A STUDY OF CHEMICAL PHOSPHORUS REMOVAL AT FOUR SEWAGE TREATMENT PLANTS

by

MURRAY TOD SCHROEDER

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: INTRODUCTION

1.1 PROBLEM STATEMENT

Phosphorus removal is an objective of advanced wastewater treatment since phosphorus is one of the primary nutrients responsible for the eutrophication of receiving waters. At treatment facilities where strict NPDES limitations apply, phosphorus removal is typically accomplished by suspended solids removal, biological action, and chemical precipitation.

Since the early 1970's, several states have legislated bans on laundry detergents that contain phosphorus. Two arguments have been presented in favor of these actions. Reducing the phosphorus loading to wastewater treatment plants will: (1) improve receiving water quality and (2) proportionally reduce the cost of phosphorus removal and sludge production.

Now that phosphate detergent bans have been implemented in the Great Lakes and Chesapeake Bay areas it is desirable to analyze available data to see whether the second argument was correct.

1.2 OBJECTIVES

The objectives of this research are to use wastewater treatment operations records to:

1) Characterize chemical phosphorus removal and chemical sludge production in terms of current chemical theory, pilot plant results, and research findings present in the literature. The effects of

important process parameters, such as pH, alkalinity, phosphorus concentrations, and chemical dose will be examined.

2) Characterize the impact of chemical dosing practices on BOD removal, suspended solids removal, and sludge production.

3) To evaluate linear regression modeling as a method for extracting information from plant operations data.

1.3 SCOPE OF STUDY

This research includes the study of operations data from the Blue Plains (Washington, D.C.), Piscataway (Accokeek, MD), Jones Island (Milwaukee, WI), and South Shore (Oak Creek, WI) wastewater treatment plants.

Chapters Three, Five, Seven, and Nine are descriptive chapters that graphically present the data for each plant and present qualitative arguments based on visual trends, and correlations.

Chapters Four, Six, and Eight present first-order empirical models of phosphorus removal and sludge production data.

1.4 METHODS

Linear correlation, linear regression, and graphical presentation were used to study the impact of chemical addition on phosphorus removal and sludge production.

The models to be presented are a subset of all possible regression models that can be formed from a given set of predictor variables. This subset was objectively selected with a sequential F test (see

Appendix C) and subjectively examined with mechanistic interpretation.

The models are used to identify multivariable relationships that may not be evident in the scatter plots. The models are not intended to be used for predictive purposes.

The regression models were formed under the assumption that the response was linearly related to each of the predictor variables. Plots of the data generally support this approximation.

Box, Hunter, and Hunter (1978) discuss the possible dangers associated with using multiple linear regression to extract information from happenstance data. The hazards include:

(1) Inconsistent data. Inconsistencies may arise, for example, from changes in measurement techniques or sampling location.

(2) Limited range of predictor variables. In controlled processes, the observed range of values on important independent variables, e.g. iron dose and pH, may be too small to reveal mechanistically plausible or theoretical relationships with the response variable (e.g. phosphate removal).

(3) Confounding effects. Confounding effects arise from collinearity between predictor variables. For example, suppose that iron dose and reactor effluent pH are linearly correlated with soluble phosphorus removal. If pH is also linearly correlated with iron dose, it may be impossible to separate the effects of the two variables. Regression equations developed with collinear predictors can exhibit unstable parameter estimates and large standard errors on the estimated parameters.

(4) Nonsense correlation. These are correlations that are descriptive, in the statistical sense, but do not have a sensible cause and effect relationship. To guard against using nonsense correlations one must assess statistical models in light of available mechanistic knowledge about the process.

These four difficulties were encountered in this study. Conclusions are based in part on the results of statistical modelling, but are also strongly based on mechanistic knowledge.

CHAPTER TWO: CHEMICAL PHOSPHORUS REMOVAL THEORY

2.1 BACKGROUND

Chemical phosphorus removal in municipal wastewater has been extensively studied for the last thirty years. In the 1960's and 1970's numerous lab, pilot, and full scale experiments were conducted to identify the process variables affecting chemical precipitation and to study the affect of precipitation on the general operation of wastewater treatment facilities (4, 15, 26, 44, 45, 52, 53, 54, 55). These efforts were prompted by a growing need for effective phosphorus removal. The information obtained in these initial experiments contributed to a better understanding of removal processes and resulted in the widespread use of chemical precipitation methods.

Most of these studies, however, were directed toward achieving an effluent phosphorus concentration of about 1 mg/l. Today some treatment plants, in particular those in the Chesapeake Bay region, are required to meet lower effluent limits on total phosphorus. For example, between 1974 and 1986, the effluent TP limits at Blue Plains have been 5 mg/l, 3 mg/l, 1.6 mg/l, 0.5 mg/l, and 0.22 mg/l. An even lower limit may be established in the future. Extrapolating past experience to these new operating conditions carries some risk. An understanding of process chemistry is necessary.

Many plants also have low effluent suspended solids limits. Filtration processes have been introduced at the Chesapeake Basin treatment facilities studied in this research (Blue Plains, Piscataway). Suspended solids concentration is an important factor in determining the amount of TP discharged from a treatment plant (1, 6, 65). Total phosphorus measurements reflect combined particulate and soluble phosphorus. Particulate phosphorus removal is controlled by the physical processes of clarification and filtration, and removal of the soluble fraction from the liquid process is controlled by chemical precipitation and biological action. The separation of precipitates and biological floc from the liquid stream are also dependent on the physical processes, so the two processes are not independent.

At the Chesapeake Basin plants of this study, chemical use was low (or nil) during earlier years when less stringent TP effluent restrictions applied. Precipitant use has increased at plants to insure that discharge limitations have been met. In many cases, the residual concentrations of soluble phosphorus (SP) are at or near theoretical solubility limits for orthophosphate. Split dosing the precipitant to primary and secondary treatment has also been introduced to provide a more efficient treatment process.

For plants such as the Wisconsin plants in this study, phosphorus removal practices have changed relatively little, since effluent limitations have remained constant at 1 mg/l TP.

The USEPA has adopted a new emphasis regarding new design and retrofitting of treatment plants for phosphorus removal. Technology Transfer Manuals (65, 67) recently issued by the USEPA emphasize the difference in operational requirements needed to attain increasingly lower effluent TP concentrations of 2, 1, 0.5, and 0.2 mg/l. These manuals emphasize the importance of considering site specifics for design (wastewater characteristics, chemical dose point, etc.). They do not rigorously discuss the theory of chemical phosphate precipitation, but a statement is included to the effect that the chemical cost and sludge quantities associated with achieving very low phosphorus concentrations are not directly proportional to the amount of phosphorus being removed. This statement suggests the importance of knowing the process chemistry that will exist.

2.2 PRECIPITATION MODELS

Despite the large body of literature on chemical phosphorus removal, there are few developed and verified mechanistic models of the process.

Chemical equilibrium and precipitation principals are well explained in environmental engineering texts (Stumm and Morgan, 1981; Benefield, Judkins, and Weland, 1982; Snoeyink and Jenkins 1980). These principles can be used to formulate a predictive model for orthophosphate precipitation in the presence of metal salts.

Equilibrium models are composed of 1) equations relating the equilibrium concentrations between soluble species, and between soluble species and solid phases, 2) mass balance equations on each system component (i.e. phosphorus, iron), and 3) an electroneutrality condition. Experimentally determined equilibrium constants are used to quantify the distributions of component species (i.e. H_3PO_4, $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) and the conditions under which solid phases are expected to exist. Many model terms are widely accepted as known, such as equilibrium constants for the phosphoric acid system. Others, such as the solubility product for the metal phosphate precipitate, are not precisely known. The solubility product for metal hydroxide is also not well defined because of its amorphous structure. Model parameters that are not well defined require calibration to the specific aqueous system for which the equilibrium model will be applied.

Ferguson and King (1977) presented the first phosphate precipitation model based on chemical equilibrium theory. This model was later shown to have a discontinuity in its ability to predict phosphate residuals near the solubility limit (31). This discontinuity was pronounced at combinations of high initial alkalinity, high pH (7.5), and low initial phosphate concentration; conditions not too unusual for some operating conditions.

Kavauaugh et al. (1978) presented a model that could be used for predicting total phosphorus removal in post precipitation with Fe(III). The three components of the model were 1) a chemical model for dissolved phosphorus removal, 2) a flocculation model, and 3) a model for suspended solids removal in a sludge blanket clarifier. The precipitation model showed reasonable agreement with pilot scale test results, but agreement was obtained by adjusting the assumed ratio of ferric hydroxide precipitate to ferric phosphate precipitate. No formal method for estimating this model parameter was offered. The equilibrium model failed to account for important operating variables such as initial pH or alkalinity.

The foundations of Ferguson and King were used by Jenkins et al. (31) to develop a computer model for predicting phosphate residuals resulting from alum or ferric addition. The discontinuity in Ferguson and King's model was identified during this effort, but it was not rectified. A need also existed at the time for laboratory model verification.

A model presented by Hermanowicz (48), at the 1987 National WPCF Conference, is currently undergoing laboratory calibration to describe the relationship between the dose of Fe(III), as ferric chloride, and the residual concentration of orthophosphate achievable in activated sludge systems.

An earlier version of the model serves as an appropriate basis for discussing the fundamental chemical concepts of phosphate precipitation. The model equations presented by Jenkins et al. (32) are listed in Table 2-1. The equations describe the equilibrium distributions of the soluble orthophosphate species, soluble iron species, and the carbonate system (open or closed to the atmosphere). Mass balance equations on phosphorus, iron, and carbon, and an electroneutrality condition complete the model.

Table 2-1 Chemical Equilibrium Model Equations (Jenkins et al. 32).

Reaction	pK	Eq. No.
$Fe_RPO_4(OH)_{3R-3}(s) = R\ Fe^{3+} + PO_4{}^{3-} + (3R-3)\ OH^-$	40.8	1
$H_3PO_4 = H^+ + H_2PO_4{}^-$	2.1	2
$H_2PO_4{}^- = H^+ + HPO_4{}^{2-}$	7.2	3
$HPO_4{}^{2-} = H^+ + PO_4{}^{3-}$	12.2	4
$Fe^{3+} + H_2O = FeOH^{2+} + H^+$	0.9	5
$Fe^{3+} + 2\ H_2O = Fe(OH)_2{}^+ + 2\ H^+$	2.7	6
$Fe^{3+} + 3\ H_2O = amFe(OH)_3(s) + 3\ H^+$	-0.5	7
$Fe^{3+}\ 4\ H_2O = Fe(OH)_4{}^- + 4\ H^+$	18.6	8
$FeH_2PO_4{}^{2+} = Fe^{3+} + H_2PO_4{}^-$	15.8	9
$H_2CO_3{}^* = H^+ + HCO_3{}^-$	6.3	14
$HCO_3{}^- = H^+ + CO_3{}^{2-}$	10.3	15
$H_2O = H^+ + OH^-$	14.0	16

Balance Equations

$$[H_3PO_4] + [H_2PO_4{}^-] + [HPO_4{}^{2-}] + [PO_4{}^{3-}] + \\ + [FeH_2PO_4{}^{2+}] + [\underline{Fe_RPO_4(OH)}_{3R-3}(\underline{s})] = c_{P,in} \qquad 17$$

$$[Fe^{3+}] + [FeOH^{2+}] + [Fe(OH)_2{}^+] + [Fe(OH)_4{}^-] + \\ + [FeH_2PO_4{}^{2+}] + R[\underline{Fe_RPO_4}(\underline{OH})_{3R-3}(\underline{s})] + [\underline{Fe(OH)}_3(\underline{s})] = c_{Fe} \qquad 18$$

$$3[Fe^{3+}] + [FeOH^{2+}] + [Fe(OH)_2{}^+] + 2[FeH_2PO_4{}^{2+}] + [H^+] - \\ - [Fe(OH)_4{}^-] - [H_2PO_4{}^-] - 2[HPO_4{}^{2-}] - 3[PO_4{}^{3-}] - \\ - [OH^-] - [HCO_3{}^-] - 2[CO_3{}^{2-}] = X\ c_{Fe} - c_{K,in} \qquad 19$$

$$[H_2CO_3{}^*] + [HCO_3{}^-] + [CO_3{}^{2-}] = c_{C,in} \\ \text{or} \\ [H_2CO_3{}^*] = K_H\ pCO_2 \qquad 21$$

In the theoretical model the formation of $FeH_2PO_4^{2+}$ has been hypothesized as the dominant iron phosphate complex. Calibration of the model to laboratory results involves adjusting the $FeH_2PO_4^{2+}$ stability coefficient, K_{FP}, and the solubility product, K_{SP}, of the metal phosphate precipitate. Jenkins et al. initially estimated these two constants by fitting the model to the tap water iron phosphate precipitation data of Recht and Ghassemi (1970). The tap water data were obtained under conditions of controlled initial phosphate concentration, iron dose, and final pH.

Ferguson and King (1977) identified seven assumptions for their alum precipitation model that are applicable to the model. These assumptions are important to consider when direct comparisons between theoretical results and full scale operations data are being made.

(1) The model describes the precipitation of orthophosphate, not other forms of soluble phosphorus. Raw sewage may contain significant quantities of soluble non-orthophosphates (condensed and organic) (18, 21). Some of these forms may be hydrolyzed to orthophosphate. Therefore, it is necessary to consider the location of metal ion addition when attempting to explain operations data in terms of the current model.

(2) Steady state is assumed. The kinetic component of the model is considered negligible. Recht and Ghassemi (1970) have shown that the reactions of Fe(III) and Al(III) with orthophosphate take place in

less than a second.

(3) Solids separation is not described. At treatment plants this mechanism of phosphorus removal will be controlled by clarifier operation and filtration processes.

(4) Precipitation is the mechanism causing phosphate removal, and not adsorption. Ferguson (18) maintains that the evidence for a precipitation mechanism is compelling, especially over the range of pH values encountered in wastewater treatment.

(5) The phosphate solid precipitates before the hydroxide during stoichiometric removal (described in the next section). This is an observed experimental result.

(6) The ratio of metal ion to phosphate is constant in the solid precipitate. Jenkins (34) has suggested that the stoichiometric coefficient, R, may be functionally related to pH.

(7) Chemical equilibrium principles are applicable.

A qualitative description of the model is useful for understanding the nature of the precipitation process and the relative importance of operating variables. For this reason, some early results of Jenkins et al. (32) will be presented along with a conceptual description of the model.

The precipitation of orthophosphate is assumed to occur in three distinct zones, each of which are described below, with reference to Figure 2-1 , a solubility diagram for orthophosphate precipitation in the presence of iron hydroxide. The curve on the figure was

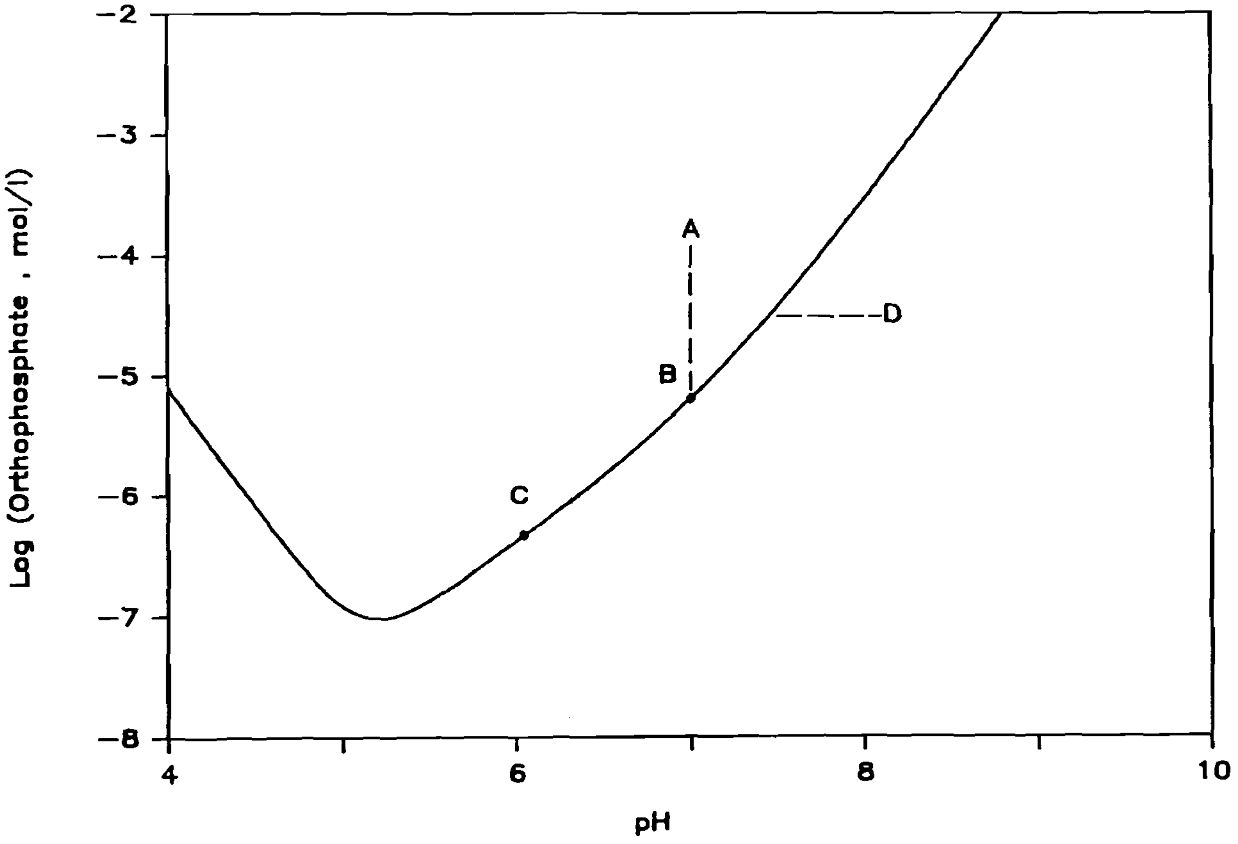


Figure 2-1 Schematic of Iron Phosphate Precipitation. Solubility Curve Represents Equilibrium Concentration of Soluble Orthophosphate Species in the Presence of Iron III Hydroxide.

calculated with the solubility relationships presented in Table 2-1. The exact location of this curve is not important in the context of the following discussion, since the location will vary depending upon the specific aqueous system (i.e. activated sludge, raw sewage).

Zone I. Initial conditions that give rise to Zone I precipitation are identified by points such as D. At these conditions the solubility product of the hydroxide is less than that of the hydroxide orthophosphate. Added metal ions preferentially bind hydroxide ions, driving the pH downward until the solubility limit of the phosphate is exceeded. The precipitant reacts only with wastewater alkalinity to form metal hydroxide. The amount of metal ion required to shift the pH is dependent upon the initial alkalinity, which is assumed to be controlled by the carbonate system. The carbonate system can be modeled as a closed system, in which the mass of carbon is conservative, or it can be modeled as an open system. In an open system at a fixed CO_2 partial pressure (pCO_2), the amount of dissolved CO_2 will be a function of pH. Assumptions regarding the open or closed nature of the process are important for properly modelling precipitation. The initial phosphate concentration makes up a small portion of the alkalinity, but it contributes negligibly to the buffering capacity of the wastewater (31).

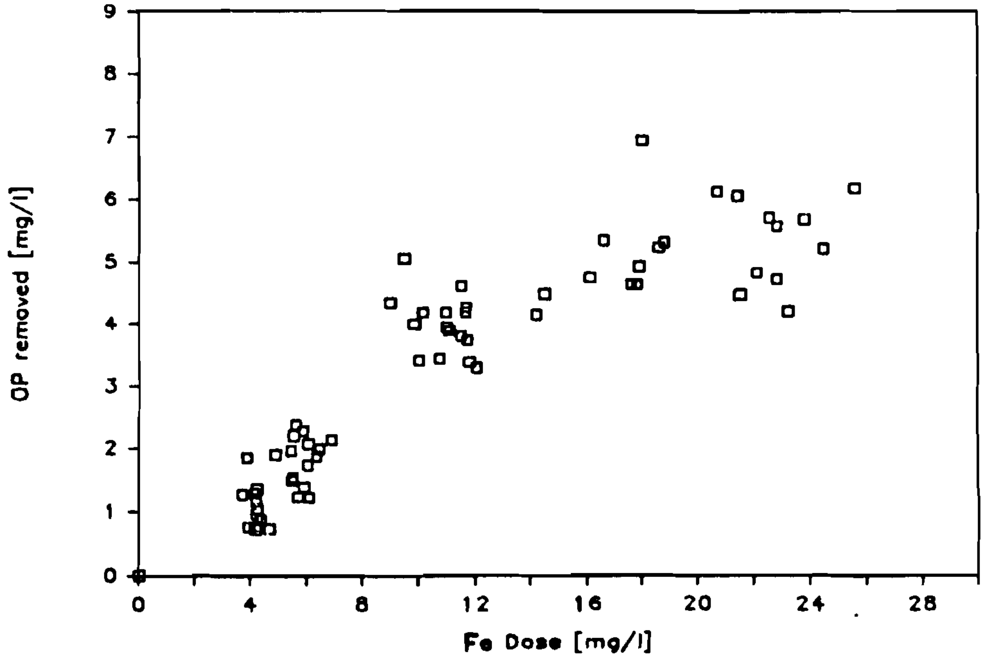
Zone II. In Figure 2-1, Zone II removal is represented by the movement from point A to point B. Zone two precipitation is characterized by the proportionate removal of orthophosphate with increasing cation dose. The stoichiometric coefficient, R, determines the molar amount of metal ion required to precipitate a mole of orthophosphate. This stoichiometric removal can proceed until the pH constraining orthophosphate solubility limit is met. Most wastewaters fall in the zone II precipitation category without the need for pH adjustment (18).

Zone III. In Figure 2-1, Zone III removal is represented by the movement from point B to point C. Phosphate removal is not directly proportional to metal salt addition, because some of the metal acts to reduce the pH.

Figure 2-2 shows orthophosphate removal data from the experimental work of Jenkins et al. (32) at a fixed pH of 7.2 and an initial phosphate concentration of 5.5 mg/l. These conditions represent the average experimental conditions of their continuous flow pilot scale aeration basin. These data suggest that phosphate removal, at pH = 7.2, is directly proportional to iron dose up to about 12 mg/l Fe, after which there is no additional phosphate removal.

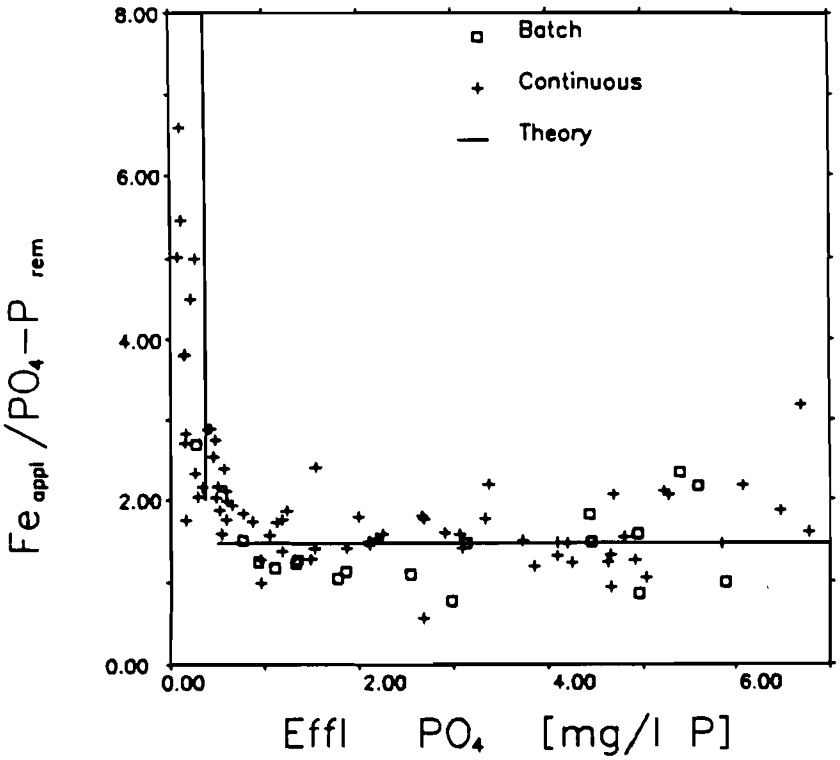
Figure 2-3 shows the mole ratio of iron to estimated phosphate removed vs. the effluent orthophosphate concentration for the same data in Figure 2-2. The denominator of the ratio, phosphate chemically removed, was calculated by subtracting the effluent orthophosphate value from the influent value, and adding 27% of the initial particulate phosphorus concentration. A phosphorus mass

Figure 2-2 Orthophosphate Removal vs. Iron (III) Dose in Activated Sludge. Controlled pH = 7.2. (Jenkins et al. (32)).



Orthophosphate removal as a function of Fe(III) dose

Figure 2-3 Fe/P_C Mole Ratio vs. Effluent Orthophosphate Concentration in Activated Sludge at pH = 7.2. (Jenkins et al. (32)).



Fe/P molar ratio as a function of effluent orthophosphate concentration

balance on the pilot scale aeration basin prior to iron addition indicated that 27% of the influent particulate phosphorus was hydrolyzed to orthophosphate over and above the biological orthophosphate requirement. Thus, instead of adjusting for background biological action by subtracting a quantity (typically 1 mg P / 100 mg BOD removed) the observed orthophosphate removals were adjusted by adding a percentage of the influent particulate phosphorus. Figure 2-3 shows that at low effluent concentrations, orthophosphate removal becomes constant at a fixed pH. The pH dependent solubility limit prevents complete orthophosphate removal.

2.3 SLUDGE PRODUCTION

The purpose of this section is to discuss the major factors affecting sludge production as it relates to chemical addition, and to present the stoichiometry for estimating the mass of precipitated chemical sludge.

The sludge mass produced by chemical addition for phosphorus removal includes 1) the mass of phosphate and hydroxide precipitates, 2) the mass of additional suspended solids removed due to chemically induced flocculation, and 3) the mass of additional dissolved solids removed (i.e., filterable through a 0.45 micron membrane filter) (66).

Chemical sludge (precipitate only) mass quantities are determined by the initial and final wastewater characteristics (pH, alkalinity, phosphate concentration), the type of chemical used, and the dose concentration.

Chemical addition to primary treatment may decrease the organic loading on secondary treatment, thereby reducing aeration requirements and biological sludge production. Factors such as this make it difficult to assess the impact of chemical addition on net solids production, and the overall cost of phosphorus removal.

2.3.1 Wastewater Conditions.

According to the theory presented in the last section, effluent orthophosphate concentrations depend on cation dose, and the initial wastewater pH, alkalinity, and phosphate concentration. If the final phosphate concentration is above the solubility limit then stoichiometric phosphate removal should result in a stoichiometric quantity of phosphate sludge.

If the metal salt is being used for pH adjustment to obtain very low phosphate residuals, or if the initial pH and alkalinity are representative of Zone I precipitation, metal hydroxide sludge will be produced. This produces more chemical sludge per unit of phosphate removed, or a non-stoichiometric chemical sludge quantity.

A recent USEPA report shows sludge generation being inversely related to effluent TP concentrations (67). Data from several plants in the Chesapeake Bay and Great Lakes basins are presented in Figure 2-4. A ratio of total sludge/ influent total suspended solids (TSS) greater than one is an implicit measure of the additional sludge

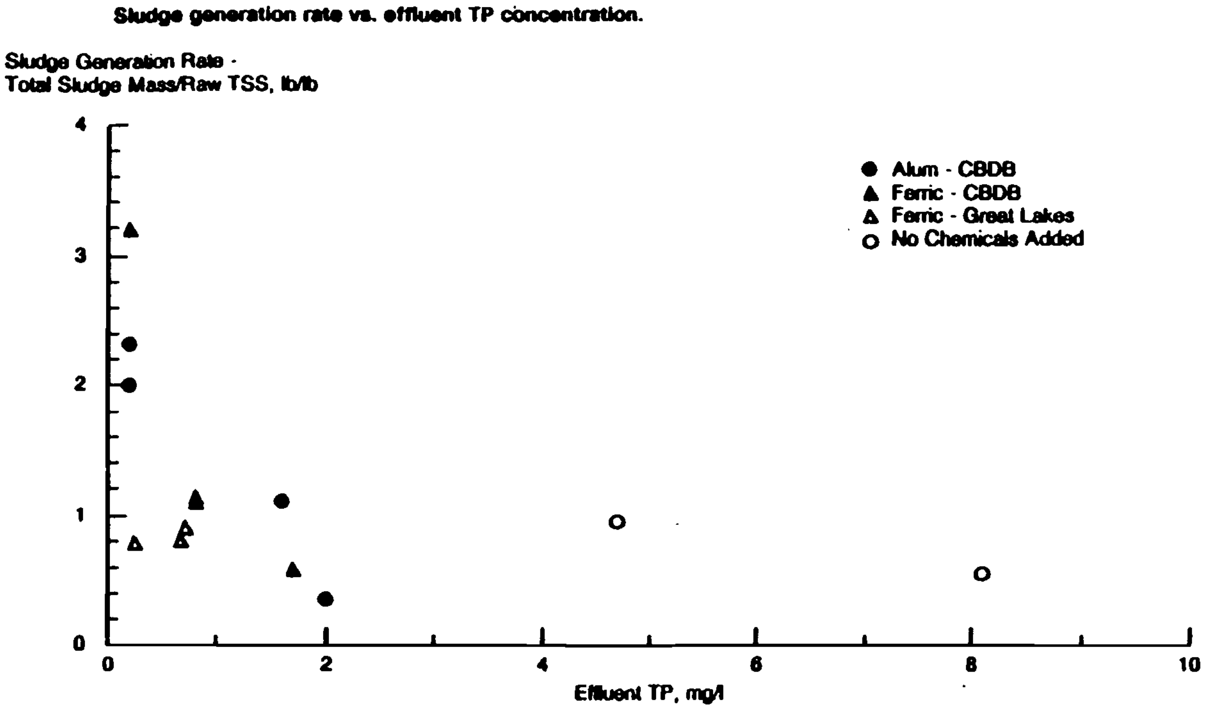


Figure 2-4 Sludge Generation vs. Effluent Total Phosphorus Data from Chesapeake Bay (CBDB) and Great Lakes Basin Treatment Plants (USEPA, 67).

production resulting from chemical use. Treatment plants from the Chesapeake Basin have increased chemical precipitant dose to attain lower total phosphorus limits. The result is that more sludge has been produced. If, however, the precipitation theory presented in the previous section is an acceptable process model then the chemical sludge mass associated with precipitation is nearly independent of effluent phosphorus (orthophosphate) concentration.

2.3.2 Chemical Precipitant.

The chemical form of the precipitant has been reported to affect the quantity of chemical sludge produced. In a pilot scale study of sludge dewatering alternatives, Cambell and LeClair (1979) observed sludge production increases of 38% and 100% (by weight) from the addition of ferric chloride and alum, respectively, to extended aeration activated sludge basins. The average initial total phosphorus concentration was 8 mg/l, and the effluents were less than 1 mg/l.

Balmer and Frederiksen (1975) studied chemical sludge production in a pre-settled domestic wastewater using alum, ferric chloride, and lime. The settled wastewater was split into three equal flows and the three precipitants were added to identical parallel flocculation and settling tanks. The precipitant doses were varied in terms of the metal ion to influent SP ratio (mass basis). For roughly the same mole ratios of cation to initial SP, they observed approximately the same sludge productions (total mass) for alum and ferric chloride. Mole ratios varied between 4 and 14.

In a designed experiment on tap water, Veldkamp (1985) found that ferric chemical sludge mass quantities were 1.2 times greater than alum sludge mass quantities precipitated under controlled initial phosphate concentrations, final pH, and precipitant dose. These results are counter those reported by LeClair and Cambell, but seem reasonable. Because iron has a higher molecular weight, it should form a heavier precipitate than aluminum per unit of precipitated phosphate. If the precipitates are $Fe_RPO_4(OH)_{3R-3}$ and $Al_RPO_4(OH)_{3R-3}$, and R is the same for both, then for stoichiometric precipitation, ferric iron would be expected to produce a sludge with 2.1 times more mass than aluminum. Observed deviations from this value in field and lab work could be the result of the different pH ranges over which the two chemicals stoichiometrically remove phosphate and deviations in the chemical composition of the precipitate. Recht and Ghassemi (1970) found that the optimal pH value for iron phosphate precipitation in tap water was between 3.5 and 4, while the optimum for aluminum was about pH 6. The results of their tap water experiments also indicated the stoichiometric ratio for aluminum phosphate is slightly greater at the optimal pH (1.2 for Fe, and 1.4 for aluminum).

2.3.3 Point of Chemical Addition.

Additional suspended and dissolved solids removal by chemical addition is dependent on the dose point. The recent USEPA Phosphorus Removal Manual (1987) presents potential TSS removal efficiencies for primary and secondary treatment, with and without metal salt addition. These data suggest that primary TSS removal is 40% - 70% without chemical addition and 60% - 75% with chemical addition, and that secondary TSS removal is 80% - 90% without chemical addition and 85% - 95% with chemical addition. The USEPA manual also suggests that 30% of the dissolved solids (i.e. filterable through a 0.45 micron membrane filter) are removed when chemicals are added to a raw wastewater, or primary effluent, and that removal of dissolved solids is negligible when chemical is added to biological oxidative processes. Sludge mass resulting from dissolved solids removal can be estimated indirectly with soluble COD, TOC, or BOD data; however, these data were not studied in this research (65, 66).

In a survey of 185 Canadian wastewater treatment plants that were retrofitted for chemical phosphorus removal, Schmidke (1985) reported average sludge mass increases of 42% and 26% at primary and conventional activated sludge plants, respectively. The percentage increases may reflect differences in the degree of enhanced suspended, and dissolved solids removal.

Gleisberg (1985) cites a study of 150 German chemical treatment plants where the average reported increase in raw sludge production was 8%, relative to conventional primary clarification. This value is considerably different than the 42% value reported by Schmidke, and due to site specific wastewater conditions and chemical dose practices.

Chemical addition is known to increase sludge production. However, the above information indicates that percentage increases in sludge production cannot be applied to individual plants because of unique wastewater compositions and chemical dosing practices.

The most recent USEPA Phosphorus Removal Manual (1987) clearly states that observed percentage increases, such as those cited above, are not useful for design purposes. The manual recommends using jar tests to estimate sludge production.

2.3.4 Estimating Chemical Sludge Production

The principles of chemical stoichiometry can be used to estimate the mass of chemical sludge produced by metal salt addition to wastewater (51, 65, 69).

The USEPA Phosphorus Removal Manual (1987) suggests that stoichiometric chemical sludge estimates should be increased by 35% for design work. This "safety factor" has not been proven to exist in controlled experimental work, and is not used in this report.

In the following discussion, the assumptions of the chemical sludge model are presented.

For stoichiometric precipitation, one mole of metal phosphate

(phosphate sludge) will form for every R moles of metal ion consumed, according to:

$$R\ Me^{3+} + PO_4{}^{3-} + 3R\text{-}3\ OH^- = Me_RPO_4(OH)_{3R-3}(s) \qquad 2\text{-}1$$

In non-stoichiometric phosphate removal, the excess metal ion is presumed to form an insoluble metal hydroxide (hydroxide sludge) according to:

$$Me^{3+} + 3OH^- = Me(OH)_3(s) \qquad 2\text{-}2$$

The amount of excess metal ion in a wastewater will be a function of several variables including pH. However, since all orthophosphate insolubilized is assumed to be in the form of $Me_RPO_4(OH)_{(3R-3)}$, then the quantity of phosphate sludge can be calculated by estimating the amount of phosphate removed. The stoichiometric coefficient, $R = 1.5$, is assumed fixed for all wastewater conditions.

Any excess iron not involved in phosphate precipitation is used to calculate the quantity of hydroxide sludge. The residual cation concentration is assumed negligible.

Unoxidized waste pickle liquor tends to form gelatinous ferrous hydroxide precipitates. The mass ratio of ferric hydroxide to ferrous hydroxide is 1.19. If all the ferrous iron not involved in phosphate precipitation is assumed to form ferric hydroxide, then the hydroxide sludge quantity calculations will be in error by +19%.

The following equations are used to predict chemical sludge quantities for the two possible cases:

Stoichiometric Precipitation

$$\mathrm{CPSL} = [(\mathrm{Me}/\mathrm{MWM})\ (1/R)] \times [(R \times \mathrm{MWM}) + \mathrm{MWPO_4} + 3(R-1)\mathrm{MWOH}]\ (8.34\ Q) \qquad 2\text{-}3$$

Non-Stoichiometric Precipitation

$$\mathrm{CHSL} = [(\mathrm{Me}/\mathrm{MWM}) - (R \times P_C/\mathrm{MWP})](\mathrm{MWM} + 3\mathrm{MWOH})(8.34\ Q) \qquad 2\text{-}4$$

$$\mathrm{CPSL} = [(\mathrm{MWM} \times R) + \mathrm{MWPO_4} + 3(R-1)(\mathrm{MWOH})](P_C/\mathrm{MWP})(8.34\ Q) \qquad 2\text{-}5$$

Where: CPSL = Chemical Phosphate Sludge, lb/day
CHSL = Chemical Hydroxide Sludge, lb/day
Me = Metal Ion Dose, mg/l
P_C = Estimated Chemically Removed P, mg/l
R = Stoichiometric Coefficient, = 1.5
MWM = Molecular Weight of Metal, mg/mmol
(55.85 for Fe, 26.98 for Al)

MWP = Molecular Weight of Phosphorus

= 30.97 mg/mmol

$MWPO_4$ = Molecular Weight of PO_4 Phosphate

= 30.97 + 4(16) = 94.97 mg/mmol

MWOH = Molecular Weight of Hydroxide

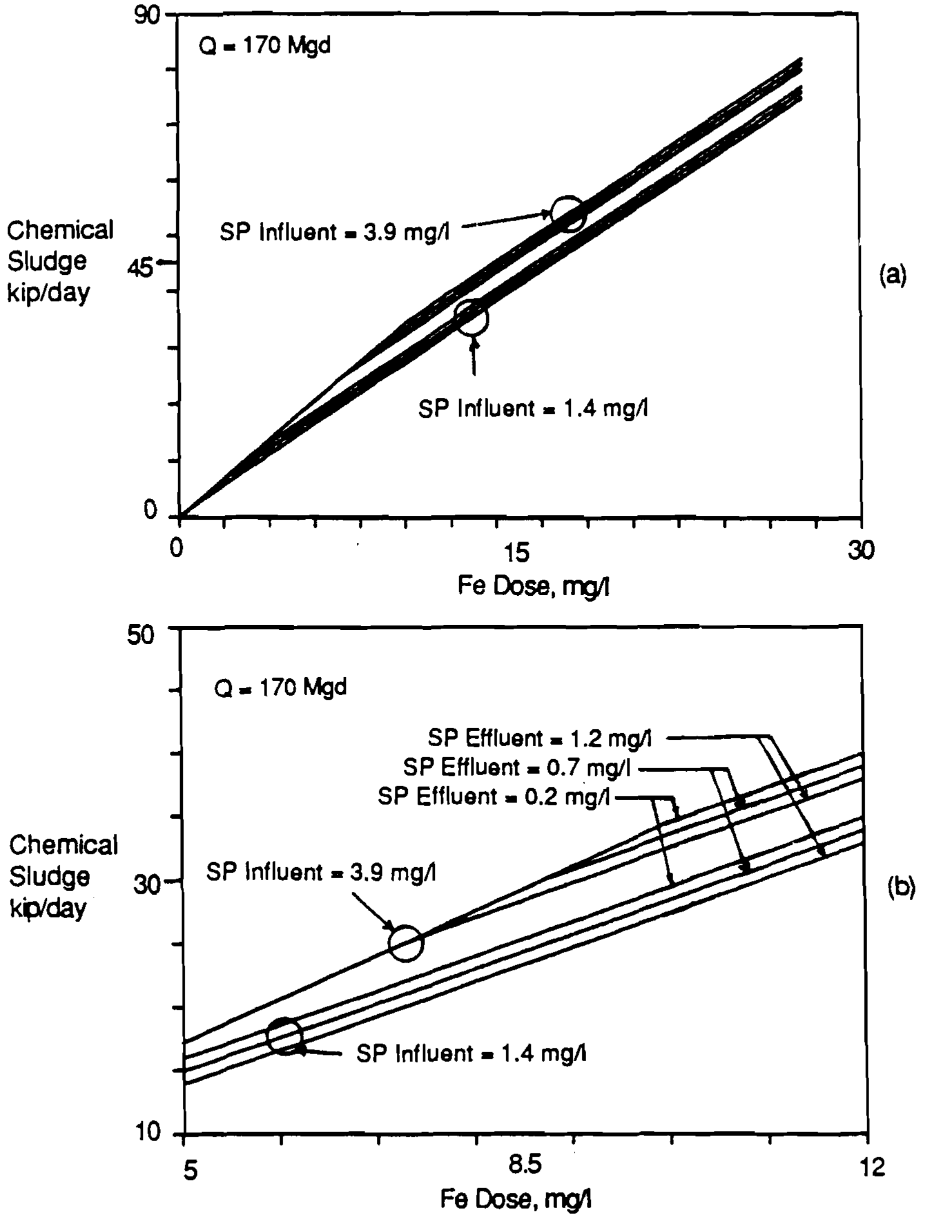
= 16 + 1 = 17 mg/mmol

Q = Flow, Mgd

Figure 2-5a shows predicted chemical sludge production as a function of iron dose for average wastewater conditions found in the primary clarifiers at Blue Plains (see Figure 3-2). The iron dose is expanded over a wider range to clearly reveal the theoretical relationship. Figure 2-5b shows the same values for the range of iron dose used since February 1984. This figure illustrates two important concepts. First, chemical sludge production is more strongly related to initial phosphate concentration than final phosphate concentration. Secondly, chemical phosphate sludge production is dependent largely on the amount of metal ion dosed.

Typically, estimates of chemical SP removal in activated sludge are adjusted for biological action by assuming 1 mg/l SP is removed biologically per 100 mg BOD removed. This adjustment means that for the plants of this study, between 0.5 and 1.5 mg/l SP would be removed biologically, with the chemical precipitation providing any additional SP removal. The following calculation illustrates how the chemical

Figure 2-5 Sensitivity of Predicted Chemical Sludge Production to Changes in Influent and Effluent Phosphate Concentrations for Conditions Representative of Blue Plains East Primary Clarifiers, February 1984 - March 1987 a) Expanded Scale, b) Representative Iron Dose Range.



sludge mass calculations are relatively insensitive to the above assumption of biological removal:

Given: MW $Fe_{1.5}PO_4(OH)_{1.5}$ = 204 and MW $Fe(OH)_3$ = 107

Assume: Flow = 300 MGD (Approximate flow at Blue Plains)

Biological SP Removal = 1 mg/l

Excess iron is used to precipitate both solids, & R = 1.5.

Calculations: One mg/l of SP removal forms 1 x (204/30.97) = 6.6 mg/l phosphate sludge, by consuming (1/30.97)(1.5 mol/mol)(55.85) = 2.7 mg/l Fe. If the 1 mg/l SP removal is assigned to biological uptake, instead of precipitation, then under the assumptions of chemical model the unreacted iron will form 2.7 x (106.85/55.85) = 5.2 mg/l hydroxide sludge instead. The concentration of total chemical sludge is reduced by (6.6 - 5.2) = 1.4 mg/l. This translates to 1.4 (8.34)(300 MGD)/1000 = 3.5 kip/day. This is small compared to the approximately 200 kip/day of secondary sludge produced at Blue Plains, and the average estimated secondary chemical sludge production of about 50 kip/day (See Chapter Four).

CHAPTER THREE: BLUE PLAINS WWTP

3.1 BACKGROUND

The Blue Plains wastewater treatment facility is located in the southern corner of Washington D.C. on the Potomac River. In 1986, Blue Plains treated an average daily flow 287 MGD, originating primarily from residential areas and office complexes. Approximately 94% of this flow originates in the District of Columbia and Maryland, with the balance coming from Virginia. The total service population is approximately 2 million (36).

In Maryland, a ban on phosphate detergents became law on December 1, 1985. A ban in Washington D.C. was signed in January 1986, but did not become fully effective until September 1986. No ban is presently in effect in Virginia.

3.2 PROCESS DESCRIPTION

Liquid treatment at Blue Plains includes screening, grit removal, primary clarification, modified aeration activated sludge, nitrification, dual-media filtration, chlorination, and post aeration.

Figure 3-1 is a schematic of the process at Blue Plains. The influent is split for primary and secondary treatment in an east plant and a west plant. In 1986 the average process flow to the east plant was 160 MGD, and the flow to the west plant was 130 MGD. The secondary effluents are combined for nitrification.

Gravity thickening and dissolved air flotation are used to thicken

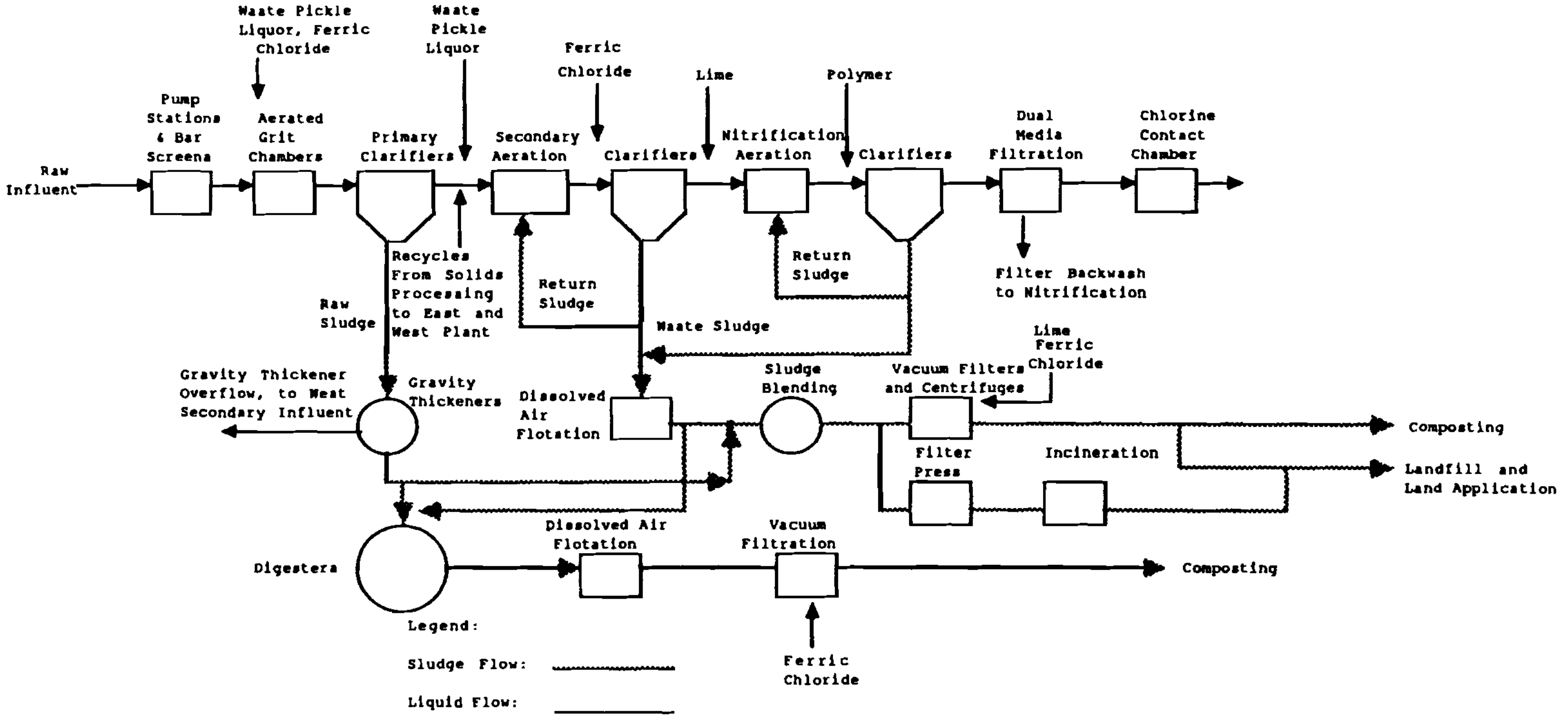


Figure 3-1 Blue Plains Process Flow Diagram.

the raw sludge and waste activated sludge, respectively. The thickened sludges are blended and either 1) anaerobically digested and further thickened before composting, 2) dewatered before composting, or 3) dewatered before incineration. Centrifuges, vacuum filters, and drum filter presses are used for dewatering. Successful vacuum filter operation requires conditioning with ferric chloride and lime. The centrifuge operation only requires conditioning with polymer.

At Blue Plains, recycle streams from the solids processing facilities are returned to liquid treatment above the east and west plant aeration basins. These recycle streams contain residual iron from the sludge conditioning, but the quantity of iron available for phosphorus removal unknown.

Until July 1985, gravity thickener overflow was routed ahead of the west primary clarifiers. From July 1985 to the present, this recycle has been returned below the west plant primaries.

Waste pickle liquor (WPL) and ferric chloride ($FeCl_3$) are used to precipitate phosphorus as well as enhance suspended solids and BOD removal. Pilot studies conducted in 1970 by the USEPA and the District of Columbia concluded that iron was a more cost effective chemical treatment than alum (37).

Prior to 1979, ferric chloride was dosed to the mixed liquor channel ahead of the secondary clarifiers. In 1979, a pilot study by Bethlehem Steel and Blue Plains plant engineers was conducted using waste pickle liquor. WPL added directly to the aeration tanks was reported to be as effective as ferric chloride in removing phosphorus.

This dosing location promoted the oxidation of ferrous iron to ferric iron (35). The study also concluded that the substitution of WPL for ferric chloride did not significantly lower the pH of the final effluent. The study was prior to nitrification startup in 1980.

Waste pickle liquor is preferred by the operators, because it is provided by the steel industry at a lower cost than ferric chloride. Ferric chloride is used when WPL is not available to meet the demand.

In 1981 dual media filter construction began in order to meet the effluent suspended solids limit. Construction was not completed until April 1983. Blue Plains was unable to meet the TP limit until mid-1983 because of the particulate phosphorus associated with the suspended solids (1). The effluent limitation on TP was 0.22 mg/l for the period of record examined in this study.

Beginning in February 1984, ferric chloride was added to the aerated grit chambers, while maintaining both ferric chloride and WPL dosing to aeration. This action was taken to reduce secondary sludge production, because the sludge treatment system was overloaded with biological sludge as a result of high organic loading from the primaries.

In April 1986, waste pickle liquor began to replace the use of ferric chloride in the primaries. In March 1987, the waste pickle liquor solutions contained about 9% by weight free sulfuric acid. Before the end of 1987, the steel industry from which Blue Plains obtains its pickle liquor is scheduled to change its treatment process so that the resulting solutions will contain approximately 1% by weight free hydrochloric acid (1).

3.3 OPERATIONS DATA

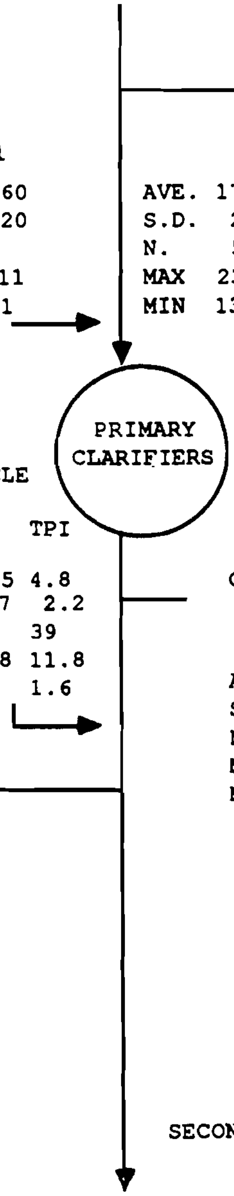
At Blue Plains, computer records are currently maintained for nearly 600 wastewater treatment parameters. In March 1987, daily values of BOD_5 (BOD), total suspended solids (TSS), total phosphorus (TP), soluble phosphorus (SP), waste pickle liquor (WPL), $FeCl_3$, flow (Q), sludge flow, and sludge solids were obtained directly from the computer data base. Data was obtained for the period from Jan 1, 1983 to March 19, 1987.

Daily values have been reduced to monthly averages for the following analyses. Most monthly averages are compiled from 20 to 31 daily measurements, with the exception of March 1987. All monthly averages regardless of the number of daily observations, are considered representative of operating conditions during the month.

Secondary influent and effluent pH and total alkalinity (as $CaCO_3$) daily averages were transcribed from handlogs for February 1, 1984 to March 17, 1987. The daily average pH values represent the simple average of three pH values, one from each eight hour work shift. In each shift, two pH measurements are averaged. In the analysis, monthly average values are simple averages, computed from the reported daily averages.

Figures 3-2 through 3-5 are simplified process flow diagrams,

Figure 3-2 Blue Plains East Primary Process Data.



IRON DOSE (mg/l)

(FEB 1984 - MAR. 1987)

	WPL	Fe3	Total
AVE.	3.93	7.36	8.60
S.D.	2.08	4.26	3.20
N.	12	38	38
MAX	6.84	15.11	15.11
MIN	0	0	0.51

INFLUENT CONDITIONS

	Q	BODI	TSSI	TPI	SPI
AVE.	171.8	121.7	133.7	4.39	2.59
S.D.	23.1	19.6	23.0	0.69	0.55
N.	51	50	51	50	43
MAX	235.2	178.6	180.3	6.02	3.86
MIN	138.3	69.1	70.8	3.25	1.41

SOLIDS PROCESSING RECYCLE

	Q	BODI	TSSI	TPI
AVE.	14.0	115.2	322.5	4.8
S.D.	3.26	36.2	113.7	2.2
N.	39	38	39	39
MAX	17.4	213.6	639.8	11.8
MIN	2.1	57.3	165.8	1.6

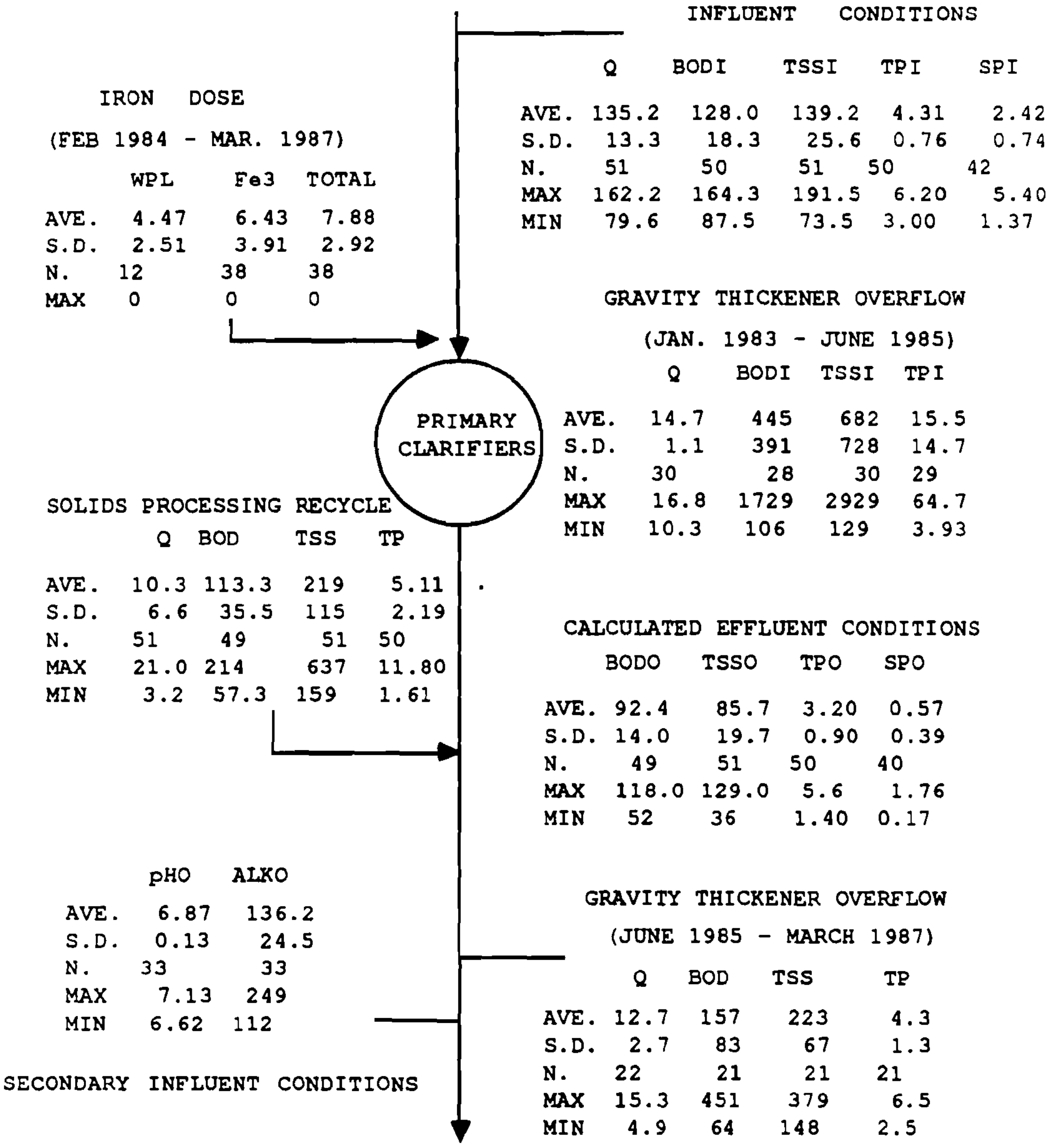
CALCULATED EFFLUENT CONDITIONS

	BODO	TSSO	TPO	SPO
AVE.	70.6	49.8	2.93	0.78
S.D.	10.5	14.7	0.97	0.54
N.	49	51	50	40
MAX	89.4	93.4	5.33	2.74
MIN	53	8	1.14	0.16

	pHO	ALKO
AVE.	6.94	133.3
S.D.	0.10	10.7
N.	33	33
MAX	7.12	156.4
MIN	6.68	109.4

SECONDARY INFLUENT CONDITIONS

Figure 3-3 Blue Plains West Primary Process Data.



INFLUENT CONDITIONS

	Q	BODI	TSSI	TPI	SPI
AVE.	135.2	128.0	139.2	4.31	2.42
S.D.	13.3	18.3	25.6	0.76	0.74
N.	51	50	51	50	42
MAX	162.2	164.3	191.5	6.20	5.40
MIN	79.6	87.5	73.5	3.00	1.37

IRON DOSE

(FEB 1984 - MAR. 1987)

	WPL	Fe3	TOTAL
AVE.	4.47	6.43	7.88
S.D.	2.51	3.91	2.92
N.	12	38	38
MAX	0	0	0

GRAVITY THICKENER OVERFLOW

(JAN. 1983 - JUNE 1985)

	Q	BODI	TSSI	TPI
AVE.	14.7	445	682	15.5
S.D.	1.1	391	728	14.7
N.	30	28	30	29
MAX	16.8	1729	2929	64.7
MIN	10.3	106	129	3.93

SOLIDS PROCESSING RECYCLE

	Q	BOD	TSS	TP
AVE.	10.3	113.3	219	5.11
S.D.	6.6	35.5	115	2.19
N.	51	49	51	50
MAX	21.0	214	637	11.80
MIN	3.2	57.3	159	1.61

CALCULATED EFFLUENT CONDITIONS

	BODO	TSSO	TPO	SPO
AVE.	92.4	85.7	3.20	0.57
S.D.	14.0	19.7	0.90	0.39
N.	49	51	50	40
MAX	118.0	129.0	5.6	1.76
MIN	52	36	1.40	0.17

	pHO	ALKO
AVE.	6.87	136.2
S.D.	0.13	24.5
N.	33	33
MAX	7.13	249
MIN	6.62	112

SECONDARY INFLUENT CONDITIONS

GRAVITY THICKENER OVERFLOW

(JUNE 1985 - MARCH 1987)

	Q	BOD	TSS	TP
AVE.	12.7	157	223	4.3
S.D.	2.7	83	67	1.3
N.	22	21	21	21
MAX	15.3	451	379	6.5
MIN	4.9	64	148	2.5

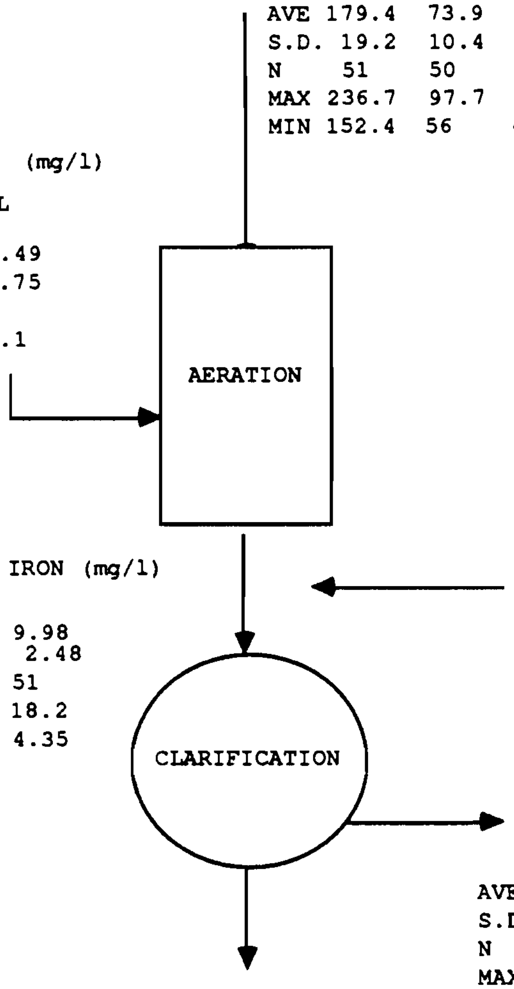
Figure 3-4 Blue Plains East Secondary Process Data.

INFLUENT CONDITIONS (mg/l)

	Q	BODI	TSSI	TPI	SPI	pHI	ALKI
AVE	179.4	73.9	67.1	2.94	0.78	6.94	133.3
S.D.	19.2	10.4	13.4	0.91	0.54	0.10	10.9
N	51	50	51	50	40	33	33
MAX	236.7	97.7	99.0	5.33	2.74	7.12	156.4
MIN	152.4	56	41.1	1.27	0.16	6.68	109.4

IRON (mg/l)

	WPL
AVE	6.49
S.D.	2.75
N	51
MAX	12.1
MIN	0



IRON (mg/l)

	Fe3
AVE	3.49
S.D.	3.60
N	51
MAX	12.30
MIN	0

TOTAL IRON (mg/l)

AVE	9.98
S.D.	2.48
N	51
MAX	18.2
MIN	4.35

Wasted Sludge (kip/day)

AVE	69.99
S.D.	19.67
N	51
MAX	114.95
MIN	33.2

EFFLUENT CONDITIONS (mg/l)

	BODO	TSSO	TPO	SPO	pHO	ALKO
AVE	13.6	19.7	0.07	0.17	6.89	104.3
S.D.	6.9	9.9	0.41	0.16	0.15	13.5
N	50	51	50	44	33	33
MAX	30	46.1	1.68	1.0	7.23	132.0
MIN	4.9	7.8	0.23	0.05	6.59	77.1

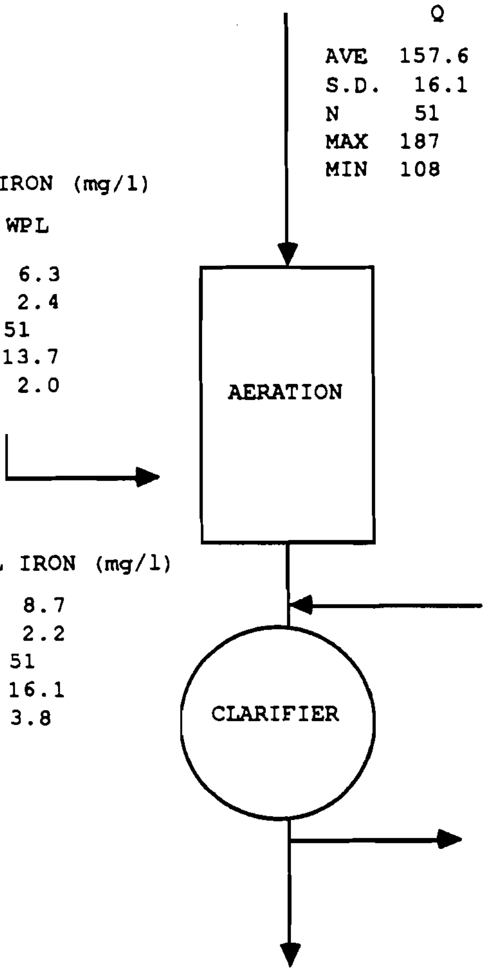
Figure 3-5 Blue Plains West Secondary Process Data.

INFLUENT CONDITIONS (mg/l)

	Q	BODI	TSSI	TPI	SPI	pHI	ALKI
AVE	157.6	96.1	104.7	3.4	0.57	6.87	131
S.D.	16.1	12.8	16.2	0.9	0.39	0.13	11.1
N	51	50	51	50	40	33	33
MAX	187	126.6	145.8	5.8	1.76	7.13	155
MIN	108	72.1	73.4	1.6	0.17	6.62	112

IRON (mg/l)

	WPL
AVE	6.3
S.D.	2.4
N	51
MAX	13.7
MIN	2.0



TOTAL IRON (mg/l)

AVE	8.7
S.D.	2.2
N	51
MAX	16.1
MIN	3.8

IRON (mg/l)

	Fe3
AVE	2.4
S.D.	2.9
N	51
MAX	11.2
MIN	0

WASTED SLUDGE

	(kip/day)
AVE	124.27
S.D.	16.49
N	51
MAX	161.32
MIN	87.63

EFFLUENT CONDITIONS(mg/l)

	BODO	TSSO	TPO	SPO	pHO	ALKO
AVE	8.8	24.7	0.68	0.14	6.68	99.2
S.D.	4.5	12.7	0.28	0.10	0.12	10.6
N	43	51	50	44	33	33
MAX	18.9	67.5	1.3	0.47	7.14	119
MIN	2.7	7.0	0.24	0.06	6.56	79.6

showing the parameters collected from the plant records and the locations at which they were measured. The primary effluent pH and alkalinity are assumed to be the same as the measured secondary influent values. This assumes that the net impact of recycle streams is zero.

BOD, TSS, TP, SP, alkalinity, and pH are measured directly above and below the aeration basis. For primary treatment analyses, the impact of recycle streams must be considered. Primary influent and effluent BOD, TSS, and TP values are estimated by mass balance calculations, taking into account the addition or subtraction of recycle flows. SP concentrations are not measured in the gravity thickener overflow recycle (GTOR) or solids processing building recycle (SPBR) streams.

Assumptions are made regarding locations where the SP concentration was not measured. The assumptions for estimating primary influent and effluent SP values are: 1) west primary influent SP concentration equals the raw influent concentration, 2) west primary effluent SP concentration equals the west secondary influent concentration, and 3) east primary effluent SP concentration is equal to the east secondary influent concentration. The east primary influent receives no recycle.

A discussion of the assumptions and a sensitivity analysis are provided in Appendix B.

3.4 RAW INFLUENT CHARACTERISTICS

Figure 3-6 shows that the total process flow at Blue Plains has decreased since 1983.

Figures 3-7a,b through 3-11a,b show the combined raw influent wastewater parameters of BOD, TSS, TP, SP, and particulate phosphorus (TP-SP). The value of these parameters increased between mid 1984 and late 1985, before dropping or leveling off. This hump in the SP data is clear in Figures 3-10a and 3-10b. The decrease in late 1985 roughly coincides with the detergent phosphate ban.

Figure 3-11b shows that particulate phosphorus mass loading decreased to its lowest observed values in 1986, before trending upward.

Figures 3-7c to 3-10c are scatter plots of concentration (mg/l) versus mass loading (kip/day). The strong positive correlation between wastewater strength and mass loading indicates that either concentration or loading may be used to develop empirical phosphorus removal and sludge production relationships.

Figures 3-7d through 3-10d are scatter plots of influent parameter concentrations vs. flow. Decreases in influent BOD and TSS are significantly correlated with increasing flow, indicating a dilution effect.

Influent TP and SP concentrations are not linearly correlated with flow. Some data is missing from 1983, when flow was higher, however, measurements of these parameters exist at the maximum flow (380 MGD). The dilution effect is not revealed, because both influent phosphorus

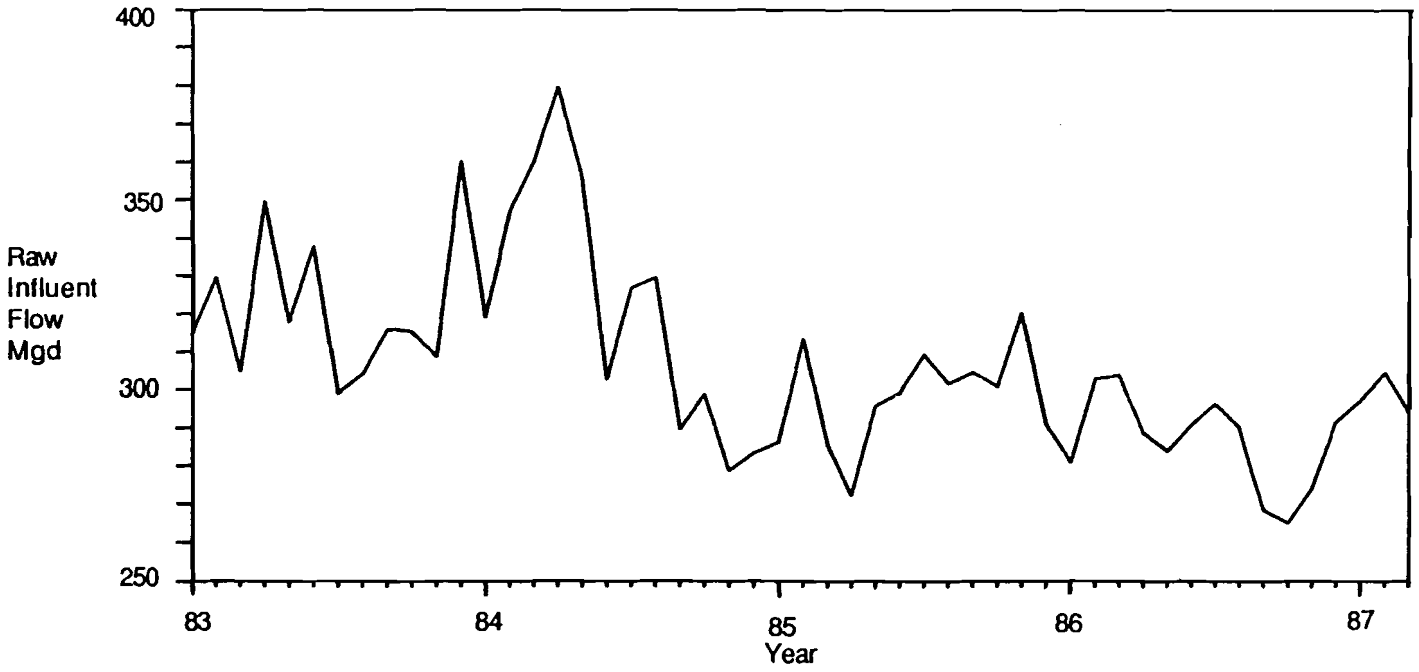


Figure 3-6 Blue Plains Raw Influent Flow.

Figure 3-7 Blue Plains Combined Raw Influent a) BOD Concentration vs. Year, b) BOD Mass Loading vs. Year, c) BOD Concentration vs. Mass Loading, d) BOD Concentration vs. Flow.

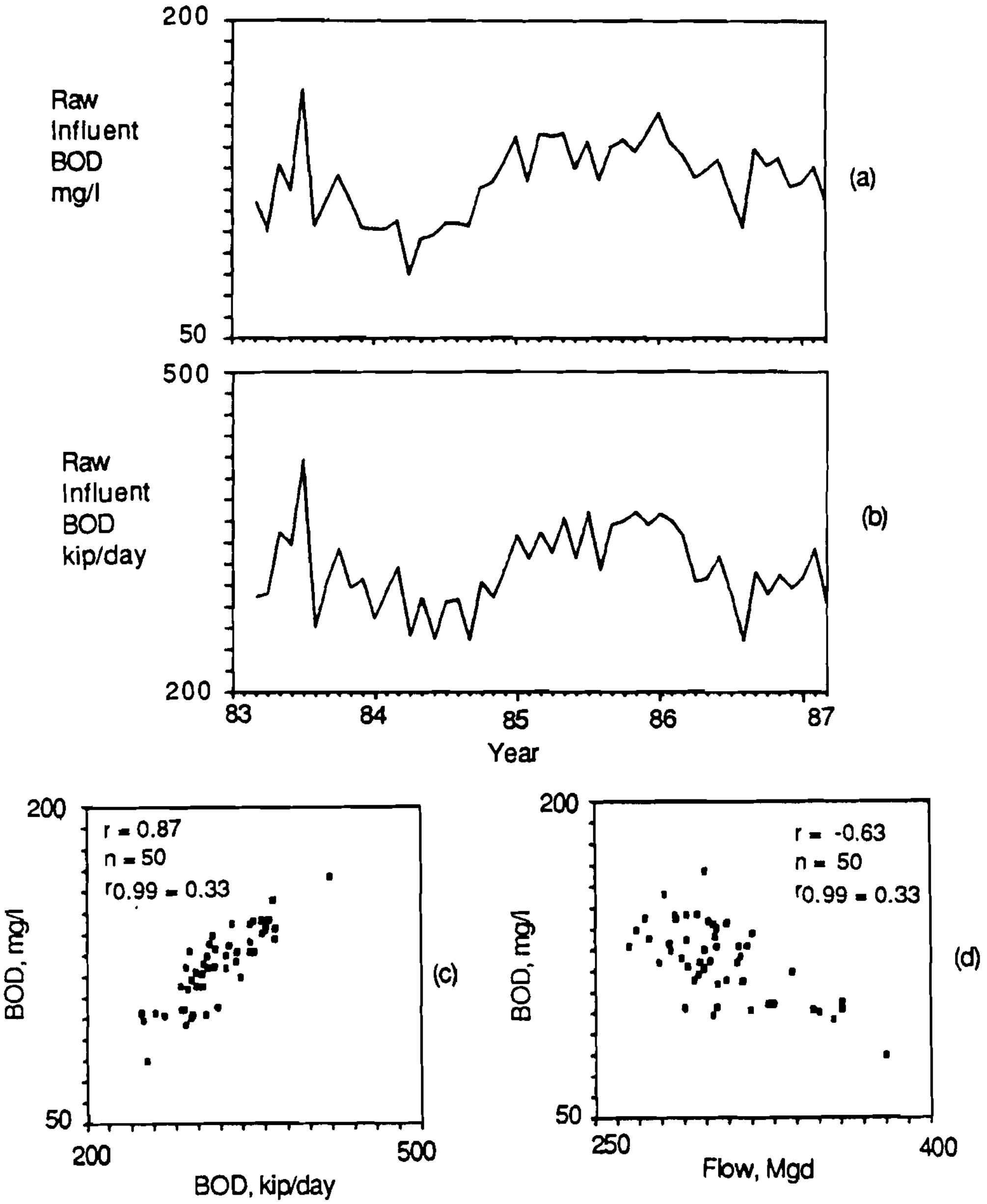


Figure 3-8 Blue Plains Combined Raw Influent a) TSS Concentration vs. Year, b) TSS Mass Loading vs. Year, c) TSS Concentration vs. Mass Loading, d) TSS Concentration vs. Flow.

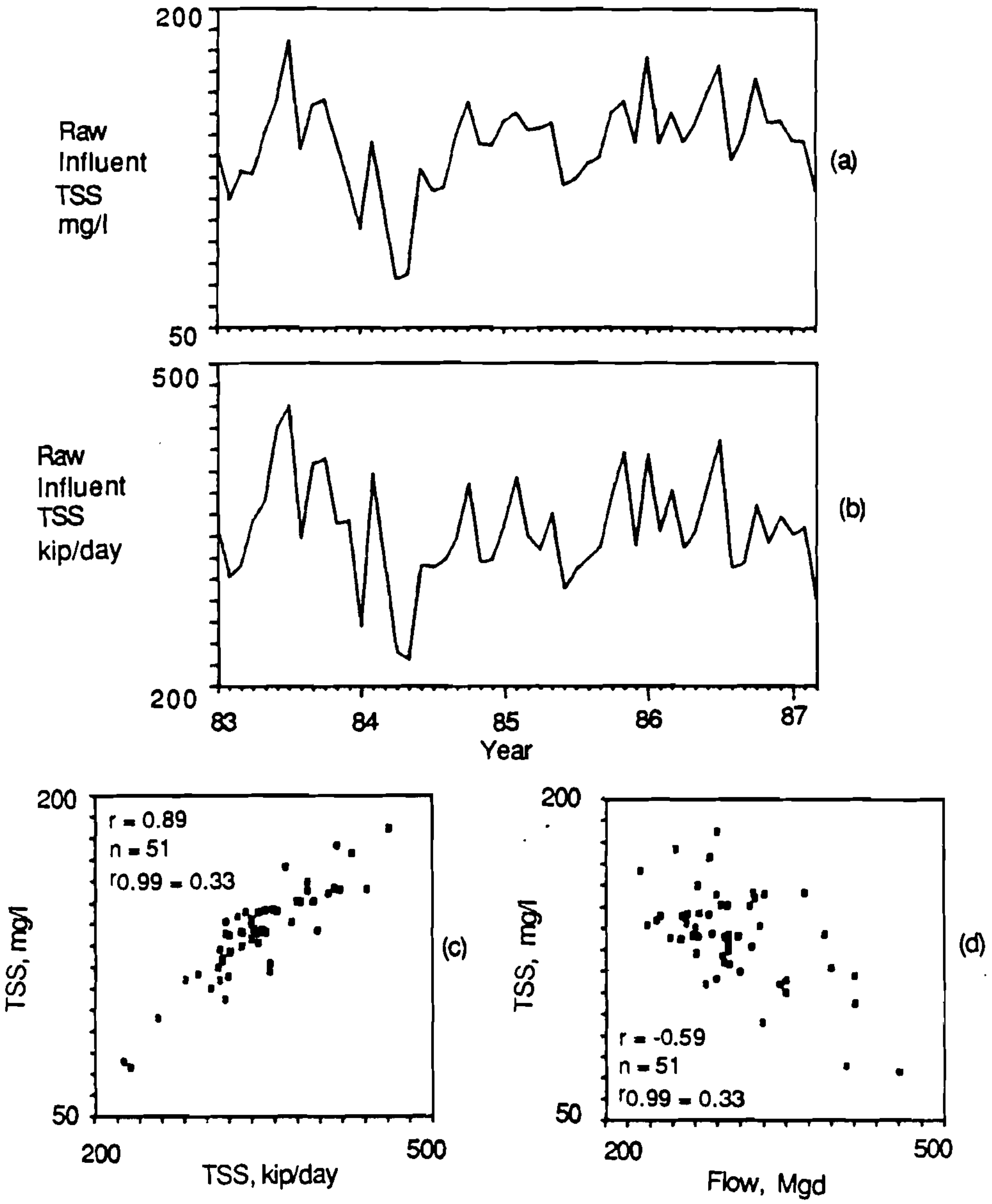


Figure 3-9 Blue Plains Combined Raw Influent a) TP Concentration vs. Year, b) TP Mass Loading vs. Year, c) TP Concentration vs. Mass Loading, d) TP Concentration vs. Flow.

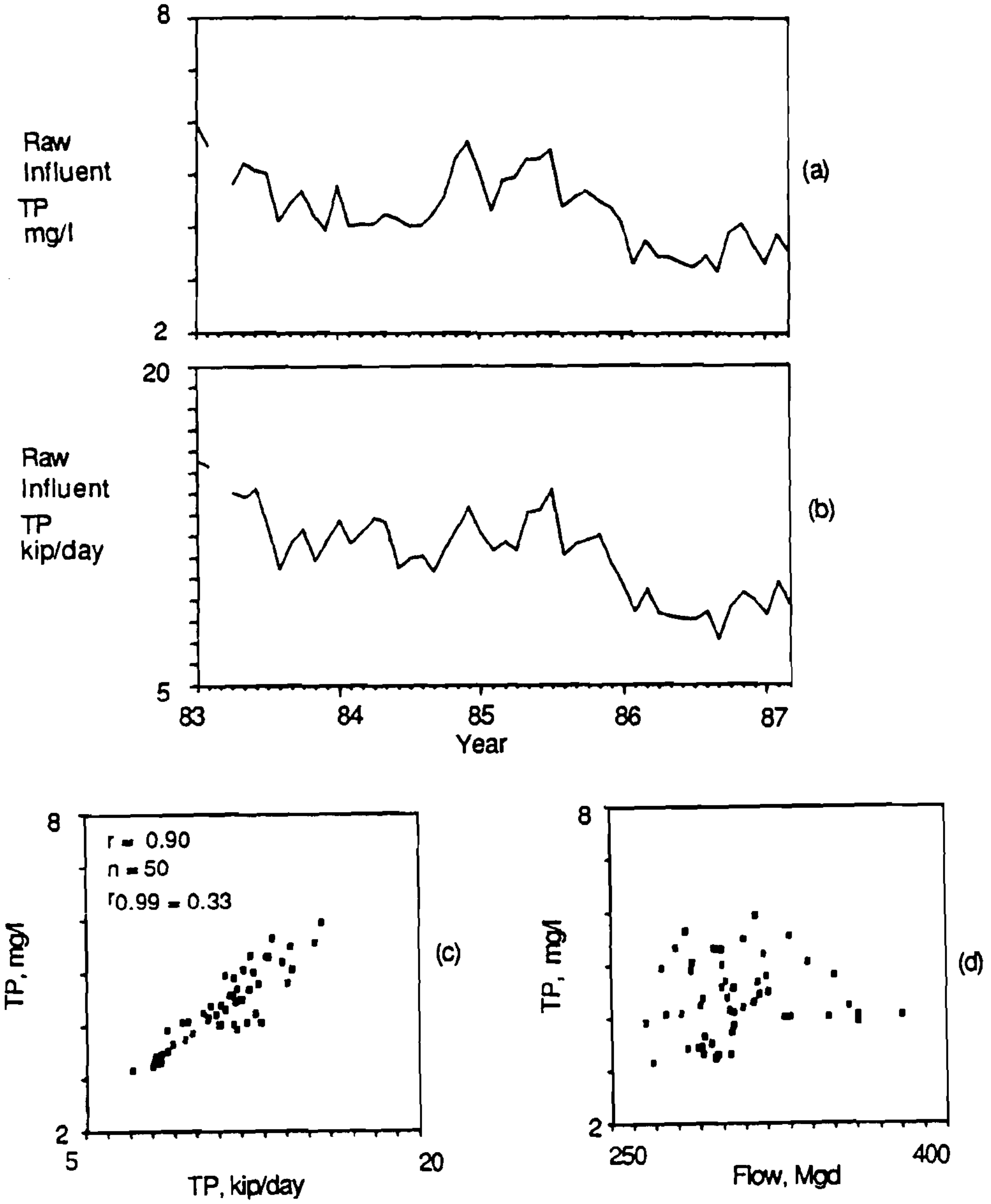


Figure 3-10 Blue Plains Combined Raw Influent a) SP Concentration vs. Year, b) SP Mass Loading vs. Year, c) SP Concentration vs. Mass Loading, d) SP Concentration vs. Flow.

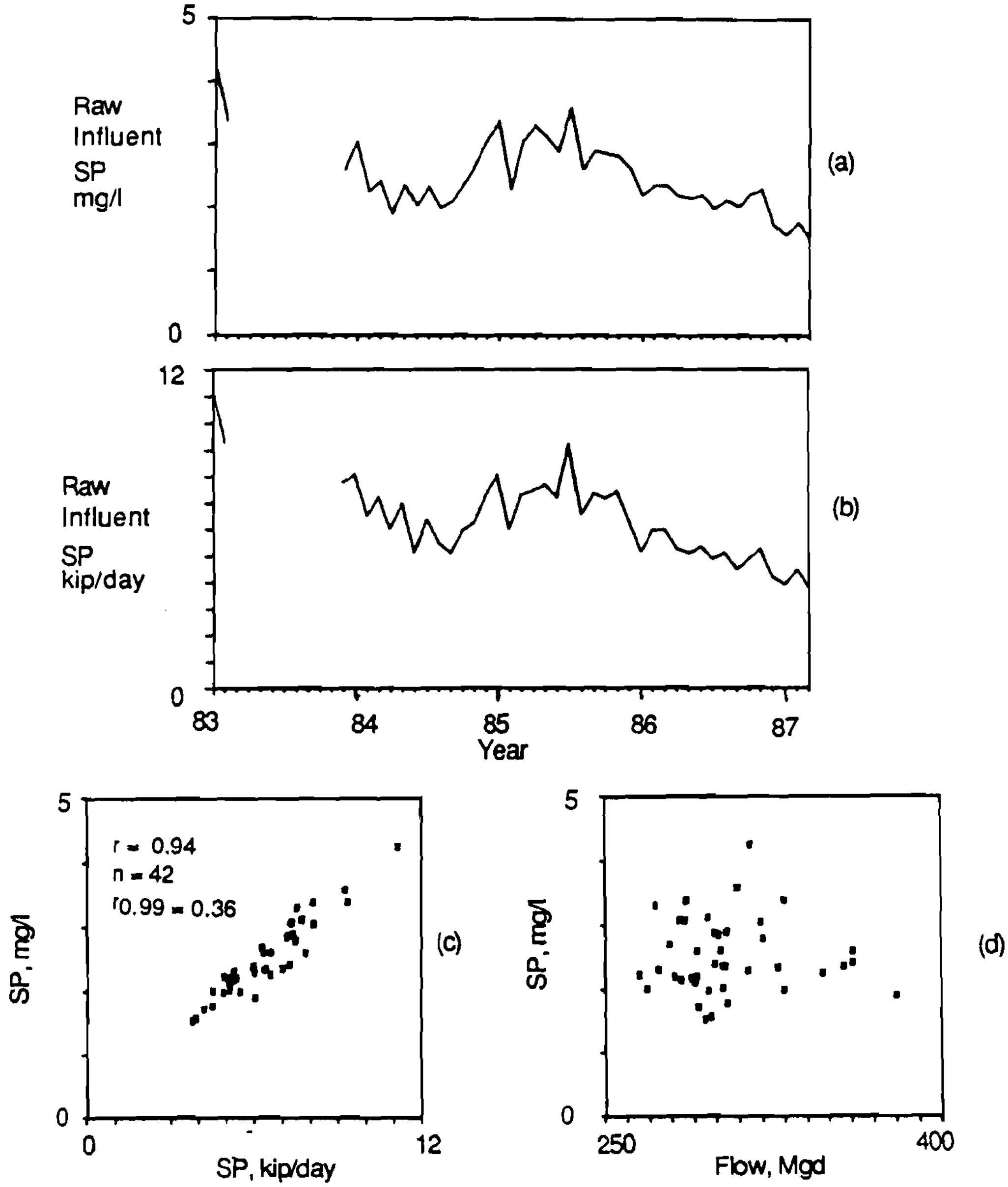
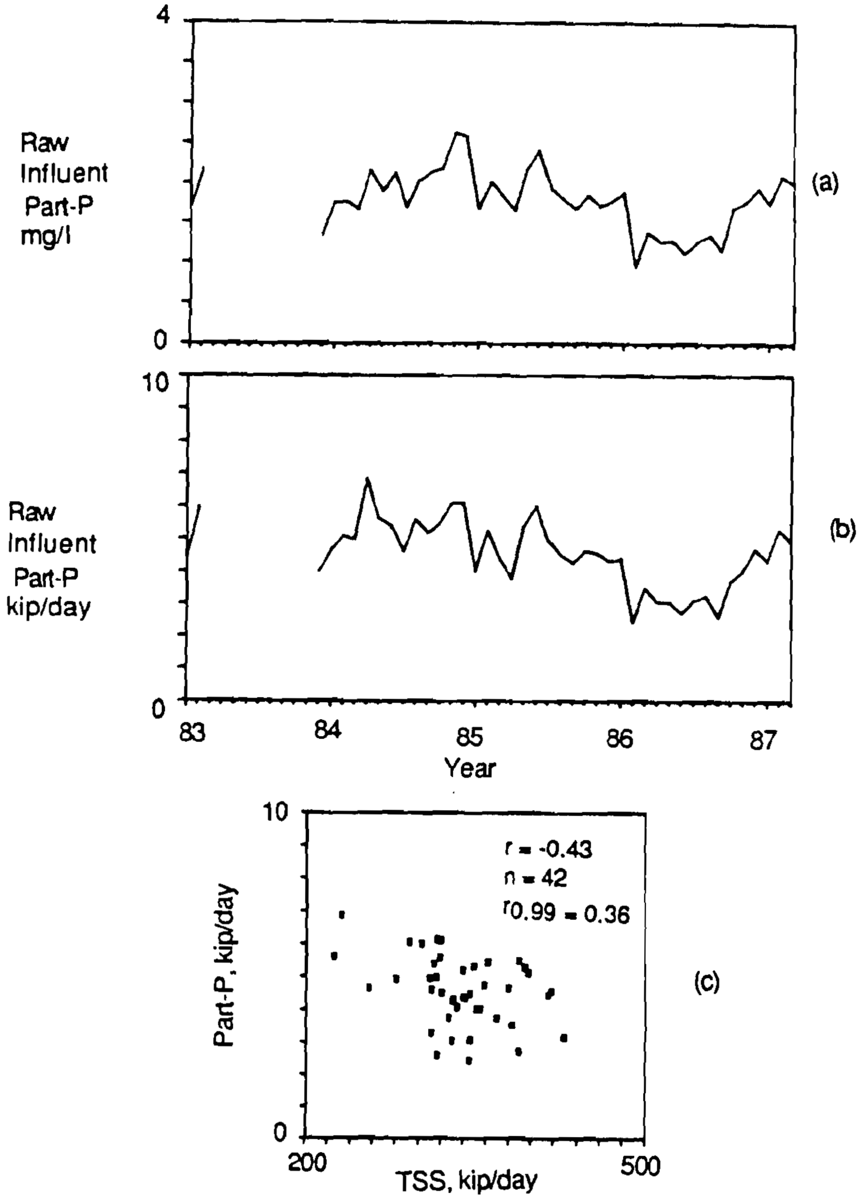


Figure 3-11 Blue Plains Combined Raw Influent a) Particulate Phosphorus Concentration vs. Year, b) Particulate Phosphorus Mass Loading vs. Year, c) Particulate Phosphorus Mass Loading vs. TSS Mass Loading, (Particulate Phosphorus = TP - SP).



concentrations and flow have decreased with time.

Figure 3-11c does not reveal the expected relationship between influent particulate mass loading and TSS loading.

3.5 PRIMARY PHOSPHORUS REMOVAL

3.5.1 Recycle Flows

Gravity thickener overflow (GTOR) was routed ahead of the west primary clarifiers prior to July 1985. Figure 3-12 shows the contribution of this recycle to influent BOD, TSS, and TP (kip/kip). The impact of the recycle is clearly revealed in subsequent plots of west primary influent conditions.

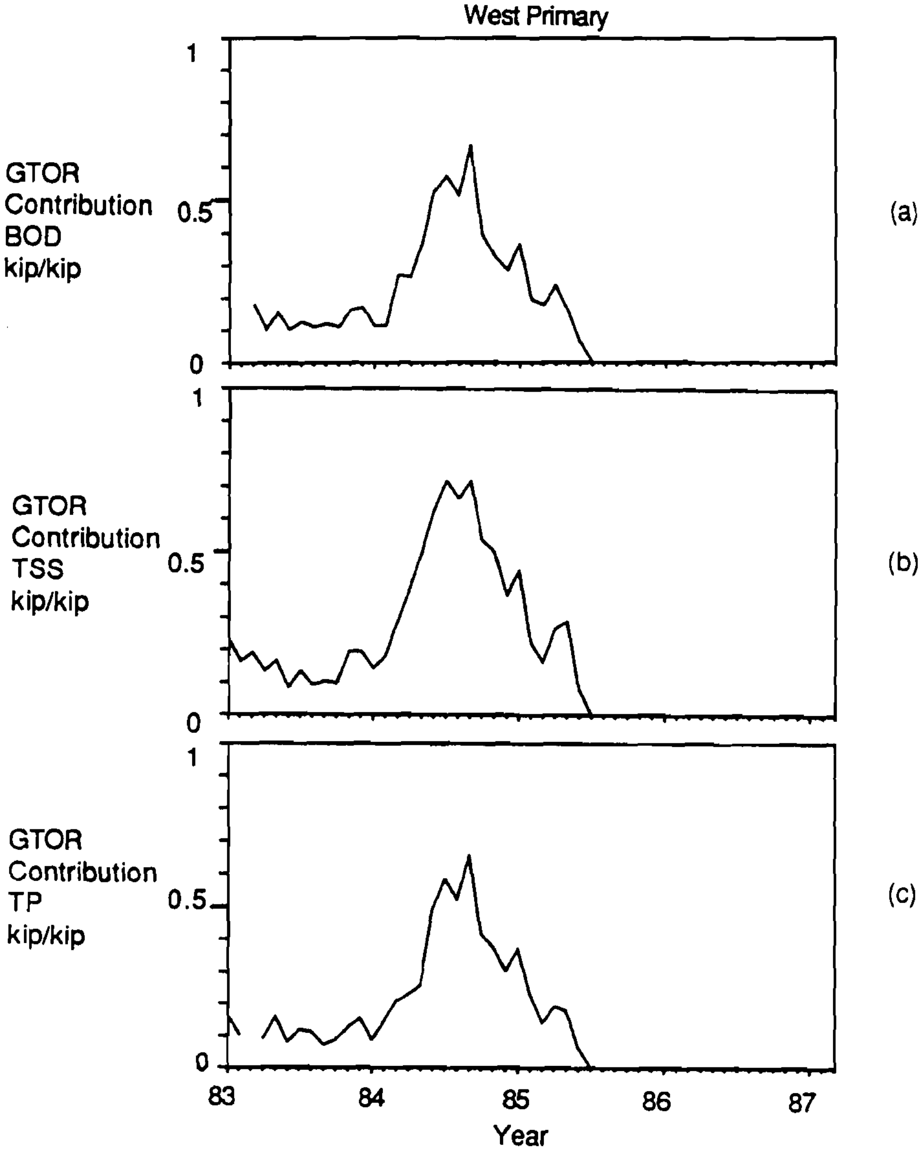
3.5.2 Soluble Phosphorus Removal

Figures 3-13 and 3-14 show the primary iron dosing and SP removal data. The time series plots show that influent phosphorus concentrations, iron dose, and SP removed increased from 1984 to mid-1985, before decreasing again.

Figures 3-14a and 3-14c indicate no apparent difference between SP removal for WPL or ferric chloride dosing. The effect of different precipitants on SP removal is formally tested in Chapter Four.

The effluent SP concentrations in Figures 3-14b and 3-14d are near the solubility limit for orthophosphate. Based on the precipitation model of Jenkins et al. (32), calibrated to the experimental tap water data of Recht and Ghassemi (58), the solubility limit for orthophosphate in <u>tap water</u> at pH = 6.94 is approximately 0.17 mg/l

Figure 3-12 Blue Plains, Percentage of a) BOD, b) TSS, c) TP in West Primary Influent Originating from Gravity Thickener Overflow Recycle.



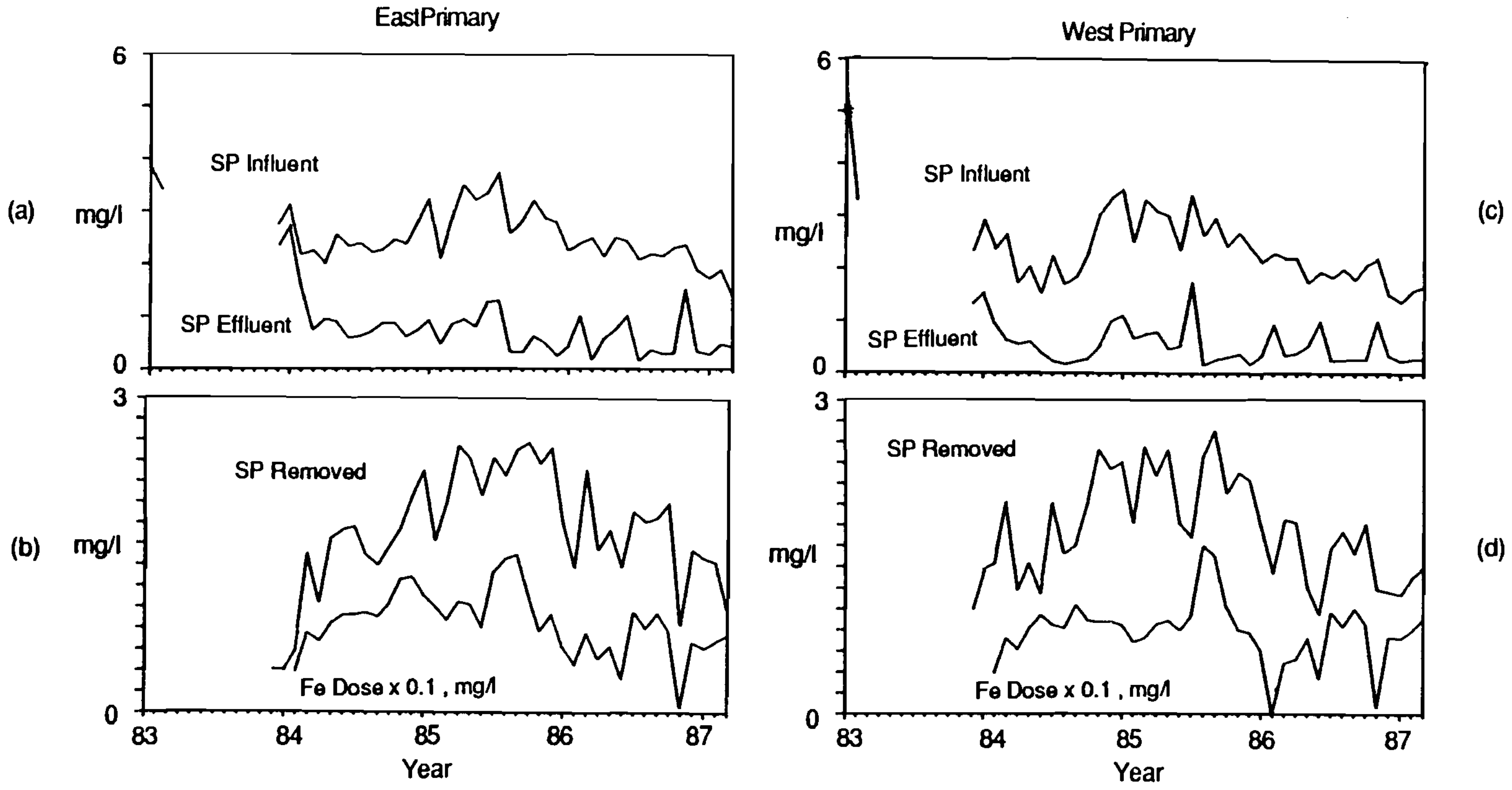


Figure 3-13 Blue Plains Primary, SP Influent and Effluent vs. Year a) East Plant, c) West Plant and SP Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

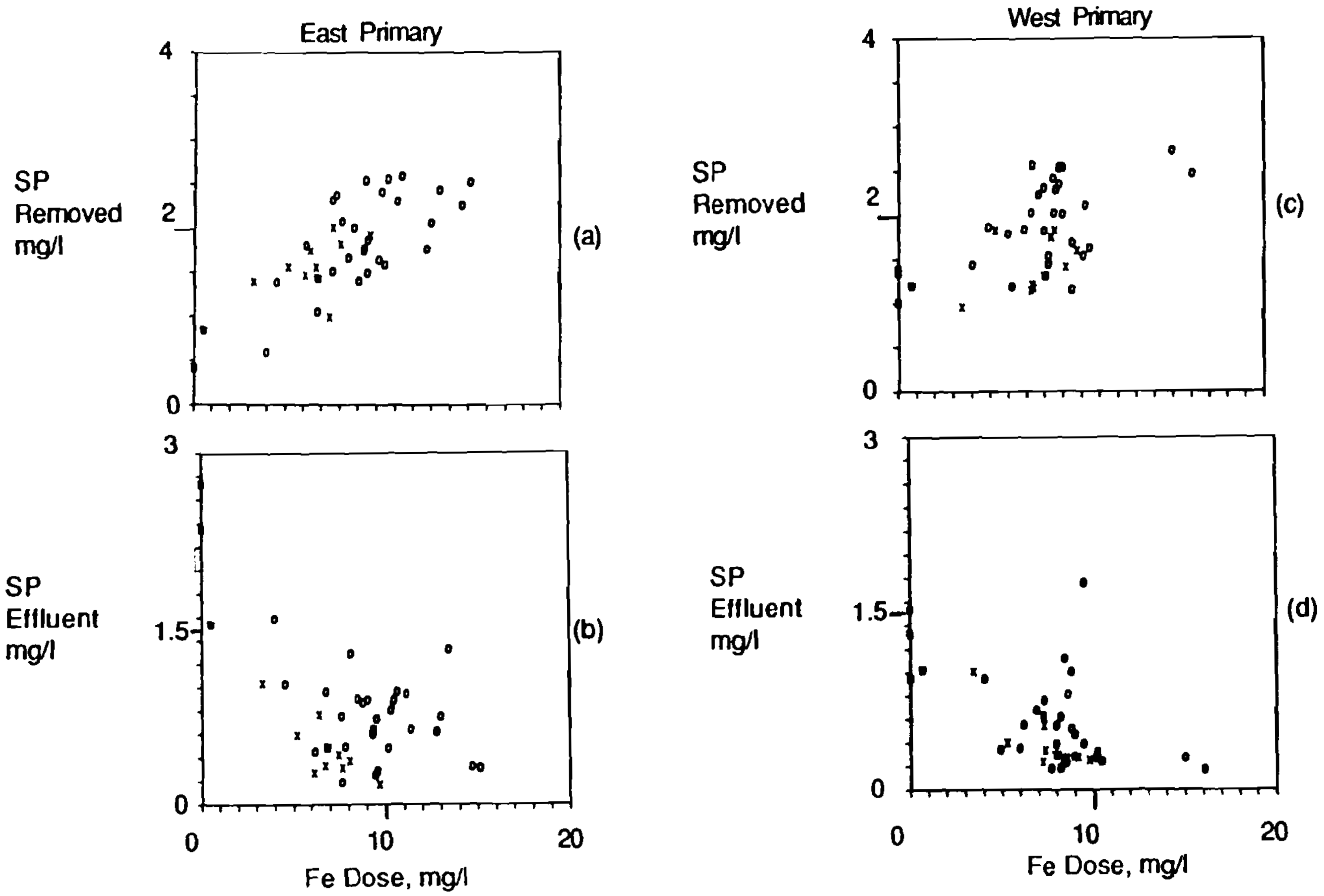


Figure 3-14 Blue Plains Primary, SP Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent SP vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

and at pH = 6.87 is 0.13 mg/l. These pH values represent average secondary influent values at Blue Plains for the east and west plants, respectively.

Figure 3-15a,c shows the relationships between SP removed and influent SP. The amount of SP removed is constrained by the amount available. This partially explains the linear trends in Figure 3-14a,c. The relationship between influent SP, SP removed, iron dose and flow is formally studied in Chapter Four.

Figure 3-16 indicates that influent SP and iron dose are mildly related in the east plant, but not in the west plant.

Figure 3-17a,c shows the Fe/P_C mole ratio and the primary effluent SP concentration. The average Fe/P_C ratios are greater than the theoretical stoichiometric value, which is approximately 1.5. Deviations from theoretical values may be attributed to inefficiencies associated with mixing, aeration, and dose point, or to the degree to which SP measurements reflect true orthophosphate concentration in primary treatment.

The time series plots of Fe/P_C show a general downward trend prior to early 1986.

3.5.3 Alkalinity and pH

Figure 3-18 shows that higher primary iron doses are generally associated with decreases in the secondary influent pH and alkalinity. Raw wastewater pH and alkalinity are not measured, so causal

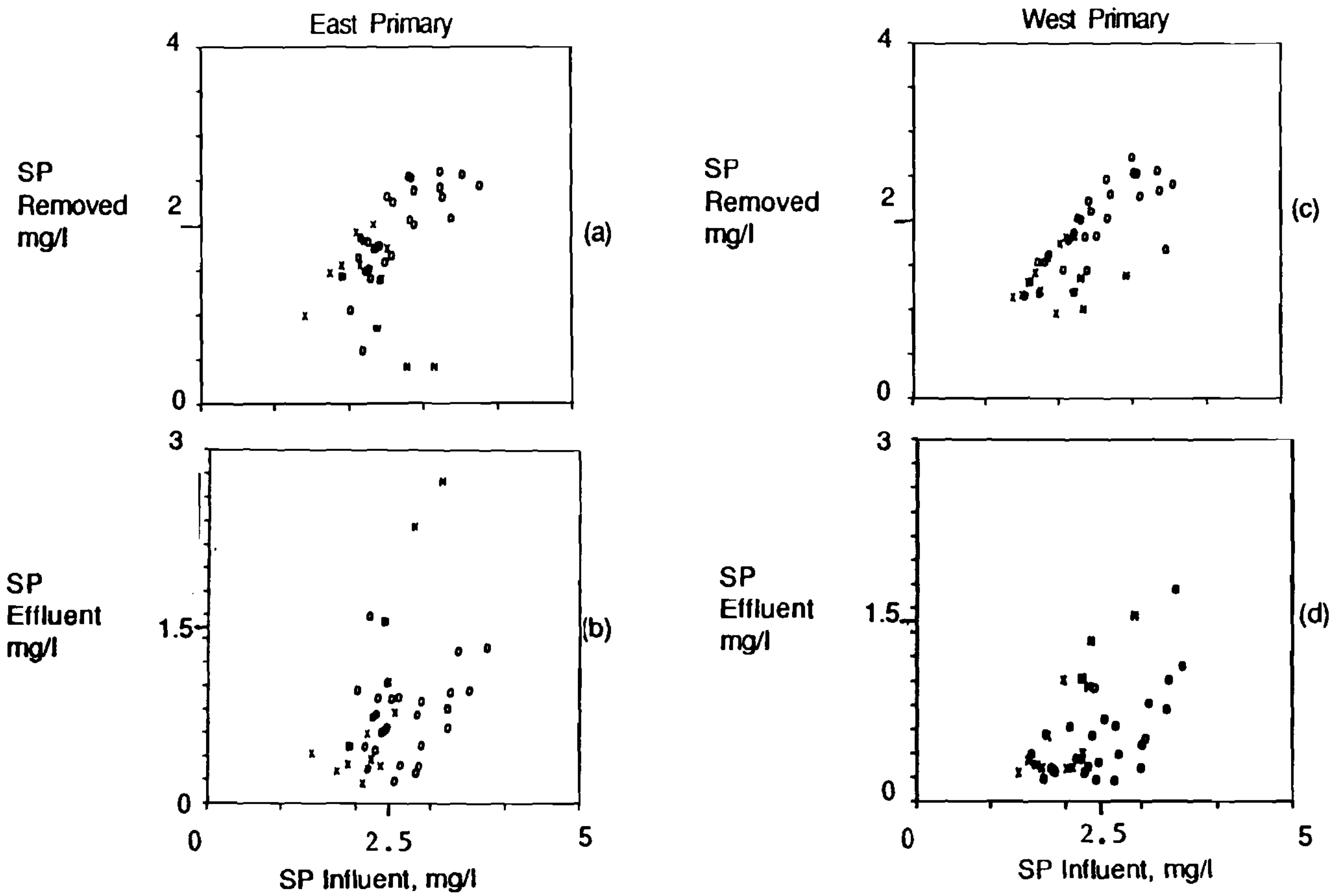


Figure 3-15 Blue Plains Primary, SP Removed vs. Influent SP a) East Plant, c) West Plant, SP Effluent vs SP Influent b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

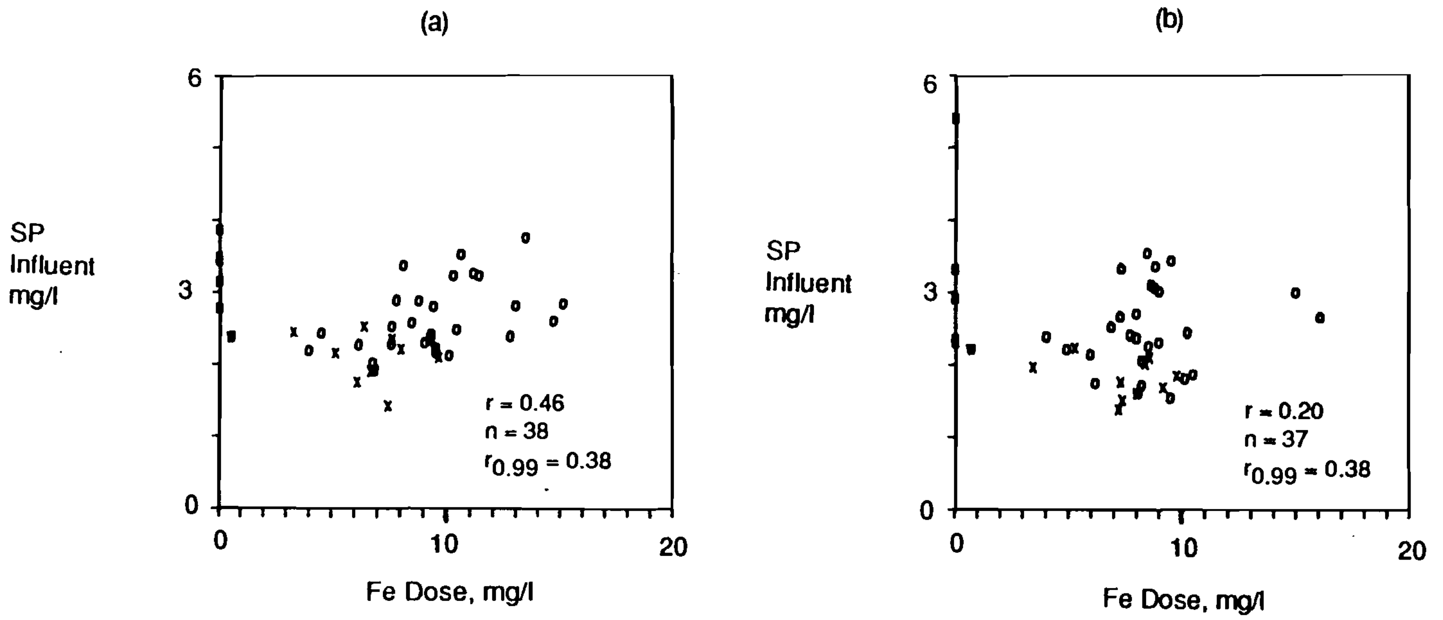


Figure 3-16 Blue Plains Primary Influent SP vs. Iron Dose a) East Plant, b) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

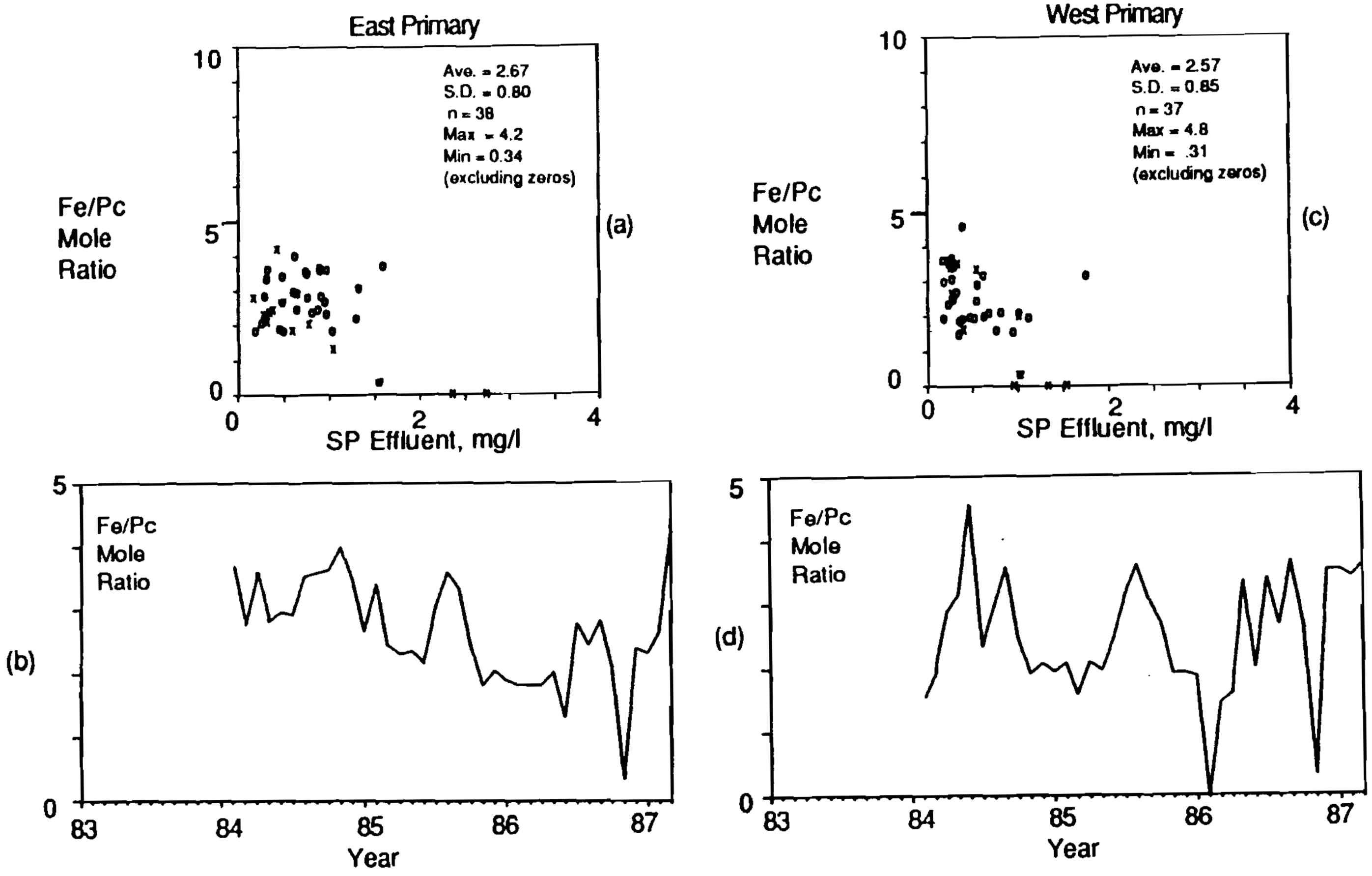


Figure 3-17 Blue Plains Primary Fe/P_C Mole Ratio vs. SP Effluent a) East Plant, c) West Plant, and Fe/P_C Mole Ratio vs. Year, b) East Plant, d) West Plant, for P_C = SPI - SPO (O = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

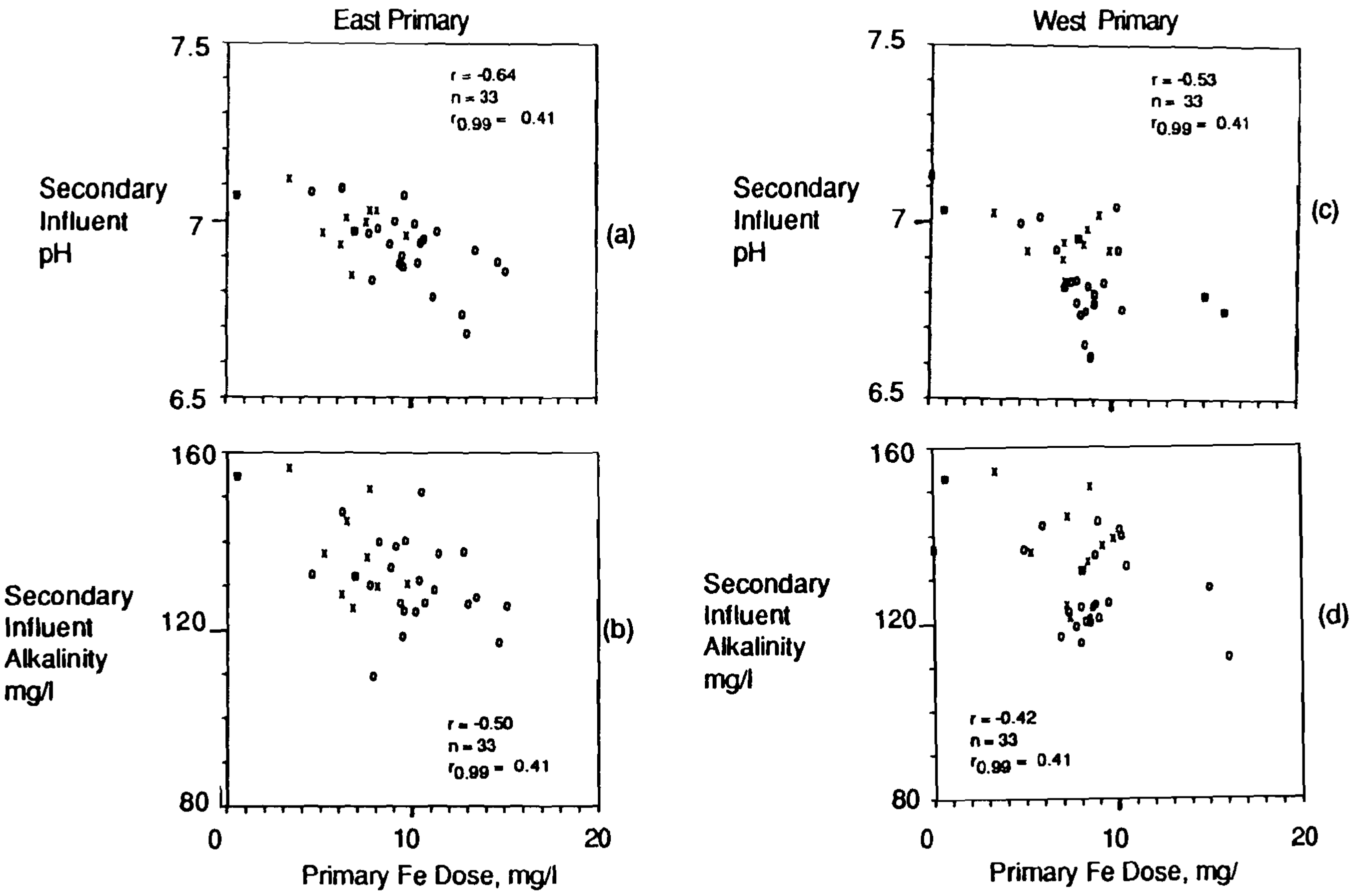


Figure 3-18 Blue Plains Primary, Secondary Influent pH vs. Primary Fe Dose a) East Plant, c) West Plant, Secondary Influent Alkalinity ($CaCO_3$) vs. Primary Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

relationships can not be assured. However, the process chemistry is consistent with the observed relationships.

3.5.4 BOD, TSS, and TP

Figures 3-20a,c and 3-22a,c show BOD and TSS removed vs. iron dose. Since enhanced BOD and TSS removal is expected to occur with iron dosing, the following model was fit to test for the existence of an effect due to iron dosing:

$$\text{dBOD or dTSS} = b_0 + b_1 Z + b_2 Z\,\text{Fe} \qquad \text{3-1}$$

where Z = 1 if iron is dosed.

= 0 if otherwise.

dBOD = BOD removed , mg/l

dTSS = TSS Removed , mg/l

Fe = Iron dose , mg/l

The dummy variable coefficient b_1 was significant ($\alpha = 95\%$) in all regressions except for the west plant TSS data. The addition of the third model term, $b_2 Z\,\text{Fe}$, did not significantly improve any regression. The simplistic interpretation is that adding iron increases the removal of BOD and TSS by a constant amount over the range of iron doses used.

There is a problem with this interpretation. The pre-iron addition data is from a period of higher flow. Lower TSS and BOD

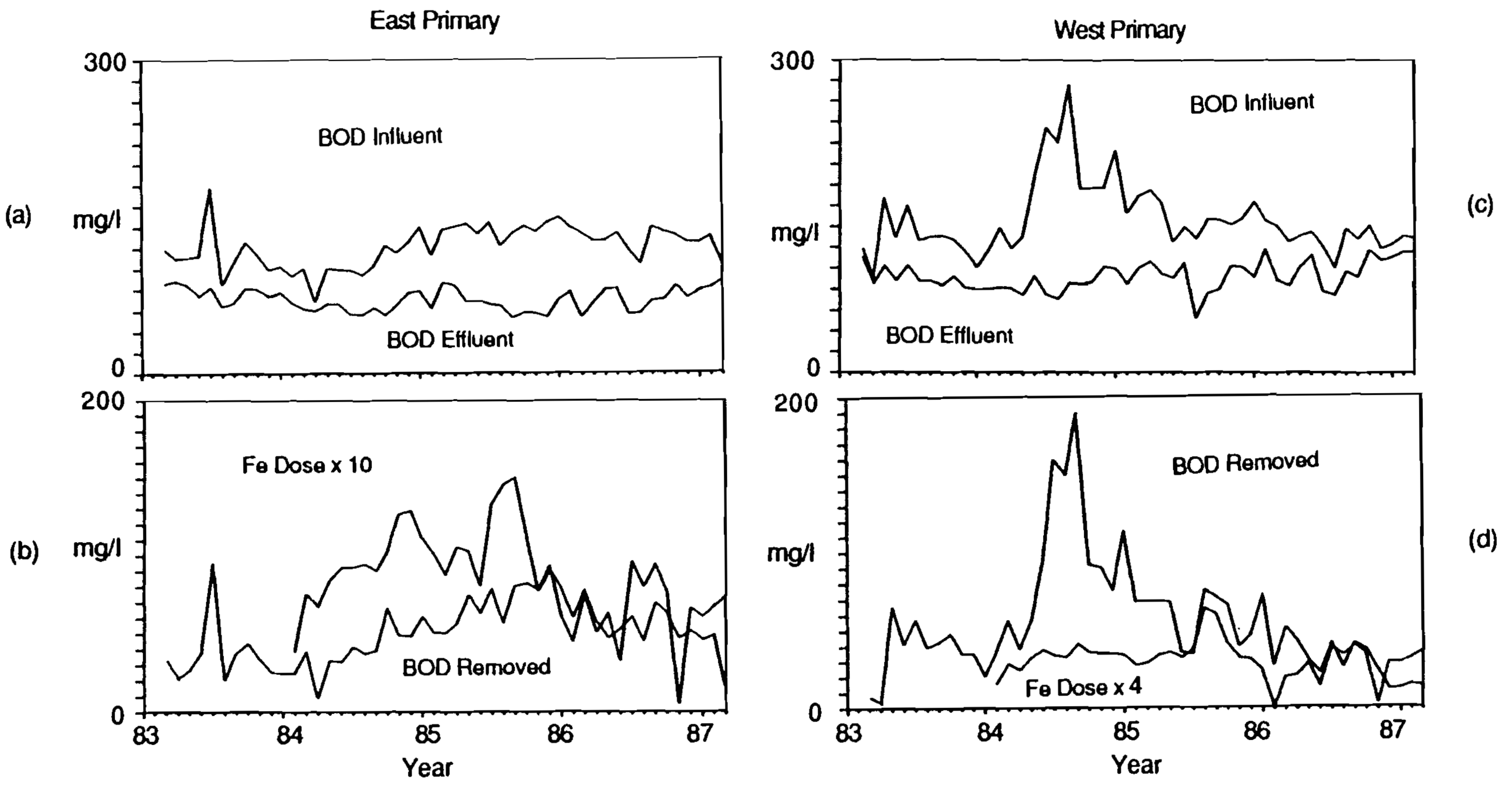


Figure 3-19 Blue Plains Primary, BOD Influent and Effluent vs. Year a) East Plant, c) West Plant and BOD Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

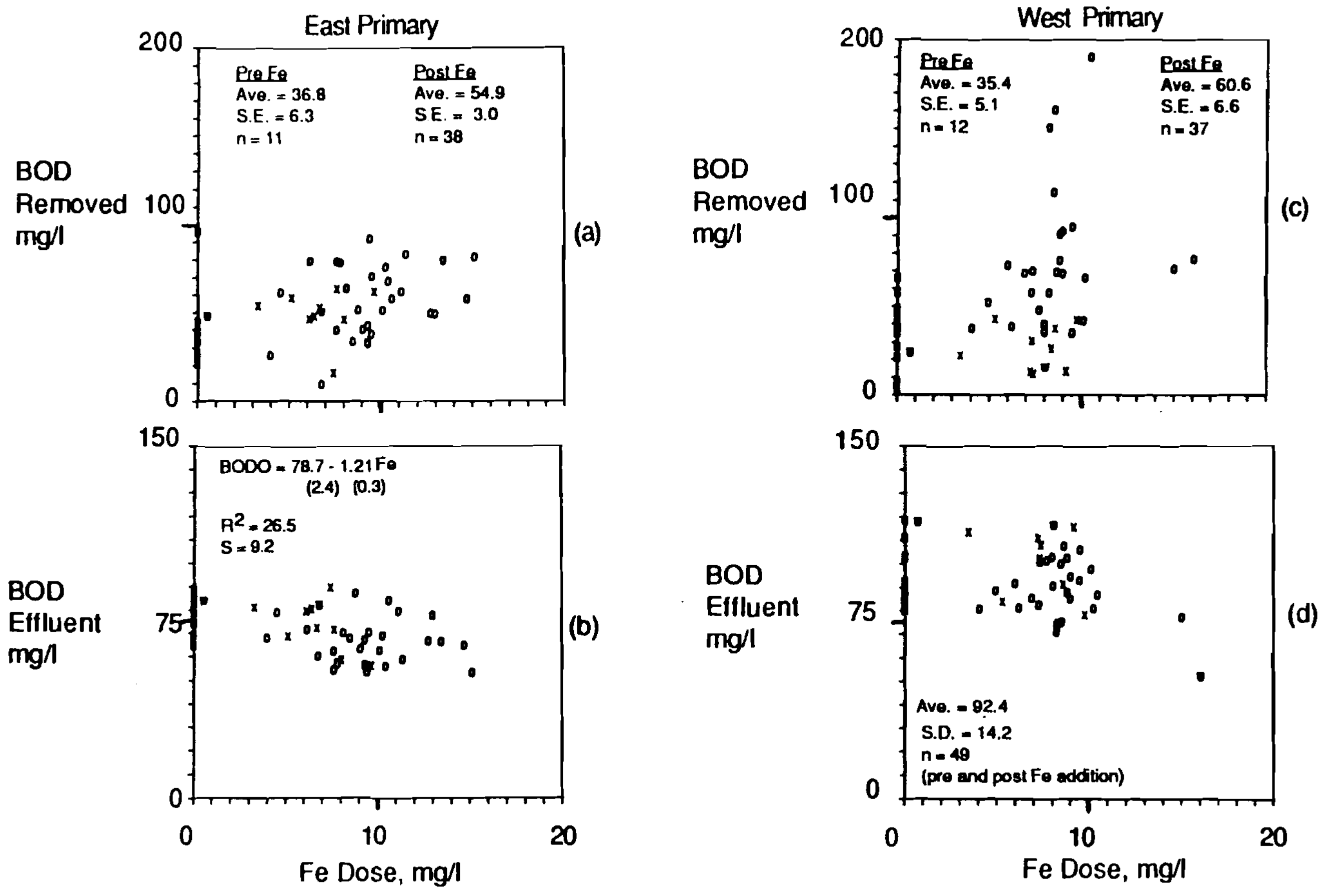


Figure 3-20 Blue Plains Primary, BOD Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent BOD vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

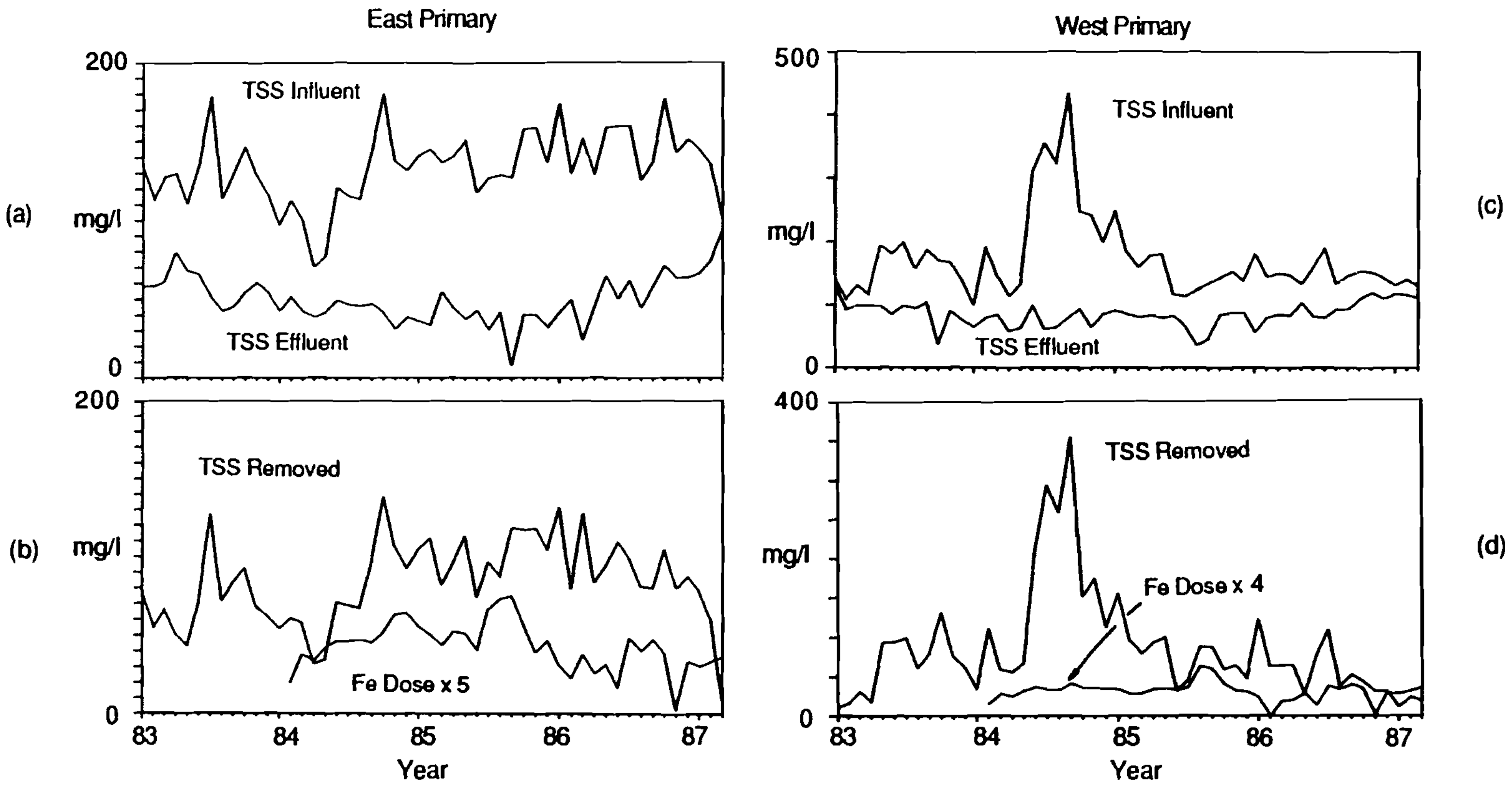


Figure 3-21 Blue Plains Primary, TSS Influent and Effluent vs. Year a) East Plant, c) West Plant and TSS Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

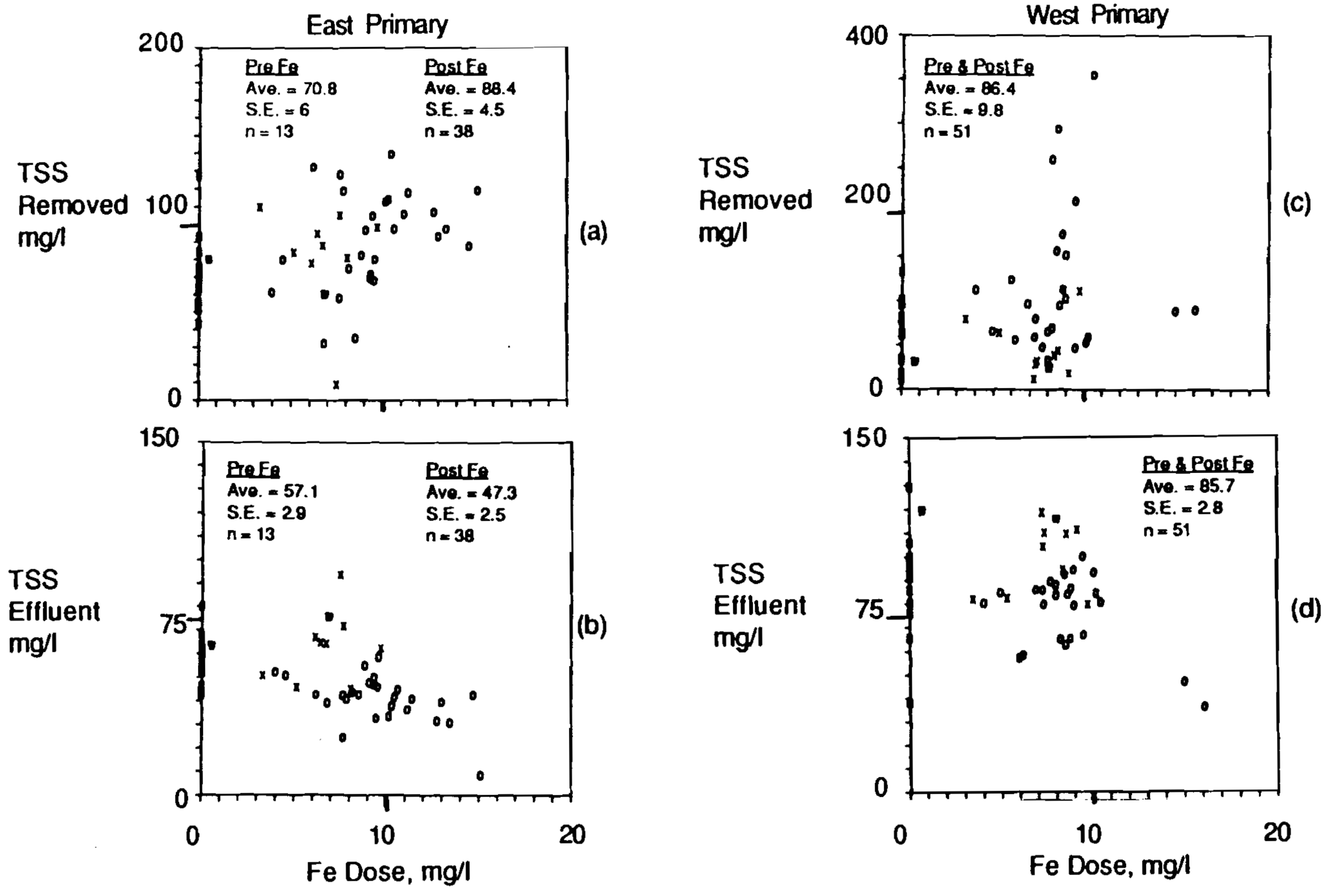


Figure 3-22 Blue Plains Primary, TSS Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent TSS vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

removal could occur if primary clarifier overflow rates were increased to compensate for increased flow. For the west primaries, the linear correlation coefficients for flow and BOD removal, dBOD, were insignificant ($r = -0.02$, $n = 49$, $r_{0.99} = 0.33$). The correlation for flow and TSS removed was also insignificant ($r = 0.15$, $n = 51$, $r_{0.99} = 0.32$). For the east plant the correlations with flow, BOD removal, and TSS removal were found to be significant (BOD-Q: $r = -0.62$, $n = 49$, $r_{0.99} = 0.33$; TSS-Q: $r = -0.59$, $n = 51$, $r_{0.99} = 0.32$). Plots of these data are not included, but the correlation coefficients reflect the observed patterns.

The same regression model of Equation 3-1 was fit to BOD and TSS effluent data. The results are presented in Figures 3-20b,d and 3-22b,d. The fit indicated that a significant reduction in effluent TSS concentrations for the east plant only. For the east plant, effluent BOD and effluent TSS were not found to be linearly correlated with flow (at 95%).

The data for the west plant are not as convincing, since the results are affected by data corresponding to the gravity thickener overflow problems in 1984. For the west plant, effluent BOD was not correlated with flow (at 95%). The correlation between effluent TSS and flow was found to be $r = -0.42$ ($n = 51$, $r_{0.99} = 0.32$).

The results of the above analyses indicate that primary iron dosing has, in general, improved the effluent quality of the east plant. The results also suggest that primary sludge production increases are not only due to chemical precipitates, but enhanced TSS removal.

Figure 3-23 shows the relationship between primary BOD removal and TSS removal.

Total phosphorus data is presented in Figures 3-24 and 3-25. The negative removal value in the east plant was for March 1987. Only a few daily measurements for primary influent and effluent phosphorus (SP and TP) were available for March 1987, and the discrepancy is probably related to the limited daily data.

For the west plant, the negative TP removal values are from February and April 1983.

Simple single variable linear relationships between TP removal, TP effluent and iron dose are not offered. TP removal is a function of SP removal and particulate phosphorus removal. However, the data clearly indicate that TP removal and effluent TP are related to iron dosing.

3.6 PRIMARY SLUDGE PRODUCTION

The primary sludge data used are combined east and west plant sludge productions. Primary sludge solids and flow measurements are taken prior to gravity thickening.

Figure 3-26a shows the reported primary sludge production between January 1983 and December 1986, with the amount and type of iron dose.

The hump in mid-1984 corresponds to: (1) the first year of iron dosing, when chemical sludge became a portion of the measured raw

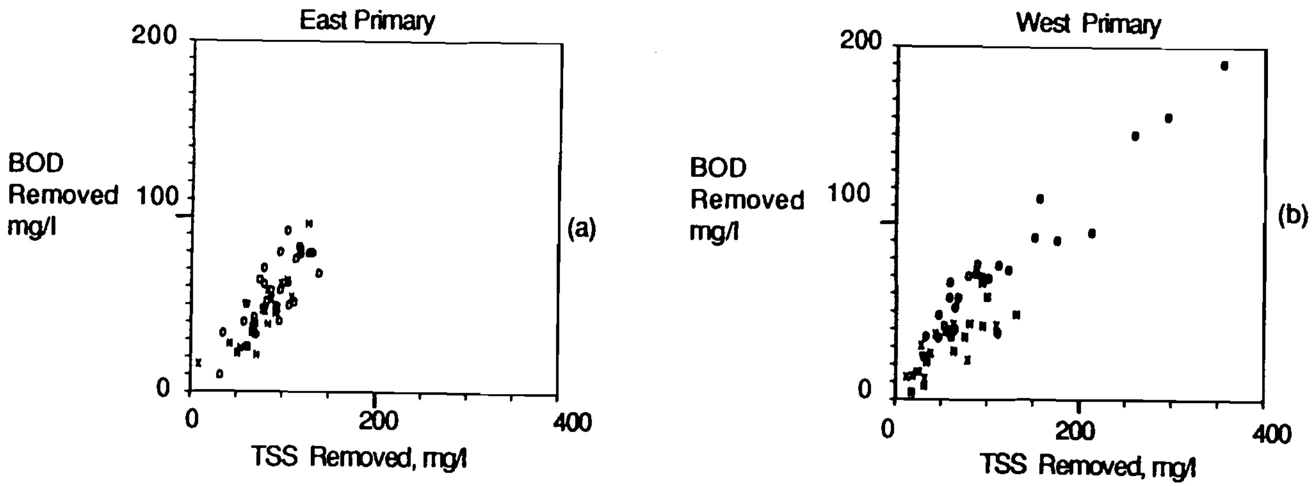


Figure 3-23 Blue Plains Primary BOD Removed vs. TSS Removed a) East Plant, b) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

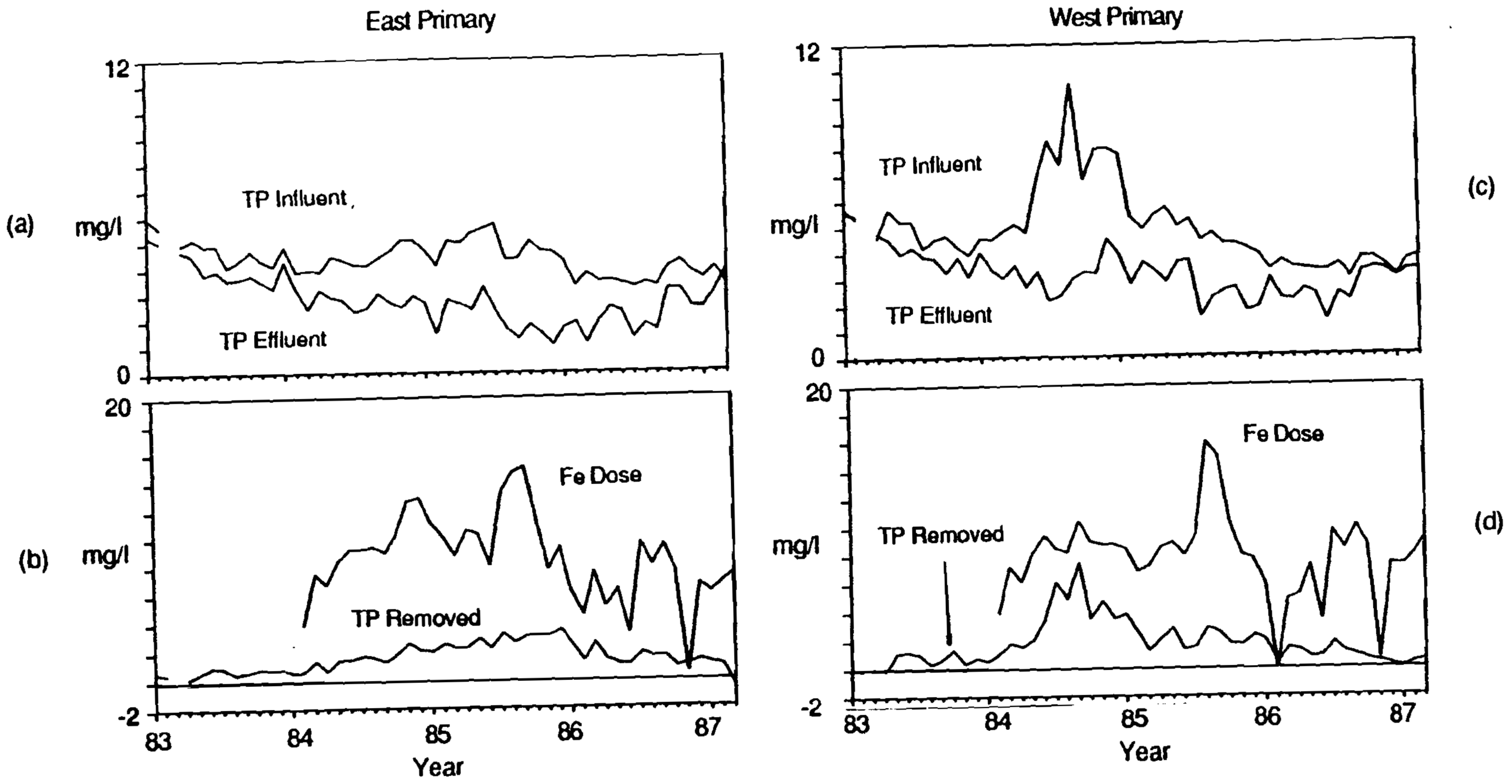


Figure 3-24 Blue Plains Primary, TP Influent and Effluent vs. Year a) East Plant, c) West Plant and TP Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

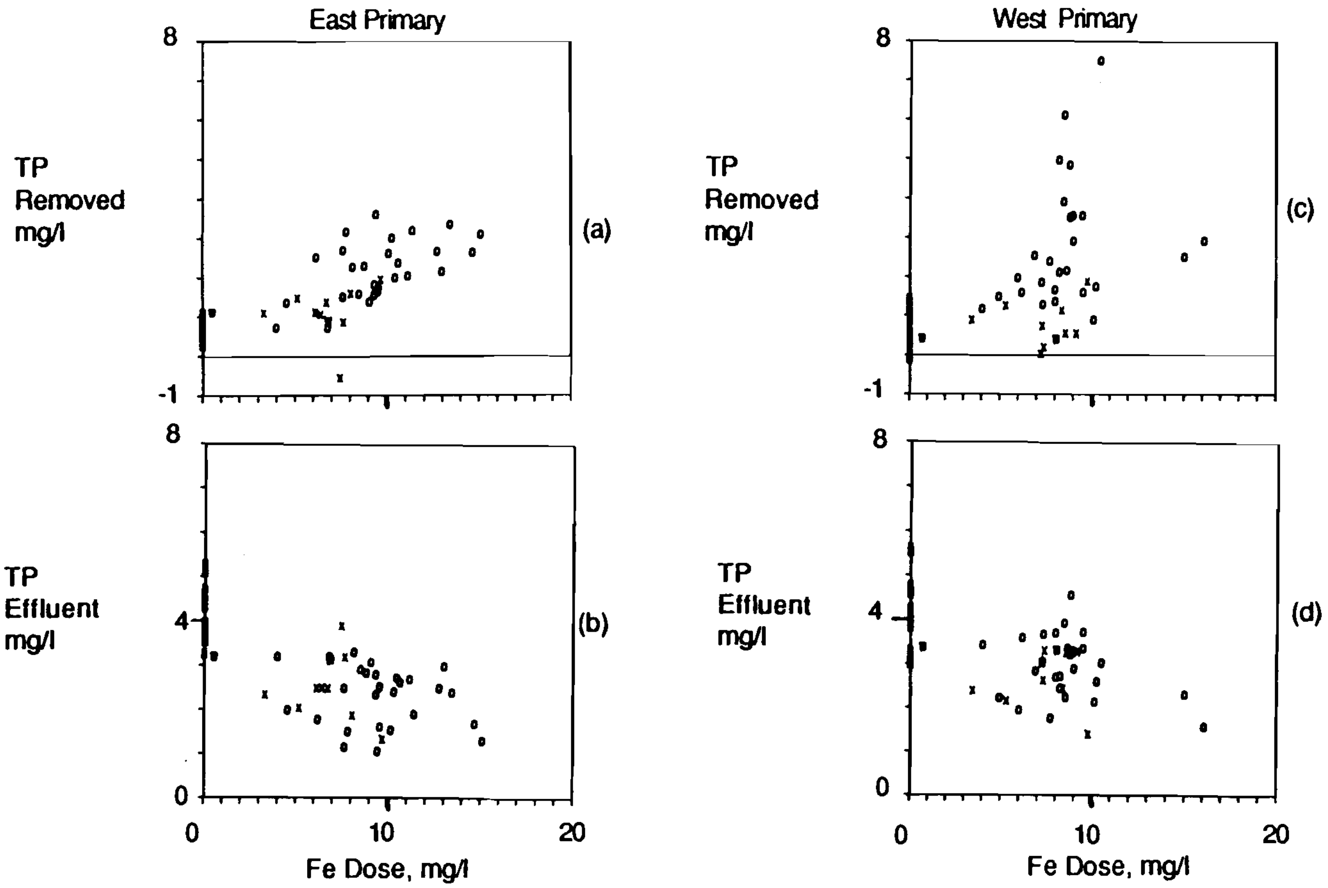
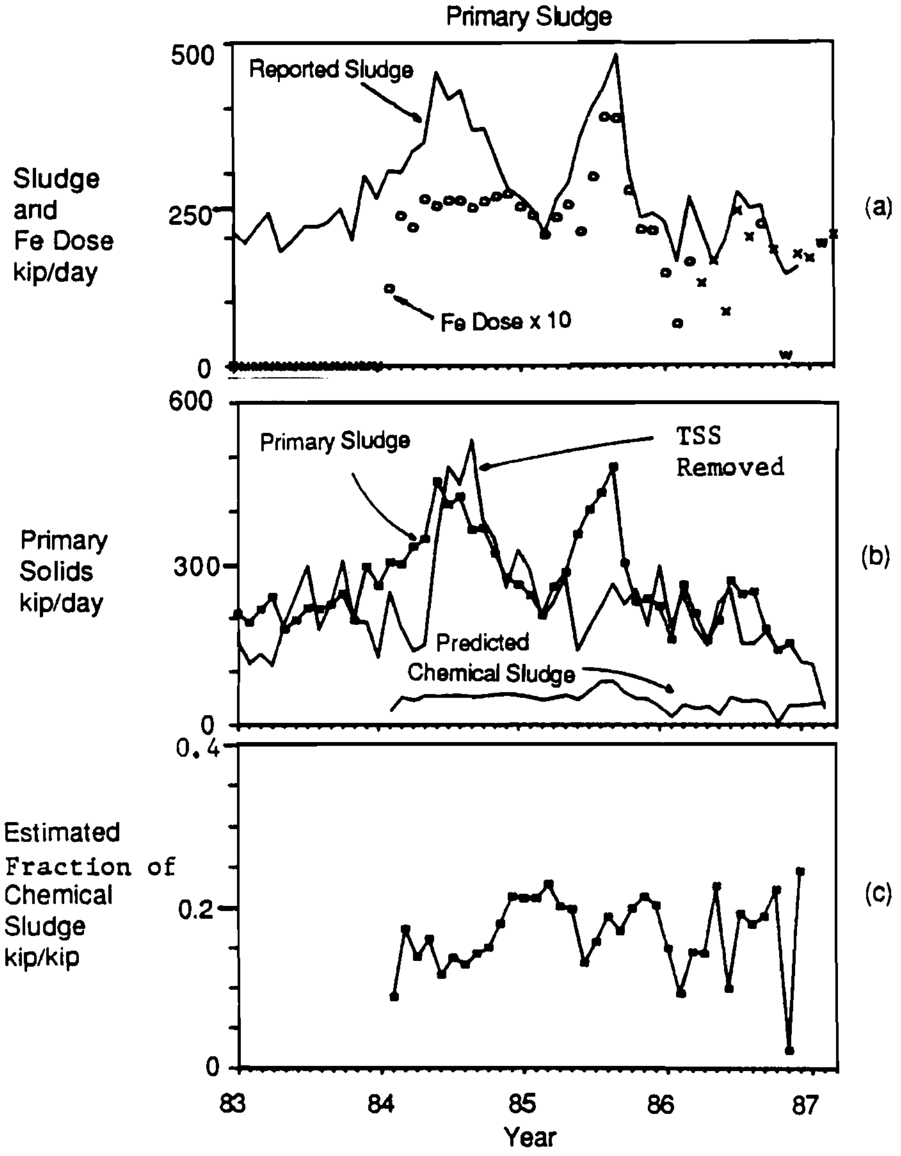


Figure 3-25 Blue Plains Primary, TP Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent TP vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

Figure 3-26 Blue Plains Primary Sludge a) Reported Sludge and Iron Dose, b) Reported Sludge, TSS Removed, and Predicted Chemical Sludge, c) Estimated Fraction of Chemical Sludge.



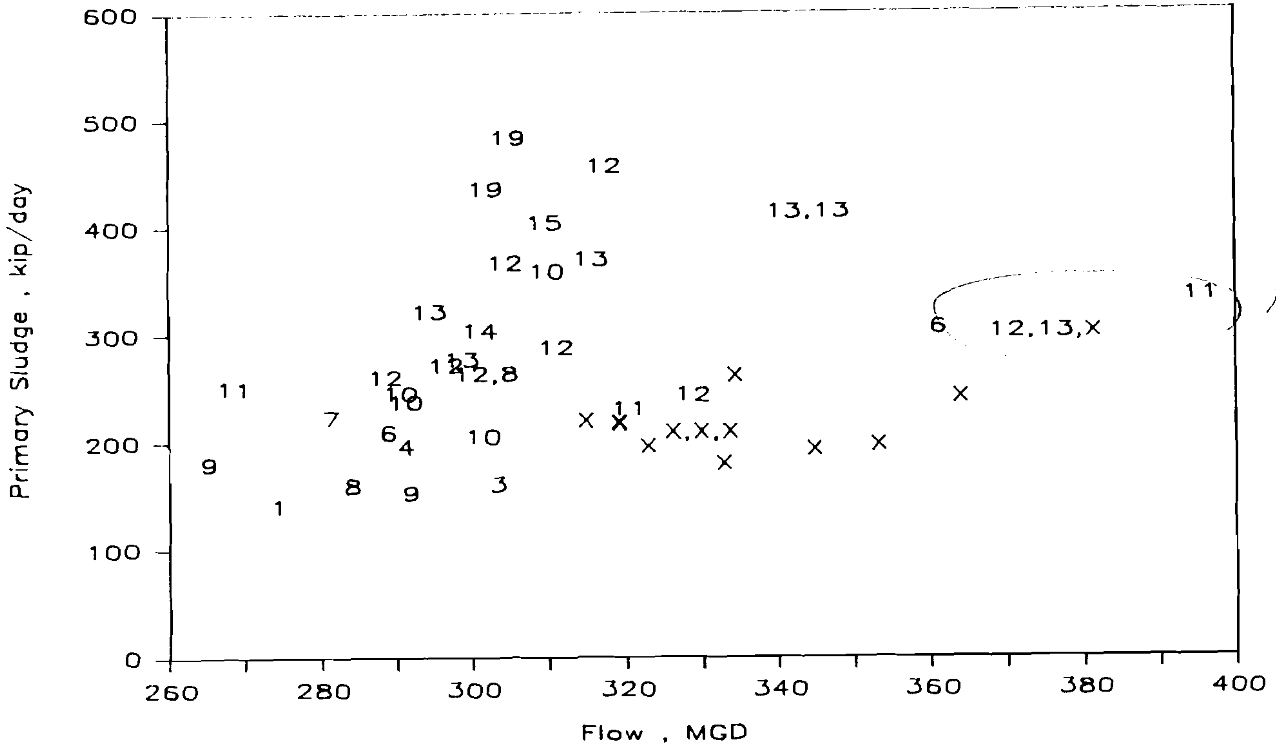
sludge, (2) a peak flow of 380 Mgd in April 1984, and (3) gravity thickener problems (see Figure 3-12). The hump in mid-1985 corresponds to a substantial increase in iron use and to an increase in wastewater strength. (See 3.4 RAW INFLUENT CHARACTERISTICS)

Figure 3-26b shows reported sludge, TSS removed, and predicted chemical sludge (Eq. 2-3, 2-4, 2-5) for primary treatment. The average ratio of chemical to total sludge (shown in Figure 3-26c) is 0.167 (S.D. = 0.047, n = 35).

Figure 3-27 shows the reported sludge production versus flow. The data labels represent iron dose in tons. The X data labels represent months where no iron was dosed. The data values at the extreme right (labeled 6,12,11,13) correspond to the first four months of iron dosing, gravity thickener overflow problems, and high flow. The data indicate that sludge production is dependent on flow and iron dose. The relationship between sludge production, TSS, iron dose, and flow is further examined in Chapter Four.

Figure 3-28b shows raw sludge production vs. iron dose. Figure 3-28c shows the relationship between sludge production and theoretical chemical sludge production, estimated with Equations 2-3 through 2-5. Since theoretical chemical sludge production is a linear function of the iron dose, this plot is similar in shape to Figure 3-28b. However, as shown in Figure 3-27, the effect of flow is partially responsible for these distorted trends.

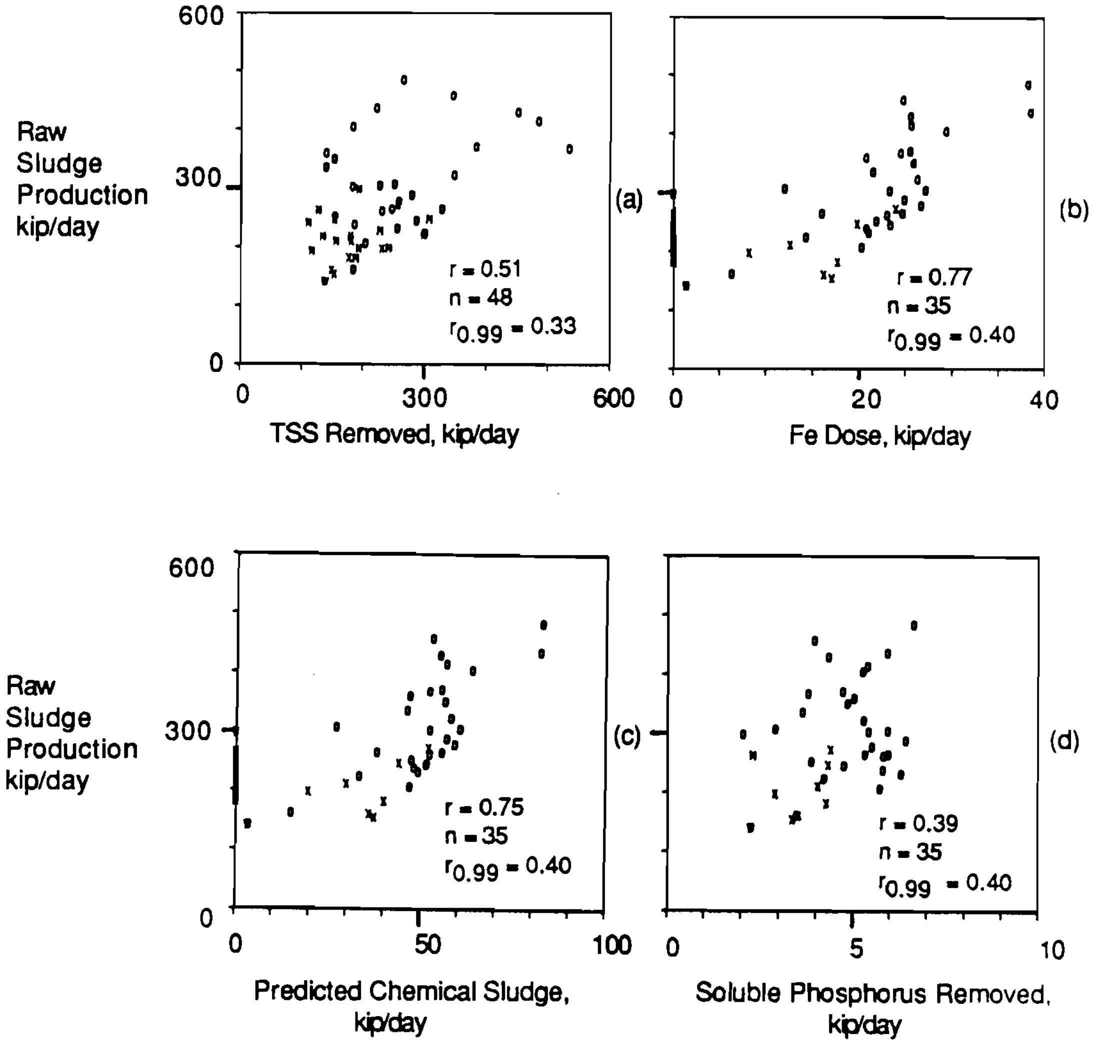
Figure 3-26b shows that primary sludge can be largely explained by suspended solids removal, with the exception of data in 1985 at peak



Feb. 84.

Figure 3-27 Blue Plains Primary Reported Sludge Production vs. Flow. Data labels represent iron dose in tons and X's denote no iron dose. Note: some data have been separated by commas to reveal the labels.

Figure 3-28 Blue Plains Primary Sludge Production vs. a) TSS Removed, b) Fe Dose, c) Predicted Primary Chemical Sludge, d) SP Removed.
(O = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = No Iron Added.)



iron dosing.

3.7 SECONDARY PHOSPHORUS REMOVAL

3.7.1 Influent Conditions

Secondary influent conditions are determined by the operation of the primary treatment plant, and by the character of the recycle streams entering below the primaries. Iron dosing to the primaries began in February 1984. Trends in secondary influent conditions that begin or end at this time may signal impacts on the secondary units resulting from the split dosing.

Figures 3-29 and 3-30 show recycle stream percentage contributions of BOD, TSS, and TP (kip/kip) to the secondary influent. Figures 3-31 and 3-32 show the concentrations of BOD, TSS, and TP in the recycles. Figure 3-33 shows the recycle flows. SP measurements are not taken in the recycles.

East Plant. Prior to 1984, the west primary effluent received the solids processing building recycle (SPBR). In March 1984 the flow was routed below the east primaries, and has contributed 13% of the BOD, 39% of the TSS, and 16% of the TP to the east secondary influent (kip/kip).

Primary iron dosing has been shown to decrease the loading of BOD, TSS, and TP on the east secondaries. However, the step impact of primary iron dosing on secondary influent characteristics is not apparent (See Figures 3-46 and 3-48) since startup of the SPBR recycle roughly coincides with the initiation of primary iron dosing.

Figure 3-29 Blue Plains, Fraction of a) BOD, b) TSS, c) TP in East Secondary Influent Originating from Solids Processing Recycle Flow.

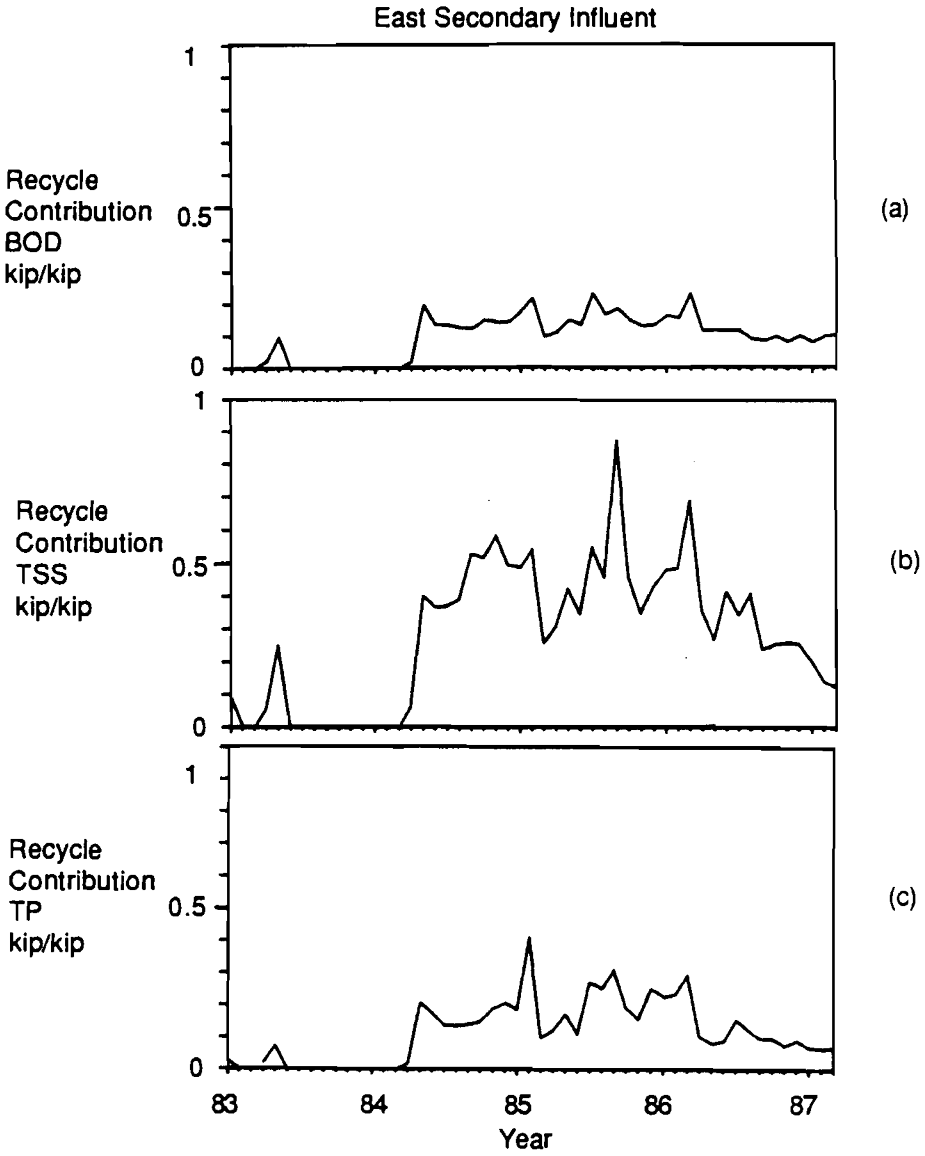


Figure 3-30 Blue Plains, Fraction of a) BOD, b) TSS, c) TP in West Secondary Influent Originating from Solids Processing and Gravity Thickener Overflow Recycles.

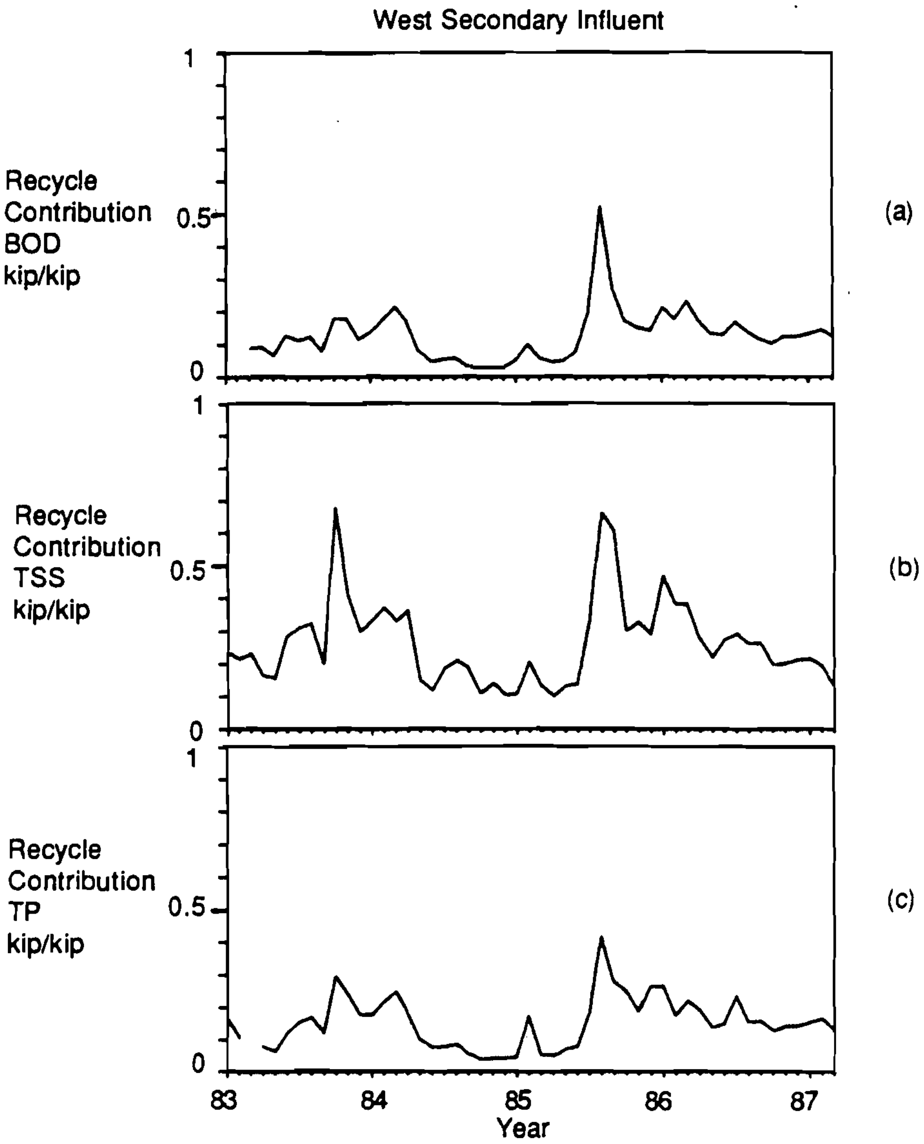


Figure 3-31 Blue Plains, Solids Processing Recycle Contribution of a) BOD, b) TSS, c) TP, to East Secondary Influent.

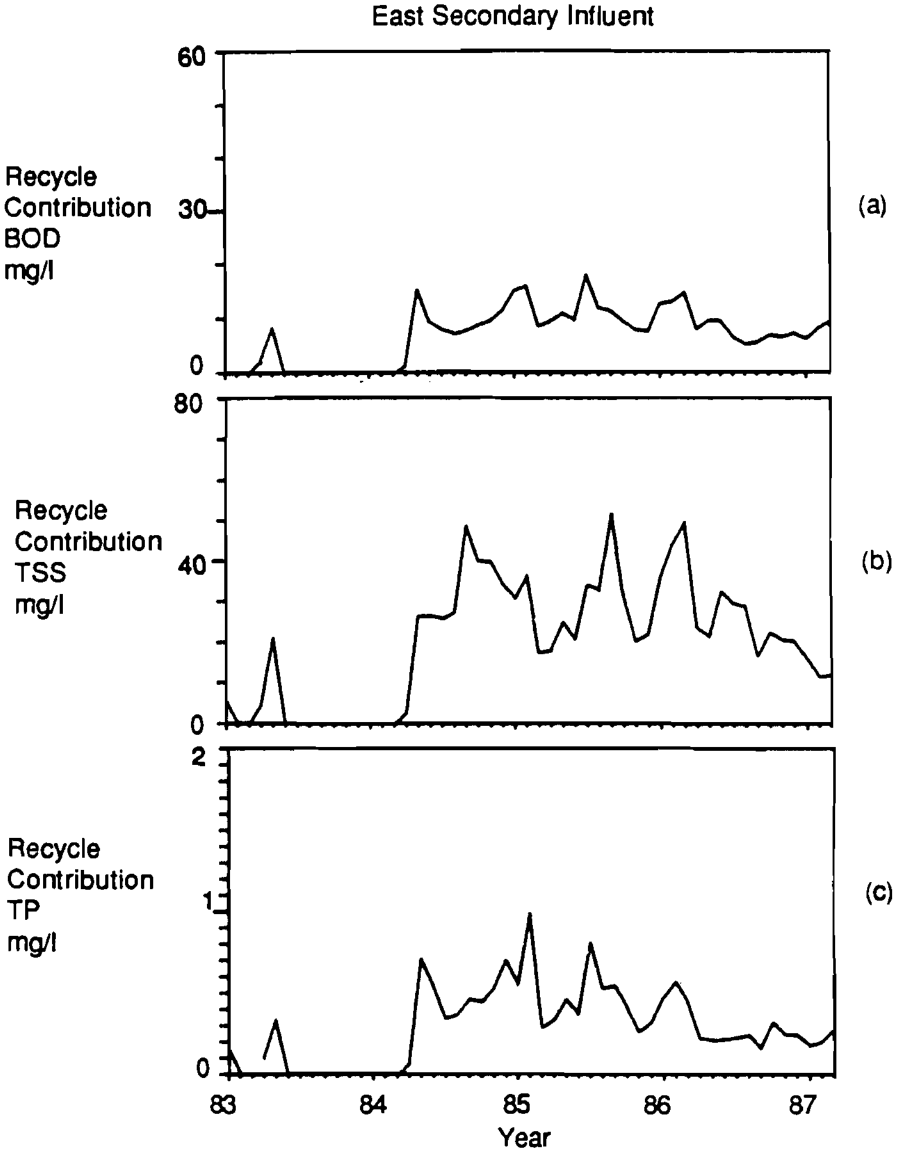


Figure 3-32 Blue Plains, Solids Processing and Gravity Thickener Overflow Contribution of a) BOD, b) TSS, c) TP, to West Secondary Influent.

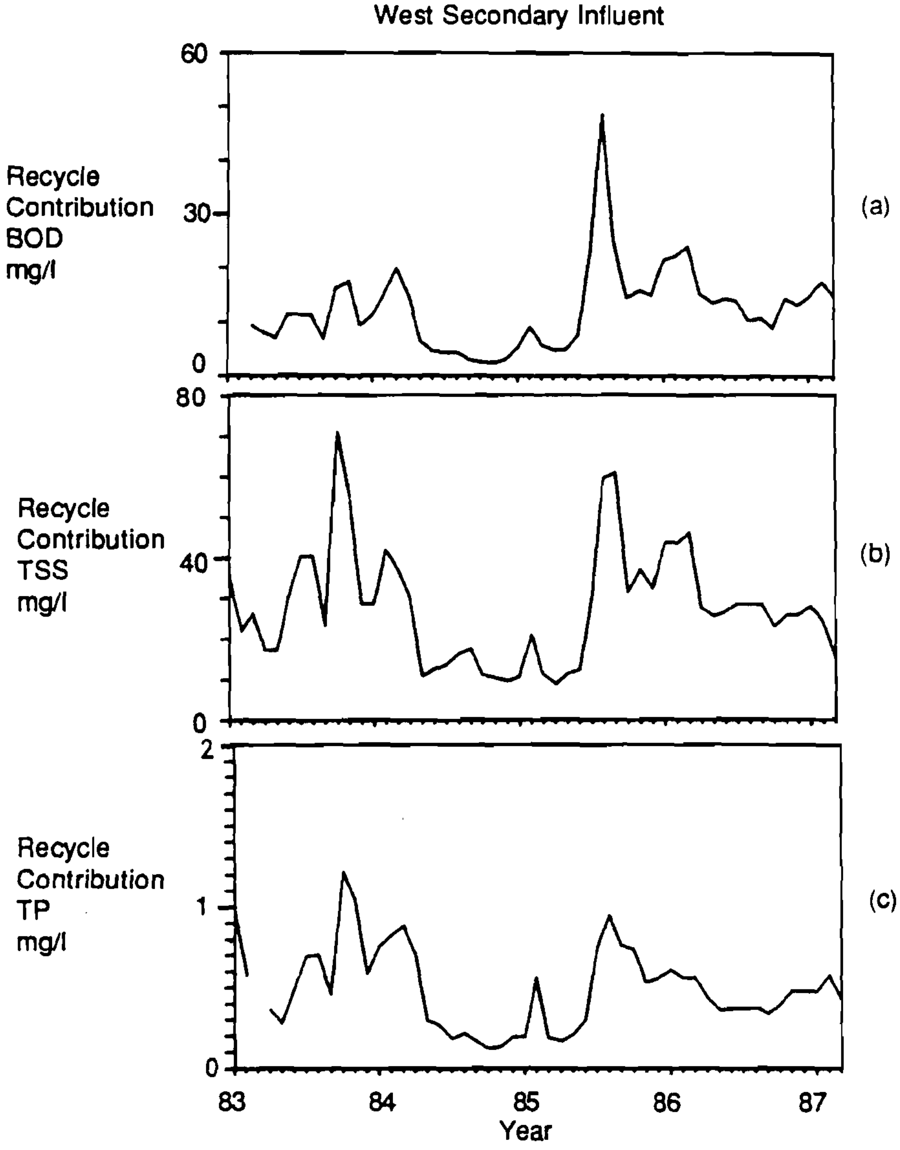
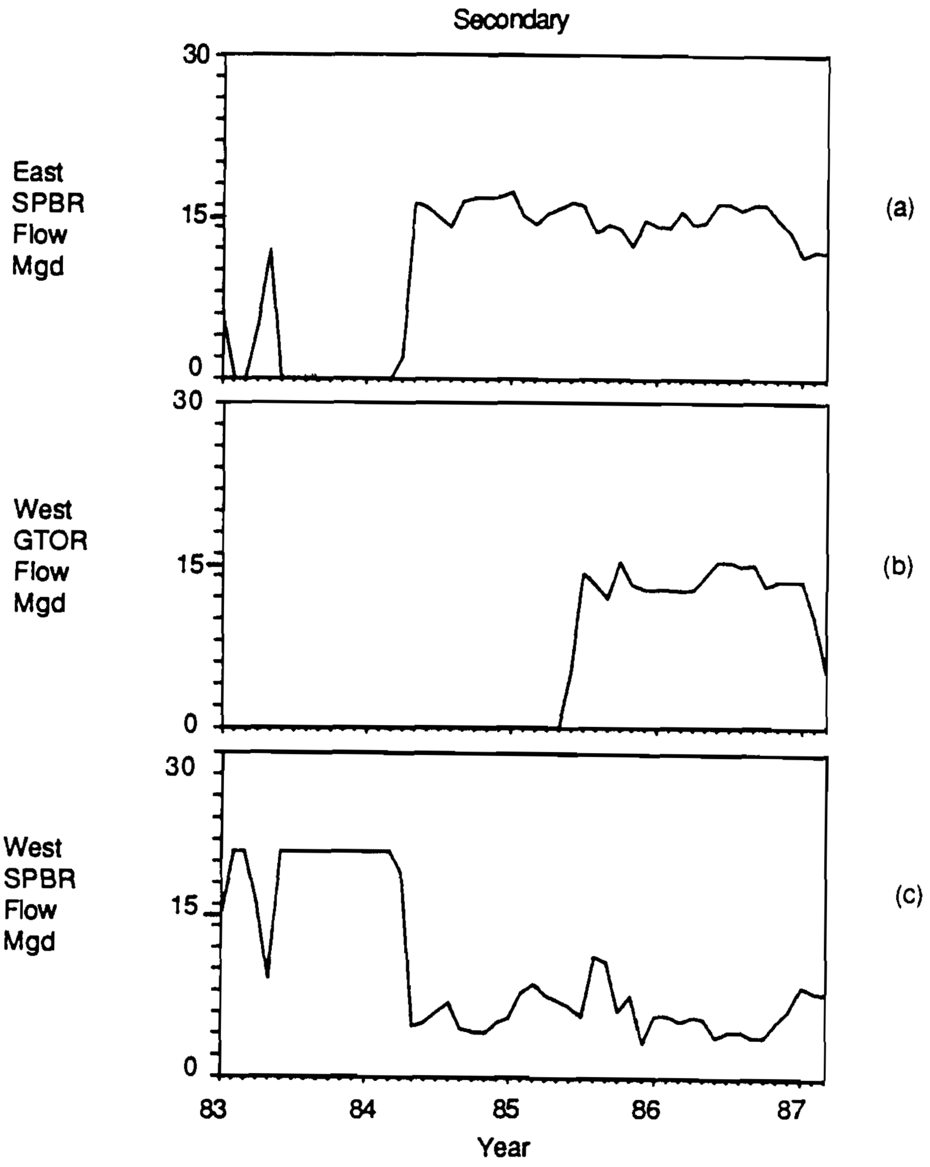


Figure 3-33 Blue Plains, Flows of Secondary Influent Recycle Streams a) Solids Processing to East Secondary b) Gravity Thickener Overflow to West Secondary, c) Solids Processing to West Secondary.



West Plant. Since March 1984 the west secondary influent has received 29% of the SPBR flow. In March 1984, 71% of the SPBR was routed to the east plant to alleviate problems caused by the gravity thickener overflow recycle (GTOR), which at the time was returned to the west primary influent. In June 1985, the GTOR was routed below the west primaries.

Since January 1983, the SPBR and GTOR have contributed on average 13% of the BOD, 26% of the TSS, and 15.3% of the TP to the west secondary influent.

The step impact of primary iron dosing on west secondary influent characteristics is not obvious (See Figures 3-46 and 3-48).

3.7.2 Secondary Iron Dosing

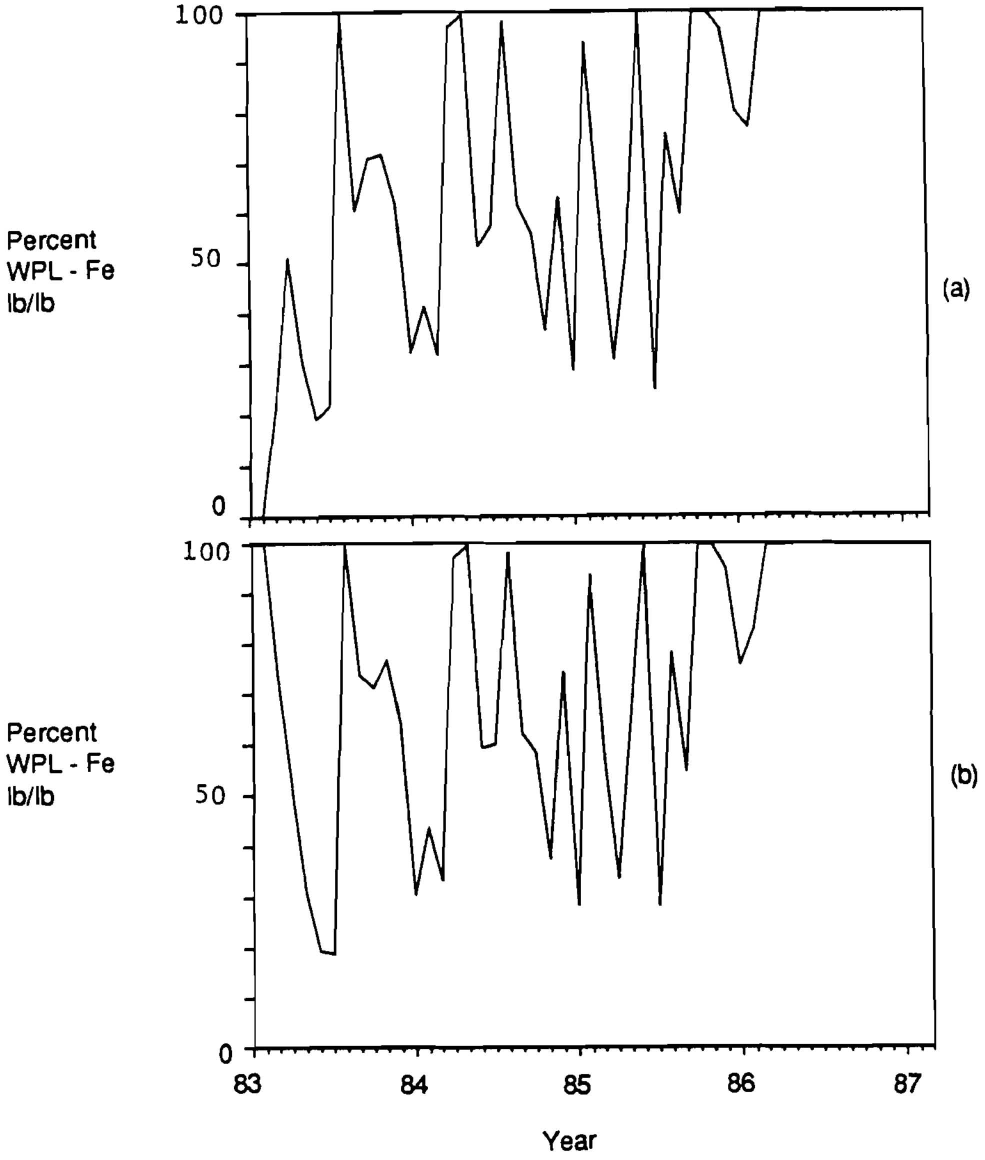
Figure 3-34 shows the ratio of WPL iron dose to total iron dose. This ratio has increased with time. WPL use was determined by availability. In April 1986, dosing of ferric chloride prior to secondary clarification was discontinued.

3.7.3 Soluble Phosphorus Removal

Figures 3-35 and 3-36 show SP and iron dose data in the secondaries. The few data points that exist prior to February 1984 indicate that secondary influent SP concentrations were higher when no iron was added to the primaries. This is consistent with the observations about primary SP removal.

Iron dose in the east and west secondaries has trended gradually

Figure 3-34 Blue Plains Secondary, Percentage of Waste Pickle Liquor Iron in Total Iron Dose a) East Plant, b) West Plant. Note: Waste Pickle Liquor and $FeCl_3$ are both used.



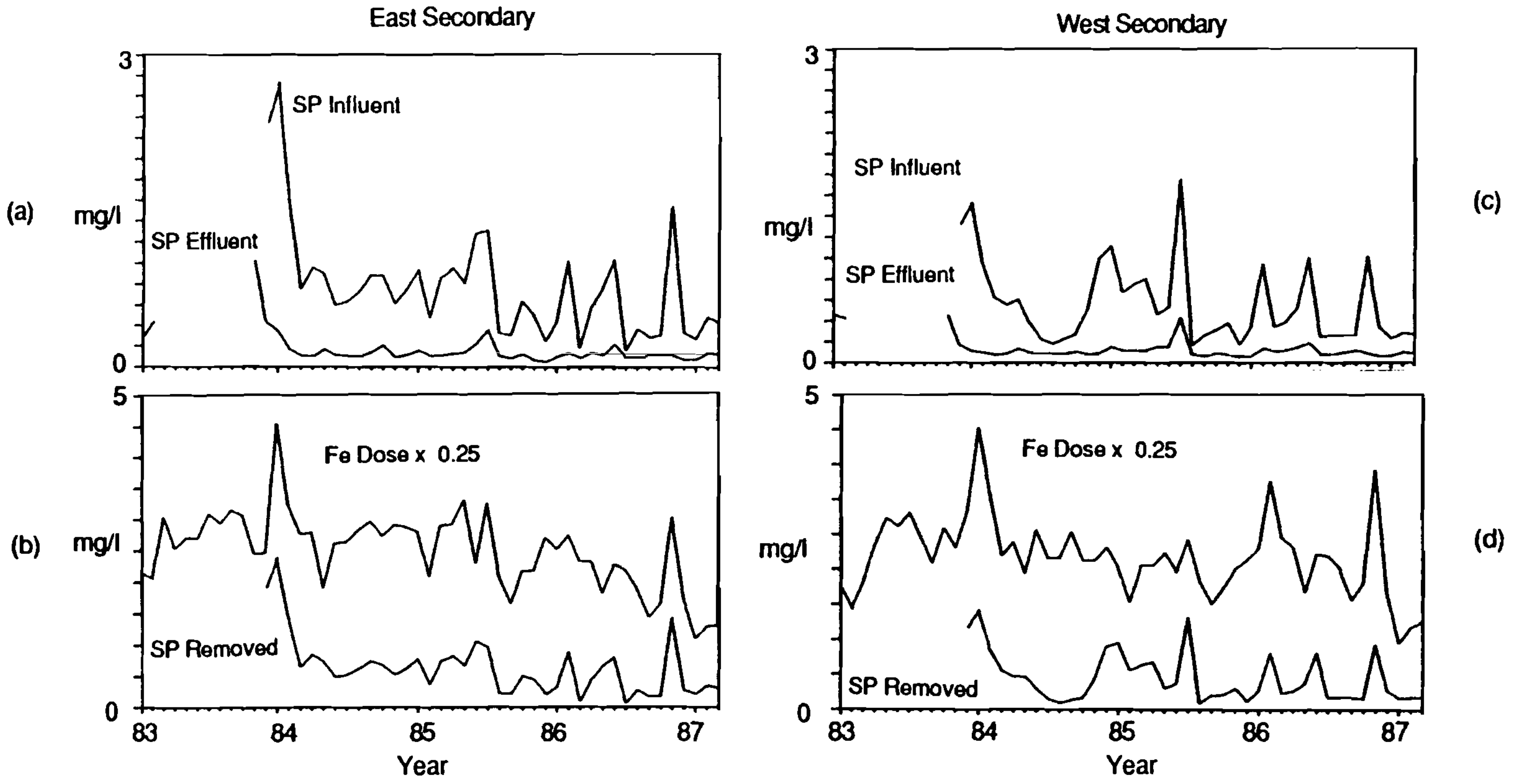


Figure 3-35 Blue Plains Secondary, SP Influent and Effluent vs. Year a) East Plant, c) West Plant and SP Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

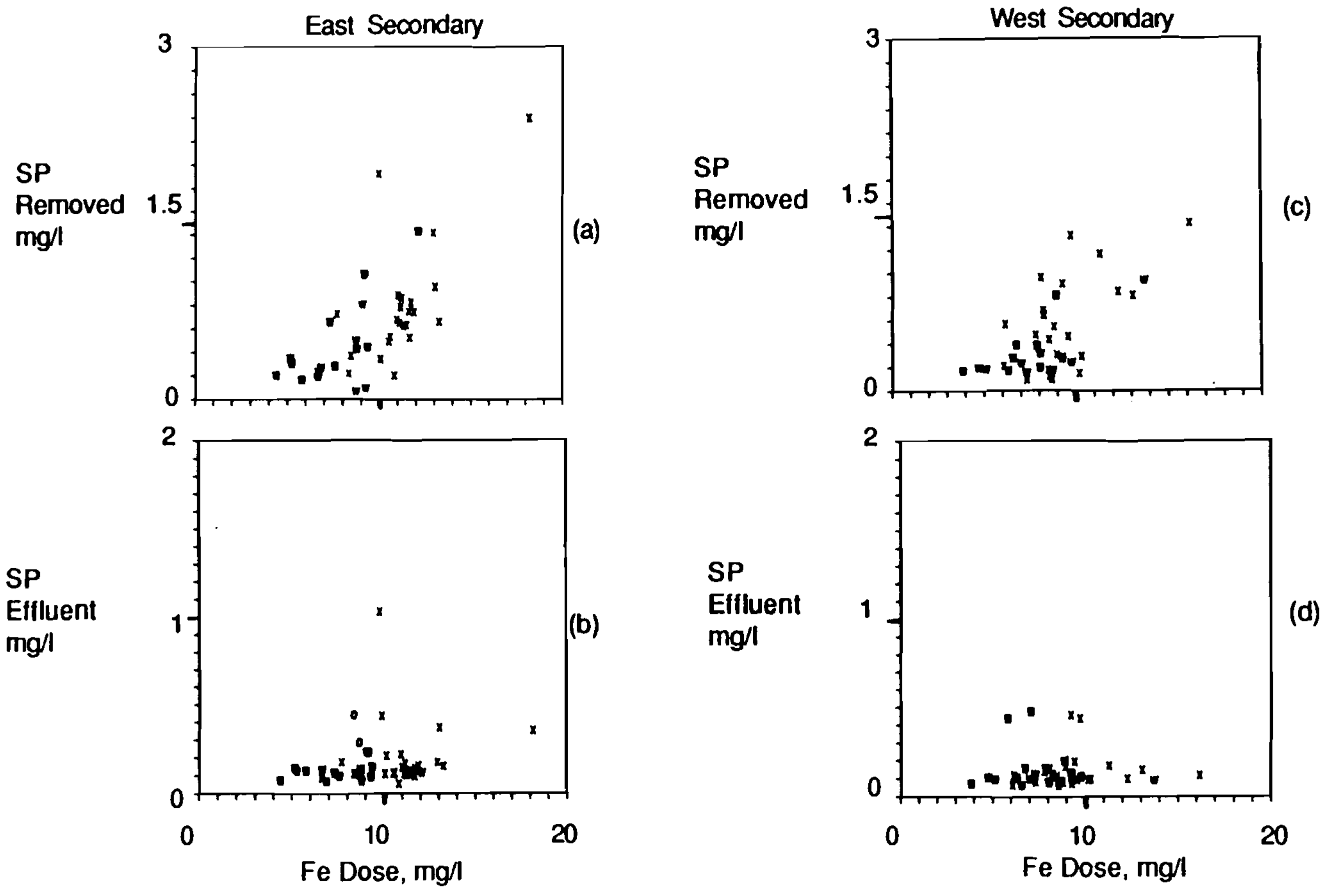


Figure 3-36 Blue Plains Secondary, SP Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent SP vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

downward with time. There is no apparent step like adjustment in secondary iron dose corresponding to the initiation of primary iron dosing in February 1984.

Figure 3-36a,c show that SP removal is not linearly related to iron dose, and Figure 3-36b,d does not reveal any relationship between iron dose and effluent SP. Since influent SP concentrations have varied from 0.16 to 2.74 mg/l in the east plant and 0.17 to 1.76 mg/l in the west plant, two separate precipitation mechanisms have been active. At high influent concentrations SP is removed stoichiometrically, while at low influent concentrations, the removal is nonstoichiometric.

Evidence for the two mechanisms is seen in Figure 3-37a,c. The elevated Fe/P_C ratios are much greater than the theoretical stoichiometric value of approximately 1.5. The data at SP effluents greater than approximately 0.2 mg/l are horizontally distributed with respect to the Fe/P_C ratio. An approximately constant Fe/P_C ratio characterizes stoichiometric phosphate removal.

Figures 3-37b,d show that Fe/P_C values prior to primary iron addition are relatively low. Since secondary iron dose appears to have trended gradually downward between 1984 and 1987, the elevated Fe/P_C ratios since 1985 are the result of fluctuations in secondary influent SP. In the east plant, a decrease in secondary effluent SP appears in mid-1985. This decrease corresponds to the initial increase in the Fe/P_C variability.

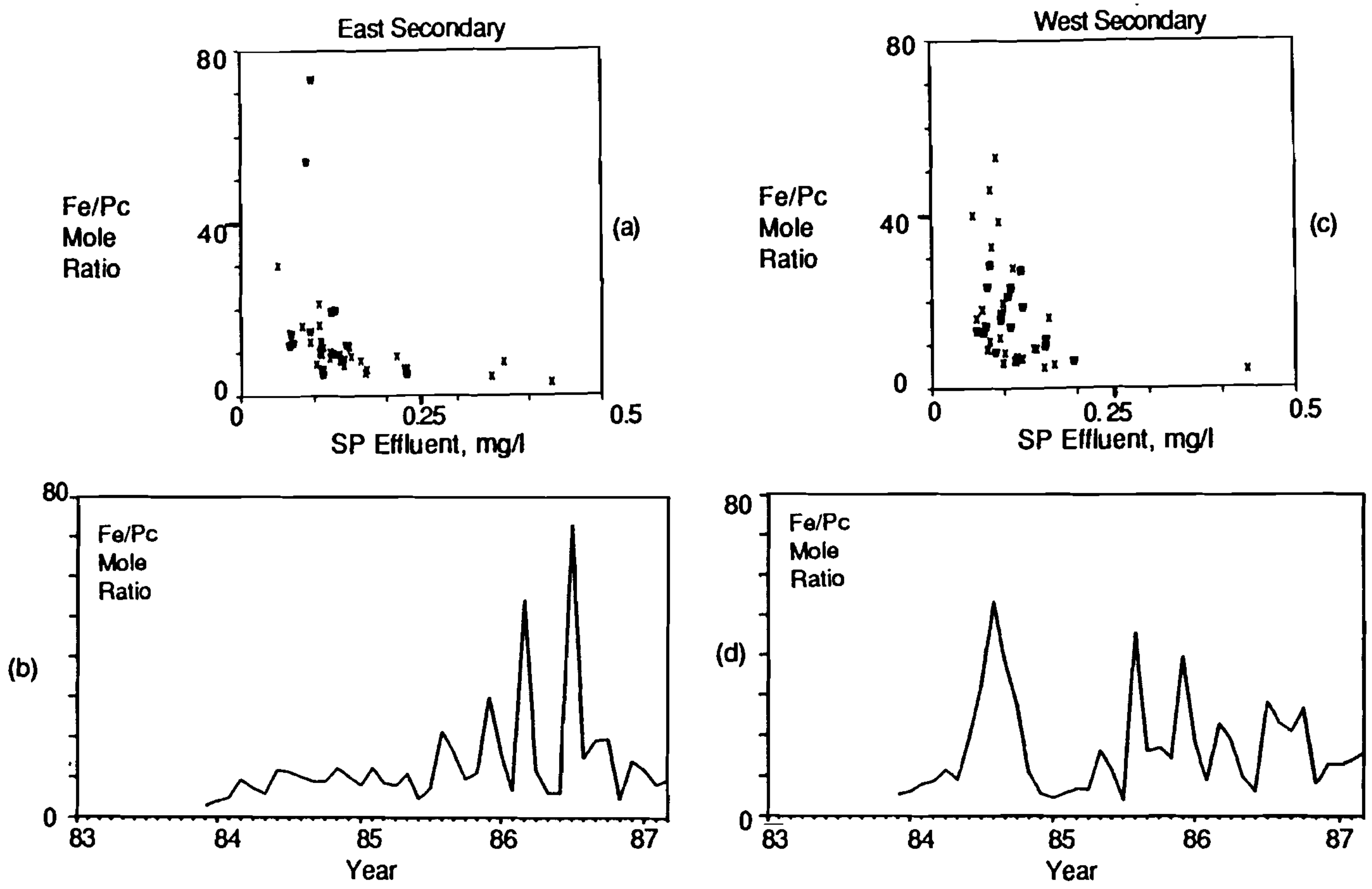


Figure 3-37 Blue Plains Secondary, Fe/P_C Mole Ratio vs.SP Effluent a) East Plant, c) West Plant, and Fe/P_C Mole Ratio vs. Year, b) East Plant, d) West Plant, for P_C = SPI - SPO (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

Figures 3-38a,c visually indicate that SP removal is determined largely by the influent SP value. The strength of this relationship suggests that variations in iron dose do not appreciably alter SP removal.

Figure 3-38b,d shows that effluent SP is related to the initial concentration. If the non-stoichiometric removal mechanism is active, this observed trend would be coincidental.

Figure 3-39 shows the logarithm of effluent SP concentrations as a function of pH. The underlying relationship is not evident, because the range of pH is too small. The theoretical curve was calculated with the solubility relationships in Table 2-1.

Figures 3-40a,c show the combined primary and secondary SP effluent data vs. the combined influent data. Figure 3-40b,d shows the combined primary and secondary Fe/P_C and SP effluent data. The Fe/P_C values above 20 have been omitted from the figure to more clearly reveal the relationship. These two plots indicate that different types of SP removal are occurring in the two parts of the plant.

3.7.4 pH and Alkalinity

The negative pH changes shown in Figure 3-42a,c indicate that some factor has increased the pH enough to counterbalance the decrease that should result from metal salt addition. Visual evidence for seasonally trending pH change exists in Figures 3-41b,d. The positive

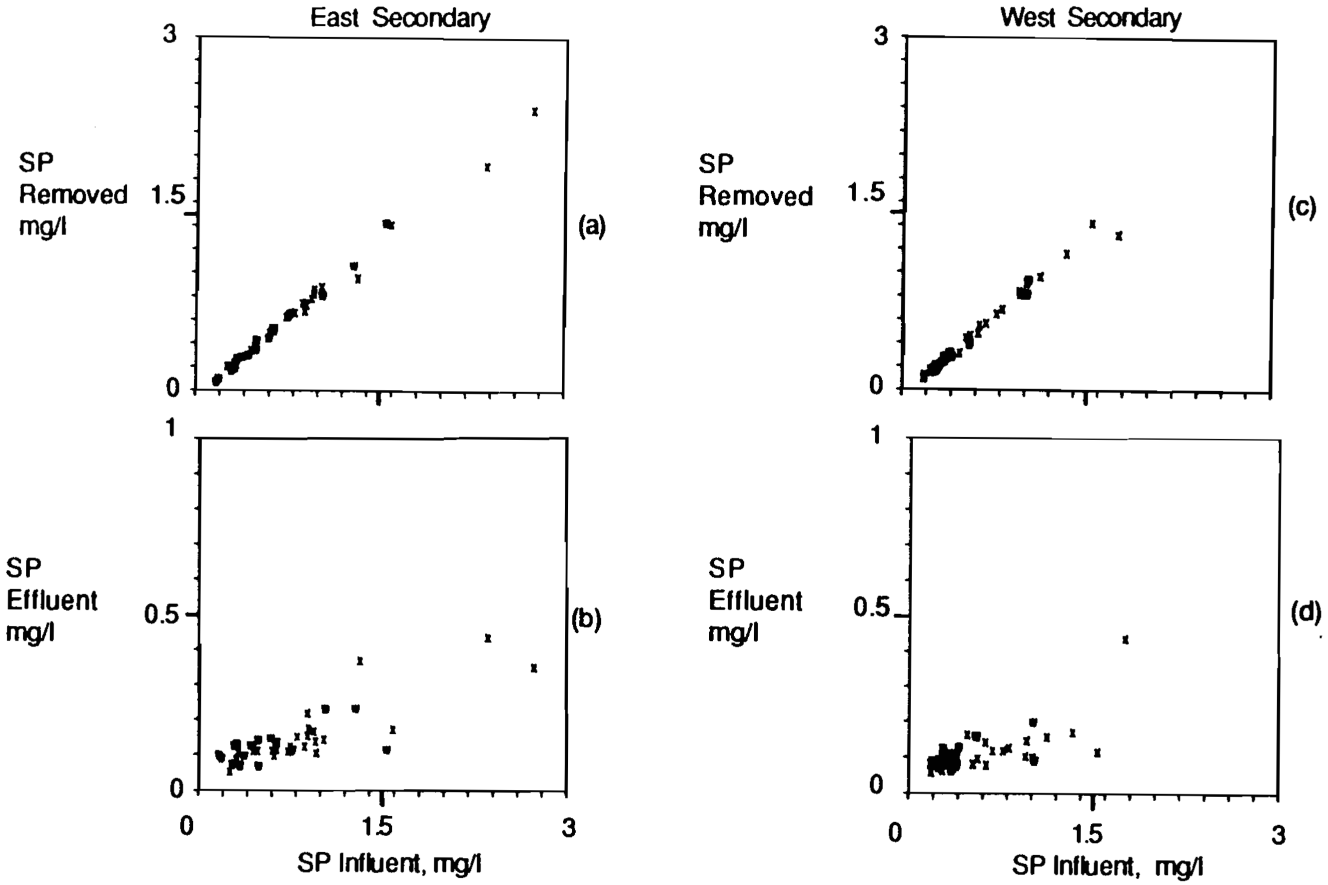
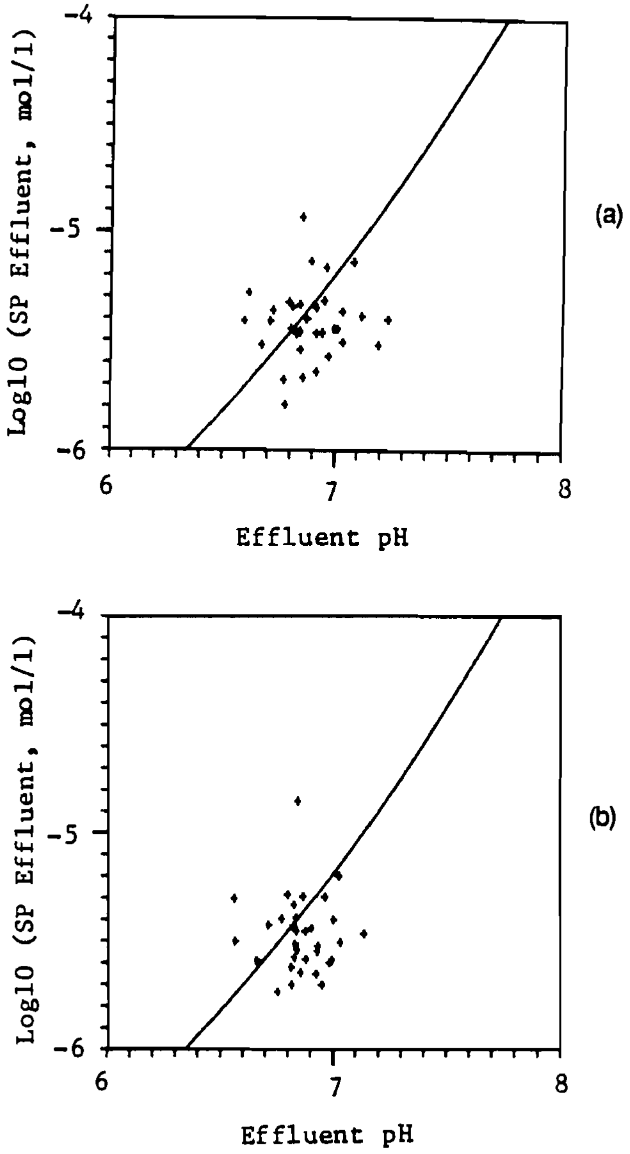


Figure 3-38 Blue Plains Secondary, SP Removed vs. Initial SP a) East Plant, c) West Plant, SP Effluent vs. Initial SP b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

Figure 3-39 Blue Plains Secondary, Log_{10} (Effluent Soluble Phosphorus, mol/l) vs. Effluent pH, a) East Plant, b) West Plant. Note: See text for discussion of theoretical curve.



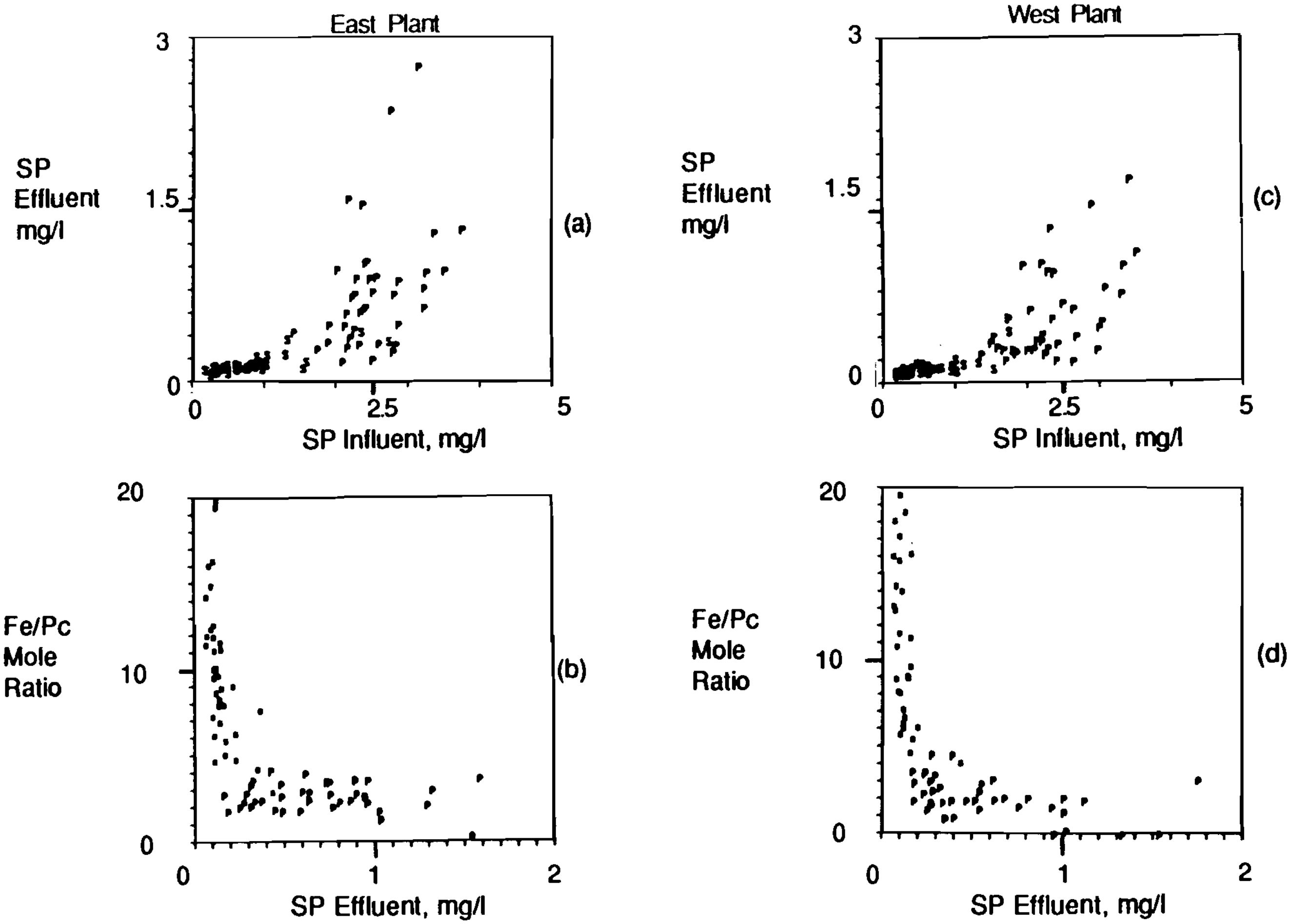


Figure 3-40 Blue Plains Primary and Secondary SP Effluent vs.SP Influent a) East Plant, c) West Plant, and Fe/P_C Mole Ratio vs. SP Effluent b) East Plant, d) West Plant, for P_C = SPI - SPO (p = Primary Data, s = Secondary Data).

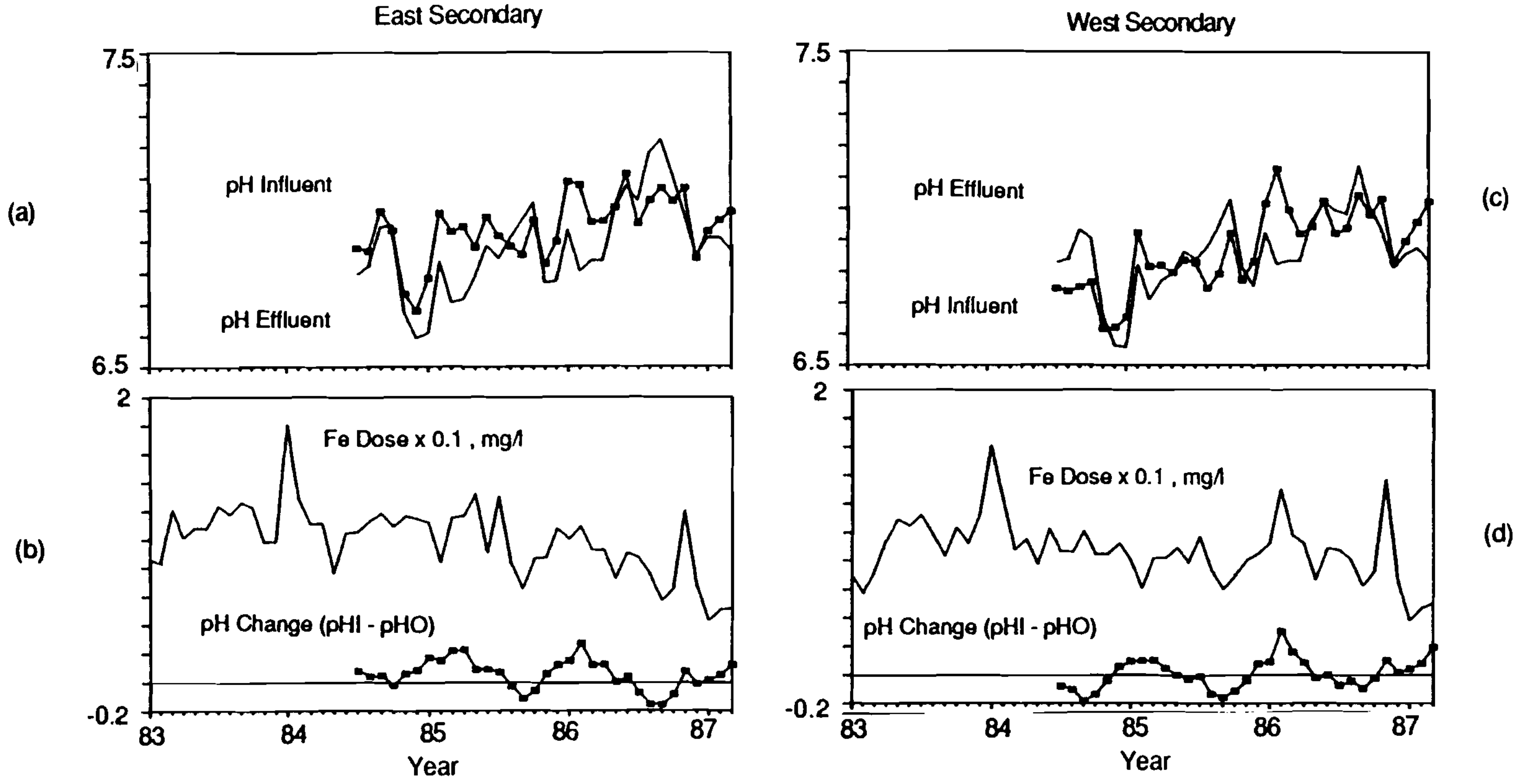


Figure 3-41 Blue Plains Secondary, pH Influent and Effluent vs. Year a) East Plant, c) West Plant and pH Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

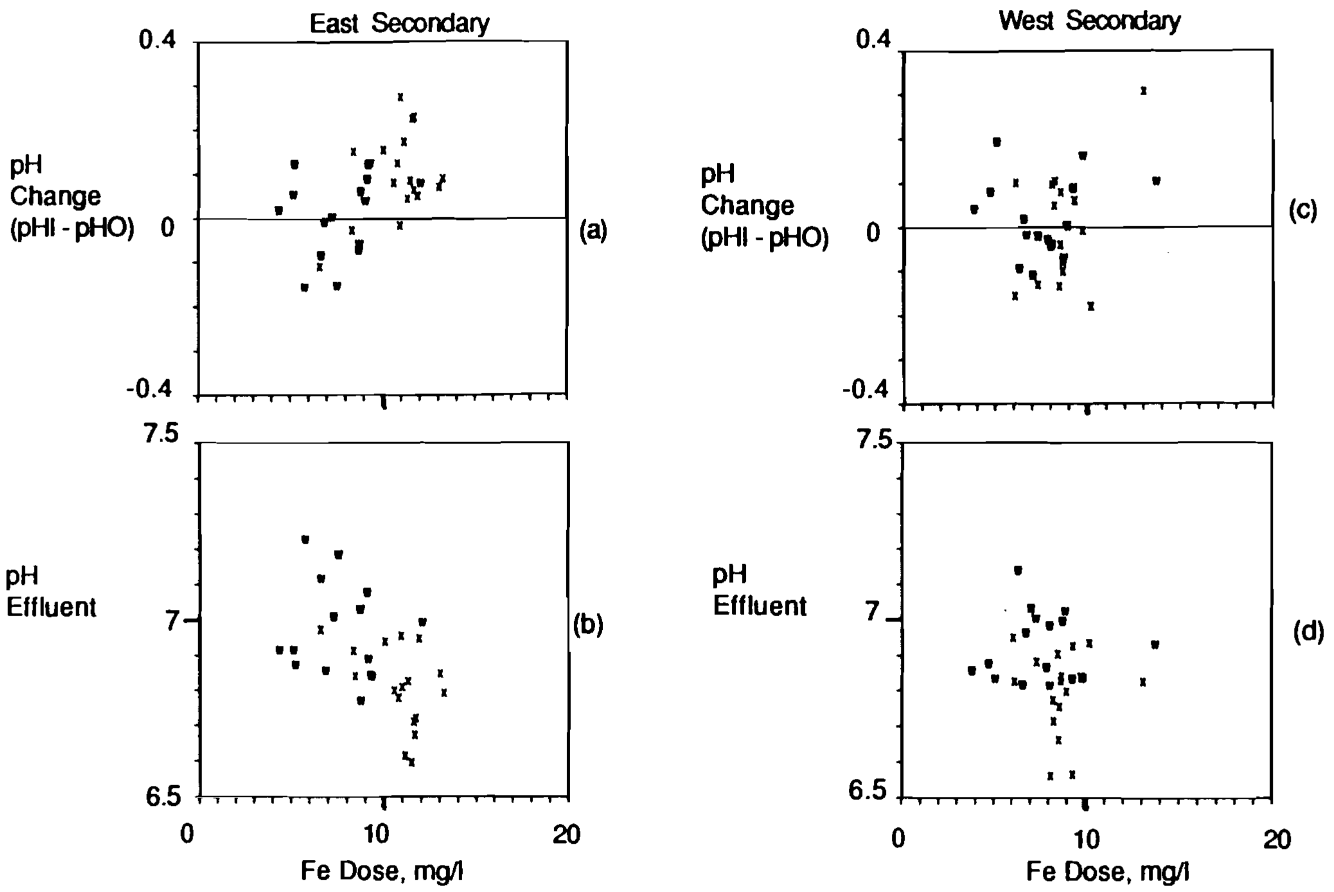


Figure 3-42 Blue Plains Secondary, pH change vs. Fe Dose a) East Plant, c) West Plant, Effluent pH vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

pH changes tend to occur in winter months, indicating relatively less influence from variables other than iron dose. Aeration intensity is a factor that may be important in controlling the pH. This factor may control the degree to which atmospheric CO_2 is equilibrated with the wastewater, however, this type of data was not studied.

Simple single variable relationships that explain pH changes and effluent values in terms of iron dose are not appropriate. Changes in pH and effluent pH values are related to the initial pH, the initial alkalinity, and the iron dose. The initial conditions are determined by the operation in the primaries and the condition of the recycle streams.

Figures 3-43a,b,c,d and 3-44a,b,c,d show the secondary alkalinity and iron dose data. The effect of iron dose on changes in alkalinity is approximated with the significant ($\alpha = 0.95$) linear regression equations. The relationships for effluent alkalinity are less well defined. Excessive alkalinity destruction can be detrimental to other chemical requirements at Blue Plains, since lime must be added during nitrification for pH control.

Figure 3-45a,c shows that pH changes are not significantly correlated with initial alkalinity. This is possible if iron dose causes the pH to change, and iron dose is highly variable.

Figure 3-45b,d shows effluent pH to be positively correlated with influent alkalinity.

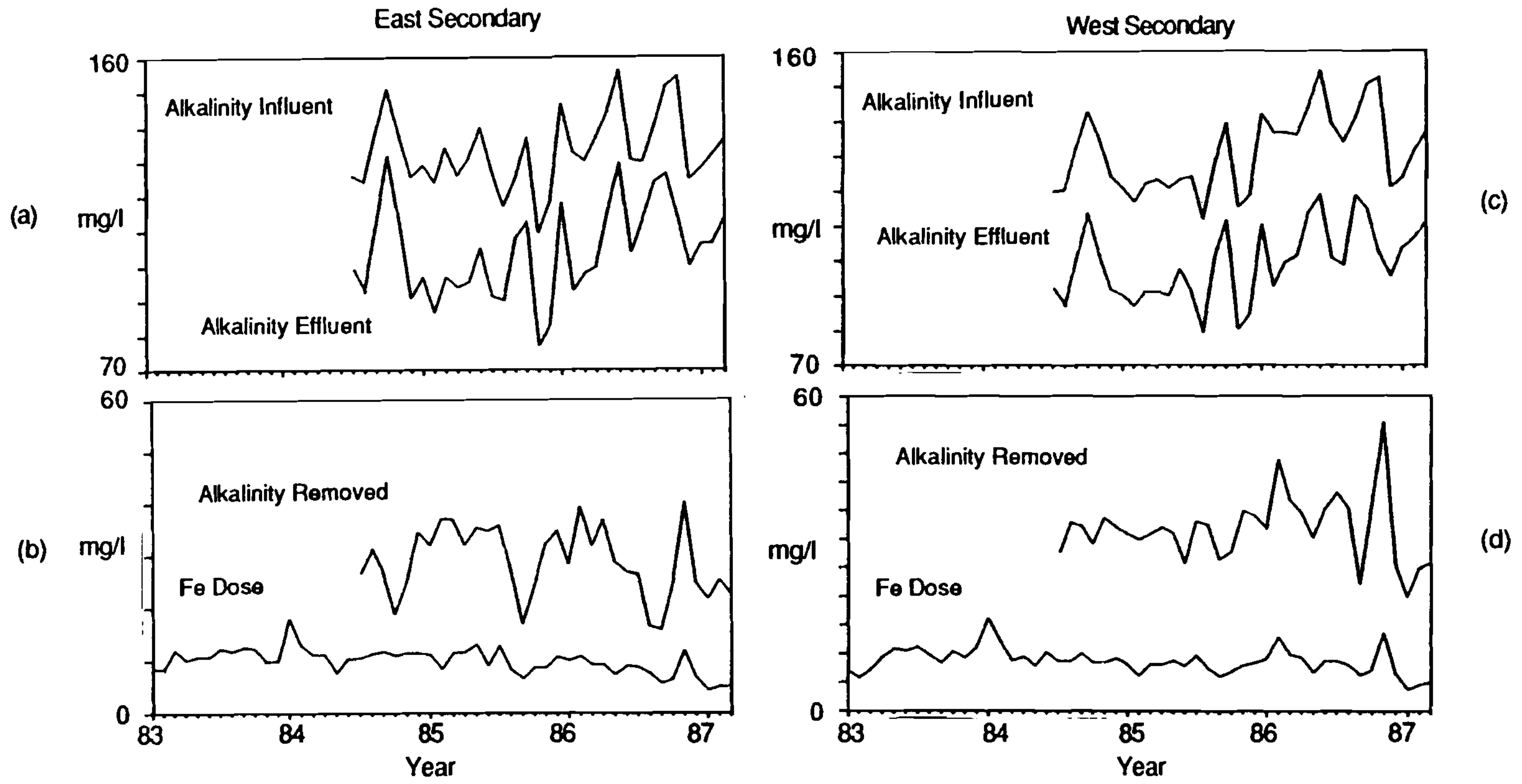


Figure 3-43 Blue Plains Secondary, Alkalinity Influent and Effluent vs. Year a) East Plant, c) West Plant and Alkalinity Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

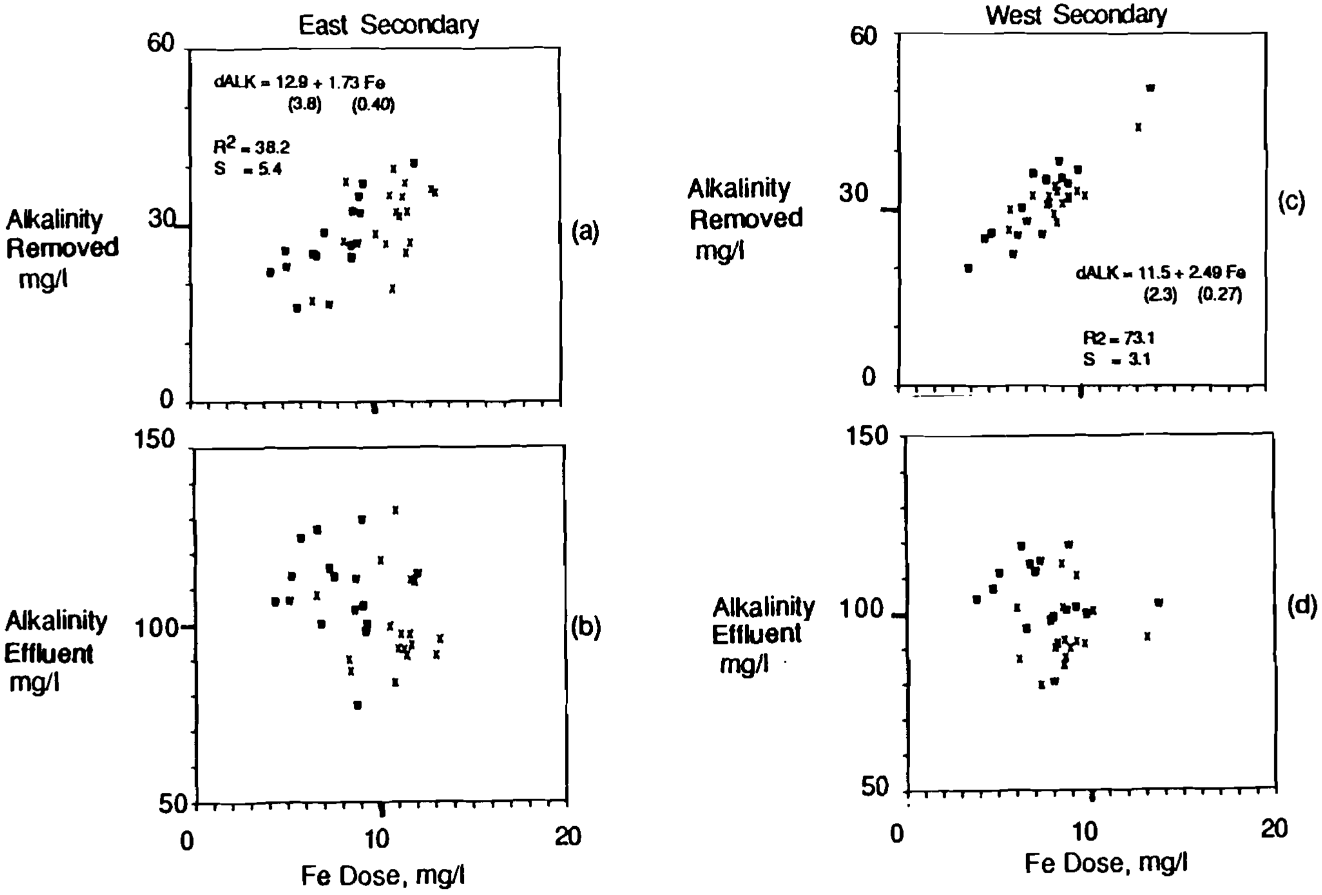


Figure 3-44 Blue Plains Secondary, Alkalinity Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent Alkalinity vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

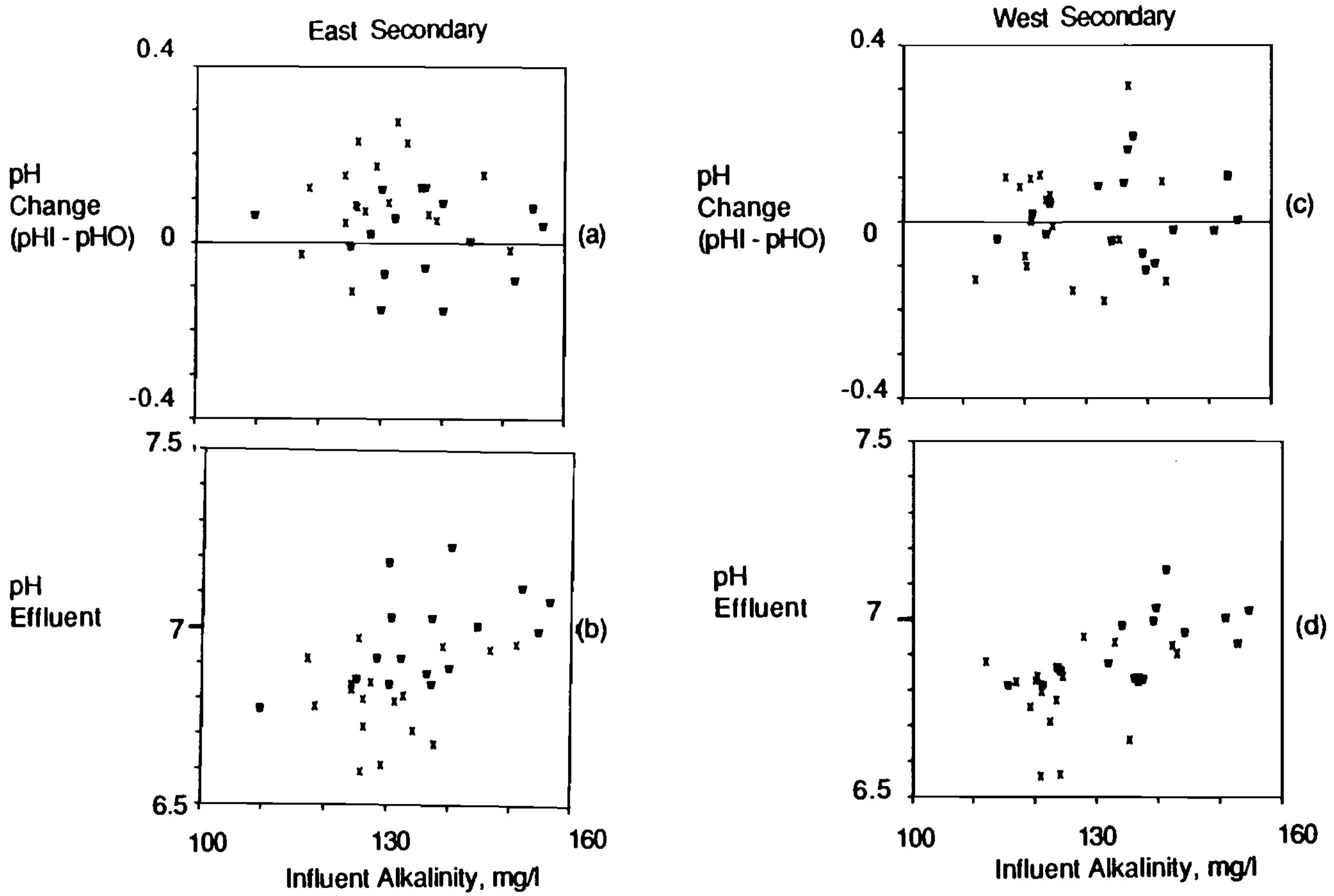


Figure 3-45 Blue Plains Secondary, pH Change vs. Influent Alkalinity a) East Plant, c) West Plant, pH Effluent vs. Influent Alkalinity c) East Plant, d) West Plant
(0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

3.7.5 BOD, TSS, and TP

Figures 3-46 through 3-51 show BOD, TSS, TP, and iron dosing data for the secondaries. There are no obvious relationships between iron dose and these variables.

3.7.6 Biological Phosphorus Removal

Figure 3-52 shows SP and TP removal versus BOD removal data. Tp and BOD removal are correlated in the east plant.

Figure 3-53 shows east plant iron dose, BOD removal, and SP removal data versus time. Many of the elevated SP removals correspond to peaks in iron dose and BOD removal, indicating that the effects of BOD removal and iron dose may be confounded.

3.8 SECONDARY SLUDGE PRODUCTION

Figures 3-54a,b show chemical sludge production, reported sludge quantities, and the iron dose. Chemical sludge production was estimated with Equations 2-3 through 2-5.

The ratio of predicted chemical sludge to reported sludge is shown in Figure 3-54c.

Figures 3-55 through 3-56 show secondary sludge production plotted against total iron dose, BOD removed, TSS removed, and SP removed.

East Plant. Predicted chemical sludge quantities in Figure 3-54a begin in December 1983, the first month for which SP removal data was available. At this time and for the next three months, total east plant secondary sludge appears to have been mostly chemical. Between

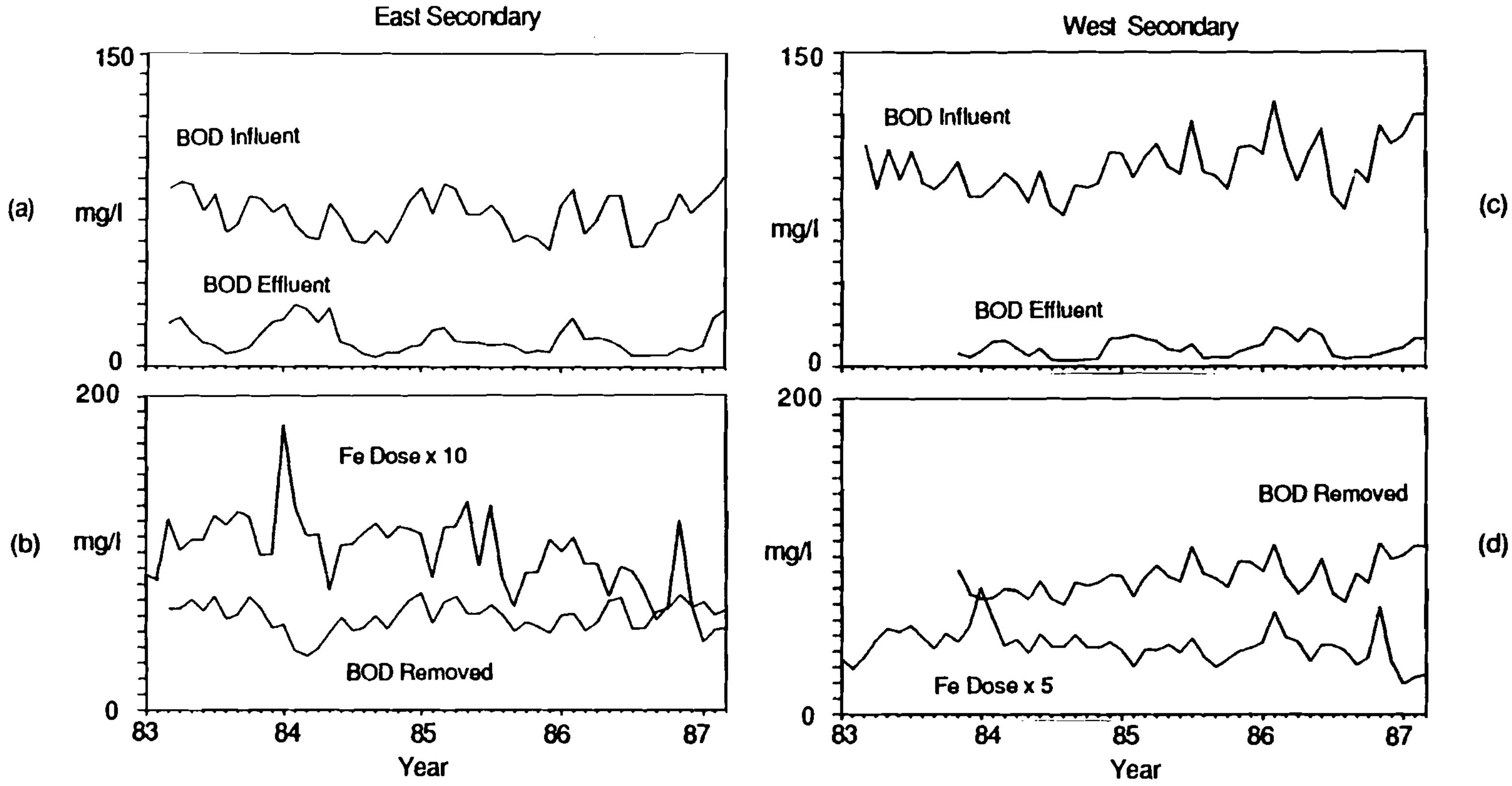


Figure 3-46 Blue Plains Secondary, BOD Influent and Effluent vs. Year a) East Plant, c) West Plant and BOD Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

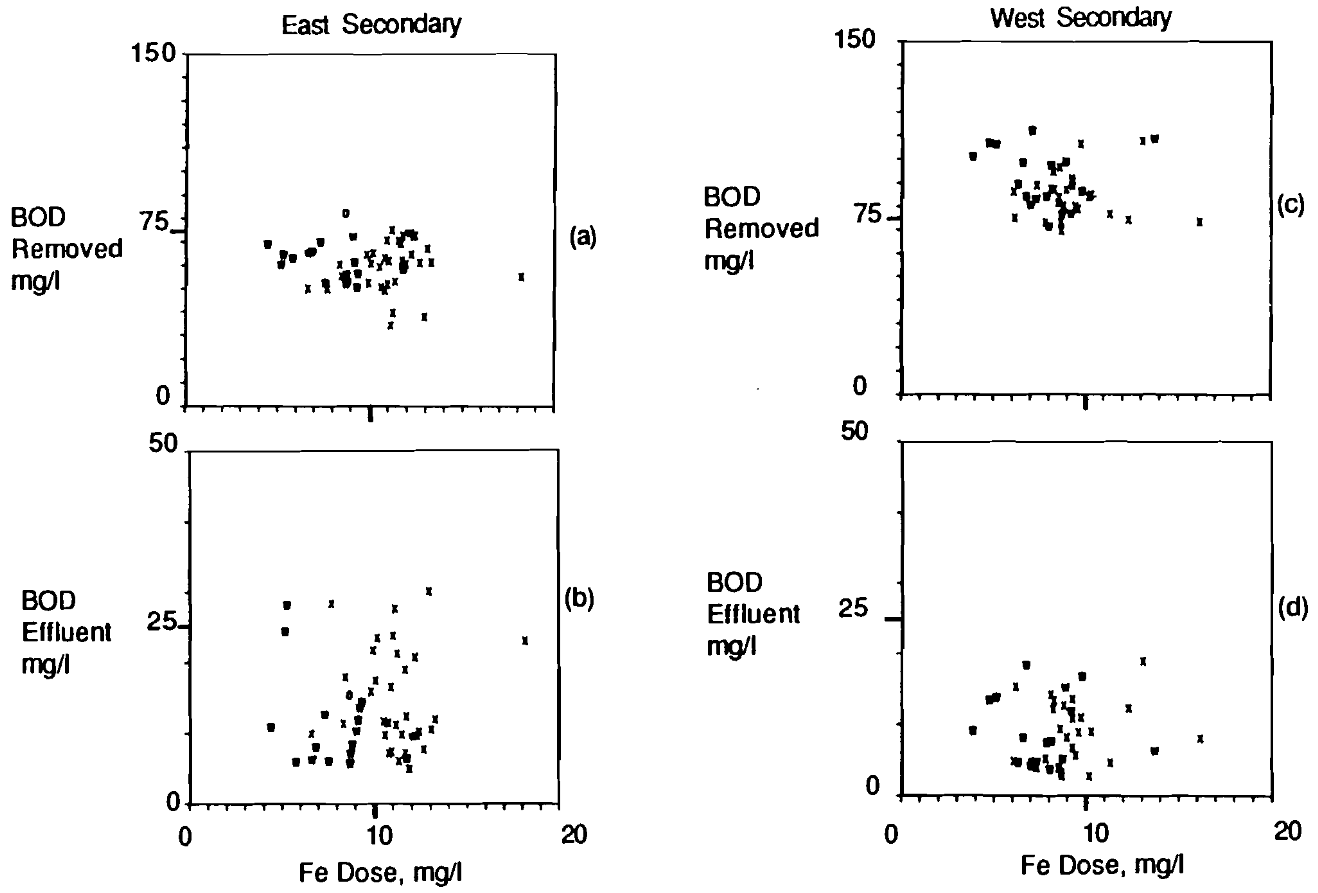


Figure 3-47 Blue Plains Secondary, BOD Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent BOD vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

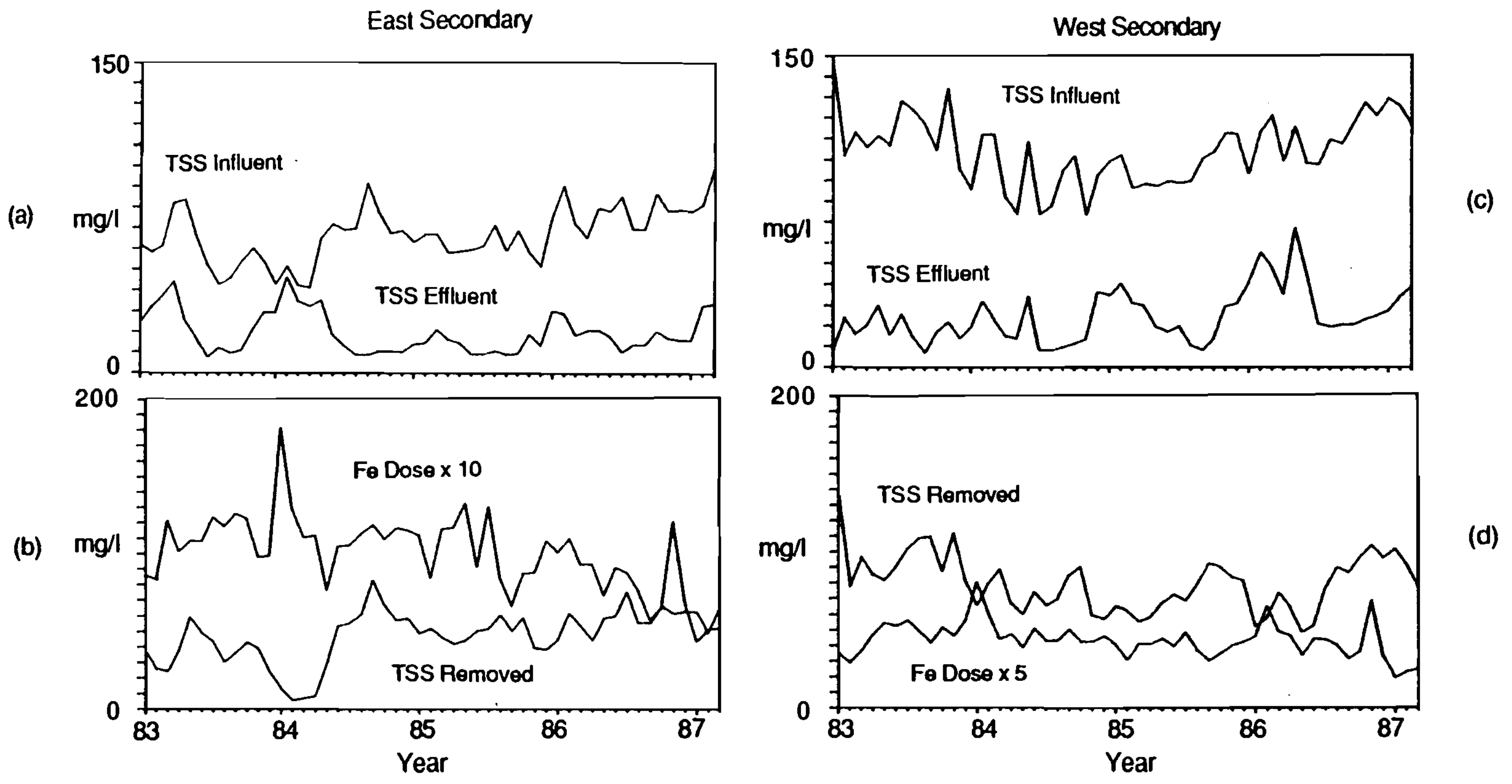


Figure 3-48 Blue Plains Secondary, TSS Influent and Effluent vs. Year a) East Plant, c) West Plant and TSS Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

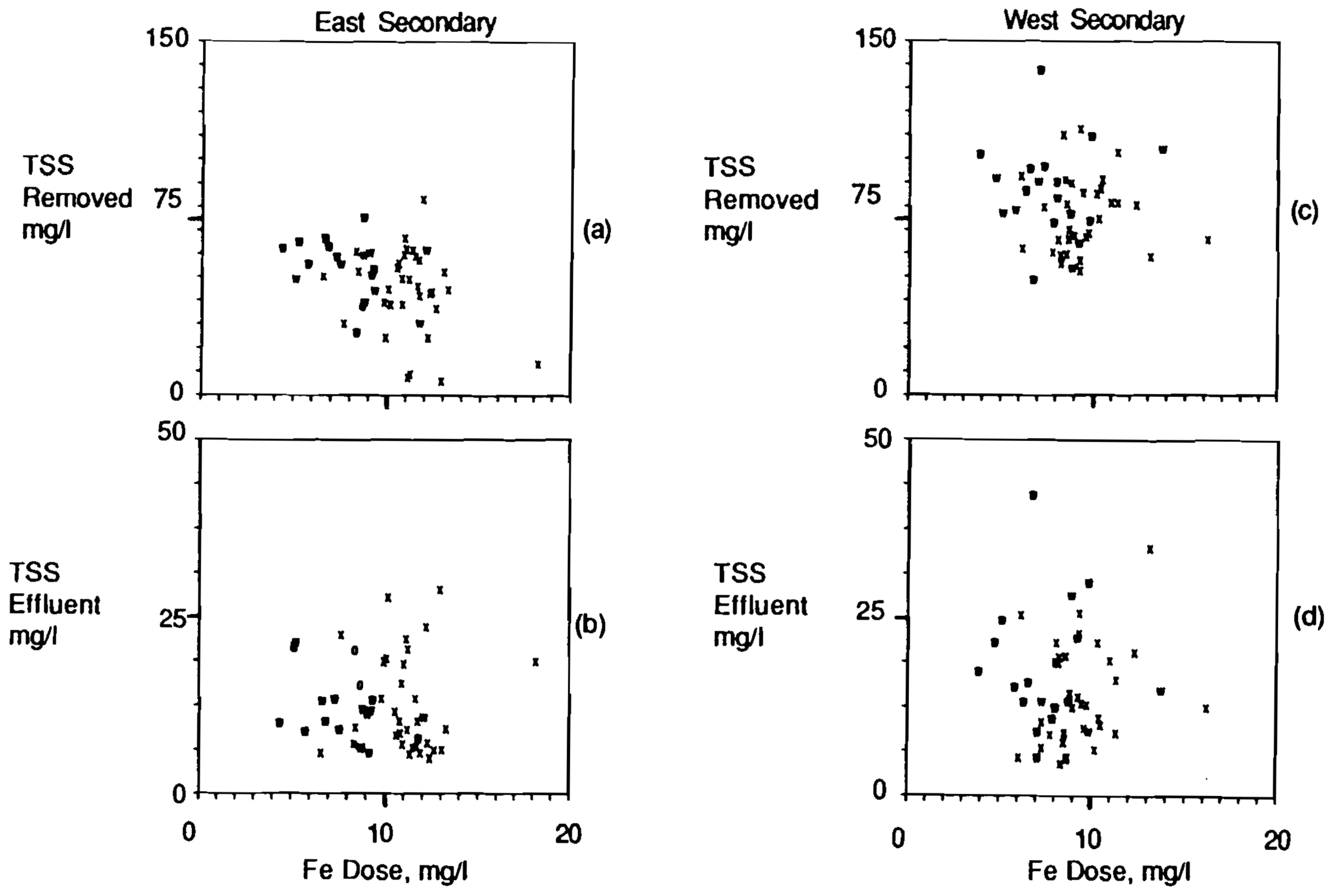


Figure 3-49 Blue Plains Secondary, TSS Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent TSS vs. Fe Dose, b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

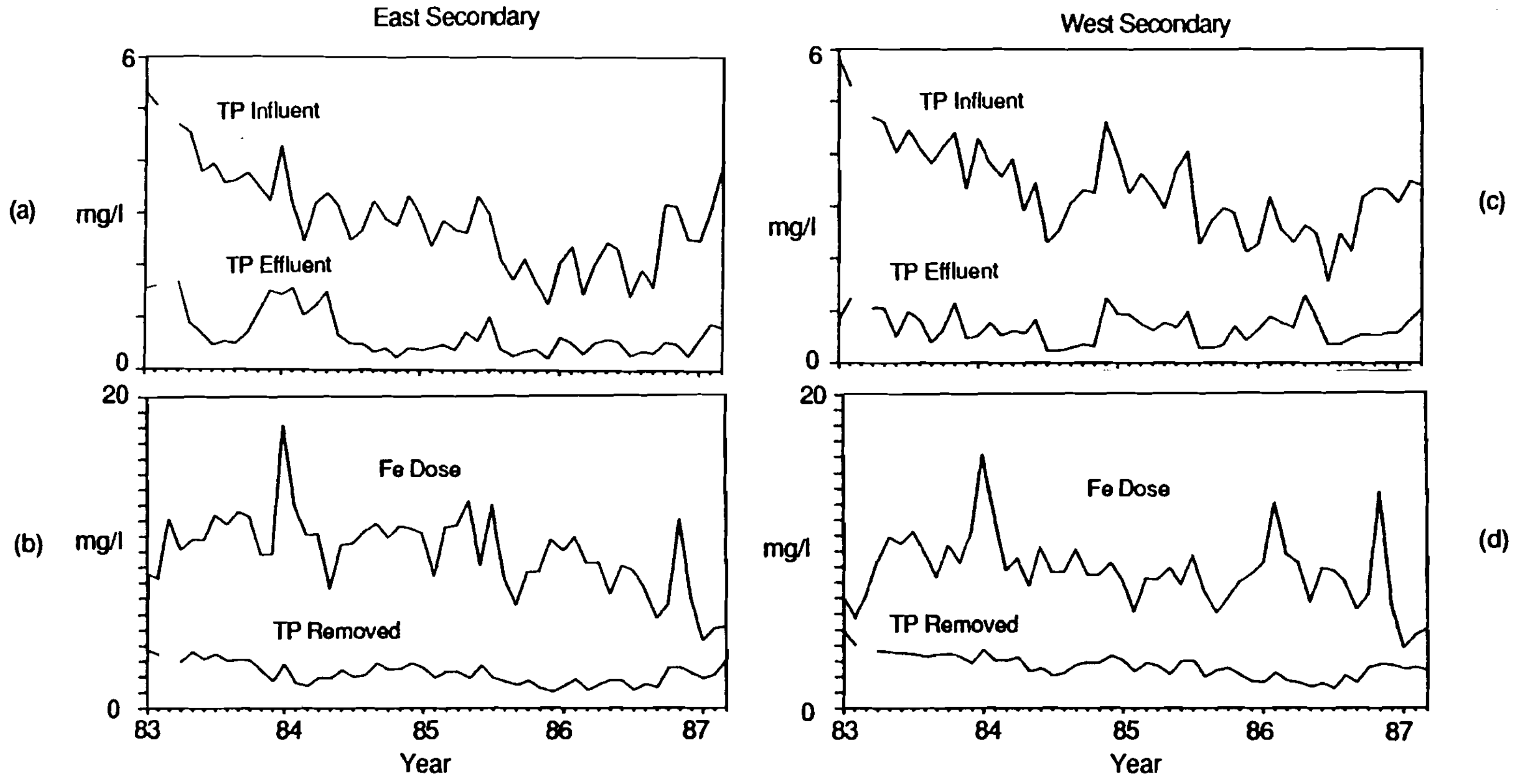


Figure 3-50 Blue Plains Secondary, TP Influent and Effluent vs. Year a) East Plant, c) West Plant and TP Removed and Fe Dose vs. Year b) East Plant, d) West Plant.

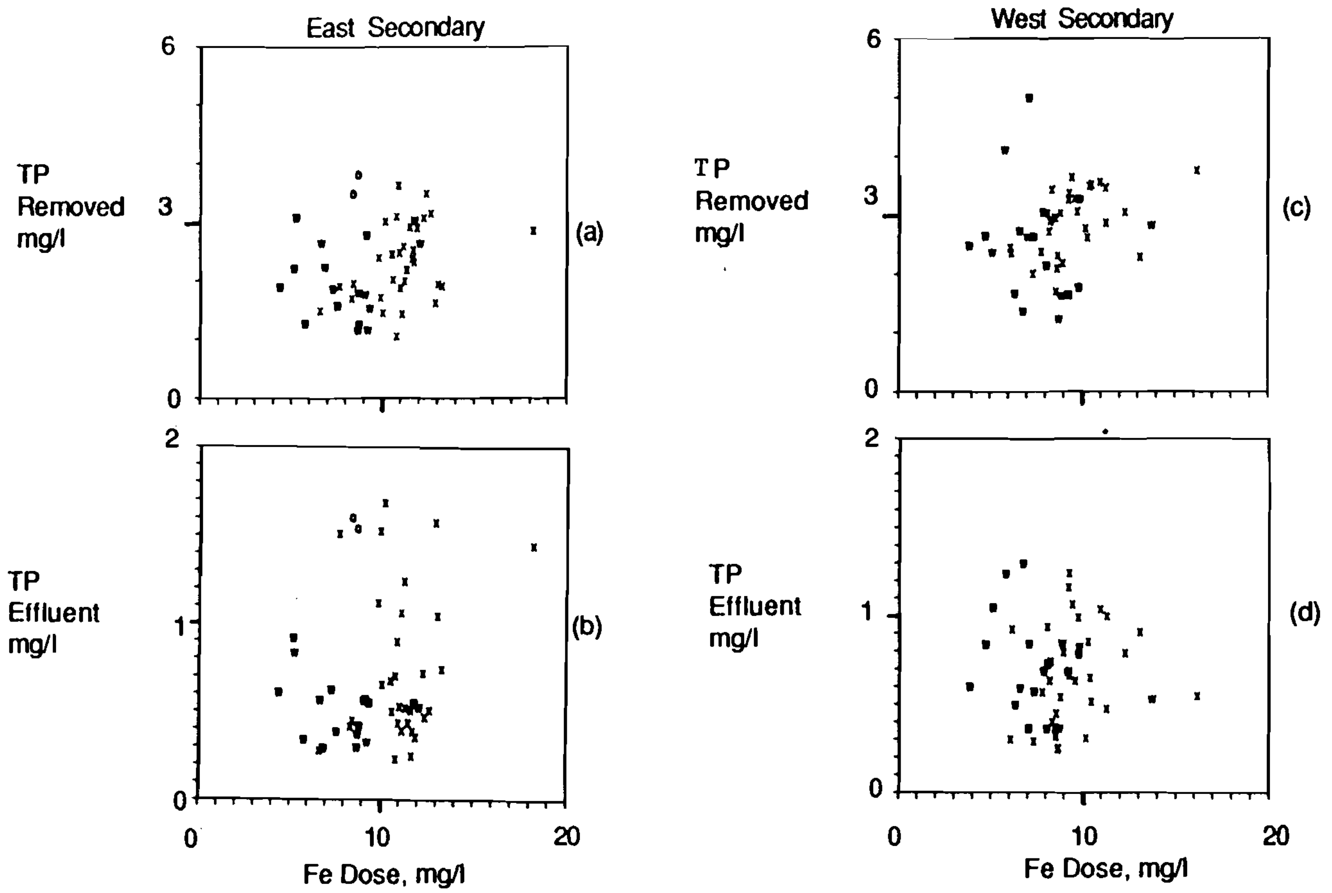


Figure 3-51 Blue Plains Secondary, TP Removed vs. Fe Dose a) East Plant, c) West Plant, Effluent TP vs. Fe Dose, b) East Plant, d) West Plant. (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron)

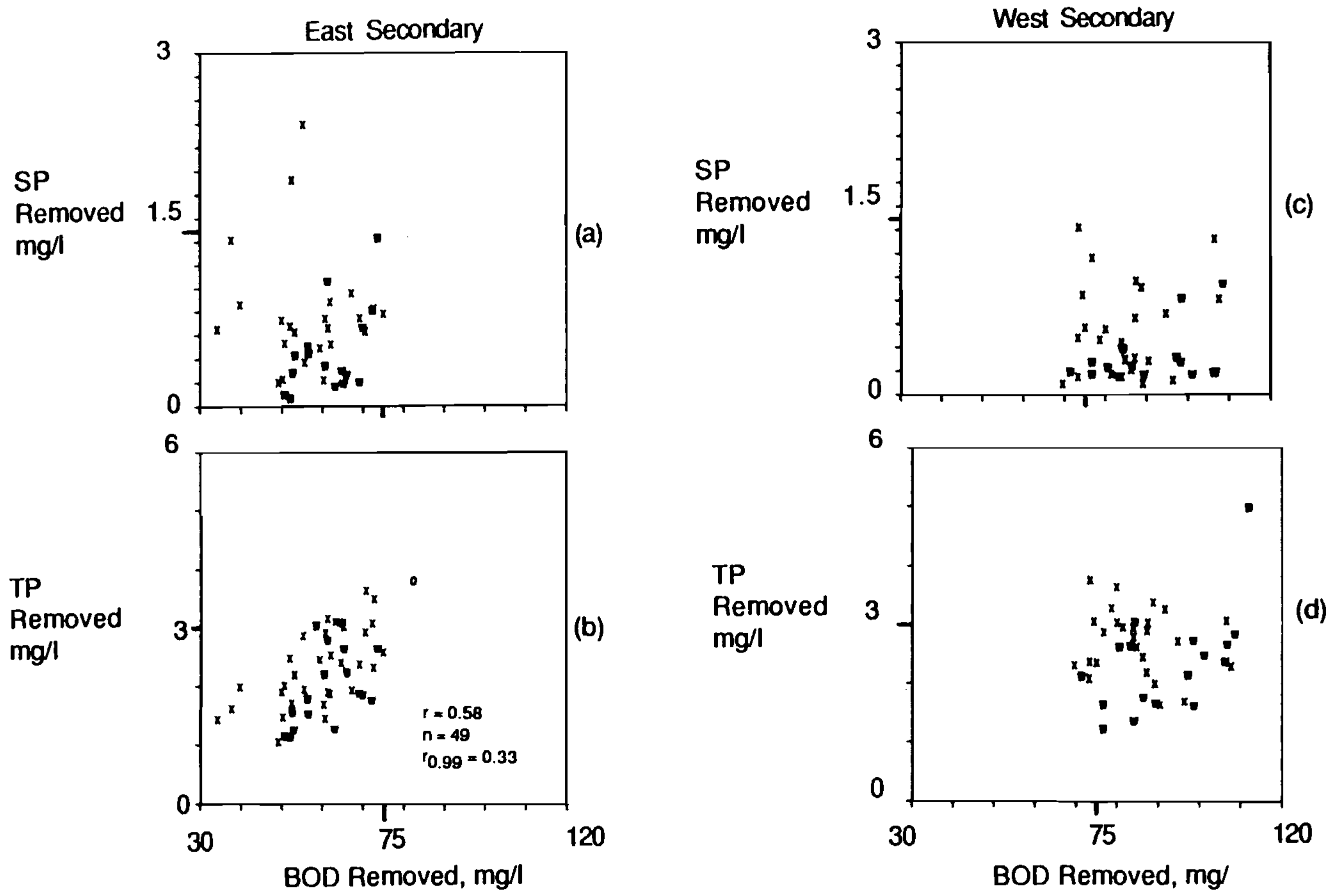


Figure 3-52 Blue Plains Secondary, SP Removed vs. BOD Removed a) East Plant, c) West Plant, TP Removed vs. BOD Removed b) East Plant, d) West Plant (0 = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = no iron).

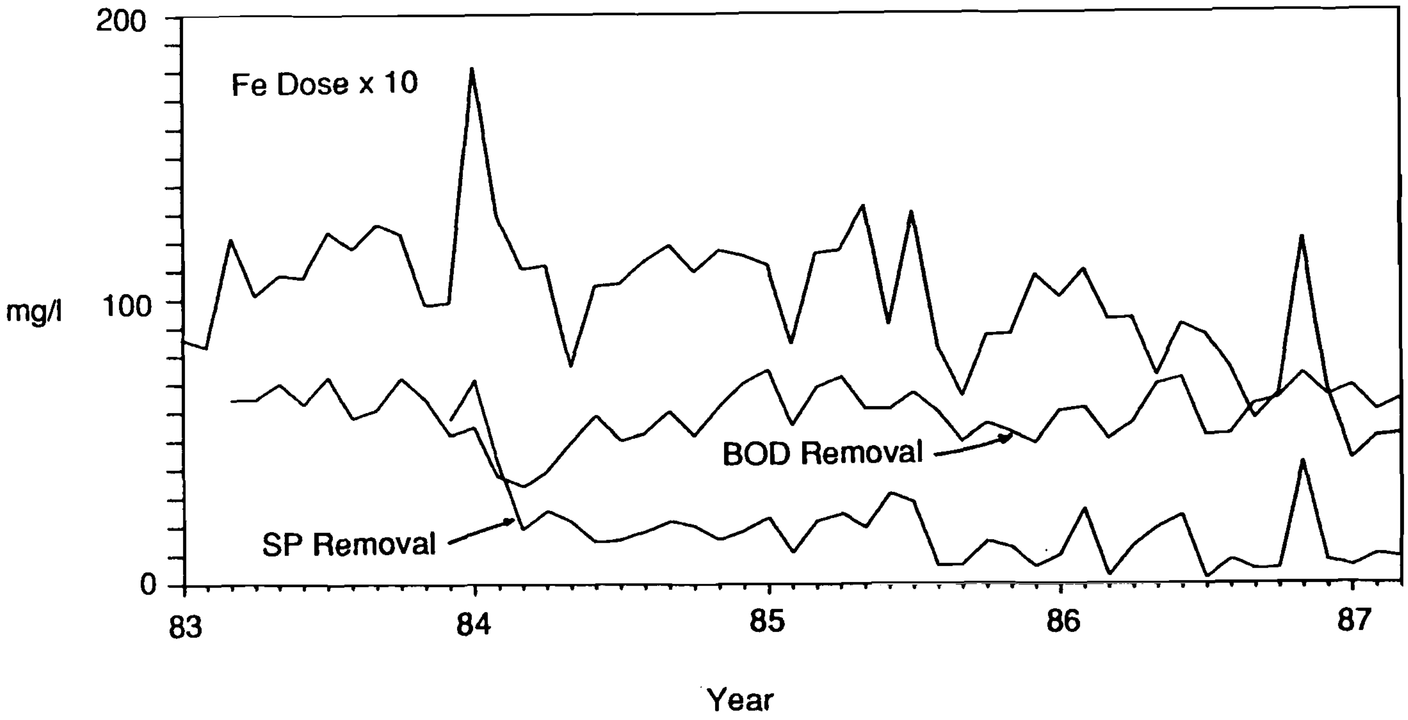


Figure 3-53 Blue Plains Secondary, Iron Dose, BOD Removal, and SP Removal.

Figure 3-54 Blue Plains Secondary, Reported Sludge, Predicted Chemical Sludge, and Iron Dose a) East Plant, b) West Plant, c) Estimated Fraction of Chemical Sludge.

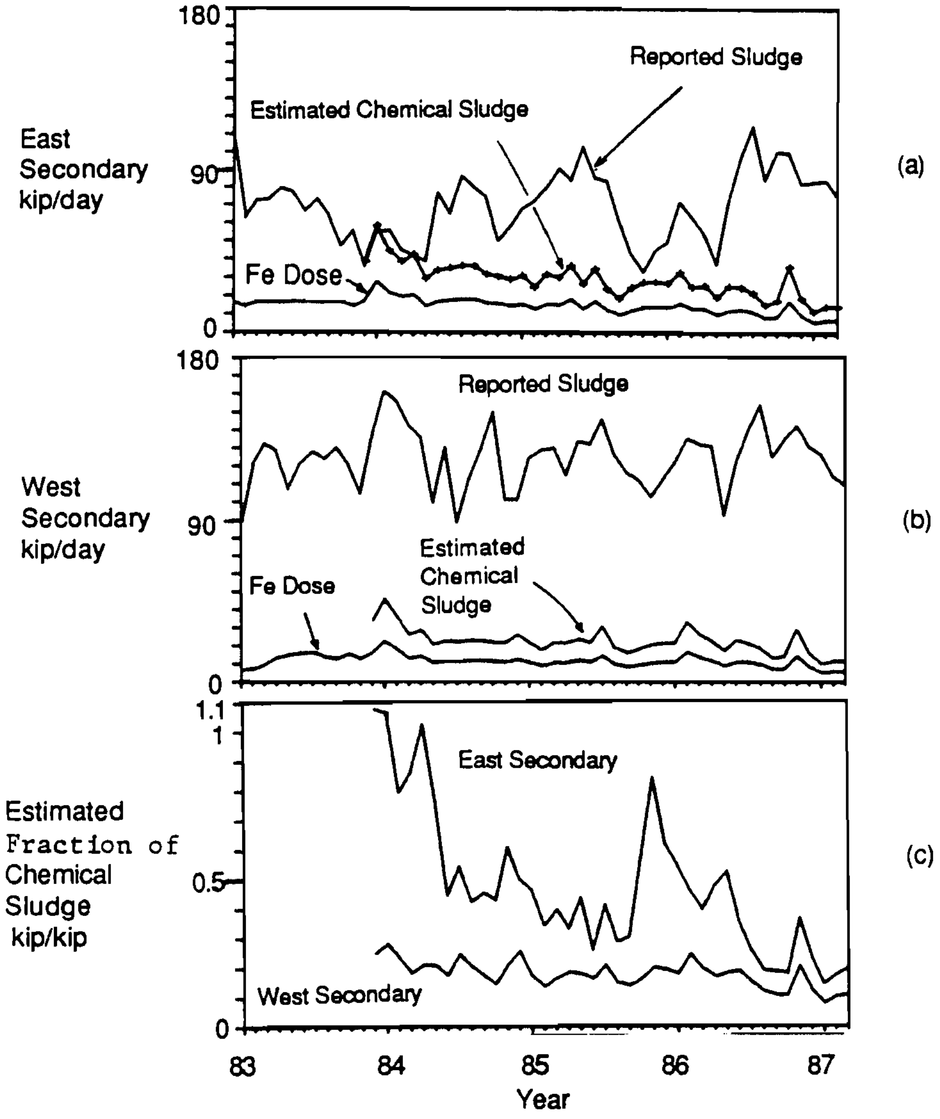


Figure 3-55 Blue Plains Secondary Sludge Production vs. Fe Dose a) East Plant, c) West Plant; Secondary Sludge Production vs. BOD Removed b) East Plant, d) West Plant.

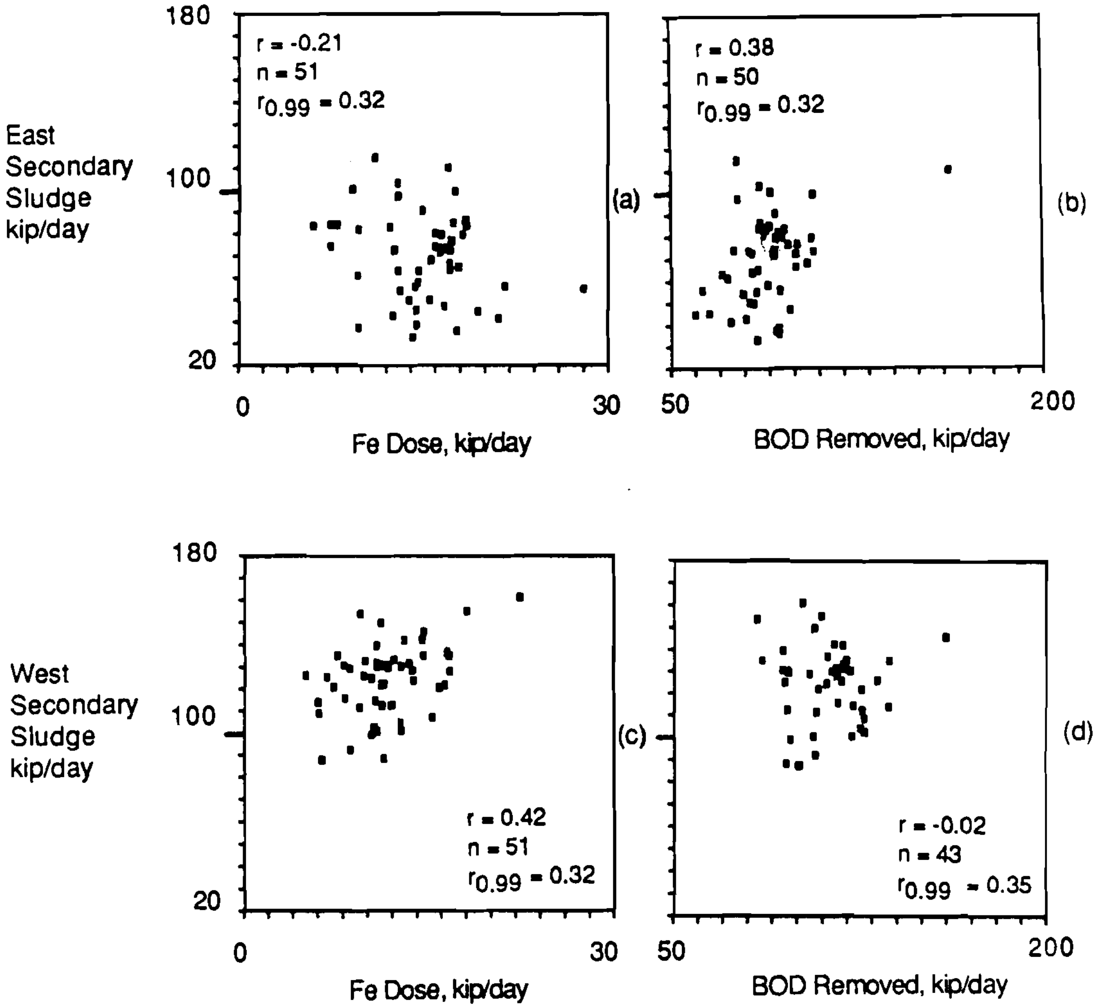
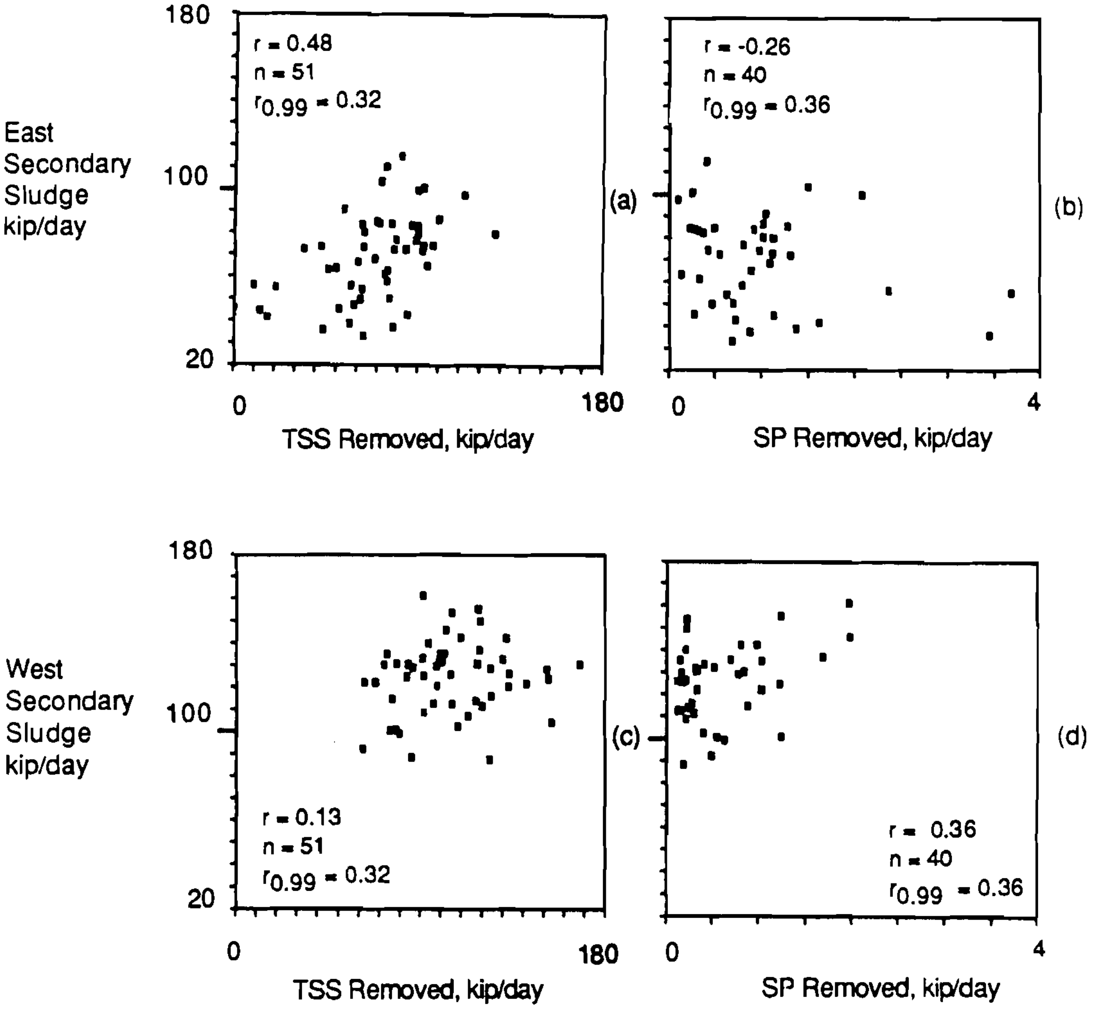


Figure 3-56 Blue Plains Secondary Sludge Production vs. TSS Removed a) East Plant, c) West Plant; Secondary Sludge Production vs. SP Removed b) East Plant, d) West Plant. (O = $FeCl_3$, W = WPL, X = $FeCl_3$ + WPL, N = No Iron)



May and June 1984 predicted chemical sludge began to make up a smaller percentage (kip/kip) of the reported sludge. The data in Figures 3-29 and 3-31 show that the solids processing building recycle (SPBR) contributed large and variable quantities of BOD and solids after April 1984.

East plant sludge production is related to recycle quality and the primary effluent quality, which is a function of primary iron dose. This makes it difficult to estimate changes in east secondary sludge production caused by secondary phosphorus removal and iron dosing. Figures 3-55a and 3-56b show no strong correlation between sludge production and iron dose or SP removal.

West Plant. Figure 3-54c shows that the estimated fraction of chemical sludge in the west plant is about half that of the east plant.

Figures 3-55b,d and 3-56a,c show that BOD and TSS removal (mass basis) in the west plant are greater than in the east plant. This is because recycle streams contribute more TSS and BOD (Figures 3-30 and 3-32), and because west primary effluent TSS and BOD are greater than the east plant (See Figures 3-20b,d and 3-22b,d).

Figures 3-55c shows a significant correlation between iron dose and sludge production.

In Chapter Four, sludge production is modeled in terms of iron dose, influent TSS, BOD removal, and SP removal.

CHAPTER FOUR: BLUE PLAINS REGRESSION ANALYSIS

4.1 REGRESSION ANALYSIS - SOME GENERAL INFORMATION

Multiple regression was used to investigate many tentative linear models. Only a few of the models considered will be presented since, to large extent, this work did not lead to insights not already noted in the previous chapter. Also, many of the regression models that had statistical significance were considered to have little appeal as engineering predictive models.

The regression examples given in this chapter illustrate an approach based on computing all possible models that can be formed from a set of independent variables that are under consideration. This approach was not used throughout the research for several reasons. In general, regression models taken under consideration should be constructed rationally from mechanistic knowledge of the system. The "all possible models" approach generates many models that are known *a priori* to hold little practical interest. Also, it is computationally inefficient in comparison to, say, step regression. But, it does clearly demonstrate several difficulties that were commonly encountered, collinearity in particular, so it was considered worthwhile to present the comprehensive examples. For the other treatment plants, fewer statistical results will be presented.

4.2 PRIMARY PHOSPHORUS REMOVAL

All possible combinations of the independent variables in the following model were fitted to primary influent and effluent data.

$$dSP = b_0 + b_1\ Fe + b_2\ SPI + b_3\ Q \qquad 4\text{-}1$$

where dSP = SPI - SPO, mg/l

Fe = Iron Dose, mg/l

SPI = Primary Influent Soluble Phosphorus, mg/l

SPO = Primary Effluent Soluble Phosphorus, mg/l

Q = Flow, MGD

Table 4-1 and Table 4-2 summarize the models fitted for the east and west plants, respectively. Seven alternate models can be formed by adding and deleting terms from the basic model. Each is represented in the tables.

Each row gives the parameter estimates for the terms that are in the particular model. For example, Model 1 has two parameters and is simply $dSP = b_0 + b_1\ Fe$. Also given in Table 4.1 are the number of observations used to fit the model ($n = 40$ in this case), the coefficient of determination (R^2), and the standard deviation of the model, S.

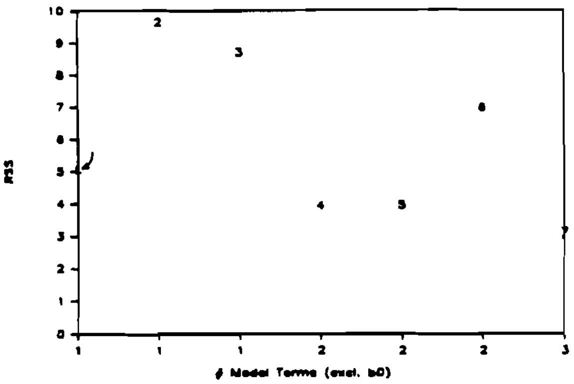
Figures 4-1 and 4-2 are plots of residual sum of squares (RSS) against the number of terms in the considered model terms. Also presented for each model, in tabular form, are the residual sum of squares (RSS), the mean square error (MSE = RSS/degrees of freedom),

Table 4-1 Blue Plains East Primary Regression Output for Equation 4-1.

MODEL: $dSP = b0 + b1\ Fe + b2\ SPI + b3\ Q$

Model	b0	b1	b2	b3	n	R2	S
1	0.70	0.13			40	0.60	0.37
	4.77	7.62					
2	0.31		0.57		40	0.25	0.50
	0.75		3.53				
3	4.17			-0.0145	40	0.32	0.48
	7.17			-4.23			
4	-0.08	0.11	0.35		40	0.69	0.33
	-0.28	7.34	3.28				
5	2.23	0.11		-0.0082	40	0.69	0.33
	4.53	6.67		-3.23			
6	2.68		0.43	-0.0121	40	0.46	0.43
	3.72		3.05	-3.79			
7	1.35	0.10	0.30	-0.0070	40	0.76	0.29
	2.55	6.64	3.09	-3.04			

Figure 4-1 Blue Plains East Primary RSS vs. Number of Model Terms (excluding b_0) and Sequential F values for Models in Table 4-1. Data labels represent model number.



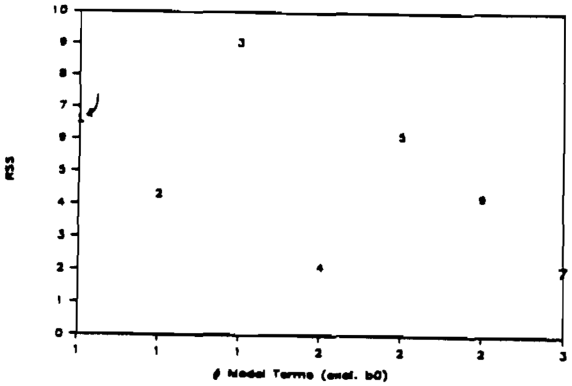
MODEL	~~TERMS~~ VARIABLES	RSS	MSE	Sequential F Value		
1	1	5.0684	0.1334			
2	1	9.6473	0.2539			
3	1	8.7031	0.2290			
4	2	3.9281	0.1062	10.7	53.9	45.0
5	2	3.9547	0.1069	10.4	53.3	44.4
6	2	6.9530	0.1879	-10.0	14.3	9.3
7	3	3.1258	0.0868	9.2	9.5	44.1

Table 4-2 Blue Plains West Primary Regression Output for Equation 4-1.

MODEL: dSP = b0 + b1 Fe + b2 SPI + b3 Q

Model	b0	b1	b2	b3	n	R2	S
1	1.16	0.081			40	0.30	0.42
	7.13	4.07					
2	0.28		0.63		40	0.54	0.34
	1.26		6.75				
3	0.71			0.007	40	0.05	0.49
	0.90			1.35			
4	-0.16	0.071	0.60		40	0.78	0.24
	-0.91	6.28	8.94				
5	0.06	0.081		0.008	40	0.35	0.41
	0.08	4.20		1.69			
6	0.73		0.67	-0.004	40	0.55	0.34
	1.35		6.50	-0.91			
7	0.16	0.071	0.62	-0.003	40	0.78	0.24
	0.42	6.20	8.49	-0.92			

Figure 4-2 Blue Plains West Primary RSS vs. Number of Model Terms (excluding b_0) and Sequential F values for Models in Table 4-2. Data labels represent model number.



MODEL	TERMS	RSS	MSE	Sequential F Value		
1	1	6.5917	0.1735			
2	1	4.3085	0.1134			
3	1	9.0334	0.2377			
4	2	2.0851	0.0564	80.0	39.5	123.3
5	2	6.1215	0.1654	2.8	-11.0	17.6
6	2	4.2145	0.1139	20.9	0.8	42.3
7	3	2.0374	0.0566	0.8	72.2	38.5

and F statistics.

The F statistics are used to test whether added terms make a statistically significant difference in the model. Models with two parameters are compared with one parameter models; three parameter models are compared with two parameter models, and so on. The "sequential" aspect of this comparison involves comparing Model 4, a two parameter model, with the preceding three one parameter models (Models 1,2, and 3). A large F value indicates that the additional parameter has significantly improved the model.

Appendix C explains the sequence order of comparison. It also explains the regression output and the use of the sequential F values.

The statistical results will be presented with a minimum of comment and explanation.

4.2.1 East Plant

Model 1, which has only Fe dose as a predictor variable has an $R^2 = 0.60$. Adding either SPI or Q to the model increases R^2 to 0.69. Adding both increased R^2 to 0.76. Putting all three variables into the model is statistically justified and the most efficient regression model in Table 4-1 is Model 7:

$$dSP = 1.35 + 0.1\ Fe + 0.3\ SPI - 0.007\ Q \tag{4.1}$$

It indicates that iron dose, initial SP, and flow are useful predictive variables.

The strongest effect in Model 7 is iron dose. The value of the estimated coefficient, $b_1 = 0.10$, corresponds to an Fe/P_c mole ratio of 5.0 [1 mg Fe/0.1 mg SP)(30.97/55.85) = 5.0]. This is considerably higher than the stoichiometric ratio for ferric orthophosphate precipitation.

Adding SPI and Q to the model does not change the estimated effect of iron dose; b_1 is always in the range 0.13 - 0.10.

The negative coefficient for Q suggests that SP removal is lower at higher flows. This effect may be related to hydraulic retention time. SP removal may be low at higher flows because of a dilution effect. A dependence of soluble phosphorus removal on clarifier overflow rates is not easily conceived.

4.2.2 West Plant

Model 4 is the most efficient in Table 4-2. As for the East Plant data, iron addition is significant. Alone, however, it does not explain much of the variation in dSP, with R^2 being only 0.3. Adding SPI improves the model substantially, increasing R^2 to 0.78. Adding Q to the model is not helpful.

The coefficient on iron dose in Model 4 corresponds to an Fe/P_c ratio of 6.8 [(1 mg Fe/ 0.071 mg dSP)(30.97/55.85) = 6.8].

4.3 EFFECT OF IRON TYPE

Since ferric and ferrous iron are not theoretically equally effective in removing phosphorus, the type of iron used is taken into account by a model designed to test for differences between soluble phosphorus removal in months when only WPL was used, when only $FeCl_3$ was used, and when both WPL and $FeCl_3$ were used in combination. Dummy variables, designated in the model by Z, were used to distinguish between the three conditions. All possible regressions of the following model were calculated using primary iron dosing data for months where iron was dosed:

$$dSP = b_0 + b_1 Fe + b_2 Z_1 + b_3 Z_1 Fe + b_4 Z_2 + b_5 Z_2 Fe \qquad 4\text{-}2$$

where $dSP = SPI - SPO$, mg/l

Fe = Iron Dose, mg/l

$Z_1 = 1$, $Z_2 = 0$ if $FeCl_3$ only is dosed

$Z_1 = 0$, $Z_2 = 1$ if WPL only is dosed

$Z_1 = 0$, $Z_2 = 0$ if Both $FeCl_3$ and WPL are dosed

The most efficient model contained only the b_0 and b_1 coefficients. Other terms were not statistically significant, indicating that it is not possible to separately assess the effectiveness of the three forms in which iron was added. This analysis is consistent with what is visually apparent in Figures 3-14a and 3.14c.

4.4 PRIMARY SLUDGE PRODUCTION

To identify variables affecting primary sludge production, all possible combinations of the following model were fit to the primary treatment data:

$$SLUK = b_0 + b_1\ dTSSK + b_2\ TSSIK + b_3\ FeK + b_4\ dSPK + b_5\ Q \qquad 4\text{-}3$$

where SLUK = Reported Primary Sludge Production (January 1983 - December 1986), kip/day

dTSSK = TSS removed, kip/day

TSSIK = Primary Influent TSS, kip/day

FeK = Iron Dose, kip/day

dSPK = Soluble Phosphorus Removed, kip/day

Q = Flow, MGD

There are 31 possible models. The estimated parameters for these are presented in Table 4-3. A plot of model residual sum of squares is included in Figure 4-3, along with the sequential F values.

Of the single variable models, the one using iron dose (FeK) explains the most variation ($R^2 = 0.46$). The amount of suspended solids removed (dTTSK) is also important. Soluble phosphorus removal and flow rate have little explanatory power.

Because dSPK data were missing for eleven months, the models in Table 4-3 that contain dSPK were fitted using eleven fewer observations than the other models. Therefore, model comparisons could not be purely objective.

Table 4-3 Blue Plains Primary Regression Output for Equation 4-3.

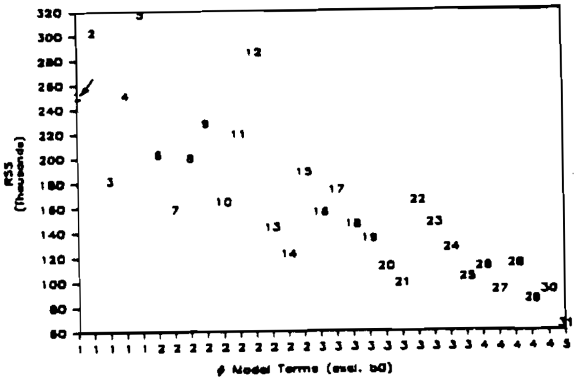
MODEL: SLUK = b0 + b1 dTSSK + b2 TSSIK + b3 FeK + b4 dSPK + b5 Q

Model	b0	b1	b2	b3	b4	b5	n	R2	S
1	165.24	0.45					48	0.26	74.0
	5.80	3.97							
2	146.66		0.31				48	0.11	81.1
	2.71		2.34						
3	192.46			4.98			48	0.46	62.8
	12.57			6.30					
4	169.73				25.68		37	0.12	84.7
	3.11				2.23				
5	42.39					0.72	48	0.06	83.0
	0.33					1.76			
6	355.38	1.30	-0.97				48	0.40	67.1
	5.64	4.71	-3.31						
7	145.70	0.26		4.17			48	0.53	59.3
	6.30	2.59		5.17					
8	108.76	0.39			18.35		37	0.30	76.6
	2.03	2.96			1.71				
9	-78.11	0.46				0.76	48	0.33	71.2
	-0.68	4.20				2.18			
10	109.41		0.22	4.73			48	0.51	60.4
	2.68		2.18	6.16					
11	56.35		0.31		23.66		37	0.24	80.2
	0.78		2.25		2.16				
12	-48.33		0.29			0.64	48	0.16	79.7
	-0.37		2.22			1.63			
13	231.43			10.08	-32.39		37	0.50	65.0
	5.30			5.05	-2.23				
14	-209.62			5.71		1.23	48	0.64	52.1
	-2.42			8.48		4.68			
15	-268.36				29.65	1.35	37	0.34	74.4
	-1.94				2.91	3.38			

Table 4-3, Continued.

Model	b0	b1	b2	b3	b4	b5	n	R2	S
16	198.86	0.51	-0.26	3.69			48	0.54	59.5
	2.82	1.54	-0.80	3.64					
17	350.11	1.48	-1.12		5.20		37	0.39	72.6
	2.92	2.92	-2.22		0.44				
18	30.50	1.61	-1.32			1.23	48	0.57	57.7
	0.32	6.47	-4.95			4.11			
19	165.36		0.17	9.26	-28.74		37	0.53	63.9
	2.65		1.46	4.53	-1.98				
20	-251.95		0.17	5.47		1.17	48	0.67	50.4
	-2.91		2.00	8.27		4.54			
21	-146.65			9.27	-24.33	1.15	37	0.66	54.6
	-1.41			5.48	-1.97	3.88			
22	-332.16		0.26		27.66	1.25	37	0.42	70.8
	-2.46		2.13		2.84	3.27			
23	-286.82	0.35			22.76	1.23	37	0.49	66.8
	-2.31	3.03			2.41	3.43			
24	186.79	0.23		8.75	-29.08		37	0.56	62.0
	3.98	2.07		4.35	-2.09				
25	-236.77	0.23		4.95		1.19	48	0.70	48.4
	-2.92	2.85		7.30		4.84			
26	367.37	1.08	-0.87	8.15	-35.99		37	0.61	59.2
	3.76	2.56	-2.08	4.20	-2.63				
27	-157.45	0.78	-0.58	3.96		1.31	48	0.73	46.4
	-1.84	2.99	-2.21	4.99		5.41			
28	-40.94	1.58	-1.27		8.16	1.32	37	0.60	59.7
	-0.30	3.79	-3.05		0.84	4.09			
29	-172.96	0.21		8.11	-21.66	1.11	37	0.70	51.6
	-1.75	2.22		4.82	-1.84	3.95			
30	-187.52		0.13	8.64	-21.67	1.11	37	0.68	53.9
	-1.76		1.38	4.99	-1.75	3.80			
31	14.44	1.22	-1.03	7.36	-29.30	1.19	37	0.78	45.6
	0.14	3.71	-3.17	4.89	-2.75	4.78			

Figure 4-3 Blue Plains Primary RSS vs. Number of Model Terms (excluding b_0) and Sequential F values for Models in Table 4-3. Data labels represent model number.



M	TERM	RSS	MSE	Sequential F Values									
1	1	251884	5475.7										
2	1	302516	6576.4										
3	1	181617	3948.2										
4	1	251222	7177.8										
5	1	317040	6892.2										
6	2	202642	4503.2	10.9	22.2	-4.7	10.8	25.4					
7	2	158060	3512.5	26.7	41.1	6.7	26.5	45.3					
8	2	199752	5875.1	8.9	17.5	-3.1	8.8	20.0					
9	2	227859	5063.5	4.7	14.7	-9.1	4.6	17.6					
10	2	164233	3649.6	24.0	37.9	4.8	23.8	41.9					
11	2	218768	6434.4	5.1	13.0	-5.8	5.0	15.3					
12	2	285746	6349.9	-5.3	2.6	-16.4	-5.4	4.9					
13	2	143571	4222.7	25.7	37.6	9.0	25.5	41.1					
14	2	122108	2713.5	47.8	66.5	21.9	47.6	71.8					
15	2	188152	5533.9	11.5	20.7	-1.2	11.4	23.3					
16	3	155805	3541.0	13.2	0.6	12.4	20.3	2.4	17.8	36.7	-3.5	-9.5	9.1
17	3	173762	5265.5	5.5	-3.0	4.9	10.3	-1.8	8.5	21.3	-5.7	-9.8	2.7
18	3	146369	3326.6	16.9	3.5	16.0	24.5	5.4	21.8	41.9	-0.8	-7.3	12.6
19	3	134880	4087.3	16.6	5.7	15.9	22.7	7.2	20.5	36.9	2.1	-3.1	13.0
20	3	111909	2543.4	35.7	18.1	34.5	45.6	20.6	42.0	68.3	12.4	4.0	30.0
21	3	98519	2985.4	34.9	19.9	33.9	43.3	22.0	40.3	62.7	15.1	7.9	30.0
22	3	165343	5010.4	7.4	-1.5	6.9	12.5	-0.2	10.7	24.0	-4.3	-8.6	4.6
23	3	147223	4461.3	12.4	2.4	11.8	18.1	3.8	16.0	31.0	-0.8	-5.6	9.2
24	3	127042	3849.8	19.6	8.1	18.9	26.2	9.7	23.8	41.2	4.3	-1.3	15.9
25	3	103124	2343.7	42.5	23.4	41.2	53.2	26.1	49.3	77.9	17.3	8.1	36.3
26	4	111961	3498.8	12.5	17.7	9.8	6.6	-0.0	-3.8	15.3	10.1	4.3	-2.5
27	4	92645	2154.5	29.3	37.6	24.9	19.6	8.9	2.7	33.7	25.3	16.0	4.9
28	4	114097	3565.5	11.7	16.7	9.1	5.8	-0.6	-4.4	14.4	9.3	3.6	-3.1
29	4	85359	2667.5	26.4	33.1	22.9	18.6	10.0	4.9	30.0	23.2	15.6	6.7
30	4	92994	2906.1	21.6	27.8	18.4	14.4	6.5	1.9	24.9	18.7	11.7	3.5
31	5	64420	2078.1	22.9	13.6	23.9	10.1	13.8					

Model 31, which has the highest R^2, contains all of the possible terms. The model lacks appeal on mechanistic grounds because the coefficient of dSPK term is negative (removing more SP decreases the amount of sludge produced). This is not a reasonable physical relationship between sludge production and SP removal. The coefficient of dSPK is highly variable from one model to another, changing, for example, from -29.3 in Model 31 to an insignificant value of 8.2 in Model 28, when FeK is dropped from the model. This kind of instability can result from collinearity between predictor variables, in this case FeK and dSP. A model that exhibits this behavior must be interpreted with caution and should not be used as a predictive model.

Model comparisons can be objectively compared with the F values if the models with dSPK are eliminated. Model 27 contains all terms except dSPK and has a low standard deviation and large R^2, but the negative coefficient of influent TSS (kip/day) does not make mechanistic sense.

Models 20 and 25, both three-term models, have roughly the same predictive power, i.e. similar R^2 and S. Both models have iron dose (FeK) and flow (Q) terms with approximately the same estimated coefficients. Model 20 contains the TSSIK term and Model 25 has the dTSSK term. There is a degree of interchangeability between the dTSSK and TSSIK terms, removal being a to large extent determined by the influent solids loading.

The estimated effects of iron dose (coefficient b_3) in Models 20 and 25 indicate that over the range of observed iron doses, primary sludge production increases about 5 to 5.5 kips for every kip of iron dosed. The average iron dose for the period modeled was 15.6 kip/day, including the first thirteen months of record when no iron was used. Assuming that the increase in primary sludge mass was due entirely to formation of chemical precipitate (i.e. assuming no enhanced suspended solids removal due to iron addition), there was an average of 28.9 percent of the total reported sludge [5(15.6) = 78 kip/day chemical sludge, or 100(78/270.2) = 28.9%]. This compares poorly with the theoretical sludge calculation in Chapter Three, which predicted an average of 16.7 % chemical sludge (percent of total sludge by weight) for the months when iron was dosed. The discrepancy probably indicates that the estimated value of b_3 reflects some degree of enhanced TSS removal, a reasonable expectation on mechanistic grounds.

4.5 SECONDARY PHOSPHORUS REMOVAL

Regression analysis verified that essentially complete removal of SP was achieved regardless of iron dose. This is consistent with theory. Iron is used in excess, as shown in Chapter 3, and precipitation is constrained by the solubility limit and the final pH.

The effect of BOD removal was significant and positive; this is consistent with the expectation that some phosphorus is removed by biological uptake. The derived regression model, however, did not reliably predict biological uptake. A predictive model of this mechanism would have to simultaneously account for chemical removal and biological uptake. The correlation between independent variables makes it impossible to separate the two mechanisms using multiple regression methods.

4.6 SECONDARY SLUDGE

All possible combinations of the following model were fitted to data from the secondary plant data from December 1983 to March 1987:

$$SLUK = b_0 + b_1\ TSSIK + b_2\ dBODK + b_3\ FeK + b_4\ dSPK \qquad 4\text{-}4$$

where SLUK = Sludge Production, kip/day

TSSIK = Influent TSS, kip/day

dBODK = BOD Removed, kip/day

FeK = Iron Dose, kip/day

dSPK = Soluble Phosphorus Removed, kip/day

Regressions for the two plants are summarized in Tables 4-4 and 4-5.

4.6.1 East Plant

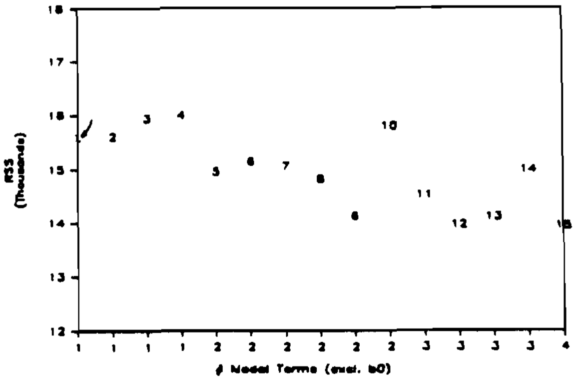
None of the regressions presented in Table 4-4 explain East Plant secondary sludge production better than the average value of 69.6 kip/day (S.D. = 20.9, n = 40). Changes in sludge production, resulting from changes in iron dose or SP removal, can not be estimated with these models. The effects are masked by the highly variable sludge values.

Table 4-4 Blue Plains East Secondary Regression Output for Equation 4-4 .

MODEL: SLUK = b0 + b1 TSSIK + b2 dBODK + b3 FeK + b4 dSPK

Model	b0	b1	b2	b3	b4	n	R2	S
1	36.37	0.33				40	0.09	20.3
	2.07	1.92						
2	18.87		0.59			40	0.09	20.3
	0.71		1.92					
3	87.77			-1.25		40	0.07	20.5
	7.77			-1.68				
4	76.23				-6.79	40	0.07	20.5
	14.67				-1.63			
5	9.67	0.23	0.42			40	0.13	20.1
	0.35	1.27	1.27					
6	55.86	0.26		-0.84		40	0.12	20.2
	2.19	1.39		-1.06				
7	47.00	0.27			-4.97	40	0.12	20.2
	2.38	1.53			-1.16			
8	40.32		0.52	-1.04		40	0.13	20.0
	1.33		1.67	-1.40				
9	20.38		0.66		-7.87	40	0.17	19.5
	0.79		2.22		-1.97			
10	84.39			-0.78	-3.59	40	0.08	20.7
	6.59			-0.70	-0.58			
11	29.13	0.17	0.41	-0.81		40	0.15	20.1
	0.88	0.85	1.24	-1.03				
12	15.36	0.12	0.56		-6.88	40	0.18	19.7
	0.57	0.63	1.67		-1.59			
13	17.10		0.68	0.17	-8.58	40	0.18	19.8
	0.49		2.07	0.14	-1.33			
14	52.60	0.25		-0.37	-3.54	40	0.12	20.4
	2.00	1.38		-0.33	-0.58			
15	10.48	0.13	0.59	0.24	-7.87	40	0.18	20.0
	0.29	0.64	1.62	0.20	-1.20			

Figure 4-4 Blue Plains East Secondary RSS vs. Number of Model Terms (excluding b_0) and Sequential F values for Models in Table 4-4. Data labels represent model number.



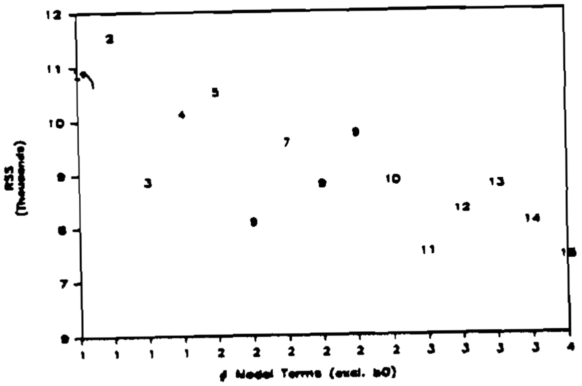
MODEL	TERMS	RSS	MSE	Sequential F Value					
1	1	15598.9	410.5						
2	1	15599.0	410.5						
3	1	15936.8	419.4						
4	1	16002.3	421.1						
5	2	14950.7	404.1	1.6	1.6	2.4	2.6		
6	2	15142.5	409.3	1.1	1.1	1.9	2.1		
7	2	15048.7	406.7	1.4	1.4	2.2	2.3		
8	2	14814.1	400.4	2.0	2.0	2.8	3.0		
9	2	14124.0	381.7	3.9	3.9	4.7	4.9		
10	2	15794.6	426.9	-0.5	-0.5	0.3	0.5		
11	3	14523.9	403.4	1.1	1.5	1.3	0.7	-1.0	3.1
12	3	13968.5	388.0	2.5	3.0	2.8	2.2	0.4	4.7
13	3	14116.1	392.1	2.1	2.6	2.4	1.8	0.0	4.3
14	3	15004.2	416.8	-0.1	0.3	0.1	-0.5	-2.1	1.9
15	4	13952.2	398.6	1.4	0.0	0.4	2.6		

Table 4-5 Blue Plains West Secondary Regression Output for Equation 4-4.

MODEL: SLUK = b0 + b1 TSSIK + b2 dBODK + b3 FeK + b4 dSPK

Model	b0	b1	b2	b3	b4	n	R2	S
1	97.88	0.21				40	0.06	16.9
	5.32	1.53						
2	130.92		-0.05			40	0.00	17.4
	6.36		-0.25					
3	98.13			2.47		40	0.23	15.3
	11.60			3.41				
4	118.46				12.15	40	0.13	16.3
	29.17				2.34			
5	112.24	0.30	-0.23			40	0.09	16.9
	5.05	1.90	-1.14					
6	67.68	0.23		2.51		40	0.30	14.8
	3.73	1.88		3.59				
7	93.63	0.19			11.63	40	0.17	16.1
	5.33	1.45			2.26			
8	106.44		-0.08	2.48		40	0.24	15.4
	5.43		-0.47	3.40				
9	141.47		-0.22		14.56	40	0.16	16.2
	7.23		-1.20		2.63			
10	98.58			2.38	0.78	40	0.23	15.5
	10.41			2.30	0.11			
11	84.30	0.34	-0.28	2.60		40	0.33	14.5
	4.13	2.48	-1.64	3.79				
12	120.47	0.36	-0.46		16.21	40	0.28	15.2
	5.97	2.49	-2.34		3.10			
13	111.44		-0.11	2.19	2.88	40	0.24	15.6
	4.62		-0.58	1.99	0.36			
14	66.83	0.23		2.61	-0.95	40	0.30	15.0
	3.45	1.86		2.58	-0.14			
15	92.25	0.35	-0.34	2.10	4.97	40	0.36	14.6
	3.88	2.52	-1.76	2.04	0.67			

Figure 4-5 Blue Plains West Secondary RSS vs. Number of Model Terms (excluding b_0) and Sequential F values for Models in Table 4-5. Data labels represent model number.



MODEL	TERMS	RSS	MSE	Sequential F Value					
1	1	10895.2	286.7						
2	1	11550.6	304.0						
3	1	8855.6	233.0						
4	1	10115.0	266.2						
5	2	10523.1	284.4	1.3	3.6	-5.9	-1.4		
6	2	8081.5	218.4	12.9	15.9	3.5	9.3		
7	2	9570.4	258.7	5.1	7.7	-2.8	2.1		
8	2	8802.7	237.9	8.8	11.6	0.2	5.5		
9	2	9735.4	263.1	4.4	6.9	-3.3	1.4		
10	2	8852.6	239.3	8.5	11.3	0.0	5.3		
11	3	7517.4	208.8	14.4	2.7	9.8	6.2	10.6	6.4
12	3	8309.2	230.8	9.6	-1.0	5.5	2.1	6.2	2.4
13	3	8770.6	243.6	7.2	-2.8	3.3	0.1	4.0	0.3
14	3	8077.2	224.4	10.9	0.0	6.7	3.2	7.4	3.5
15	4	7423.0	212.1	0.4	4.2	6.4	3.1		

4.6.2 West Plant

The most efficient model in Table 4-5 is Model 3, a simple linear function of iron dose. The model is weak and is the result of the weak correlation between sludge production and iron dose (see Figure 3-55c). The model is not useful for estimating changes in sludge production that have resulted from changes in iron dose.

4.7 SUMMARY

The following conclusions can be drawn from the analyses presented in Chapters Three and Four:

1) The average Fe/P_C ratio does not accurately characterize primary SP removal (east and west plants) because there seems to be periods of time when SP removal was stoichiometric and other periods when it was non-stoichiometric.

2) Monthly average Fe/P_C ratios show a downward trend between the initiation of primary iron dosing and the phosphate detergent ban approximately two years later. Therefore, any observed reductions in chemical dose should not be attributed entirely to the phosphate detergent ban. They resulted, at least in part, from improved precipitation efficiency and partly the ban lowering phosphorus loading.

3) Multiple linear regression models indicate that changes in primary sludge production were not related to changes in primary influent SP.

4) Iron dose, influent TSS (or TSS removed) and flow should be used to estimate primary sludge production. The best models indicate that chemical dosing is responsible, on average, for about 30% of the sludge production (mass basis). This 30% includes chemical solids production and enhanced solids removal. Plots and regression analyses indicate that dosing iron to the primary settling basins enhanced BOD and TSS removal, but the incremental removal due to this could not be reliably quantified. Stoichiometric calculations indicate that dosing iron to the primary settling basins produced primary sludge mass quantities that contained, on average, 17% chemical precipitate.

5) At Blue Plains the data suggest that iron dosing has caused significant changes in primary sludge production. Also, the efficiency of primary soluble phosphorus precipitation has increased since primary iron dosing was initiated in 1984. Therefore, reductions in primary sludge production between 1985 and 1986 are due, in part, to more efficient iron use as well as the decrease in iron requirement associated with the decreased phosphorus loading.

6) Secondary soluble phosphorus precipitation has been accomplished most of the time with a non-stoichiometric iron dose. Any reduction in secondary influent SP will not result in a proportional reduction in iron dose. SP removal is constrained by the final pH. Regression models were not helpful in characterizing secondary soluble phosphorus removal.

7) On average, the estimated (stoichiometric) chemical sludge was 27 percent of the reported secondary sludge. Large variations in the

secondary sludge production obscure the effects of iron dosing and SP removal. Regression was not helpful in relating the variables to sludge production. Some variation results from fluctuations in primary effluent quality, which may be related to the pattern of iron dosing in the primary basins, and to the magnitude and composition of sludge treatment return flows.

CHAPTER FIVE: PISCATAWAY WWTP

5.1 BACKGROUND

The Piscataway wastewater treatment plant in Accokeek, Maryland, treats an average flow of 17 MGD, and discharges into the lower reach of Chesapeake Bay. The plant services an estimated 135,250 persons.

In Maryland, a ban on phosphate based detergents became law on December 1, 1985.

5.2 PROCESS DESCRIPTION

The plant consists of grit removal, primary clarification, step aeration activated sludge, secondary clarification, nitrification, final clarification, mixed media filtration, chlorination, and post aeration. Figure 5-1 shows the process train at Piscataway.

Raw sludge and waste activated sludge are gravity thickened. Thickened sludge is anaerobically digested, stabilized with lime, or placed in holding before vacuum filter dewatering. Ferric chloride and polymer are used as dewatering conditioners. Ultimate disposal consists of land application, or composting in the case of non-stabilized sludges.

Solids processing recycle, filter backwash, and gravity thickener overflow are returned to the influent pump station. Filter backwash is also returned directly to the nitrification reactors.

Before March 1987, chemical phosphorus removal was accomplished by

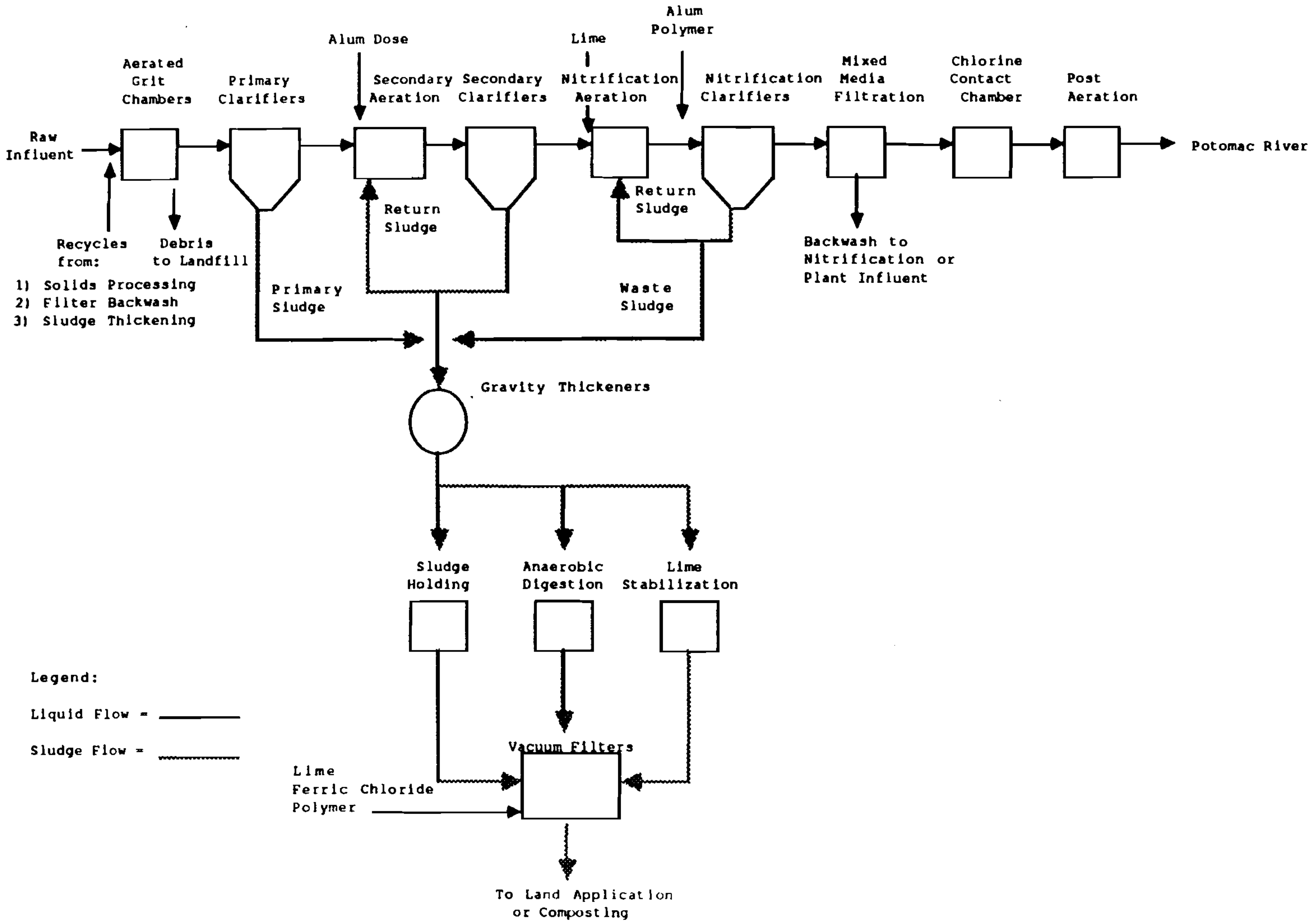


Figure 5-1 Piscataway Wastewater Treatment Process Flow Diagram.

split dosing with liquid alum to the secondary aeration basins and the effluent from the nitrification reactors. Polymer is added before final settling for improved floc formation. Lime is added to nitrification for pH control, however, the quantity is not metered. Nitrification effluent pH is metered. Alum dosing to the secondary aeration basins was discontinued in March 1987, as part of a study to quantify biological phosphorus removal.

5.3 OPERATIONS DATA

Most data used in following analyses were obtained from copies of monthly summary sheets. Secondary effluent and nitrification effluent soluble orthophosphate data for July 1984 through June 1985 were obtained from a report by McNamee, Porter, and Seeley (50). Lime use data was provided by plant operators during a plant visit in March 1987.

Soluble phosphorus is measured as orthophosphate at Piscataway, and is denoted by OSP in this chapter. Also, particulate phosphorus is estimated with TP - OSP, and it is denoted with Non-OSP.

The impact of the phosphate detergent ban will be assessed in terms of orthophosphate loading, not TP loading, since detergent phosphates are usually soluble orthophosphates.

5.4 RAW INFLUENT CONDITIONS

Figure 5-2 shows the influent wastewater flow for January 1980

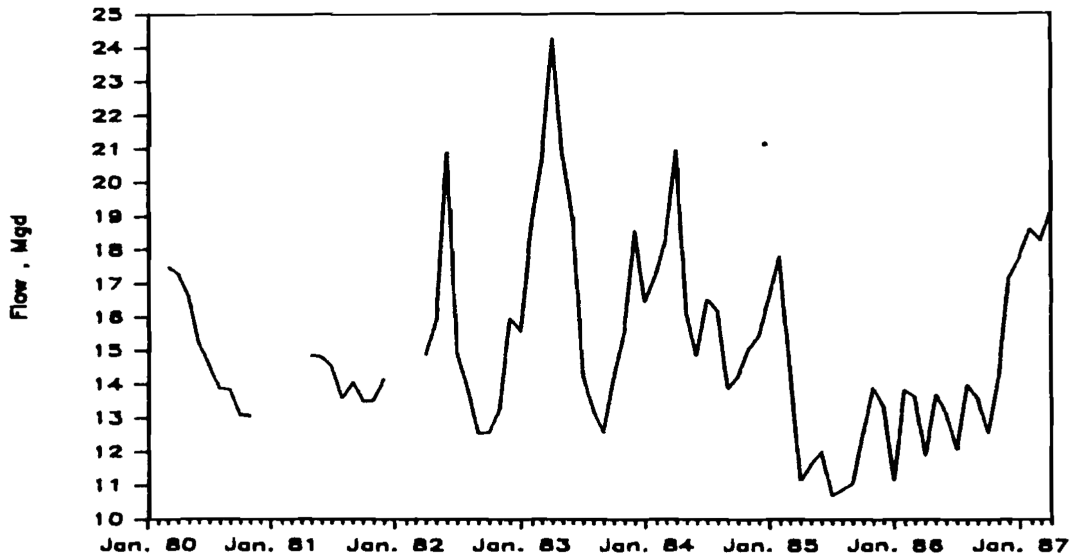


Figure 5-2 Piscataway, Influent Flow vs. Month.

through April 1987. Low flow for the data record occurred in July 1985, and the flow remained low until mid-1986. This low flow period roughly coincides with the first months of the phosphate detergent legislation.

Figures 5-3 through 5-7 show the influent raw wastewater conditions. Figure 5-3d and 5-4d indicate that the wastewater strength decreases with increasing flow. Evidence for a storm water dilution effect is presented in Figure 5-8a, which shows that flow is positively correlated with rainfall.

The dilution effect is not evident in Figure 5-6d, which shows influent SP versus flow data. The time trend in the phosphorus data does not reveal the dilution effect.

Figures 5-3b through 5-5b show that the mass loading of BOD_5 (BOD), total suspended solids (TSS) and total phosphorus (TP) decreased during 1985. Although the data is incomplete, orthophosphate (OSP) mass loading appears to have decreased since 1985 (See Figure 5-6b). The decrease in orthophosphate should be related to the ban, while the decrease in non-orthophosphate loading (Figure 5-7b) should be related to the decrease in suspended solids loading during 1985. Figure 5-8c shows an insignificant correlation between non-orthophosphate and suspended solids loading. If influent soluble phosphorus (not measured) is primarily in the form of orthophosphate, then Non-OSP should provide an estimate of particulate phosphorus. However, if the influent soluble phosphorus contains a large fraction

Figure 5-3 Piscataway, Raw Influent BOD_5 a) Concentration vs. Year, b) Mass Loading vs. Year, c) Concentration vs. Mass Loading, d) Concentration vs. Flow.

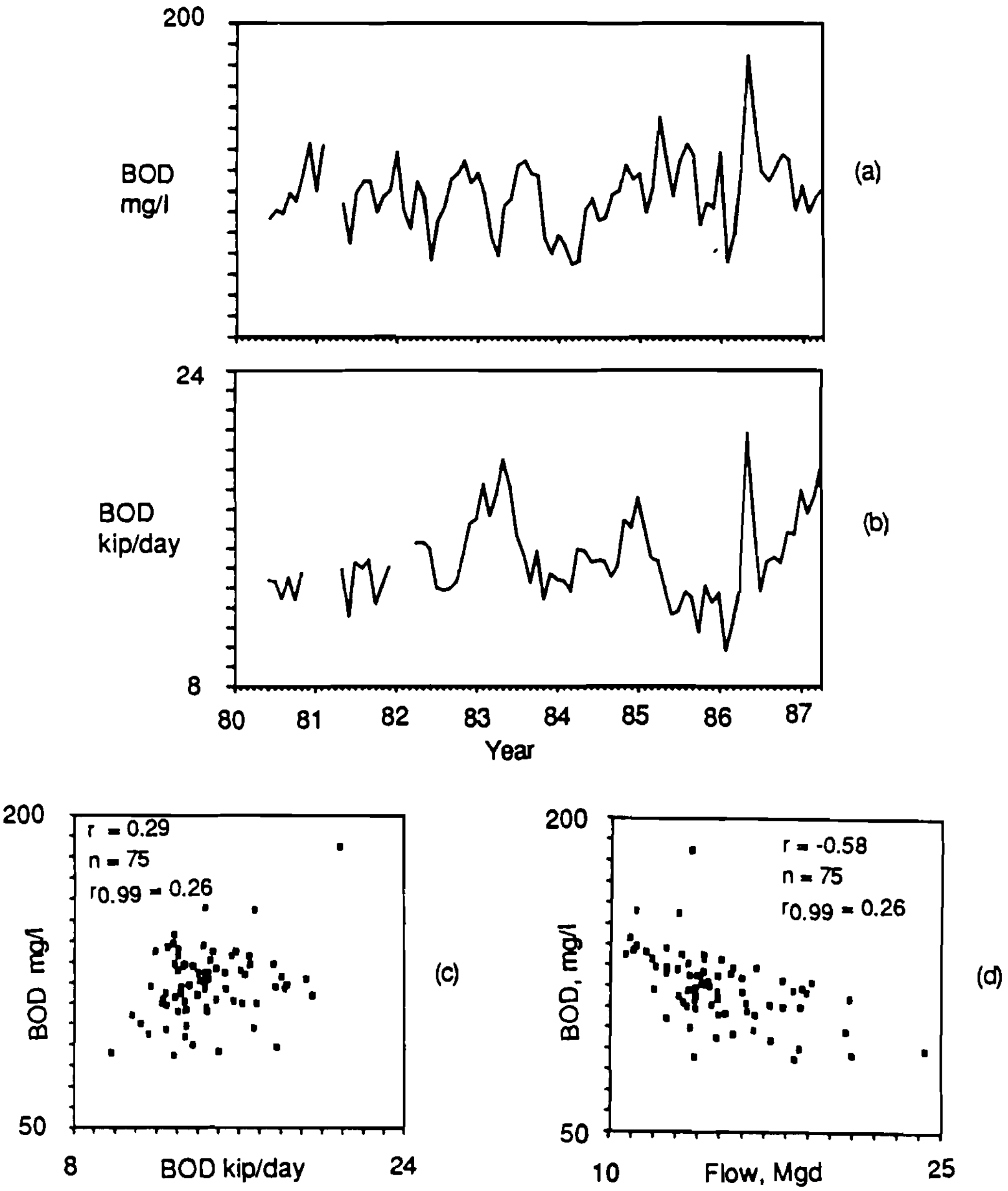


Figure 5-4 Piscataway, Raw Influent TSS, a) Concentration vs. Year, b) Mass Loading vs. Year, c) Concentration vs. Mass Loading, d) Concentration vs. Flow.

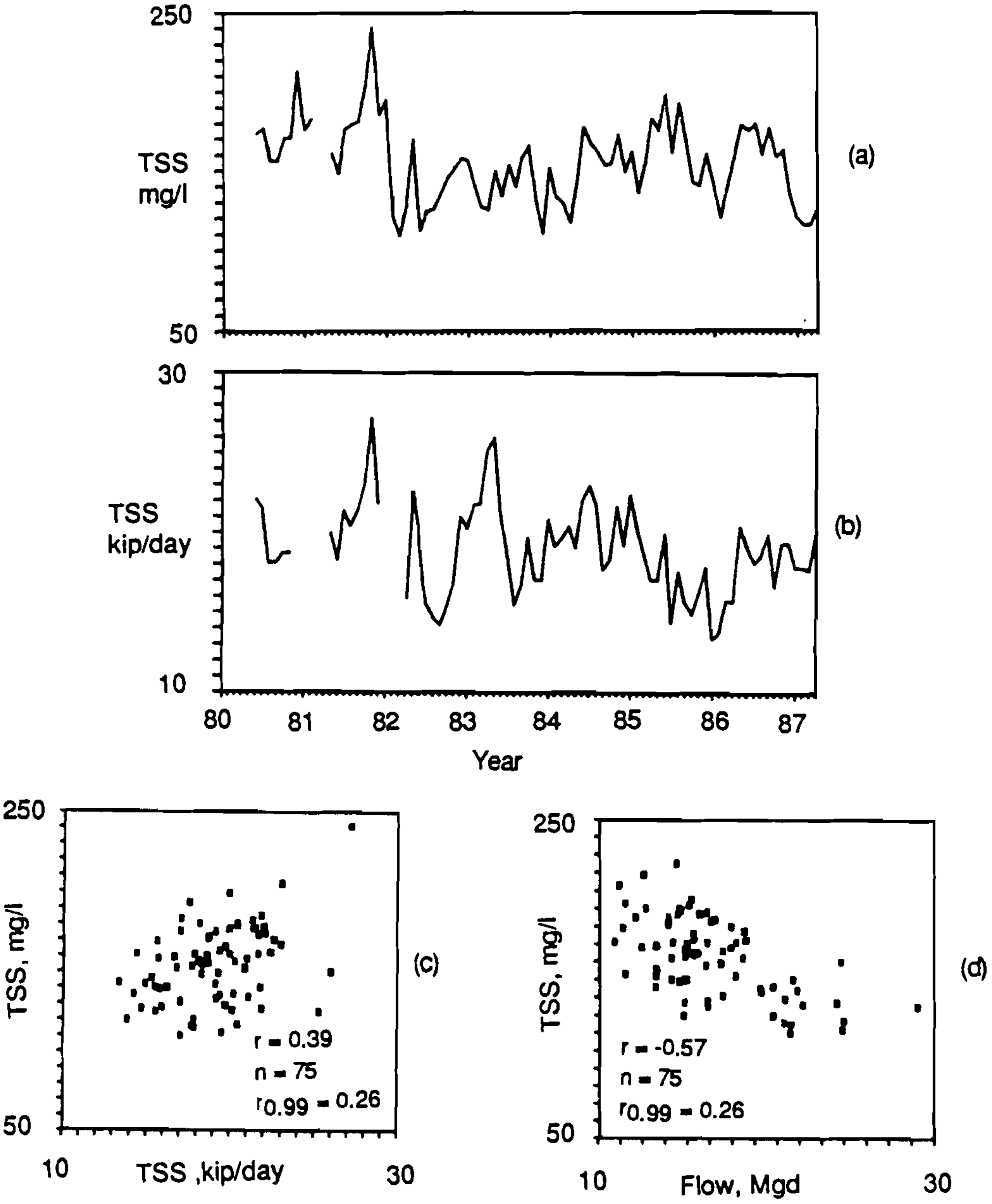


Figure 5-5 Piscataway, Raw Influent TP, a) Concentration vs. Year, b) Mass Loading vs. Year, c) Concentration vs. Mass Loading, d) Concentration vs. Flow.

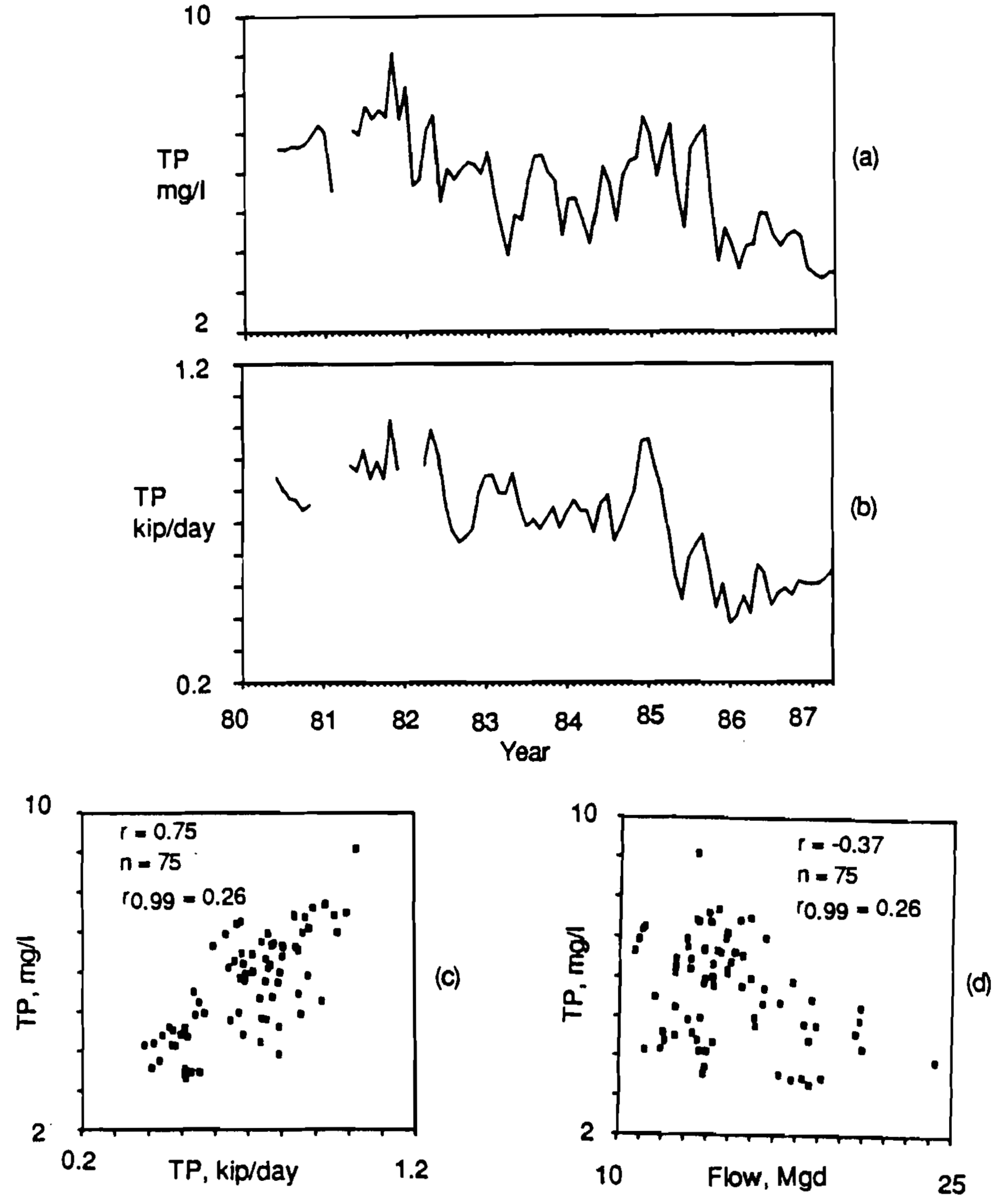


Figure 5-6 Piscataway, Raw Influent Orthophosphate, a) Concentration vs. Year, b) Mass Loading vs. Year, c) Concentration vs. Mass Loading, d) Concentration vs. Flow.

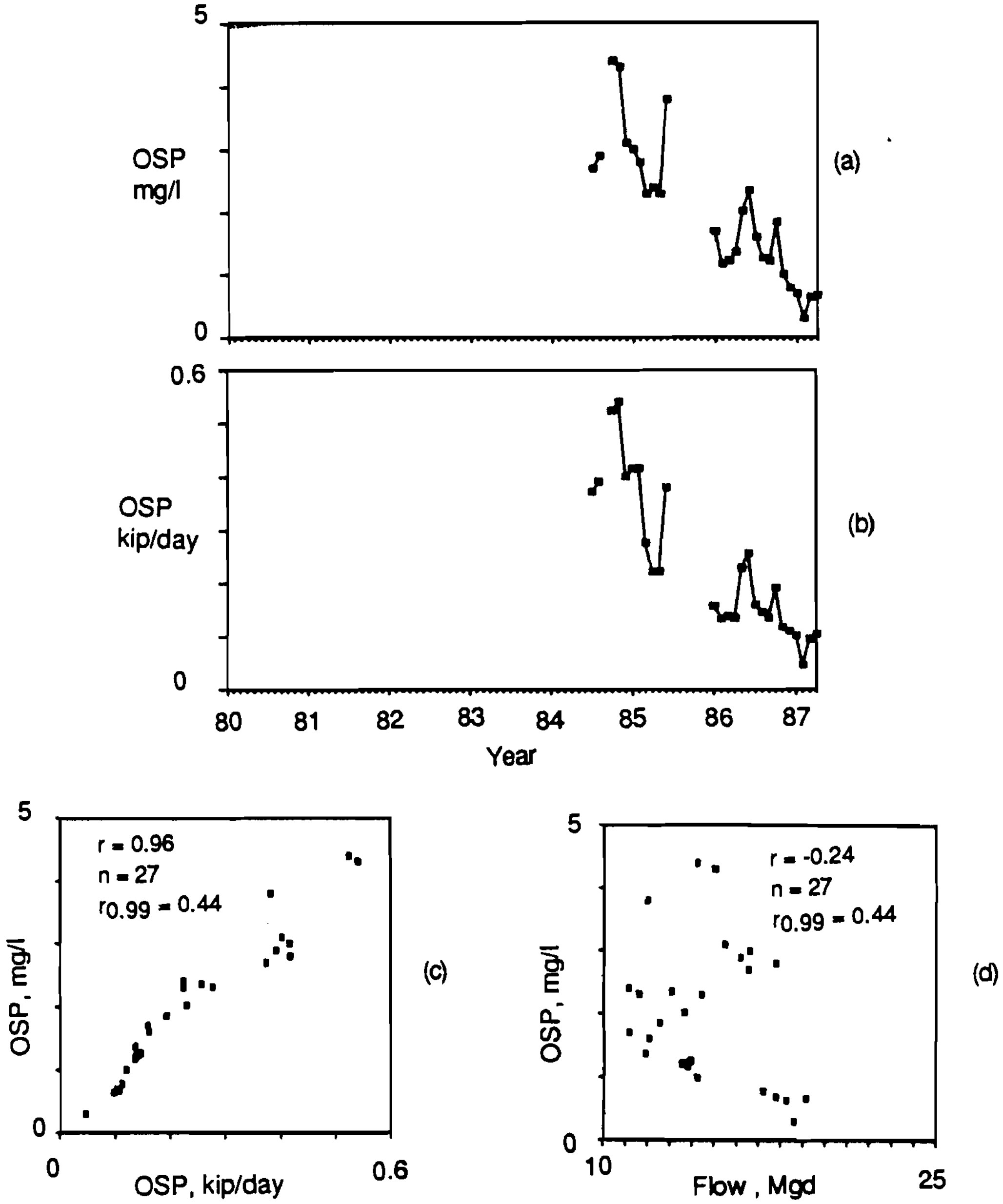


Figure 5-7 Piscataway, Raw Influent Non-Orthophosphate (Non-OSP = TP-OSP), a) Concentration vs. Year, b) Mass Loading vs. Year, c) Concentration vs. Mass Loading, d) Concentration vs. Flow.

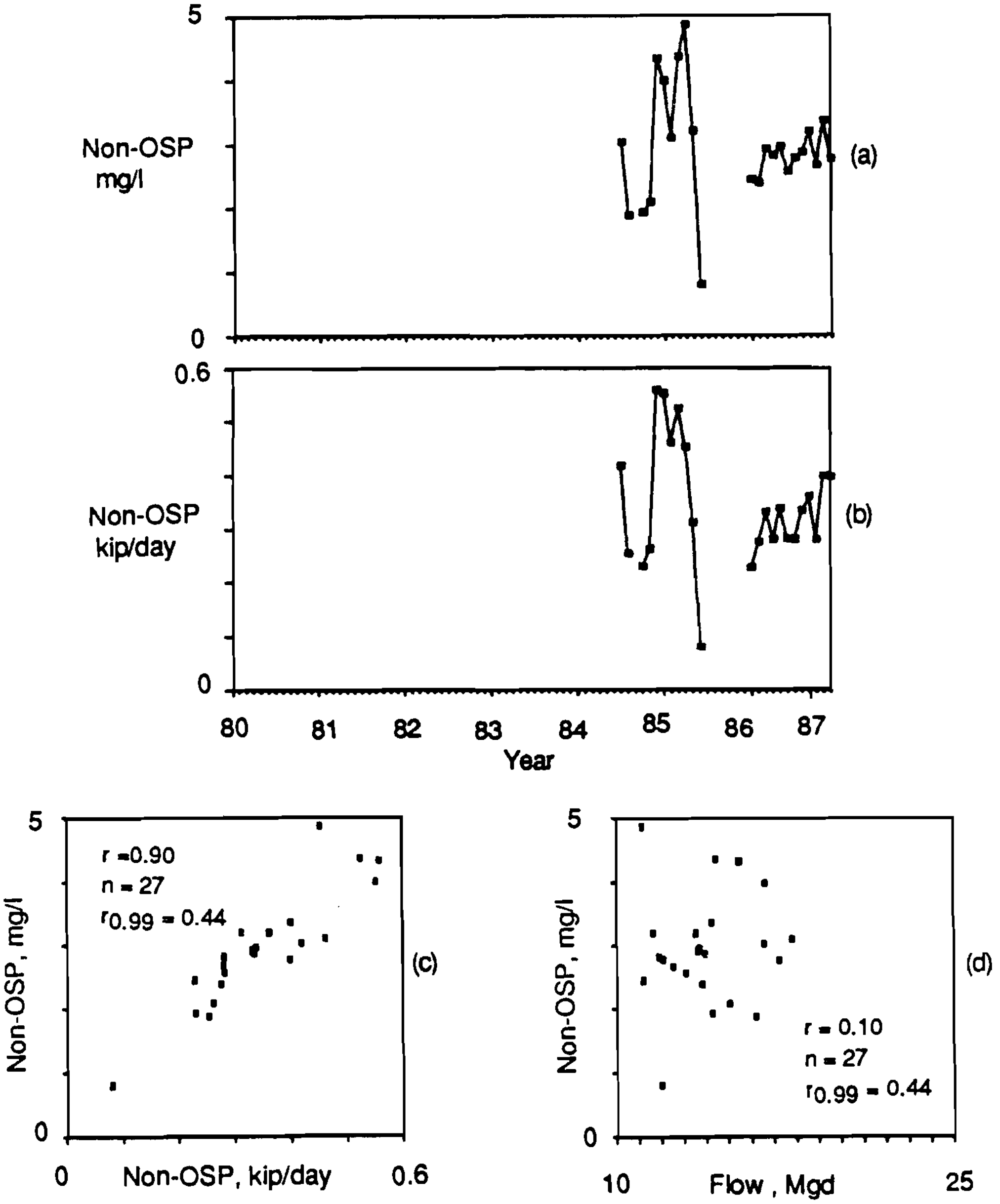
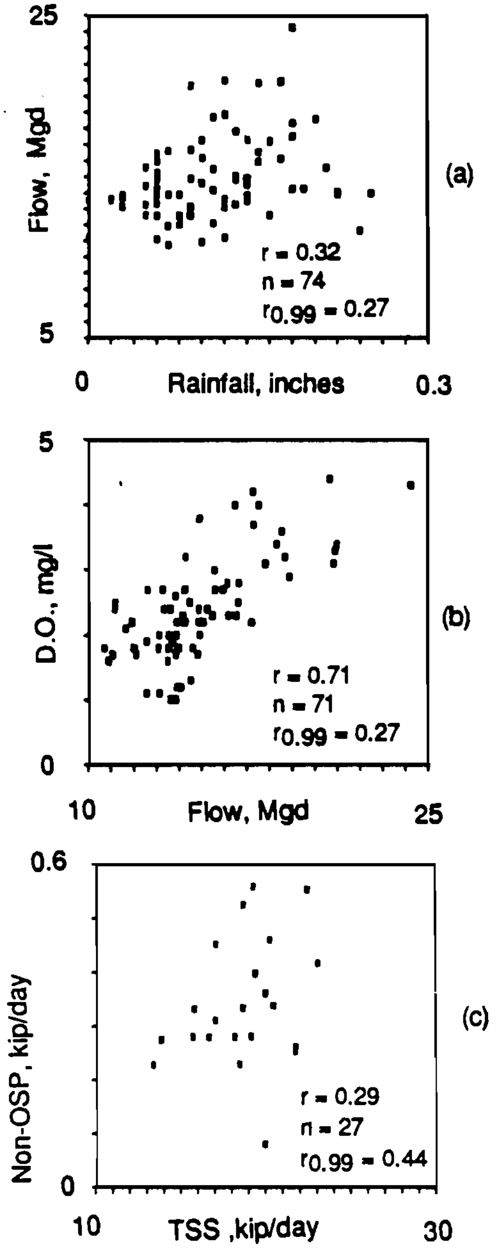


Figure 5-8 Piscataway, a) Influent Flow vs. Rainfall, b) Influent Dissolved Oxygen vs. Flow, c) Non-Orthophosphate (TP-OSP) vs. TSS.



of condensed or organic phosphorus then the estimate of particulate P will be in error. The correlation in Figure 5-8c is influenced by the lowest influent non-orthophosphate value. There is no reason to believe that the point is an outlier. The relationship probably suffers from a lack of non-orthophosphate (TP-OSP) data corresponding to the low solids loading data points in late 1985.

5.5 RECYCLE FLOWS

Figure 5-9 shows raw influent and grit chamber effluent concentrations of BOD, TSS, and TP. Gravity thickener overflow, solids processing recycle, and filter backwash are recycled to the influent pump station, and are not included in the raw wastewater samples. They are reflected in the grit chamber effluent data. These recycle loads are periodic and highly variable.

Lime is used for sludge stabilization and pH control in nitrification, so the return flow might affect pH and alkalinity. Lime use data reflects the total amount received at the plant during a month (28). The amount of this quantity used for sludge conditioning and pH control (nitrification) are not known. The amount of excess lime and ferric iron (from dewatering) in the return flows are also unknown.

Figure 5-10a shows the reported lime use at the plant since October 1982. Prior to July 1981, 30% (volume basis) of the sludge requiring stabilization was processed in the digesters. The remaining

Figure 5-9 Piscataway, Comparison of Raw Influent and Grit Chamber Effluent a) BOD, b) TSS, c) TP.

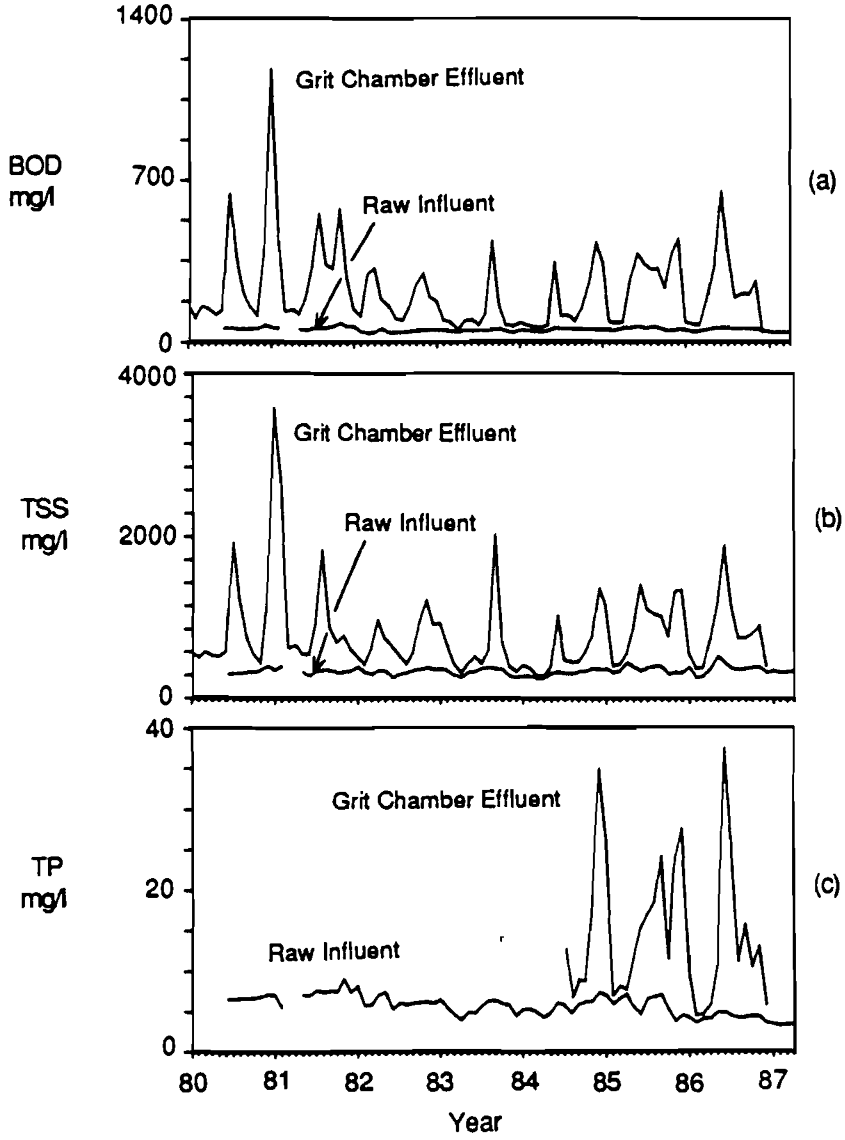
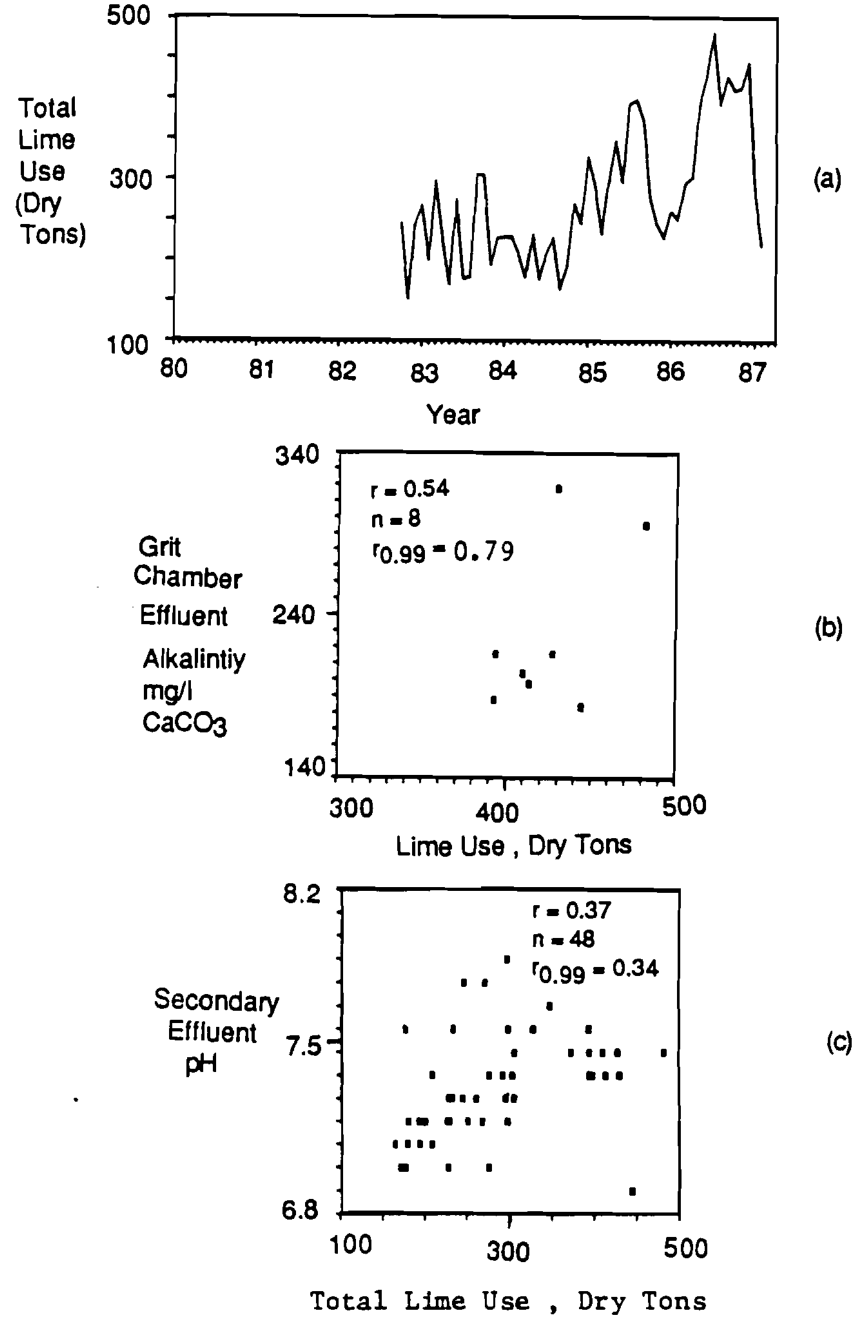


Figure 5-10 Piscataway, a) Reported Plant Lime Use, b) Grit Chamber Effluent Alkalinity vs. Total Lime Use, c) Secondary Effluent pH vs. Total Lime Use.



was stabilized with lime. After July 1981 and until digester operation was discontinued in July 1984, the quantity of sludge to the digesters was 11% (volume basis). Lime use increased as digesters were removed from service.

Figure 5-10b shows the relationship between lime use and grit chamber effluent alkalinity. The reported correlation is not significant at the 99% or 95% ($r_{0.95} = 0.62$) confidence levels.

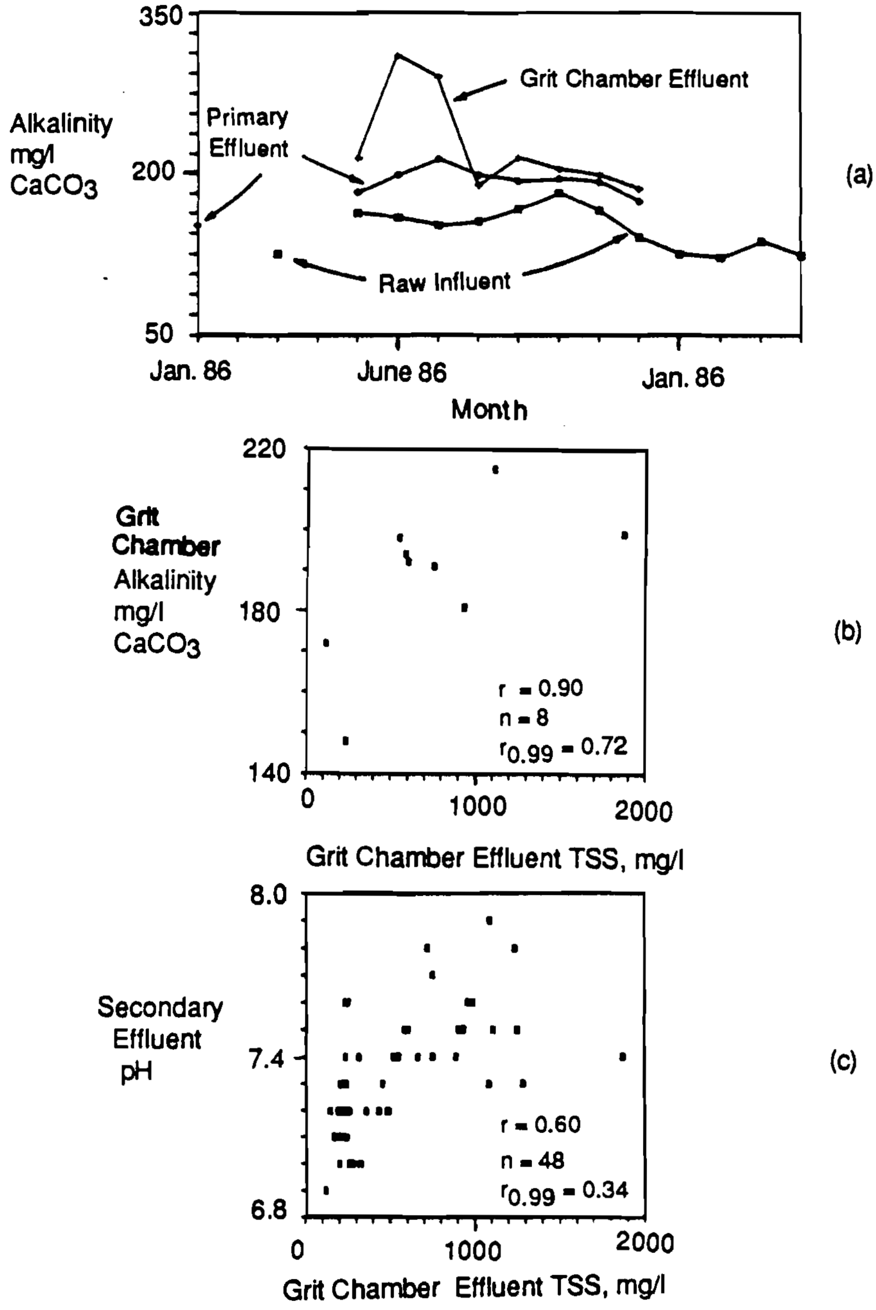
Wastewater pH is only measured in the raw influent and secondary, nitrification, and final effluents. The impact of lime use on wastewater pH is shown in Figure 5-10c, which shows a significant correlation between secondary effluent pH and total lime use.

Figure 5-11a shows the relationship between alkalinity measurements in the raw influent, grit chamber effluent, and primary effluent. Measurements at these three locations are usually taken once a month. The average raw influent for the time period on the Figure is 143 mg/l and the average primary effluent (secondary influent) is 188 mg/l.

Figure 5-11b shows the relationship between grit chamber effluent alkalinity (only measured since January 1986) and grit chamber effluent total suspended solids. If increasing grit chamber effluent TSS is related to solids processing with lime, then an increase in alkalinity below the grit chamber is expected.

Figure 5-11c shows a significant correlation between secondary effluent pH and grit chamber effluent TSS (the linear correlation

Figure 5-11 Piscataway, a) Raw, Grit Effluent, and Primary Effluent Alkalinity vs. Month, b) Grit Chamber Effluent Alkalinity vs. Grit Chamber Effluent TSS, c) Secondary Effluent pH vs. Grit Chamber Effluent TSS.



coefficient for pH on $\log_{10}$ TSS is slightly better , $r = 0.67$).

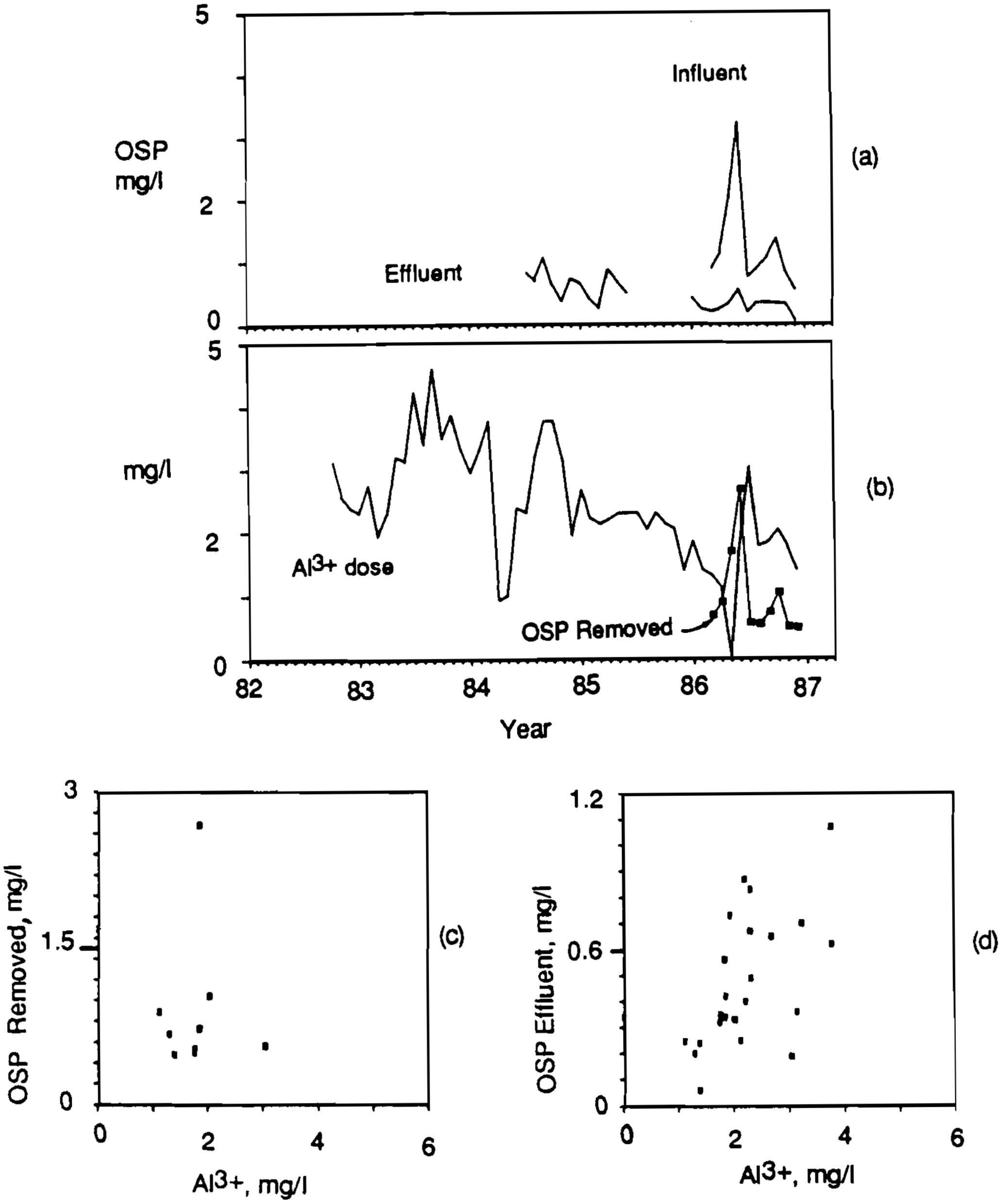
The recycle from solids processing appears to be important with respect to phosphorus precipitation. Lime in the recycle has elevated the wastewater pH and alkalinity, both of which can be detrimental to alum phosphate precipitation. Elevated alkalinity increases the amount of chemical required for adjusting pH toward the optimal precipitation value. The optimum pH for total phosphorus removal with alum was shown by Hais et al. (1973) to be in the range of 6.3 to 6.6. The experiments of Hais were conducted in a pilot scale step feed aeration system. Step feed aeration is used at Piscataway. Diamadopoulos et al. (1984) reported that there is a region around pH = 8 where neither calcium nor aluminum are very efficient at removing phosphorus in activated sludge, and that phosphate precipitation by calcium, naturally present in the wastewater, does not proceed readily until the pH approaches 10. Balmer et al. (1974) reported that lime precipitation of phosphorus in pre-settled domestic wastewater occurred more favorably at pH values above 11.2.

Several researchers have noted that biological uptake of phosphorus proceeds more readily as pH increases between 5.5 and 8.5 (65).

5.6 SECONDARY PHOSPHORUS REMOVAL

Figure 5-12 shows available orthophosphate removal data and the alum (Al^{3+}) dosing data. The relationship between orthophosphate

Figure 5-12 Piscataway Secondary, a) Influent and Effluent Orthophosphate vs. Year, b) Orthophosphate Removed and Al^{3+} vs. Year, c) Orthophosphate Removed vs. Al^{3+} Dose, d) Effluent Orthophosphate vs. Al^{3+} Dose.



removal and alum dose is not clear in Figure 5-12c. Orthophosphate removal is studied in more detail in Chapter Seven.

Figure 5-12d indicates that effluent orthophosphate concentrations are positively correlated with alum dose. This trend may be explained by a time effect. The data in Figure 5-12a,b show that both effluent orthophosphate and alum dose were decreasing between July 1984 and December 1986.

Figure 5-13 shows the Al/P_C molar ratio vs. effluent orthophosphate concentration. All data are from 1986, after the phosphate detergent ban legislation.

5.6.1 Alkalinity and pH

Figure 5-14c shows that alkalinity removal is not significantly correlated with alum dose. Also, there is no obvious relationship between the effluent alkalinity and alum dose (Figure 5-14c). This may be caused by the highly variable influent alkalinity values, a result of the lime recycle.

Figures 5-15c and 5-15d show no linear relationships for pH change and effluent pH vs. alum dose. The pH in the raw influent is lower than the secondary effluent. This signifies that the acidic action of alum is being partially offset by the lime recycle to the grit chambers.

Figure 5-16a is a plot of effluent orthophosphate (log scale and mol/l concentration) vs. pH effluent. The observed pH range is too

Figure 5-13 Piscataway Secondary, a) Al/P_C Mole Ratio vs. Effluent Orthophosphate, b) Al/P_C Mole Ratio vs. Year, for P_C = OSPI-OSPO.

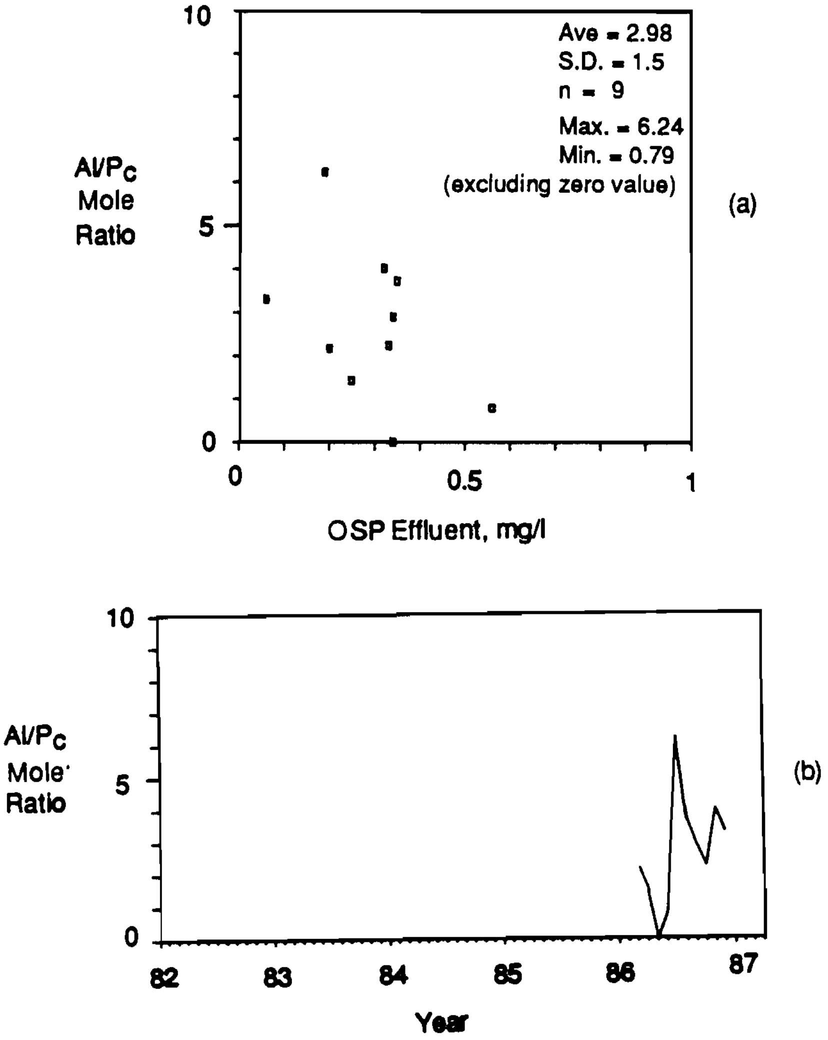


Figure 5-14 Piscataway Secondary, a) Influent and Effluent Alkalinity vs. Year, b) Alkalinity Removed and Al^{3+} vs. Year, c) Alkalinity Removed vs. Al^{3+} Dose, d) Effluent Alkalinity vs. Al^{3+} Dose.

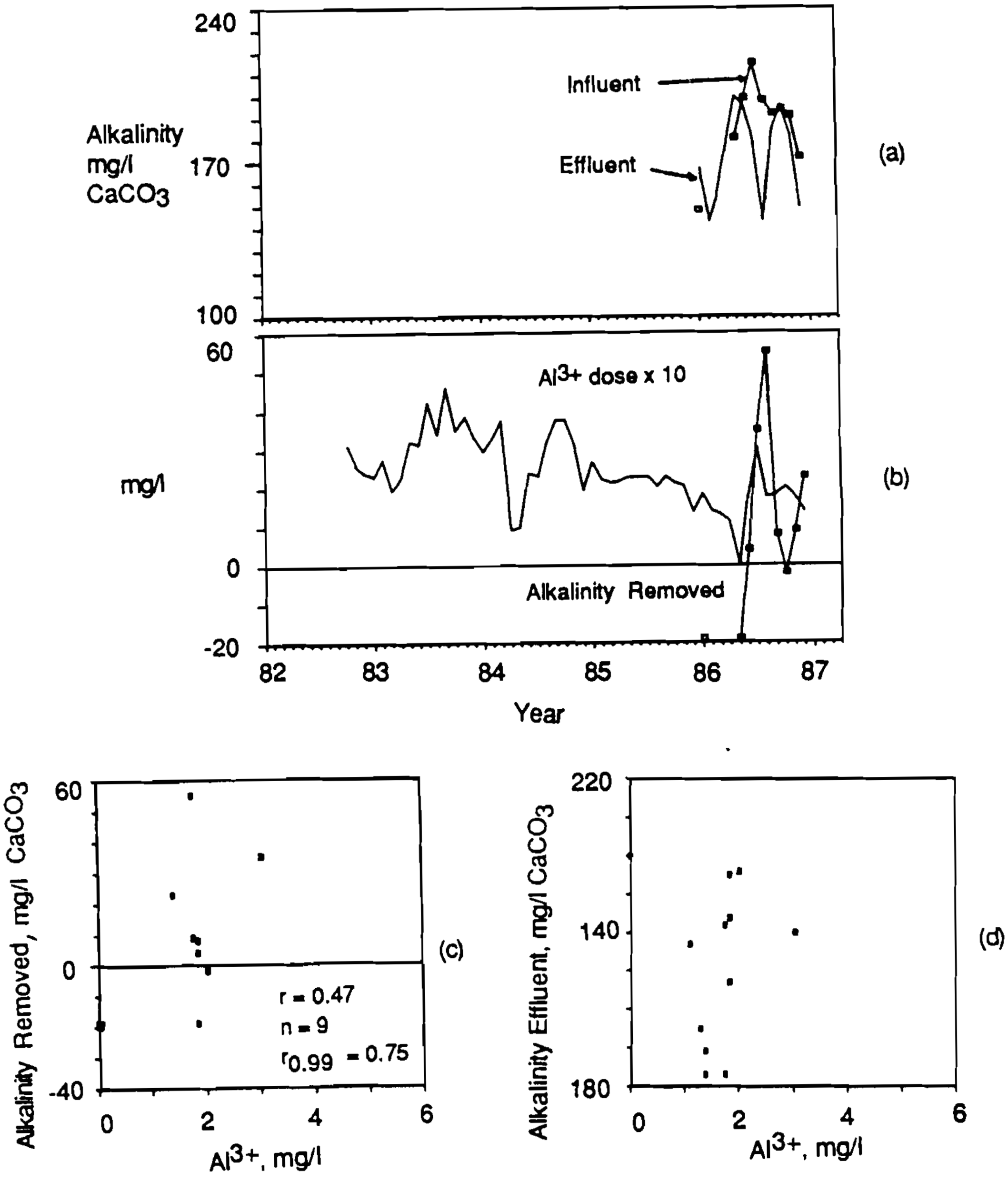


Figure 5-15 Piscataway Secondary, a) Raw Influent and Secondary Effluent pH vs. Year, b) pH Removed and Al^{3+} vs. Year, c) pH Removed vs. Al^{3+} Dose, d) pH vs. Al^{3+} Dose.

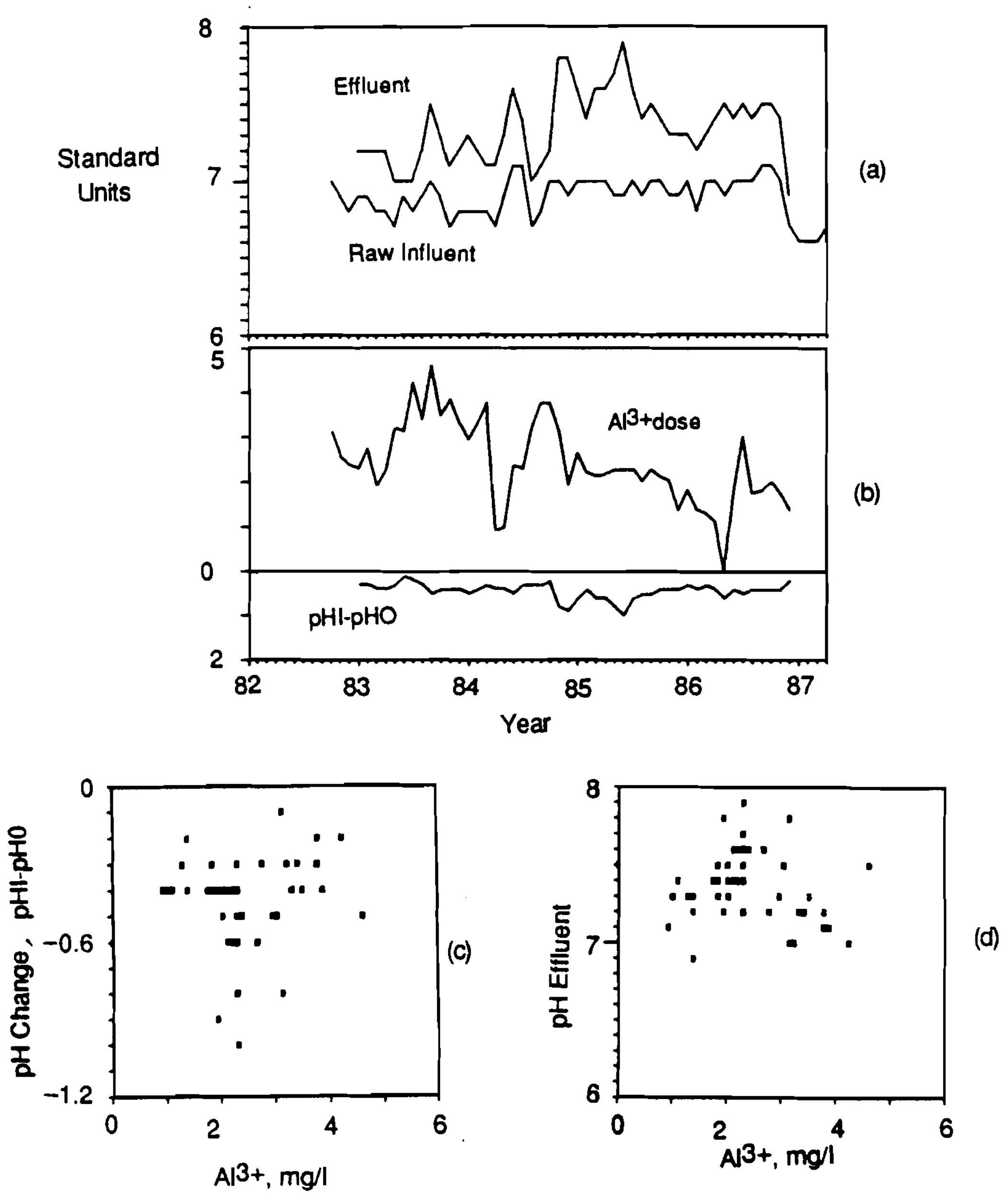
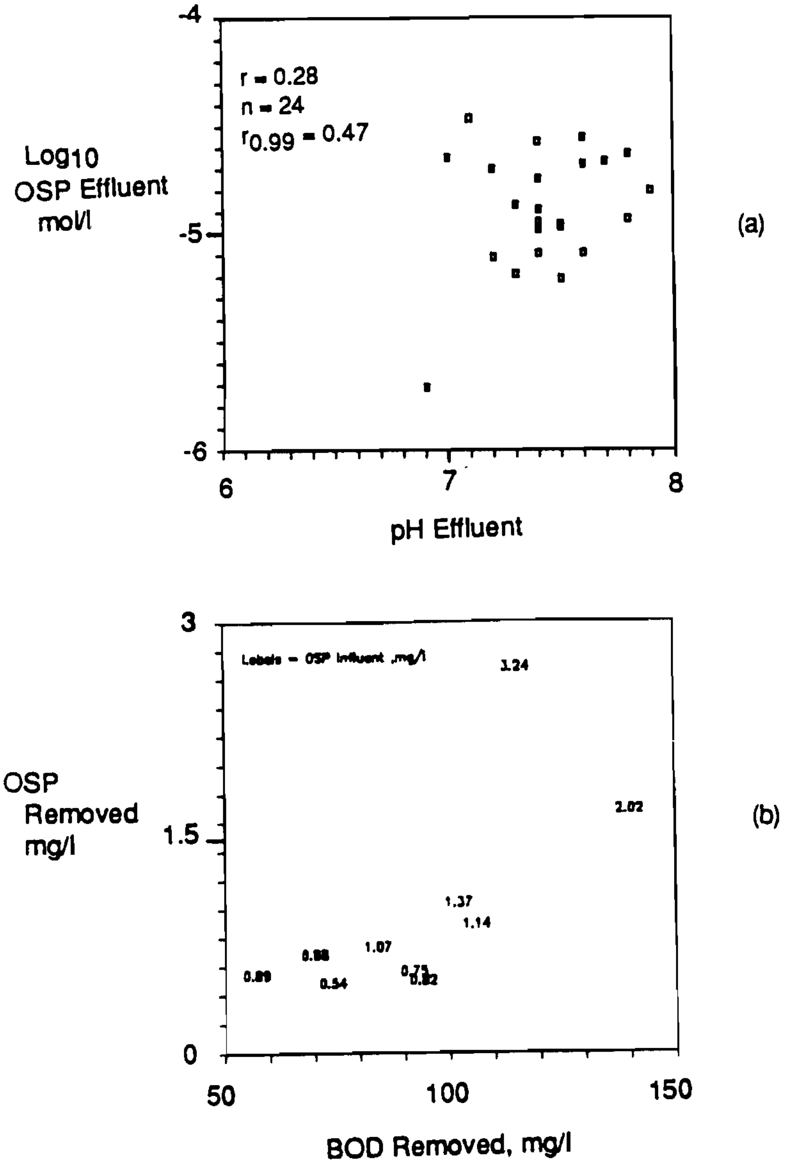


Figure 5-16 Piscataway Secondary, a) Log_{10} (Effluent Orthophosphate, mol/l) vs. Effluent pH, b) Orthophosphate Removal (OSPI-OSPO) vs. BOD Removal.



small, given the variability in OSP concentration, to reveal any solubility limit relationship.

5.6.2 Biological Removal

Figure 5-16b indicates that orthophosphate removal is caused by biological uptake. However, the OSP removal relationship is distorted by the trend of increasing secondary influent OSP values, which are identified with data labels.

5.6.3 BOD, TSS, and TP

Figures 5-17 through 5-19 show that there are no strong linear relationships between alum dose and BOD removal, TSS removal, effluent BOD, effluent TSS, and effluent TP. Figure 5-19c shows a weak correlation between TP removal and alum dose ($r = 0.39$, $n = 34$, $r_{0.99} = 0.40$).

5.7 TERTIARY PHOSPHORUS REMOVAL

Figure 5-20 shows the orthophosphate and alum dose data for the tertiary nitrification process. From July through October 1984 and April through June 1985 the effluent pump station at Piscataway was out of service. During these months the final effluent was routed through a polishing pond before discharge. Plant operators were concerned that the pond storage was contributing phosphorus to the treated wastewater, and that the discharge permit of 0.18 mg/l on TP

Figure 5-17 Piscataway Secondary, a) Influent and Effluent BOD vs. Year, b) BOD Removed and Al^{3+} vs. Year, c) BOD Removed vs. Al^{3+} Dose, d) Effluent BOD vs. Al^{3+} Dose.

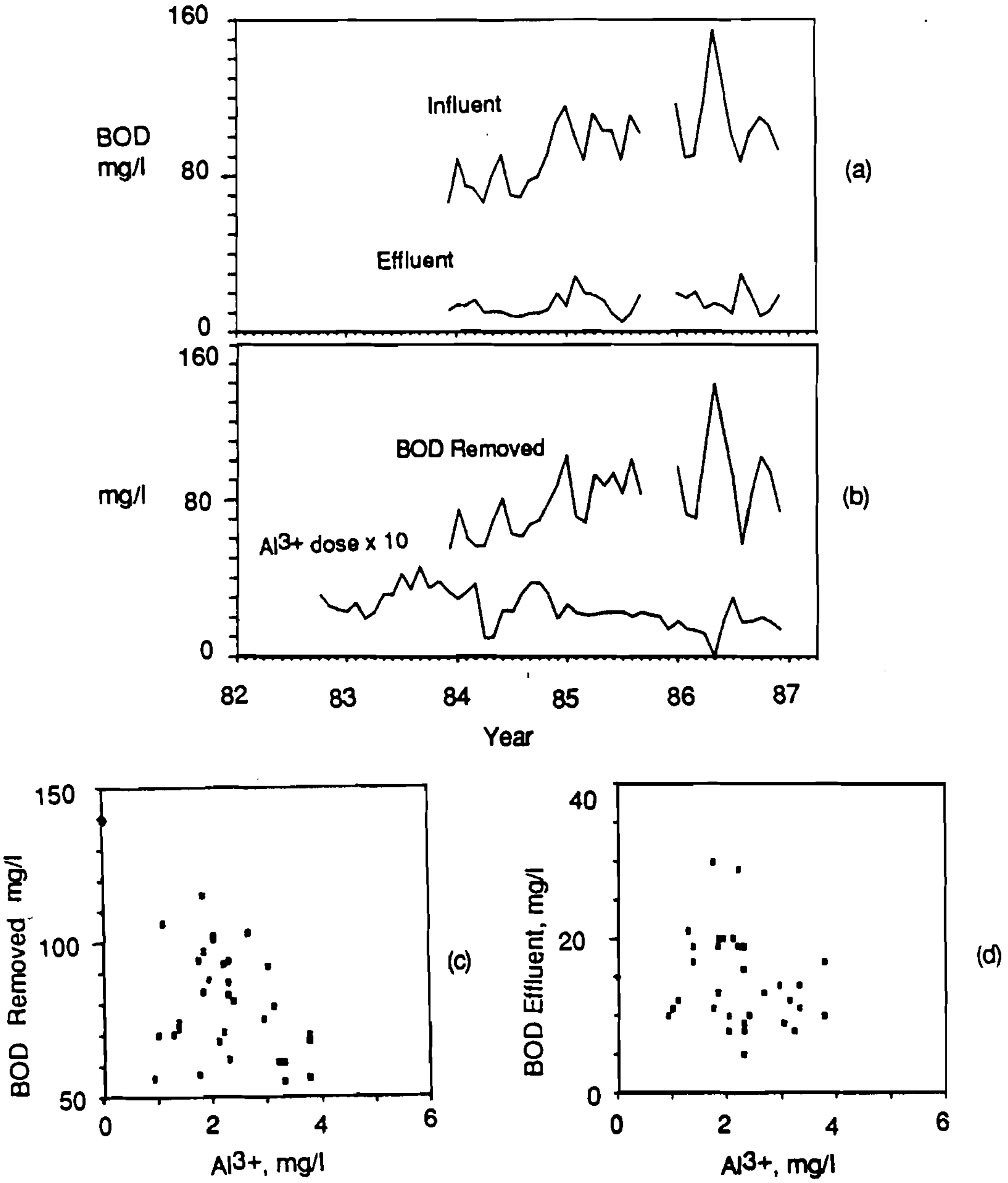


Figure 5-18 Piscataway Secondary, a) Influent and Effluent TSS vs. Year, b) TSS Removed and Al^{3+} vs. Year, c) TSS Removed vs. Al^{3+} Dose, d) Effluent TSS vs. Al^{3+} Dose.

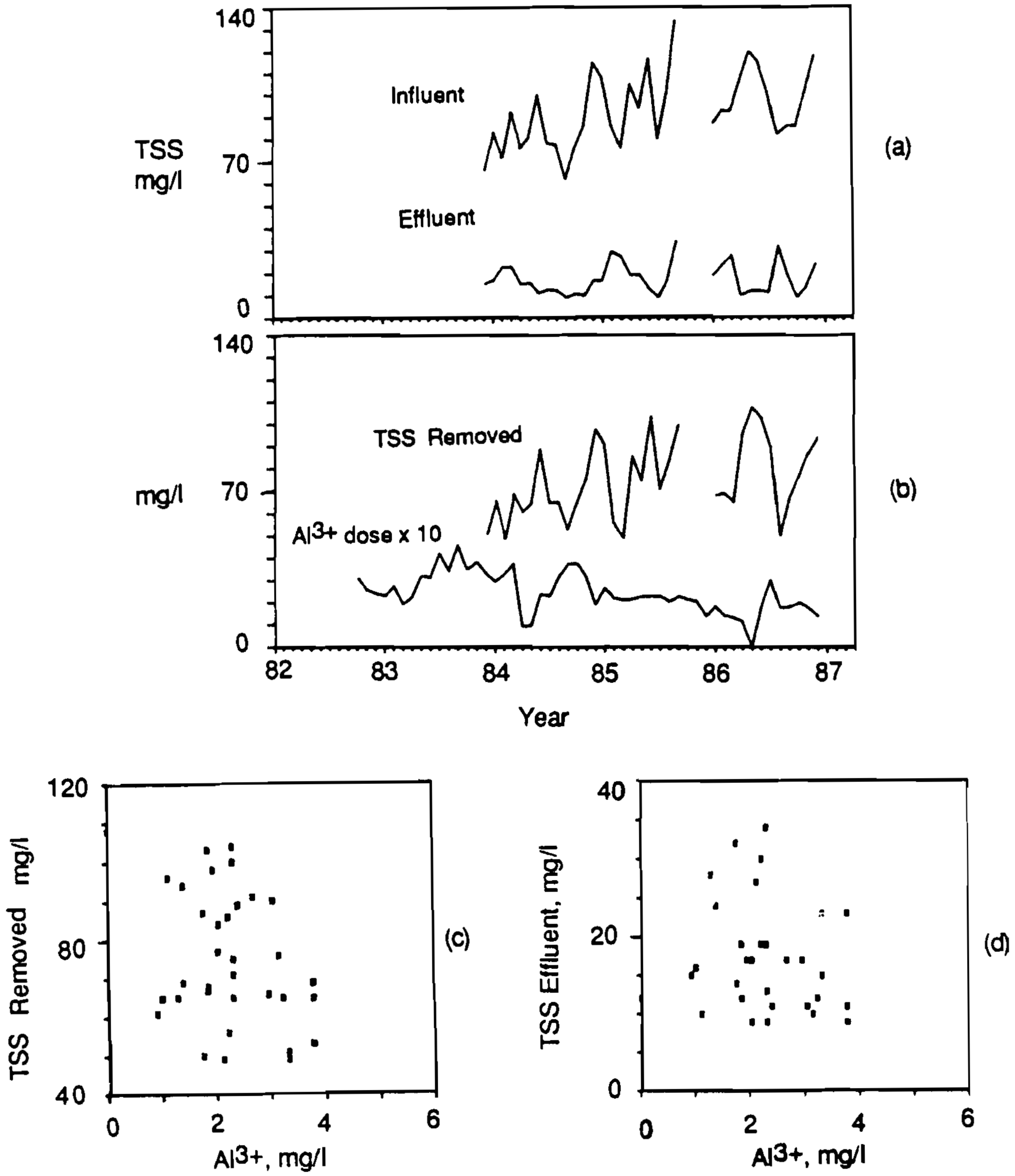


Figure 5-19 Piscataway Secondary, a) Influent and Effluent Total Phosphorus vs. Year, b) TP Removed and Al^{3+} vs. Year c) TP Removed vs. Al^{3+} Dose, d) Effluent TP vs. Al^{3+} Dose.

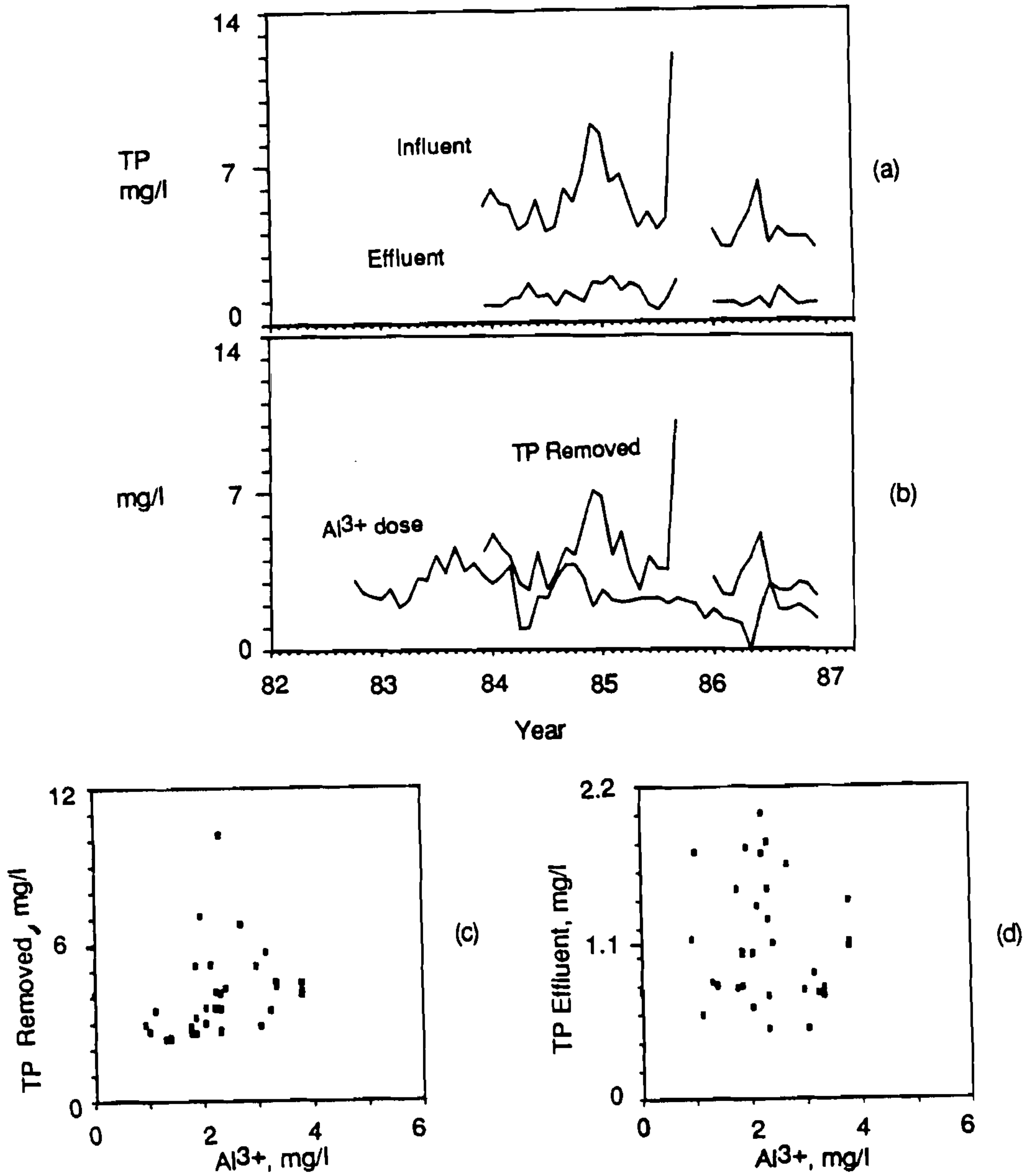
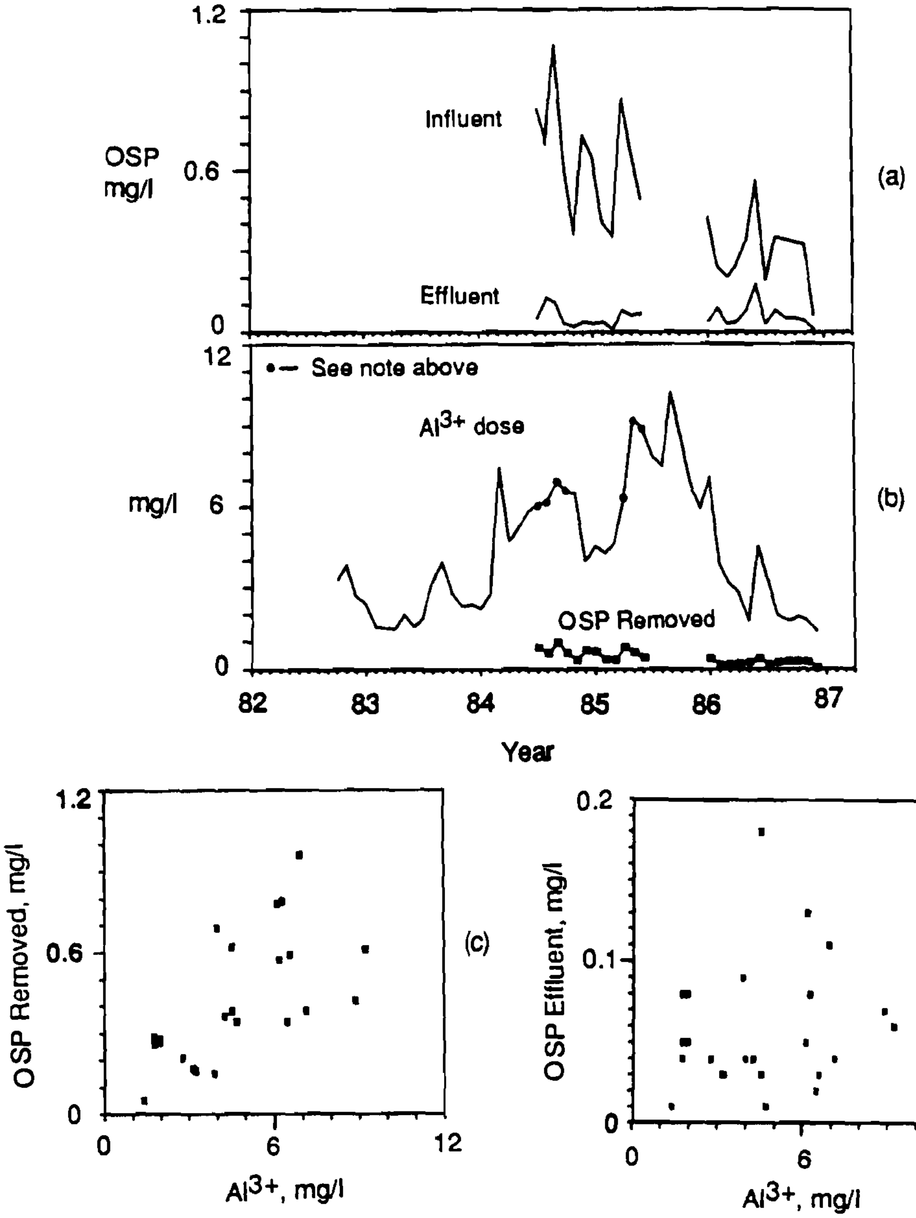


Figure 5-20 Piscataway Nitrification, a) Influent and Effluent Orthophosphate vs. Year, b) Orthophosphate Removed and Al^{3+} vs. Year, c) Orthophosphate Removed vs. Al^{3+} Dose, d) Effluent Orthophosphate vs. Al^{3+} Dose. Note: Dots represent operator controlled alum overdoses. See discussion in text.



could not be met. As a precaution they used extraordinarily high alum doses, trying to attain a tertiary effluent TP target value of 0.05 mg/l. The normal target value is 0.15 mg/l TP (30). Figure 5-20d shows that effluent OSP rarely exceeded 0.1 mg/l. The months with high alum doses in Figure 5-20b are identified by solid dots.

Figure 5-20c shows a linear relationship between orthophosphate removed and alum dose. This relationship is distorted by the lack of OSP data for several months of high alum use. It may also be distorted by the downward trending alum dose and influent OSP concentration. The effluent concentrations are roughly constant (Ave. = 0.058, S.D. = 0.04, n = 24) and small relative to the influent concentrations. The amount of OSP removed is essentially the amount entering the process.

The OSP removal - alum relationship can be interpreted using Figure 5-21a, which shows the Al/P_C mole ratio vs. effluent orthophosphate, with the same X-axis scaling as Figure 5-13. The average Al/P_C mole ratio of 14.7 (S.D. = 7.4, n = 24) is considerably greater than the stoichiometric ratio of approximately 1.5 The precipitation is non-stoichiometric.

5.7.1 Alkalinity and pH

Figure 5-22 shows the data for alkalinity and alum. The destruction of alkalinity by nitrification is probably greater than the destruction caused by alum addition. Lime is added to the

Figure 5-21 Piscataway Nitrification, a) Al/P_C Mole Ratio vs. Effluent Orthophosphate, b) Al/P_C Mole Ratio vs. Year, for P_C = OSPI-OSPO.

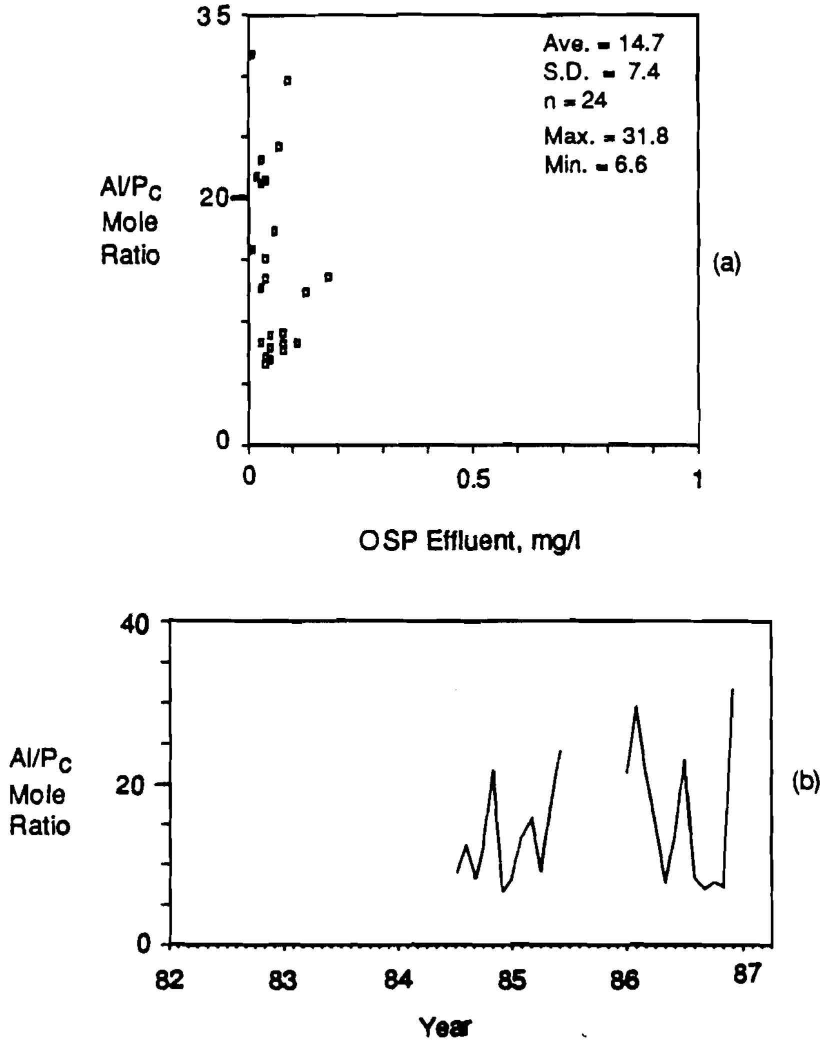
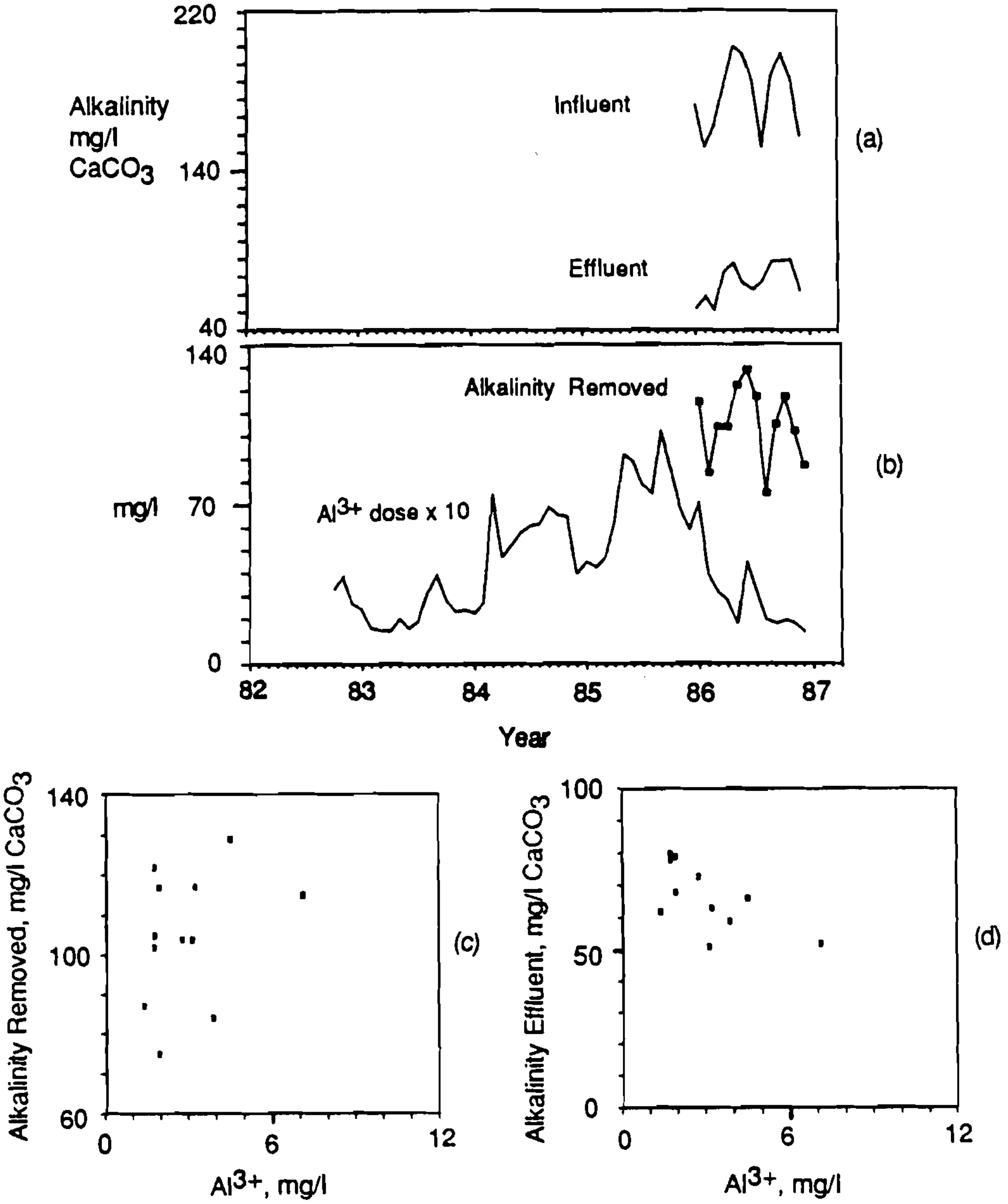


Figure 5-22 Piscataway Nitrification, a) Influent and Effluent Alkalinity vs. Year, b) Alkalinity Removed and Al^{3+} vs. Year, c) Alkalinity Removed vs. Al^{3+} Dose, d) Effluent Alkalinity vs. Al^{3+} Dose.



nitrification reactors in variable amounts to maintain adequate alkalinity.

The factors mentioned above are also relevant to changes in pH and effluent pH (Figures 5-23c and 5-23d).

Figure 5-24 shows that the underlying theoretical relationship between effluent orthophosphate (log scale) and effluent pH, is not revealed because both pH and OSP are essentially fixed values.

5.7.2 BOD, TSS, and TP

Figure 5-25d indicates that nitrification effluent BOD is reduced at higher alum doses. One would expect to see a similar pattern for effluent TSS, and it is weakly evident in Figure 5-26d. There is also a weak correlation between effluent TP and alum dose (Figure 5-27d), because effluent OSP is small (ave. = 0.058 mg/l) and particulate phosphorus is associated with suspended solids.

Figure 5-23 Piscataway Nitrification, a) Influent and Effluent pH vs. Year, b) pH Removed and Al^{3+} vs. Year, c) pH Removed vs. Al^{3+} Dose, d) pH vs. Al^{3+} Dose.

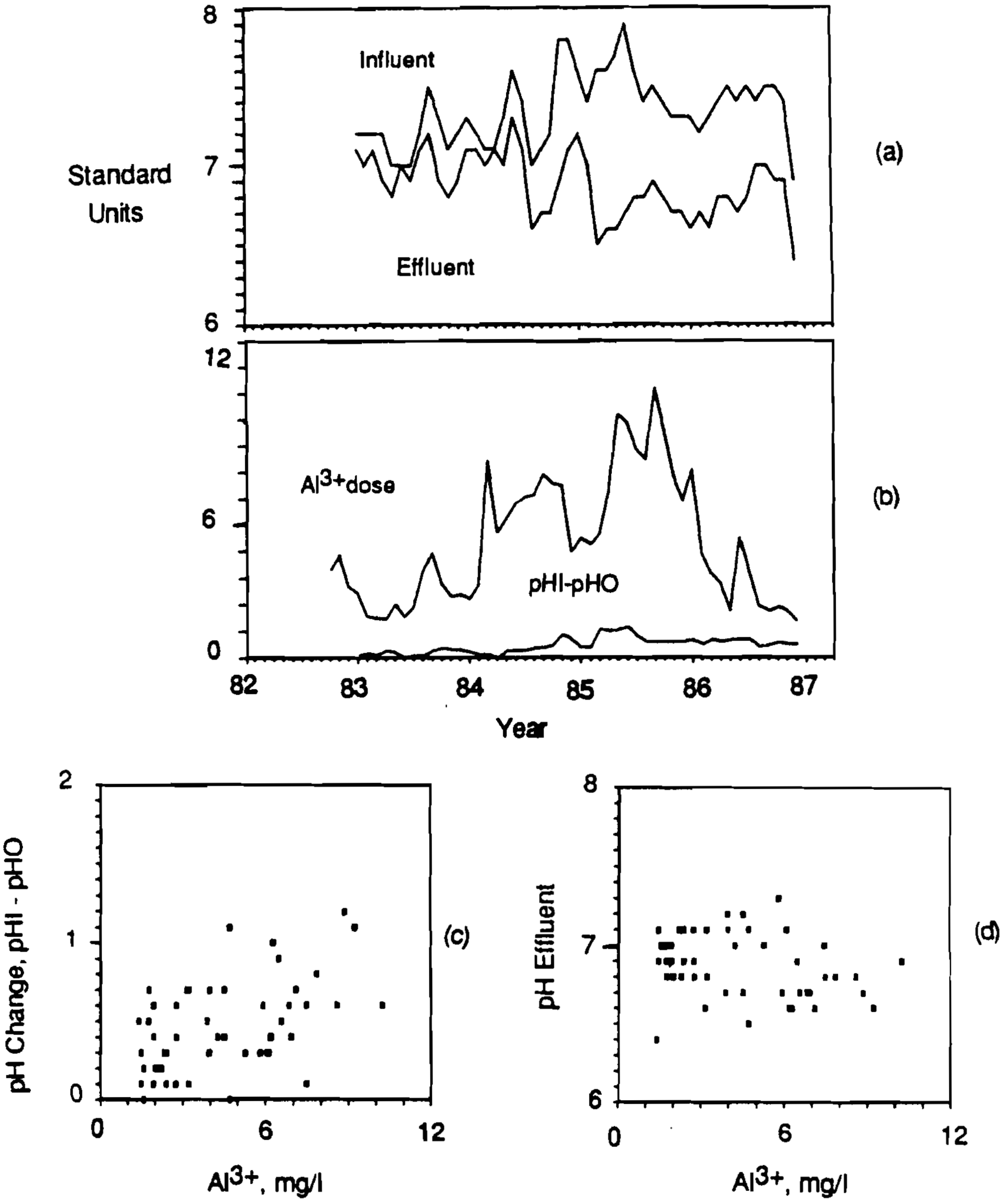


Figure 5-24 Piscataway Nitrification, a) Log_{10} (Effluent Orthophosphate, mol/l) vs. Effluent pH, b) Orthophosphate Removal vs. BOD Removal.

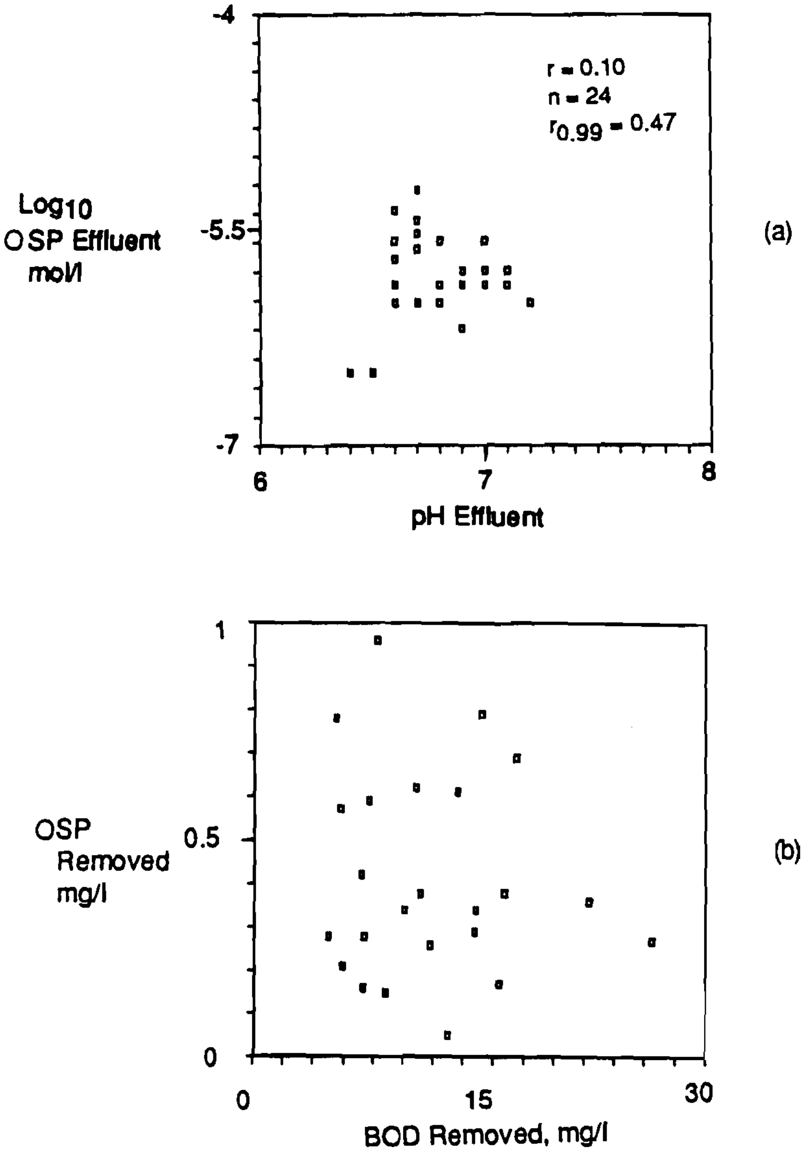


Figure 5-25 Piscataway Nitrification, a) Influent and Effluent BOD vs. Year, b) BOD Removed and Al^{3+} vs. Year, c) BOD Removed vs. Al^{3+} Dose, d) Effluent BOD vs. Al^{3+} Dose.

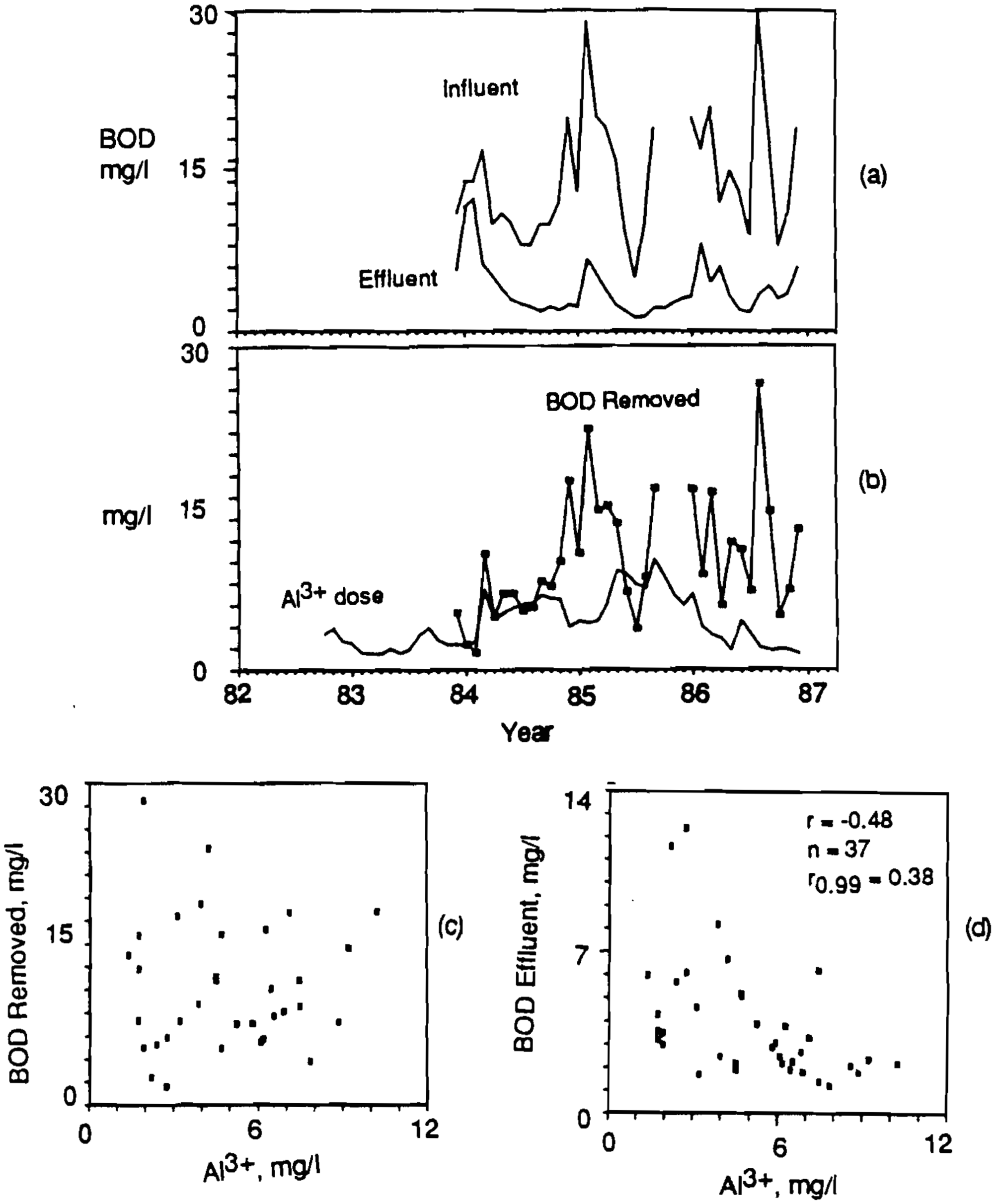


Figure 5-26 Piscataway Nitrification, a) Influent and Effluent TSS vs. Year, b) TSS Removed and Al^{3+} vs. Year, c) TSS Removed vs. Al^{3+} Dose, d) Effluent TSS vs. Al^{3+} Dose.

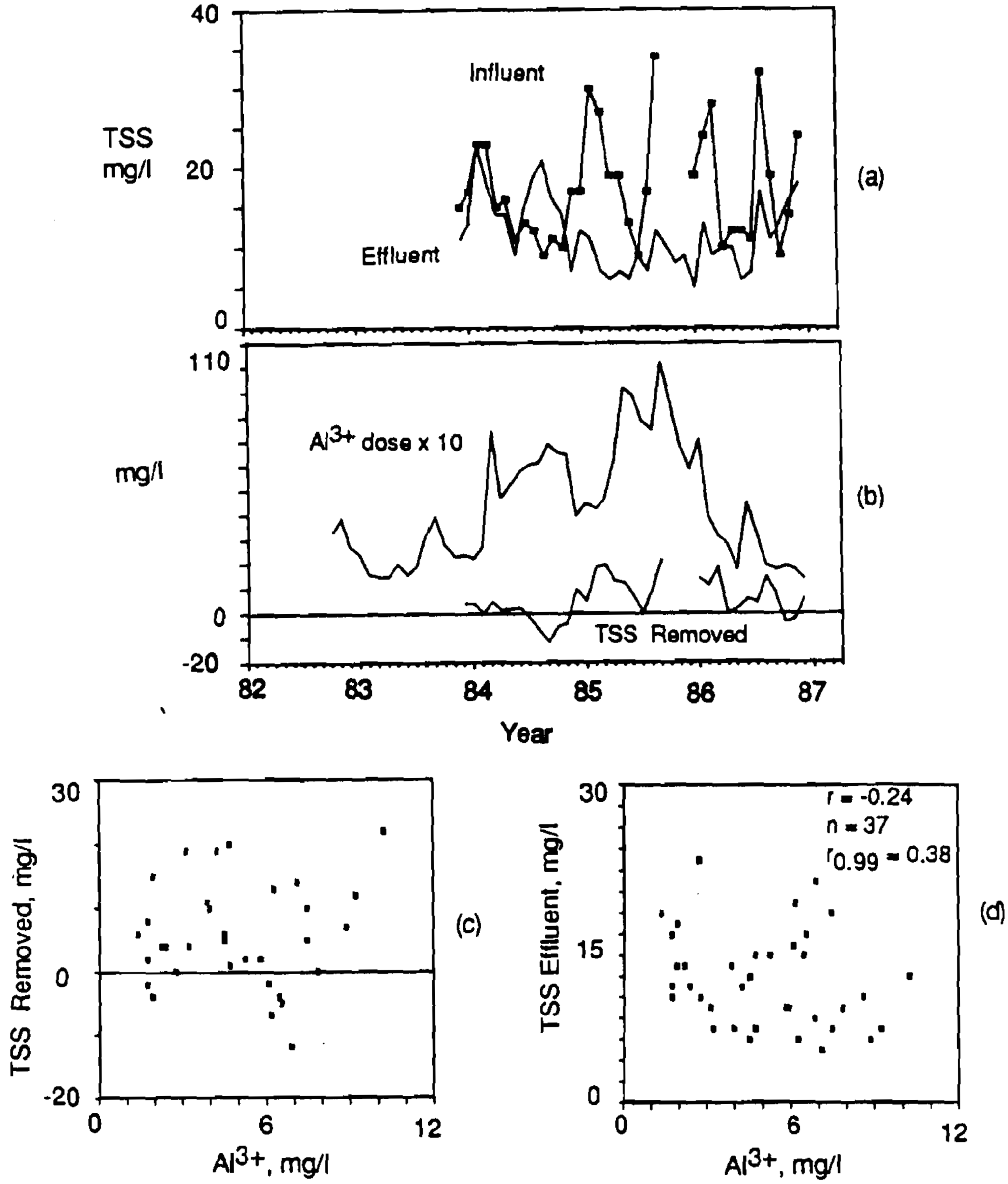
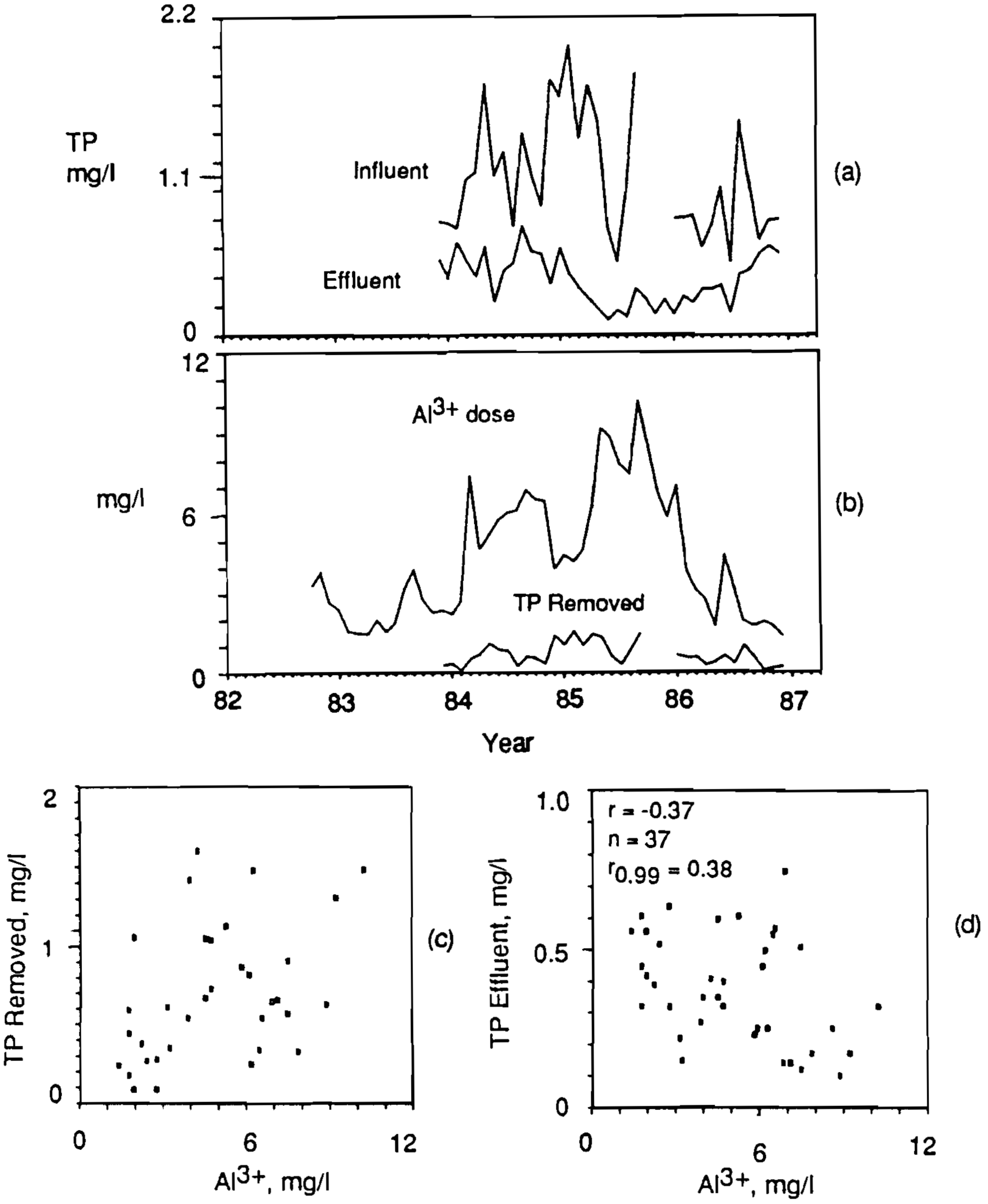


Figure 5-27 Piscataway Nitrification, a) Influent and Effluent Total Phosphorus vs. Year, b) TP Removed and Al^{3+} vs. Year, c) TP Removed vs. Al^{3+} Dose, d) Effluent TP vs. Al^{3+} Dose.



CHAPTER SIX: PISCATAWAY REGRESSION ANALYSIS

6.1 STATISTICAL ANALYSIS

6.1.1 Secondary Treatment Process

The phosphorus removal data for the secondary process consists of only 12 observations, from 1986, after the detergent ban legislation was implemented in Maryland. This is a very small data base and regression analysis provided no useful predictive models. The relation of dSOP to aluminum dose, dBOD, pHI, ALKI, and OSPI was investigated by multiple linear regression, as discussed in Chapter 4. Alum dose and phosphorus concentrations were as mg/l.

BOD removal and OSPI were the only variables that were significant when considered alone. The correlation of dSOP with OSPI was strong because dSOP = OSPI-OSPO ≈ OPSI; OSPO is nearly constant and very small. When both dSOP and BOD are put into the model, dBOD becomes insignificant. This happens because dBOD and OSPI are strongly correlated (Figure 5-16b) and OSPI dominates the regression. The result is that an independent estimate of biological P removal cannot be made from these data.

6.1.2 Nitrification Process

The data from July 1984 - June 1985 and calender year 1986 (n = 24 observations) were analyzed using multiple linear regression. No useful predictive models were developed.

OSP removal in the nitrification process was characterized as being non-stoichiometric with respect to soluble phosphorus, based on the Al/P_C ratios (Figure 5-21). The system operates with an excess of alum and precipitation is non-stoichiometric with respect to soluble phosphorus. The excess alum is sufficient to buffer changes in influent quality.

6.2 SUMMARY

The following conclusions are drawn regarding the Piscataway plant:

1) It is not possible to make a quantitative assessment of the effect of the phosphate detergent ban on alum requirements for precipitation in the secondary treatment process. There is insufficient phosphorus data (nine months with both influent and effluent soluble phosphorus data) to classify the stoichiometry of aluminum phosphate precipitation. Alum use in the secondary plant had been decreased steadily over a period of time. Over the same general period of time, the use of lime for sludge stabilization was high enough that sludge return flows raised the secondary process pH from a typical value of about 7 to about 7.5; alkalinity increased correspondingly.

2) Alum dosing to the nitrification treatment process has been consistently non-stoichiometric. Under these conditions, reducing influent phosphorus concentration would not lead to savings in alum.

3) Phosphate removal in the secondary and tertiary treatment processes cannot be usefully modeled by multiple linear regression.

CHAPTER SEVEN: SOUTH SHORE WWTP

7.1 BACKGROUND

The South Shore wastewater treatment facility is located in Oak Creek, Wisconsin. Wastewater originates in the southern and western portions of the Milwaukee Metropolitan Sewerage District's 420 square mile service area.

In July 1979, the State of Wisconsin legislated a ban on phosphate based detergents. This ban was repealed in July 1982. A second ban became law in January 1984.

7.2 PROCESS DESCRIPTION

Figure 7-1 is a schematic of the South Shore plant. The operation consists of preliminary treatment (coarse screening and grit removal), primary clarification, activated sludge, final clarification, and chlorination.

Primary sludge is anaerobically digested. Waste activated sludge is thickened by dissolved air flotation and sent either to digesters or to Jones Island for processing into Milorganite. The digested solids are lagooned, dewatered, and distributed as an agricultural soil conditioner or some sludge may be sent to the Jones Island Milorganite operation. Incineration is used to treat solids from the preliminary process.

Recycle lagoon supernatant and incineration process water return to the process stream at the head of the plant. The location of the

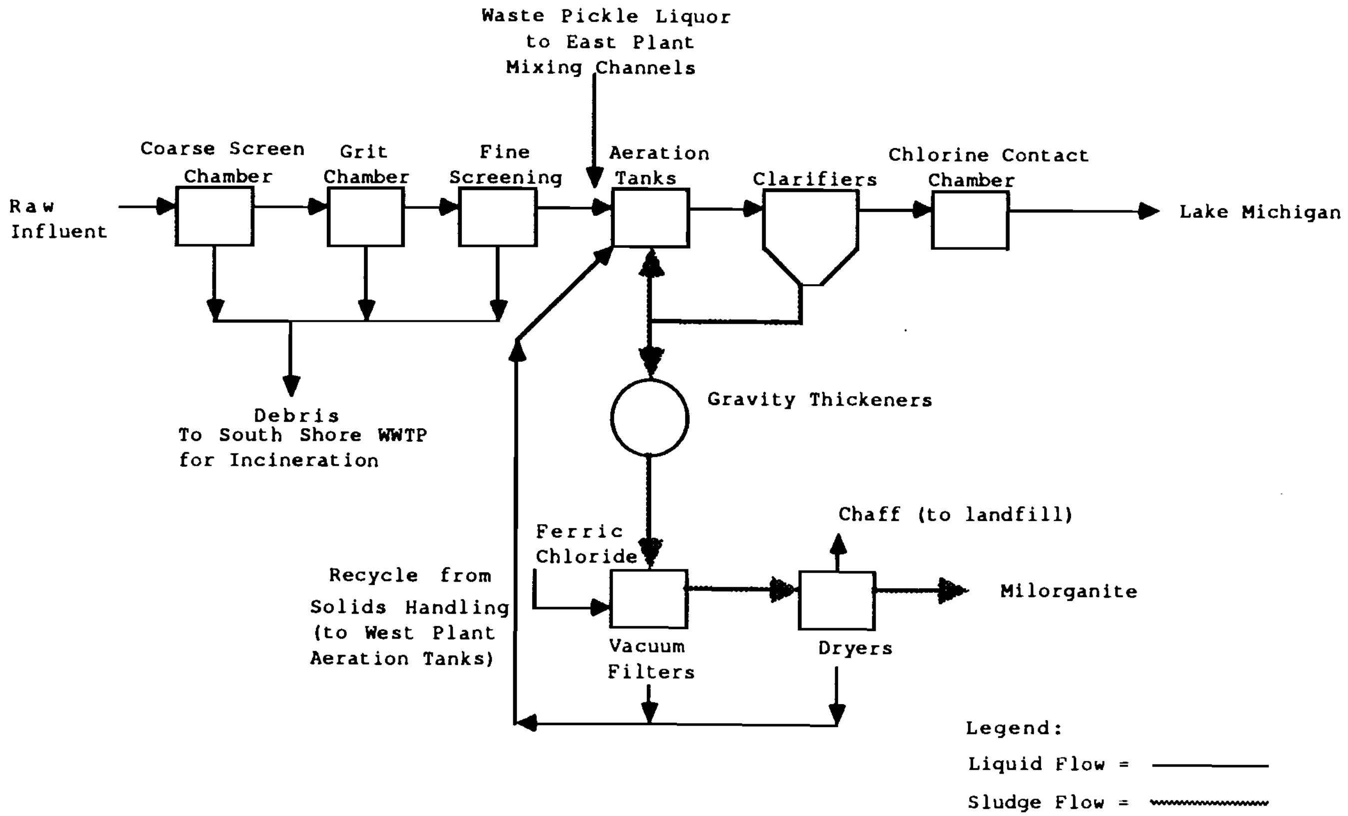


Figure 7-1 South Shore Process Flow Diagram.

recycle reentry has changed several times, due to construction and hydraulic problems. On several occasions the recycle channel has been plugged, causing the lagoon decant to enter above the raw influent sampler. Although these periods of time are not know precisely, plant operators indicated that most of the problems were prior to 1980 and more recently in 1987. Prior to November 1976 all influent sampling was taken below the lagoon recycle point. The lagoon recycle flows are not known for most months of the data base, but operators have indicated that this flow is approximately 0.75 Mgd, and that it varies considerably.

Presently, phosphorus removal is accomplished by the addition of chlorine oxidized WPL at the inlet to the primary clarifiers. Prior to October 1980, unoxidized WPL was either added to the aeration basins or ahead of the primaries. A plant scale study in 1980 (25) indicated that the oxidation of the iron would improve phosphorus removal efficiency and that dosing ahead of the primaries would help to improve floatation thickener operation by decreasing the inorganic fraction in the waste activated sludge.

7.3 OPERATIONS DATA

Operating data was obtained from an existing data base at the University of Wisconsin-Madison, and from two trips to the facility in September 1986 and March 1987.

7.4 RAW INFLUENT CONDITIONS

Figure 7-2 shows that the process flow at South Shore has increased since 1975.

Figures 7-3 and 7-4 show influent BOD and TSS data. Since about 1980, influent BOD and TSS concentrations have decreased slightly. Mass loads of these parameters appear relatively constant for the same period.

Figures 7-3d through 7-6d show a relatively strong dilution effect.

Figure 7-5b does not reveal any large increase or decrease in TP loading at or near the 1982 and 1984 phosphate detergent legislative actions. The shift in 1979 is somewhat disguised by the downward trending data from 1975 to 1982.

Figure 7-6b shows that influent SP loading decreased from 1978 to sometime in 1981 before increasing until early 1983. The effects of the ban are more clear here.

Figure 7-7b indicates that influent particulate phosphorus decreased steadily from 1978 to 1982.

7.5 PRIMARY PHOSPHORUS REMOVAL

7.5.1 Recycle Flows

Wastewater samples are taken downstream from the lagoon decant recycle at the effluent end of the grit channels. These are referred to in the text as the "flow-plus-recycle" measurements. Figure 7-8 shows the difference between the flow-plus-recycle measurements and

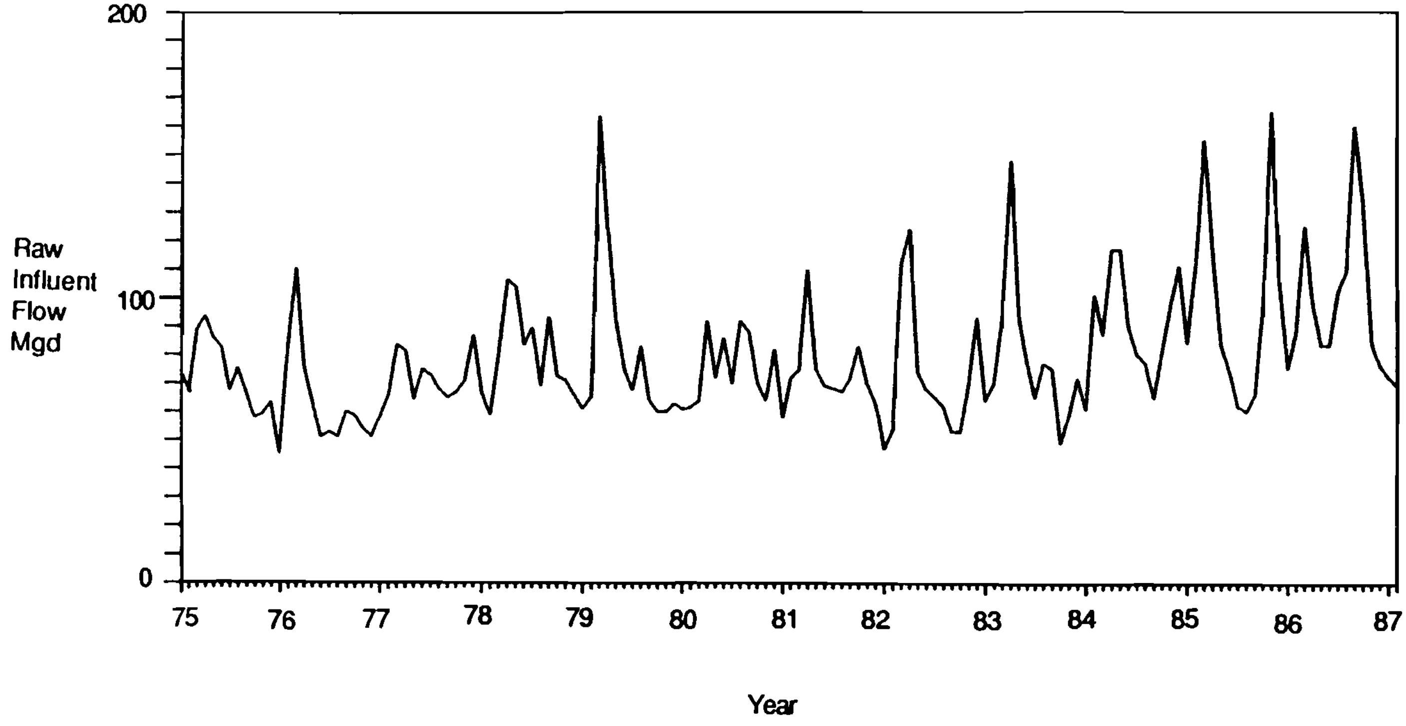


Figure 7-2 South Shore Raw Influent Flow.

Figure 7-3 South Shore Raw Influent a) BOD Concentration, b) BOD Mass Loading, c) BOD Concentration vs. Mass Loading, d) BOD Concentration vs. Flow.

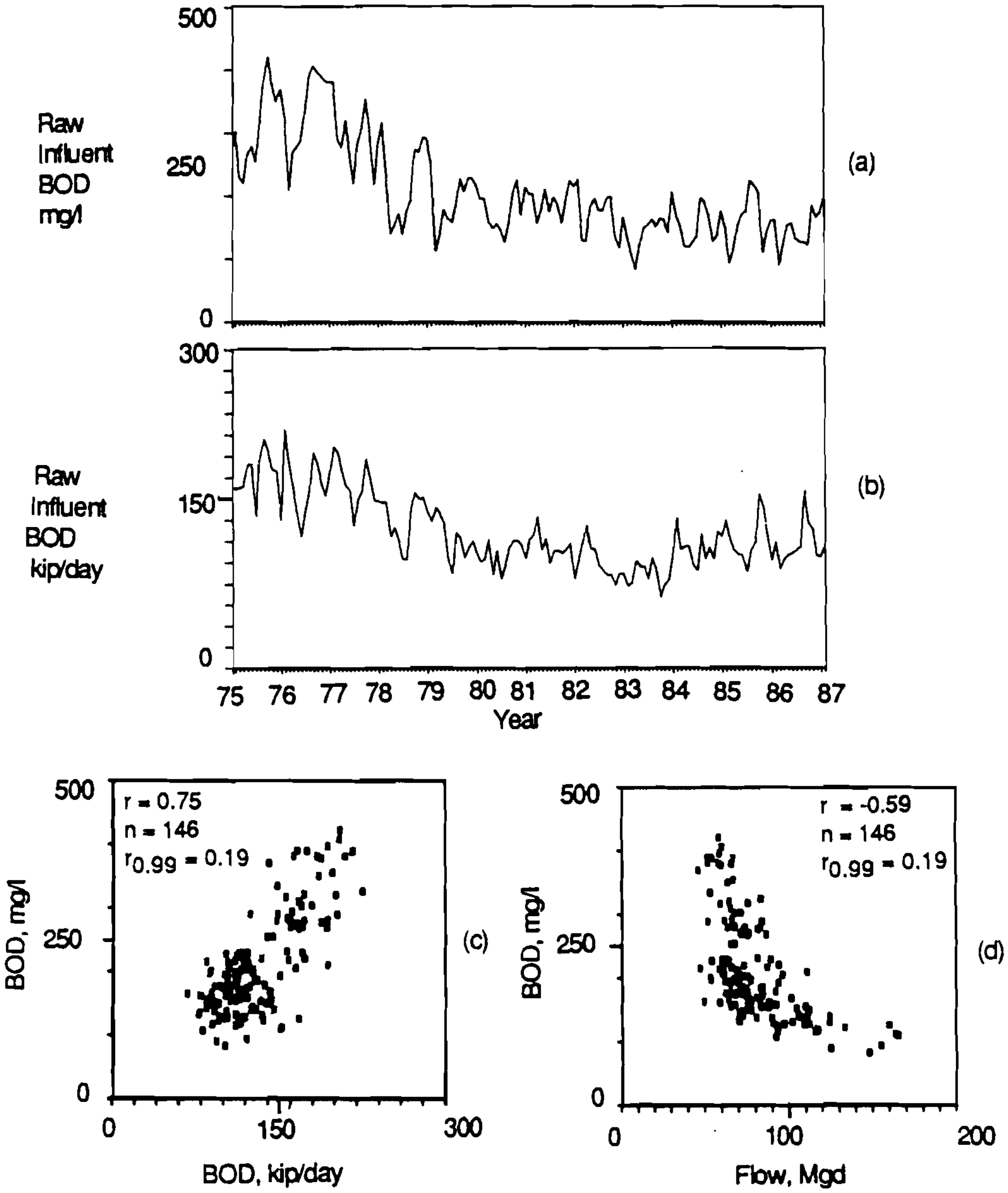


Figure 7-4 South Shore Raw Influent a) TSS Concentration, b) TSS Mass Loading, c) TSS Concentration vs. Mass Loading, d) TSS Concentration vs. Flow.

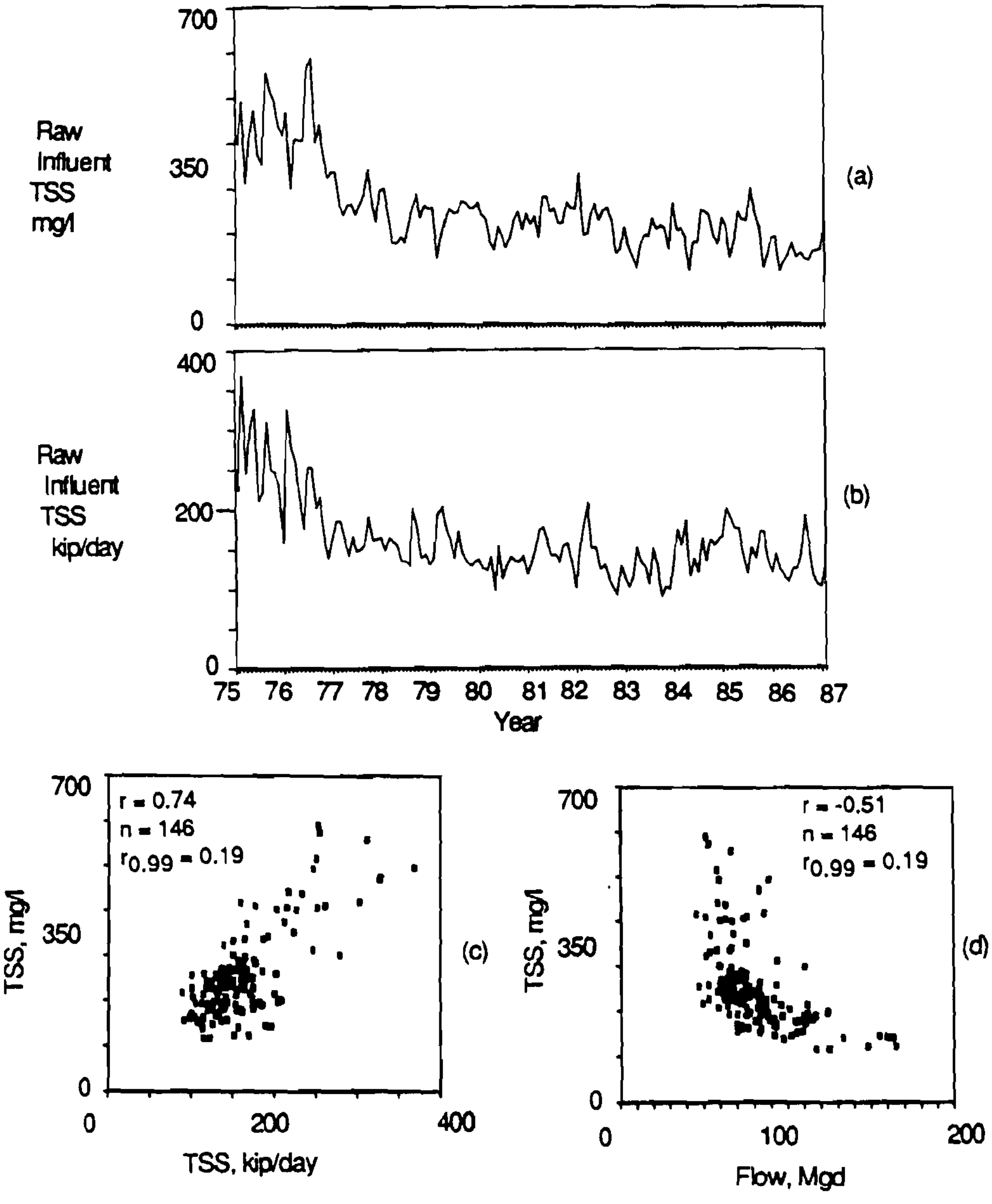


Figure 7-5 South Shore Raw Influent a) TP Concentration, b) TP Mass Loading, c) TP Concentration vs. Mass Loading, d) TP Concentration vs. Flow.

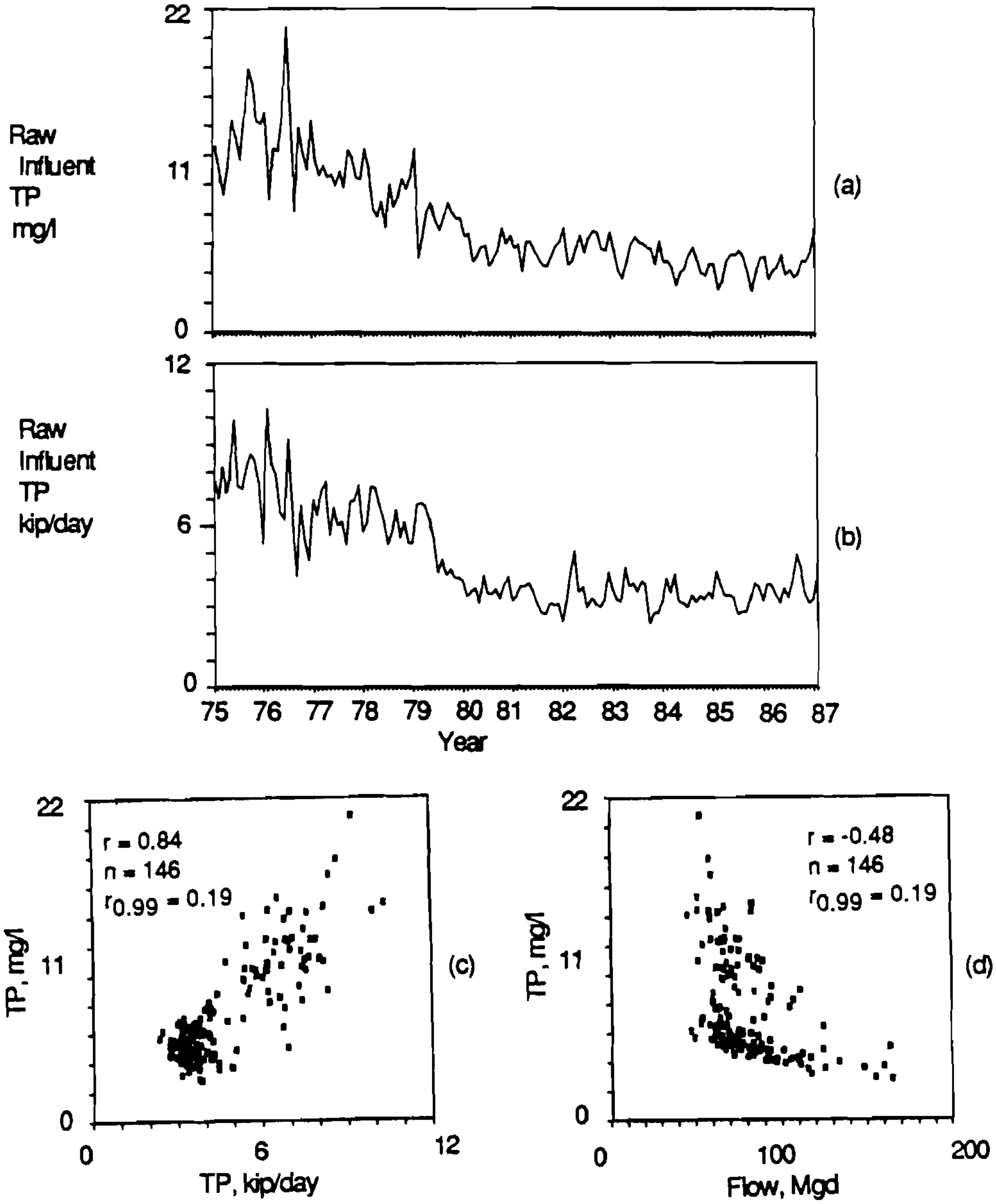


Figure 7-6 South Shore Raw Influent a) SP Concentration, b) SP Mass Loading, c) SP Concentration vs. Mass Loading, d) SP Concentration vs. Flow.

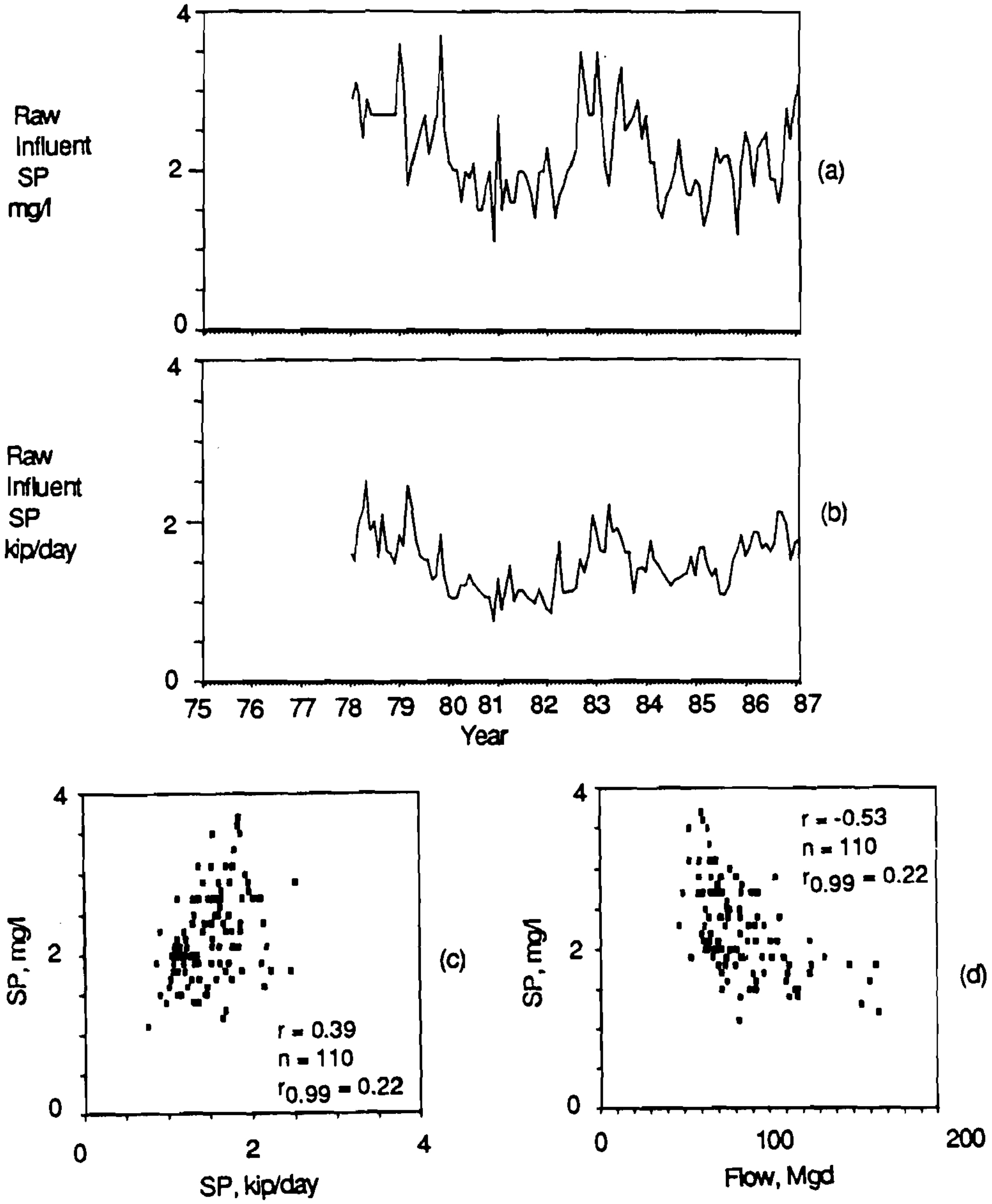


Figure 7-7 South Shore Raw Influent a) Calculated Particulate Phosphorus Concentration (TPI - SPI), b) Calculated Particulate Phosphorus Mass Loading, c) Calculated Particulate Phosphorus (TPI - SPI) Mass Loading vs. Suspended Solids Mass Loading.

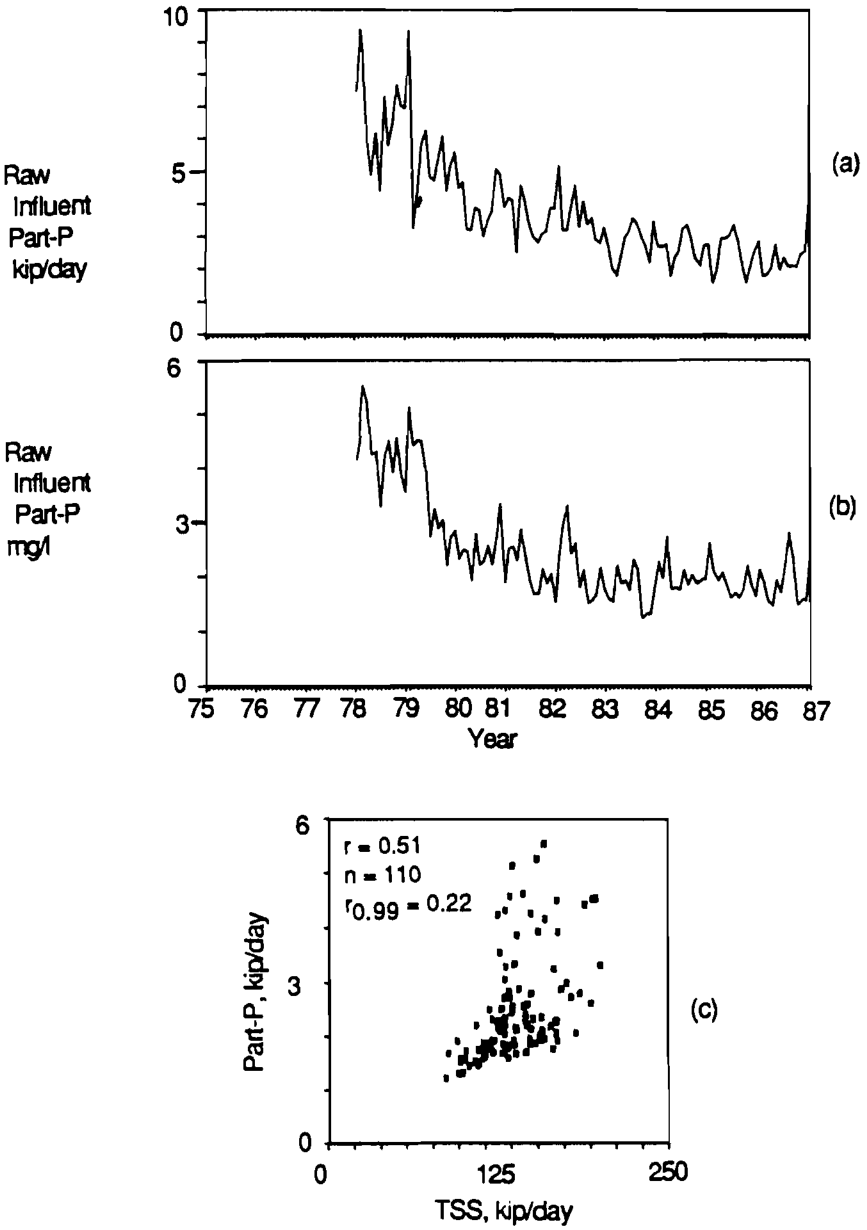
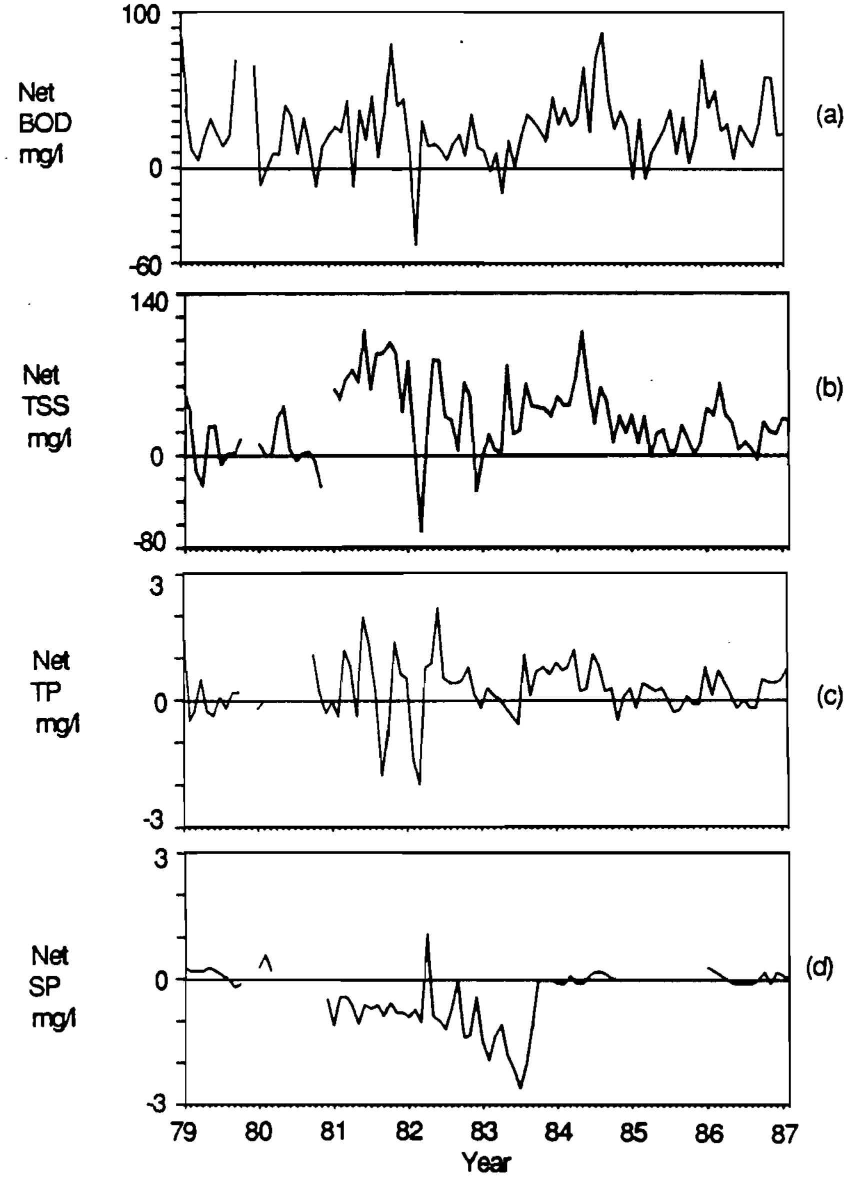


Figure 7-8 South Shore Net Contribution of Lagoon Decant to Raw Influent Concentrations of a) BOD, b) TSS, c) TP, d) SP. See discussion in text.



the raw influent measurements.

In Figure 7-8d there is a series of large negative differences between October 1980 and September 1983. During this period of time, the chlorinated WPL addition point was ahead of the recycle measurement. Excluding the data from October 1980 through September 1983, the impact of the recycle on primary influent SP concentrations appears to be small. A maximum net difference of 0.6 mg/l occurred in February 1980.

The average net contribution of TP due to the recycle is 0.25 mg/l (S.D.= 0.7, n = 90). Since a TP determination would include iron phosphate floc, the data from the upstream WPL addition are included in the average.

The average contribution of suspended solids from the recycle is 30.1 mg/l (S.D. = 32, n = 95). Chemical sludge solids (calculated with Equations 2-3 through 2-5) are subtracted from the recycle-plus-flow measurement for October 1980 through September 1983. This eliminates the contribution of suspended solids caused by the formation of iron precipitates (assuming that grit chamber removal is negligible). The average estimated chemical sludge for this time period is 12.6 mg/l.

The average BOD increase is 25.3 mg/l (S.D. = 22, n = 96). The assumption is that chemical addition above the recycle did not significantly alter the flow-plus-recycle measurement from October 1980 through September 1983.

7.5.2 Soluble Phosphorus Removal

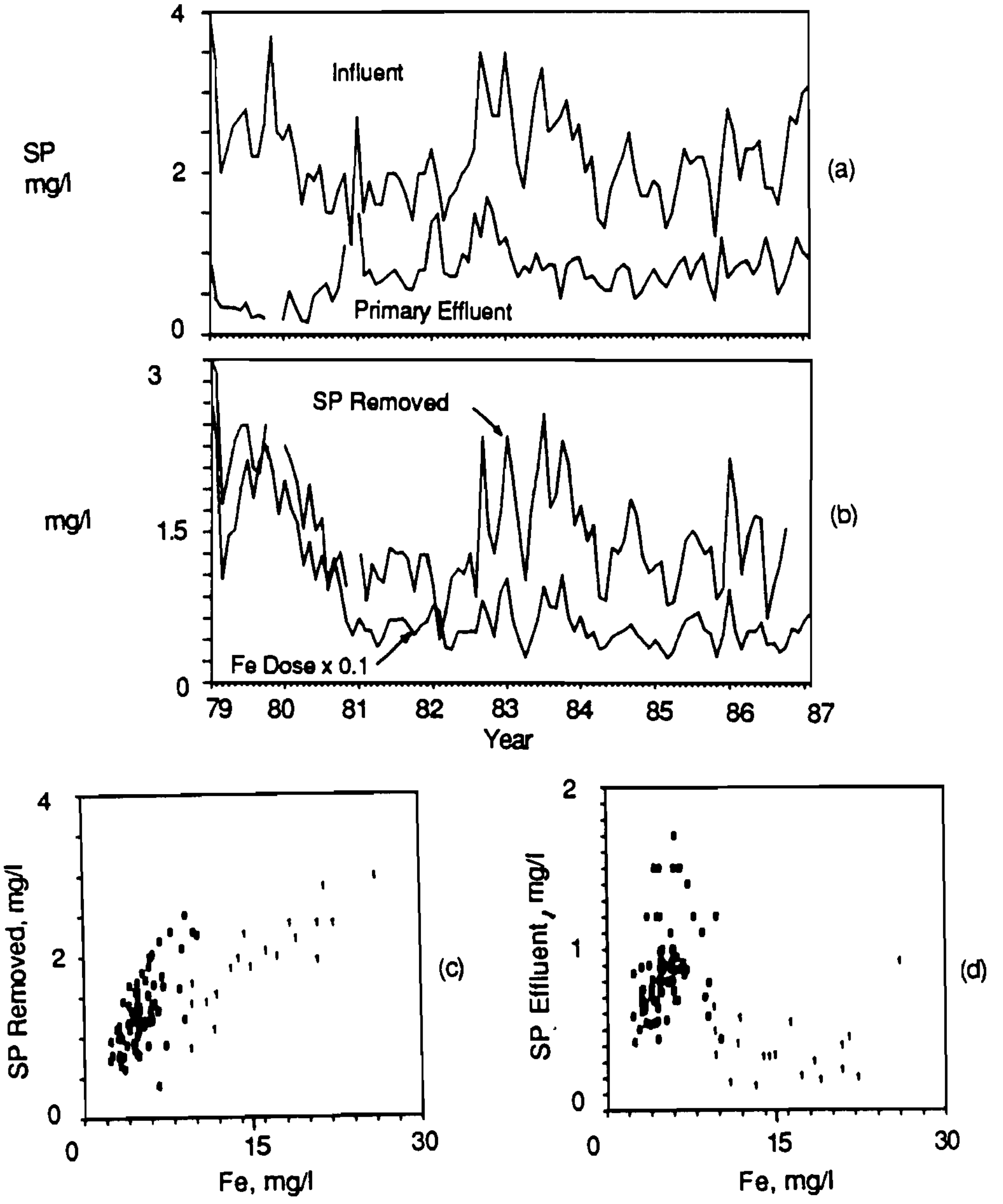
To quantify the impact of oxidized waste pickle addition on phosphorus, TSS, and BOD removal in the primary treatment plant, primary influent parameters have been estimated as follows:

> <u>Primary Influent BOD</u>. Assume that WPL addition above the flow-plus-recycle measurement had no impact on BOD. Use flow-plus-recycle measurements regardless of iron dose points.
>
> <u>Primary Influent TSS</u>. Assume that WPL addition above the flow-plus-recycle measurement increased suspended solids concentration by an amount equal to the chemical precipitate predicted by Equations 2-3 through 2-5. Use flow-plus-recycle measurements minus the quantity of chemical solids.
>
> <u>Primary Influent TP</u>. For October 1980 through September 1983 assume that precipitated phosphorus did not settle before reaching the primary clarifiers. Use flow-plus-recycle measurements.
>
> <u>Primary Influent SP</u>. Use raw influent measurements for October 1980 through September 1983. Use raw influent measurements for November 1979, December 1979, March 1980 through September 1980, and all of 1985. Flow-plus-recycle measurements are unavailable for these time periods. Use flow-plus-recycle measurements for the remaining dates.

Primary effluent parameter values are available from 1979 to the present.

Figure 7-9 shows SP and iron data for a period covering WPL and

Figure 7-9 South Shore Primary a) Influent and Effluent SP vs. Year, b) Fe Dose and SP Removed vs. Year, c) SP Removed vs. Fe Dose, d) SP Effluent vs. Fe Dose. (0 = oxidized WPL, 1 = WPL)



oxidized WPL addition. SP removal in Figure 7-9c appears to be linearly related to iron dose under both conditions (WPL: $r = 0.86$, $n = 19$, $r_{0.99} = 0.53$ and OX-WPL: $r = 0.66$, $n = 76$, $r_{0.99} = 0.26$). The iron dose is lower when chlorine oxidation was practiced, and approximately the same range of SP removals were achieved. This increase in SP removal efficiency can be attributed to the more efficient Fe^{+3} source (oxidized WPL).

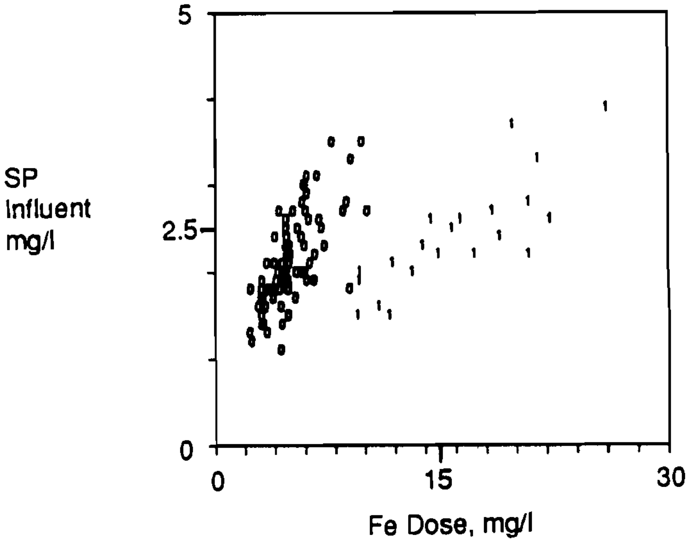
Figure 7-10 shows influent SP and iron dose to be linearly correlated (WPL: $r = 0.82$, $n = 21$, $r_{0.99} = 0.50$; and OX-WPL: $r = 0.69$, $n = 77$, $r_{0.99} = 0.26$).

The relationships between SP removed, flow, iron dose, and initial SP is are further studied in Chapter Eight.

Figure 7-9d shows that effluent SP concentrations were different for the two periods of different iron source. For unoxidized WPL addition, the average primary effluent SP concentration was 0.38 mg/l (S.D. = 0.19, n = 19). The average effluent SP concentration for oxidized WPL addition was 0.80 mg/l (S.D. = 0.30, n = 85). The correlation between effluent SP and Fe dose is significant ($r = 0.29$, $n = 85$, $r_{0.99} = 0.25$).

Unoxidized WPL was used when the first detergent phosphate ban was implemented. The removal efficiency of WPL was shown in a plant scale study to be less effective at removing SP than oxidized WPL. However, the concentrations of effluent SP were quite different for the two types of iron addition. Different chemical mechanisms could be in

Figure 7-10 South Shore Primary Influent SP vs. Iron Dose (0 = oxidized WPL, 1 = WPL).



effect at these two effluent SP concentrations, as shown in Figure 7-11, a plot of the Fe/P_C mole ratio against the primary effluent SP concentration. The outlier in this figure ($Fe/P_C = 9$) corresponds to an unusually small SP removal. The post WPL chlorination average Fe/P_C mole ratio was 2.32 (S.D. = 1.0, n = 75). The pre-chlorination average Fe/P_C ratio was 4.46 (S.D. = 0.78, n = 19). The pre-chlorination ratio may be higher because of 1) the inefficient use of unoxidized WPL and 2) non-stoichiometric precipitation to the relatively low effluent concentrations. The changes in chemical dosing practice, near the time of the initial phosphate detergent ban, make it difficult to assess the impact of changing phosphate concentrations on chemical requirements.

Chemical SP removal has been stoichiometric since 1981, therefore, changes in influent SP concentration, caused by detergent bans in 1982 and 1984, should result in linear adjustments of chemical requirement.

7.5.3 pH

Raw influent and final effluent pH values are shown in Figure 7-12. Wastewater alkalinity was not measured at South Shore. Theoretically, the observed increase in initial wastewater pH will result in a higher solubility limit for orthophosphate.

Figure 7-11 South Shore Primary a) Fe/P_C Mole Ratio vs. SP Effluent b) Fe/P_C Mole Ratio vs. Year. (for P_C = SPI - SPO). (0 = oxidized WPL, 1 = WPL)

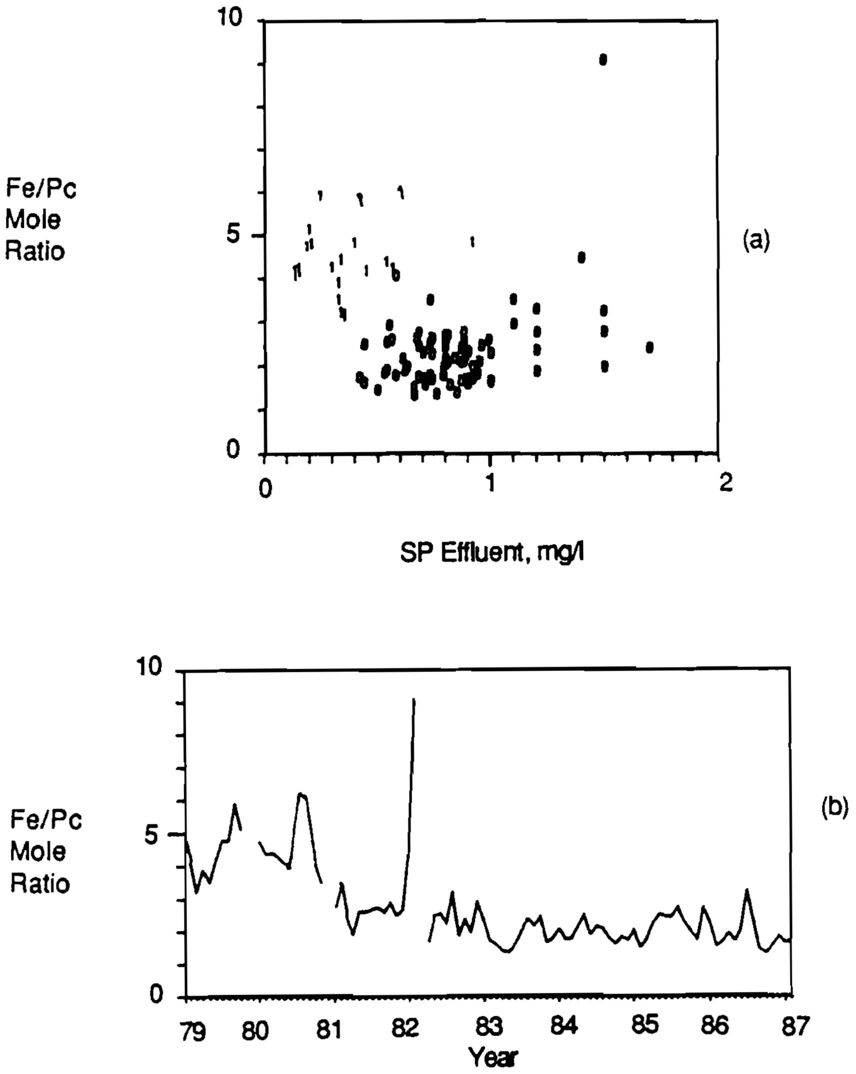
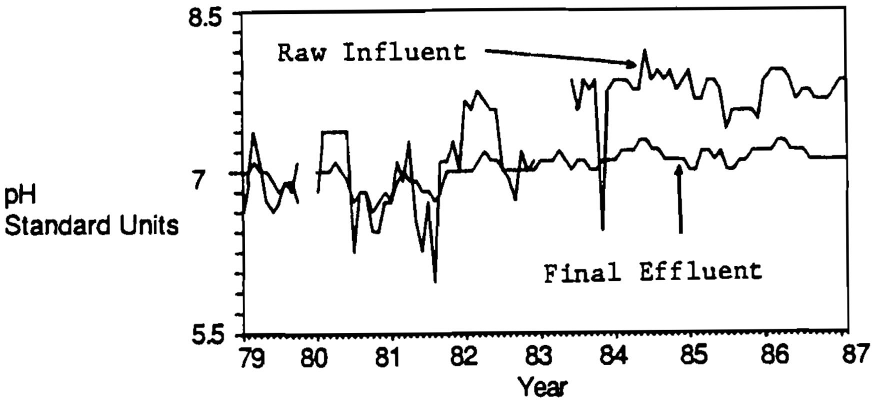


Figure 7-12 South Shore Raw Influent and Final Effluent pH vs. Year.



7.5.4 BOD, TSS, and TP

Figures 7-13c through 7-15c show the relationships of WPL dose and BOD, TSS, and TP removal.

Figures 7-13d and 7-15d show that primary effluent BOD and TP concentrations increase with iron dose (WPL:BOD, $r = 0.77$, $n = 19$, $r_{0.99} = 0.53$; TP, $r = 0.69$, $n = 19$) (OX-WPL:BOD, $r = 0.41$, $n = 77$, $r_{0.99} = 0.26$; TP, $r = 0.55$, $n = 77$). The time series plots of influent and effluent BOD and TP show that influent peaks correspond to effluent peaks.

Figure 7-16 suggests that influent TSS and iron dose are linearly related (WPL:$r = 0.86$, $n = 19$, $r_{0.99} = 0.53$; OX-WPL: $r = 0.31$, $n = 76$, $r_{0.99} = 0.26$). The correlation of TSS removed (mg/l) and influent TSS is highly significant (all data, $r = 0.94$, $n = 94$, $r_{0.99} = 0.24$). The collinearity between influent TSS, iron dose, and TSS removed mean that enhanced solids removal needs to be assessed with a different method than simply calculating the slope of the data in Figure 7-14c.

Figure 7-14d shows that effluent suspended solids is independent of oxidized WPL iron dose ($r = 0.21$, $n = 77$, $r_{0.99} = 0.26$: ave. = 75.7, S.D. = 17, $n = 77$). For unoxidized WPL use, the increasing trend may be related to poorly settling gelatinous ferrous hydroxide precipitate ($r = 0.66$, $n = 19$, $r_{0.99} = 0.53$). The plant scale study (25) concluded that the switch to oxidized WPL resulted in decreased iron content in the waste activated sludge.

Figure 7-13 South Shore Primary a) Influent and Effluent BOD vs. Year, b) BOD Removed and Fe Dose vs. Year, c) BOD Removed vs. Fe Dose, d) BOD Effluent vs. Fe Dose. (0 = oxidized WPL, 1 = WPL)

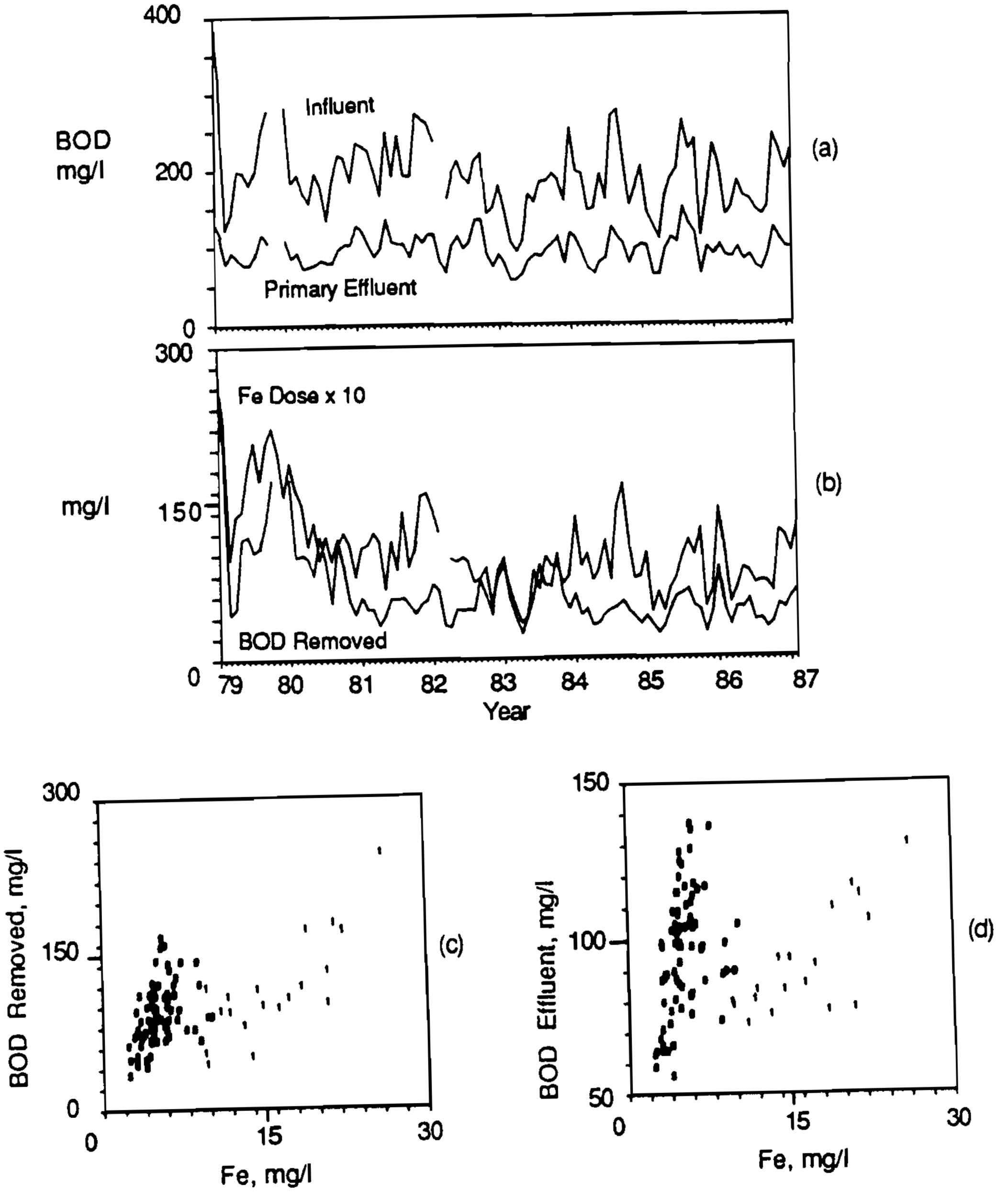


Figure 7-14 South Shore Primary a) Influent and Effluent TSS vs. Year, b) TSS Removed and Fe Dose vs. Year, c) TSS Removed vs. Fe Dose, d) TSS Effluent vs. Fe Dose. (0 = oxidized WPL, 1 = WPL)

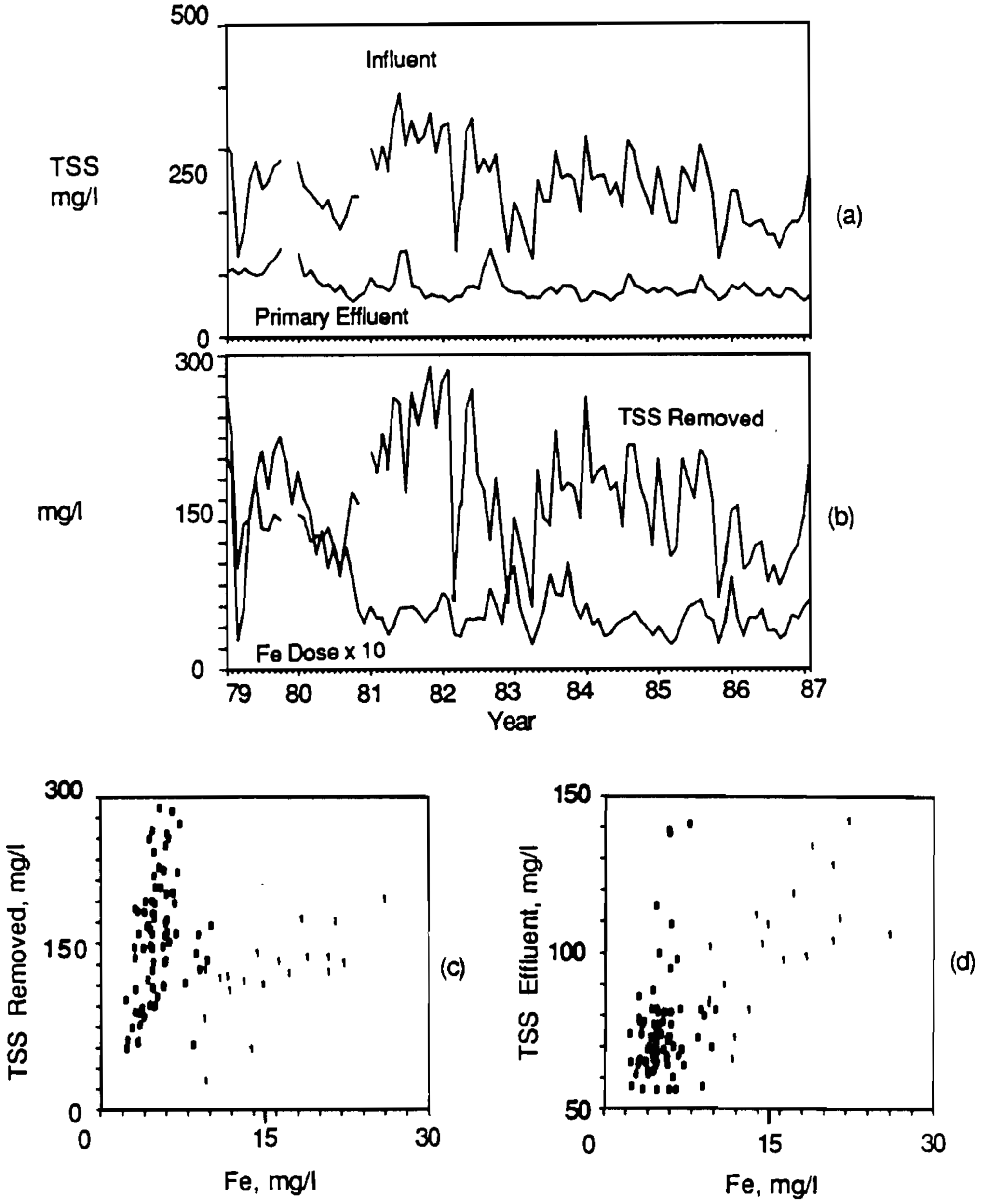


Figure 7-15 South Shore Primary a) Influent and Effluent TP vs. Year, b) TP Removed and Fe Dose vs. Year, c) TP Removed vs. Fe Dose, d) TP Effluent vs. Fe Dose (0 = oxidized WPL, 1 = WPL).

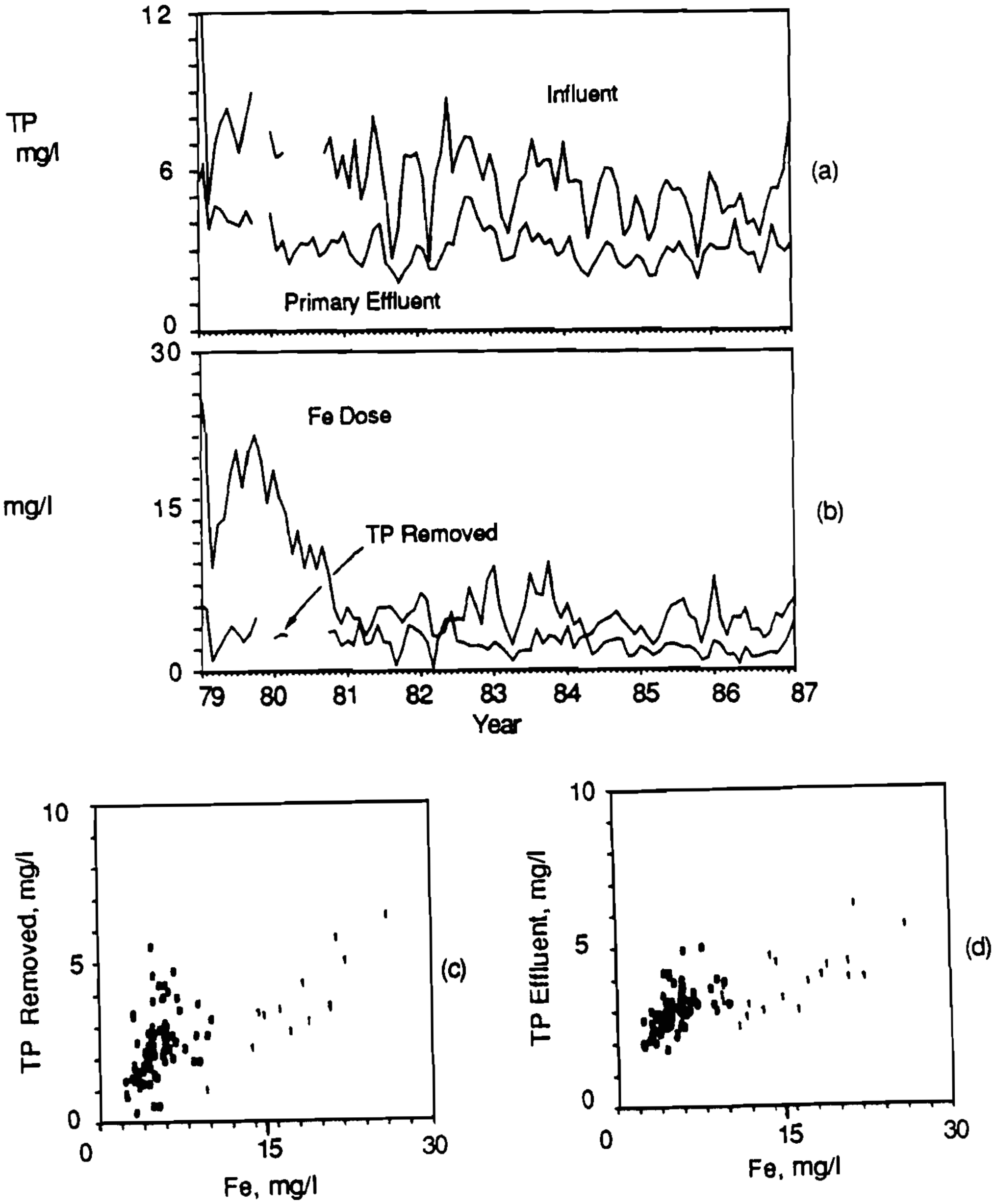
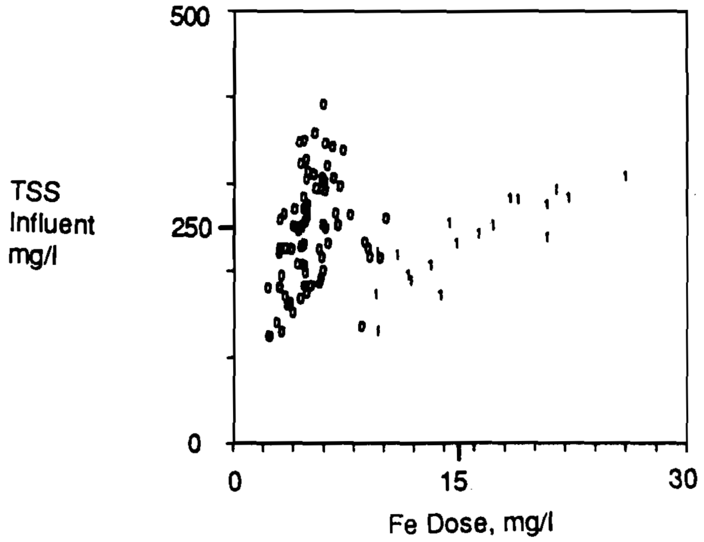


Figure 7-16 South Shore Primary Influent TSS vs. Iron Dose
(0 = oxidized WPL, 1 = WPL).



7.6 SECONDARY PHOSPHORUS REMOVAL

Figure 7-17 shows secondary SP removal, BOD, and primary iron dose data.

Figure 7-18 shows that secondary SP removal is significantly correlated with BOD removal ($r = 0.50$, $n = 95$, $r_{0.99} = 0.24$).

Figure 7-18b shows that secondary SP removal is not strongly dependent on primary iron dose for oxidized WPL addition ($r = 0.29$, $n = 76$, $r_{0.99} = 0.26$). The same figure suggests that secondary SP removal is related to unoxidized WPL addition ($r = 0.60$, $n = 19$, $r_{0.99} = 0.53$). These observations support the observations of the 1980 plant study which were conducted to eliminate iron carry over into the secondaries. It should be noted that the iron dose ranges are not the same for both types of iron.

7.7 PRIMARY SLUDGE PRODUCTION

Figure 7-19a shows reported primary sludge production, TSS removed (with previously stated assumptions about influent TSS), and predicted chemical sludge (Equations 2-3 through 2-5). The predicted chemical sludge averages 19.7% (by weight) of the reported sludge total prior to oxidized WPL use, and 6.7% after.

Figure 7-19b shows the relationship between observed sludge production and predicted chemical sludge. These figures indicate that changes in chemical sludge production that have resulted from changes

Figure 7-17 South Shore Secondary a) Primary Effluent and Final Effluent SP, b) Primary Iron Dose and Secondary SP Removed, c) Secondary BOD Removed and Secondary SP Removed.

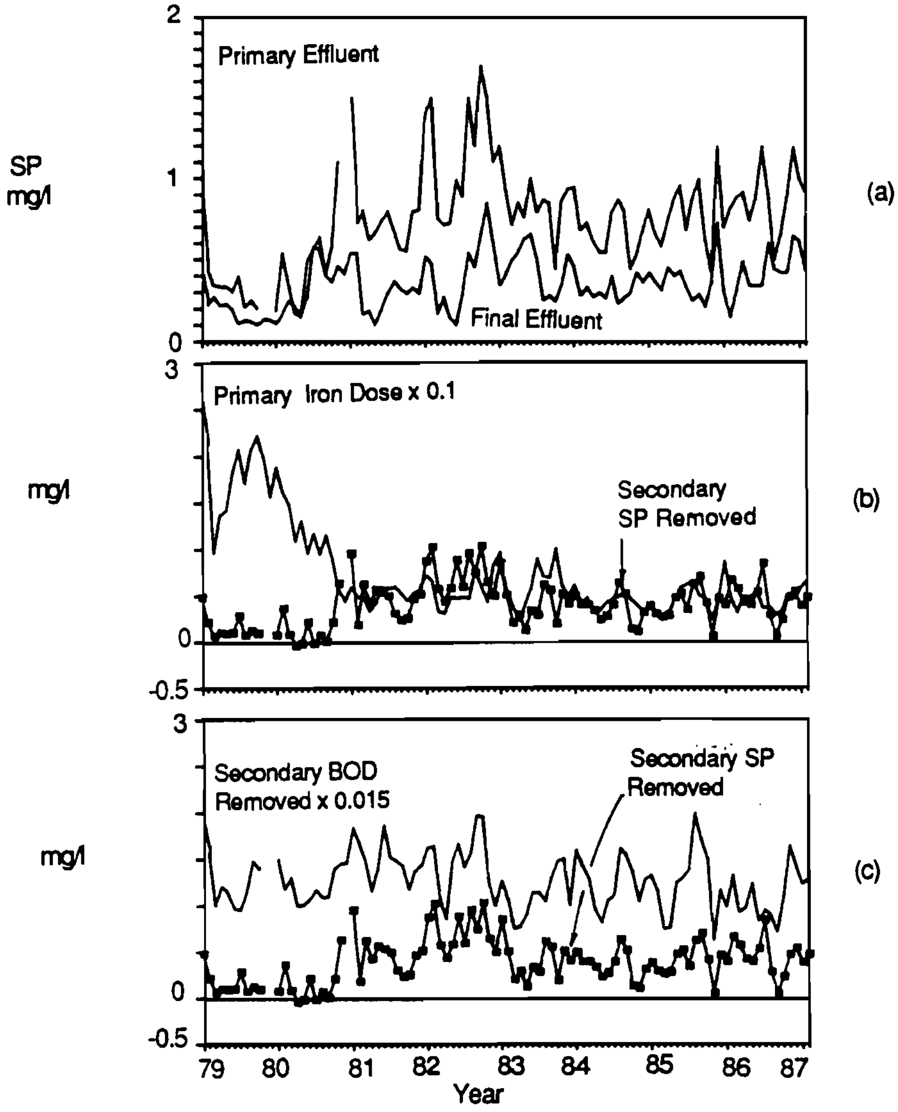


Figure 7-18 South Shore Secondary a) SP Removed vs. BOD Removed, b) Secondary SP Removed vs. Primary Iron Dose. (0 = oxidized WPL, 1 = WPL)

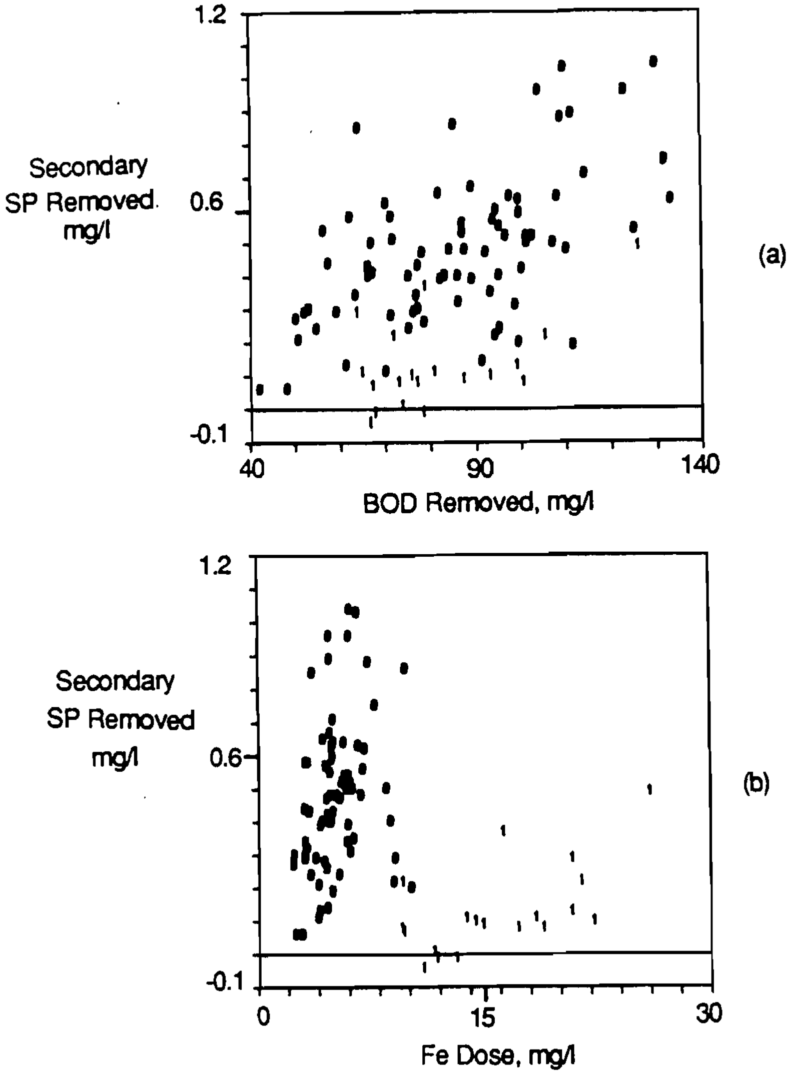
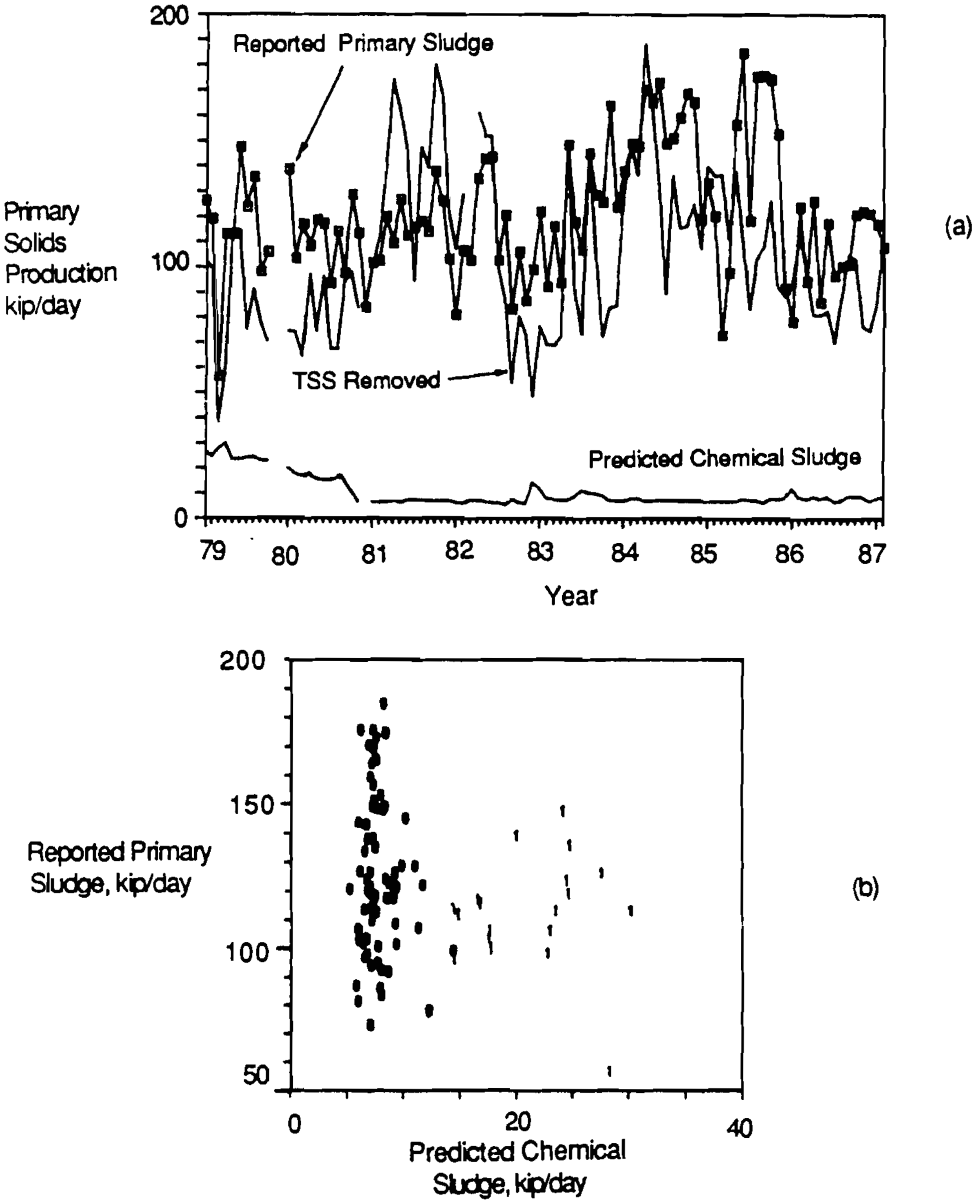


Figure 7-19 South Shore a) Reported Sludge, TSS Removed, and Predicted Chemical Sludge vs. Year, b) Reported Primary Sludge vs. Predicted Chemical Sludge. (0 = oxidized WPL, 1 = WPL)



in chemical dose or phosphate loading, will be undetectable due to the variation in total sludge production.

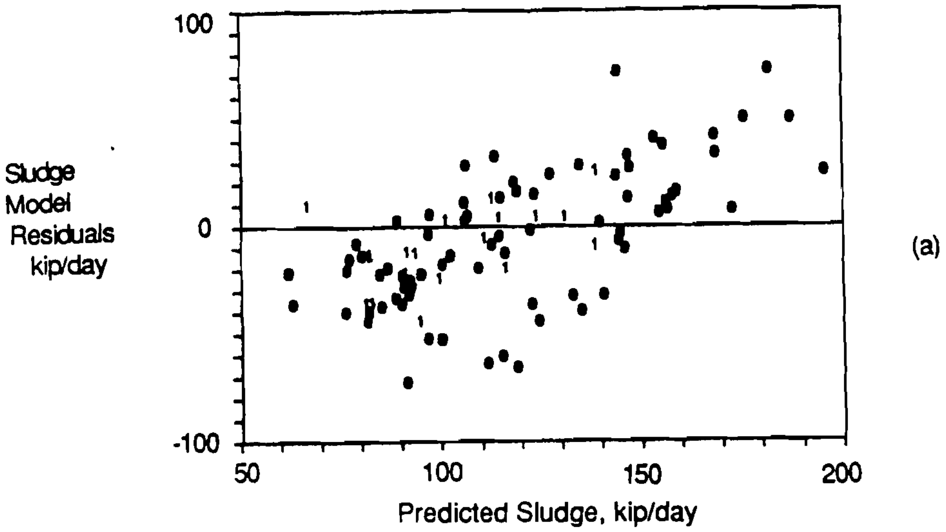
The following mass balance model was used to predict raw sludge production in terms of solids removal and chemical sludge production:

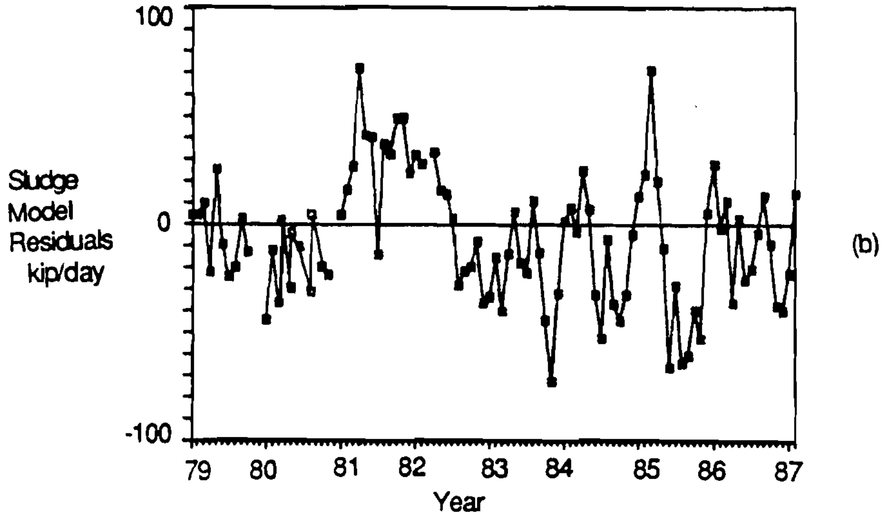
RAW SLUDGE = (TSSIN - TSSOUT) + CHEMICAL SLUDGE (estimated)

Chemical sludge was estimated with Equations 2-3 through 2-5.

Figure 7-20 shows the sludge model residuals for the sludge model plotted against the predicted values and year. Clearly, the model is lacking. The residuals were found to be random when plotted against influent and effluent TSS, influent and effluent SP, predicted chemical sludge, iron dose, flow and some limited grit removal data. A linear trend similar to Figure 7-20a was observed when the residuals were plotted against TSS removed. No explanation of this inadequacy is offered.

Figure 7-20 South Shore Primary Sludge Model Residuals vs. a) Predicted Sludge, b) Year. (0 = oxidized WPL, 1 = WPL)





CHAPTER EIGHT: SOUTH SHORE REGRESSION ANALYSIS

8.1 SOLUBLE PHOSPHORUS REMOVAL

All possible combinations of the independent variables in the following model were fitted to data for the periods of pre-oxidized WPL addition (1/79 - 9/80) and oxidized WPL addition (10/80 - 2/87). The results are summarized in Tables 8-1 and 8-2, and Figure 8-1 and 8-2.

$$dSP = b_0 + b_1\, Fe + b_2\, SPI + b_3\, pHI + b_4\, Q \qquad 8\text{-}1$$

where dSP = Soluble Phosphorus Removed, mg/l

Fe = Iron Dose, mg/l

SPI = Influent Soluble Phosphorus, mg/l

pHI = Raw Influent pH

Q = Flow, MGD

8.1.1 Pre-Oxidized WPL Addition

Iron dose (Model 1) explains considerable variation (Table 8-1). Model 2, which has only SPI as an independent variable, indicates that essentially 87% of the influent soluble phosphorus is removed. Putting Fe and SPI into the model, to get Model 5, is not statistically justified; the iron term dose not significantly improve Model 2 ($\alpha = 95\%$).

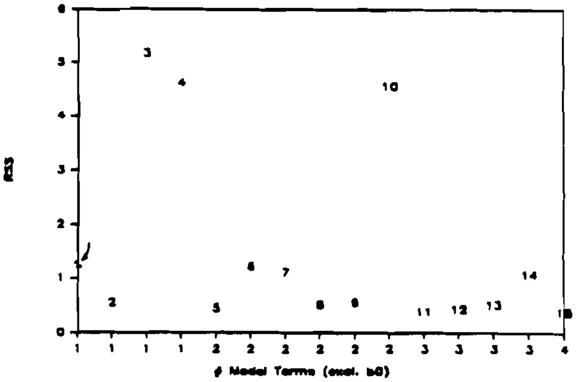
The estimated parameters of Model 5 are much different than those

Table 8-1 South Shore Pre-Oxidized WPL Addition, Regression Output for Equation 8-1.

MODEL: dSP = b0 + b1 Fe + b2 SPI + b3 pHI + b4 Q

Model	b0	b1	b2	b3	b4	n	R2	S
1	0.40	0.10				19	0.77	0.273
	1.86	7.46						
2	-0.081		0.87			19	0.90	0.182
	-0.47		12.16					
3	4.29			-0.34		19	0.05	0.552
	1.68			-0.92				
4	2.63				-0.008	19	0.15	0.521
	6.48				-1.73			
√ 5	-0.07	0.029	0.67			19	0.92	0.169
	-0.43	1.92	5.35					
6	-0.72	0.10		0.15		19	0.77	0.277
	-0.50	7.19		0.78				
7	-0.21	0.11			0.005	19	0.80	0.263
	-0.46	7.12			1.54			
8	-1.09		0.90	0.14		19	0.90	0.181
	-1.15		11.94	1.08				
9	-0.03		0.86		-0.0005	19	0.90	0.187
	-0.09		10.78		-0.25			
10	3.78			-0.17	-0.008	19	0.16	0.533
	1.52			-0.47	-1.48			
11	-1.38	0.033	0.68	0.18		19	0.93	0.162
	-1.61	2.23	5.64	1.56				
12	-0.29	0.039	0.63		0.002	19	0.92	0.169
	-1.02	2.11	4.85		0.94			
13	-1.08		0.88	0.15	-0.001	19	0.91	0.185
	-1.11		10.85	1.13	-0.47			
14	-1.07	0.12		0.12	0.004	19	0.80	0.268
	-0.75	6.96		0.64	1.43			
15	-1.48	0.040	0.65	0.17	0.002	19	0.93	0.164
	-1.68	2.27	5.11	1.42	0.78			

Figure 8-1 South Shore Pre-Oxidized WPL Addition, RSS vs. Number of Model Terms (excluding b_0) and Sequential F Values for Models in Table 8-1. Data labels represent model number.



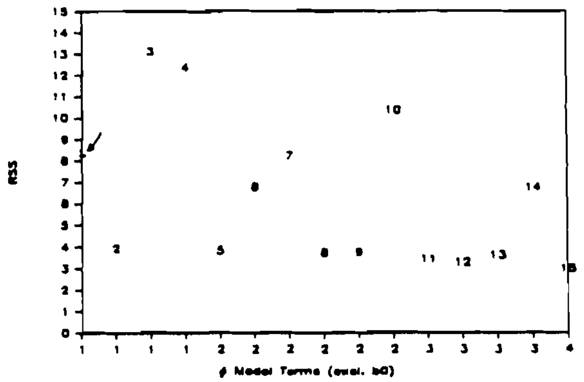
MODEL	TERMS	RSS	MSE	Sequential F Value					
1	1	1.27	0.0747						
2	1	0.56	0.0330						
3	1	5.17	0.3044						
4	1	4.61	0.2714						
5	2	0.46	0.0285	28.6	3.7	165.7	146.0		
6	2	1.22	0.0765	0.6	-8.7	51.7	44.3		
7	2	1.11	0.0691	2.4	-7.9	58.9	50.7		
8	2	0.52	0.0326	22.9	1.2	142.6	125.4		
9	2	0.56	0.0349	20.4	0.1	132.4	116.3		
10	2	4.55	0.2845	-11.5	-14.0	2.2	0.2		
11	3	0.39	0.0261	2.4	31.8	27.3	5.0	6.3	159.1
12	3	0.43	0.0287	0.9	27.6	23.6	3.2	4.5	143.7
13	3	0.51	0.0343	-1.7	20.7	17.3	0.2	1.3	117.7
14	3	1.08	0.0718	-8.7	2.0	0.4	-7.7	-7.2	48.4
15	4	0.38	0.0269	0.6	2.0	5.1	26.1		

Table 8-2 South Shore Oxidized WPL Addition, Regression Output for Equation 8-1.

MODEL: dSP = b0 + b1 Fe + b2 SPI + b3 pHI + b4 Q

Model	b0	b1	b2	b3	b4	n	R2	S
1	0.42	0.17				76	0.43	0.337
	3.36	7.54						
2	-0.27		0.73			76	0.74	0.230
	-2.40		14.37					
3	0.67			0.08		71	0.01	0.436
	0.88			0.82				
4	1.90				-0.0070	76	0.17	0.409
	11.80				-3.87			
5	-0.28	0.03	0.66			76	0.74	0.228
	-2.49	1.45	9.39					
6	-1.44	0.19		0.23		71	0.49	0.316
	-2.37	7.99		3.08				
7	0.04	0.20			0.0026	76	0.45	0.336
	0.13	6.04			1.20			
8	-0.91		0.72	0.09		71	0.72	0.234
	-2.16		13.14	1.62				
9	-0.61		0.80		0.0023	76	0.75	0.226
	-2.85		12.97		1.86			
10	0.29			0.23	-0.0083	71	0.22	0.390
	0.43			2.35	-4.27			
11	-1.269	0.057	0.60	0.13		71	0.74	0.226
	-2.91	2.37	8.10	2.36				
12	-0.999	0.078	0.693		0.048	76	0.78	0.213
	-4.25	3.20	10.45		3.42			
13	-0.95		0.781	0.053	0.002	71	0.73	0.232
	-2.26		11.19	0.89	1.37			
14	-1.53	0.20		0.22	0.001	71	0.49	0.317
	-2.41	5.98		2.84	0.52			
15	-1.609	0.096	0.658	0.078	0.005	71	0.77	0.213
	-3.79	3.71	9.12	1.43	3.10			

Figure 8-2 South Shore Oxidized WPL Addition, RSS vs. Number of Model Terms (excluding b_0) and Sequential F Values for Models in Table 8-2. Data labels represent model number.



MODEL	TERMS	RSS	MSE	Sequential F Value					
1	1	8.40	0.1136						
2	1	3.92	0.0529						
3	1	13.13	0.1903						
4	1	12.36	0.1670						
5	2	3.81	0.0521	88.1	2.1	178.8	164.0		
6	2	6.78	0.0997	16.3	-28.7	63.8	56.0		
7	2	8.24	0.1129	1.4	-38.3	43.3	36.5		
8	2	3.71	0.0546	86.0	3.8	172.7	158.6		
9	2	3.74	0.0512	91.0	3.4	183.3	168.2		
10	2	10.35	0.1523	-12.8	-42.3	18.2	13.2		
11	3	3.42	0.0511	7.5	65.6	94.3	5.6	6.2	135.6
12	3	3.27	0.0455	11.7	77.0	109.2	9.6	10.3	155.7
13	3	3.61	0.0539	3.7	58.8	86.0	1.9	2.4	125.2
14	3	6.75	0.1007	-29.2	0.3	14.8	-30.2	-29.9	35.8
15	4	2.99	0.0453	9.6	6.3	13.7	83.1		

estimated from the one variable Models 1 and 2. In models that have only Fe terms, the value of b_1 is about 0.1. When SPI is in the model, b_1 is about 0.03. These values have no useful mechanistic interpretation.

The iron dose coefficient in Model 1, b_1=0.1, corresponds to an Fe/Pc ratio of 5.5 [(1 mg Fe/0.10)(30.97/55.85) = 5.5]. This is higher than the stoichiometric ratio for the precipitation of orthophosphate. The ratio may be inflated because the the ferrous iron in the WPL is not fully oxidized. The coefficient b1 = 0.029 of Model 5 corresponds to an Fe/Pc ratio of 19.1, which is unreasonably high.

The effects of collinearity (see Figures 7-9 and 7-10) make it impossible to separate the effects of iron dose and initial SP on phosphorus removal. These models have no utility for predicting operating results.

8.1.2 Oxidized WPL Addition

Again collinearity between iron dose and SPI is evident when Models 1, 2, and 5 are compared in Table 8-2. The coefficients in the models have no useful mechanistic interpretation. The models themselves have no predictive value.

8.2 PRIMARY SLUDGE PRODUCTION

All possible combinations of the independent variables in the following model were fitted to data for the periods of pre-oxidized WPL addition (1/79 - 9/80) and oxidized WPL addition (10/80 - 2/87).

$$SLUK = b_0 + b_1\ dTSSK + b_2\ TSSIK + b_3\ FeK + b_4\ dSPK + b_5\ Q \qquad 8\text{-}2$$

where SLUK = Primary Sludge Production, kip/day

dTSSK = TSS Removed, kip/day

TSSIK = Influent TSS, kip/day

FeK = Iron Dose, kip/day

dSPK = Soluble Phosphorus Removed, kip/day

Q = Flow, MGD

Regression output for the two sets of data are summarized in Tables 8-3 and 8-4.

8.2.1 Pre-Oxidized WPL Addition

Model 1, which explains only 34% of the variation, has TSS removed as a useful predictor. Flow rate, Q, is also significant in a one variable model. The negative flow term suggests that less sludge is produced at higher flows, which may reflect changes in hydraulic detention time.

Iron dose and SP removal terms are insignificant in all models.

Model 9 has two variables, flow and TSS removed. Again, the coefficient on flow is negative. Model 12 is slightly better (higher R2 and lower S) and uses influent TSS and Q. The relative importance of Q is larger in Model 12 because the flow term now accounts for

Table 8-3 South Shore Pre-Oxidized WPL Addition, Regression Output for Equation 8-2.

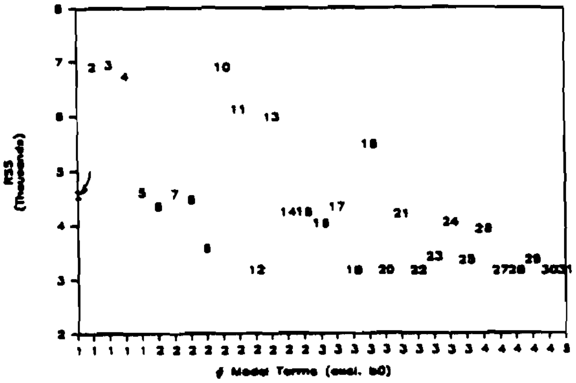
MODEL: SLUK = b0 + b1 dTSSK + b2 TSSIK + b3 FeK + b4 dSPK + b5 Q

Model	b0	b1	b2	b3	b4	b5	n	R2	S
1	65.65	0.58					19	0.34	16.4
	3.99	2.97							
2	103.39		0.06				19	0.01	20.2
	3.30		0.32						
3	110.45			0.27			19	0.00	20.2
	5.19			0.13					
4	124.01				-8.47		19	0.03	19.9
	8.13				-0.75				
5	149.21					-0.44	19	0.34	16.4
	11.66					-2.95			
6	84.38	0.66	-0.17				19	0.37	16.5
	3.20	3.07	-0.91						
7	63.21	0.58		0.24			19	0.34	16.9
	2.61	2.88		0.14					
8	74.18	0.57			-5.92		19	0.36	16.7
	3.42	2.84			-0.62				
9	104.77	0.42				-0.32	19	0.49	14.9
	4.42	2.15				-2.13			
10	103.51		0.08	-0.24			19	0.01	20.8
	3.20		0.29	-0.09					
11	88.07		0.36		-23.15		19	0.12	19.6
	2.73		1.26		-1.43				
12	98.46		0.45			-0.66	19	0.54	14.1
	4.49		2.67			-4.33			
13	103.23			5.07	-32.30		19	0.14	19.3
	4.95			1.42	-1.61				
14	133.30			2.04		-0.50	19	0.39	16.3
	7.18			1.17		-3.20			
15	142.60				13.73	-0.58	19	0.39	16.3
	10.27				1.17	-3.07			

Table 8-3, Continued.

Model	b0	b1	b2	b3	b4	b5	n	R2	S
16	80.49	0.75	-0.36	2.52			19	0.42	16.4
	3.04	3.27	-1.42	1.09					
17	86.05	0.70	-0.24		4.39		19	0.38	17.0
	3.07	2.49	-0.69		0.25				
18	96.66	0.08	0.40			-0.61	19	0.54	14.5
	4.06	0.24	1.37			-2.36			
19	71.88		0.33	4.72	-44.04		19	0.21	19.1
	2.13		1.17	1.33	-1.98				
20	98.68		0.48	-0.45		-0.66	19	0.54	14.5
	4.36		2.25	-0.24		-4.20			
21	136.94			1.13	7.19	-0.55	19	0.39	16.7
	6.08			0.33	0.31	-2.51			
22	96.13		0.49		-3.75	-0.64	19	0.54	14.5
	4.00		2.26		-0.29	-3.74			
23	103.97	0.38			9.31	-0.42	19	0.51	15.1
	4.34	1.91			0.83	-2.16			
24	61.83	0.53		3.82	-24.02		19	0.42	16.4
	2.62	2.67		1.24	-1.38				
25	95.66	0.39		1.56		-0.37	19	0.52	15.0
	3.74	1.98		0.96		-2.32			
26	73.29	0.66	-0.23	3.75	-13.95		19	0.43	16.8
	2.47	2.34	-0.66	1.19	-0.60				
27	97.45	0.05	0.43	-0.27		-0.63	19	0.54	15.0
	3.78	0.11	0.93	-0.10		-1.96			
28	95.76	0.04	0.45		-2.88	-0.62	19	0.54	15.0
	3.81	0.10	1.04		-0.18	-2.28			
29	96.23	0.39		1.45	0.88	-0.38	19	0.52	15.5
	3.20	1.88		0.45	0.04	-1.70			
30	96.38		0.49	-0.06	-3.40	-0.64	19	0.54	15.0
	3.49		2.15	-0.02	-0.16	-3.20			
31	95.46	0.04	0.45	0.07	-3.18	-0.61	19	0.54	15.6
	3.16	0.10	0.90	0.02	-0.14	-1.78			

Figure 8-3 South Shore Pre-Oxidized WPL Addition, RSS vs. Number of Model Terms (excluding b_0) and Sequential F Values for Models in Table 8-3. Data labels represent model number.



M	TERM	RSS	MSE	Sequential F Values									
1	1	4575.3	269.1										
2	1	6906.1	406.2										
3	1	6939.5	408.2										
4	1	6726.9	395.7										
5	1	4597.5	270.4										
6	2	4349.5	271.8	0.8	9.4	9.5	8.7	0.9					
7	2	4569.6	285.6	0.0	8.2	8.3	7.6	0.1					
8	2	4469.0	279.3	0.4	8.7	8.8	8.1	0.5					
9	2	3566.3	222.9	4.5	15.0	15.1	14.2	4.6					
10	2	6902.8	431.4	-5.4	0.0	0.1	-0.4	-5.3					
11	2	6119.7	382.5	-4.0	2.1	2.1	1.6	-4.0					
12	2	3181.0	198.8	7.0	18.7	18.9	17.8	7.1					
13	2	5976.9	373.6	-3.8	2.5	2.6	2.0	-3.7					
14	2	4234.6	264.7	1.3	10.1	10.2	9.4	1.4					
15	2	4238.0	264.9	1.3	10.1	10.2	9.4	1.4					
16	3	4031.2	268.7	1.2	2.0	1.6	-1.7	10.7	7.8	-3.2	7.2	0.8	0.8
17	3	4332.1	288.8	0.1	0.8	0.5	-2.7	8.9	6.2	-4.0	5.7	-0.3	-0.3
18	3	3168.6	211.2	5.6	6.6	6.2	1.9	17.7	14.0	0.1	13.3	5.0	5.1
19	3	5475.0	365.0	-3.1	-2.5	-2.8	-5.2	3.9	1.8	-6.3	1.4	-3.4	-3.4
20	3	3169.1	211.3	5.6	6.6	6.2	1.9	17.7	14.0	0.1	13.3	5.0	5.1
21	3	4208.3	280.6	0.5	1.3	0.9	-2.3	9.6	6.8	-3.7	6.3	0.1	0.1
22	3	3163.6	210.9	5.6	6.7	6.2	1.9	17.7	14.0	0.1	13.3	5.1	5.1
23	3	3408.0	227.2	4.1	5.1	4.7	0.7	15.4	11.9	-1.0	11.3	3.6	3.7
24	3	4054.1	270.3	1.1	1.9	1.5	-1.8	10.5	7.6	-3.2	7.1	0.7	0.7
25	3	3359.8	224.0	4.4	5.4	5.0	0.9	15.8	12.3	-0.8	11.7	3.9	3.9
26	4	3931.2	280.8	0.4	1.4	-2.7	5.5	-2.7	1.0	-2.7	-1.9	0.4	-2.0
27	4	3166.1	226.2	3.8	5.2	0.0	10.2	0.0	4.6	-0.0	1.1	3.9	0.9
28	4	3161.4	225.8	3.9	5.2	0.0	10.2	0.0	4.6	0.0	1.1	4.0	0.9
29	4	3359.4	240.0	2.8	4.1	-0.8	8.8	-0.8	3.5	-0.8	0.2	2.9	0.0
30	4	3163.5	226.0	3.8	5.2	0.0	10.2	0.0	4.6	0.0	1.1	3.9	0.9
31	5	3161.3	243.2	3.2	0.0	0.0	0.8	0.0					

Table 8-4 South Shore Oxidized WPL Addition, Regression Output for Equation 8-2.

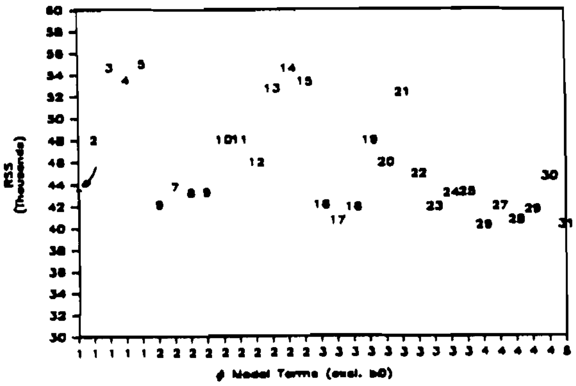
MODEL: SLUK = b0 + b1 dTSSK + b2 TSSIK + b3 FeK + b4 dSPK + b5 Q

Model	b0	b1	b2	b3	b4	b5	n	R2	S
1	85.82	0.35					76	0.18	24.3
	8.63	4.05							
2	86.84		0.23				76	0.10	25.5
	6.51		2.89						
3	135.35			-3.38			77	0.01	27.0
	8.88			-0.76					
4	124.23				0.27		76	0.00	26.9
	11.87				0.02				
5	127.53					-0.04	77	0.00	27.1
	11.94					-0.35			
6	101.00	0.67	-0.31				76	0.21	24.0
	7.58	3.20	-1.69						
7	82.95	0.35		0.71			76	0.18	24.5
	4.22	3.91		0.17					
8	74.83	0.37			10.03		76	0.19	24.3
	4.92	4.16			0.96				
9	93.23	0.36				-0.10	76	0.19	24.3
	7.27	4.13				-0.92			
10	89.43		0.23	-0.61			76	0.10	25.6
	3.93		2.73	-0.14					
11	84.15		0.23		2.74		76	0.10	25.6
	4.92		2.89		0.25				
12	94.95		0.30			-0.22	76	0.14	25.1
	6.85		3.43			-1.82			
13	135.93			-5.35	7.49		76	0.01	26.9
	8.81			-1.03	0.56				
14	138.95			-3.38		-0.04	77	0.01	27.2
	7.53			-0.76		-0.35			
15	127.03				2.30	-0.05	76	0.00	27.0
	10.15				0.19	-0.41			

Table 8-4, Continued.

Model	b0	b1	b2	b3	b4	b5	n	R2	S
16	99.16	0.68	-0.31	0.45			76	0.21	24.2
	4.57	3.17	-1.67	0.11					
17	86.80	0.81	-0.41		17.35		76	0.24	23.8
	5.47	3.60	-2.13		1.61				
18	100.07	0.81	-0.45			0.10	76	0.22	24.1
	7.43	2.63	-1.52			0.60			
19	89.02		0.23	-1.66	4.90		76	0.10	25.8
	3.88		2.68	-0.32	0.38				
20	93.36		0.30	0.39		-0.23	76	0.14	25.3
	4.14		3.28	0.09		-1.80			
21	143.27			-6.40	12.56	-0.10	76	0.02	27.0
	7.72			-1.18	0.83	-0.72			
22	82.91		0.33		15.41	-0.31	76	0.16	25.0
	4.97		3.67		1.29	-2.22			
23	79.86	0.40			17.65	-0.18	76	0.22	24.1
	5.17	4.43			1.53	-1.50			
24	79.31	0.36		-1.68	12.13		76	0.19	24.5
	3.97	3.99		-0.35	1.00				
25	89.89	0.36		0.84		-0.10	76	0.19	24.5
	4.27	3.99		0.20		-0.92			
26	99.52	0.84	-0.46	-4.30	23.50		76	0.25	23.8
	4.66	3.69	-2.28	-0.89	1.83				
27	99.26	0.81	-0.45	0.20		0.10	76	0.22	24.3
	4.55	2.61	-1.50	0.05		0.59			
28	86.94	0.83	-0.44		16.98	0.02	76	0.24	23.9
	5.42	2.72	-1.48		1.48	0.10			
29	89.94	0.39		-3.55	23.01	-0.20	76	0.22	24.2
	4.32	4.28		-0.73	1.67	-1.63			
30	93.36		0.32	-3.58	20.75	-0.33	76	0.17	25.1
	4.17		3.50	-0.70	1.46	-2.30			
31	99.52	0.85	-0.46	-4.29	23.40	0.00	76	0.25	24.0
	4.63	2.76	-1.55	-0.88	1.72	0.02			

Figure 8-4 South Shore Oxidized WPL Addition, RSS vs. Number of Model Terms (excluding b_0) and Sequential F Values for Models in Table 8-4. Data labels represent model number.



M	TERM	RSS	MSE	Sequential F Values									
1	1	43771.6	591.5										
2	1	48035.3	649.1										
3	1	54659.7	728.8										
4	1	53466.8	722.5										
5	1	54995.1	733.3										
6	2	42132.3	577.2	2.8	10.2	21.7	19.6	22.3					
7	2	43754.3	599.4	0.0	7.1	18.2	16.2	18.8					
8	2	43229.4	592.2	0.9	8.1	19.3	17.3	19.9					
9	2	43272.6	592.8	0.8	8.0	19.2	17.2	19.8					
10	2	48022.3	657.8	-6.5	0.0	10.1	8.3	10.6					
11	2	47992.9	657.4	-6.4	0.1	10.1	8.3	10.7					
12	2	45954.0	629.5	-3.5	3.3	13.8	11.9	14.4					
13	2	52699.1	721.9	-12.4	-6.5	2.7	1.1	3.2					
14	2	54569.2	737.4	-14.6	-8.9	0.1	-1.5	0.6					
15	2	53341.9	730.7	-13.1	-7.3	1.8	0.2	2.3					
16	3	42125.4	585.1	0.0	2.8	1.9	2.0	10.1	10.0	6.5	18.1	21.3	19.2
17	3	40674.4	564.9	2.6	5.5	4.5	4.6	13.0	13.0	9.3	21.3	24.6	22.4
18	3	41921.9	582.2	0.4	3.1	2.2	2.3	10.5	10.4	6.9	18.5	21.7	19.6
19	3	47924.4	665.6	-8.7	-6.3	-7.1	-7.0	0.1	0.1	-3.0	7.2	10.0	8.1
20	3	45948.9	638.2	-6.0	-3.4	-4.3	-4.2	3.2	3.2	0.0	10.6	13.5	11.6
21	3	52323.3	726.7	-14.0	-11.8	-12.5	-12.5	-5.9	-6.0	-8.8	0.5	3.1	1.4
22	3	44919.9	623.9	-4.5	-1.9	-2.7	-2.6	5.0	4.9	1.7	12.5	15.5	13.5
23	3	41916.8	582.2	0.4	3.2	2.3	2.3	10.5	10.4	6.9	18.5	21.7	19.6
24	3	43156.7	599.4	-1.7	1.0	0.1	0.2	8.1	8.1	4.7	15.9	19.0	17.0
25	3	43248.3	600.7	-1.9	0.8	-0.0	0.0	7.9	7.9	4.5	15.7	18.8	16.8
26	4	40223.8	566.5	3.4	0.8	3.0	13.6	10.1	21.4	8.3	3.0	5.2	5.3
27	4	41920.5	590.4	0.3	-2.1	0.0	10.2	6.8	17.6	5.1	-0.0	2.1	2.2
28	4	40668.6	572.8	2.5	0.0	2.2	12.7	9.2	20.3	7.4	2.2	4.3	4.5
29	4	41608.2	586.0	0.9	-1.6	0.5	10.8	7.4	18.3	5.7	0.5	2.6	2.8
30	4	44608.9	628.3	-4.0	-6.3	-4.3	5.3	2.1	12.3	0.5	-4.3	-2.3	-2.2
31	5	40223.6	574.6	0.0	3.0	0.8	2.4	7.6					

differences in solids removal.

8.2.2 Oxidized WPL Addition

Model 1, containing the single dTSSK term, is the best regression in Table 8-4. It only explains 18% of the variation, but adding more variables to the model does not significantly improve the prediction. Iron dose and SP terms are insignificant in all models.

8.3 SUMMARY

The following conclusions are drawn based on the observations and analyses presented in Chapters Seven and Eight:

1) The average Fe/P_C mole ratio of 2.32, and the relatively high primary effluent SP values (Ave. = 0.8 mg/l) indicate that SP removal occurred stoichiometrically during the period of oxidized WPL addition.

2) No useful causal relationship between SP removal and iron dose was developed.

3) The fraction of estimated chemical sludge is small in comparison to observed primary sludge production (19.7% by weight for unoxidized WPL, and 6.7% by weight for oxidized WPL).

4) Multiple regression analyses indicated that changes in iron dose and SP removal did not affect primary sludge production for the periods of unoxidized and oxidized WPL addition.

CHAPTER NINE: JONES ISLAND WWTP

9.1 BACKGROUND

The Jones Island sewage treatment plant is located on the shore of Lake Michigan at the harbor entrance to Milwaukee, Wisconsin. The wastewater originates from industries, offices, and residential areas in the eastern and northern portions of the Milwaukee Metropolitan Sewerage District's (MMSD) 420 square mile service area.

In July 1979, the State of Wisconsin legislated a ban on phosphate based detergents. This ban was repealed in July 1982. A second detergent phosphate ban became law in January 1984.

9.2 PROCESS DESCRIPTION

The plant consists of a newer west plant, which treats approximately 40% of the flow, and an original east plant, which treats the remaining flow. Figure 9-1 is a schematic of the facility prior to November 1986.

Prior to November 1986, the liquid process operation included preliminary treatment (coarse screening, grit removal, and fine screening), activated sludge, secondary clarification, and chlorination. In November 1986, primary clarifiers replaced the original pretreatment steps. High Lake Michigan lake levels in late 1986 forced the temporary abandonment of preliminary treatment.

In the original preliminary treatment configuration, debris solids were landfilled or shipped to South Shore for incineration.

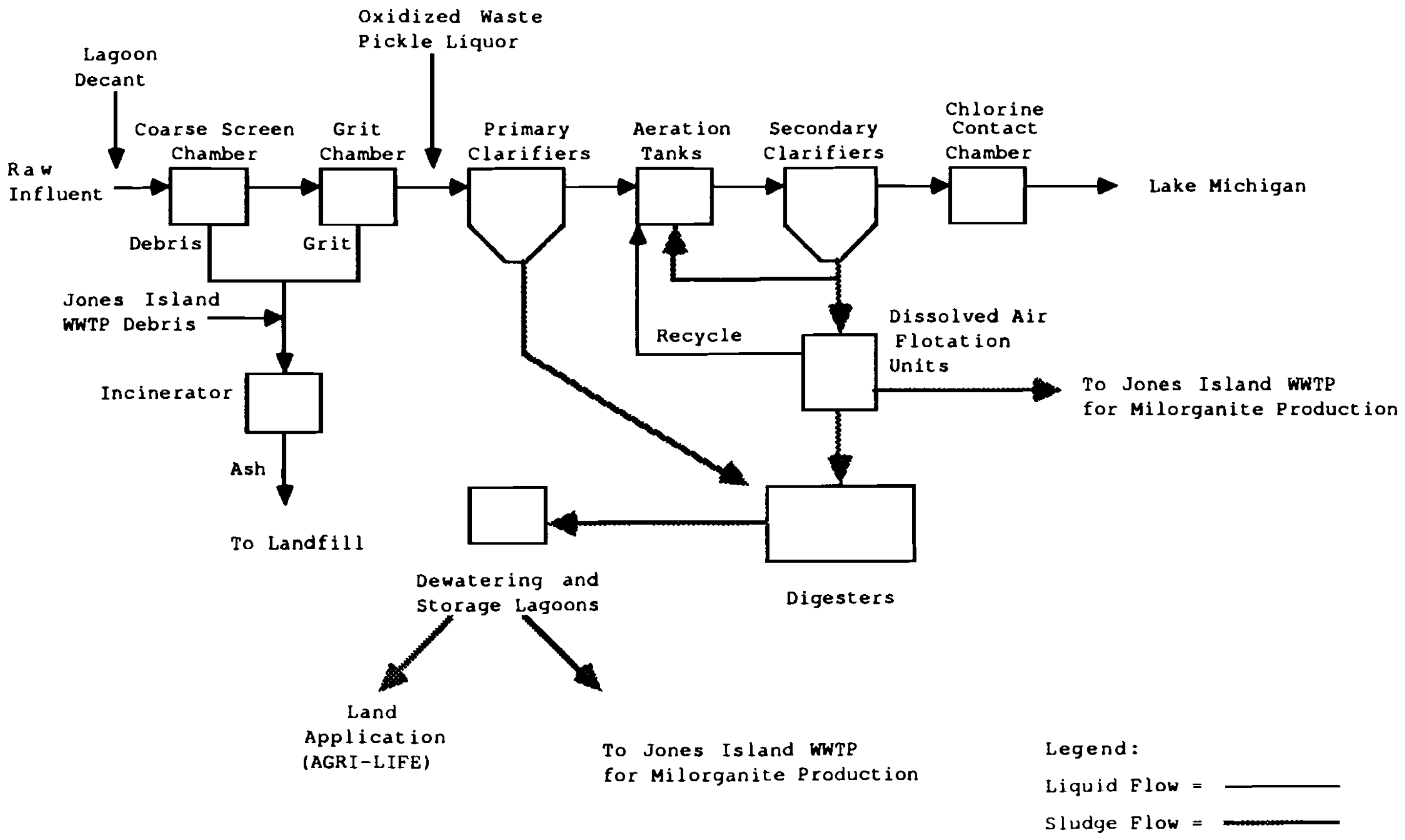


Figure 9-1 Jones Island Process Flow Diagram.

Vacuum filters are used to dewater gravity thickened waste activated sludge. Heat drying of dewatered sludge is the final step in the production of Milorganite, a revenue generating fertilizer.

Chemical phosphorus removal is accomplished by the addition of iron at two points. In the east plant, waste pickle liquor (WPL) is added to the mixing channels ahead of aeration. In the west plant, sludge dewatering filtrate is recycled to the aeration basins. Ferric chloride is used for sludge conditioning. Additional iron enters the west plant with waste activated sludge from the east plant.

9.3 OPERATIONS DATA

Operations records were obtained from an existing data base at the University of Wisconsin-Madison. The data base was expanded on two trips to the facility in September 1986 and March 1987.

9.4 RAW INFLUENT CONDITIONS

Figure 9-2 shows that the influent flow to the plant has been reasonably stationary. (ave. = 131.1, S.D.= 15.8, n = 142).

Figures 9-3a,b and 9-4a,b show raw influent wastewater BOD and TSS conditions in terms of both concentration and mass loading. Both BOD and TSS decreased gradually from 1975 to 1981. Starting in late 1982, there was approximately one year of increased values. Correlation coefficients on Figures 9-3d and 9-4d indicate no significant dilution effect.

Figures 9-5 through 9-7 show influent phosphorus data. Soluble

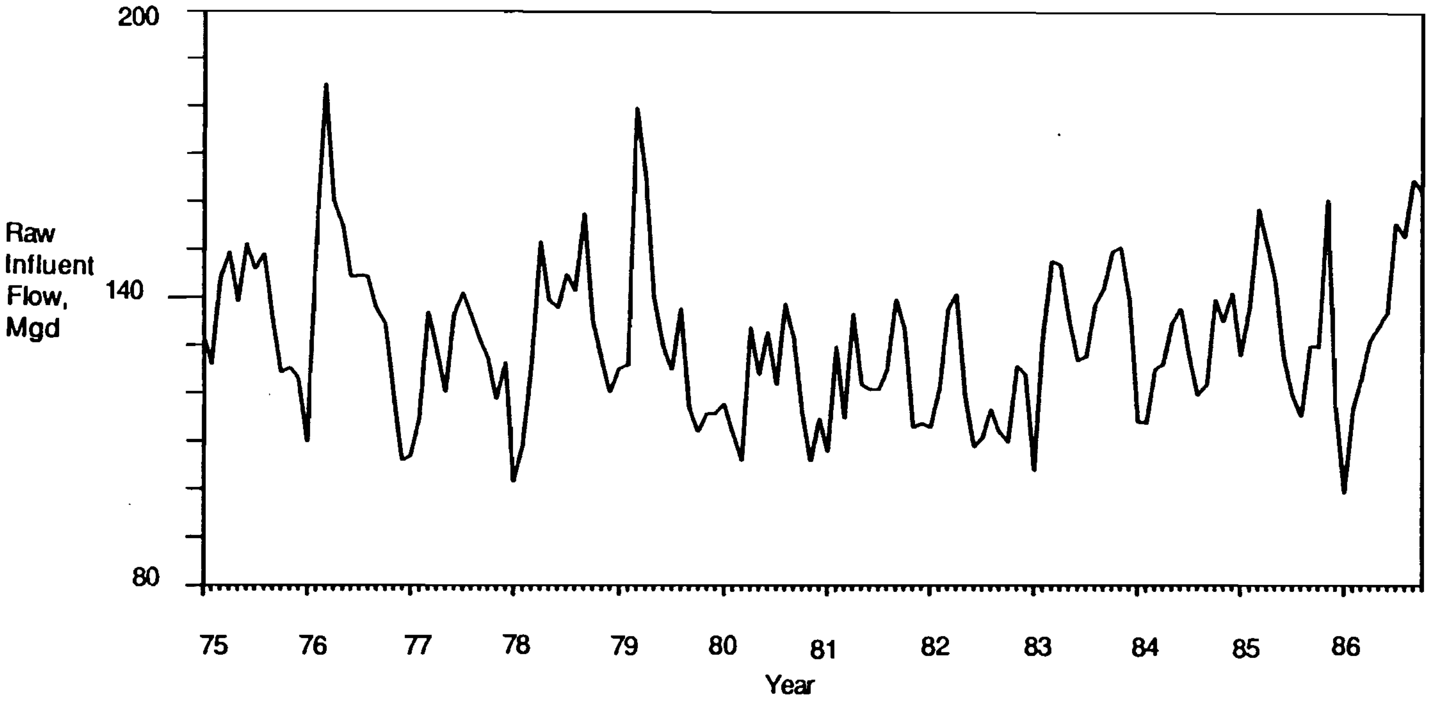


Figure 9-2 Jones Island Raw Influent Flow.

Figure 9-3 Jones Island Raw Influent a) BOD Concentration, b) BOD Mass Loading, c) BOD Concentration vs. Mass Loading, d) BOD Concentration vs. Flow.

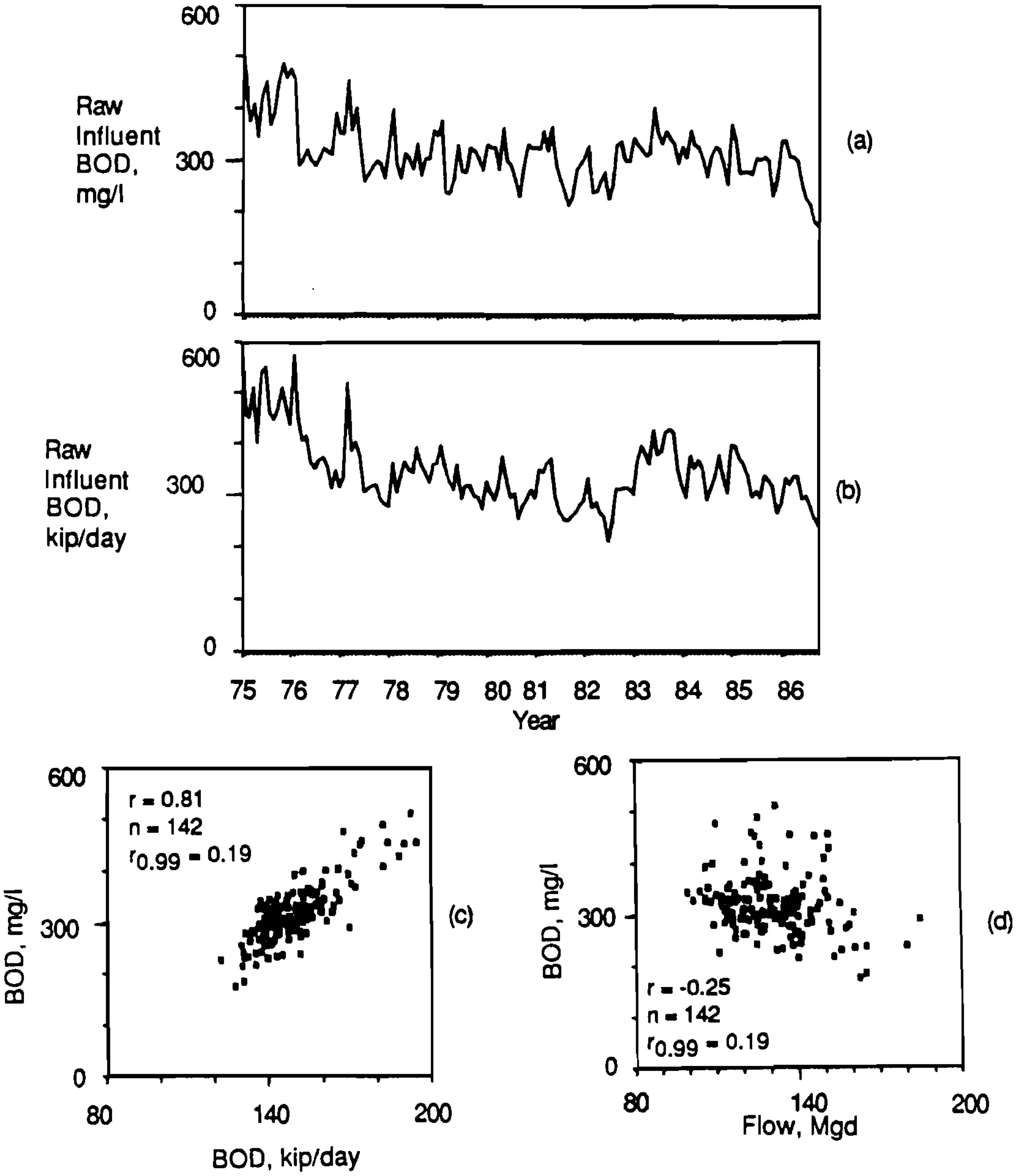


Figure 9-4 Jones Island Raw Influent a) TSS Concentration, b) TSS Mass Loading, c) TSS Concentration vs. Mass Loading, d) TSS Concentration vs. Flow.

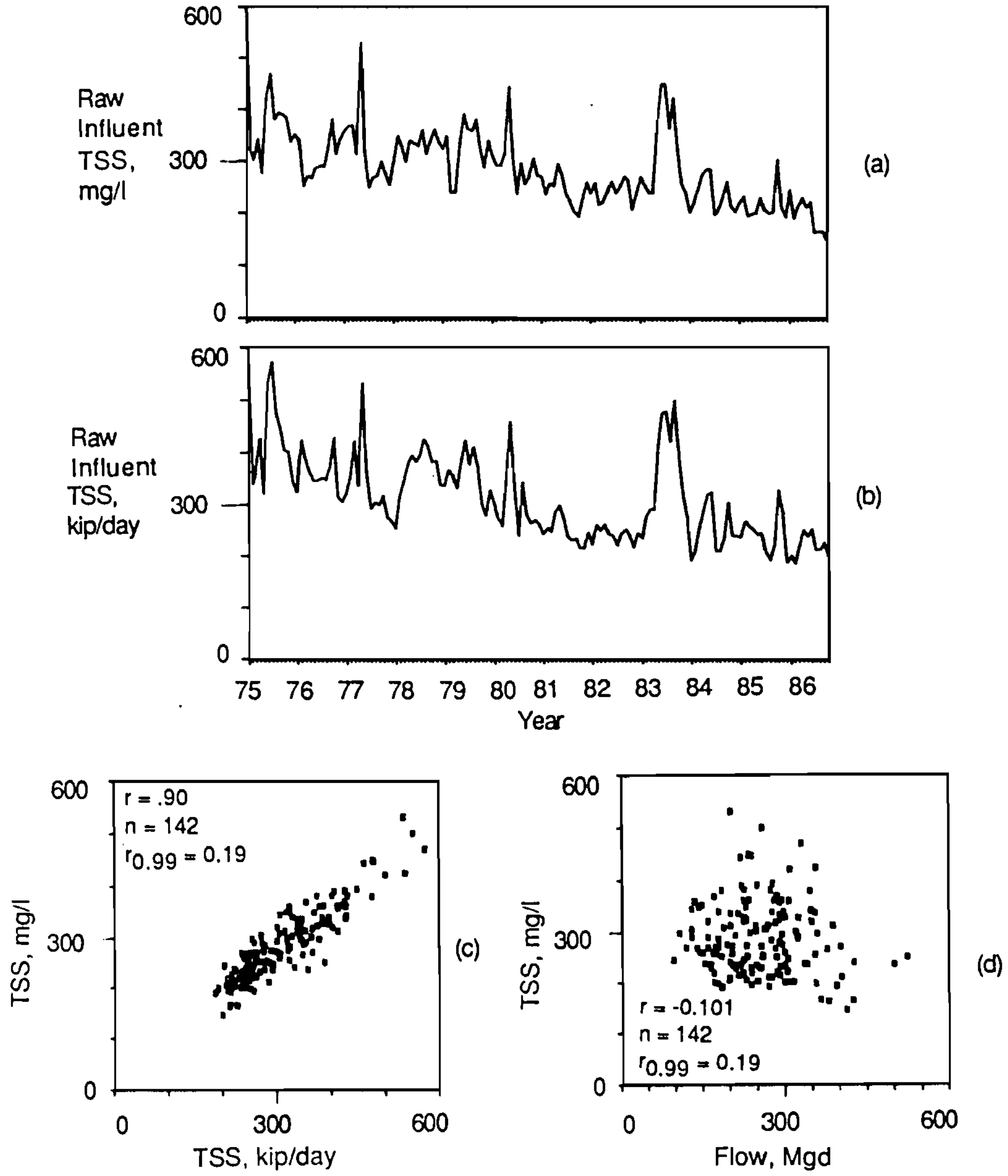


Figure 9-5 Jones Island Raw Influent a) TP Concentration, b) TP Mass Loading, c) TP Concentration vs. Mass Loading, d) TP Concentration vs. Flow.

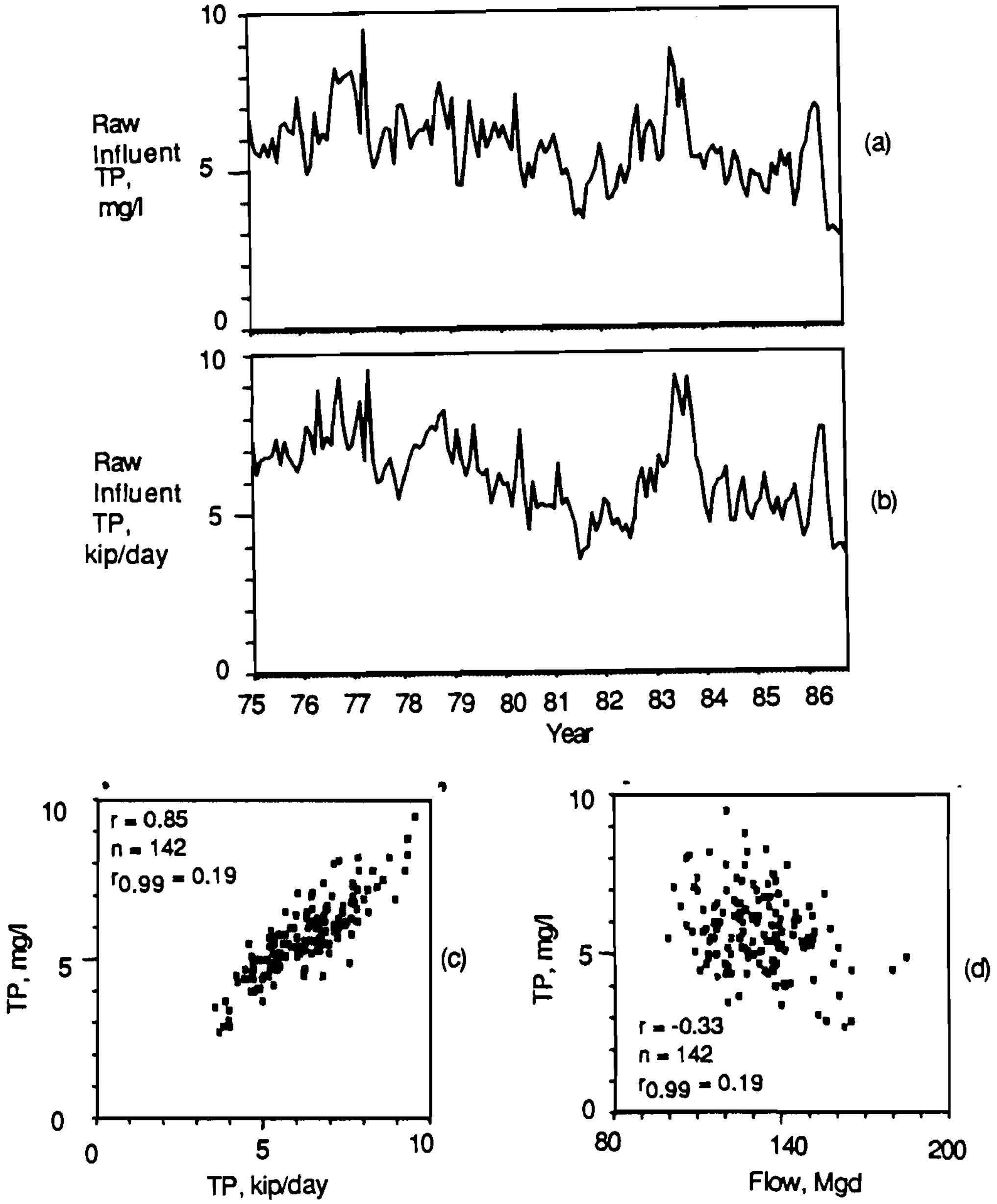


Figure 9-6 Jones Island Raw Influent a) SP Concentration, b) SP Mass Loading, c) SP Concentration vs. Mass Loading, d) SP Concentration vs. Flow.

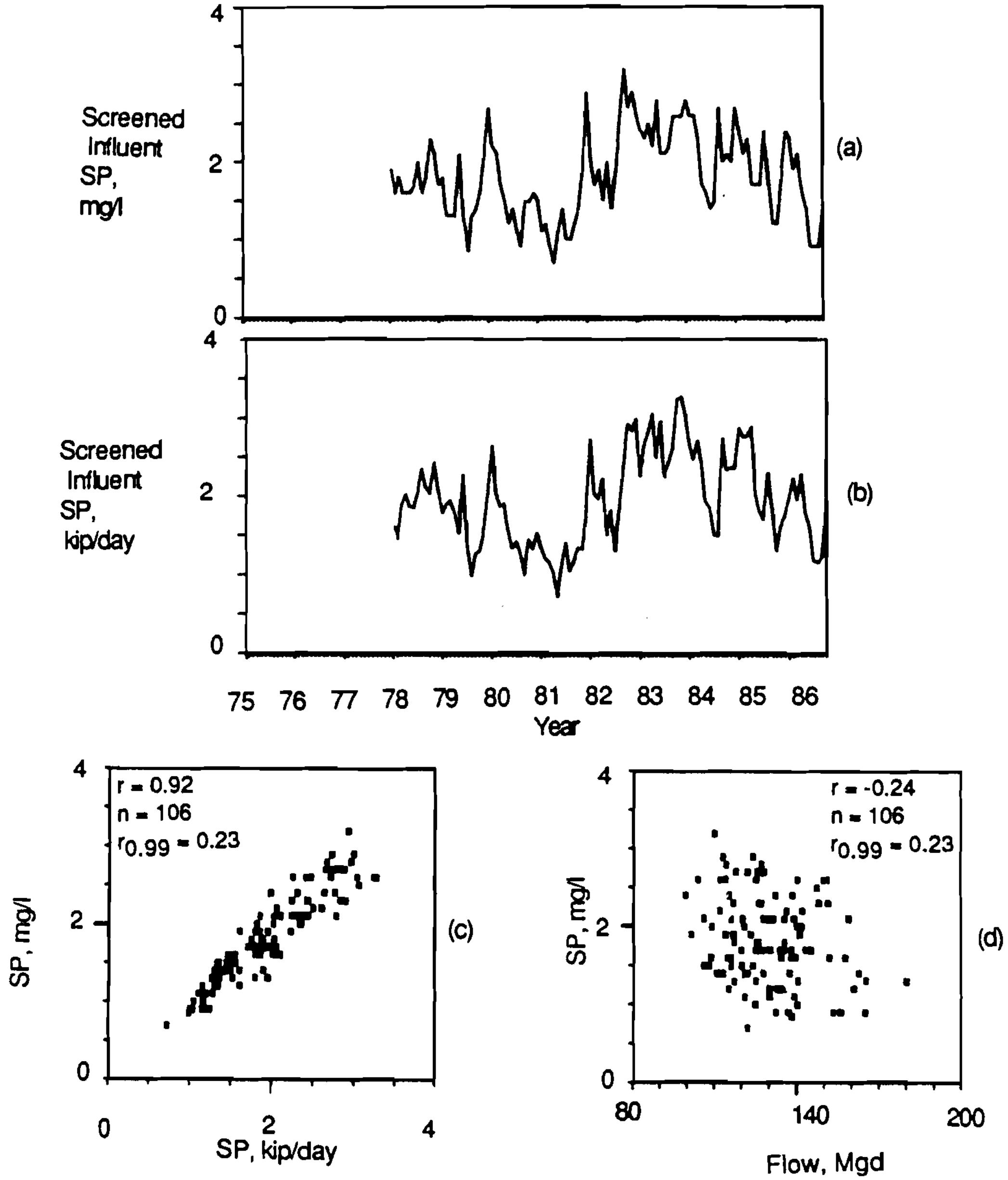
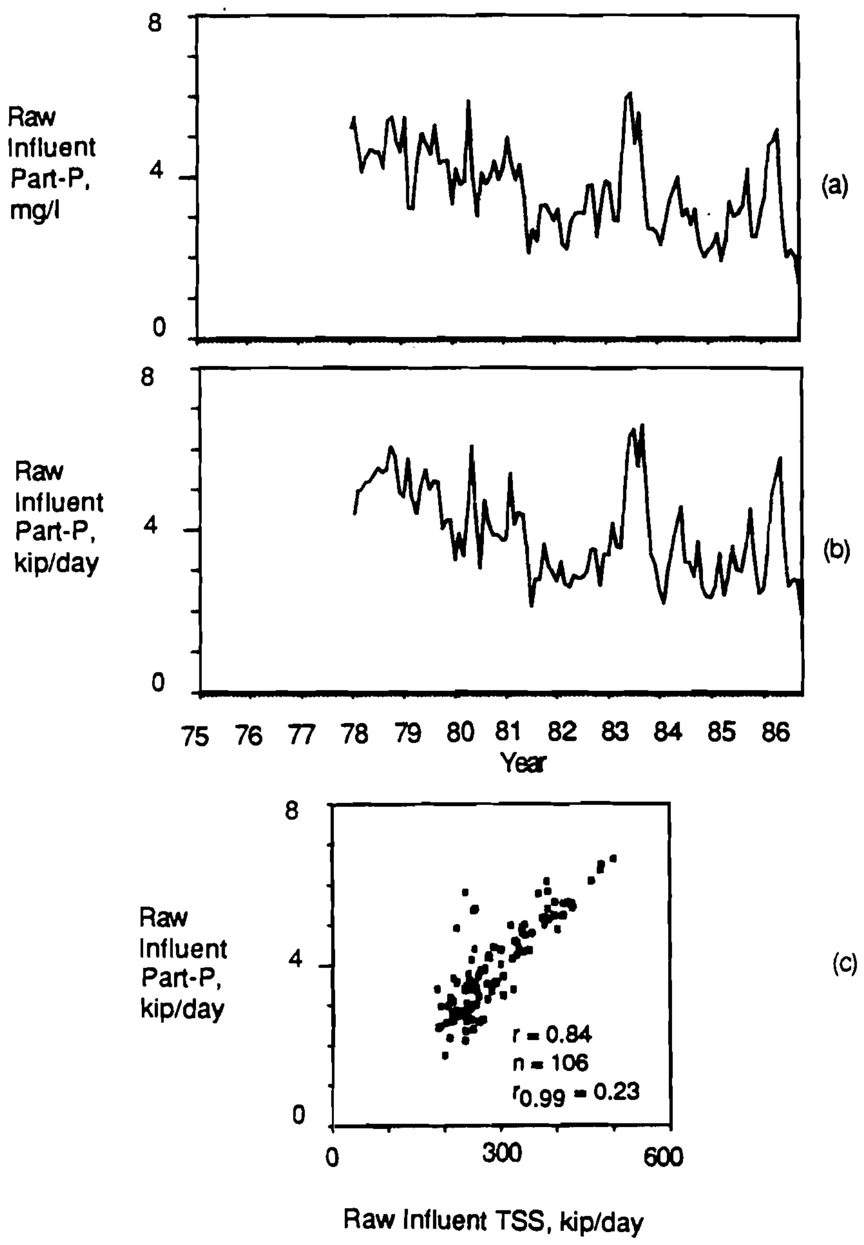


Figure 9-7 Jones Island Raw Influent a) Calculated Particulate Phosphorus Concentration (TPI - SPI), b) Calculated Particulate Phosphorus Mass Loading, c) Calculated Particulate Phosphorus (TPI - SPI) Mass Loading vs. Suspended Solids Mass Loading.



phosphorus (SP) measurements were not taken in the raw influent. The screened effluent is probably an adequate measure of the raw influent value since pre-treatment primarily removes large screenable and settleable solids.

The total phosphorus (TP) and particulate phosphorus (TPI - SPI) raw influent trends in Figures 9-5 and 9-7 closely resemble influent BOD and TSS trends, with a peak from mid-1982 to mid-1983. SP mass loading appears to have decreased steadily until mid-1981 before trending upward until late 1983. Since late 1983 influent SP concentrations and mass loading have been trending downward. These increases and decreases in influent SP trends roughly correspond to the detergent phosphate legislation.

Figure 9-7c shows a highly significant correlation between influent particulate phosphorus (TP -SP) and influent suspended solids.

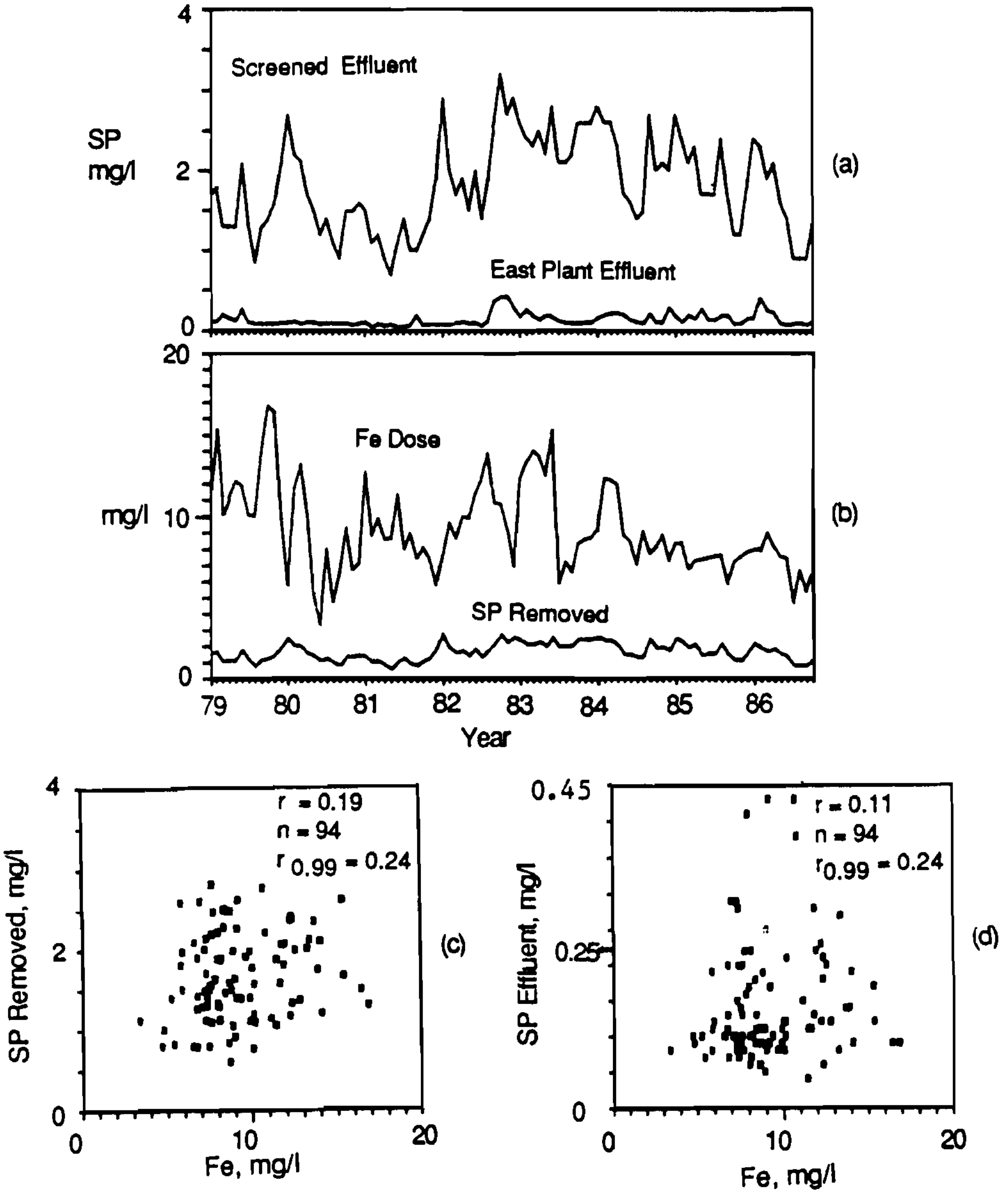
9.5 EAST PLANT

9.5.1 Soluble Phosphorus Removal

Measurements of screened effluent and east plant effluent wastewater parameters (available since 1979) were used to study changes resulting from WPL addition to the east plant.

Figure 9-8c shows that SP removal in the east plant is not significantly correlated with iron dose. Figure 9-8d shows that many of the residual SP values are very low (ave. = 0.14, S.D. = 0.08, n = 94) and independent of iron dose. It is possible that many of these

Figure 9-8 Jones Island East Plant a) Influent and Effluent SP vs. Year, b) Fe Dose and SP Removed (SPI - SPO) vs. Year, c) SP Removed vs. Fe Dose, d) SP Effluent vs. Fe Dose.



values are at or very near the solubility limit for orthophosphate.

Figure 9-9a shows the Fe/P_C mole ratio plotted against east plant effluent SP. SP removal appears to be both stoichiometric and non-stoichiometric. This partially explains why the relationship in Figure 9-8c is not linear. Figure 9-9b indicates that in the early 1980's iron was added in excess of the stoichiometric requirement.

Figure 9-10 shows effluent SP data plotted against final effluent pH. The theoretical curve was calculated with the model presented in Chapter Two.

9.5.2 pH

Screened effluent pH data are available for 1983 to the present. This screened value is consistently 0.1 pH unit higher than the raw influent pH. To make use of more data, Figure 9-11 shows raw influent and final effluent pH data since 1979. The pH change is in the expected direction (Figure 9-11c).

9.5.3 Biological Removal

Figures 9-12 shows that SP removal is significantly correlated with BOD removal, F/M ratio, air sewage ratio, and sludge age. Increased aeration can promote biological growth and subsequent nutrient removal. This may partially explain the relationships in Figures 9-12a and 9-12b. Increased sludge ages theoretically result in lower substrate effluents, which may partially explain Figure 9-12d. BOD removal is a measure of biological action and settled particulate

Figure 9-9 Jones Island East Plant a) Fe/P_C Mole Ratio vs. SP Effluent b) Fe/P_C Mole Ratio vs. Year (for P_C = SPI - SPO).

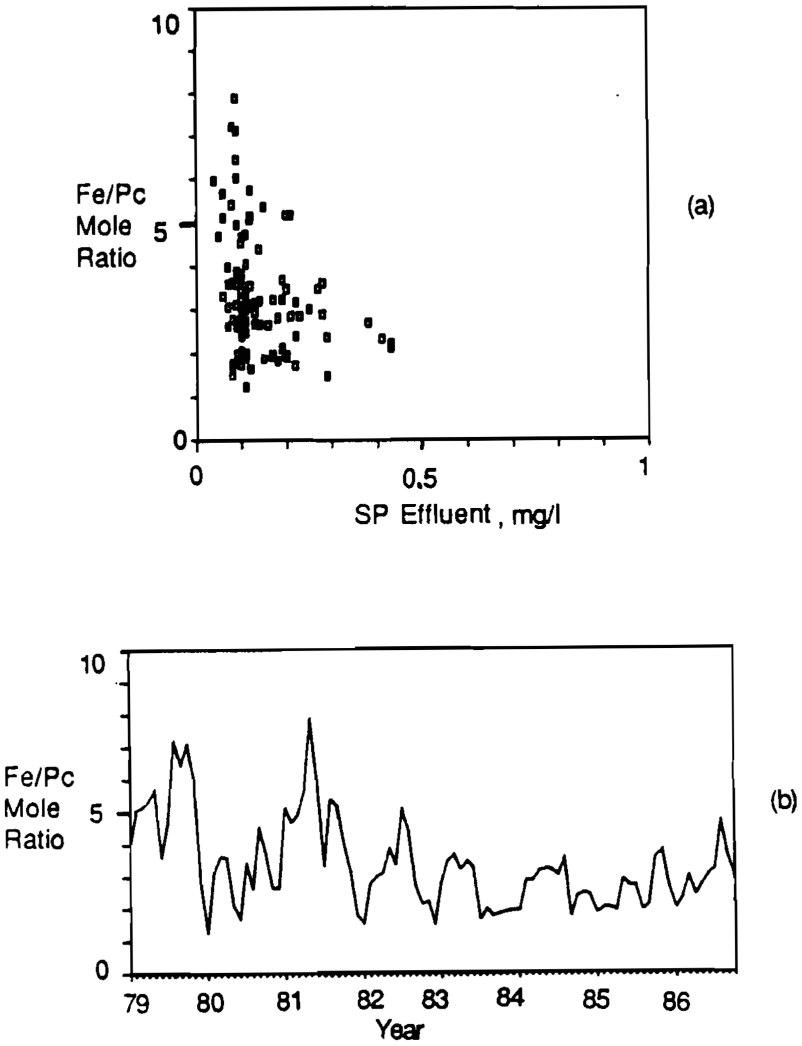


Figure 9-10 Jones Island East Plant a) Log_{10} Effluent Soluble Phosphorus mol/l vs. Final Effluent pH.
Note: See text for discussion on theoretical curve.

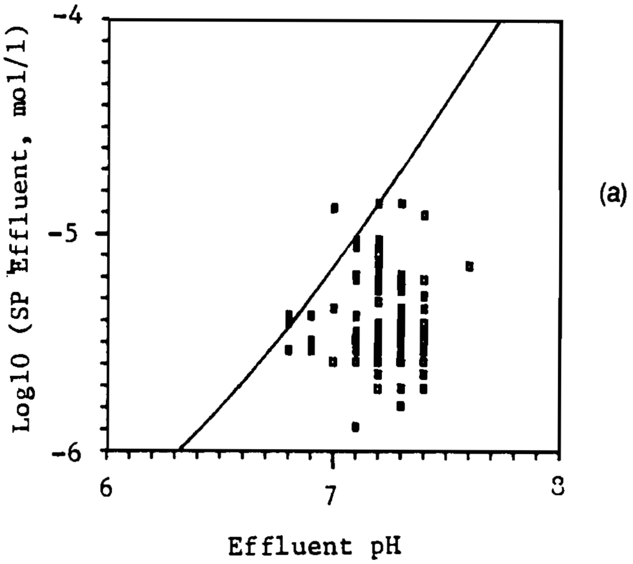
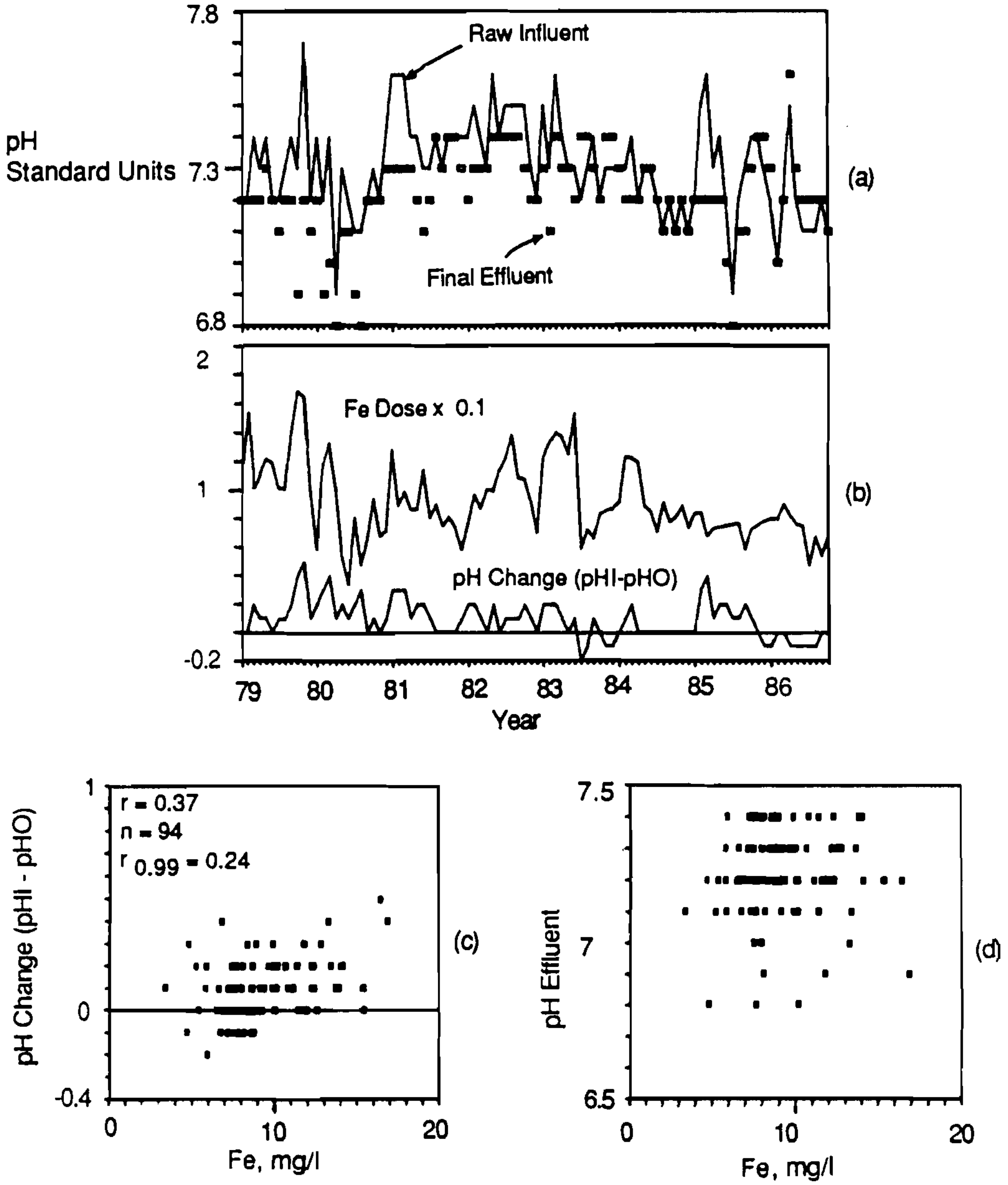


Figure 9-11 Jones Island East Plant a) Raw Influent and Final Effluent pH vs. Year, b) Iron Dose and pH Change vs. Year, c) pH Change vs Fe Dose, d) Final pH vs. Fe Dose.



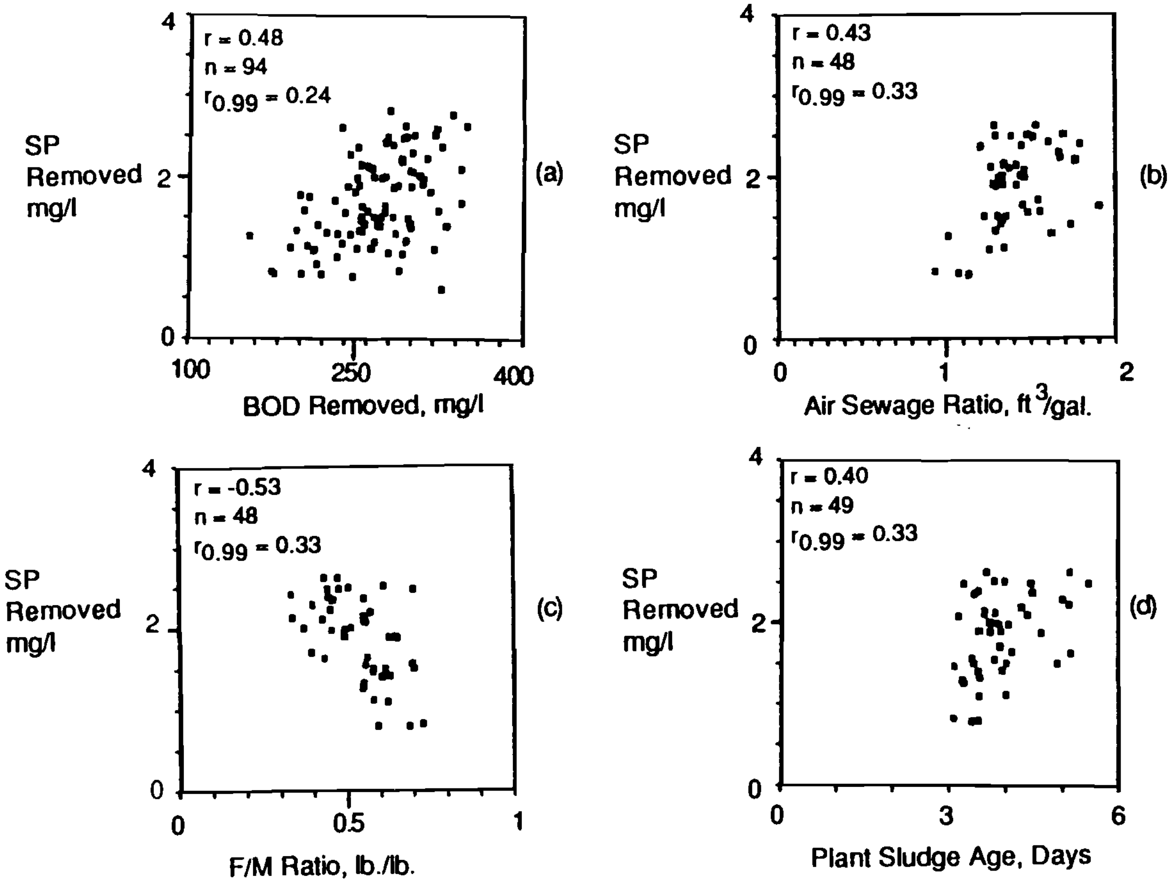


Figure 9-12 Jones Island East Plant a) SP Removed vs. BOD Removal, b) SP Removed vs. Air Sewage Ratio, c) SP Removed vs. F/M Ratio, d) SP Removed vs. Average Sludge Age for Entire Plant.

BOD, because primary clarifiers are not used.

9.5.4 BOD, TSS, and TP

Figures 9-13 through 9-15 do not show any strong relationships between iron dose and BOD, TSS, and TP removal or the effluent values of these parameters. Figures 9-14c and 9-15c indicate that TSS and TP removal increase with increasing iron dose. However, this trend may be the result of a time effect. Screened influent suspended solids and TP have decreased over most of the time period studied and this coincides with decreasing iron doses (Fe:TSSI, $r = 0.29$, $n = 94$, $r_{0.99} = 0.24$; Fe:TPI, $r = 0.38$, $n = 94$).

9.6 WEST PLANT

The quantity of soluble iron in the sludge processing recycle that goes to the west plant is not measured, and west plant effluent measurements of phosphorus BOD and TSS are not taken. Also, the precipitation potential of iron in sludge wasted from the east plant to the west is unknown. For these reasons, the analysis of west plant phosphorus removal is based upon the following assumptions:

1) The amount of iron available for precipitation in the conditioning recycle is proportional to conditioning ferric chloride use.

2) Mass balance calculations on wastewater flows and parameter concentrations can be used to estimate west plant effluent concentrations of BOD, TSS, TP, and SP. Assume negligible sludge

Figure 9-13 Jones Island East Plant a) Influent and Effluent BOD vs. Year, b) BOD Removed and Fe Dose vs. Year, c) BOD Removed vs. Fe Dose, d) BOD Effluent vs. Fe Dose.

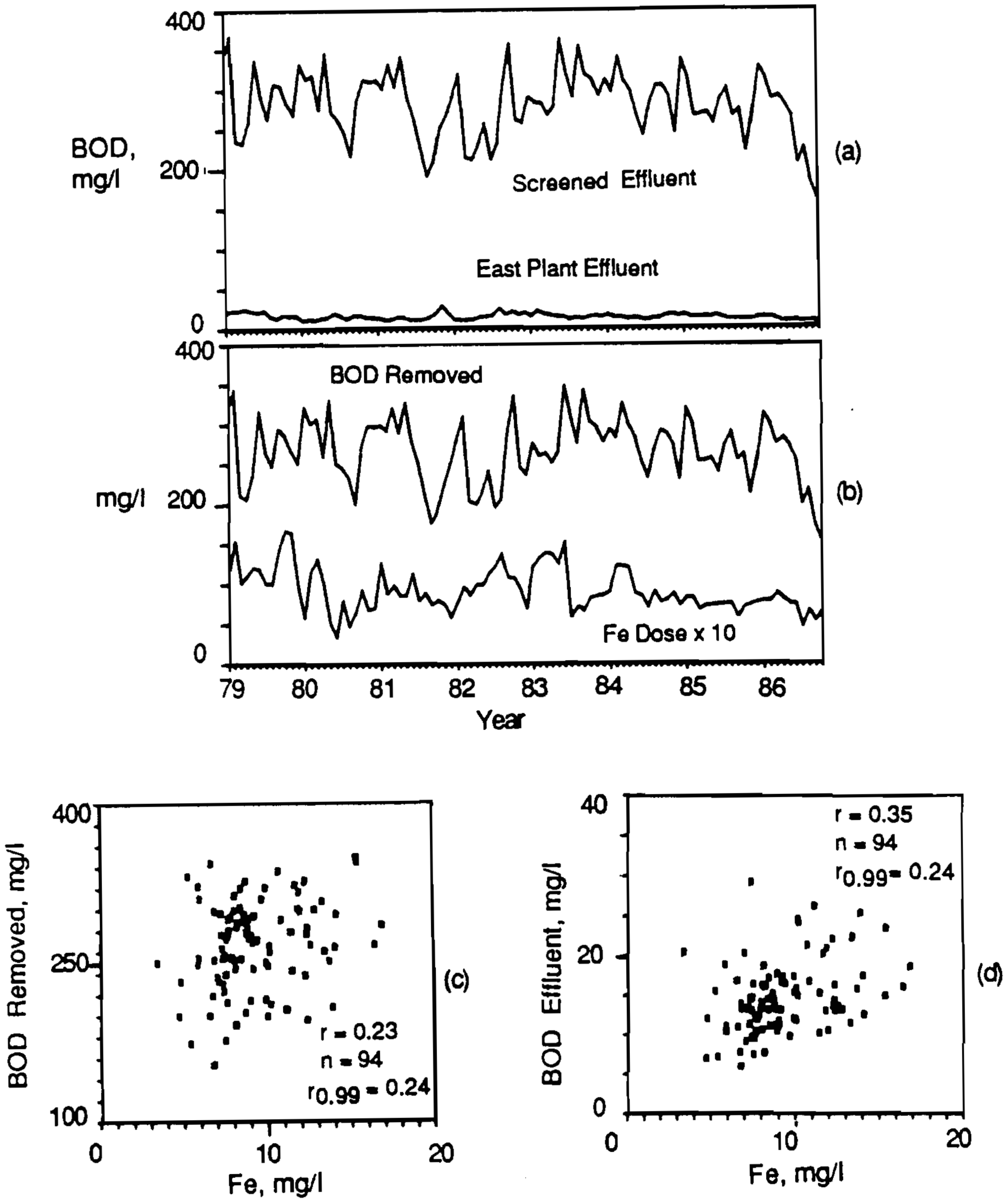


Figure 9-14 Jones Island East Plant a) Influent and Effluent TSS vs. Year, b) TSS Removed and Fe Dose vs. Year, c) TSS Removed vs. Fe Dose, d) TSS Effluent vs. Fe Dose.

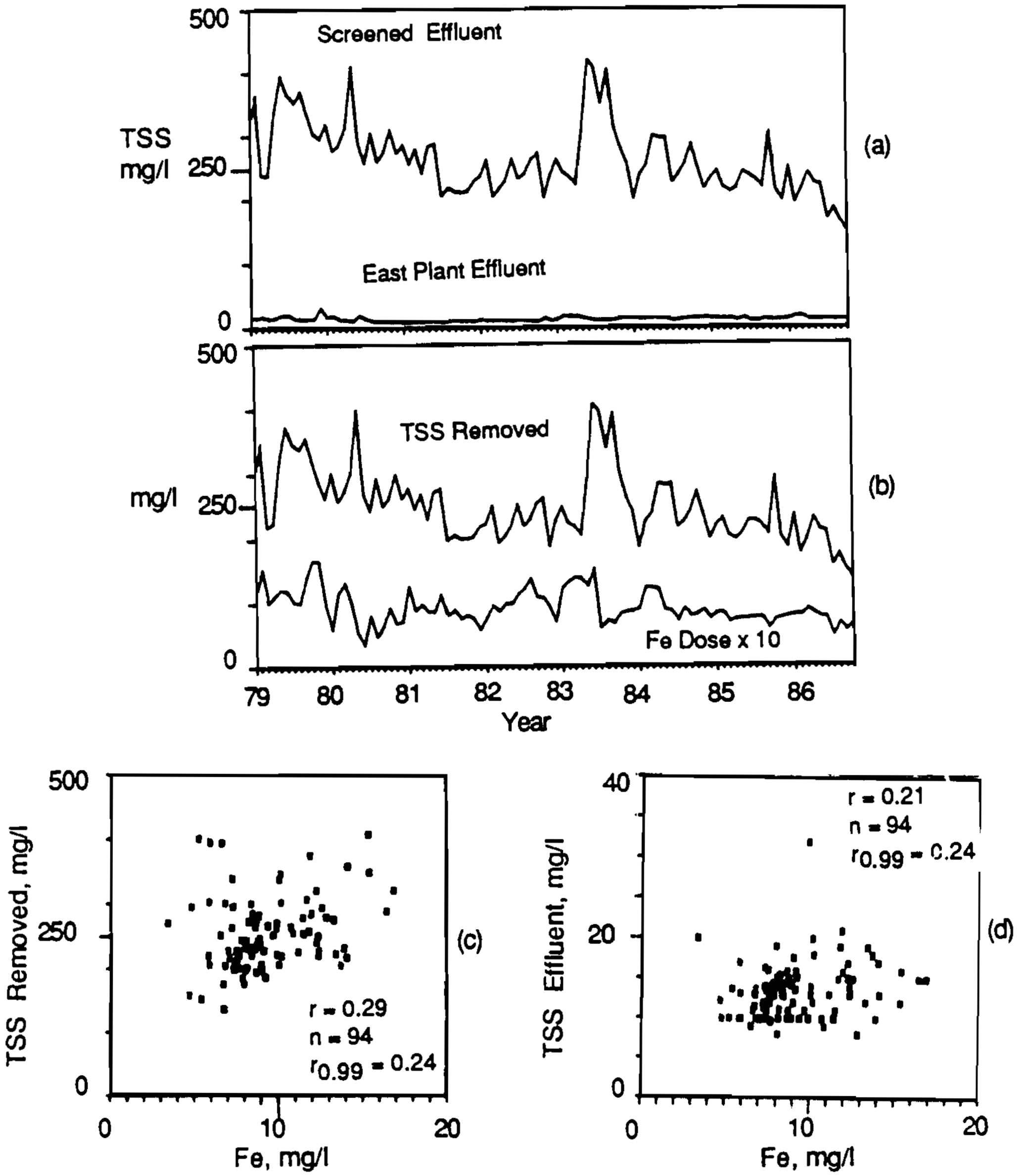
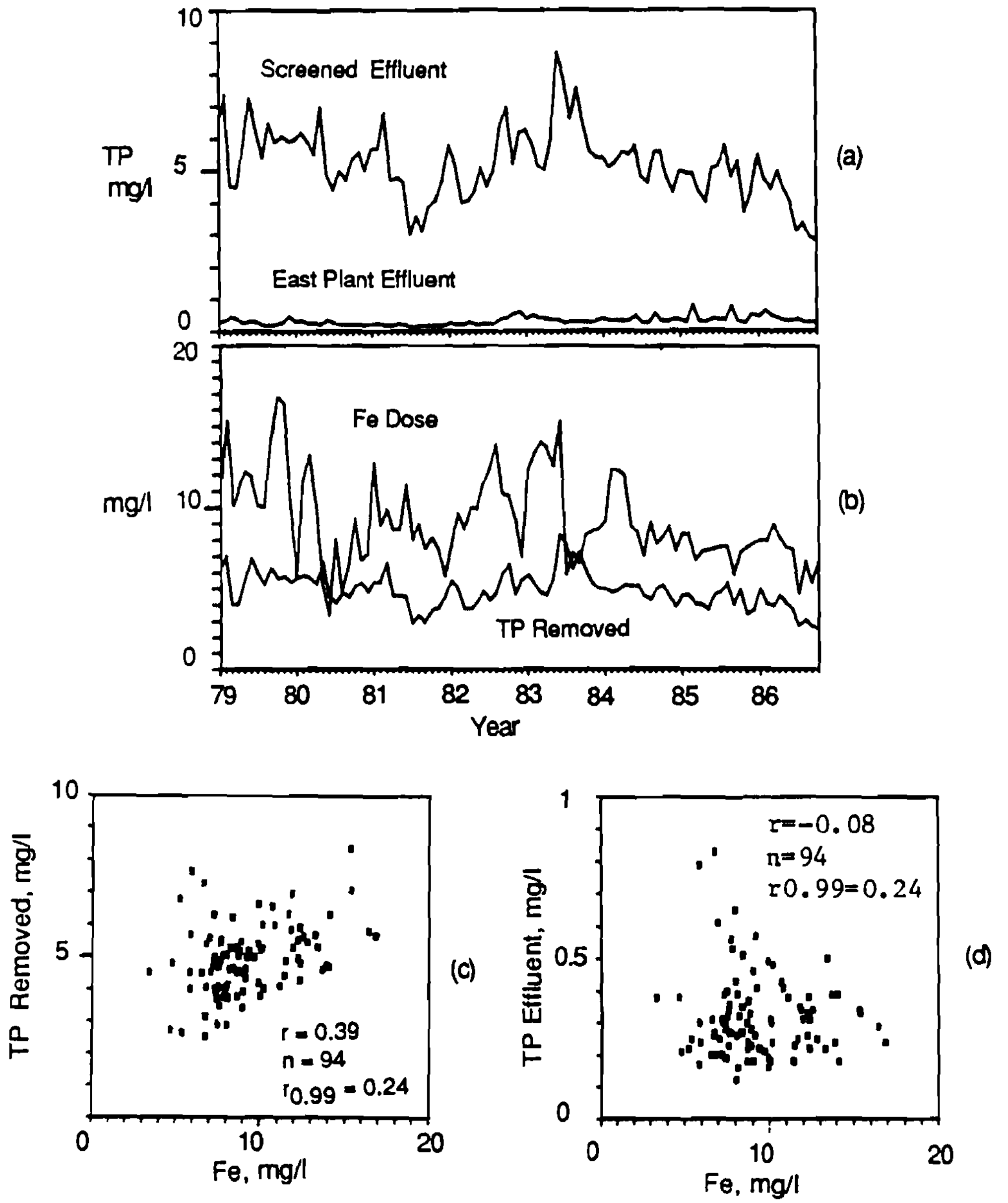


Figure 9-15 Jones Island East Plant a) Influent and Effluent Total Phosphorus vs. Year, b) TP Removed and FeDose vs. Year, c) TP Removed vs. Fe Dose, d) TP Effluent vs. Fe Dose.



flows.

3) The amount of iron added to the west plant from the east plant waste sludge flow is either a) small in comparison to the amount of iron available from conditioning, or b) a constant value, so that variation in SP removal will not be affected by this contribution.

Data for ferric chloride use ($FeCl_3$ (lbs.)/dry ton sludge), waste activated sludge flows, and sludge solids concentrations were used to calculate $FeCl_3$ use in kips/day.

East plant and total process flow; and screened, east plant effluent, and final effluent measurements of BOD, TSS, TP and SP were used in a mass balance calculation to estimate west plant effluent BOD, TSS, TP, and SP.

Figure 9-16 shows the calculated data. Figure 9-16c reveals no obvious relationship between conditioning iron use and SP removal in the west plant. Figure 9-16d indicates that effluent SP concentration decreases with increasing condition iron use, however the correlation coefficient is insignificant at 99% confidence. Elimination of the largest $FeCl_3$ value does not make the correlation significant.

Figure 9-17a is a plot of $FeCl_3/P_c$ (mass/concentration) vs. the estimated west plant effluent SP. The shape of the relationship is very similar to Figure 2-3. At the low effluent SP concentrations the ratio of iron to SP removed is relatively large, suggesting that non-stoichiometric precipitation may occasionally occur.

Figure 9-16 Jones Island West Plant a) Screened Effluent and Estimated Effluent SP, b) Ferric Chloride Use in Conditioning and SP Removed, c) SP Removed vs. $FeCl_3$ Use, d) SP Effluent vs. $FeCl_3$ Use. See text for discussion on estimated values.

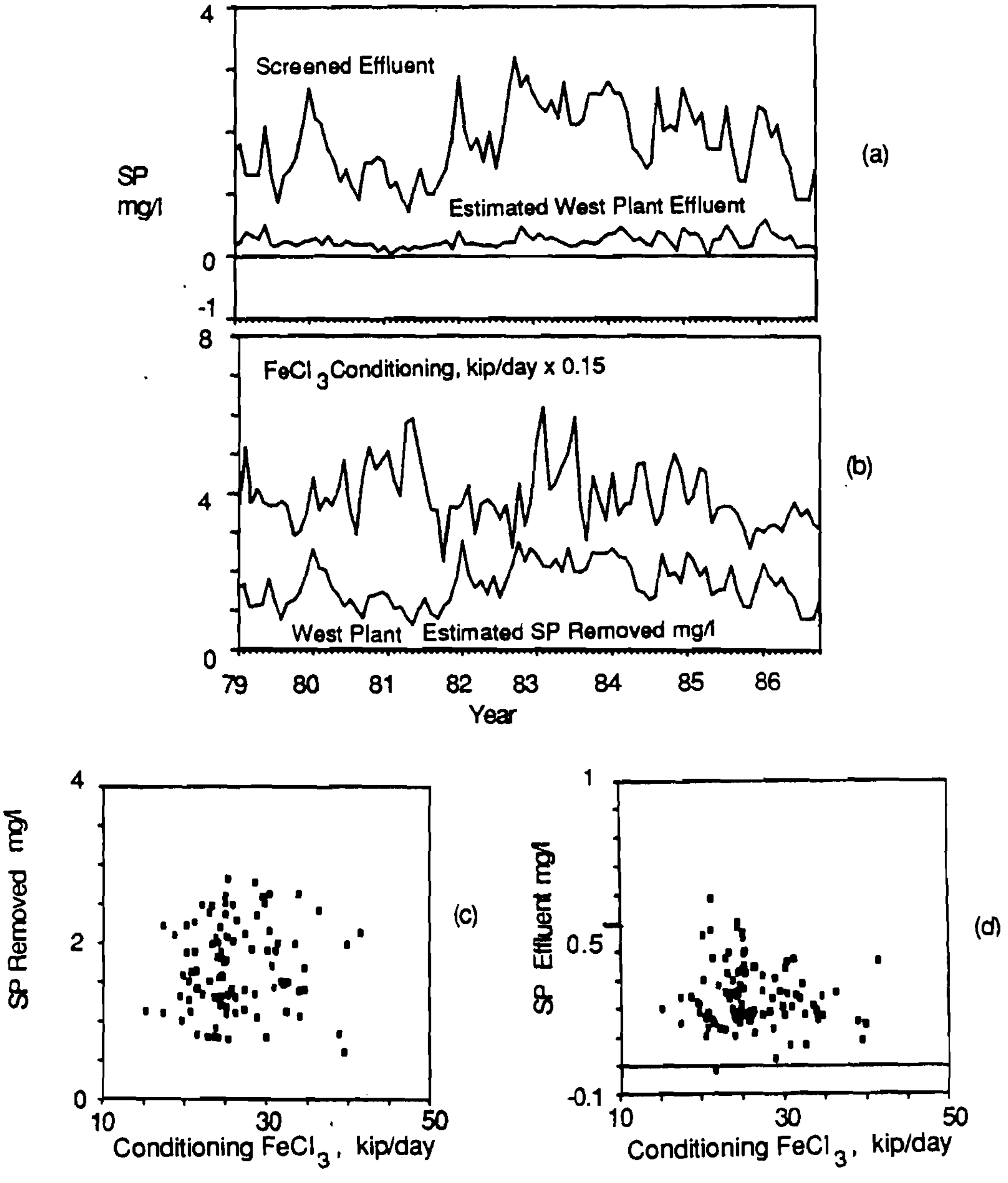
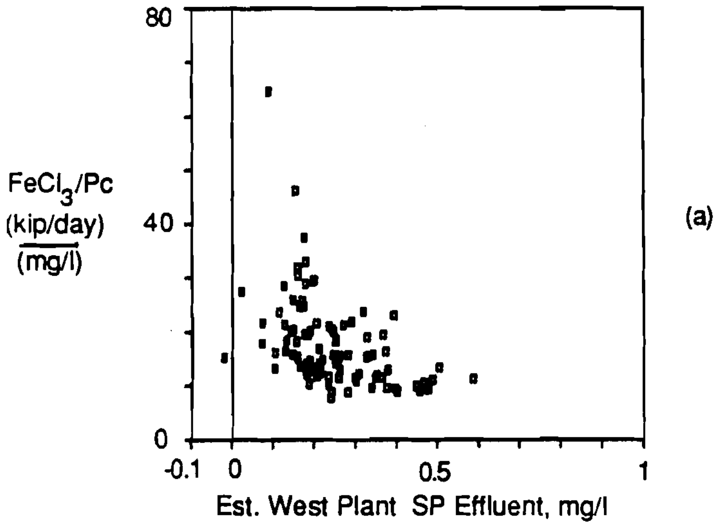
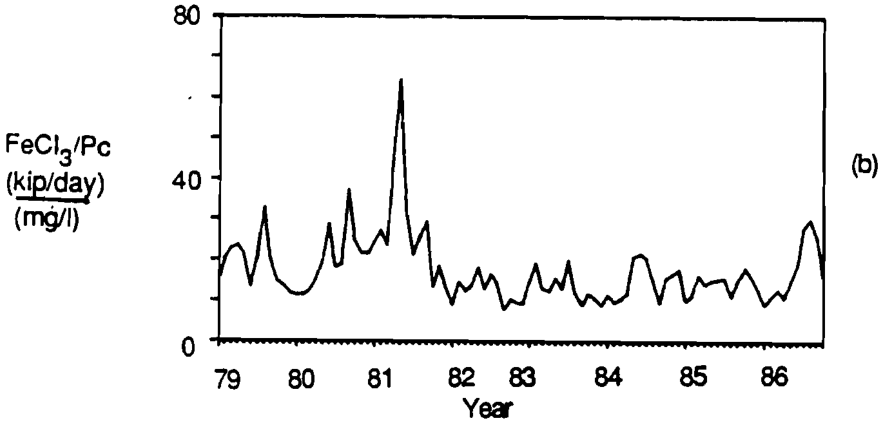


Figure 9-17 Jones Island West Plant a) $FeCl_3/P_c$ ratio for vs. Effluent SP, b) $FeCl_3/P_c$ ratio vs. Year. (P_c = SPI - SPO) Note: See text for discussion on estimated values.





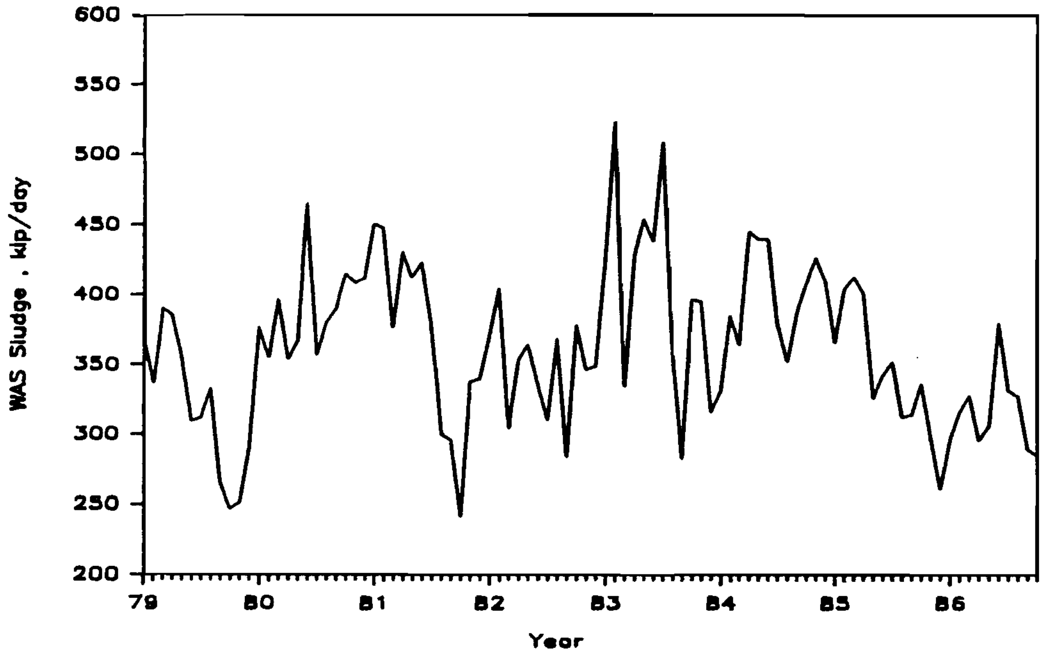


Figure 9-19 Jones Island Waste Activated Sludge Production for East and West Plants.

9.8 SUMMARY

The following conclusions can be drawn based from the preceding analyses:

1) SP removal in the east plant activated sludge has been both stoichiometric and non-stoichiometric.

2) Iron in the sludge dewatering recycle appears to cause both stoichiometric and non-stoichiometric precipitation in the west plant.

3) No increase in sludge production related to the amount of soluble phosphorus removed or the amount of iron added for phosphorus precipitation could be detected.

CHAPTER TEN: CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

Operating data were studied to evaluate chemical phosphorus precipitation at four sewage treatment plants. Relationships between wastewater conditions (e.g. soluble phosphorus concentrations, pH, etc.), chemical dose, and sludge production were examined graphically, and with correlation and linear regression.

Conclusions specific to each plant were given at the end of the appropriate chapters. For the reader's convenience, these are reiterated here.

10.1.1 Blue Plains Treatment Plant

1) The average Fe/P_C ratio does not accurately characterize primary SP removal (east and west plants) because there seems to be periods of time when SP removal was stoichiometric and other periods when it was non-stoichiometric.

2) Monthly average Fe/P_C ratios show a downward trend between the initiation of primary iron dosing and the phosphate detergent ban approximately two years later. Therefore, any observed reductions in chemical dose should not be attributed entirely to the phosphate detergent ban. They resulted, at least in part, from improved precipitation efficiency and partly the ban lowering phosphorus loading.

final pH. Regression models were not helpful in characterizing secondary soluble phosphorus removal.

7) On average, the estimated (stoichiometric) chemical sludge was 27 percent of the reported secondary sludge. Large variations in the secondary sludge production obscure the effects of iron dosing and SP removal. Regression was not helpful in relating the variables to sludge production. Some variation results from fluctuations in primary effluent quality, which may be related to the pattern of iron dosing in the primary basins, and to the magnitude and composition of sludge treatment return flows.

10.1.2 Piscataway Treatment Plant

1) It is not possible to make a quantitative assessment of the effect of the phosphate detergent ban on alum requirements for precipitation in the secondary treatment process. There is insufficient phosphorus data (nine months with both influent and effluent soluble phosphorus data) to classify the stoichiometry of aluminum phosphate precipitation. Alum use in the secondary plant had been decreased steadily over a period of time. Over the same general period of time, the use of lime for sludge stabilization was high enough that sludge return flows raised the secondary process pH from a typical value of about 7 to about 7.5; alkalinity increased correspondingly.

2) Alum dosing to the nitrification treatment process has been

consistently non-stoichiometric. Under these conditions, reducing influent phosphorus concentration would not lead to savings in alum.

3) Phosphate removal in the secondary and tertiary treatment processes cannot be usefully modeled by multiple linear regression.

10.1.3 South Shore Treatment Plant

1) The average Fe/P_C mole ratio of 2.32, and the relatively high primary effluent SP values (Ave. = 0.8 mg/l) indicate that SP removal occurred stoichiometrically during the period of oxidized WPL addition.

2) No useful causal relationship between SP removal and iron dose was developed.

3) The fraction of estimated chemical sludge is small in comparison to observed primary sludge production (19.7% by weight for unoxidized WPL, and 6.7% by weight for oxidized WPL).

4) Multiple regression analyses indicated that changes in iron dose and SP removal did not affect primary sludge production for the periods of unoxidized and oxidized WPL addition.

10.1.4 Jones Island Treatment Plant

1) SP removal in the east plant activated sludge has been both stoichiometric and non-stoichiometric.

2) Iron in the sludge dewatering recycle appears to cause both stoichiometric and non-stoichiometric precipitation in the west plant.

3) No increase in sludge production related to the amount of soluble phosphorus removed or the amount of iron added for phosphorus precipitation could be detected.

10.1.5 General Conclusions

1) Operating data can be used to classify chemical precipitation in a plant as stoichiometric or nonstoichiometric. Plots of soluble phosphorus removal vs. cation dose, and cation/P_C mole ratio vs. effluent soluble phosphorus concentration are similar to those obtained in controlled experimental work, though less clear because of temporal changes in initial phosphorus concentration and other variables.

The classification is important in terms of chemical requirement. Plants that operate in the non-stoichiometric region cannot be expected to notice proportional reductions in chemical dose if influent soluble phosphorus concentrations decrease. Stoichiometric precipitation processes should experience linear reductions in chemical dose.

2) Quantitative relationships between chemical dose and soluble phosphorus removal could not be developed with the linear regression methods used, and no estimates of chemical savings due to phosphate detergent bans are offered. The following problems were experienced, a) collinearity between iron dose and influent soluble phosphorus concentration (e.g. South Shore), b) small ranges of theoretically

significant predictor variables (e.g. effluent pH), and c) mixed precipitation mechanisms (Blue Plains primary, time trend from non-stoichiometric precipitation to stoichiometric precipitation).

3) The linear regression methods used show that changes in soluble phosphorus mass loading have not resulted in detectable changes in sludge production at South Shore and Blue Plains. This indicates that phosphate detergent bans, by themselves, have not significantly reduced sludge mass quantities.

4) Stoichiometric calculations indicate that chemical sludge mass quantities are small in comparison to the reported sludge quantities at South Shore and Blue Plains.

5) This study has shown that process variables, such as pH and alkalinity change, vary in qualitative patterns that are consistent with theory.

6) Flow dilution can cause significant changes in influent wastewater strength at Blue Plains, South Shore, and Piscataway. Regression analyses on the data from Blue Plains and South Shore indicate that influent flow has a significant impact on soluble phosphorus removal. Flow may affect SP removal by partially determining influent SP concentration.

10.2 RECOMMENDATIONS

Based on the above general conclusions and analyses presented in this report, the following recommendations for further work can be made.

1) Operating data from the Blue Plains secondary treatment process should be compared with chemical model predictions of Jenkins et al. (32), and Hermanowicz et al. (48).

2) Chemical equilibrium models should be formed to account for the use of waste pickle liquor and aluminum as precipitants. These models should be verified in lab scale primary and biological precipitation systems.

3) Full scale phosphorus precipitation should be studied under experimentally designed conditions. The theoretically important variables of final pH, initial alkalinity, and initial orthophosphate concentration should be included in the design.

4) The computer data base at Blue Plains is extensive and the records are freely available from the plant operators. Further studies of wastewater treatment operations should use this resource.

13. Diamadopoulos, Evangelos, and Andrew Benedek, "Aluminum Hydrolysis Effects on Phosphorus Removal from Wastewaters," Journal WPCF, Vol. 56, No. 11, November 1984, pp. 1165-1172.

14. Diamadopoulos, Evangelos, and Andrew Benedek, "The Precipitation of Phosphorus From Wastewater through pH Variation in the Presence and Absence of Coagulants," Water Research (G.B.), Vol. 18, No. 9, 1984, pp. 1175-1179.

15. Directo, Leon S., et. al., "Phosphorus Removal by Chemical Addition to Secondary and Tertiary Treatment Systems," Proc. of the 29th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1972, pp. 369-387.

16. Draper, N.R. and Smith, H., Applied Regression Analysis, John Wiley & Sons, New York, (1981).

17. Earnest, Lawrence A., "Milwaukee Metropolitan District Plant Scale Experience With Phosphorus Removal 1970 - 1977 - Jones Island Plant," presented at The Sanitary Engineering Institute, Wastewater Treatment and Disposal, University of Wisconsin - Extension, Madison, Wisconsin, March 2-3, 1978.

18. Ferguson, John F. and Thomas King, "A Model for Phosphate Precipitation," Journal WPCF, Vol. 49, No. 4, April 1977, pp. 646-658.

19. Ferguson, John F., et. al, "Calcium Phosphate Precipitation at Slightly Alkaline pH Values," Journal WPCF, Vol. 45, No. 4, April 1973, pp. 620-631.

20. Finch, G.R., et. al., "Laboratory Methodology for Optimizing Phosphorus Precipitation," Proc. of the International Conference on Management Strategies for Phosphorus in the Environment, Lisbon, July 1-4, 1985.

21. Finstein, M.S., and Joseph V. Hunter, "Hydrolysis of Condensed Phosphates During Aerobic Biological Sewage Treatment," Water Research (G.B.), Vol. 1, 1967, pp. 247-254.

22. Gannet Fleming Environmental Engineers, Inc., "The Effect of a Ban on Phosphates in Household Detergents on the Treatment of Municiple Wastewater," Report prepared for The Soap and Detergent Association, February, 1985.

23. Geinopolos, Anthony and Frank I. Vilen, "Process Evaluation - Phosphorus Removal," Journal WPCF, Vol. 43, No. 10, October 1971, pp. 1979-1990.

24. Gleisberg, D., "Production, Dewaterability and Agricultural Suitability of Sludge Resulting from Chemical Wastewater Treatment," Proc. of the International Conference on Management Strategies for Phosphorus in the Environment, Lisbon, July 1-4, 1985.

25. Grinker, Joseph, "Process Change Results in Savings While Meeting Phosphorus Limits," Presented at The Central States Water Pollution Control Association, Inc., Annual Meeting, Bloomingdale, Illinois, May 20, 1982.

26. Hais, Alan B., et. al., "Alum Addition to Activated Sludge with Tertiary Solids Removal," EPA 670/2-73-037, August 1973.

27. Hartig, John H. and Frank J. Horvath, "A Preliminary Assessment of Michigan's Phosphorus Detergent Ban," Journal WPCF, Vol. 54, No. 2, February 1982, pp. 193-197.

28. Hellenbrand, Kay A., Plant Engineer, Washington Suburban Sanitary Commission, Accokeek, MD, Personal Communication, November 1987.

29. Jacke, Robert, "Phosphate Ban Lowers Removal Costs," Water and Wastes Engineering, Vol. 16, No. 8, August 1979, pp. 33-35.

30. Jacobs, Donald S., Senior Plant Superintendent, Washington Suburban Sanitary Commission, Accokeek, MD, Personal Communication, March 1987.

31. Jenkins, David and Associates, and James Engineering Inc., " A Computer Model for Phosphate Precipitation with Alum and Ferric Chloride," Report submitted to The Soap and Detergent Association, November, 1984.

32. Jenkins, David, et. al., "The Development and Testing of a Model for Iron Phosphate Precipitation in Activated Sludge," Unpublished progress report submitted to The Soap and Detergent Association, September 1986.

33. Jenkins, David ,et. al., "Chemical Processes for Phosphate Removal," Water Research (G.B.), Vol. 5 , 1971, pp. 369-389.

34. Jenkins, David, personal communication, March, 1987.

35. Jones, E.R, "Phosphorus Removal with Iron Salts," presented at USEPA's International Seminar on Control of Nutrients in Municipal Wastewater, San Diego, CA. September 9-11, 1980.

36. Jones, E.R. et. al., "Phosphorus Removal Experiences at AWT Facilities," presented at the 1984 ASCE Environmental Engineering Conference, Los Angeles, CA. June 25-27, 1984.

37. Jones, E.R., " Bio-Chemical Phosphorus Removal - The Trials of Determining the Chemical of Choice," presented at the Pollution Control Association of Ontario's technical seminar, "Bridging the Gap between Research and Full Scale Operation in Wastewater Treatment," Canada Centre for Inland Waters, Burlington, Ontario, March 7, 1980.

38. Jones, E.R., and Susan D. Hubbard, "Maryland's Phosphate Ban - History and Early Results," Journal WPCF, Vol. 58, No. 8, August 1986, pp. 816-822.

39. Karlsson, Ingemar, "Chemical Phosphorus Removal in Combination with Biological Treatment," Proc. of the International Conference on Management Strategies for Phosphorus in the Environment, Lisbon, July 1-4, 1985.

40. Kavanaugh, Michael C., et. al., "Phosphorus Removal by Post-Precipitation with Fe(III)," Journal WPCF, Vol. 50, No.2, February 1978, pp. 216-233.

41. Kerecz, B.J., et. al., "Use of Spent Pickle Liquor to Remove Phosphates in Municipal Sewage Treatment Plants," presented at the 53rd Annual Conference of the Water Pollution Control Federation, Las Vegas, NV., October 1980.

42. Kirk, P.W.W., et. al., "Phosphorus Removal by Pre-Precipitation of Sewage; Metal Removal, Sludge Characteristics and Treatment Efficiency," Proc. of the International Conference on Management Strategies for Phosphorus Removal in the Environment, Lisbon, July 1-4, 1985.

43. Lan, J.C., et. al., " Phosphorus Removal in the Activated Sludge Process," Water Research (G.B.), Vol. 17, No. 9, 1983, pp. 1193-1200.

44. Leary, Ray D., et. al., "Phosphorus Removal using Waste Pickle Liquor," Journal WPCF, Vol. 46, No. 2, February 1974, pp. 284-300.

45. Levin, G.W., et. al., "Pilot Plant Tests for Phosphate Removal Processes," Discussion, Journal WPCF, Vol. 46, No. 2, February 1974, pp. 404-408.

46. Lijklema, Lambertus, "Interaction of Orthophosphate with Iron (III) and Aluminum Hydroxides," Environmental Science and Technology, Vol. 14, No. 5, May 1980, pp. 537-541.

47. Long, D.A., and J.A. Nesbitt, "Removal of Soluble Phosphorus in an Activated Sludge Plant," Journal WPCF, Vol. 47, No. 1, January 1975, pp. 170-184.

48. Luedecke, Cornelia, S.W. Hermanowicz, and David Jenkins, "Ferric Phosphate Precipitation in Activated Sludge: Model Verification," Presented at the WPCF 60th Annual Conference, Philadelphia, PA, October 5-8, 1987.

49. Maki, Alan W., et. al., "The Impact of Detergent Phosphorus Bans on Receiving Water Quality," Water Research (G.B.), Vol. 18, No. 7, 1984, pp. 893-903.

50. McNamee, Porter, and Seeley, Engineers/Architects, Ann Arbor, MI, "Retrofitting POTWS for Phosphorus Removal in the Chesapeake Bay Drainage Area," Second Draft Report, March 1987.

51. Metcalf & Eddy, Inc., Wastewater Engineering: Treatment Disposal Reuse, McGraw-Hill Book Company, New York, (1979).

52. Milbury, William F., et. al., "Operation of Conventional Activated Sludge for Maximum Phosphorus Removal," Journal WPCF, Vol. 43, No. 9, September 1971, pp. 1890 - 1901.

53. Minton, Gary R., and Dale A. Carlson, "Combined Biological-Chemical Phosphorus Removal," Journal WPCF, Vol. 44, No. 9, September 1972, pp. 1736-1755.

54. Mulbarger, M.C., "The Three Sludge System for Nitrogen and Phosphorus Removal," EPA Document PB-213-778, April 1972.

55. Mulbarger, Michael C., and Donald G. Shifflett, "Combined Biological and Chemical Treatment for Phosphorus Removal," Chemical Engineering Progress Symposium Series- Water, Vol. 67, No. 107, 1970, pp. 107-116.

56. Pallesen, Lars, et. al., "Environmental Intervention Analysis: Wisconsin's Ban on Phosphate Detergents," Water Research (G.B.), Vol. 19, No. 3, 1985, pp. 353-362.

57. Philip, David, "Phosphorus Removal at the Lower Molonglo Water Quality Control Centre," Journal WPCF, Vol. 57, No. 8, August 1985, pp. 841-846.

58. Pieczonka, Paul and N.E. Hopson, "Phosphorus Detergent Ban - How Effective?," Water and Sewage Works, Vol. 11, No. 7, July 1974, pp. 52-55.

59. Recht, H. L., and M. Ghassemi, "Kinetics and Mechanism of Precipitation and Nature of the Precipitate Obtained in Phosphate Removal from Wastewater Using Al(III) and Fe(III) Salts," Federal Water Quality Administration Report No. 17010 EKI, (1970).

60. Schmidtke, N.W., "Estimating Sludge Quantities at Wastewater Treatment Plants Using Metal Salts to Precipitate Phosphorus," Proceedings of the International Conference on Management Strategies for Phosphorus in the Environment, Lisbon, July 1985.

61. Sonzogni, William C., and Thomas M. Heidtke, "Effect of Influent Phosphorus Reductions on Great Lakes Sewage Treatment Costs," AWRA Water Resources Bulletin, Vol. 22, No. 4, August 1986, 623-627.

62. Snoeyink, Vernon L. and Jenkins, David, Water Chemistry, John Wiley & Sons, New York, (1980).

63. Stumm, Werner, and Morgan, James J., Aquatic Chemistry, John Wiley & Sons, New York, (1981).

64. Ulmgren, Lars, "Swedish Experiences in Chemical Treatment of Wastewater," Journal WPCF, Vol. 47, No. 4, April 1975, pp. 696-703.

65. U.S. Environmental Protection Agency, "Phosphorus Removal," EPA/625/1-87/001 U.S. E.P.A. Water Engineering Research Laboratory, Cincinnati, Ohio, (1987).

66. U.S. Environmental Protection Agency, "Process Design Manual for Phosphours Removal," EPA 625/1-76-001a, Office of Technology Transfer, Washington, D.C., April 1976.

67. U.S. Environmental Protection Agency, "Retrofitting POTWs for Phosphorus Removal in the Chesapeake Bay Drainage Basin," EPA/625/6-87/016, U.S. E.P.A. Water Engineering Research Laboratory, Cincinnati, Ohio, (1987).

68. Veldkamp, R.G., "Modeling Phosphate Sludge Production," Water Science and Technology, Vol. 17, No. 2&3, 1985, pp.107-119.

69. Vesilind, P. Aarne, Treatment and Disposal of Wastewater Sludges, Ann Arbor Science Publishers, Inc., Ann Arbor, MI, (1981).

APPENDICES

APPENDIX A - NOTATION

A.1 Variables

A systematic shorthand notation is used to identify variables. Parameters are identified with a base notation. For example, soluble phosphorus is SP. Appended to this base notation are letters signifying whether the variable measures an influent (I) to or an effluent (O) from a process. For example, TPI is influent total phosphorus. A "K" is appended if the units are in kips/day. No letters are appended if the units are mg/l concentrations. The prefix "d" indicates a difference: the influent value minus the effluent. For example, dTSSK represents the change in total suspended solids in units of kips/day.

ALK	Total Alkalinity, as $CaCO_3$
BOD	Five Day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
Fe	Iron dose, mg/l as Fe
Fe3	Ferric Chloride dose, as Fe
GTOR	Gravity Thickener Overflow Recycle
OSP	Soluble Orthophosphate, as P
OX-WPL	Oxidized Waste Pickle Liquor, as Fe
P_c	Estimate of Chemically Precipitated Phosphorus
pH	$\log_{10}$ (Hydrogen Ion Concentration mol/1)

Q	Flow, MGD
TOC	Total Organic Carbon
TP	Total Phosphorus, as P
TSS	Total Suspended Solids
SPBR	Solids Processing Building Recycle
SP	Soluble Phosphorus, as P
WPL	Waste Pickle Liquor, as Fe

A.2 Statistical Terms

Ave.	Simple Average Value
F	F Ratio, see Appendix C
Max	Maximum Observed Value
Min	Minimum Observed Value
N or n	Number of Observations
r	Linear Correlation Coefficient
$r_{0.99}$	Linear Correlation Coefficient at 99% Confidence
$r_{0.95}$	Linear Correlation Coefficient at 95% Confidence
R^2 or R2	Squared Multiple Correlation Coefficient
S	Standard Error of Predicted Mean Value
S.D.	Standard Deviation
S.E.	Standard Error of the Mean Value

APPENDIX B - SENSITIVITY ANALYSIS

The following assumptions are made about Blue Plains soluble phosphorus concentrations at points where no data exist.

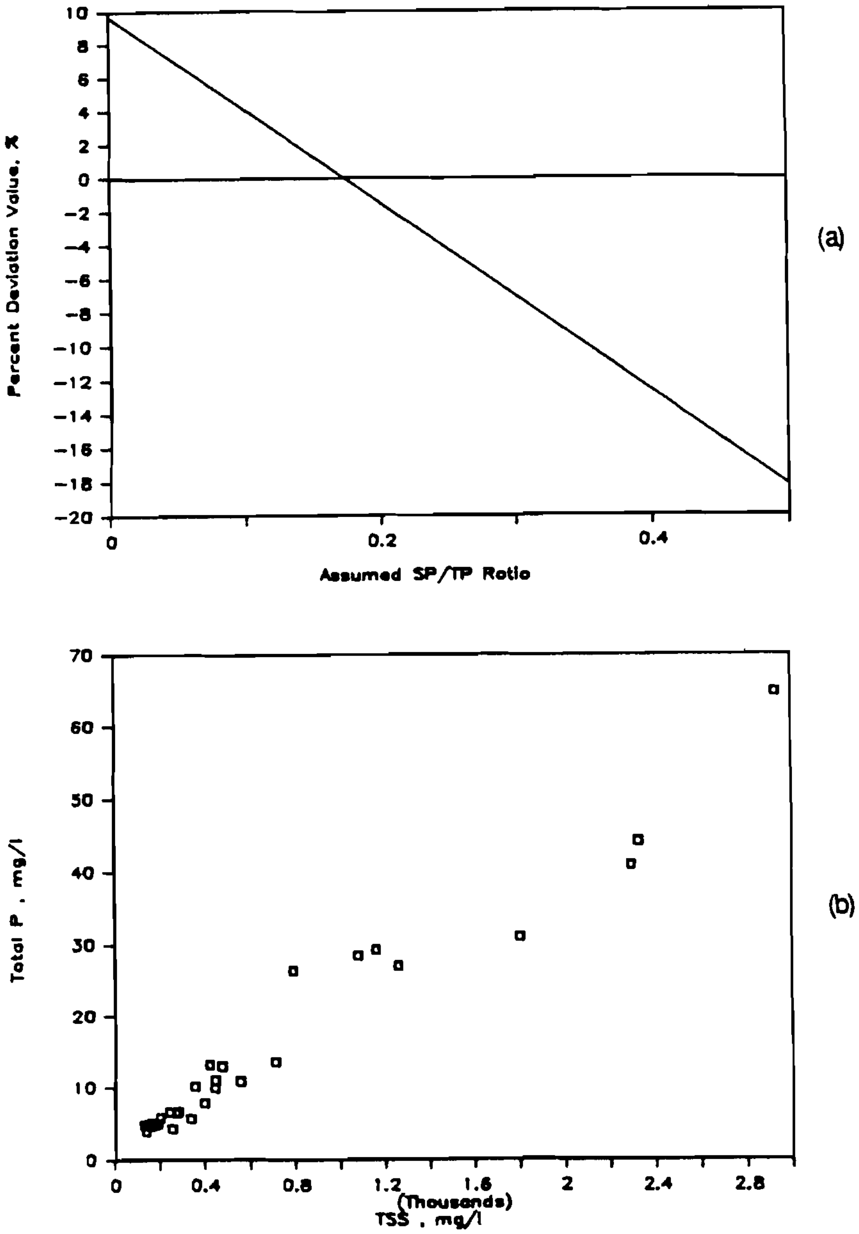
1) Assume the soluble phosphorus concentration ahead of the west primary to equal the raw influent concentrations.

This will be true for data after June 1985. Since July 1985 the gravity thickener overflow has been rerouted below the west primary clarifiers.

For the data between January 1983 and June 1985 inclusive, the soluble phosphorus concentration ahead of primary clarification will be impacted by the GTO. To test the assumption, the assumed SP value is compared to a calculated value based on an estimate of the SP/TP ratio in the recycle stream. TP is measured in the recycle. The estimate of SP/TP will range from zero to one. The primary influent is estimated by performing a mass balance on the soluble phosphorus at the recycle reentry point.

Figure B-1a shows the percent deviation of the calculated SP concentration from the assumed value as a function of estimated SP/TP ratios in the gravity thickener overflow. The figure shows that if the actual SP/TP ratio in the recycle were between 0% and 35% then the assumed primary influent SP concentration would be in error at most plus or minus 10%.

Figure B-1 Blue Plains a) Percent Deviation of Average SP Concentration as a Function of Assumed SP/TP Ratio in GTOR to West Primary Influent, Jan. 1983 - June 1985, b) TP vs. TSS for GTOR to West Primary Influent, Jan. 1983 - June 1985.



A possible estimate of SP in the GTOR would be the same concentration as the secondary influent. This would make the average SP/TP recycle ratio 0.67/14.7 = 0.045, yielding an underestimate of influent SP of about 7%. The 14.7 value is the average TP in the GTOR for the period of time when the recycle was above the west primaries.

Figure B-1b shows the TP vs. TSS relationship for the gravity thickener overflow. This relationship should strengthen as the ratio of SP to TP decreases.

2) <u>Assume that the west primary effluent soluble phosphorus concentrations from January 1983 through June 1985 are equal to the west secondary influent concentrations.</u>

Figure B-2a shows the percent deviation of the calculated soluble concentration from the assumed condition as a function of assumed SP/TP ratio in the solids processing building recycle.

Figure B-2b shows the TP to TSS relationship in the SPBR recycle.

3) <u>Assume that the east primary effluent soluble phosphorus concentrations are equal to the east secondary influent soluble phosphorus concentrations</u>.

This assumption is affected by the SPBR. Figure B-3a shows the sensitivity of the assumption as a function of assumed SP/TP ratios in the recycle.

Figure B-2 Blue Plains a) Percent Deviation of Average SP Concentration as a Function of Assumed SP/TP Ratio in SPBR to West Secondary Influent, Jan. 1983 - June 1985, b) TP vs. TSS for SPBR to West Secondary Influent, Jan 1983 - June 1985.

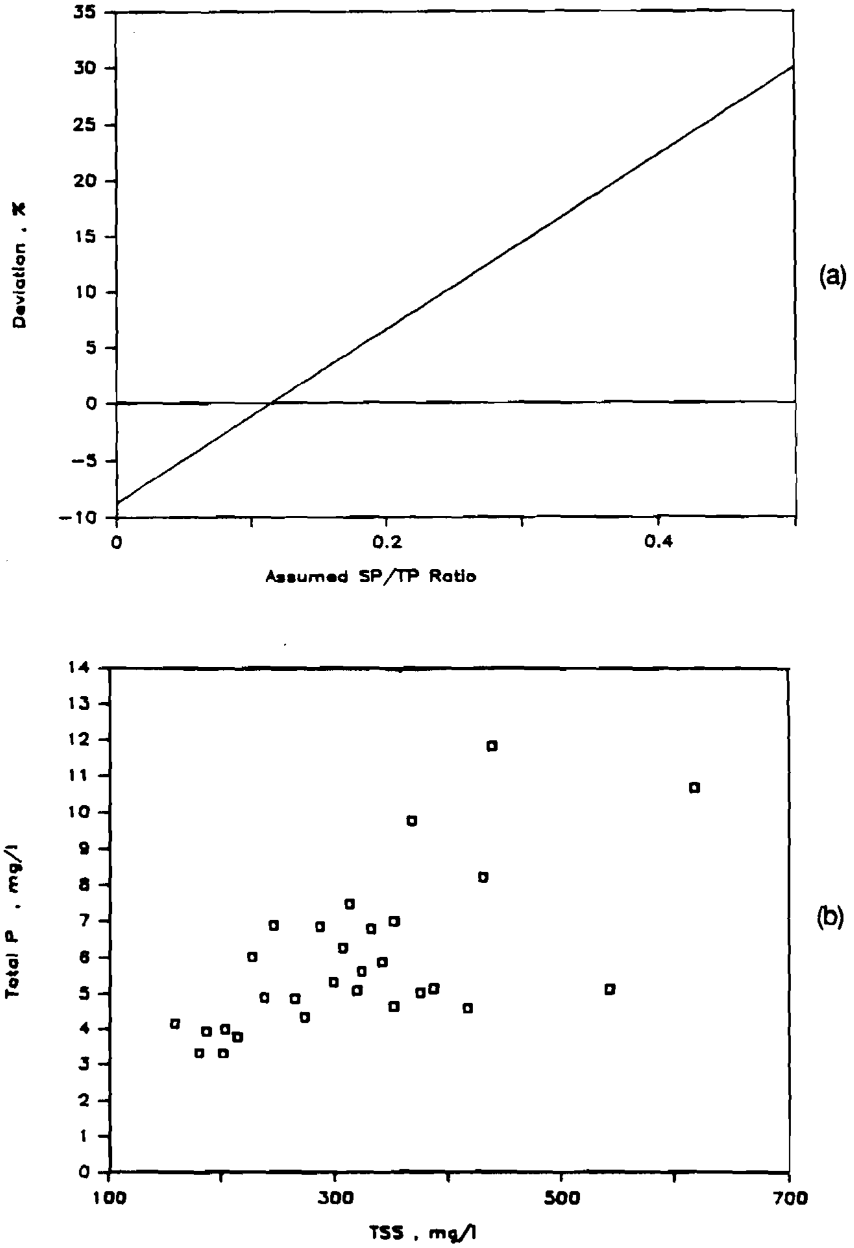
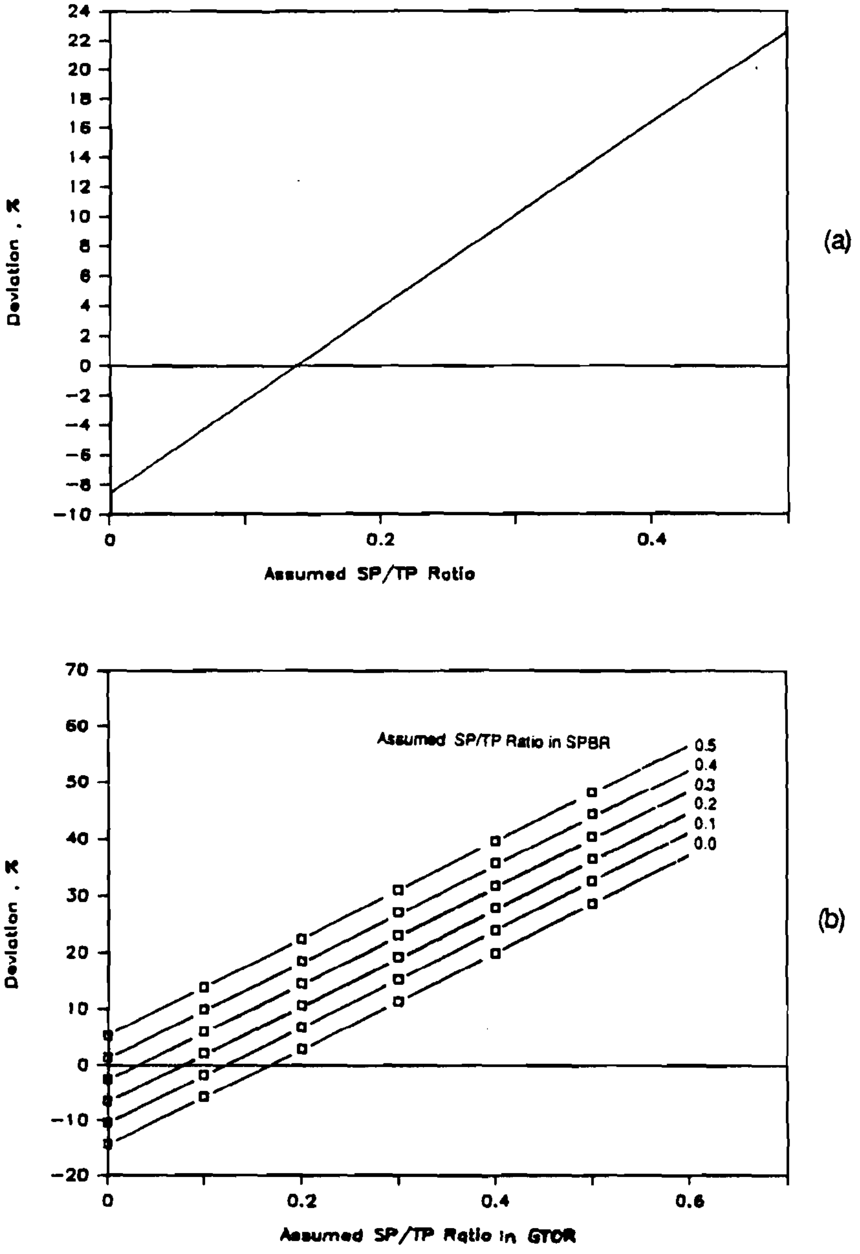


Figure B-3 Blue Plains, Percent Deviation of Average SP Concentration as a Function of Assumed SP/TP Ratios for a)SPBR to East Primary Effluent, Jan. 1983 - March 1987, b) SPBR and GTOR Below the West Primary Effluent, June 1985 - March 1987.



4) Assume that the west primary effluent soluble phosphorus concentrations are equal to the west secondary influent concentrations for the period June 1985 through March 1987.

In this case the quantity of SP in both the SPBR and GTOR are unknown. Figure B-3b shows the sensitivity of the assumption as a function of assumed SP/TP ratios in both recycle streams.

APPENDIX C - REGRESSION OUTPUT AND SEQUENTIAL F TABLE

Certain results from multiple regression analysis are summarized in tables and figures Chapters Four and Eight. This appendix explains the statistics that are reported in those tables and figures.

Regression Output Tables

The regression output tables summarizes partial results of the regression analysis. They contain:

(a) The parameter estimates for each of the possible models that can be constructed from the specificed independent variables. The complete model is referenced under the table title.

(b) The Student-t ratio (coefficient/standard deviation of coefficient) for each estimated parameter is shown under the estimated parameter value.

(c) The number of observations (n), the squared multiple correlation coefficient (R^2), and the standard error of the estimated mean value (S) are given for each regression.

Regression Output Figures

The figure consists of a plot of the residual sum of squares (RSS) for all the models plotted against the number of parameters in each model. A similar plot of mean square error ($\mathrm{MSE} = \mathrm{RSS}/\upsilon$) might have been used. The plot is helpful in identifying model that have few parameters and low RSS.

The figure also contains a table of Model number, RSS, MSE, and Sequential F Values. For a detailed explanation of the F values the reader is referred to Draper and Smith (16). A brief explanation follows.

Given a multiple linear regression with k terms, an F value can be used to test the following hypothesis:

H_o : q additional terms do not statistically improve a reduced model of k terms.

H_1 : Otherwise.

The appropriate F statistic is computed from

$$F = [(SSW - SSE)/q] / MSE$$

where SSW = RSS from reduced model of k terms.

SSE = RSS from full model of k + q terms.

MSE = Mean square error (s^2) of full model.

This computed F statistic is compared the tabulated value of F for q and n-p degrees of freedom , where n = number of observations and p = number of estimated parameters in the full model.

The sequential F values presented in this report compare models that differ by the addition of only one term. Thus, for the addition of a single term, q=1.

The tables of Sequential F values in this report are interpreted as follows. In the example presentation, Figure C-1, the underlined row lists, reading from left to right, F values for testing Model 4 against Models 1, 2, and 3, respectively. Model 4 has 3 parameters (2 "terms" plus the coefficient b_0). Models 1, 2, and 3 have two parametes. The double underlined row in Table C-1 gives the F values for testing Model 7, a 4 parameter model, against Models 4, 5, and 6, which have three parameters.

In order to use these F values to test whether adding the additional parameter has significantly improved the fit of the model one must know how many observations were used to fit the model. This information is given in the "Regression Output Table."

Table C-1 Example F Table.

MODEL	TERMS	RSS	MSE	Sequential F Value		
1	1	1.2704	0.0747			
2	1	0.5602	0.0330			
3	1	5.1740	0.3044			
4	2	0.4556	0.0285	28.6	3.7	165.7
5	2	1.2233	0.0765	0.6	-8.7	51.7
6	2	0.5220	0.0326	22.9	1.2	142.6
7	3	0.3922	0.0261	2.4	31.8	5.0