Title: Optimization of The Two Stage Alum Phosphorus Removal Process Using Linear Programming Techniques

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OPTIMIZATION OF THE TWO STAGE ALUM PHOSPHOROUS REMOVAL PROCESS USING LINEAR PROGRAMMING TECHNIQUIES

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OPTIMIZATION OF THE TWO STAGE ALUM PHOSPHOROUS REMOVAL PROCESS USING LINEAR PROGRAMMING TECHNIQUES

by

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This paper is based on the analysis of data collected during the operation of the Rock Creek Facility through two summer permit seasons. The dedication of all of the operators, plant supervisors, laboratory analysts, and the process control analyst to collect, analyze, and document the many data points is the sole reason for the successful operation of the treatment facility as well as the quality of data used in this paper.

I would like to thank everyone at Unified Sewerage Agency for their support and ideas during the development of the concepts outlined in this paper, as well as their support and understanding of my continuing education.

A special thanks and acknowledgement must go to Carlo Spani who really taught me how the process works and spent many hours working with me throughout this project. I would not have been able to complete this work without his input and personal dedication to knowledge and learning.

Finally, a special thanks to my wife, Marianne, and my children Matthew and Anna for their patience and unselfishness to give me the time and support to perform this work.

PREFACE

The Rock Creek Facility is a 20 MGD tertiary treatment facility located in Hillsboro, Oregon. The drainage basin for the treatment plant contains the rapidly growing area west of Portland and includes the Sunset Corridor. Population growth has been rapid during the past 5 years and will continue in the future. The effluent from the treatment plant is discharged directly to the Tualatin River. The Tualatin River is an extremely sensitive receiving stream. The river's flow gets very low during the summer months resulting in the river acting more like a lake than a river. Additional river flow is augmented through stored water from a dam on its upper reaches that allows a minimum flowrate of 150 cfs to be maintained. Even at this flowrate, the wasteload on the river from 5 treatment facilities requires advanced treatment processes or no discharge from the facilities during this low flow period.

The Rock Creek AWTP currently treats to a level much higher than the Environmental Protection Agency's secondary treatment standards. The plant is required to treat to a level of 7.5 mg/l Biochemical Oxygen Demand (BOD), 7.5 mg/l Total Suspended Solids (TSS), 1.5 mg/l Free Ammonia (NH_3), and 1.5 mg/l phosphorous (PO_4). The plant must meet a new permit standard for phosphorous beginning May 1, 1993. This standard will require PO_4 concentration of less than 0.1 mg/l. This is one of the most stringent effluent parameters for phosphorous removal in the United States.

A pilot plant was operated in 1987 to determine the most cost effective method for treating the waste to the required high levels of phosphorous removal. The pilot demonstrated that the most cost effective process for phosphorous removal was the two stage alum addition process. Alum, coupled with the activated sludge process, has been used frequently throughout the United States to meet effluent limits in the range of 1.0 mg/l, but not to meet the low levels below 0.1 mg/l. The use of the two stage alum process in this instance will be unique. A facility implementing this process has been designed and is currently under construction. The facility will be completed and placed into operation to begin treating to the new effluent limits beginning May 1, 1993.

This paper is based on the full scale pilot operated during the summers of 1990 and 1991. This pilot was operated to develop an understanding of the two stage alum phosphorus removal process, develop operating experience on a full scale basis, and to determine the effect of the high quality effluent on the receiving stream.

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LIST OF ABBREVIATIONS

A_i	Alkalinity Concentration, mg/l
Al	Aluminum
$Al_{applied}$	Aluminum Applied
Alum	Aluminum Sulfate
$Alum_{applied}$	Alum Applied
BIOALK	Biological Uptake of Alkalinity in the Aeration Basin, mg/l
$CaCO_3$	Calcium Carbonate
C_i	Phosphorus Concentration, mg/l
$L_{applied}$	Lime Applied
lb	Pound or Pounds
L_i	Lime Feed Dosage, mg/l
MGD	Million Gallons per Day
mg/l	Milligrams per liter
P	Elemental Phosphorus
PO_4	Total Phosphorus
P_{rem}	Phosphorus Removed
RHS	Right Hand Side Variable
W_i	Alum Removal Ratio ($P_{rem}/Alum_{applied}$)
X_i	Alum Feed Dosage, mg/l

ABSTRACT

OPTIMIZATION OF THE TWO STAGE ALUM PHOSPHORUS REMOVAL PROCESS USING LINEAR PROGRAMMING TECHNIQUES

BACKGROUND

New permit standards based on the Total Mass Discharge Limits (TMDL) for the Tualatin River will require Unified Sewerage Agency's Rock Creek and Durham Treatment Facilities to discharge effluent phosphorus (PO_4) concentrations less than 0.1 mg/l by May 1993. Various process alternatives were evaluated by the Agency's consultants using bench scale jar tests and pilot testing. The two stage alum process was selected as the preferred alternative. Facilities have been designed and are currently under construction to meet the new discharge standard using this process.

Minor modifications to the existing facility were made and the two stage alum process was operated for three months during the summer of 1990 and six months during 1991 to evaluate the operation of the process on a full scale basis (14.5 mgd). Data from the full scale pilot was evaluated and an optimization model using linear programming techniques was developed to optimize chemical addition.

Linear Programming (LP) is a mathematical procedure for determining optimum allocation of scarce resources. This modeling technique is used extensively in manufacturing and the petroleum industry. The use of these procedures in optimizing chemical feed in plant operations in the wastewater industry is unique.

OBJECTIVE

This paper discusses the development of a linear model for operation of the two stage alum phosphorous removal process at the Rock Creek Treatment Facility. The model runs on an IBM compatible microcomputer using a student version of the program LINDO (Linear, Interactive, Discrete, Optimizer).

The objective function for this optimization model minimizes the costs for the process by minimizing the dosages for alum and lime to the process stream. The units of the objective

function are dollars. The model minimizes the cost of chemical addition at each of the potential feed points for both alum and lime. The objective function will determine the cost to treat one MGD. The cost multiplied by the plants flowrate will give the total cost of chemicals for treatment.

The models constraints are those factors that have a direct relationship to the PO_4 concentrations before and after each unit process and the chemical dosages. Examples of model constraints are influent PO_4 concentration, desired effluent PO_4 concentration, pumping rate limitations, alkalinity requirements, and the necessary alum dosages and PO_4 removal rates at each process point.

The model was calibrated and represents the actual field conditions that occur during full scale operation of the treatment plant. Use of this model during the operation of the plant has provided for better understanding of the interrelationships that occur at each of the processes and has identified points where the plant staff can work to lower the overall chemical usage.

The critical process parameter that should be used as the target parameter for optimization of this process is the secondary effluent PO_4 concentration. Maximizing the phosphorus removed by the secondary treatment process resulting in the lowest possible secondary effluent PO_4 concentration will give the lowest treatment cost.

INTRODUCTION

This paper summarizes the development of the linear model for operation of the two stage alum phosphorous removal process at Unified Sewerage Agency's Rock Creek Facility. The model runs on an IBM compatible microcomputer using a student version of the program LINDO (Linear, Interactive, Discrete, Optimizer).

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This paper will discuss the development and operating results for this model. This model can be used by process analysts to evaluate the feasibility for obtaining low level phosphorus concentrations utilizing the two stage alum phosphorus removal process.

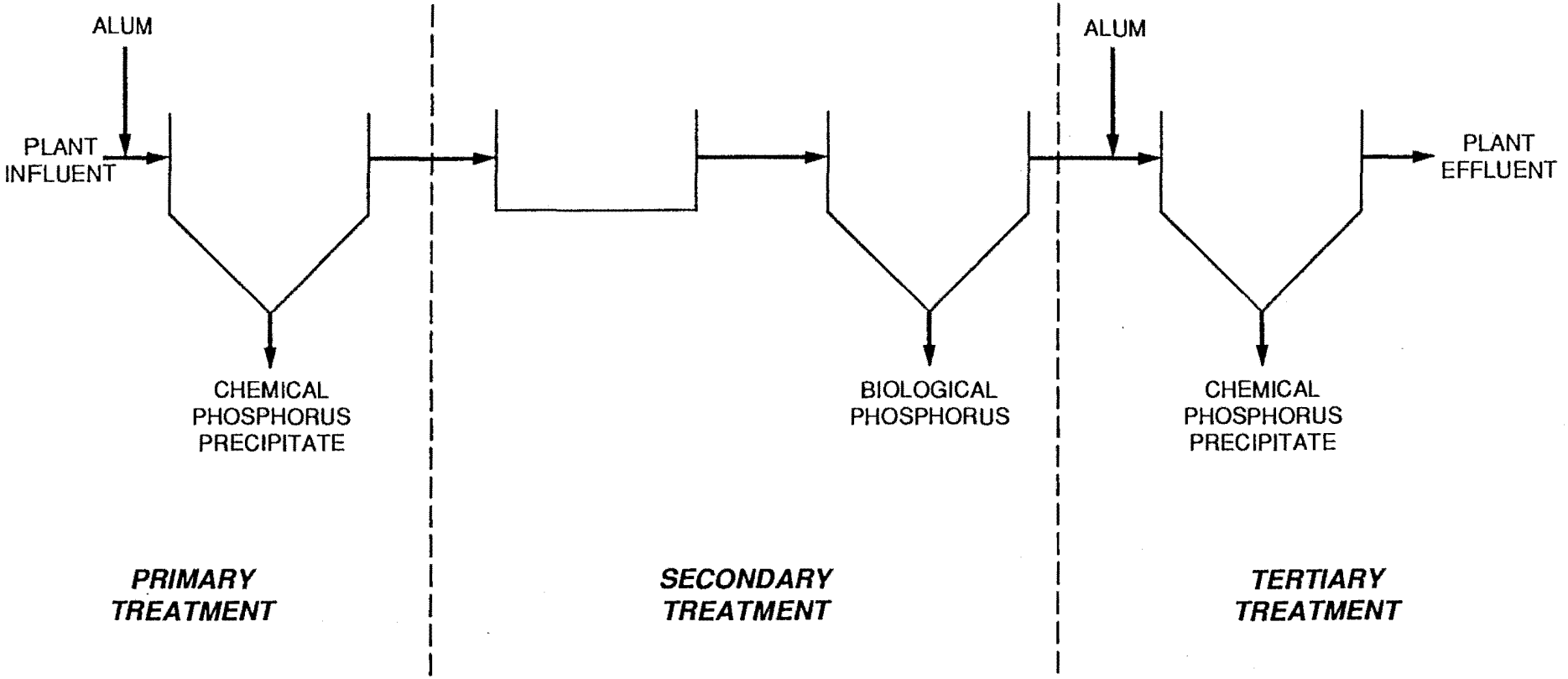
PROCESS DESCRIPTION

Phosphorus removal from wastewater requires the conversion of phosphorus into a particulate form and then the removal of the particulates from the wastewater. The types of particulates that phosphorus can be converted to in a wastewater treatment facility are either chemical or biological. These particulates are then removed from the wastewater resulting in lower phosphorus concentrations in the treatment plants effluent.

The two stage alum phosphorus removal process shown in Figure 1, utilizes the addition of alum for chemical removal of phosphorus in the primary and tertiary processes and the biological removal of phosphorus in the secondary process. The removal capability of phosphorus in each of these three processes has an effect the other two processes. For

Figure 1

TWO STAGE ALUM PHOSPHORUS REMOVAL PROCESS



Unified Sewerage Agency

example, if less phosphorus is removed in the primary process, then the secondary and tertiary processes must remove more to meet the required effluent standard. The intent of the model discussed in this paper is to develop an algorithm for predicting the phosphorus removal for each of these three processes and determine the chemical dosages at the primary and tertiary processes that will minimize the amount of chemicals used while meeting the desired effluent standard.

CHEMICAL PRECIPITATION OF PHOSPHORUS USING ALUM

Two major reactions that occur when alum is added to a phosphorus containing water are the alum with the phosphorus and the alum with the alkalinity in the water. The alum also reacts with other constituents in the water to a lesser extent. The two major reactions of the alum with the phosphorus and alkalinity will be discussed here. The effect of the reaction of alum with the other constituents in the water along with the efficiencies of these reactions will be taken into consideration during the development of the algorithms.

Phosphorus Chemistry

Phosphorus is found in wastewater in three principal forms: orthophosphate ion, polyphosphates, and organic phosphorus compounds. In raw sewage there are substantial amounts of all three of these phosphorus forms. Because the phosphorus is present in more than one form, both organic and inorganic, the only satisfactory measure of treatment plant removal efficiency must be based on the total phosphorus entering the plant in the raw wastewater and the total phosphorus discharged in the plant effluent. Therefore, phosphorus as described in this paper will always be in the form of total phosphorus and symbolized with PO_4.

Phosphorus Precipitation Using Alum

Aluminum ions combine with phosphate ions to form aluminum phosphate as follows:

$$AL^{3+} + PO_4^{3-} \text{-------} > AlPO_4$$

The above equation indicates that the mole ratio for $AL:PO_4$ is 1:1. Inasmuch as the mole ratio for $P:PO_4$ is also 1:1, the mole ratio for Al:P is 1:1 or Al/P = 1, when both aluminum and phosphorous are expressed in terms of gram-moles or lb-moles. On a weight, rather that a mole basis, this means that 27 lb of Al will react with 95 lb of PO_4 to form 122 lb of $AlPO_4$. Since each 95 lb (1 lb-mole) of PO_4 contains 31 lb (1 lb-mole) of P, the weight relationship between Al and P is 27 lb of Al to 31 lb of P or 0.87 for this reaction.

The principal source of aluminum for use in phosphorus precipitation is "alum", a hydrated aluminum sulfate, having the approximate formula $Al_2(SO_4)_3 \cdot 14H_2O$ (molecular weight of 594). The liquid form of the chemical, which is also known as "filter alum", averages about 17% soluble aluminum expressed as Al_2O_3 or 9.1% expressed as Al. Its reaction with PO_4^{3-} may be written as follows:

$$Al_2(SO_4)_3 \cdot 14H_2O + 2PO_4^{3-} \text{-----} > 2AlPO_4 + 3SO_4^{2-} + 14H_2O$$

The sulfate remains in solution as SO_4^{2-}. The above reaction indicates that 1 lb-mole of alum (594 lb) will react with 2 lb-moles (190 lb) of PO_4^{3-} containing 62 lb phosphorus to form 2 lb-moles (244 lb) of $AlPO_4$. The weight ratio of alum to phosphorus is, therefore, 9.6:1.

To summarize this information for use in this paper,"stoichiometricly", 1 mole of aluminum (Al) is required to react with 1 mole of phosphorus (PO_4) and 9.6 lb of alum will react with 1 lb of phosphorus. Therefore, using a standard volume of 1 liter, 9.6 mg/l alum will react with 1 mg/l phosphorus.

Alkalinity Reduction

The solubility of the aluminum phosphate precipitate is dependent on the pH of the water. The optimum pH for removal of phosphorus by precipitation is between a pH range of 5.5 - 6.5, although removals will occur above a pH of 6.5. The alkalinity of the water is a measure of the waters capability to buffer changes in pH. Addition of alum to a water will lower the pH of the water because of neutralization of the alkalinity and release of carbon dioxide. This reaction is as follows:

$$Al_2(SO_4)_3 \cdot 14H_2O + 6HCO_3^- \text{-----} > 2Al(OH)_3 + 6CO_2 + 14H_2O + 3SO_4^{2-}$$

Alkalinity consumption by this reaction is theoretically 0.5 mg/l as $CaCO_3$ per mg/l alum added, but this is subject to competition for the aluminum ions from other side reactions. Jar testing on the wastewater at the Rock Creek Facility shows that using the value of 0.5 mg/l is acceptable. This value will be used in this model with no further analysis.

PHOSPHORUS REMOVAL UTILIZING BIOMASS CONVERSION

Phosphorus is removed in the secondary treatment process utilizing the activated sludge process. In this process, primary effluent is mixed with an aerobic biomass and aerated. After an aeration period of 6 - 8 hours the aerobic biomass is settled from the wastewater and returned to the aeration basin influent leaving a relatively clear effluent. During the aeration period, the biomass feed on the organic material in the wastewater. The biomass utilizes the organics for food providing the biomass an opportunity to grow and reproduce. The biomass is wasted (pumped from) the system to maintain a predetermined ratio of biomass to incoming organics.

As the biomass metabolizes the organic material in the wastewater, it requires nitrogen, phosphorous, and trace metals to sustain its growth. Therefore, the growth of biomass in the system utilizes phosphorus and the wasting of the biomass removes the phosphorus that has been converted to biomass. The standard rule of thumb for phosphorus required in a conventional secondary treatment process, such as that utilized at the Rock Creek Facility, is 1 part phosphorus to 100 parts of organic. Recent developments in this area of treatment technology

provides for phosphorus removal rates that exceed this rule of thumb. The Rock Creek Facility has an anoxic zone incorporated into its aeration basin design which provides an environment for additional phosphorus uptake, depending on the mode of operation.

The Rock Creek Facility is also required to remove ammonia nitrogen (NH_3-N). The secondary treatment process is also being utilized to remove the NH_3-N by conversion to nitrate (NO_2-N) through the biological process of nitrification. During this conversion of NH_3-N to NO_2-N alkalinity is consumed. The alkalinity required for nitrification was evaluated and considered in this model.

The extent of phosphorus removal for the Rock Creek Facility's secondary process was measured on a daily basis by measuring the concentration of phosphorus entering and leaving the process. This data was evaluated and the removal rate of phosphorus in the secondary process was determined for use in the model.

OPTIMIZATION MODEL DEVELOPMENT

The optimization model was developed to determine the most cost effective operation of the two stage alum phosphorous removal process at the Rock Creek Facility. The model will determine the best distribution of alum and dosage rates within the treatment plant.

The model was developed as a linear model to be solved using the techniques of linear programming. In this technique, an objective function is determined that is either maximized or minimized within the constraints defined by a series of linear equations. A mathematical method, called the Simplex Method, is used to find a common solution to the series of linear equations that will also provide the minimum or maximum solution to the objective function. The software LINDO[1] was used to perform the optimization of this model.

UNIT PROCESS CHEMICAL BALANCE MODEL

Alum can be added to each of the unit processes in the treatment plant. The amount of phosphorous (PO_4) removed in the process is dependent upon many variables. This model will consider many variables such as: volume of alum added, alkalinity of the wastestream, concentration of phosphorous entering the process, and biological phosphorus uptake. This model assumes that the treatment plant is four elements. Each element is modeled independently and connected in series. The effluent from the previous element will be the influent to the following element.

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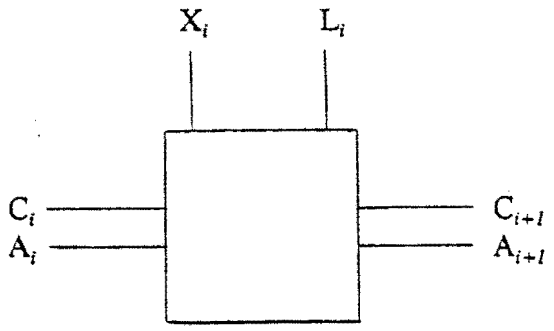
[1] Schrage, Linus, User's Manual for Linear, Integer, and Quadratic Programming with LINDO, (Redwood City, CA: The Scientific Press), 1989.

To describe the model, a generic element will be developed. This element is a black box with a mass balance performed on all parameters that enter and leave it. The generic element is shown in Figure 2.

Figure 2
Generic Process Element



where X_i = Alum Dosage in mg/l
L_i = Lime dosage in mg/l as $CaCO_3$
C_i = PO_4 Concentration in mg/l entering the unit process
C_{i+1} = PO_4 Concentration in mg/l leaving the unit process
A_i = Alkalinity Concentration in mg/l as $CaCO_3$ entering the process
A_{i+1} = Alkalinity Concentration in mg/l as $CaCO_3$ leaving the process

This generic process element is used to determine the phosphorous removal for each unit process. The removal of phosphorous in the element is determined by the amount of phosphorus removed for the given alum dosage to that element. Given that the phosphorus removed (P_{rem}) is a function of the alum added (X_i) designated as $f(X_i)$on a weight to weight basis, the following equations describe the phosphorus removal in the element:

$$C_{i+1} = C_i - P_{rem}$$

then

$$C_{i+1} = C_i - f(X_i)$$

To mathematically model this function, a correlation of the phosphorus removed to the alum added must be developed. The following equation defines this function:

$$f(X_i) = P_{rem}/Alum_{applied} * X_i$$

Thus, if $P_{rem}/Alum_{applied} = W_i$, the effluent phosphorus when given the influent phosphorus for that element would be:

$$C_{i+1} = C_i - [(W_i)X_i]$$

This equation shows the basic algorithm for removal of phosphorus by chemical precipitation used in this model. The effluent concentration of phosphorous is equal to the influent concentration minus the amount of phosphorous removed in the process. The amount of phosphorous removed is dependent upon the alum dosage, X_i, Alum Removal Ratio, W_i.

This same logic can also be used to develop the algorithm for determination of the alkalinity consumed at each process element due to the feeding of alum. As described in an earlier section, 0.5 mg/l alkalinity is consumed for every 1 mg/l of alum added to the wastestream. The amount of alkalinity required is determined by the following equation:

$$A_{i+1} = A_i + L_i - 0.5\, X_i$$

where L_i = Lime Dosage in mg/l
X_i = Alum Dosage in mg/l
A_i = Alkalinity Concentration in mg/l as $CaCO_3$ entering the process
A_{i+1} = Alkalinity Concentration in mg/l as $CaCO_3$ leaving the process

This equation shows that the element's effluent alkalinity is equal to the influent alkalinity plus the lime dosage minus 0.5 times the alum dosage.

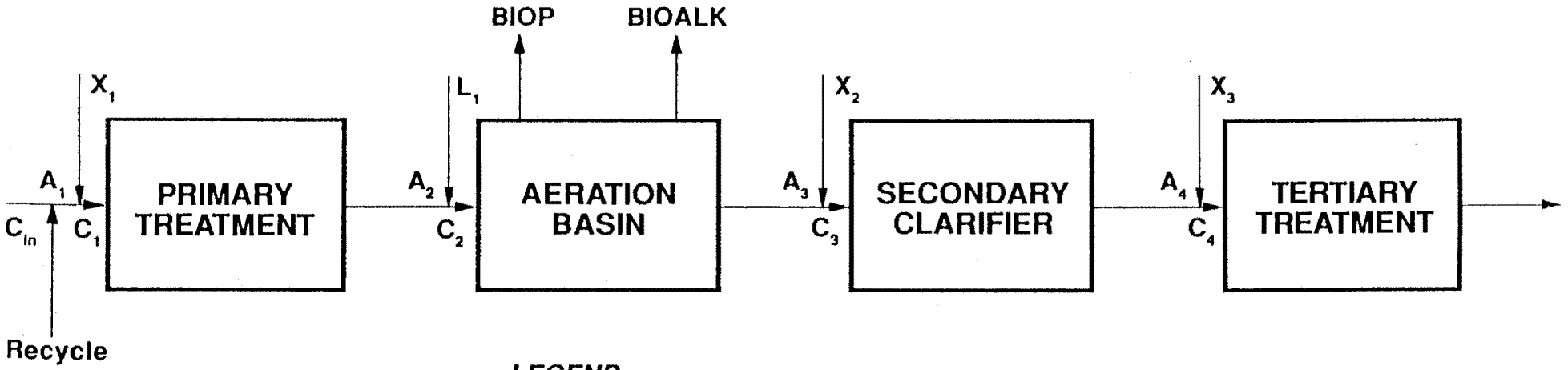
The model was developed using four elements to describe the treatment plant. The first element describes the primary treatment process. The second and third elements describe the aeration basin and secondary clarifier for the secondary treatment processes. This model was developed in this manner to take advantage of the feeding of alum to the secondary clarifier. This option was not used in this paper, but the treatment plant has this capability. The fourth and final element describes tertiary treatment. This includes both the tertiary clarifier and the effluent filters. Figure 3 diagrams the completed model of the two stage alum phosphorus removal process for the Rock Creek Facility.

MODEL OBJECTIVE FUNCTION

The objective function for this optimization model is to minimize the costs for this process by minimizing the dosages for alum and lime to the process. The units of the objective function are dollars per MGD. The model minimizes the cost of chemical addition at each chemical feed point. The models objective function is:

MIN .4475 X1 + .4475 X2 + .4475 X3 + .4848 L1

The Two Stage Alum Phophorus Removal Process



LEGEND

X_i = Alum Feed

L_i = Lime Feed

C_i = PO_4, mg/L

A_i = Alkalinity, mg/L

As displayed by this curve on Figure 5, this equation represents the data points throughout its range very well.

This equation was then used as the algorithm to develop a group of tables that predict the value of the PO_4/Alum removal ratio, W_1, for a variety of influent phosphorus concentrations. Table 2 shows the range of values for an influent PO_4 of 6 mg/l. Tables for influent PO_4 values ranging from 6 mg/l to 10.5 mg/l are displayed in Appendix C.

Table 2 shows the predicted phosphorus removals for a range of alum feed rates at an influent PO_4 of 6 mg/l. The table shows the optimum removal rate at a $PO_{4rem}/Alum_{applied}$ of 0.06. This corresponds to an alum dosage rate of 66 mg/l and a primary effluent PO_4 of 1.74 mg/l. The optimum efficiency for PO_4 removal with this influent concentration is 71%.

This information was then used to develop the model constraint for the primary process. The equation is developed using the generic model element and applying it to this process as follows:

$$C_{i+1} = C_i - [(W_i)(X_i)]$$

For the primary treatment process:

$$C2 = C1 - [(W1)(X1)]$$

Substituting for W1:

$$C2 = C1 - 0.06\ X1$$

Moving all coefficients to the left had side and the variables to the right had side:

$$0.06\ X1 - C1 + C2 = 0$$

This equation is then the equation to be used as the constraint for the primary treatment process when the influent value, C1, is 6.0 mg/l.

The model also provides for the user to set feed constraints on the alum feed to the primary process. The equations for the maximum and minimum feed rates are:

$$X1 <= value$$

and

$$X1 >= value$$

These constraints can be used if the user desires to set a minimum or maximum feed rate for the alum pumping to the primary process. These can be deleted and not used if no restriction on feed rate is desired.

TABLE 2

PRIMARY PO4 REMOVAL ALGORITHM

(Prem/Alum = 0.00028765*Alum/Pin^2 - 0.01206*Alum/Pin + 0.162367)

Pin = 6

ALapp/Pin wt/wt	Prem/ALapp wt/wt	AL app mg/l	Prem mg/l	Eff. PO4 mg/l	% Rem
2	0.14	12.00	1.67	4.33	27.88%
3	0.13	18.00	2.32	3.68	38.63%
4	0.12	24.00	2.85	3.15	47.49%
5	0.11	30.00	3.28	2.72	54.63%
6	0.10	36.00	3.61	2.39	60.22%
7	0.09	42.00	3.87	2.13	64.43%
8	0.08	48.00	4.05	1.95	67.44%
9	0.08	54.00	4.16	1.84	69.41%
10	0.07	60.00	4.23	1.77	70.53%
11	0.06	66.00	4.26	1.74	70.96%
12	0.06	72.00	4.25	1.75	70.88%
13	0.05	78.00	4.23	1.77	70.46%
14	0.05	84.00	4.19	1.81	69.87%
15	0.05	90.00	4.16	1.84	69.28%
16	0.04	96.00	4.13	1.87	68.87%
17	0.04	102.00	4.13	1.87	68.81%
18	0.04	108.00	4.16	1.84	69.27%
19	0.04	114.00	4.23	1.77	70.43%
20	0.04	120.00	4.35	1.65	72.45%

$$C4 >= .24$$

and

$$C2 <= C3 + 1.9$$

Arranging coefficients:

$$C2 - C3 <= 1.9$$

A constraint for a minimum removal rate for this process is not necessary. The model will not attempt to minimize the removal in this process, because this process has no cost.

Secondary Sedimentation

Many treatment plants remove phosphorus by adding alum to their secondary clarifier. This model has this capability. No operating data was developed during the pilot by feeding alum to this feed point. For this reason, the equations dealing with feeding to this process are:

$$- C4 + C3 = 0$$

and

$$X2 = 0$$

These equations pass the phosphorus value through this element. Therefore, the PO_4 concentration leaving the aeration basin, C3, equals the value of the secondary effluent, C4.

Tertiary Treatment

The development of the constraints for the tertiary treatment process was similar to that used in the primary process. The $Alum_{applied}/PO_{4in}$ was plotted against the $PO_{4rem}/Alum_{applied}$ as in the primary process. This is shown in Figure 8. An adequate regression analysis was not available for this set of data. The data tables were created by visually selecting a value for $PO_{4rem}/Alum_{applied}$ for each $Alum_{applied}/PO_{4in}$ value in increments of 25 from the plot.

Using this technique, a group of tables that predict the value of the PO_4/Alum Removal Ratio, W_3, for a variety of secondary effluent phosphorus concentrations were developed. Table 3 shows the range of values for a secondary effluent PO_4 of 0.25 mg/l. Tables for secondary effluent PO_4 values ranging from 0.2 mg/l to 0.44 mg/l are displayed in Appendix D.

Table 3 shows the predicted phosphorus removals for a range of alum feed rates at a secondary effluent PO_4 of 0.25 mg/l. The table shows the optimum removal rate at a $PO_{4rem}/Alum_{applied}$ of 0.0045. This corresponds to an alum dosage rate of 44 mg/l and an plant effluent PO_4 of 0.02 mg/l. The optimum efficiency for PO_4 removal with this secondary effluent concentration is 90%.

This information has been used to develop the model constraint for the tertiary process. The equation is developed using the generic model element and applying it to this process as follows:

TABLE 3

TERTIARY PO4 REMOVAL ALGORITHM

Pin = 0.44					
ALapp/Pin wt/wt	Prem/ALapp wt/wt	AL app mg/l	Prem mg/l	Eff. PO4 mg/l	% Rem
50	0.016	22.00	0.35	0.09	80.00%
75	0.011	33.00	0.36	0.08	82.50%
100	0.0085	44.00	0.37	0.07	85.00%
125	0.007	55.00	0.39	0.06	87.50%
150	0.0058	66.00	0.38	0.06	87.00%
175	0.005	77.00	0.39	0.06	87.50%
200	0.0045	88.00	0.40	0.04	90.00%
225	0.0038	99.00	0.38	0.06	85.50%
250	0.0034	110.00	0.37	0.07	85.00%
275	0.0032	121.00	0.39	0.05	88.00%
300	0.0028	132.00	0.37	0.07	84.00%
325	0.0026	143.00	0.37	0.07	84.50%
350	0.0024	154.00	0.37	0.07	84.00%
375	0.0022	165.00	0.36	0.08	82.50%
400	0.002	176.00	0.35	0.09	80.00%
425	0.0019	187.00	0.36	0.08	80.75%
450	0.0018	198.00	0.36	0.08	81.00%
475	0.0018	209.00	0.38	0.06	85.50%
500	0.0017	220.00	0.37	0.07	85.00%

$$C_{i+1} = C_i - [(W_i)(X_i)]$$

For the tertiary treatment process:

$$C5 = C4 - [(W3)(X3)]$$

Substituting for W3:

$$C2 = C1 - 0.0045\ X3$$

Arranging coefficients:

$$0.0045\ X3 - C4 + C5 = 0$$

This equation is then the equation that was used as the constraint for the tertiary treatment process when the secondary effluent value, C4, is 0.25 mg/l.

The model also provides for the user to set feed constraints on the alum feed to the tertiary process. The equations for the maximum and minimum feed rates are:

$$X3 <= value$$

and

$$X3 >= value$$

These constraints can be used if the user desires to set a minimum or maximum feed rate for the alum pumping to the tertiary process. These can be deleted and not used if no restriction on feed rate is desired.

Alum Pumps

The alum feed pumps are limited to the volume of alum that they can deliver at the desired plant flowrate. The alum pumps for the Rock Creek Facility were evaluated and at a plant flow rate of 15 MGD they will feed a maximum rate of 200 mg/l. Using this value as the maximum feed rate the following equations were developed:

$$X1 <= 200$$

and

$$X2 <= 200$$

and

$$X3 <= 200$$

These constraints represent the physical limitations of the treatment plant. These will need to be modified if the design flowrate for the treatment plant changes from the 15 MGD that was used in determining these maximum feed values.

Alkalinity Consumption and Addition

Alkalinity consumption can occur at each of the 4 process units. Lime is added only to the secondary influent or aeration basin influent. Alkalinity is consumed by both the feeding of alum and the biological processes. A detailed analysis for alkalinity consumption is not necessary. The ratio of 0.5 mg/l alkalinity consumed per 1.0 mg/l alum added will be used for this model.

The alkalinity entering the treatment plant is defined by the variable A1. This variables Right Hand Side (RHS) value defines the plants influent alkalinity in mg/l. This value historically has been 120 mg/l.

A minimum alkalinity is required to ensure that a pH greater than 6.0 is continuously carried in the plant effluent. Historical data shows that if a target effluent alkalinity of 40 mg/l is used, the pH standard can be consistently met. The alkalinity required by the effluent is defined by the variable A5. The RHS value defines the desired effluent alkalinity of 40 mg/l.

Alkalinity is consumed whenever alum is added to the process. The constraint definitions for each of the alum feed points are:

$$.5\ X1 - A1 + A2 = 0$$

for the primary process and

$$- A3 + A4 = 0$$

for the secondary clarifier and

$$.5\ X3 - A4 + A5 = 0$$

for the tertiary process.

The constraint for the aeration basin specifies the alkalinity utilized by the nitrification process as a constant. This constant, BIOALK, was determined from the analysis of historical data. The value utilized in this model was 140 mg/l. The addition of lime, L1, to increase the alkalinity is at the aeration basin influent. The constraint definition for the alkalinity balance across the aeration basin is:

$$- L1 - A2 + A3 + BIOALK = 0$$

The lime feed system also has an upper limit to the amount of lime that it can feed. This upper limit is 250 mg/l at a plant flowrate of 15 MGD. This constraint is defined by the equation:

$$L1 <= 250$$

Various other process costs such as sludge production and energy costs can also be used as constraints in this model. These constraints were not utilized in this model due to the lack of data available to develop these algorithms.

MODEL OPERATION

The model using the objective function and constraints developed for this paper was placed into the format acceptable as input to LINDO. Figure 9 displays the completed linear model ready for analysis. The model was run under a variety of input conditions and the results were compared to the data from the full scale pilot operation.

MODEL CALIBRATION

The model was calibrated using input phosphorus concentration of 7.0 mg/l. The model output was very close to actual operating conditions at that point. The model's input PO_4 concentration was then varied and compared to the plants actual operating conditions. Minor modifications to the model constraints were required to obtain a feasible solution from the model and to get an acceptable correlation with the tertiary alum feed.

Two constraints were modified to calibrate the model. The minimum allowable secondary treatment effluent PO_4 was lowered from 0.24 mg/l to 0.23 mg/l. The Alum Weight Ratio, W3, for the tertiary process was lowered from 0.0045 where a 90% efficiency was selected from the table to 0.0032 which showed an 88% efficiency. Modification of these constraints allowed the model to represent the actual operating conditions very well. The results of these model calibration runs are summarized in Table 4. A summary of the actual operating data is provided in the same format in Table 5.

The major differences in the actual data when compared to the model was in the primary and secondary effluent concentrations. The model consistently showed lower values. After closer analysis of these variables, it appears that these appeared higher in actual operating conditions due to the differences in secondary system operating modes during 1990 and 1991. A closer look at the 1991 operating data shows that the model predicts these values within an acceptable range.

The model represents the actual operating conditions very well. For example, at the influent phosphorus concentration of 7.0 mg/l, the mean primary alum dose was 85 mg/l (median 86 mg/l) and the mean tertiary alum dose was 59 mg/l (median 57 mg/l). The model had a primary alum dose (X1) of 85 mg/l and a tertiary alum dose (X3) of 56 mg/l. The difference between the feed rates of the model and actual operating conditions were never less than 5% throughout the range of influent phosphorus concentrations of 7.0 mg/l to 10.0 mg/l.

PROCESS ANALYSIS

The two stage alum phosphorus removal process was analyzed using the linear model to determine the areas of the process that create the best opportunity for minimizing chemical

Figure 9
Optimization Model

```
!  LINDO MODEL
!  Two Stage Alum Addition For PO4 Removal
!  by Dale Richwine
!  Unified Sewerage Agency
!
!  FN:  PO4_NEW.dat
!
!  Objective Function
MIN .4475 X1 + .4475 X2 + .4475 X3 + .4848 L1
    + 0 C1 + 0 C2 + 0 C3 + 0 C4 + 0 C5 + 0 CIN + 0 BIOP + 0 BIOALK
ST
!
! PO4 CONCENTRATION INPUT & LIMITS
!
! Influent PO4 Concentration
  CIN  =  6.0
! Recycle PO4 to Plant Inf.
  C1 - CIN  =  0.1
! Effluent PO4 Concentration
  C5  <=  0.05
!
! ALUM ADDITION
!
! Pri. Inf. Alum Add
   0.06 X1 - C1 + C2 = 0
! Primary Alum Feed Limits
    X1  <=  150
    X1  >=  25
! PO4 Used by A/S
   C3 - 0.060125 C2 = 0.110588
! Sec. Clar. Alum Add
   - C4 + C3  =  0
   X2 = 0
! Secondary Treatment Limits
   C2 - C3  <= 1.9
   C4 >= 0.23
! Tertiary Alum Add
   0.0032 X3 - C4 + C5 = 0
! Tertiary Treatment Limits
   X3   >=  30
!
! CHEMICAL FEED LIMITATIONS
!
! X1 Alum Pump Limit
  X1  <=  200
! X2 Alum Pump Limit
  X2  <=  200
! X3 Alum Pump Limit
  X3  <=  200
! L1 Lime Feeder Limit
  L1  <=  250
!
! ALKALINITY REQUIREMENTS
!
! Plant Inf. Alk.
  A1 = 120
! Desired Plant Eff. Alk.
  A5 >=  40
! Min. Desired AB Eff. Alk.
! Pri. Alk. Rem
 .5 X1 - A1 + A2 =   0
! AB Alk. Rem. w/ Nitr. + Lime Add
 - L1 - A2 + A3 + BIOALK  =  0
  BIOALK =  140
! Sec. Clar. Alk. Rem.
  - A3 + A4 =   0
! Tertiary Alk. Rem
  .5 X3 - A4 + A5  =   0
!
END
```

TABLE 4

MODEL CALIBRATIION DATA SUMMARY

RUN NO.	C4 LIMIT	C2-C3 LIMIT	CIN	C2	C4	C5	PRIM ALUM DOSE	TERT ALUM DOSE	COST $
1	0.23	1.9	6	1.99	0.23	0.05	69	56	$115.20
2	0.23	1.9	7	1.99	0.23	0.05	85	56	$126.70
3	0.23	1.9	8	1.99	0.23	0.05	102	56	$138.20
4	0.23	1.9	9	1.99	0.23	0.05	119	56	$149.69
5	0.23	1.9	10	1.99	0.23	0.05	135	56	$161.19

TABLE 5

ROCK CREEK FACILITY
PHOSPHORUS REMOVAL DATA
1990/1991

C1 mg/l	C2 mg/l	C4 mg/l	C5 mg/l	PRIM ALUM DOSE Mean/Median	TERT ALUM DOSE Mean/Median
5.5-6.4	2.1	0.24	0.05	80/77	65/69
6.5-7.4	2.2	0.32	0.06	85/86	59/57
7.5-8.4	2.2	0.34	0.06	99/101	64/63
8.5-9.4	2.4	0.44	0.07	113/113	55/55
9.5-10.4	2.6	0.55	0.10	121/124	51/52

usage, therefore costs. After reviewing the model and process data in detail, the emphasis of the evaluation was given to the secondary process and to the effluent permit standards.

Secondary Process Limitations

The secondary process provides the best opportunity for optimizing treatment costs. This is because additional removals in this process through biomass absorption will not increase the costs of operation and will also not require additional usage of chemicals.

The most sensitive constraint in the model is the limitation of the secondary effluent (C4) to 0.23 mg/l. If this constraint is lowered, as shown in Table 6, without modification to the amount that the secondary process can remove (C2-C3), the overall cost of treatment will be reduced. This is due to an increase in the primary alum dose to remove additional PO_4 loading to the secondary treatment process. This results in the C4 value being lower, which requires less alum to be fed to the tertiary system. The overall volume of alum required is reduced, resulting in lower treatment costs.

Modifications to the mode of operation of the secondary treatment process to provide for increased removal of phosphorus will not have any benefit for reducing chemical usage unless the secondary effluent concentration also is lowered. The model data, summarized on Table 7, shows that with the secondary effluent limit (C4) at 0.20 mg/l the secondary process is only removing 1.29 mg/l of phosphorus. This is below the allowable constraint of 1.9 mg/l. This analysis demonstrates that the most sensitive constraint for the process is the secondary effluent concentration (C4).

Influent Phosphorus Concentration

The most logical constraint that will effect process costs is the concentration of the influent phosphorus (CIN). This variable was input into the model at values ranging from 6 mg/l to 10 mg/l. This range represents the range of values that occurred during the plant's operation throughout the 1990/1991 seasons. As shown in Table 4, where this constraint was varied, the costs of treatment increased from $115.20 per MGD at a concentration of 6 mg/l to $161.19 per MGD for a concentration of 10 MGD. This shows an increase in operating costs of $11.50 per MGD for each 1 mg/l increase in influent phosphorus loading. All increases in influent phosphorus concentration were most optimally removed in the primary process. As the data in Table 4 demonstrates, there was no change in the optimum primary effluent concentration of phosphorus (C2) throughout the range of points that was input.

The model is a useful tool to determine the cost savings that the treatment plant will receive due to the phosphate detergent ban. Since the ban, influent phosphorus loadings have dropped from 10 mg/l to 6 mg/l or 42%. This relates to a cost savings of about $46.00 per MGD. For the Rock Creek Facility this will result in a savings of $665.00 per day in chemical costs for phosphorus removal.

TABLE 6

C4 LIMIT CONSTRAINT EVALUATION

RUN NO.	C4 LIMIT	C2-C3 LIMIT	CIN	C2	C4	C5	PRIM ALUM DOSE	TERT ALUM DOSE	COST $
1	0.20	1.9	6	1.49	0.20	0.05	77	47	$114.46
2	0.20	1.9	7	1.49	0.20	0.05	94	47	$125.97
3	0.20	1.9	8	1.49	0.20	0.05	110	47	$137.46
4	0.20	1.9	9	1.49	0.20	0.05	127	47	$148.96
5	0.20	1.9	10	1.49	0.20	0.05	144	47	$160.46
6	0.23	1.9	6	1.99	0.23	0.05	69	56	$115.20
7	0.23	1.9	7	1.99	0.23	0.05	85	56	$126.70
8	0.23	1.9	8	1.99	0.23	0.05	102	56	$138.20
9	0.23	1.9	9	1.99	0.23	0.05	119	56	$149.69
10	0.23	1.9	10	1.99	0.23	0.05	135	56	$161.19

TABLE 7

SECONDARY PROCESS CONSTRAINT EVALUATION

RUN NO.	C4 LIMIT	C2-C3 LIMIT	CIN	C2	C4	C5	PRIM ALUM DOSE	TERT ALUM DOSE	COST $
2	0.20	1.9	7	1.49	0.20	0.05	94	47	$125.97
7	0.23	1.9	7	1.99	0.23	0.05	85	56	$126.70
11	0.24	2	7	2.15	0.24	0.05	82	59	$126.94
12	0.25	2.1	7	2.32	0.25	0.05	80	63	$127.18
13	0.26	2.3	7	2.48	0.26	0.05	77	66	$127.43
14	0.25	2.3	7	2.32	0.25	0.05	80	63	$127.18
15	0.24	2.3	7	2.15	0.24	0.05	82	59	$126.94
20	0.23	2.3	7	1.99	0.23	0.05	85	56	$126.70
21	0.20	2.3	7	1.49	0.20	0.05	94	47	$125.97
22	0.20	2.5	7	1.49	0.20	0.05	94	47	$125.97

TABLE 8

EFFLUENT STANDARD EVALUATION

RUN NO.	C4 LIMIT	C2-C3 LIMIT	CIN mg/l	C2 mg/l	C4 mg/l	C5 mg/l	PRIM ALUM DOSE	TERT ALUM DOSE	COST $
16	0.23	1.9	7	1.99	0.23	0.02	85	66	$133.16
7	0.23	1.9	7	1.99	0.23	0.05	85	56	$126.70
17	0.23	1.9	7	1.99	0.23	0.07	85	50	$122.38
18	0.23	1.9	7	1.99	0.23	0.10	85	41	$115.92
19	0.23	1.9	7	2.14	0.24	0.14	83	30	$106.83