.
3. Wastewater treatment by chemical precipitation is reliable and predictable.
4. A high degree of nitrification can be achieved by the chemical precipitation treatment system proposed in this study because of the decreased biological solids production in the secondary process.
5. Chemical precipitation by the addition of alum in the primary process can be adapted to existing plants or incorporated into the design of new plants with a minimum of capital outlay and additional equipment required.

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THE OPERATION OF A COMPLETELY MIXED
ACTIVATED SLUDGE PILOT PLANT EMPLOYING
ALUM ADDITION FOR PHOSPHORUS REMOVAL

by

David Lee Foley

(ABSTRACT)

The public concern which has materialized in recent years regarding the quality of the nation's surface waters has created a need to upgrade wastewater treatment processes. New treatment objectives, in general, relate to the removal of phosphorus, achieving nitrification, and essentially eliminating the carbonaceous oxygen demand of wastewaters prior to discharge. The objective of this study was to operate a pilot plant scale activated sludge type treatment plant, using domestic sewage and employing alum as a coagulant in the primary process. Alum addition and flocculation were provided prior to a conventional primary clarification process. The secondary treatment consisted of a combination of the complete-mixed and plug-flow process operated in series.

It was found that this treatment scheme was capable of removing 95 percent of the total phosphate content of the municipal wastewater in contrast to the 20 to 30 percent removal normally provided by conventional activated sludge plants. The more efficient primary process gave an average reduction in phosphorus of 67 percent. The reduced

carbonaceous and nutrient load to the secondary biological process provided more complete phosphate removal and resulted in a reduction in hard-to-handle secondary sludge. In addition to consistently high removals of phosphorus, the pilot plant achieved 93 percent nitrification and reduced influent BOD by 87 percent, on the average.

Chemical precipitation was found to be a stable and predictable means of upgrading the effluent of conventional secondary wastewater treatment plants. With a minimum of equipment and capital outlay, the chemical precipitation scheme could be adapted to existing plants or incorporated into the design of new plants.