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MASS BALANCE MODEL AND FIELD CALIBRATION FOR PHOSPHORUS REMOVAL FROM MUNICIPAL WASTEWATERS

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MASS BALANCE MODEL FOR PHOSPHORUS REMOVAL FROM MUNICIPAL WASTEWATERS

Oh, endless task! One begins with no knowledge except that what one is doing is probably wrong, and that the right path is heavy with mist.

Robertson Davies, *The Rebel Angels*, 1981

Abstract

Of the wastewater treatment plants (WTPs) in the province of Québec that are effecting a phosphorus (P) removal program, chemical addition and precipitation is the primary form of P-removal, with biomass growth and/or enhanced biological P-removal (EBPR) providing secondary removals. An overall P-removal of approximately 66% was achieved at these WTPs in 1994.

Dessau Inc. of Laval, McGill University and École Polytechnique were contracted by the Ministry of the Environment and Fauna of Québec to perform an evaluation of chemical P-removal from Québec municipal wastewaters and the optimization of existing processes. Part of this evaluation and optimization involved clarifying the mechanisms and interactions during chemical P-removal. Many key models from literature were reviewed, but were not entirely adequate.

A static steady-state P-removal model was therefore developed, accounting for the reactions and removals of soluble and particulate forms of orthophosphate and polyphosphate/organic phosphorus. The model traces the path of each P-fraction throughout the chemical removal process, accounting for P-precipitation and adsorption, as well as reductions of TSS and BOD_5. Computer programs were constructed for the model, with specific programs written for primary treatment, activated sludge, biofiltration and facultative aerated lagoons.

Samples were gathered at 11 WTPs during June-July 1994; these field data were used to calibrate the computer programs. Computer program output generally agreed with the field data to within 10%. Several of the WTPs sampled obtained a total-P removal of approximately 90% with metal dosed:P molar ratios often below 1.

Résumé

Parmi les stations de traitement des eaux usées du Québec qui éffectuent une déphosphatation, la précipitation accomplie avec une addition de produits chimiques est la première méthode de déphosphatation. La croissance de biomasse et/ou la déphosphatation biologique accrue accomplissent la déphosphatation secondaire. L'efficacité de la déphosphatation de ces stations en 1994 était d'environ 66%.

Dessau Inc. de Laval, McGill University et l'École Polytechnique furent détenus par le ministère de l'environnement et de la faune du Québec pour évaluer la déphosphatation chimique des eaux usées des municipalités québécoises et d'optimiser les processus existants. Compris dans cette évaluation et cette optimisation était une étude des mécanismes et interactions présente durant la déphosphatation chimique. Plusieurs modèles présent dans la litérature disponible furent étudiés, mais aucun ne fut adéquat.

Un modèle statique à état continu fut dévelopé qui tenait compte des réactions et les enlèvements des formes solubles et particulaires d'orthophosphate, de polyphosphate et de phosphore organique. Le modèle suit le trajet de chaque forme de phosphore le long du processus d'enlèvement chimique tenant compte de la précipitation et de l'adsorption du phosphore, ainsi que la réduction des concentrations des MES et de la DBO_5. Des logiciels furent dévelopés pour le modèle incluant des programmes spécifique pour le traitement primaire, de boues activées, la biofiltration et les étangs aérés.

Onze stations furent échantillonnées en juin et juillet 1994. Ces données servirent à la calibration des logiciels. Les logiciels était en accord avec les données accumulées à 10% près. Plusieurs des stations échantillonnées obtenaient une déphosphatation d'environ 90% avec des rapports entre les ions métalliques dosées et le phosphore souvent inférieur à un.

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I must thank my parents, RoseAnn and Greg Hart, first and foremost; their support and encouragement were always with me.

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This phase of the study would not have been possible without the assistance of countless engineers and technicians at wastewater treatment plants across Québec; special thanks go out to Messrs. Pierre Purenne and Yves Lafleur at the MUC wastewater treatment plant.

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Table of Contents

Page

List of Tables viii
List of Figures ix
Nomenclature x

1.0 INTRODUCTION 1
  1.1 Background and Situation in Québec 1
  1.2 Objectives 3

2.0 LITERATURE REVIEW 4

  2.1 Process Technologies 4
  2.2 Coagulant Chemistry and Removal Mechanisms 7
  2.3 Phosphorus Removal Modelling 9
    2.3.1 Summary 21

3.0 MATERIALS AND METHODS 23

  3.1 Orthophosphates 26
  3.2 Total Phosphorus 26
  3.3 Hydrolyzable Phosphorus 27
  3.4 Long-Chain Polyphosphate 27
  3.5 COD 27
  3.6 Alkalinity 28
  3.7 TSS and VSS 28
  3.8 Detection Limits and Quality Control 28

4.0 FIELD SAMPLING AND DATA ANALYSIS 30

  4.1 Field Sampling 30
    4.1.1 Fabreville 33
    4.1.2 Montreal Urban Community 34
    4.1.3 Pincourt 35
    4.1.4 Victoriaville 37
    4.1.5 St-Jean Baptiste 38
    4.1.6 Marieville 39
    4.1.7 Châteauguay 40
    4.1.8 Rigaud 41
    4.1.9 St-Georges 43
    4.1.10 Haute-Bécancour (Black Lake) 45
    4.1.11 Mont-St-Grégoire 46
  4.2 Data Analysis 48
    4.2.1 Phosphorus vs. Solids Relationships in Wastewater 49
    4.2.2 Metal to Phosphorus Ratios in the Sludge 51

5.0 PHOSPHORUS MASS BALANCE MODEL 52

5.1 Developmental Motive 52
5.2 Conceptual Model Description 53

6.0 COMPUTER PROGRAMS 59

6.1 Introduction 59
6.2 General Assumptions 61
6.2.1 General Computer Program Calibration Methodology 61
6.3 Primary Clarifier 65
6.3.1 Assumptions 65
6.3.2 Methodology 66
6.4 Activated Sludge 67
6.4.1 Assumptions 67
6.4.2 Methodology 68
6.5 Biofiltration 69
6.5.1 Assumptions 69
6.5.2 Methodology 70
6.6 Aerated Lagoons 71
6.6.1 Assumptions 71
6.6.2 Methodology 72

7.0 CALIBRATION RESULTS AND DISCUSSION 73

7.1 Calibration Results: Agreement with Field Data 73
7.1.1 Wastewater Effluent Variables 73
7.1.2 Sludge Production and P-Content 75
7.2 Computer Programs 77
7.3 Improvements to P-Removal Performance 79

8.0 CONCLUSION 81

8.1 Field Data 81
8.2 Mass Balance Model and Computer Programs 82

References 84

Appendix A: Field Data A1
Appendix B: Computer Programs Sample Output A24

List of Tables

2.1: Synopsis of P-Removal Performance 5

3.1: Laboratory Analyses 25
3.2: Detection Limits 29
3.3: Percentage Recovery for Standard and Spiked Samples 29

4.1: WTPs Sampled 31
4.2: Field Data Summary 32
4.3: Wastewater P:TSS Relationships 50
4.4: Metal:Phosphorus Ratios; Dosed to Wastewater and Sludge Content 51

5.1: Distributions of Forms of Phosphorus in the Mass Balance Model 58

6.1: Average Calibrated Model Parameters 64

7.1: Computer Program Output Agreement with Field Data 74
7.2: Phosphorus Content of Sludge: Computer Program Output and Field Data 75
7.3: Sludge Production: Computer Program vs. Actual 76

A4.1: Laboratory Results; Fabreville A2
A4.2: Laboratory Results; Fabreville A3
A4.3: Laboratory Results; MUC A4
A4.4: Laboratory Results; MUC A5
A4.5: Laboratory Results; Pincourt A6
A4.6: Laboratory Results; Pincourt A7
A4.7: Laboratory Results; Victoriaville A8
A4.8: Laboratory Results; Victoriaville A9
A4.9: Laboratory Results; St-Jean-Baptiste A10
A4.10: Laboratory Results; St-Jean-Baptiste A11
A4.11: Laboratory Results; Marieville A12
A4.12: Laboratory Results; Marieville A13
A4.13: Laboratory Results; Châteauguay A14
A4.14: Laboratory Results; Châteauguay A15
A4.15: Laboratory Results; Rigaud A16
A4.16: Laboratory Results; Rigaud A17
A4.17: Laboratory Results; St-Georges A18
A4.18: Laboratory Results; St-Georges A19
A4.19: Laboratory Results; Haute-Bécancour A20
A4.20: Laboratory Results; Haute-Bécancour A21
A4.21: Laboratory Results; Mont-St-Grégoire A22
A4.22: Laboratory Results; Mont St-Grégoire A23

List of Figures

2.1: Soluble Residual Phosphate and pH Ranges Where Zones of Model Apply 14
2.2: Precipitation Regions for pH=6.8 19

3.1: Sample History 24

5.1: P Mass Balance Model 56
5.2: P Mass Balance Model; Predicted P-Distribution at MUC WTP 57

6.1: Process Diagrams and Chemical Addition Points 60
6.2: General Calibration Methodology 63

Nomenclature

AS	Activated sludge
AL	Aerated lagoon(s)
BF	Biofiltration
$BOD_5(P)$	Particulate five day biochemical oxygen demand (mg/L; kg/d)
$BOD_5(S)$	Soluble five day biochemical oxygen demand (mg/L; kg/d)
$BOD_5(T)$	Total five day biochemical oxygen demand (mg/L; kg/d)
COD	Chemical oxygen demand (mg/L)
DO	Dissolved oxygen
DOM	Dissolved organic matter
EBPR	Enhanced biological phosphorus removal
FA	Fulvic acid
HA	Humic acid
ISS	Inert suspended solids; (D) decantable or (ND) non-decantable (mg/L)
Me	Metal (iron, Fe, or aluminum, Al)
Me:P	Molar ratio of amount of coagulant dosed:amount of phosphorus in the wastewater at the point of dosage (unless otherwise specified in the text)
MLSS	Mixed liquor suspended solids (mg/L)
MLVSS	Mixed liquor volatile suspended solids (mg/L)
Non-ortho-P	Polyphosphate and/or organic phosphorus (mg/L)
Ortho-P	Orthophosphate (mg/L)
PC	Primary clarifier
PO_4	Orthophosphate (mg/L)
p.e.	Person equivalents
Poly-P	Long-chain polyphosphate (g Poly-P released/g VSS as %)
SVI	Sludge volume index
TOC	Total organic carbon
TS	Total solids (mg/mg dry basis)
TSS	Total suspended solids (mg/L)
TVS	Total volatile solids (mg/mg dry basis)
VSS	Volatile suspended solids; (D) decantable or (ND) non-decantable (mg/L)
WT	Wastewater treatment
WTP	Wastewater treatment plant

Subscripts, Prefixes and Suffixes

eff	Effluent
inf	Influent
P	Abbreviated form of "phosphorus" except in ortho-P (orthophosphate) and Poly-P (long-chain polyphosphate)
tot	Total

Chapter 1. INTRODUCTION

1.1 Background and Situation in Québec

Municipal wastewater discharge is one of the main contributors to the eutrophication of receiving water bodies. Population growth and the use of fertilizer and household detergents combine to increase the amounts of nitrogen and phosphorus in lakes and rivers. In the epilimnion layer, the aquatic zone where the majority of photosynthesis occurs, phosphorus (P) is usually the limiting nutrient, therefore increased amounts lead to increased biological activity during summer months (Imboden, 1974).

Detergent phosphorus bans help to reduce wastewater treatment plant (WTP) effluent-P levels, and assist in reducing eutrophication since most P in detergents is in the bioavailable form (Hartig et al., 1990). Reductions at the point of origin of industrial sources can further reduce P-loading to WTPs. These are not, however, solutions to the difficulties encountered in reducing WTP effluent-P, since discharge concentrations are often only temporarily stabilized. Even with these regulations and programs, further reductions in municipal effluent-P levels are required. Chemical dosing to control effluent-P levels, alone or as a supplement to biological processes, has therefore become widespread in wastewater treatment (de Haas et al., 1993; Jenkins and Hermanowicz, 1991).

Wastewater discharges generally have a significant effect on the P-concentration in receiving water bodies, when comparing levels upstream and downstream of a typical WTP. Garber (1977) demonstrated that a 75% reduction in effluent-P during full-scale studies with ferric chloride greatly reduced the effect of a wastewater on the river into which it was discharged. Furthermore, Bothwell (1992) demonstrated in experiments adding P-slugs to river algal communities that algae exposed to P-concentrations of 60 μg P/L for 1 min/hr grew as rapidly as those exposed to continuous concentrations of 1 μg P/L. In order to prevent eutrophication of receiving waters, it is therefore important to further understand P-removal processes so that stable low effluent-P levels can be maintained.

As part of Québec's Program for Exploratory Environmental Research, Dessau Inc. of Laval, McGill University and École Polytechnique were contracted by the Ministry of the Environment and Fauna of Québec (MEF; referred to as MENVIQ prior to 1994) to perform an evaluation of chemical P-removal from Québec municipal wastewaters and the optimization of existing processes.

As of January 1994, 70% of the population in Québec was served by WTPs. Approximately 70% (2.5 Mm^3/d) of this wastewater is treated by WTPs that must meet a certain effluent-P concentration, viz. 0.5-1.0 mg P/L. In Québec, 26% of P-loading to receiving waters is from municipal WTP effluents; the remainder is from non-point sources. 79% of Québec's WTP effluent-P is of human origin; the remainder comes from various detergents and cleaners (Grenon, 1994). Forms and distributions of phosphorus in municipal wastewater vary according to a wastewater's characteristics, but municipal wastewater contains on average:

- 50% orthophosphates;
- 30% polyphosphates;
- 20% organic phosphorus (Jenkins and Hermanowicz, 1991).

In 1992, the wastewater undergoing some form of treatment in Québec contained approximately 3 000 tonnes (t) of P in the influent. Wastewater containing 2 000 t/y P was treated by plants using some form of P-removal, and 1 000 t/y P enters WTPs that have no P-removal programs. Furthermore, 30% of Québec's population has no wastewater treatment, and the majority (74%) of P-loading to receiving waters is from agricultural sources.

The main P-removal process in Québec is chemical addition and precipitation; secondary removals are also achieved in biological treatment processes -- biomass growth and/or enhanced biological P-removal (EBPR). The most common metal salts used in chemical P-precipitation are ferric chloride, alum or ferrous sulfate. On average, 66% P-removal is achieved in these plants, leading to a 700 t/y P-release from WTPs with P-removal (Gosselin, 1995).

WTP processes must be investigated more in-depth, examining the efficiency of, and our knowledge surrounding, P-removal processes. Global parameters such as total P, COD and TSS are too often used to define wastewater treatment objectives, process specifications and operational parameters. P can be found in a number of diverse particulate and soluble forms; therefore, its characterization in wastewater is of great importance in understanding the complex interactions that take place during the various processes studied in this research.

1.2 Objectives

In order to clarify the mechanisms and interactions during chemical P-removal, a phosphorus mass balance model was needed, one that would account for soluble and particulate forms of orthophosphate and polyphosphate/organic phosphorus. The model presented here traces the path of each P-fraction throughout the chemical removal process, accounting for P-precipitation, hydrolysis and adsorption, as well as solids removal. Computer programs were constructed, with the model incorporated into specific programs written for primary treatment, activated sludge, biofiltration and facultative aerated lagoons. Over 99% of the wastewater treated in Québec is done so in WTPs of the types covered by these computer programs. This thesis presents the laboratory results and data analysis of field sampling carried out during June and July, 1994, at 11 WTPs across Québec. The field data were used to modify and calibrate the four types of programs such that the output mimicked the field data as closely as possible. The calibration results are discussed, with a view to deriving mechanistic insights from the parameter values.

This model and the ensuing computer programs were to serve as relatively accurate prediction tools, assisting in process evaluation and comparison at the level of conceptual design, for a subsequent phase of the MEF study.

Chapter 2. LITERATURE REVIEW

This chapter includes a summary review of current P-removal treatment processes and the generally accepted mechanisms applicable to chemical precipitation. More specifically, it includes a review of P-removal modelling, an important field of investigation in P-removal processes and mechanisms.

2.1 Process Technologies

Several publications summarize conventional and novel P-removal technologies and processes, their efficiencies and applicability to wastewater treatment (Comeau and Paradis, 1994; Wiechers, 1986; Yeoman et al., 1988), therefore this will not be discussed at length in this literature review. EPA Design Manual: Phosphorus Removal tabulates extensive performance data for chemical addition to WTPs for P-removal (EPA, 1987). Certain more recent information pertinent to chemical P-removal combined with other removal technologies is, however, presented in Table 2.1 below.

Further to Table 2.1, research has been carried out on the effects of chemical dosing on biological P-removal processes. *In vitro* tests showed that ferric ions cause cytoplasmic membrane damage to EBPR bacteria, causing release of poly-P; this was not observed with ferrous ions (de Haas and Greben, 1991) The authors recommended taking particular care when dosing chemicals to activated sludge (AS) systems, for the following reasons:

- An apparent suppression of EBPR mechanisms, also observed by Lötter (1991);
- Mixed liquor has an inherent capacity for chemical P-removal even with no chemical addition (the extent depending on influent characteristics); and,
- Residual capacity for P-fixation in mixed liquor remains when dosing is ceased, still observed after one full sludge age, implying efficient ferric phosphate fixation in the biomass.

Table 2.1: Synopsis of P-Removal Performance

Source	WTP Description	Specifics	$\frac{\text{mole Me}_{dose}}{\text{mole P}_{rem}}$	P-Reduction (unless otherwise stated)	Comments
Brooks, 1994	Sirofloc™ Process	Alum coagulation, adsorption to magnetite particles, followed by magnetite-magnet flocculation	1.3-1.9 Al^{3+}	7.5→0.9 mg P/L as PO_4	- Al/P of 1.3 if 70% Al of is recycled. - Treatment time of < 20 min if have a magnetite s.g. of 5.2 and settling velocity of 10m/h
de Haas et al., 1993	AS with EBPR	Alum dosed from 150 to 350 mg/L	0.8-1.8 Al^{3+}	7.9→1.0 mg P/L as P_{tot} 5.6→0.7 mg P/L as $PO_{4\ sol}$	
de Haas and Greben, 1991; Lijklema, 1980	Experiments with AS and synthetic solutions				Fe^{3+} formed *in situ* from Fe^{2+} was more effective at P precipitation than Fe^{3+} added directly
den Engelse, 1993	Activated sludge	Marginal improvement in P-removal at Me:P of 2	1.5 (Fe^{2+} or Al^{3+})	Effluent PO_4 < 1 mg P/L	Effluent-P < 0.1 mg P/L difficult to achieve because of effect of effluent TSS
Eggers et al., 1991	Crystalactor® PO_4^{3-} precipitates as $Ca_3(PO_4)_2$ in a Ca^{2+} and OH^- rich reactor	AS effluent passed through reactor, then rapid sand filters		Crystalactor®: 7.5→1.7 mg P/L as PO_4 Rapid sand filters: 1.7→0.5 mg P/L as PO_4	Illustrates importance of solids removal to achieve low P_{eff}
Fujimoto et al. 1991	Anaerobic sludge digestors	Dosing ferric chloride to supernatant to assist upstream EBPR	1.1 (Fe^{3+})	90% removal of 193 mg P/L as P_{tot} 72 mg P/L as PO_4	High %removal, although residual P-concentration is still relatively high

Table 2.1: **Synopsis of P-Removal Performance (continued)**

Source	WTP Description	Specifics	$\frac{\text{mole Me}_{dose}}{\text{mole P}_{rem}}$	P-Reduction (unless otherwise stated)	Comments
Leeuw and de Jong, 1993	Activated sludge	Comparison of EBPR vs. conventional AS with side-stream P-stripping	$FeSO_4$ dosing	EBPR: 10→0.9 mg P/L AS: 10→2.5 mg P/L	- EBPR performed as well or better than AS with side-stream P-stripping. - EBPR required occasional $FeSO_4$ dosing to maintain effluent quality.
Lötter, 1991	Mixed liquor batch tests: $\tau = 30$ min	ML spiked with 50 mg P/L as PO_4	1.1 (Fe^{2+} or Fe^{3+})	50→1 mg P/L as PO_4	Ferrous salts had slower reaction rates than ferric, but same final results: presumably because of time for oxidation of $Fe^{2+} \rightarrow Fe^{3+}$.
Lötter, 1991	Extended aeration	Successful P-rem with alum dosage, then effluent deteriorated; regained P-rem by dosing $FeSO_4$	2.0 (Al^{3+})	Effluent PO_4 < 1 mg P/L achieved 95% of the time with $FeSO_4$	Had lost EBPR while dosing alum; small degree of EBPR returned when $FeSO_4$ dosing began.
Nieuwstad et al., 1988	Activated Sludge	Simultaneous prec. and filtration; Post-precipitation and filtration.	Simultaneous: 2.6-6.5(Fe^{3+}) Post: n.a.	Simultaneous: 0.6→0.06 mg P/L as P_{tot} Post: 5.4→0.4 mg P/L as P_{tot}	Premature filter fouling at higher Me:P
Olesen, 1990	Rotor- aerated oxidation ditches	Ferrous sulfate dosing	0.7 to 1.1 (Fe^{2+})	10→0.9 mg P/L	
Rensink et al., 1991	Phostrip® supernatant fed to a Crystalactor®	Phostrip®: P-removal from EBPR mixed liquour by addition of excess acetate under anaerobic conditions, then MLSS removal		8-15 mg P/L $P_{tot\text{-}inf}$ reduced to less than 0.1 mg P/L	- $Ca_3(PO_4)_2$ has possible future industrial uses. - Approximately 4 kg/(p.e.·yr) pellets formed.

Laboratory tests indicated that "continuous iron salt addition...results in reduced chemical precipitation efficiency which in turn leads to high required chemical doses" (Lötter, 1991). The author hypothesized that the build-up of metal phosphates on the biomass affected the membrane transport system and, in turn, EBPR efficiency. As expected with chemical dosing, a reduction in the fraction of long-chain poly-P in the sludge was observed, therefore a more accurate indicator of the effects of chemical addition on EBPR might be the change of the metabolic rate or activity of EBPR bacteria during chemical addition. Results also suggested that long-chain poly-P storage was lower during chemical addition.

2.2 Coagulant Chemistry and Removal Mechanisms

Iron chemistry in water and wastewater aquatic systems is reported to be the same as that of aluminum (Pankow, 1991). Trivalent aluminum and iron cations are generally believed to exist in solution with six hydrated water molecules, as $[Al(H_2O)_6]^{3+}$ or $[Fe(H_2O)_6]^{3+}$ (Matijevic, 1961; Pankow, 1991). Rebhun and Lurie (1993) presented a simplified version of Al(III) coagulant-flocculant chemistry as follows:

$$[Al(H_2O)_6]^{3+} \rightarrow [Al(H_2O)_5OH]^{2+} \overset{OH^-}{\underset{\text{polymerization}}{\rightarrow}} [Al_6(OH)_{15}]^{3+}{}_{(aq)} \underset{\text{pH 4 to 7}}{\rightarrow} [Al_8(OH)_{20}]^{4+}{}_{(aq)} \rightarrow \ldots$$

At higher pH values, there is a greater abundance of aluminate in equilibrium solutions:

$$\ldots \overset{OH^-}{\rightarrow} [Al(OH)_3(H_2O)_3]_s \overset{OH^-}{\underset{\text{alkaline pH}}{\rightarrow}} [Al(OH)_4]^-$$

Cationic polymers such as $[Al_8(OH)_{20}]^{4+}{}_{(aq)}$ are the principal hydrolysis products and the effective flocculants, especially in the removal of dissolved organic matter (DOM) (Narkis et al., 1991; Rebhun and Lurie, 1993). Many other monomeric and polymeric species are reported to exist in these aquatic systems.

Given the nature of cationic inorganic coagulants such as aluminum and iron salts, the most significant coagulation mechanisms involved in P-removal are expected to be precipitation with the coagulant, adsorption to the surface of a precipitated species and entrapment, or *sweep floc*, of particulates. Perikinetic flocculation, or random ***Brownian*** motion, and orthokinetic flocculation, caused by mixing and settling, combine to increase particle size and settling (Montgomery, 1985).

Rebhun and Lurie (1993) summarized the removal mechanisms of DOM (humic and fulvic acids) by ferric or aluminum salt addition. At a pH of 6-7, the reaction of DOM with monomeric and polymeric Al complexes is kinetically faster than the precipitation of $Al(OH)_3(s)$, although $Al(OH)_3(s)$ is the principal final precipitate. The DOM-Al precipitates are then removed through adsorption and other interactions (e.g. sweep floc if unsettleable) with $Al(OH)_3(s)$. Jiang et al. (1993) concluded that metal hydroxide precipitation and sweep floc played a significant role in the removal of both particulate and dissolved organic matter at higher coagulant doses. Jiang et al. (1993) also proposed the adsorption of polymerized cationic coagulant species onto the surface of particulate organic matter (algae) and the precipitation of DOM as significant removal mechanisms. Due to the inherent P-content of certain forms of organic matter, P-removal might follow a similar behaviour as do DOM and particulate organic matter.

Similarly, de Haas and Greben (1991) observed an adsorptive behaviour with ferric phosphate fixation in AS biomass. Reaction pathways proposed by Dousma and Bruyn (1976) (*in Lijklema, 1980*) suggested very effective phosphate binding to polymers formed after the addition of concentrated metal solutions to phosphate solutions. Complexes with Al:P molar ratios as low as 1:1 were observed. Similar reaction pathways and intermediates are proposed elsewhere (Pankow, 1991; Rebhun and Lurie, 1993).

Removal, or insolubilization of PO_4^{3-} by adsorption to a hydroxide surface results in the release of an OH^-. Competition between PO_4^{3-} and OH^- ions explains the higher levels of P-removal observed at pH values less than neutrality (Lijklema, 1980). A pH of approximately 5 was found to be the optimum for phosphate adsorption. Hydroxide precipitates were observed to still have an appreciable adsorptive capacity for phosphates after 1 hr of contact with phosphate solutions.

Even though pH values and ranges quoted in the literature vary for optimal P-removal, it is generally agreed that iron salts have a lower optimal pH, but that significant P-removal can still be achieved over wide pH ranges. Optimal P-removal occurs in the following ranges: $pH \approx 8$ for Fe^{2+} ; $pH = 5.5\text{-}6.5$ for Al^{3+} ; $pH = 4.5\text{-}5.5$ Fe^{3+} (EPA, 1987; Recht and Ghassemi, 1970).

2.3 Phosphorus Removal Modelling

Models dealing with phosphorus behaviour, distributions and/or removal have been the subject of research not only when considering chemical P-removal in wastewater treatment, but also in modelling EBPR, solid/liquid P-models in wastewater lagoons with no chemical addition, as well as modelling the dynamic interactions between soluble and particulate phosphorus in eutrophic lakes (Comeau et al., 1985; Houng and Gloyna, 1984; Lung et al., 1976). As well, databases have been assembled with considerable amounts of information on efficiencies of P-removal using chemical addition (CANVIRO, 1988; Prested et al., 1977)

Six key papers were reviewed dealing specifically with predicting and/or modelling P-removal from wastewater through chemical addition and precipitation; these will be discussed below.

In 1972 under the *Canada-Ontario Agreement on Great Lakes Quality*, Prested et al. (1977) developed algebraic relationships between influent phosphorus and chemical dosage, in anticipation of the 1.0 mg P/L effluent limit to be instituted during 1974-76. By regressing data from jar tests and full-scale treatability studies, the goal was to develop expressions sufficiently reliable for preliminary design, perhaps reducing or even eliminating jar testing requirements. The resulting equations predicted actual chemical doses to within ± 30%. In full-scale operation with ferric chloride and alum, the molar ratios of metal added to phosphorus in the wastewater at the point of addition, to achieve an effluent of 1.0 mg/L, were as follows:

Chemical	**Raw Wastewater Addition** (molar ratios)	**Mixed Liquor Addition** (molar ratios)
Fe:P	1.8	0.9
Al:P	1.2	0.7

These results favour chemical addition to the mixed liquor. A parallel cost analysis favoured ferric chloride over alum. Similar results reported by EPA (1987) found ferric chloride to be more efficient on a molar basis during mixed liquor addition.

Pöpel (1969) assumed that the principal insoluble complex formed upon addition of an iron or aluminum coagulant to wastewater was of the form $Me_n(OH)_{3m}(PO_4)_{n-m}$ (*n and m are stoichiometric coefficients*), and that hydroxyl and phosphate ions were the two most important ligands in terms of affinity towards complex formation with Fe^{3+} or Al^{3+} (Fe^{3+} used as an example). It was assumed that in pH ranges of 3-6 and 8-11, exchanges take place continuously until equilibrium is reached:

for a pH range of 3-6:

$$Fe_n(OH)_{3m}(PO_4)_{n-m} + dOH^- + 2dH_2O = Fe_n(OH)_{3(m+d)}(PO_4)_{n-m-d} + dH_2PO_4^- \qquad 2.1$$

for a pH range of 8-11:

$$Fe_n(OH)_{3m}(PO_4)_{n-m} + 2dOH^- + dH_2O = Fe_n(OH)_{3(m+d)}(PO_4)_{n-m-d} + dHPO_4^{2-} \qquad 2.2$$

A pH of 6-8 is usually encountered in sewage treatment, therefore both of these equations apply partially with the equilibrium constant stated as follows:

$$K = P_f^d/(OH^-)^{zd} \qquad 2.3$$

where: K = equilibrium constant;
P_f = the final phosphate concentration after precipitation, as $H_2PO_4^-$ and HPO_4^{2-};
d = stoichiometric coefficient
and $1 < z < 2$.

K is therefore a measure of the degree of precipitate formation of the metals dosed with the phosphate and hydroxyl ions. Pöpel's model was therefore based on representing the exchange reactions in the form of a Freundlich adsorption isotherm:

$$\frac{(P_i - P_f)}{C_a} = k \cdot \frac{P_f^{q1}}{(OH^-)^{q2}} \qquad 2.4$$

where: $P_{i,f}$ = initial and final phosphate concentrations
C_a = amount of coagulant added (moles Me/L)
k, q1, q2= empirical constants from general form of Freundlich isotherm

The model's basic form, Equation 2.7, results from algebraic manipulation of this general form:

$$\frac{\varepsilon}{(1+\varepsilon)^{q1}} = k' \cdot \beta \cdot P_i^{q1} \cdot (H^+)^{q2} \qquad 2.5$$

where: $\varepsilon = (P_i - P_f) / P_i$ = removal efficiency
$\beta = C_a / P_i$
$k' = k / k^{q2}_{water}$

Plotting ε vs. the logarithm of the L.H.S. of Equation 2.5 yields the following equation, linear for $0.45 < \varepsilon < 0.95$:

$$\varepsilon = c + b \cdot \log(\varepsilon/(1-\varepsilon)^{q1}) \qquad 2.6$$

where: b = slope of the line
c = vertical intercept

Equations 2.5 and 2.6 combine to give:

$$\varepsilon = k_1 + k_2 \cdot \log\beta + k_3 \cdot \log P_i + k_4 \cdot pH \qquad 2.7$$

where: $k_1 = c + b \cdot \log(k')$
$k_2 = b$
$k_3 = b \cdot q1$
$k_4 = b \cdot q2$

At constant phosphate and pH values, Equation 2.7 reduces to:

$$\varepsilon = k_1' + k_2 \cdot \log\beta$$

$$\text{where: } k_1' = k_1 + k_3 \cdot \log P_{i,const} - k_4 \cdot \log(pH_{const})$$

Pöpel's experimental results suggested that the Me:P ratio and the initial P-concentration both had a significant effect on the removal efficiency, but that pH on the other hand, was of no significance if close to neutrality. Results also indicated that particular wastewater compositions influenced the efficiency of the coagulation process, and that ferric chloride had a more stable performance over a range of operating conditions than did alum.

Ferguson and King (1977) developed what seems to be the first steady-state unit-process P-removal model based explicitly, at least in part, on solid:liquid chemical equilibrium. This model describes the precipitation of orthophosphate using alum, ultimately to determine the residual phosphate concentration following a given chemical dose. The model does not consider the removal of total-P, the possibility of an adsorption removal mechanism, nor the fate of precipitated $AlPO_4(s)$, the removal of which is assumed to be 100%. Wastewater is assumed to have a constant flow and composition.

Ferguson and King assumed that $AlPO_4(s)$ was less soluble than $Al(OH)_3(s)$, and would precipitate first. Contradictory to thermodynamic data, the authors found "compelling" evidence against adsorption and supporting precipitation in the 5-8 pH range, although they suggested that adsorption might be responsible for high removals observed in other studies at pH above 8 or below 5. These assumptions were not discussed in detail.

Three possible conditions, or "removal zones", for P-removal were described in this paper:

Zone I: Stoichiometric removal. Insufficient aluminum added, therefore the phosphate that is removed is directly proportional to the alum dose;

Zone II: Less than stoichiometric removal. Doses approaching stoichiometry, calculated from the solid:liquid equilibrium of the aluminum phosphate precipitate; and,

Zone III: Stoichiometric aluminum dose exceeded by 25%; aluminum hydroxide and phosphate precipitate. A single residual phosphate concentration is possible for a given pH assuming solid:liquid equilibrium.

First, it was necessary to estimate the final pH based on what was expected following chemical addition, and once all reactions had taken place. This depended on the initial pH, the chemical nature of the wastewater to be treated, the precipitation that occurred and the CO_2 transport during treatment. The operational pH range was assumed to be 5.0 to 7.5 in Zone I, with a decreasing operational pH range near 6.0 in Zone III. Recht and Ghassemi (1970) also observed that as the dose of coagulant increased, a higher degree of P-removal was possible, but that the pH range for optimal P-removal narrowed.

The precipitate in Ferguson and King's model had an Al:P stoichiometric ratio of 1.4, the simplest representation of which is $Al_{1.4}PO_4(OH)_{1.2}(s)$. $AlH_2PO_4^{2+}(aq)$ was, for simplicity, assumed to be the single residual Al-P complex, thus excluding polymeric species from this study. Stability constants for the aqueous and solid phase phosphate and hydroxide complexes were such that the model's phosphate residual conformed with laboratory results, and was in relative agreement with values quoted in the literature.

Zone I removal involved determining the final pH to ensure that it was in the proper range, and then calculating the phosphate removed based on the aluminum added.

For Zone II, mass balances for Al and PO_4 were solved for one equation with two parameters: pH and ($PO_{4\,\mathrm{initial}} - Al_{\mathrm{dose}}/1.4$). Figure 2.1 shows the results of these calculations, the y-axis representing the sum of all soluble phosphate residuals. The authors arbitrarily set the boundary between Zone I and II as the point where the calculated residual exceeded the stoichiometric residual by 25%.

Zone III calculations relied on the previously mentioned assumption, that the aluminum hydroxide-phosphate species was preferentially formed over aluminum hydroxide. From phase equilibria at a given pH, all concentrations were fixed if both solids precipitated.

The Al^{3+} concentration was fixed as a function of pH from the $Al(OH)_3(s)$ solubility equation, and therefore the minimum PO_4^{3-} concentration was also fixed.

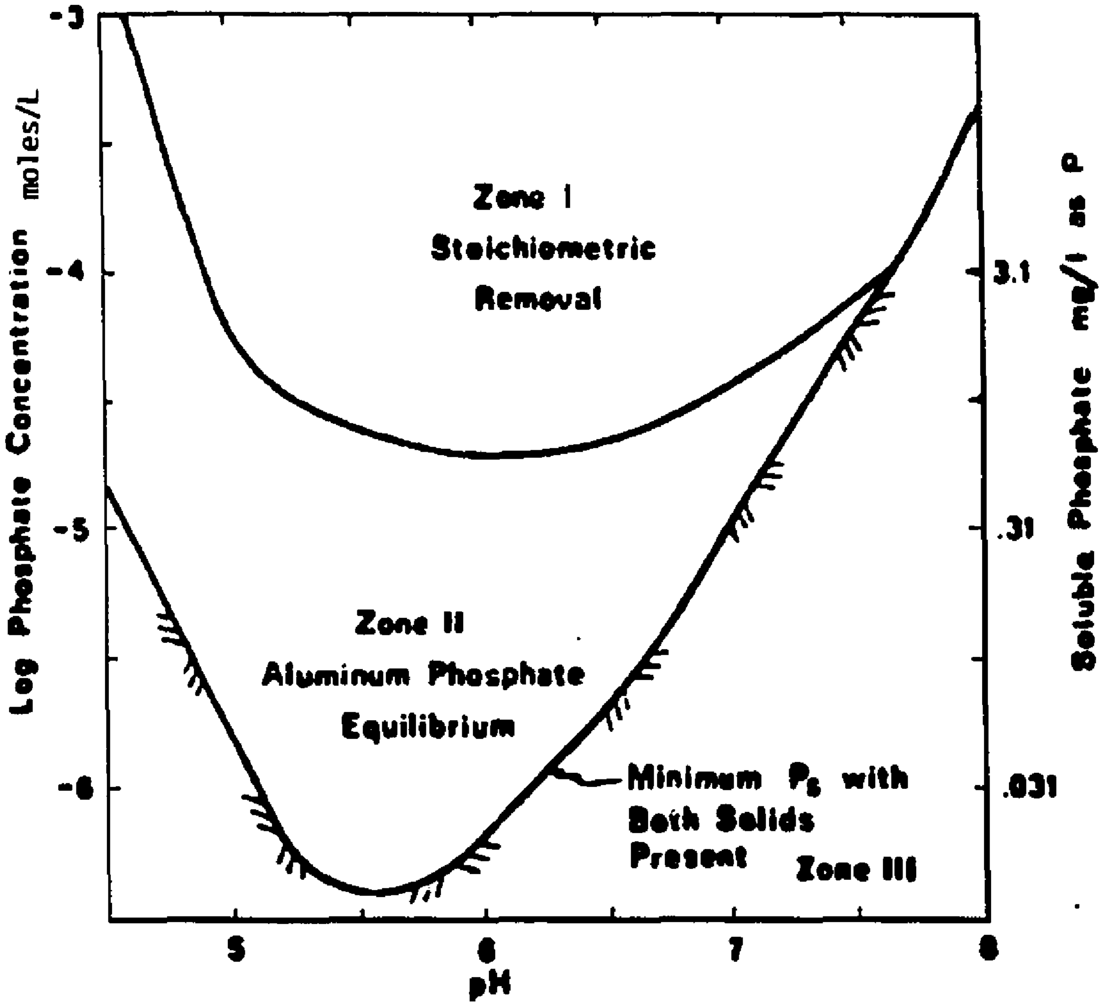


Figure 2.1: **Soluble Residual Phosphate and pH Ranges where Zones of Model Apply**

(Source: Ferguson and King, 1977)

The phosphate residuals in all cases consisted of different complexes depending on the pH of the systems.

Kavanaugh et al. (1978) developed a model predicting the performance of P-removal through post-precipitation with ferric ions. Specifically, the authors elaborated an equilibrium model for dissolved orthophosphate removal, a flocculation model and a model of solids removal in a sludge blanket clarifier (SBC). Not only are the flocculation and solids removal models of interest to those seeking design limits for new or existing processes, or insight into the effects and sensitivity of principal process parameters, but they are also of interest in this thesis because of the significant effect which effluent TSS have on effluent total-P concentrations.

The P-removal model assumed that hydroxyl and phosphate ions compete for ferric ions in solution, and that the soluble phosphate concentration was controlled by $FePO_4(s)$. Neglecting the presence of soluble iron-phosphate complexes or other iron or phosphate species, the following equation described the final orthophosphate concentration:

$$P_{t_f} = \frac{\Delta P_{t_0}}{2} + \sqrt{\left(\Delta P_{t_0}\right)^2 + \kappa} \tag{2.8}$$

where:

P_{t_f}, P_{t_0} = equilibrium *and* initial soluble ortho – P concentrations, respectively

$$\Delta = \frac{1+\gamma-\beta}{1+\gamma}$$

$$\beta = \frac{Fe_{dosed}}{P_{t_0}};\ \gamma = \frac{Fe(OH)_3}{FePO_4}(final)$$

$$\kappa = \frac{K_{FePO_4(s)}}{\alpha(1+\gamma)}\left[1+\frac{OH^-}{K_{Fe(OH)_2^+}}+\frac{(OH^-)^2}{K_{Fe(OH)_2^+}\cdot K_{FeOH^{2+}}}\right]$$

$$\alpha = \left[1+\frac{H^+}{K_{HPO_4^{2-}}}+\frac{(H^+)^2}{K_{H_2PO_4^-}\cdot K_{HPO_4^{2-}}}+\frac{(H^+)^3}{K_{H_3PO_4}\cdot K_{H_2PO_4^-}\cdot K_{HPO_4^{2-}}}\right]^{-1}$$

The model assumed that ferric ions reacted only with phosphate ions (γ=0) when the metal dosed to phosphate molar ratio (β) was less than or equal to 1, and that iron hydroxide was formed for β>1 (when $\gamma = \beta - 1$). Adjustments of γ were required in some cases so that predicted results agreed with experimental results. These discrepancies were explained by hydroxide/phosphate ligand competition, as well as the possible existence of other precipitates and adsorbed complexes.

Kavanaugh et al.'s (1978) flocculation model described the change in the number of primary particles, with a rough fit between the observed turbidity removal data and the flocculation model.

$$\frac{n_1(t=0)}{n_1(t=\theta)} = \left(K_{agg} \cdot G \cdot \theta + 1\right) \qquad 2.9$$

where: n_1 = particle concentration
θ = hydraulic retention time
G = root mean square velocity gradient
$K_{agg} = \frac{\bar{\alpha}\phi\delta}{\pi}$; $\bar{\alpha}$ = fraction of effective particle collisions
ϕ = floc volume fraction = $\sum \frac{4}{3}\pi \cdot r_1^3 \cdot n_1$
δ = particle size distribution
r_1 = mean particle radius

Assuming that residual TSS is proportional to the concentration of primary particles (n_1), this model can be used for preliminary predictions of required values of θ and G for desired solids removal.

Two solids removal models for the SBC were proposed, one based on an unrealistic solids removal of 100%, that predicted a theoretically impossible value of $\bar{\alpha} = 8$ (must have $\bar{\alpha} < 1$) when calibrated with actual data. The other model represented the SBC as a suspended deep-bed filter, with the fluidized particles trapping incoming suspended solids. The authors recognized that the models required further study before being used for anything but estimating design limits and SBC feasibility.

Another phosphate precipitation model based on chemical equilibria was developed by Arvin and Peterson (1980). They proposed that phosphate precipitates as a calcium-metal-phosphate complex, as a function of the pH, calcium activity and the ionic strength of the water at a fixed Me:P ratio. As an addition to their earlier work, carbonate was included in the precipitation product, thus accounting for prior deviations from laboratory results. Experimental results indicated the presence of both calcium and carbonate in the phosphate precipitate, the principal phosphate being precipitated represented as:

$$Ca_kFe_m^{2+}Fe_n^{3+}Al_u^{3+}(H_2PO_4)_f(HCO_3)_c(OH)_h$$

where: k, m, n, u, f, c and h are stoichiometric coefficients

Other metal oxides, hydroxides, carbonates and phosphates are assumed to precipitate as well. The equilibrium soluble phosphate concentration (C_p) is written as:

$$C_p = C_{H_2PO_4^-} + C_{HPO_4^{2-}} + C_{CaHPO_4(aq)} + C_{CaPO_4^-}$$

Combining the relationships defining the solubility products, complexation and acidity constants of the solid phase, soluble complexes and the acids involved in the system under consideration, the following general form of the phosphate concentration relationship was derived in previous work:

$$C_p = 10^{-\alpha}\frac{a_H^{(\beta+\varepsilon)}a_{HCO_3}^{\varepsilon}}{a_{Ca}^{\frac{1}{2}(\beta+1)}}\left[\frac{1}{\gamma_1}+\frac{K_{2,P}\left(\frac{1}{\gamma_2}+K_{C,1}\cdot a_{Ca}\right)}{a_H}+\frac{K_{C,2}\cdot K_{2,P}\cdot K_{3,P}\cdot a_{Ca}}{\gamma_1\cdot a_H^2}\right] \qquad 2.10$$

where: a_i = activity of compound i: H^+, Ca^{2+} or HCO_3^-
α = a constant containing the solubility products
β, ε = constants depending on the composition of the phosphate solid complex
γ_1, γ_2 = activity coefficients of mono- and divalent ions (same value used for like-charged ions)
$K_{C,1}$, $K_{C,2}$ = $CaHPO_4(aq)$ and $CaPO_4^-$ complexation constants
$K_{2,P}$, $K_{3,P}$ = $H_2PO_4^-$ and HPO_4^{2-} acidity constants

Dosage affects the value of the constants β and ε, through relationships between the stoichiometric coefficients of all species in the Ca-metal-phosphate precipitate. Depending upon the Me:P ratio and on other system conditions, different solids precipitate, resulting in many possible relationships and subsequent expressions for β and ε. The authors also derived an expression for the hydrogen activity corresponding to the minimum phosphate solubility.

Optimal phosphate removal was reported in the pH range of 6.6-8.8. The authors attributed these considerably higher results (compared to Ferguson and King, and Recht and Ghassemi, 1970), to different reference points, in that some reported results were functions of the operating conditions, whereas theirs were with respect to specific fixed system values. Other observations included:

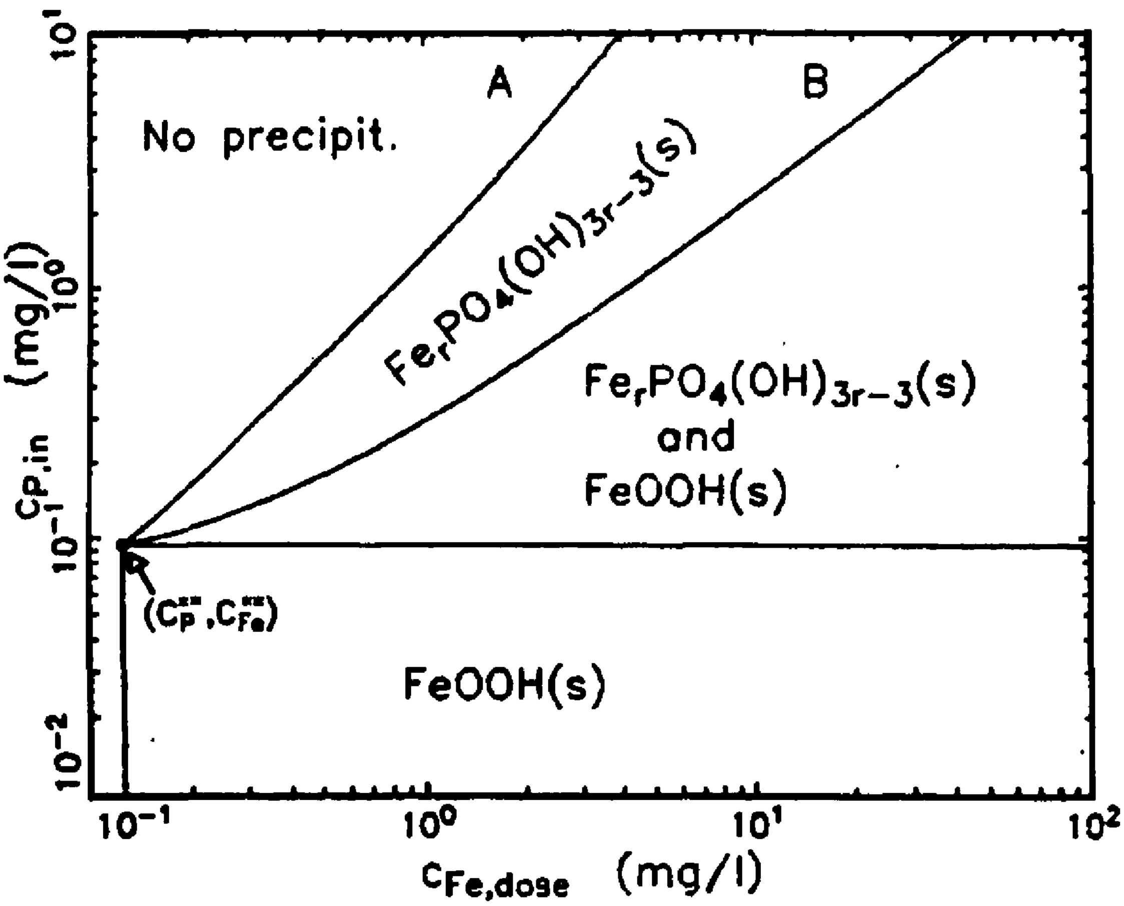
- Minimum phosphate solubility at high calcium activity; highly pH-sensitive phosphate solubility at low calcium activities;
- Minimum phosphate solubility and reduced sensitivity to pH changes at low bicarbonate activities;
- Similar performance for iron- and aluminum-based chemicals;
- Lower phosphate solubility at higher chemical dosage;
- Lower optimal pH at higher dosages; and,
- Reduced or eliminated bicarbonate activity significance with (i) increased coagulant dosage (decreased ε value) and/or (ii) increased sludge age (and hence, precipitation times).

Luedecke et al. (1989) constructed a chemical model for ferric addition assuming four precipitation regions:

- No precipitation;
- Precipitation of a ferric hydroxy-phosphate solid;
- Precipitation of a ferric hydroxide solid; or,
- Co-precipitation of both solids.

Similarly to several previously discussed models, this model was based primarily on solid:aqueous equilibrium behaviour of iron phosphate and iron hydroxide complexes. It was centred on the formation of a ferric hydroxy-phosphate precipitate:

$$r \cdot Fe^{3+} + PO_4^{3-} + (3r - 3) \cdot OH^- \leftrightarrow Fe_rPO_4(OH)_{3r-3}(s) \quad pK_s = ? \qquad 2.11$$



<u>Figure 2.2</u>: Precipitation Regions for pH=6.8
(assumed values r=2.5, pK_s=96.7, pK_{FP}=-21.5)
(Source: Luedecke et al., 1989)

The authors assumed a value of r=2.5, while analysis of laboratory data indicated a pK_s=96.7. Figure 2.2 was derived from mass balances and equilibrium concentration expressions for the components of this system. The authors noted that fixed concentrations of Fe^{3+} (C_{Fe}^{**}) and PO_4^{3-} (C_p^{**}) co-exist under conditions of co-precipitation at a given pH, as did Ferguson and King (1977). Conditions follow for the three possible precipitation regions remaining:

- <u>no precipitation</u>: the concentration of iron dosed ($C_{Fe,\,dose}$) is less than the fixed soluble iron equilibrium concentration (C_{Fe}^{**});
- <u>ferric hydroxide precipitation</u>: influent phosphate ($C_{P,\,influent}$) is less than the maximum equilibrium soluble phosphate concentration (C_p^{**}); or,

- ferric hydroxy-phosphate precipitation: $C_{P,\,influent}$ and $C_{Fe,\,dose}$ are less than C_p^{**} and C_{Fe}^{**}, respectively, but insufficient iron is dosed to reduce the phosphate concentration to C_p^{**}. *(C_P^{**} calculated from relationships of Equation 2.11, the dissociation of phosphates and Fe^{3+} hydrolysis)*

The Luedecke et al. (1989) model predicted a decreasing Fe-dosed:P-removed ratio with decreasing $C_{P,eq}$, close to the r value of 2.5. Values of Fe-dosed:P-removed increased sharply at C_P^{**} when ferric hydroxide is formed. The authors suggested that the observed trend of an increasing Fe-dosed:P-removed ratio with decreasing $C_{P,\,eq}$ (past their predicted C_P^{**}) was due to phosphate removal through adsorption on the precipitates, in competition with hydroxyl groups.

The authors therefore split $C_{P,\,eq}$ into two fractions, a final dissolved residual ($C_{P,res}$) and that adsorbed on the precipitates ($C_{P,\,ads}$). Equation 2.12 accounts for the adsorption equilibrium:

$$C_{P,ads} = k_a \cdot X_a \cdot \frac{\left[PO_4^{3-}\right]_{res}}{\left[OH^-\right]^3} \qquad \textbf{2.12}$$

where: k_a = adsorption coefficient
X_a = amount of adsorbent adjusted for the number of hydroxyl groups
$= (3r-3)\cdot C_{P,prec} + C_{Fe,prec}$
$C_{p,prec}$ = concentration of hydroxy-phosphate precipitate
$C_{Fe,prec}$ = concentration hydroxide precipitate

With this addition, Leudecke et al. (1989) predicted similar $C_{P,\,res}$ vs. Fe:P behaviour in their model as compared to their laboratory results.

2.3.1 Summary

Models presented here vary in their degree of complexity and applicability. Only one (Kavanaugh et al., 1978) considers subsequent solids removal, and even then as a separate case; adsorption is neglected by all except Luedecke et al. (1989). Pöpel predicts the final P-concentration using a Freundlich isotherm to model the competitive adsorption of phosphate and hydroxyl to a metal hydroxy-phosphate precipitate. In brief however, the models discussed here deal only with soluble ortho-P, and on one hand, this is a benefit because of the detail which some of them give to this fraction's behaviour. On the other hand though, considering only soluble ortho-P is also a limiting factor in overall WTP performance modelling.

The earliest modelling effort by Pöpel (1969) describes the complete removal process in one "black box" equation, and therefore has limited application in describing treatment bottlenecks and deficiencies. Experimentally determined model parameters varied considerably due to wastewater characteristics and physical process parameters, therefore this model can be used only for forecasting removal efficiencies in the range of 45% to 95%. Similarly, the algebraic linear equations derived by Prested et al. (1977) are useful for predicting treatment performance and chemical demand, but have relatively high (± 30%) variability and uncertainty.

The foundations of several models are based on chemical equilibria, even though they elaborate on different aspects of the P-removal mechanisms and behaviour. Ferguson and King (1977) assume stoichiometric removal at low doses, orthophosphate residual determined by chemical equilibrium with other species, and a fixed residual orthophosphate determined by solid:liquid equilibrium under conditions of overdose. Similar assumptions and precipitation regions were applied in the Luedecke et al. (1989) and Kavanaugh et al. (1978) models, with respect to assuming that metal cations react preferentially with phosphate ions, and that metal hydroxides are formed at higher doses and under various other conditions.

Ferguson and King's (1977) experimental work highlighted the value of adjusting pH before coagulant addition in terms of increased efficiency in phosphate removal and therefore decreased chemical requirements. However, since it is limited to soluble ortho-P, it has limited application, to primary or secondary effluents of relatively stable composition and low in particulate-P.

Kavanaugh et al. (1978) did not consider a hydroxy-phosphate precipitate as did other models reviewed here (Arvin and Peterson, 1980; Ferguson and King, 1977; Pöpel, 1969) nor did they consider the mechanism of phosphate adsorption onto iron phosphate or hydroxide. Specifically, their model estimates the chemical doses required for a particular residual soluble orthophosphate. Kavanaugh et al's solids removal models might provide valuable tools in estimating particulate P-removal, given the relationship between TSS and P.

Degree of complexity or attention to relatively insignificant details are not prerequisites in elaborating an effective P-removal predictive model. Arvin and Peterson's (1980) model and observations can be simplified in some cases, for example, by stating that lower phosphate residuals and wider optimal pH ranges are possible in low alkalinity wastewater (also observed by Kavanaugh et al., 1978), or that high chemical doses, or high sludge recycles rates, can overcome the difficulties encountered with high alkalinity wastewater.

The objective behind the construction of some models was not only to predict dosage requirements, but also to predict the form and concentration of effluent phosphorus. The foci of some models are dramatically different. An integrated approach is needed, considering the overall picture in terms of the interactions between removal mechanisms and the ramifications this may have in terms of the treatment efficiency of other wastewater parameters.

Chapter 3. MATERIALS AND METHODS

Field data were required concerning the physico-chemical P-removal step in WTPs of various types across Québec, in order to calibrate the computer programs, as well as to obtain further information on general performance. Field sampling was therefore necessary.

The analyses that were performed on each sample are listed in Table 3.1. Results of particular tests performed on samples from each WTP are found in Chapter 4 and in Appendices. Figure 3.1 illustrates a sample's history during a typical day of sampling, as well when the various analyses took place. Samples were generally gathered before noon and were 24-hour composites where possible. When a WTP had no composite samplers at a desired sampling point, a portable composite sampler was installed the day prior to sampling. When no composite sampler was available (failure or unavailability), three separate grab samples were taken and combined.

Samples were placed in coolers with ice packs and transferred to the appropriate laboratory, McGill University Environmental Engineering Laboratory or Proserco Inc., depending upon what analyses were required. McGill used high density polyethylene (HDPE) containers washed and rinsed with hydrochloric acid and deionized water between uses (APHA et al., 1992; McGill University, 1992). Proserco supplied single use HDPE containers with the appropriate preservative.

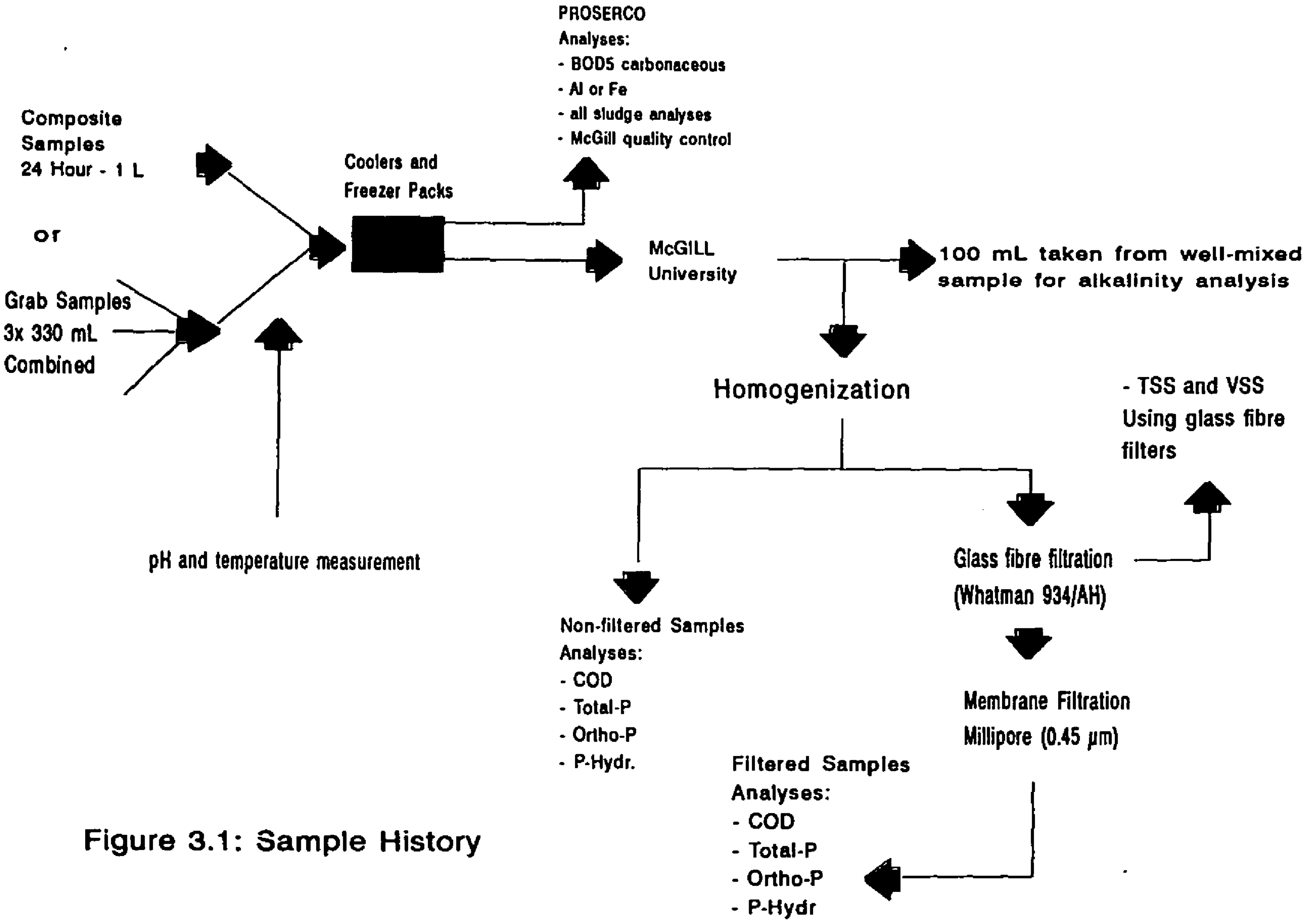


Figure 3.1: Sample History

Table 3.1: Laboratory Analyses

Measurement	Sampling Point			
	Influent/Effluent	Mixed Liquor	Intermediate Point	Sludge
Total phosphorus (filtered and un-filtered)	x	x	x	x (un-filtered)
Orthophosphate (filtered and un-filtered)	x	x	x	
Polyphosphates (filtered and un-filtered)	x (St-Georges only)	x (Long-chain)	x (St-Georges only)	
Inorganic phosphorus				x
TSS	x	x	x	
VSS	x	x	x	
TS				x
VS				x
BOD_5	x			
COD (filtered and un-filtered)	x	x	x	
Al/Fe	x			x
Alkalinity	x	x	x	
pH	x			
Temperature	x			
Flowrate	x			
Chemical dosage	x			

For the P-analyses performed at McGill, a procedure was developed in which two absorbance readings were taken on each sample, the first measurement taken at a set time before the final reading. This arose from inconsistent results found in triplicate P analyses performed before the sampling began. A new manufacturing method had apparently resulted in some PhosVer 3® pouches receiving inadequate amounts of chemical. In order to be confident with the analytical results, a second pouch of PhosVer 3 ® was added to those samples from a set of duplicates or triplicates that seemed to have incomplete colour development as compared to the others in a set. Consistent results were then obtained.

3.1 Orthophosphates

The same procedure was used for filtered and unfiltered samples. Samples were homogenized before analysis. Analyses for reactive-P were performed in duplicate on the day the samples were gathered, as per Hach Method 10011 (ascorbic acid coloration) (Hach Co., 1993), using a Spectronic 20D spectrophotometer at λ=890 nm with a red filter. An initial absorbance reading was taken at 5 minutes of reaction time, and if a significant difference between the duplicate readings was observed, another PhosVer 3® pouch was added to the sample with the lower absorbance. The final absorbance was read at 10 minutes. The ortho-P analyses were, in fact, tests for reactive-P. While it is true that small amounts of condensed-P and poly-P will hydrolyze to the soluble form during storage and analysis, it is impossible to measure this fraction during field studies. The reactive-P analysis was performed immediately upon arrival at the laboratory, and is assumed to represent the ortho-P fraction.

3.2 Total Phosphorus

The same procedure was used for filtered and unfiltered samples. Samples were homogenized before analysis. Total-P analyses were performed in triplicate on the day the samples were gathered or the following day. Hach Method 10013 (sulfuric acid/persulfate digestion, ascorbic acid coloration) (Hach Co., 1993) was used with a Spectronic 20D spectrophotometer at λ=890 nm with a red filter. An initial absorbance reading was taken at 20 minutes of reaction time, and if a significant difference between the triplicate readings was observed, another PhosVer 3® pouch was added to the sample with the lower absorbance. The final absorbance was read at 30 minutes.

3.3 Hydrolyzable Phosphorus

The same procedure was used for filtered and unfiltered samples. Samples were homogenized before analysis. Hydrolyzable-P analyses were performed in triplicate on the day after the samples were gathered. Hach Method 10012 (sulfuric acid digestion, ascorbic acid coloration) (Hach Co., 1993) was used with a Spectronic 20D spectrophotometer at λ=890 nm with a red filter. An initial absorbance reading was taken at 20 minutes of reaction time, and if a significant difference between the triplicate readings was observed, another PhosVer 3® pouch was added to the sample with the lower absorbance. The final absorbance was read at 30 minutes.

3.4 Long-Chain Polyphosphate

Mixed liquor samples were homogenized before analysis. The long-chain polyphosphate tests were carried out as soon as the samples arrived in the laboratory, following the procedure described by Comeau et al., (1990). The procedure required adding sodium acetate to a final concentration of approximately 250 mg/L to a fresh sample of mixed liquor, followed by an anearobic stirring phase. Filtered ortho-P tests performed on the mixed liquor sample before and after the anaerobic phase indicated the ortho-P concentration that could be attributed to EBPR.

3.5 COD

Filtered and unfiltered COD tests used the same procedure, and were carried out in duplicate on homogenized samples. Closed reflux method COD tests (Hach Company, 1992) were performed on the same day as samples were gathered or on the following day.

Absorbance was read using a Spectronic 20D spectrophotometer at λ=620 nm with no light filter.

3.6 Alkalinity

Alkalinity analyses (APHA et al., 1992; McGill University, 1992) were performed as soon as the samples arrived in the laboratory. Un-filtered non-homogenized samples were used.

3.7 TSS and VSS

Filtrations were performed as soon as the samples arrived in the laboratory. TSS and VSS were carried out using methods 2540-D & E in Standard Methods (APHA et al., 1992). The following volumes of samples were used, tested in duplicate or triplicate:

- 100 mL of deionized water for the blank
- 50→100 mL of influent
- 100 mL of effluent
- 10 mL of mixed liquor

3.8 Detection Limits and Quality Control

Approximately 10% of the tests carried out at McGill University were repeated at Proserco's laboratory. These results are indicated with brackets in Tables A4.1 to A4.22. Significant differences were often observed between TSS and VSS results from McGill analyses and the quality control performed at Proserco. Following consultation with Proserco, no satisfactory explanation was found; Proserco did not use Whatman brand glass fibre filters, but this is not expected to be responsible for the observed discrepancies. As great care was taken in performing tests in duplicate or triplicate at the McGill Environmental Engineering Laboratory, these results were used for the data analysis and computer program calibration. The McGill and Proserco Inc. detection limits are listed in Table 3.2.

Table 3.2: **Detection Limits**

Laboratory	Analysis	Detection Limit	Units
McGill	Phosphates and total phosphorus (P)	0.05*	mg/L
	COD	12*	mg/L
Proserco Inc.	BOD_5	2	mg/L
	Total iron (Fe)	0.02	mg/L
	Total aluminum (Al)	0.8	mg/L
	Phosphates (P)	0.05	mg/L
	Inorganic and total phosphorus (P)	0.10	mg/L

* Detection limits calculated as per APHA et al., 1992

In accordance with Standard Methods (APHA et al., 1992), standards and spiked samples were included as a regular part of the testing regime. The percentage recoveries of all quality control testing at McGill are listed in Table 3.3.

Table 3.3: **Percentage Recovery for Standard and Spiked Samples**

	Orthophosphate	Total Phosphorus	COD
Standard	98 ± 1.9%	97 ± 2.4%	100 ± 3.1%
Spiked Samples	97 ± 2.1%	98 ± 3.6%	100 ± 2.1%

One shortcoming of the laboratory procedure was encountered in filtering high concentrations of mixed liquor. Obtaining 10 mL of filtrate was a difficult and time-consuming task, and since it was to be used for the analyses of soluble components only, the filter was not eluted. With such dense residue on the filter, colloidal or soluble matter may have been retained in the filter paper, possibly distorting the results.

Chapter 4. FIELD SAMPLING AND DATA ANALYSIS

4.1 Field Sampling

Sampling was carried out at 11 WTPs in Québec over a five week period during June and July 1994. These were chosen such that at least one WTP using each major type of treatment found in the province would be visited. Each WTP visited uses chemical P-removal in their treatment train with either an iron or aluminum based coagulant; several WTPs receive alum sludge from municipal water purification plants. A maximum of four sampling points per day was planned for each WTP, depending upon the type of treatment. Table 4.1 presents a summary of the dates, number, and sampling points during visits to each WTP.

In the following sections, the units and terms employed are defined below:

- concentrations of all forms of P are given in mg/L of P; the long-chain poly-P results are an exception, being quoted in terms of g Poly-P released per g of MLVSS in the sample;
- the Me:P ratios represent the amount of coagulant added divided by the amount of total phosphorus at the point of dosage, both quoted on a molar basis;
- the removal efficiencies for various P-fractions are quoted on an overall (influent-effluent) basis, and do not account for any mass flux due to transformations (precipitation, adsorption, or hydrolysis);
- sludge contents of Fe, Al and P are quoted on a dry mass basis;
- phosphorus concentrations are total-P unless otherwise stated; and,
- **unless otherwise stated, all values quoted are averages.**

Results from all plants sampled are summarized in Table 4.2, and discussed in the following subsections.

Table 4.1: **WTPs Sampled**

WTP	Treatment Type	Coagulant	Sampling Dates 1994	Sampling Points
MUC	Extended Primary	$FeCl_3$	05-06-08/07	I/E/S
Fabreville	Extended Primary	Alum	18→21/07	I/E/S
Pincourt	Activated Sludge - Conventional	Alum	29/06→01/07	I/E/ML/S
		$FeCl_3$	20-21/07	
Victoriaville	Activated Sludge - Conventional	$Fe_2(SO_4)_3$ (+ Biological)	05-06-08/07	I/E/ML/S
St-Jean Baptiste	Activated Sludge - Oxidation Ditch	Alum (+ Biological)	29/06→01/07	I/E/S
Marieville	Activated Sludge - Oxidation Ditch	Biological	12-13/07	I/E/ML/S
Châteauguay	Biofiltration	Alum	18→21/07	I/E/BW/S
Rigaud	Facultative Aerated Lagoon	$Fe_2(SO_4)_3$	25→27/07	I/E/M/S
St-Georges	SBR	Alum sludge (+ Biological)	11-13-15/07	I/E/ML/S
Haute-Bécancour (Black Lake)	SBR	$Fe_2(SO_4)_3$ (+ Biological)	12-13-15/07	I/E/ML/S
		+ $Fe_2(SO_4)_3$ periodically	15/07	
Mont St-Gregoire	RBC	Alum	25→27/07	I/E/M/S

Legend:
I: Influent following screening
E: Final effluent
ML: Mixed liquor prior to chemical addition
BW: Biofilter backwash
M: Intermediate treatment point prior to chemical addition
S: Sludge

Table 4.2: Phosphorus Distributions and Removals at WTPs Sampled

Parameter	Fabreville		C.U.M.		Pincourt		Victoriavl		St-Jean		Marievil		Château		Rigaud**		St-Georg		Haute-Bé		Mt-St-Gré		Average*	
	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
Influent **P tot**	2.72	100	1.9	100	1.52	100	3.36	100	9.12	100	4.6	100	1.8	100	4.44	100	2.1	100	1.84	100	5.8	100	3.56	100
Psol	1.78	65	0.64	34	0.95	63	2.05	61	5.67	62	2.76	60	0.86	48	2.83	64	0.9	43	1.21	66	4.1	71	2.16	61
Psol O	1.69	62	0.43	23	0.69	45	1.56	46	5.34	59	2.44	53	0.74	41	2.54	57	0.71	34	1.08	59	4.05	70	1.93	54
Psol N-O	0.09	3	0.21	11	0.26	17	0.49	15	0.23	3	0.32	7	0.12	7	0.29	7	0.19	9	0.13	7	0.05	1	0.23	6
Ppart	0.94	35	1.26	66	0.57	38	1.31	39	3.45	38	1.84	40	0.94	52	1.61	36	1.2	57	0.63	34	1.7	29	1.40	39
Ppart O	0.2	8	0.09	4	0.03	2	0.53	16	0.9	10	0.07	2	0.27	15	0.9	20	0.6	28	0.08	4	0.62	11	0.39	11
Ppart N-O	0.74	27	1.17	62	0.54	36	0.78	23	2.55	28	1.77	38	0.67	37	0.71	16	0.6	29	0.55	30	1.08	19	1.01	28
Me:P Molar Ratio	2.03		2.83		1.90		0.60		0.60		1.80		1.00		0.90		-		1.25		1.60		1.55	
Effluent **P tot**	0.74	100	0.57	100	0.17	100	0.35	100	0.57	100	0.2	100	0.53	100	1.00	100	0.63	100	0.45	100	3	100	0.52	100
Psol	0.12	16	0.12	21	0.05	29	0.31	89	0.25	44	0.06	30	0.25	47	0.44	44	0.22	35	0.06	13	0.65	22	0.19	36
Psol O	0.09	12	0.03	5	0.04	23	0.29	83	0.22	39	0.04	20	0.23	43	0.26	26	0.18	29	0.04	9	0.63	21	0.14	27
Psol N-O	0.03	4	0.09	16	0.01	6	0.02	6	0.03	5	0.02	10	0.02	4	0.18	18	0.04	6	0.02	4	0.02	1	0.05	9
Ppart	0.62	84	0.45	79	0.12	71	0.04	11	0.32	56	0.14	70	0.28	53	0.56	56	0.41	65	0.39	87	2.35	78	0.33	64
Ppart O	0.24	32	0.17	30	0.04	24	0.02	5	0.11	19	0.05	25	0.14	27	0.49	49	0.16	25	0.2	44	1.9	63	0.17	33
Ppart N-O	0.38	52	0.28	49	0.08	47	0.02	6	0.21	37	0.09	45	0.14	26	0.07	7	0.25	40	0.19	43	0.45	15	0.16	31
Removal **P tot**	1.98	73	1.33	70	1.35	89	3.01	90	8.55	94	4.4	96	1.27	71	3.44	77	1.47	70	1.39	76	2.8	48	3.04	85
Psol	1.66	93	0.52	81	0.9	95	1.74	85	5.42	96	2.7	98	0.61	71	2.39	84	0.68	76	1.15	95	3.45	84	1.97	91
Psol O	1.6		0.4		0.65		1.27		5.12		2.4		0.51		2.28		0.53		1.04		3.42		1.79	
Psol N-O	0.06		0.12		0.25		0.47		0.2		0.3		0.1		0.11		0.15		0.11		0.03		0.18	
			0																					
Ppart	0.32	34	0.81	64	0.45	79	1.27	97	3.13	91	1.7	92	0.66	70	1.05	65	0.79	66	0.24	38	-0.65	-38	1.07	76
Ppart O	-0.04		-0.08		-0.01		0.51		0.79		0.02		0.13		0.41		0.44		-0.12		-1.28		0.22	
Ppart N-O	0.36		0.89		0.46		0.76		2.34		1.68		0.53		0.64		0.35		0.36		0.63		0.85	

* excluding: values from Mont-St-Grégoire for influent and removal, particulate-P values from Victoriaville for effluent and removal

** extremely variable results; average of July and October values

Note that fractions "Removed" will not sum to 100%, and that negative results indicate an increase in this fraction over the treatment process

4.1.1 Fabreville

Fabreville is a physico-chemical WTP treating municipal wastewater in Laval, a large island municipality North of Montreal.

The influent is fed through a canal from the grit removal/flocculation basins to three parallel rectangular primary sedimentation tanks. With a maximum flowrate of 36 000 m^3/d, the retention time in the grit removal/flocculation basins is approximately 15 minutes, with an additional 5 minutes in the canal feeding the sedimentation tanks. A fine screening unit was not operational during the sampling period.

The Fabreville WTP must meet a monthly effluent total-P concentration of 1.0 mg/L, and a mean annual concentration of 0.8 mg/L. To achieve this, liquid alum is injected mid-way through the aerated grit removal basins to effect a physico-chemical P-removal. A premixed solution of Percol 725, an anionic flocculant aid, is added to the flow at the exit of these basins.

Sampling at Fabreville took place from July 18-21. The East interceptor, 100% of which always undergoes physico-chemical P-removal, received a flow of 15 000 m^3/d during this period, at a temperature and pH of 17°C and 7.5, respectively. Alum was dosed at 4.6 mg Al/L with a 0.2% (m/v) solution of Percol 725 to wastewater containing 2.70 mg P/L and 86 mg TSS/L. At the time of sampling, ferric sulfate was dosed to the sludge reservoirs for odour control. Approximately 15 m^3/d of sludge with a solids content of 28% (m/m) is produced. Out of interest, a sample of the filter press filtrate was taken on July 19 and analyzed for soluble orthophosphates. The P concentration was < 0.05 mg/L, a result of the inherent P-fixing ability of the chemical sludge, but perhaps also due to the addition of ferric sulfate. Results from laboratory tests are compiled in Tables A4.1 and A4.2.

The Fabreville WTP had a total-P removal exceeding 70%, with the effluent concentration always lower than 0.80 mg/L. The soluble-P percentage removal was between 87% and 97%. The influent P was composed mainly of orthophosphates. The concentrations of the variables of interest were relatively constant, particularly those in the effluent, indicating a reasonably stable treatment.

Since soluble non-ortho-P was not found in any appreciable quantities in the influent, adsorption of this fraction to $Al(OH)_3$ was not expected to be a significant removal pathway at Fabreville.

Particulate-P removal, which ranged from 25 to 65%, seemed to be the limiting factor in achieving higher levels of total-P removal. Non-ortho-P represented 77% of the particulate-P in the effluent. As expected from physico-chemical treatment, the concentration of particulate ortho-P was higher in the effluent than in the influent. However, unlike other WTPs sampled, this fraction's influent concentration was relatively high (5 to 20% of influent-P).

Soluble BOD_5 removal was significant: 54%.

The concentration of aluminum increased across this WTP, from 0.25 mg Al/L in the influent to 0.8 mg Al/L in the effluent. Sludge contained 4.5% Al and 2% P.

4.1.2 Montreal Urban Community

The Montreal Urban Community WTP (MUC) uses primary treatment consisting of screening, grit removal, and sedimentation tanks with chemical addition.

Ferric chloride in solution is added at the entrance to the grit removal tanks, while Percol 902, a high molecular weight anionic polymeric flocculant aid, is added at the exit of these tanks. The MUC must respect an effluent total-P limit of 0.5 mg/L annually, with a weekly maximum of 0.75 mg/L.

Samples were gathered from the MUC WTP on July 5, 6, and 8, at which time the flow was 2.27 Mm^3/d at a temperature of 21°C and a pH of 7.3. This wastewater contained 1.90 mg P/L and 96 mg TSS/L. On the days sampled, ferric chloride was dosed at 9.5

mg/L Fe, combined with 0.48 mg/L of polymer solution. Results from laboratory tests are compiled in Tables A4.3 and A4.4.

On July 4 and 5, a broken one-way valve in a conduit linking the South interceptor to the Rivière des Prairies led to an increased flow and dilution of the influent. This can be seen most notably in the results of the P, BOD_5, and COD tests from July 5, found in Tables A4.3 and A4.4.

The results of most analyses were relatively constant for most variables. The effluent concentration of total-P was 0.57 mg/L, corresponding to a 70% removal. Soluble ortho-P removal exceeded 90%, 19% apparently from adsorption of soluble non-ortho-P to iron precipitates (eg. $Fe(OH)_3$).

The concentration of particulate ortho-P was always higher in the effluent than in the influent, a behavioural pattern expected from this type of treatment, given incomplete removal of precipitates. Particulate non-ortho-P removal was between 70 and 80%. This WTP's treatment in terms of P-removal would clearly benefit from more efficient TSS and particulate-P removals.

Nearly 2 mg Fe/L of the injected coagulant was found in the effluent in combined soluble and particulate forms, the high concentration attributed to the high ratio of Fe:P at the addition point. This substantial dosage was, however, necessary in order to reach the required average annual effluent concentration of 0.50 mg P/L. The sludge contained 1.8% Fe and 6.4% P.

4.1.3 <u>Pincourt</u>

Domestic wastewater from a population of approximately 11 000 is treated at the Pincourt WTP in a conventional activated sludge process. The influent undergoes fine screening following bulk screening. This stream is then combined with the mixed liquor recycle before being fed to the three aeration basins, the effluent of which is fed to the secondary clarifiers. The grit removal units and sand filters were not in operation during the sampling campaign, nor was the sludge digestor.

Pincourt's effluent-P limit is 1 mg/L. Alum is usually used for P-removal and no polymer is used. The coagulant is added in the conduits between the aeration basins and the secondary clarifiers. Ferric chloride trials occurred from July 5 to August 26.

Pincourt was sampled from June 28-July 1 during operation with alum, as well as on July 20 and 21 during the ferric chloride trials. During the first period of sampling, the flow was 9 300 m^3/d, the temperature was 17°C and the pH was 7.5. Alum was added at 2.8 mg Al/L to wastewater containing 1.51 mg P/L and 120 mg TSS/L. During the ferric chloride trials, the flowrate was 5 800 m^3/d, to which 4.65 mg Fe/L was added. Results from laboratory tests are compiled in Tables A4.5 and A4.6.

The abnormal results of July 21 with respect to P, COD, TSS and VSS are likely due to the fact that all samples gathered on that day were grab samples since the composite samplers were not functioning properly. The samples were gathered during mid-morning, at which time the wastewater is more concentrated. It should also be noted that it rained on June 27-28, which explains the significantly higher flowrates during this sampling period.

The total-P concentration in the effluent was 0.18 mg/L, representing a removal of 90%. Soluble-P was always removed in excess of 95%, while the removal of the soluble non-ortho-P fraction was nearly 100%. Even though the influent concentration of the soluble non-ortho-P was not always significant (0.10 to 0.50 mg/L P), it seems that adsorption to mixed liquor biomass is an apparent advantage of the activated sludge treatment process, also observed by de Haas and Greben (1991).

Particulate-P had a removal of 80%, lower than that of the soluble-P fraction, and accounted for 65 to 80% of the effluent total-P. The concentration of particulate ortho-P was slightly higher in the effluent than in the influent, a result of incomplete chemical solids removal.

EBPR was observed at this WTP even though there were no intended anoxic or anaerobic zones in the aeration tanks. MLVSS contained 0.27% g poly-P/g VSS.

The removals of BOD_5 and TSS were 93% and 88%, respectively. Laboratory tests indicated that the sludge contained 3.5% P and 4.5% Al. Chemical addition did not necessarily raise the concentration of metals in the effluent since half of these samples contained less aluminum than the influent.

4.1.4 Victoriaville

This WTP treats the wastewater of approximately 39 000 people from the municipalities of Victoriaville, Arthabasca and Ste-Victoire using a conventional activated sludge process. Approximately 50% of the flowrate to this WTP is from a margarine/edible oil plant, with lower flows coming from a coffin factory and a textile mill.

Following screening, the influent is fed in parallel into four 3 500 m^3 rectangular aeration tanks. After secondary clarification in four parallel 690 m^3 rectangular tanks, the wastewater is directed to eight sand filters before being discharged.

Victoriaville must meet an effluent total-P concentration of 1.0 mg/L between May and November. A 12% solution of ferric sulfate is added at the exit of the aeration tanks to effect this P-removal.

Samples were gathered from Victoriaville on July 5, 6 and 8. During this period, the flowrate was 35 000 m^3/d at 16°C and a pH of 7.3. Ferric sulfate was dosed at 3.5 mg Fe/L to wastewater containing 3.36 mg P/L and 95 mg TSS/L. Results from laboratory tests are compiled in Tables A4.7 and A4.8.

The concentration of total-P in the effluent was 0.36 mg/L, corresponding to a removal of 90%. The percentage removal of soluble ortho-P was only 80%, this low removal no doubt a result of the low Fe:P ratio (0.6); similarly, only 85% of the soluble-P fraction was removed. As observed at Pincourt, the removal of soluble non-ortho-P was nearly 100%. The sand filters following secondary clarification lead to a 95% removal of particulate-P.

EBPR was present at this WTP even though there were no intended anoxic or anaerobic zones in the aeration tanks. MLVSS contained 0.37% g poly-P/g VSS.

The effluent concentration of iron was less than 0.04 mg Fe/L and the sludge contained 4.3% Fe and 3.5% P.

4.1.5 St-Jean Baptiste

The St-Jean Baptiste WTP uses two oxidation ditches (1 000 m^3 each) operating in parallel to treat municipal wastewater from a community of approximately 2 250 people as well as the effluent from a poultry slaughter house. The two secondary clarifiers are each 350 m^3 in volume.

The influent is fed to the oxidation ditches following screening and grit removal. In order to meet the effluent limit of 1.0 mg/L P between May and November, liquid alum is added at the exit of the oxidation ditches.

Sampling occurred at this WTP from June 28-July 1. The flow at this time was 2 500 m^3/d at a temperature and pH of 17°C and 7.2, respectively. Alum was dosed at 5.1 mg Al/L to wastewater containing 9.12 mg P/L and 266 mg TSS/L. Results from laboratory tests are compiled in Tables A4.9 and A4.10.

Several process anomalies occurred during the sampling campaign. Rain on June 27 and 28 led to an increase in the WTP's flow from 1 850 m^3/d to the measured 2 500 m^3/d. Process conduits were washed with a bleach solution on June 27 which may have lead to lower treatment efficiency the following day. An aerator was not functioning on June 27 and 28. Lastly, the slaughter-house was closed on July 1 for the Canada Day national holiday, evident from the decreased concentrations of several parameters that day.

The concentration of total-P in the effluent was 0.57 mg/L, representing a removal of 94%. Soluble-P had a removal of 96% while particulate-P and ortho-P (both soluble and particulate forms) had removals of 96% and 88%, respectively. The apparent adsorption of soluble non-ortho-P onto metal hydroxide precipitates (approximately 90% removal) was observed at St-Jean Baptiste as well.

The concentrations of BOD_5, COD and TSS were almost halved after the slaughter house was closed, while the P-concentration decreased by only 10%. The concentration of Al in the effluent (0.62 mg/L) was lower than that in the influent (5.1 mg/L), although the mechanisms of this high removal efficiency are unknown. The ratio of Al:P was 0.6. The sludge contained 5.6% Al and 3.6% P.

4.1.6 Marieville

The Marieville WTP treats the wastewater from approximately 5 000 people with two oxidation ditches operating in parallel. As well, this WTP receives the effluent from both a cheese and a glue factory. The wastewater is directed to the two aeration basin/clarifier units following screening and grit removal.

This WTP must meet an effluent-P concentration of 1 mg/L between May and November. EBPR is the principal method used at this WTP. Ferric sulfate is added as needed if the operators feel they will exceed their effluent requirements.

During the July 12, 13, and 15 sampling, this WTP received a flow of 3 800 m^3/d at a temperature and pH of 22°C and 7.5, respectively. On July 15, 14.7 mg Fe/L was dosed. The influent contained 4.6 mg P/L and 125 mg TSS/L. Results from laboratory tests are compiled in Tables A4.11 and A4.12.

On July 5, the contents (scum, solids, etc.) of the secondary clarifiers were completely recycled into the aeration tanks as part of the regular plant maintenance. This significantly increased the F/M loading to the aeration tanks and created localized anearobic zones.

The quality of the treatment could therefore have deteriorated for a certain time following this recycle.

The effluent total-P concentration was 0.20 mg/L, corresponding to a removal of 96%. This was through EBPR and other mechanisms, since ferric sulfate was only dosed for 18 hours on the last day of sampling. MLVSS contained 0.16% g poly-P/g VSS. Removals of most P-fractions approached 100%. The poor %-removals of ortho-P were due to the low influent concentration of this fraction.

TSS and BOD_5 had removals of 92% and 96% and effluent concentrations of 9 and 5 mg/L, respectively.

During normal operation, iron concentrations were lower in the effluent than in the influent. When ferric sulfate was added, the iron concentration in the effluent rose from 0.35 to 1.21 mg Fe/L. Sludge contained 6.5% Fe and 2.5% P, which suggest that iron is dosed on a more regular basis.

4.1.7 Châteauguay

The Châteauguay WTP operates twelve biofilters to treat the domestic wastewater from a population of approximately 45 000.

After screening, the wastewater passes through two parallel grit removal tanks and is directed to three parallel primary clarifiers, each with a volume of 945 m^3. The fine screens following the decanters were not in operation during the sampling. Treatment continues with the biofiltration step, the number of units in operation depending upon the flowrate. Each filter has a surface area of 49 m^2 and is 2 m deep. The theoretical solids retention capacity before washing is 2.5 kg TSS/m^3 of filter bed. When backwashed, the biological sludge is recycled to the head of the treatment train before grit removal. Filter effluent undergoes ultraviolet disinfection before discharge. Sludge undergoes two-stage anaerobic digestion before dewatering and disposal.

Châteauguay may not exceed 1 mg/L total-P in its effluent, and therefore doses a standard liquid alum solution in a rapid mixing unit upstream from the primary clarifiers.

During the July 18-21 sampling dates, the flowrate was 34 100 m^3/d at a temperature and pH of 18°C and 7.5, respectively. An alum dose of 2.5 mg Al/L was added to wastewater containing 1.8 mg P/L and 60 mg TSS/L. P and TSS concentrations at the chemical addition point were actually much higher than these values because of the recycled biofiltration sludge. Results from laboratory tests are compiled in Tables A4.13 and A4.14.

The daily effluent total-P concentration at this WTP never exceeded 0.60 mg/L, representing a removal of 70%. P-distributions were relatively constant over the sampling dates. Due to its dilute nature, this wastewater is particularly well suited for treatment by pre-precipitation and biofiltration.

The relatively low ratio of Al:P (approximately 1.0), as well as possibly poor primary clarifier performance, could explain the poor removals of both soluble and particulate-P (approximately 70%). As at other biological WTPs, the 83% removal of soluble non-ortho-P was significant.

Both TSS and BOD_5 removals were approximately 80%. The concentration of Al in the effluent was less than 0.2 mg/L, while the sludge contained 4.0% Al and 3.2% P.

4.1.8 Rigaud

Three aerated lagoons in series treat the wastewater from Rigaud, a municipality with a population of approximately 2 400. The WTP also treats the effluent from a neighbouring food processing plant and the Federal Customs and Excise training facility. Each lagoon is 33 m wide, 137 m long and 3 m deep, designed to treat a flowrate of 2 000 m^3/d. The retention time for each lagoon is approximately 10 days.

After screening, the influent is fed to the lagoons. The first two lagoons are aerated. The first half of the third lagoon is aerated intermittently, the second half behaving as a sedimentation basin. The WTP had operated for five years as of the summer of 1994; in 1993 the sludge depths in the first and second lagoons were 0.3 and 0.2 m, respectively. The operator had noticed no subsequent increase in sludge depth.

The Rigaud WTP must meet an effluent limit of 1 mg/L total-P between May and November. In order to meet this limit, ferric sulfate is added in the conduit between the second and third lagoons. Alum was used during the first year of operation.

Samples were gathered from July 25-27 and again on October 25 and 26. In July the flowrate was 1 600 m^3/d at a temperature and pH of 20°C (10°C in October) and 7.6, respectively. During the two sampling periods, a ferric sulfate dose of 5.3 mg Fe/L was added to wastewater containing 4.4 mg P/L and 140 mg TSS/L. Results from laboratory tests are compiled in Tables A4.15 and A4.16.

The laboratory results from the July and October influent samples varied considerably, both from one period to the next, and within each sampling period. Long retention times in aerated lagoons explains this behaviour, due to the lag time between the influent and the effluent. The concentrations and P-distributions at the point of dosage and in the effluent were much more constant. Rigaud is fed by several pumping stations that are flow-activated and as such, the wastewater reaching the WTP can have widely varying characteristics. In July the effluent total-P concentration was 0.65 mg/L, while in October it was [illegible]5 mg/L. In general, 20% of the soluble-P and 50% of the particulate-P were removed in the first two lagoons.

Even though the Fe:P ratio was low (0.9), the percentage removal of soluble ortho-P resulting from chemical addition was 90%. During the July sampling, soluble non-ortho-P comprised 2% of the influent total-P, while in October this value was 19%. It is possible that temperatures affect not only the treatment efficiency but the P-distributions in the influent. Seasonal activity at the food processing plant might also affect influent-P concentrations and distributions.

The percentage removal of particulate-P varied between 62% and 88% in July, and 0 and 52% in October. This significant decrease can be explained by the lower temperatures in October. BOD_5 and TSS removals also decreased with temperature, while the iron concentrations in the effluent remained constant. This suggests that temperature fluctuations, within operating ranges, affect biological activity or TSS and particulate-P removal more than it does chemical precipitation and sedimentation.

Iron in the effluent (1.9 mg Fe/L) is likely in the form of $FePO_4$ since Fe:P ratios are relatively low. As well, the effluent VSS is presumably resuspended biomass because aerators at the head of the last lagoon impede sedimentation of solids of low specific gravity. The effluent TSS and VSS concentrations were higher in October than in July.

The treatment efficiency in terms of P-removal would likely have increased significantly using flow- or load-controlled dosing and/or with improved solids removal.

4.1.9 St-Georges

St-Georges is one of two WTPs in Québec using the sequencing batch reactor (SBR) treatment process. This WTP receives the wastewater from a population of approximately 19 000 and the effluent from a textile mill.

The influent undergoes screening and grit removal and is then fed alternately to one of three SBRs, each with a volume of 6 430 m^3. An aerated mixing stage follows the filling stage, followed by an unaerated (anoxic/anaerobic) mixing stage, and finally a sedimentation stage.

The WTP's effluent-P limit of 1 mg/L total-P is achieved mainly through EBPR with no chemical products being added at the WTP. Alum sludge is, however, pumped into the sewer network from the municipal water purification plant.

Samples were gathered from this WTP on July 11, 13 and 15, during which time the flowrate was 14 400 m^3/d, at a temperature and pH of 17°C and 7.3, respectively. The wastewater contained 2.1 mg P/L and 110 mg TSS/L. A power failure on July 9 and 10 could have affected the microbial population and in turn the effluent quality in the days that followed. Results from laboratory tests are compiled in Tables A4.17 and A4.18.

Since many of the variables of interest in the analyses had relatively small influent concentrations, the percentage removals may seem low. The effluent total-P concentration was 0.63 mg/L, corresponding to a 70% removal. The influent-P was composed of 43% soluble-P and this fraction's removal varied between 66% and 93%. There was no apparent relationship between the soluble-P removal and that of particulate-P, this latter being between 53% and 88%.

Particulate ortho-P represented 19%-46% of the influent-P, a result no doubt of the alum sludge in the wastewater, and had removals of between 38% and 95%. Particulate-P in general was reduced by 66%. Due to alum sludge, the concentration of particulate ortho-P in the influent was high; this WTP's influent-P contained the highest percentage of particulate ortho-P of all the plants sampled. Although the daily values varied widely, the concentrations of influent particulate ortho-P were higher at St-Jean Baptiste, Rigaud and Mont St-Grégoire than at St-Georges. This is likely due to the low flowrates and significant industrial loads at the former three WTPs, leading to relatively concentrated influents.

Another apparent benefit of the alum sludge in the influent is the 76% removal of soluble-P. Soluble-P removal decreased from 92% at pH=6.9 to 65% at pH=7.4, in agreement with EPA (1987) and Recht and Ghassemi (1971). It was unclear if variables other than the pH change affected the P-removal behaviour at St-Georges.

The significant linear relationship between TSS and particulate non-ortho-P in the influent suggests that the alum sludge loading from the filtration plant is not constant. VSS in mixed liquor contained 0.28% long chain polyphosphates, evidence of the EBPR at this

WTP. The concentration of aluminum in the effluent remained constant at approximately 0.25 mg Al/L, while the sludge contained 2.8% Al and 2% P.

4.1.10 Haute-Bécancour (Black Lake)

The municipalities of Thetford Mines and Black Lake, approximate population 30 000, are served by this WTP, the only SBR in Québec treating municipal wastewater other than St-Georges. The three reactors each have a volume of 7 350 m^3. The treatment process is essentially the same as that of St-Georges.

The effluent-P concentration limit at this WTP is 1 mg/L. This is achieved not only through the P-uptake due to biomass growth, but also by adding ferric sulfate slugs to the reactor in use during each cycle.

Samples were gathered from Haute-Bécancour on July 12, 13 and 15, during which time the flowrate was 22 600 m^3/d and the temperature and pH were 14°C and 7.7, respectively. Ferric sulfate was added at an equivalent of 4.1 mg Fe/L to wastewater containing 1.8 mg P/L and 71 mg TSS/L. Results from laboratory tests are compiled in Tables A4.19 and A4.20.

The effluent total-P concentration was 0.45 mg/L, corresponding to a removal of 76%. The soluble-P removal was 95%, the majority of which came from the precipitation of the ortho-P since this was the predominant fraction in the influent soluble-P. Soluble non-ortho-P represented 7% (0.13 mg P/L) of the influent, and 4% (0.02 mg P/L, not measured) of the effluent. The relatively high (85%) removal of soluble non-ortho-P is a trend common to the biological WTPs.

As expected from an incomplete removal of $FePO_4$, the concentration of particulate ortho-P was lower in the influent (0.07 mg/L, 4% of the total-P) than it was in the effluent (0.20 mg/L, over 40% of the total-P). The percentage removal of particulate non-ortho-P was 65%, but because of the poor particulate ortho-P removal, the overall particulate P-removal was 38%.

No significant relationship existed between the TSS and BOD_5, and the concentrations and distributions of the various forms of phosphorus. A significant fraction of the iron added (35%, 1.5 mg Fe/L) was lost in the effluent; it is difficult to say in what form these losses were. Sludge contained 1.0% P and 3.2% Fe.

4.1.11 Mont-St-Grégoire

This WTP uses a rotating biological contactor (RBC) process to treat the wastewater from a small municipality and the effluent from a poultry farm and slaughter house.

Following screening the influent is directed to a primary clarifier (182 m^3) that overflows into the RBC tank. The RBC has a surface area of 10 777 m^2. The flow is then directed to a secondary clarifier with a volume of 166 m^3.

The phosphorus effluent discharge limit set for this WTP is 1 mg/L. A liquid alum solution is added midway through the RBC tank in attempts to meet this limit.

During the July 25-27 sampling period, the flowrate was 160 m^3/d at a temperature and pH of 20°C and 7.9, respectively. An equivalent alum dose of 8.2 mg Al/L was added to wastewater that contained 5.8 mg P/L and 170 mg TSS/L. Results from laboratory tests are compiled in Tables A4.21 and A4.22.

This WTP obtained a 50% removal of total-P with effluent concentrations of 3.0 mg/L. Several pertinent observations can be made with respect to the treatment at this WTP. Considering the WTPs already discussed, an 85% removal of total-P is expected with an Al:P ratio of 1.6. Poor mixing and/or short circuiting at the point of addition are likely largely responsible for the poor treatment observed at Mont St-Grégoire.

The alum solution presently in use was received three years prior to the sampling date; it is possible that some crystallization had occurred, and that this is responsible for a coagulant conduit blockage on July 27. Higher effluent-P concentrations were observed that day with respect to the other days' samples, however the influent concentrations were higher as well. A power failure on July 23 might have had some lingering effects on the treatment performance at the time of sampling.

Consistent with other biological treatment processes, significant removal of soluble non-ortho-P was observed. Since there was a considerable increase of particulate ortho-P from 0.62 mg/L in the influent to 1.90 mg/L in the effluent, the performance of the secondary clarifier is questionable. There was a 60% removal of particulate non-ortho-P.

At 90%, BOD_5 removal was high, while the TSS concentration in the effluent was 50 mg/L. The concentration of Al was approximately 2.0 mg/L in the effluent, and the sludge contained 4% P and 4% Al.

4.2 Data Analysis

Refer to Table 4.2 for pertinent results from the laboratory analyses

Difficulties with interpreting the field data arise when comparing absolute against percentage removals. The St-Jean Baptiste field data is a good example, where 0.3 out of 0.33 mg P/L soluble non-ortho-P is removed. Small variations in the absolute value of the P-removed will have large effects on the observed % removal rate, and must be considered when reviewing the field data results and analyses. Conversely, a P-fraction accounting for a more significant amount of influent total-P, but with a lower absolute removal, may have misleadingly low % removals.

Discounting phase changes, the removal of particulate-P from all WTPs was 77%, excluding the unrepresentative results from Victoriaville and Mont St-Grégoire. Particulate-P ranged from 14% (Victoriaville) to 87% (Haute-Bécancour) of the effluent-P. Activated sludge WTPs are exceptions, with particulate-P removals exceeding 80%. Improving clarifier performance or the addition of a solid-liquid separation step (such as the sand filters at Victoriaville) would no doubt improve the performance with respect to P-removal, given that the majority of effluent-P is in the particulate form.

Although the proportions of soluble ortho- and non-ortho-P in the effluent varied according to treatment type, soluble-P in the effluent was generally found in the form of ortho-P. Depending upon the Me:P ratio, up to 95% removal of soluble-P was observed at different WTPs, leading to an effluent soluble ortho-P concentration below 0.10 mg/L. Table 4.2 illustrates that several WTPs obtained a total-P removal of approximately 90% with Me:P ratios often below 1.0. High levels of P-removal were achieved at other WTPs with higher ratios of Me:P. Generally, more chemical is needed for precipitation during primary treatment than in secondary treatment due to a more variable influent, competing reactions (EPA, 1987), and the concomitant contaminant removal with biological processes; this is evident with the enhanced performance of the activated sludge and oxidation ditch WTPs.

In general, WTPs using iron-based chemicals (ferric chloride, ferric sulfate) had higher metal ion concentrations in the effluent than the WTPs using aluminum based chemicals (alum, alum sludge). Higher ratios of Al:P nearly always led to higher concentrations of Al in the effluent.

WTPs incorporating some type of biological treatment (with the exceptions of Rigaud: *aerated lagoon* and Mont St-Grégoire: *RBC*) had soluble non-ortho-P removals in excess of 79% and effluent concentrations below 0.05 mg/L.

Microorganisms in an activated sludge WTP that have only met their metabolic requirements contain 2% g P/g VSS (Metcalf and Eddy, 1991). EBPR is considered to be a significant removal mechanism when the P-concentration in the mixed liquor is equal or greater than 0.1% g poly-P/g VSS on a dry basis (Comeau et al., 1990). Four WTPs therefore had EBPR:

Victoriaville:	0.37%
St-Georges:	0.28%
Pincourt:	0.27%
Marieville:	0.16%

It was surprising to find such values at Pincourt and Victoriaville, WTPs that were supposedly strictly aerobic. However, a low residual dissolved oxygen (DO) value, intermittent fluctuations in DO or anaerobic "dead zones" in the basins could explain this behaviour.

Although this behaviour was not certain, it seems that at St-Georges, with a decrease in pH (within operating limits), there is an increase in soluble-P removal.

4.2.1 Phosphorus vs. Solids Relationships in Wastewater

Several significant relationships between TSS and P were observed in the field data, as summarized in Table 4.3. The results from this study indicate that effluent suspended solids contain from 3-4% P, confirming that TSS have a significant effect on the effluent

P-concentration. Only P:TSS ratios with standard deviations less than ± 10% were tabulated.

Table 4.3: Wastewater P:TSS Relationships

WTP	Parameter of Interest	Ratio P:TSS (mass:mass % average)
Fabreville	Effluent P-tot	3.0
Fabreville	Effluent P-part	2.5
MUC	Influent P-tot	1.9
MUC	Influent P-part	1.3
MUC	Effluent P-part	1.8
Victoriaville	Influent P-tot	3.6
Marieville	Effluent P-part	1.4
Châteauguay	Influent P-tot	3.0
Châteauguay	Effluent P-part	2.4
Rigaud (July)	Effluent P-tot	4.4
Rigaud (July)	Effluent P-part	2.7
St-Georges	Influent P-tot	1.9
St-Georges	Influent P-part	1.1
Haute-Bécancour	Effluent P-tot	3.1
Haute-Bécancour	Effluent P-part	2.7
Mont St-Grégoire	Influent P-part	1.4
Mont St-Grégoire	Effluent P-part	4.2

Note: all values quoted on a dry basis

4.2.2 Metal to Phosphorus Ratios in the Sludge

The average metal (iron or aluminum) to P-ratios dosed and found in the sludge are listed in Table 4.4.

Table 4.4: Metal:Phosphorus Ratios; Dosed to Wastewater and Sludge Content

WTP; metal used	DOSED TO WW	SLUDGE	
	Me:P-total	Me:P-total	Me:Inorganic-P
Fabreville; Al	2.0	2.6	3.3
MUC; Fe	2.8	2.4	3.3
Pincourt; Al / Fe	1.9 / -	1.5 / 0.7	1.8 / 1.0
Victoriaville; Fe	0.6	0.7	0.9
St-Jean Baptiste; Al	0.6	1.7	2.3
Marieville; Fe	1.8	1.4	1.6
Châteauguay; Al	1.0	1.5	1.8
Rigaud; Fe	0.9	-	-
St-Georges; Al	-	1.6	3.0
Haute-Bécancour; Fe	1.3	1.9	3.0
Mont St-Grégoire; Al	1.6	1.0	1.4

Note: all ratios quoted on a molar basis

The Fe or Al:P distributions in the sludge should give some idea of removal efficiencies and mechanisms. Neglecting solids not associated with chemical precipitation, ratios greater than unity (in Me:P-total in the sludge) at some WTPs suggest that a significant amount of hydroxide is precipitating and/or the precipitate is in the form of a hydroxy-phosphate precipitate.

Given the poor operating conditions at Mont St-Grégoire, the low Me:P ratios in the sludge are not surprising considering that since a significant amount of the dosed aluminum (>1 mg Al/L) is lost in the effluent (in combined soluble and solid forms), little of the metal is expected to have reacted with the P.

Chapter 5. PHOSPHORUS MASS BALANCE MODEL

5.1 Developmental Motive

As discussed in Chapter 1, a significant amount of the P-load to Québec receiving waters originates from WTP effluents. The treatment processes of principal interest are physico-chemical, activated sludge, biofiltration and aerated lagoons, since WTPs of these types together account for over 99% of the municipal wastewater treated in Québec (Gosselin, 1995).

Difficulties arise in identifying the shortcomings in P-removal processes, in terms of treatment types and the removal mechanisms involved in each treatment. A need exists for a comparative tool by which to evaluate the most promising replacement technologies for Québec. This tool must distinguish between physico-chemical (precipitation, sedimentation) and biological (EBPR and biomass growth) phosphorus removal. Furthermore, it must distinguish between different P-forms since each treatment type affects and/or removes these fractions differently. A WTP's influent-P distribution depends strongly on the source of the wastewater (municipal, industrial), therefore this model must allow for these variations.

In pursuing this goal the objectives were to:

- Develop a conceptual model for P-mass balances;
- Prepare computer mass balance programs incorporating this model into pertinent treatment processes; and,
- Calibrate each program with field data.

These results will be applied to the next phase of this Québec MEF study.

5.2 Conceptual Model Description

Few data exist detailing P-forms at various stages of different treatment processes, therefore a mechanistic model was developed in order to approximate this treatment. This model was based most specifically on the following mechanisms:

- Chemical precipitation of soluble orthophosphate;
- Adsorption of soluble poly/organic phosphorus;
- Hydrolysis of particulate poly/organic phosphorus to soluble orthophosphate; and
- Sedimentation of the particulate phosphorus forms.

The reactions of metal cation-based coagulants in wastewater are relatively well known (Luedecke et al., 1989; Pankow, 1991; Rebhun and Lurie, 1993). For the purposes of this model, we are assuming that the metallic cations will react preferentially with soluble orthophosphate anions in the following manner, where Me^{3+} is in the form of Al^{3+} or Fe^{3+} (EPA, 1987; Hart and Lorange, 1995):

$$Me^{3+} + PO_4^{3-} \rightarrow MePO_4 \qquad 5.1$$

where:
- Mw Ratio of $FePO_4/Fe$ = 150.8/55.9 = 2.7
  (55.9 g of Fe (162.2 g $FeCl_3$; 370 g $Fe_2(SO_4)_3 \cdot 9\ H_2O$) reacts with 31 g of P to form 150.8 g of $FePO_4$)
- Mw Ratio of Fe:P = 56/31 = 1.8
- Mw Ratio of $AlPO_4/Al$ = 122/27 = 4.52
  (54 g of Al (594.5 g of $Al_2(SO_4)_3 \cdot 14\ H_2O$) reacts with 61.9 g of P to form 243.9 g of $AlPO_4$)
- Mw Ratio of Al:P = 27/31 = 0.87

Therefore, the production of metal phosphate is determined as follows:

$FeCl_3$: $(P_{inf} - P_{eff}) \times 1.8 \times 2.7$
Alum: $(P_{inf} - P_{eff}) \times 0.87 \times 4.52$

Remaining coagulant is assumed to react with the wastewater's alkalinity and to form metal hydroxide precipitates (with soluble non-ortho-P adsorption occurring) in the following manner:

$$Me^{3+} + 3OH^{-} \rightarrow Me(OH)_3 \qquad 5.2$$

- Mw ratio of $Fe(OH)_3/Fe = 107/56 = 1.91$
- Mw ratio of $Al(OH)_3/Al = 78/27 = 2.89$

Therefore, the production of metal hydroxide is determined as follows:

$FeCl_3$: $[(\text{Fe dosage}) - (P_{inf} - P_{eff}) \times 1.8] \times 1.91$
Alum: $[(\text{Al dosage}) - (P_{inf} - P_{eff}) \times 0.87] \times 2.89$

Figure 5.1 represents a graphical interpretation of the physico-chemical P-removal mass balance model. The left-hand side represents the P-distributions in the wastewater influent, the right-hand side represents the P-distributions following chemical addition (usually being the wastewater effluent). Liquid streams are split into soluble and particulate forms, and each in turn into ortho-P and poly/organic P-fractions. The streams at the bottom of the figure comprise the solid-phases (sludge) resulting from precipitation, adsorption, and sedimentation. P in the sludge is assumed to originate from :

- Inherent concentration in biomass;
- Decanted chemical precipitates; and/or,
- Decanted influent particulate-P.

A key feature of this model is that precipitated solids decant with less than 100% efficiency, and condensed P-forms found in the influent hydrolyze and decant with varying efficiencies. This aspect of P-removal is not addressed in the other models reviewed in the literature.

From the field data, values for the influent and effluent were known. This model then represents a hypothesis, expanded upon in the computer programs that follow, offering an explanation for the mechanisms which result in the effluent and sludge values in the field data. This explanation is offered in the form of the suggested values of the calibrated model parameters. Computer programs ensued and are explained in detail in Chapter 6. The actual values of the model parameters were determined by calibrating the computer programs with the field data from Chapter 4. At any point along this model's treatment train, 100% of the influent-P can be accounted for in various forms. Table 5.1 summarizes the distributions of P-fractions at all points prior to and following chemical addition for P-removal. These distributions were calculated using the calibrated model parameters from Table 6.1, which were themselves arrived at from the field data. Figure 5.2 presents one such example, illustrating the results of the *Primary Clarifier--Ferric Chloride* program's calibration using the MUC WTP field data. Referring to Figure 6.1, Table 5.1 represents the P-distributions around the point of chemical addition; further treatment steps in the processes studied are accounted for in the individual computer programs.

Some of the models reviewed in Section 2.3, such as those of Ferguson and King (1977) and Luedecke et al. (1989), use adjusted equilibrium constants, and make additional compensation through inserted constants and sometimes entire reaction mechanisms, so that their predicted results were in agreement with experimental data. The model developed here effected the same allowances through its model parameters, with estimated values provided through the calibration sequence.

FIGURE 5.1

FATE OF PHOSPHORUS IN A WASTEWATER TREATMENT PLANT

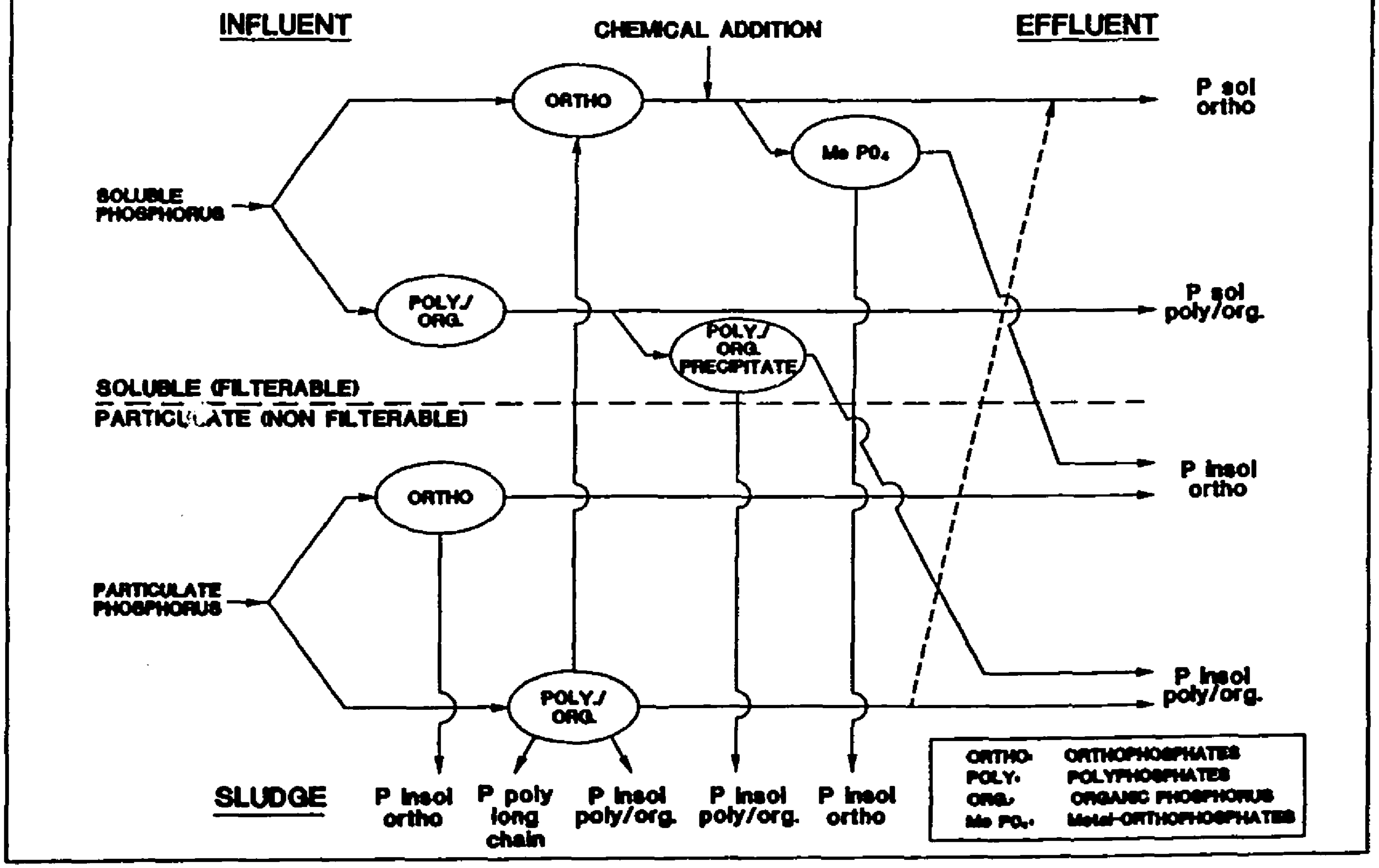
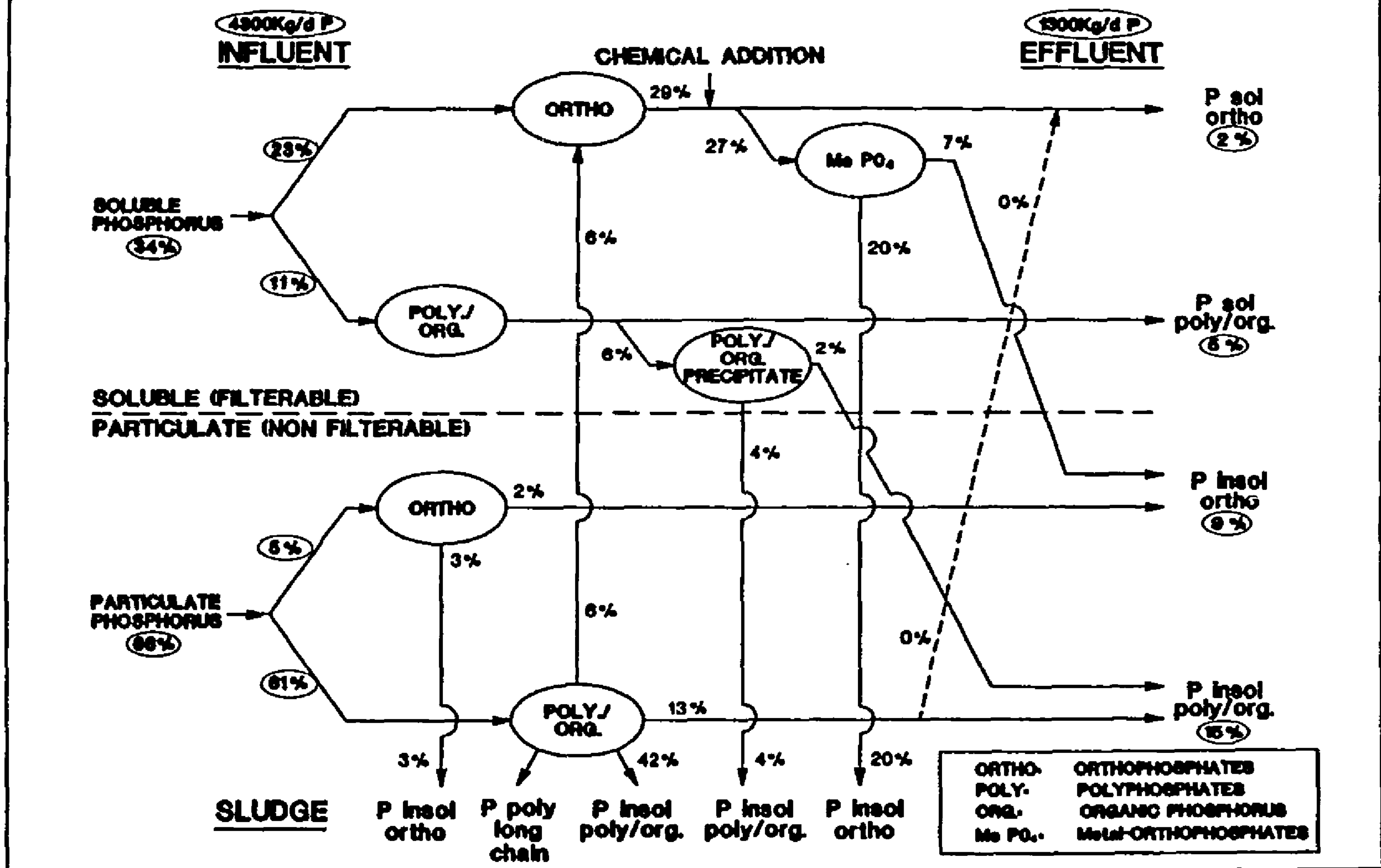


FIGURE 5.2

PHYS-CHEM - $FeCl_3$ - MUC - July 5-8, 94



ORTHO-	ORTHOPHOSPHATES
POLY-	POLYPHOSPHATES
ORG.-	ORGANIC PHOSPHORUS
Me PO₄-	Metal-ORTHOPHOSPHATES

Table 5.1: **Distributions of Forms of Phosphorus in the Mass Balance Model**

	Phys-Chem	Activated Sludge		Biofilter	Aerated Lagoons
	Alum	$Fe_2(SO_4)_3$	Alum	Alum	$Fe_2(SO_4)_3$
	%	%	%	%	%
Influent					
Soluble Phosphorus	65	61	62	48	64
Ortho-P	62	46	45	41	57
Poly/Org.	3	15	17	7	7
Particulate Phosphorus	35	39	38	52	36
Ortho-P	8	16	2	15	20
Poly/Org.	27	23	36	37	16
Poly/Org.→Soluble Ortho-P	2.7	4.6	7.2	3.7	2.9
Precipitates					
$MePO_4$	60.2	41.5	49.6	32.2	50.9
Poly/Org. precipitate	1.7	14.3	13.6	4.7	0
Sludge					
P insol ortho from decanted $MePO_4$	55.4	39.4	47	23.5	45.8
P insol poly/org. from decanted poly/org. precipitate	1.6	13.5	13	3.3	0
P insol ortho from influent particulate-P	4.2	6.4	0.8	6.5	11.0
P insol poly/org. from influent particulate-P	11.6	12.9	20.1	23.3	7.4
Effluent					
P sol ortho from influent	4.7	9.1	1.5	12.5	9.0
P sol ortho from hydrolyzed P insol poly/org.	0	0.5	0.9	0	1.1
P sol poly/org.	1.3	0.8	3.4	2.4	7.0
P insol ortho from influent particulate-P	2.8	9.6	1.2	8.5	9.0
P insol ortho from non-decanted $MePO_4$	4.8	2.1	2.6	8.7	5.1
P insol poly/org. from influent particulate-P	12.6	5.0	7.8	10.0	4.6
P insol poly/org. from non-decanted poly/org. precipitate	0.1	0.7	0.6	1.3	0

Note that: **-Influent distributions are generally from Table 4.2 and model parameters used to calculate intermediate and final distributions are from Table 6.1; effluent distributions are therefore not in every case the same as the field data in Tables 4.2 or 7.1**

Chapter 6. COMPUTER PROGRAMS

6.1 Introduction

Preliminary computer programs were developed using Lotus 123. These were then modified using Microsoft Excel 4.0 into the computer programs that were the basis for the present study. The computer programs were calibrated, and in certain cases modified, using available data from the field sampling, for the following treatment processes:

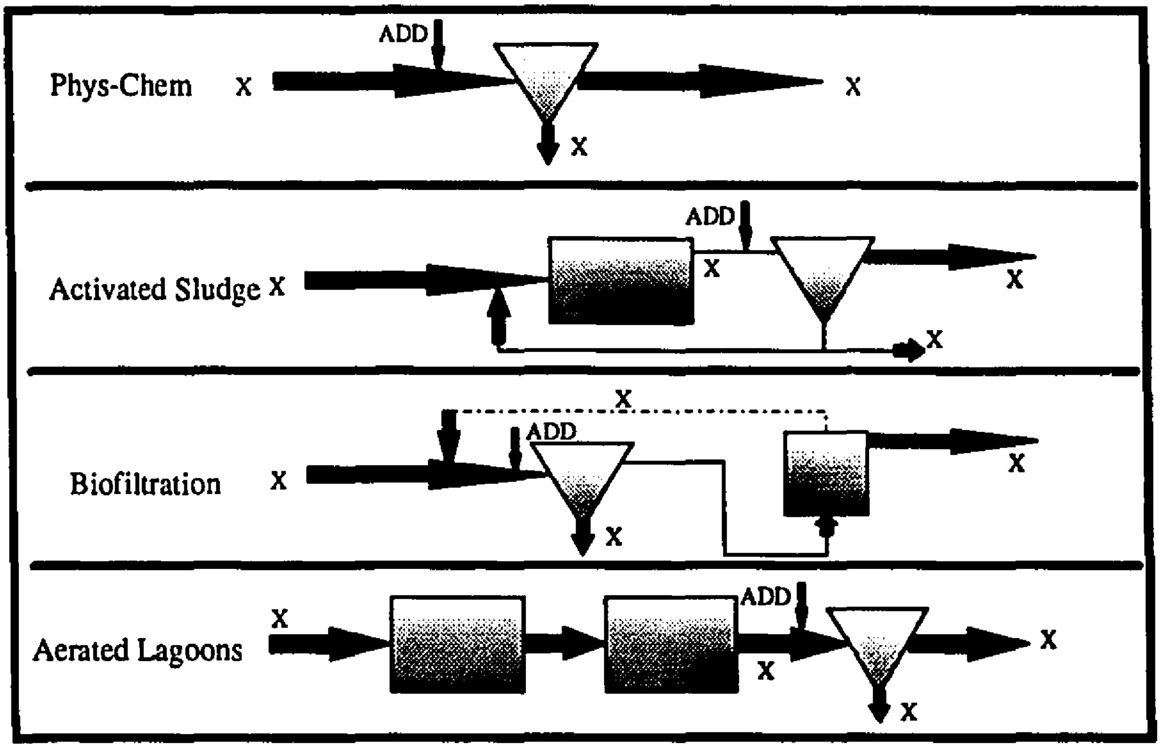
- Primary clarifier with chemical addition (ferric chloride and alum);
- Activated sludge with simultaneous chemical precipitation (ferric sulfate and alum);
- Aerated lagoons with chemical addition (ferric sulfate); and
- Biofiltration with pre-precipitation (alum).

The mass balance model described in Chapter 5 was applied at the "ADD" points in Figure 6.1 for each treatment process (i.e. the point where chemicals were added), while the "X" points indicate where samples were gathered during the field sampling.

In addition to including the physico-chemical P-removal model, the computer programs include mass balances for TSS, VSS and BOD_5; sludge characteristics are also described in the output. Refer to Appendix B for examples of the final calibrated computer programs.

In these computer programs, the user must supply values for the shaded cells, and mass balance calculations are automatically completed. Initial P-distributions were left as user-defined variables, although results from laboratory analyses yielded suggested values and ranges. Refer to Table 4.2 for average P values from all WTPs sampled.

Since the processes for which these programs were developed have certain inherent differences in terms of treatment mechanisms, each program contains particular model parameters that may not be found in other programs. With the database available from the field sampling, the calibrations provided the closest approximations of the parameters for modelling the treatment processes in the computer programs. Table 6.1 lists the model parameters applicable to each treatment type, as well as the average results from the respective calibrations. Refer to Figure 5.2 for an example of a graphical interpretation of the effects which the *Primary Clarifier - Ferric Chloride* calibrated parameter values have on P-distributions for the MUC WTP field data.



<u>Figure 6.1</u>: Process Diagrams and Chemical Addition Points

The parameters through which the computer programs were calibrated are built-in inefficiencies to allow for non-optimal chemical reactions or removals during treatment. The user can modify the model parameter values in the computer programs as new information becomes available, or based upon inherent characteristics of a specific treatment process.

The results of the calibrations, along with the field data, will help shed light on the removal mechanisms of the different processes, and outline other technical characteristics such as sludge production, P-removal efficiency, and non-stoichiometric metal dosage requirements. The following sections will outline the assumptions made in the computer programs as well as the calibration methodology and results.

6.2 General Assumptions

The assumptions and simplifications used in constructing the computer programs resulted from several stages of development and modification and were made to the best knowledge of the author and associates of this project. As stated in Chapter 5, programs for each treatment process centred on the mechanistic model for chemical removal presented in Figure 5.1. This model follows the stoichiometry presented in Equations 5.1 and 5.2. Assumptions pertaining to the computer programs in general are as follows:

- Operating pH is close to neutrality, and chemical addition causes no significant alkalinity depletion; both assumptions proved valid according to the field data;
- Soluble-P use due to biological growth is equal to 2% of VSS produced, or 2% of the yield multiplied by the BOD_5 removed (soluble or total, depending upon the treatment type);
- Soluble:total BOD_5 is on average 60% in the influent and 80% in the effluent (as indicated by Châteauguay and Fabreville data).

Values for the yield terms were either preset (aerated lagoons) or determined during calibration (activated sludge); the biofiltration program did not include a yield term, since the VSS production was determined empirically (see Section 6.5). Other assumptions that are particular to a treatment type are listed in the following sections.

6.2.1 General Computer Program Calibration Methodology

Final values of the computer program parameters were obtained during calibration. These suggested values were based on the programs and the field data; as mentioned in Chapter 5, the user may wish to alter them based on further information. It is also possible that different combinations of parameter values would yield the same output. For example, values of ortho-P and non-ortho-P % removals are not always the same, but in some cases, they could have been with modification of the chemical precipitate % removal. It was not possible to make conclusions on certain aspects of the treatment mechanisms.

Refer to Table 6.1 for final parameter values from calibrated computer programs.

The calibration methodology involved a conventional hierarchical procedure, as illustrated in Figure 6.2. The decision-making process used in calibrating the computer programs followed a systematic approach based on the mechanistic processes affecting each treatment type.

A procedure resulted, demanding intuitive and rational decision-making in order to calibrate the programs. Reliable initial estimations of many model parameters in Step 2.0 of Figure 6.2 were possible using field data. In proceeding to Step 3.0, the sensitivity of a treatment process (and therefore, of a computer program) to a given parameter, or set of parameters, was evaluated before deciding on a path to follow when continuing with the calibration. This suggested what modifications to effect, and therefore which parameter to adjust, during a calibration sequence.

For example, the program output variables are more sensitive to adjustments in the efficiency of chemical precipitate removal than to the efficiency of influent particulate-P removal, considering the significant mass flux from soluble forms to precipitated solids following chemical addition. Close attention must therefore be paid to the removal mechanisms particular to a treatment process when carrying out a given calibration. This decision-making process varied depending upon the treatment type in a particular computer program. The procedure to follow was not obvious, as outlined in the following sections.

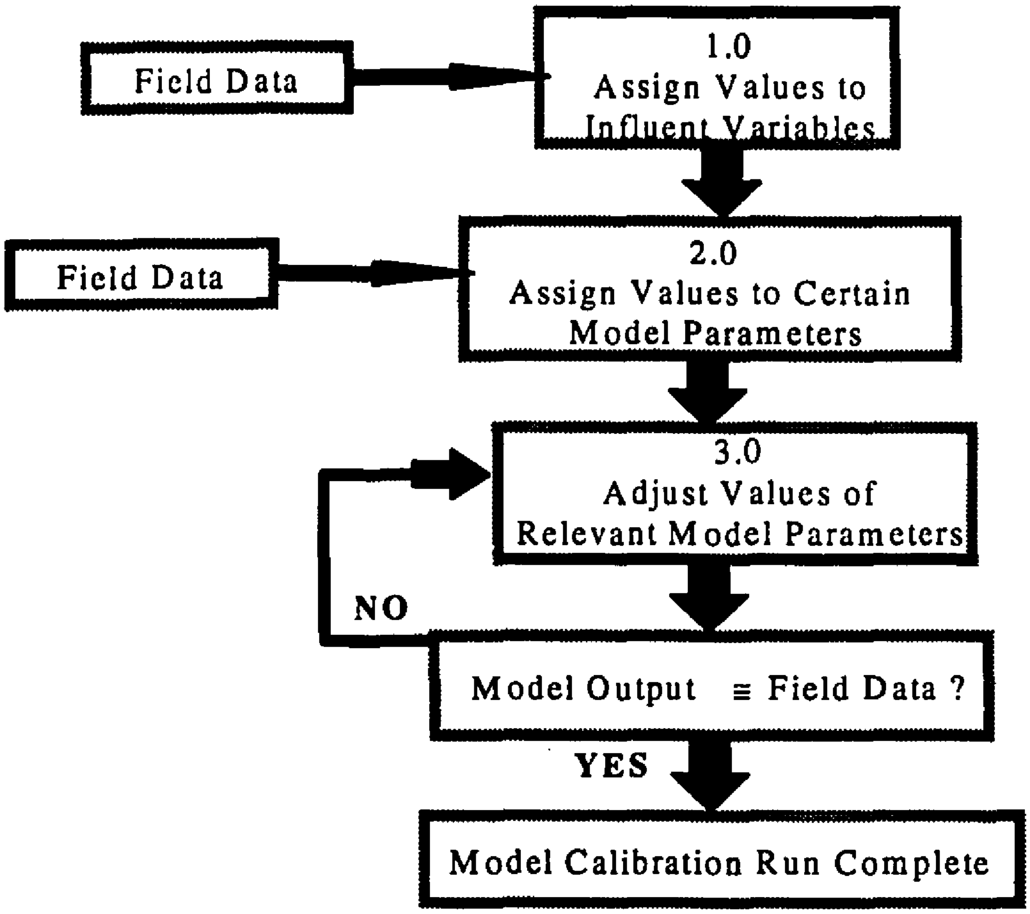


Figure 6.2: **General Calibration Methodology**

The quantity and consistency of field data determined the rigour, and to a certain extent, the accuracy of a particular program calibration. The most representative data sets from the sampling campaign were used. It was decided prior to commencing the calibrations that a ±20% agreement between the field data and computer program output would be considered acceptable. As shown in Table 7.1, models were generally in close agreement with field data. When possible, several calibration "runs" were completed for a given program. The calibration for a given treatment type's program was completed by taking the average of the most successful "runs", i.e. those that most closely mimicked the field data.

Table 6.1: Average Calibrated Model Parameter Values

Model Parameter (all values in % unless otherwise specified)	FC		AS		BF	AL
	$FeCl_3$	Alum	$Fe_2(SO_4)_3$	Alum	Alum	$Fe_2(SO_4)_3$
VSS(D)/VSS	87	78	-	-	80	-
ISS(D)/ISS	72	56	-	-	88	-
Loading from Sludge Treatment	-	-	5	5	-	-
Y(kg VSS produced/kg BOD_5 consumed)	-	-	0.9	0.8	-	0.5
K_d(day^{-1}) Endogenous Respiration	-	-	0.01	0.025	-	0.37***
Particulate Ortho-P Decanted*	-	-	-	-	-	10
Particulate Non-Ortho-P Decanted*	-	-	-	-	-	10
Molar Ratio of Me:P(at point of dosage)	2.83	2.03	0.6	1.9	1.04	0.97
Particulate Non-Ortho-P Hydrolyzed to Soluble Ortho-P*	10	10	20	20	10	20
Soluble Ortho-P reacting with Me	94	93	82	95	72	85
Soluble Non-Ortho-P Adsorbing to $Me(OH)_3$	52	58	95	80	65	0
Excess Coagulant Reacting with Alkalinity	77	84	100	100	96	0
VSS(D) Decanted	90	90	-	-	90	-
VSS(ND) Decanted	35	18	-	-	18	-
ISS(D) Decanted	95	90	-	-	90	-
ISS(ND) Decanted	30	15	-	-	32	-
TSS Decanted	-	-	99.8	99.8	-	90
Chemical Precipitates Decanted	75	92	95	95	73	90
BOD_5(Particulate) Decanted	90	82	-	-	82	-
Particulate Ortho-P Decanted**	60	60	40	40	43	50
Particulate Non-Ortho-P Decanted**	68	48	70	70	11	50
BOD_5(Soluble) Reduction	75	46	-	-	46	-
Sludge Solids Content	3	3	-	-	3	-
Particulate Non-Ortho-P Hydrolyzed to Soluble Ortho-P**	0	0	10	10	0	20

- not applicable
* before dosage
** after dosage
*** at 20°C
Note: See Nomenclature for definitions

6.3 Primary Clarifier

Separate programs were developed for processes using ferric chloride or alum. The laboratory results of four days of sampling at the Fabreville WTP, compiled in Table A4.1 and A4.2, served in the calibration of the *Primary Clarifier - Alum* computer program. Four independent calibration runs were performed, and the results were averaged to provide the final calibrated model parameters. Field data from three days of sampling at the Montreal Urban Community WTP, compiled in Tables A4.3 and A4.4, served to calibrate the *Primary Clarifier - Ferric Chloride* computer program. Parameters pertinent to this treatment process are listed in Table 6.1. Refer to Appendix B for a sample output.

6.3.1 Assumptions

Further to general model assumptions, one major assumption was made in order to calibrate the *Primary Clarifier* programs (and *Biofiltration*), viz. that 90% of the decantable inert suspended solids (ISS(D)) and volatile suspended solids (VSS(D)) fractions are sedimented, and furthermore, that when combined, these fractions form 95% of the TSS removed during treatment. Non-decantable ISS (ISS(ND)) and VSS (VSS(ND)) are assumed to form the remaining 5% of TSS removed during treatment. With these assumptions and the laboratory results for influent and effluent TSS and VSS, one can then calculate initial calibration values for the following parameters:

- The amount of the following solids fractions removed during treatment:
    - VSS(D)
    - VSS(ND)
    - ISS(D)
    - ISS(ND)
- The ratios of VSS(D)/VSS and ISS(D)/ISS in the influent.

6.3.2 Methodology

From Figure 6.1, the calibration sequence and decision-making process for this program were as follows:

Step 1. (i) Set influent variables using field data.

(ii) Set initial P-distributions using field data.

Step 2. (i) With the previously discussed assumption of 90% decantable solids removal, calculate initial values of VSS(D), VSS(ND), ISS(D), and ISS(ND).

(ii)
- Me:P: accurate estimation possible with field data;
- Particulate non-ortho-P hydrolyzed to soluble ortho-P: set at 10% for processes with relatively short (≈1 hr) hydraulic retention times (hydrolysis parameter at exit of clarifier set at 0 for this program);
- Soluble ortho-P reacting with Me: accurate estimation possible with field data;
- Soluble non-ortho-P adsorbing to $Me(OH)_3$: accurate estimation possible with field data; and
- Excess coagulant reacting with alkalinity: for many reasons, this is a difficult parameter to estimate, and will be discussed separately below.

Step 3. (i) Decantable and non-decantable solids removal values may need slight adjustment, especially if chemical solids form a significant fraction of the effluent TSS (see discussion in Section 7.2).

(ii) The effluent concentration of particulate ortho-P, and non-ortho-P if a significant *quantity* of the soluble phase is adsorbed (see 2. **(ii)** above), governs the value of the chemical precipitate removal efficiency parameter.

(iii) BOD_5 (soluble and total) removals result from direct calculations using laboratory results.

(iv) Fine-tuning is accomplished by adjusting the particulate ortho- and non-ortho-P removal efficiencies (since chemical precipitate removal values exert the greatest effect on these effluent variables).

In attempts to calculate the amount of excess coagulant reacting with alkalinity, several variables must be considered, including Me concentrations in the influent and effluent (soluble and particulate, phosphate- and hydroxide-associated etc.), Me concentrations in the sludge, and sludge production itself. In all computer programs, $MePO_4$ and $Me(OH)_3$ fractions are removed with the same efficiency (same parameter). With few precise values for sludge production available from the WTPs, the percentage of excess coagulant reacting with alkalinity must be estimated from the influent and effluent Me concentrations from laboratory results, also using the previously estimated percentage of coagulant reacting with soluble ortho-P. This is a rough approximation, since the exact fate of the metals found in the influent is unknown, and the characteristics of the metals leaving the WTP in terms of phase and chemical composition are not clear.

The above procedure yields a low estimation of the soluble non-ortho-P reaction with alkalinity, because Me found in the influent is not expected to pass through a treatment process untouched, and therefore the change in Me concentration across a WTP is likely due not only to inefficient chemical solids removal, but to other physico-chemical factors as well. However, since this parameter serves more to fine-tune the computer programs, it has a diminished effect on the effluent-P distributions and concentrations.

6.4 Activated Sludge

Programs were developed for WTPs using alum or ferric sulfate. Because of inconsistent laboratory results (mostly at Pincourt), it was necessary to use averages of the influent and effluent concentrations and P-distributions from the field data listed in Tables A4.6-A4.9 for calibrating both *Activated Sludge* programs. Parameters pertinent to this treatment process are listed in Table 6.1; high Y values and low K_d values in the activated sludge programs were necessary to obtain the sludge productions quoted by WTP operators. Refer to Appendix B for a sample output.

6.4.1 Assumptions

Further to the general assumptions previously listed, it was assumed in constructing this program that:

- MLVSS concentration remained the same with chemical addition.
- VSS are 100% biodegradable.

6.4.2 Methodology

From Figure 6.1, the calibration sequence and decision-making process for this program were as follows:

Step 1. (i) Assign reasonable values to effluent variables using field data.

(ii) Set influent variables using field data.

(iii) Set initial P-distributions using field data.

Step 2. (i) • Set aeration basin volume and MLSS concentration from field data, then vary Y and K_d within typical ranges until the program's daily sludge production approximates actual values;

- assume MLVSS = (%VSS in the influent) · (MLSS);
- τ, F/M and θ all calculated using conventionally accepted methods (Metcalf & Eddy, 1991);

(ii) • Me:P: accurate estimation possible with field data;

- Particulate non-ortho-P hydrolyzed to soluble ortho-P: set at 20% for processes with longer (several hours or more) hydraulic retention times (hydrolysis parameter following secondary clarifier set at 10%);
- Soluble ortho-P reacting with Me: accurate estimation possible with field data;
- Soluble non-ortho-P adsorbing to $Me(OH)_3$: accurate estimation possible with field data;
- Excess coagulant reacting with alkalinity: for many reasons, this is a difficult parameter to estimate (see discussion in Section 6.3.2).

Step 3. (i) Influent loading coming from sludge treatment assumed to be 5% (included in Step 3. because even though this parameter is located at the beginning of the program and calibration sequence, it is unverifiable).

(ii) The effluent concentration of particulate ortho-P, and non-ortho-P if a significant *quantity* of this soluble phase is adsorbed (see Section 6.3.2, Step 2.(ii)), governs the value of the chemical precipitate removal efficiency parameter.

(iii) Particulate ortho- and non-ortho-P removal efficiencies allow for fine-tuning since chemical precipitate removal values exert the greatest effect on these effluent variables.

Victoriaville had sand filters following the secondary clarifiers, therefore in comparing the *Activated Sludge - Alum* computer program results with field data, it was assumed in this case that particulate-P values in the effluent from the secondary clarifiers were reduced by a further 50%.

6.5 Biofiltration

The *Biofiltration* computer program was calibrated for processes using alum. The program comprised the integration of a biofiltration unit into the *Primary Clarifier* program, the effluent from the latter being fed to the former. The procedure and data used to effect this calibration differed notably from other programs. Four days of field data (Tables A4.10-A4.11) and four months of operational reports supplied by the WTP operators complemented each other, neither of the two providing all necessary data. Operational reports supplied the concentrations of all influent variables, while the P-distributions used were from the average influent results from field data. The program was calibrated such that the biofiltration effluent mimicked as closely as possible the concentrations from the monthly reports, and the distributions from the field data. Final calibrated parameters represent the averages of three runs. Parameters pertinent to this treatment process are listed in Table 6.1. Refer to Appendix B for a sample output.

6.5.1 Assumptions

Equations 6.1 and 6.2 were obtained through a linear regression ($R^2 = 0.57$ and 0.77, respectively) of two months of operating data provided by the WTP operators:

$$\mathrm{TSS}_{\mathrm{eff}} = \frac{14.03 \cdot \mathrm{TSS}_{\mathrm{inf}}}{\#\text{ of filters} \cdot \text{volume of one filter}} + 22.9 \qquad 6.1$$

$$\mathrm{BOD}_5(\mathrm{S})_{\mathrm{eff}} = \frac{98.78 \cdot \mathrm{BOD}_5(\mathrm{S})_{\mathrm{inf}}}{\#\text{ of filters} \cdot \text{volume of one filter}} - 9.2 \qquad 6.2$$

Note: all concentrations in Equations 6.1-6.3 are in kg/d and pertain to the biofilter influent or effluent

In addition, while Equation 6.3 is specific to the Québec Urban Community biofiltration pilot plant data from which it was derived in 1986, Châteauguay's data fit well, therefore it was also incorporated into the program:

$$\text{VSS (backwash sludge)} = 0.75 \cdot (\text{VSS}_{\text{inf}} - \text{VSS}_{\text{eff}}) + 0.43 \cdot (\text{BOD}_5(\text{S})_{\text{inf}} - \text{BOD}_5(\text{S})_{\text{eff}}) \qquad 6.3$$

Biofiltration backwash sludge is recycled to the head of the WTP, along with supernatant from sludge digestors and sludge dewatering. According to WTP operators, this combined additional flow is approximately 7-8% of the WTP influent flow; its composition was calculated from average monthly values from operational reports. Given the composition of the WTP influent (field data and monthly reports), an automatic calculation of the composition of the final influent to the primary clarifier was thus incorporated into the computer programs.

6.5.2 Methodology

An iterative calibration ensued, adjusting the primary clarifier parameters until the computer program's biofiltration effluent values matched the field data as closely as possible.

Accordingly, the calibration methodology was as follows:

Step 1. (i) Set influent concentrations to WTP (before recycle) using monthly averages from operation reports.

Computer program then automatically calculates feed to primary clarifiers.

(ii) Set initial P-distributions.

These distributions were calculated using both the field data and the monthly reports; the same values were then always used.

Step 2. Same procedure followed as Step 2 in Section 6.3.2.

Step 3. Same procedure followed as Step 3 in Section 6.3.2.

The final goal was not only to have the clarifier effluent mimic the data from the monthly reports, but to have the computer program's effluent from the biofiltration units match the monthly reports and field data as closely as possible in terms of concentrations and distributions, respectively.

Using the actual values of physical characteristics of the filters (number, area, depth) and data from monthly reports, values were calculated for the following parameters, in agreement with theoretical values:

- (kg TSS retained)/(m^3 of filter media), before backwash;
- (m^3 sludge produced during each backwash)/(m^3 of filter media); and,
- operational time between backwashes.

6.6 Aerated Lagoons

The aerated lagoon computer program was modified and calibrated for WTPs using ferric sulfate. Averages of the field data from sampling on July 25-27 and October 25 and 26 at the municipality of Rigaud, summarized in Tables A4.16-A4.17, were used to calibrate the programs, with some data rejected due to extreme values. Parameters pertinent to this treatment process are listed in Table 6.1. Refer to Appendix B for a sample output.

6.6.1 Assumptions

The Québec MEF favours the Eckenfelder equations for the design of facultative aerated lagoons (applied to the first two lagoons in a series of at least three, or the first in a series of two lagoons):

$$\frac{S_e}{S_0} = \frac{1 \cdot C.F.}{1 + K \cdot t} \tag{6.4}$$

where: S_0 = Influent $BOD_5(T)$, mg/L
S_e = Effluent $BOD_5(T)$, mg/L
K = Overall first-order BOD_5 removal rate constant, d^{-1}
t = Hydraulic retention time of one lagoon, d
C.F. = Correction factor, to allow for larger deposits subject to anaerobic decomposition (1.2 in summer; 1.05 in winter)

Particulate-P forms were assumed to have a 10% removal in the lagoons upstream of the chemical addition point; field data indicated highly fluctuating values for these parameters.

6.6.2 Methodology

Further to these assumptions, the calibration methodology was as follows:

Step 1. Set influent variables: temperature, flow, concentration, distribution.

Step 2. (i) Y and K are fixed at most commonly observed values in Québec, viz. 0.50 and 0.37, respectively.

(ii) Set number of lagoons and dimensions: program calculates hydraulic retention time and temperature-adjusted K.

(iii) Same procedure as outlined in Section 6.3.2, Step 2. (ii) (Particulate non-ortho-P hydrolyzing to soluble ortho-P set at 20% before chemical addition and 20% after, due to the long retention times involved).

Step 3. (i) Calculate net TSS removal across all lagoons, accounting for VSS production from BOD_5 removal.

(ii) The effluent concentration of particulate ortho-P, and non-ortho-P if a significant *quantity* of the soluble phase is adsorbed. (see Step 2. (ii) in section 6.3.2) governs the value of chemical precipitate removal efficiency from the last lagoon.

(iii) Particulate ortho- and non-ortho-P removal efficiencies allow for fine-tuning since chemical precipitate removal values exert the greatest effect on these effluent variables.

Chapter 7.0. CALIBRATION RESULTS AND DISCUSSION

This chapter will discuss specific aspects of the P mass balance model and ensuing computer programs, and in some cases, present recommendations for future investigations and possible improvements. As well, the calibration results and agreement with field data will be presented and discussed. Finally, areas of interest and attention for WTP P-removal performance improvement will be discussed. For a synopsis of the field data, refer to Chapter 4.2.

7.1 Calibration Results: Agreement with Field Data

At the outset, it was decided that an *a priori* error of 20% was acceptable in a program output's agreement with field data. Final model parameters were chosen in a heuristic manner, rejecting poor runs on a rational, intuitive, case-by-case basis.

7.1.1 Wastewater Effluent Variables

Table 7.1 represents the agreement between average effluent values at the WTPs used in the calibrations, and the average calibrated computer program output for the given treatment types.

Output from *Primary Clarifier* computer programs, except for VSS variables, was in excellent agreement with the field data, attributable to the consistency of both the field data and model parameters from the individual calibration runs. Deviation in VSS variables is attributed to the variation of influent TSS:VSS ratios, as well as the possibility that the decantable and non-decantable solids removal assumptions discussed in Section 6.3.1 are not valid, even though *Biofiltration* VSS predictions, based in part on the same assumptions, are relatively accurate.

Table 7.1: **Computer Program Output Agreement with Field Data**

Effluent Variable		PC		AS		BF	AL	
		$FeCl_3$	Alum	$Fe_2(SO_4)_3$	Alum	Alum	$Fe_2(SO_4)_3$	
							July	Oct.
Total-P	**Field Data (mg/L)**	0.57	0.74	0.35*	0.17	0.64	0.66	1.5
	Output Agreement (%)	+2	+3	+6*	+0	-17	+33	-55
Soluble-P	**Field Data (mg/L)**	0.12	0.12	0.31	0.05	0.25	0.24	0.72
	Output Agreement (%)	+11	+33	-10	+0	+7	+70	-42
Particulate -P	**Field Data (mg/L)**	0.45	0.62	0.04*	0.12	0.28	0.40	0.80
	Output Agreement (%)	+1	-13	+50*	+0	-17	+18	-41
TSS	**Field Data (mg/L)**	24.6	24.6	-	-	9.0	15.0	42.0
	Output Agreement (%)	-9	+4	-	-	+3	+7	-29
VSS	**Field Data (mg/L)**	19.4	23.0	-	-	6.0	10.0	30.0
	Output Agreement (%)	-34	-17	-	-	+7	+40	-10
BOD_5(T)	**Field Data (mg/L)**	12.7	14.0	-	-	5.7	<5	20.0
	Output Agreement (%)	+3	+2	-	-	-19	-	-57

PC	Primary Clarifier
AS	Activated Sludge
BF	Biofiltration
AL	Aerated Lagoons
*	Assuming that 50% of the secondary clarifier effluent particulate-P in the computer program output is removed by the sand filters

The output from the *Activated Sludge* programs was in close agreement with the field data. The only comparison though, can be between P-concentrations, since TSS, VSS and BOD_5 concentrations were fixed as a requirement at the beginning of the program.

Output from the *Biofiltration* programs mimicked actual field data within the limits set. The 19% difference for BOD_5 is insignificant at such low concentrations (~5 mg/L) and the 17% difference for P-total represents a concentration of merely 0.1 mg P/L.

Inherently difficult to model, *Aerated Lagoons* programs did not provide output in close agreement with the field data. The influent data varied considerably from one day to the next, even with composite samples. Since solids removal is particularly sensitive to temperature fluctuations, it was not surprising that effluent particulate-P was higher in October than in July. Furthermore, the computer programs' TSS and total-P effluent variables were in poorer agreement with field data in October than in July. Difficulty also occurred in using the Eckenfelder equation (Equation 6.4) because it did not predict BOD_5 well, but this did not affect the P-results significantly since there is such a large ratio (100:2) between the two.

7.1.2 Sludge Production and P-Content

Output from computer programs included sludge concentrations of particulate total-P, ortho-P and non-ortho-P, while laboratory data provided the concentrations of total-P and inorganic-P. Much supposition would be required to use the field data and program outputs for anything but the comparison of total-P concentrations in the sludge.

Referring to Table 7.2, *Primary Clarifier* programs predict the P-content of final sludge reasonably well. A comparison between *Activated Sludge* output and field data is not possible since the programs do not include calculations of the sludge P-content. Discrepancies between the *Biofiltration* program's output and field data are likely due to the fact that analyses were performed on digested, dewatered sludge, while the program output represents decanted primary sludge.

Table 7.2: Phosphorus Content of Sludge: Computer Program Output and Field Data

Computer Program	Predicted (P:TSS) (mass:mass)	Actual (P:TSS) (mass:mass)
Primary Clarifier $FeCl_3$	1.4	1.8
Primary Clarifier Alum	2.6	2.0
Biofiltration Alum	0.7	3.1

Note: all values quoted on a dry basis

No specific parameters served the function of calibrating sludge production in the computer programs. Comparisons were, however, possible between the models' predicted sludge production, and the values of sludge produced as quoted by WTP operators. Refer to Table 7.3 below.

Table 7.3: **Sludge Production: Computer Program vs. Actual**

Computer Program	Predicted Production*	Actual Production*	Comments
Primary Clarifier $FeCl_3$	117 t/Mm^3 (-3%)	120.5 t/Mm^3 (1993)	Predicted production calculated using average 1993 flowrate (1.75 Mm^3/d) since value during sampling was considerably higher (2.27 Mm^3/d).
Primary Clarifier *Alum*	79.5 t/Mm^3 (-3%)	82.7 t/Mm^3 (1992)	
Activated Sludge *Alum*	0.8 t/d (+42%)	0.56 t/d (01-06/1994)	No sludge digestion.
Activated Sludge $Fe_2(SO_4)_3$	2.6 t/d (+8%)	2.4 t/d (1993)	Assuming 40-50% VSS reduction during aerobic digestion**.
Biofiltration *Alum*	2.7-4.0 t/d (+42-110%)	1.9 t/d (1992-92)	Assuming 40-80% VSS reduction during anaerobic digestion**.

All sludge production values are on a dry basis

[*] Stringent comparisons (using t/Mm^3) of *Primary Clarifier* programs were realized using the large database assembled in earlier stage of MEF study (Hart and Lorange, 1995)

[**] Metcalf and Eddy, 1991

Because of the attention given to solids removal and the consistent field data, *Primary Clarifier* programs predict sludge production to within 3% of actual productions. The comparison was done with averages from an extensive database of sludge production assembled at an earlier stage of this study (Hart and Lorange, 1995), since no specific sludge production data were available at the time of sampling.

An indirect sludge production calibration was possible in *Activated Sludge* programs by modifying the kinetic coefficients so that a program's production matched as closely as possible that quoted by WTP operators. Taking into account reductions in VSS during sludge digestion, *Activated Sludge* programs, particularly the *Ferric Sulfate* program, predicted sludge production reasonably well. The 0.24 t/d (+42%) difference observed in the *Alum* program is likely due to a combination of the abnormally high influent flowrates at the WTP used to calibrate the program (Pincourt) during the first sampling period, the relatively narrow scope afforded by the sampling period, and/or inaccuracies of quoted sludge production values.

As discussed in Section 6.5.1, Equation 6.3, and therefore the *Biofiltration* program's biofilter backwash sludge VSS concentration, represented field data and monthly reports relatively well. Châteauguay's primary sludge (including biofiltration backwash) is anaerobically digested, therefore assumptions and further calculations are necessary in order to compare the program output and field data. Even so, the programs do not predict sludge production very closely (+42-110%). Refer to the values and comments in Table 7.3.

Aerated Lagoons programs calculated sludge accumulation as per Roche (1986), although no comparison was possible, and it was not a focus of this research.

7.2 Computer Programs

The applicability of a given computer program to a WTP with the same treatment type, but significantly different influent characteristics, is of importance. The same % removals may not apply if the absolute values of a given contaminant's removal were significantly different. The inherent mechanistic behaviour is not likely to change significantly in different WTPs with the same treatment type, but the programs may need tailoring, as do various treatment processes, to the characteristics of a given wastewater. As discussed at the outset of Chapter 6, the user may wish to alter model parameter values in light of further information on a specific treatment process or WTP.

Luedecke et al. (1989) observed that approximately 27% of particulate-P and 5% of soluble non-orthophosphate was hydrolyzed to soluble orthophosphate during control experiments. The hydrolysis parameter values of between 0-20% in the computer programs are therefore reasonable in light of these observations.

ISS and VSS removal calculations, and the assumptions behind them, do not explicitly take into account solids flux between soluble and precipitated species following chemical addition. For example, using the average values from Table 4.2 and the model assumptions, the average quantity of $MePO_4$ precipitated is at least 9 mg P/L, while the concentrations of TSS removed generally have much higher values. However, if the influent TSS was low and there is significant production and poor removal of $MePO_4$ or $Me(OH)_3$, chemical solids could form a significant fraction of both the solids removed and effluent TSS. In such cases, the ISS and VSS removal parameters would require further adjustment during the later stages of the calibration sequence so that model results mimicked the field data. A useful modification to the programs would therefore be to separate the influent TSS, effluent TSS and precipitated chemical solids variables, allowing for parallel calculations.

With respect to the discussion in Section 6.2.1 on coagulant reaction with alkalinity and metal distributions, a similar beneficial modification in the computer programs would include metal (Fe or Al) mass balances, distinguishing between soluble and particulate forms. This would afford much greater insight into the fate of dosed metals and P in a WTP, in terms of interactions and P-removal mechanisms.

Akin to the discussion on reaction with alkalinity, several models discussed in Chapter 2 evaluate the Me:P ratio in their principal precipitate, a metal hydroxy-phosphate. The model of Luedecke et al. (1989) predicts an initially decreasing Fe:P ratio (to approximately 2.5) with a decreasing residual equilibrium soluble phosphate concentration ($C_{P,eq}$); Fe:P increases sharply at the minimum phosphate solubility when ferric hydroxide is formed. They suggested that the increasing Fe:P ratio with decreasing $C_{P,eq}$ observed in their laboratory results was due to phosphates being also removed through adsorption on the precipitates, in competition with hydroxyl groups. Although the principal precipitate of the model presented in Chapter 5 was a metal phosphate, adsorption to metal hydroxides was also explicitly included in the model's removal mechanisms and subsequent computer program calculations.

Furthermore, this P-removal model always included simultaneous consideration of phosphate precipitation, hydroxide formation and subsequent adsorption, unlike some of the models discussed in Chapter 2 (Ferguson and King, 1979; Kavanaugh et al., 1978; Luedecke et al., 1989). The output from the computer programs did not always allow for the calculation of Me:P sludge ratios, which can serve as an indirect estimation of

Me:P ratios in precipitated solids. Me:P ratios from the field data, listed in Table 4.4, can provide indications as to the P-removal mechanisms at each WTP.

Examining another aspect of the field data and computer program calibration results, the average calibrated "soluble non-ortho-P adsorption to $Me(OH)_3$" parameters for the *Activated Sludge* programs, and the high % removals observed at the biological WTP (except Rigaud and Mont St-Grégoire) are of interest. Bunch and Grifin (1992) observed rapid reductions in BOD_5 and COD in a contact stabilization AS process, and theorized that colloidal and particulate organics were adsorbed to the microorganisms and used at a later time as substrate. Field data suggest similar behaviour in the WTPs sampled, especially since Me:P ratios are on average less than 1; the high % removals of TSS inherent in well-run AS processes should not be overlooked.

7.3 Improvements to P-Removal Performance

Several aspects of an overall treatment process must be considered when weighing alternatives to improved WTP P-removal performance. For example, coagulant fast-mixing and slow-mixing stages must maximize efficiency and effectiveness through chemical dose and flocculation time, while considering both financial and operational constraints. Furthermore, den Engelse (1993) advised using load-controlled dosage in larger WTPs serving in excess of 100 000 p.e., when the savings (i.e. chemical use, sludge production) would outweigh the costs of on-line equipment and maintenance. Increased influent monitoring would allow process adjustments in response to WTP performance, thus ensuring a more consistent and acceptable effluent.

In addition, when adding chemicals to an AS process to supplement EBPR, one must consider the chemical choice, the best point of chemical addition, load-controlled chemical dosage, and the possible need for pH adjustment. Chemical addition should focus on removing only the P not removed by biological processes. One suggestion to accomplish this is a control strategy, providing stable P, COD and TSS removals, that ceases chemical addition when effluent ortho-P drops below 0.5 mg P/L (Lötter, 1991). The optimization of chemical P-removal processes, with or without parallel biological treatment, leads to concomitant reductions of COD and TSS (Levine et al., 1985; Rand Development Corp., 1971).

As observed from the relationships in Table 4.3 and from the literature (den Engelse, 1993; Nieuwstad et al., 1988), it is clear that particular attention must be paid to TSS removal, since it is a potential bottle-neck in achieving acceptable effluent-P levels. WTP influent-P is generally evenly distributed across particle sizes (15-35% soluble, <0.45μm) (Levine et al., 1985). Following primary and secondary treatment, the majority (50-70%) of effluent-P is associated with filterable solids, even when coagulants are used. These authors also reported experimental results whereby chemical treatment preferentially removed particulate-P associated with particles larger than 0.1μm; 30-85% of TOC in the settled wastewater was associated with this particle size. Low molecular weight (< 1 000 amu) substances were not affected by coagulant dose, while higher molecular weight (>10 000 amu) substances were removed by up to 90% at higher (unspecified) doses.

At lower temperatures, Marklund (1993) noted that SBR effluent concentrations of P and TSS increased, with longer retention times having no effect. Effluent TSS concentrations below 20 mg/L were recommended to achieve an effluent-P of less than 1 mg P/L. Cripps and Hanæus (1993) noted that in WTP ponds, most of the effluent-P was in the particulate form - and under 5μm - which will not settle even with long quiescent conditions, least of all in the pH, hydraulic and temperature gradients commonly found in WTPs. The turbidity and median particle size in the pond regions with long retention times were not lower than in the main stream near the effluent. Remaining particles did not have the ability (mass, density) to settle, therefore improvements were required for the initial coagulation and flocculation conditions.

WTPs must be regarded as overall integrated systems, the global picture demonstrating that modifications to one treatment train have impacts on others. Many alternatives exist when attempting to improve a WTP's P-removal performance, from changes to the main process used, to relatively simple variations in operating conditions.

Chapter 8. CONCLUSIONS

As part of an overall study of chemical P-removal in Québec, a P mass balance model was constructed, tracing soluble and particulate orthophosphate and poly/organic phosphorus forms across a chemical P-removal process. Through assumptions and simplifications, the model accounted for the main mechanisms that are generally accepted today as the principal pathways for P-removal following chemical addition: orthophosphate precipitation, soluble phosphorus adsorption to hydroxide precipitates, and the hydrolysis and sedimentation of influent particulate phosphorus. P mass balance models were incorporated into computer programs representing the four WTP types responsible for the treatment of over 99% of the wastewater treated in Québec: *Primary Clarifiers, Activated Sludge, Biofiltration and Facultative Aerated Lagoons*. The goal was to devise a flexible tool for process comparison, one that would detail P-fractions across the solid/liquid streams. The user must input values for influent variables, and the computer programs yield the effluent values. Calibrations provided suggested values for the treatment parameters upon which the model is based, and around which the computer programs were constructed. The user has the option to modify these parameters if needed.

8.1 Field Data

Data were collected during field sampling at 11 WTPs across the province; this database will likely be of value to other researchers. From an analysis of the results in Chapter 4, the following conclusions can be made:

- Several WTPs obtained total-P removal of approximately 90% with Me:P-total ratios often below 1; up to 95% removal of soluble-P was observed at different WTPs with Me:P ratios from 0.6 to 1.8;
- The majority of effluent-P was in the particulate form, with the exception of Victoriaville which passed its secondary effluent through sand filters, illustrating the importance and effect of solids removal on overall P-removal.

- EBPR existed at supposedly strictly aerobic activated sludge WTPs (Pincourt and Victoriaville);
- WTP performance, especially particulate P-removal, significantly deteriorates with decreases in temperature;
- Biological treatment supplemented with chemical addition generally had soluble non-ortho-P removals in excess of 79% (effluent-P < 0.05 mg P/L); and
- WTPs using iron based chemical ($FeCl_3$ or $Fe_2(SO_4)_3$) generally had higher effluent metal concentrations than did WTPs using aluminum based coagulants (alum, alum sludge);

8.2 Mass Balance Model and Computer Programs

The computer programs were calibrated such that their output mimicked field data as closely as possible. It can be concluded that:

- Computer program output generally agreed with field data generally within 10% (ca. 20% discrepancies in *Biofiltration* representing insignificant absolute differences);
- The *Aerated Lagoons* program modelled the field data poorly due to the difficulties in modelling this treatment process, inconsistent field data and the relative inapplicability of the Eckenfelder equation;
- *Primary Clarifier* programs modelled sludge production quite closely; *Activated Sludge* programs modelled sludge production reasonably well (*$Fe_2(SO_4)_3$* more so than *Alum*);
- The excellent calibration results in the *Primary Clarifier* programs were due partly to the consistent field data (liquid stream calibration results), and partly to the availability (for comparison purposes) of a database accumulated at an earlier stage of the MEF study (sludge stream calibration results); and,
- Only a terse comparison of predicted vs. actual sludge P-content was possible; *Primary Clarifier* programs predicted the P-content to ±22-30%.

Sources in the literature, observations, and conclusions formed during and following the calibrations suggested many possible future modifications to the chemical P-removal mass balance model and the associated computer programs, for example:

- modifications to the computer programs so that P-fractions' mass fluxes, and hence solids fractions (which are both accounted for in calculations), are clearly expressed for analytical purposes;
- analyses for soluble and particulate metals in the influent and effluent, which would lend further insight on the fate of dosed metals and the nature of metals and chemical solids in the effluent;
- further analyses on solids in the influent and effluent to better define the decantable and non-decantable fractions.

From the calibration results, the existing model, and computer programs built around it, reproduce with reasonable accuracy the quantitative and qualitative effects of chemical addition for P-removal, and can therefore be employed as a useful predictive tool for conceptual design.

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APPENDIX A

FIELD DATA

Table A4.1: Laboratory Results; Fabreville

Sample	Flow m3/d	Dose mg Al/L	pH	Temp °C	P(tot)(N-F) mg/L	P(inorg.) mg/L	COD(F) mg/L	COD(N-F) mg/L	BOD5(sol) mg/L	BOD5(tot) mg/L	Al(tot) mg/L	Fe(tot) mg/L	Alkalinity mg CaCO3/L
07/18/94													
Influent East--1 L composite	15131	4.5	7.49		2.30		64(58)	101	<10	51	<0.20		198
Effluent East--1 L composite			7.61		0.65		29	55	6	14	0.90		179
Dewatered sludge(mg/kg)**					18800	14200					44800		
07/19/94													
Influent East--1 L composite		4.5	7.60	17.0	3.44		58	208		30	0.40	0.89	210
Effluent East--1 L composite			7.60	15.0	0.89		28	81	12	15	0.70	0.31	182
Dewatered sludge(mg/kg)**					20700	16200					46300	7800	
07/20/94													
Influent East--1 L composite	15648	4.5	7.38	17.0	2.81		45	147	25	43	<0.20		199
Effluent East--1 L composite			7.46	15.0	0.75		31	55	10	14	<1.00		176
Dewatered sludge(mg/kg)**					18500	16600					51200		
07/21/94													
Influent East--1 L composite	14345	5.0	7.64	17.6	2.31		37	125	24	40	<0.20		197
Effluent East--1 L composite			7.59	17.0	0.67		20	37	13	13	<0.70		178
Dewatered sludge(mg/kg)**					21300	15600					35700		

** mg/kg dry basis

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.2: Laboratory Results; Fabreville

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/18/94																	
Influent East--1 L composite	80.6(37.0)	64.4(31.0)	2.9	3.6	2.30	0.69	30.0	0.69	30.0	0.00	0.0	1.61	70.0	0.55	23.9	1.06	46.1
Effluent East--1 L composite	20.7	16.0	3.1	4.1	0.65	0.09	13.8	0.07	10.8	0.02	3.1	0.56	86.2	0.24	36.9	0.32	49.2
Dewatered sludge(mg/kg)**	290600	197600			18800												
07/19/94																	
Influent East--1 L composite	85.7	79.3	4.0	4.3	3.44	2.02	58.7	1.95	56.7	0.07	2.0	1.42	41.3	0.20	5.8	1.22	35.5
Effluent East--1 L composite	27.0	24.5	3.3	3.6	0.89	0.15	16.9	0.11	12.4	0.04	4.5	0.74	83.1	0.27	30.3	0.47	52.8
Dewatered sludge(mg/kg)**	299600	193000			20700												
Supernatant(sludge treatment)								<0.05									
07/20/94																	
Influent East--1 L composite	84.7	72.3	3.3	3.9	2.81	1.94	69.0	1.94	69.0	0.00	0.0	0.87	31.0	0.12	4.3	0.75	26.7
Effluent East--1 L composite	26.3	18.7	2.9	4.0	0.75	0.09	12.0	0.09	12.0	0.00	0.0	0.66	88.0	0.21	28.0	0.45	60.0
Dewatered sludge(mg/kg)**	262300	171200			18500												
07/21/94																	
Influent East--1 L composite	93.0	81.0	2.5	2.9	2.31	1.38	59.7	1.19	51.5	0.19	8.2	0.93	40.3	0.29	12.6	0.64	27.7
Effluent East--1 L composite	24.5	17.5	2.7	3.8	0.67	0.14	21.4	0.10	14.9	0.04	6.5	0.53	78.6	0.25	37.3	0.28	41.3
Dewatered sludge(mg/kg)**	189900	129900			21300												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

Table A4.3: Laboratory Results; M.U.C.

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Fe(tot)	Alkalinity
	m3/d	mg Fe/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/05/94														
Influent--54% S + 46% N comp.	2530800	9.3	7.2-S; 7.4-N	21.0	0.34	0.42	0.56	1.61		69	158	49	0.55	174
Effluent--1 L composite			7.10	21.0	<0.05	0.14	0.18	0.49		42	60	6	2.49	153
Sedimented sludge(mg/kg)**								21250	19000				86600	
07/06/94														
Influent--54% N +46% S comp.	2146249	9.7			0.46	0.54	0.60	1.93		76	215	78	0.81	177
Effluent--1 L composite					<0.05(0.12)	0.21	0.07	0.55(0.60)		52	85(39)	13	2.65	155(156)
Sedimented sludge(mg/kg)**								12900	6100				96000	
Dewatered sludge(mg/kg)**								17800	16400				67500	
07/08/94														
Influent--55% N + 45% S comp.	2130630	9.7			0.50	0.61	0.77	2.15		65	187	79	0.93	170
Effluent--1 L composite					<0.05	0.23	0.12	0.68		44	82	19		138
Sedimented sludge(mg/kg)**								14000	8500				58500	

** mg/kg dry basis

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.4: Laboratory Results; M.U.C.

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/05/94																	
Influent--54% S + 46% N comp.	73.0	53.3	2.2	3.0	1.61	0.56	34.8	0.34	20.9	0.22	13.9	1.05	65.2	0.08	5.0	0.97	60.2
Effluent--1 L composite	16.3	8.3	3.0	5.9	0.49	0.18	37.5	0.03	5.1	0.16	32.4	0.31	62.5	0.12	23.5	0.19	39.0
Sedimented sludge(mg/kg)**	34200	20500			21250												
07/06/94																	
Influent--54% N +46% S comp.	107.0	77.0	1.8	2.5	1.93	0.60	31.2	0.46	23.8	0.14	7.4	1.33	68.8	0.08	4.1	1.25	64.6
Effluent--1 L composite	28.3(19)	27.7(11)	1.9	2.0	0.55	0.07	13.0	0.03	4.5	0.05	8.4	0.48	87.0	0.19	33.6	0.29	53.4
Sedimented sludge(mg/kg)**	40600	22800			12900												
Dewatered sludge(mg/kg)**	290200	145200			17800												
07/08/94																	
Influent--55% N + 45% S comp.	118.7	94.0	1.8	2.3	2.15	0.77	35.6	0.50	23.3	0.27	12.3	1.38	64.4	0.11	5.1	1.27	59.3
Effluent--1 L composite	29.3	22.3	2.3	3.1	0.68	0.12	17.9	0.03	3.7	0.10	14.3	0.56	82.1	0.21	30.0	0.36	52.1
Sedimented sludge(mg/kg)**	56300	27500			14000												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

Table A4.5: Laboratory Results; Pincourt

** mg/kg dry basis   *** g Poly-P released/g VSS (%)   Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Al(tot)	Fe(tot)	Alkalinity
	m3/d	mg Al/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
06/28/94															
Influent--1 L composite	6613	3.8	7.48	16.0						47	182	66	0.95		163
Effluent--1 L composite			7.10	17.0	(<0.10)			(0.19)		13(<15)	31(<15)	<=2	0.51		140(121)
Mixed liquor--2 x 1 L inst.			7.05	18.5						23					451
Dewatered sludge(mg/kg)**								29650	26100				41300		
06/29/94															
Influent--1 L composite	9523	2.6	7.70	18.5	0.82	0.46	0.92	1.84		47	188	[illegible]	0.46		230
Effluent--1 L composite			7.14	16.5	<0.05	0.07	<0.05	0.15		15	30	3	0.49		183
Mixed Liquor--1 L composite			7.18	23.0	1.02	54.06	0.82	102.00		38	5446				361
Dewatered sludge(mg/kg)**								39000	24000				39300		
06/30/94															
Influent--1 L composite	10622	2.4	7.38	16.0	0.61	0.68	0.82	1.48		89	153	44	1.40		173
Effluent--1 L composite			6.91	17.0	<0.05	0.08	<0.05	0.23		33	49	4.5	0.48		209
Mixed Liquor--1 L composite			7.16	19.5	0.85	64.26	0.92	168.81		73	6545				344
Dewatered sludge(mg/kg)**								35800	14700				51200		
07/01/94															
Influent--1 L composite	10622	2.4	7.53	16.0	0.63	0.64	1.12	1.23		63	102	46	<0.20		238
Effluent--1 L composite			7.12	16.0	<0.05	0.07	0.05	0.15		31	40	4	0.35		209
Mixed Liquor--1 L composite			7.18	19.0	0.53	56.10	0.65	158.10		70	5474				445
07/20/94		mg Fe/L													
Influent--1 L composite	5554	5.2		17.9	1.83	1.91	2.14	3.20						0.39	223
Effluent--1 L composite				18.9	0.05	0.14	0.07	0.34						0.12	165
Mixed Liquor--3 x 330 mL inst.					0.12	68.67	0.17	192.95							373
Acetate test--Poly-P***								0.28 %							
Dewatered sludge(mg/kg)**								31100	22300					39400	
07/21/94															
Influent--3 x 330 mL inst.	5948	4.1		18.2	2.93	9.33	3.03	22.71			979			0.45	264
Effluent--3 x 330 mL inst.				19.6	<0.05	0.05	<0.05	0.14			18			0.14	151
Mixed Liquor--3 x 330 mL inst.					0.05	81.35	0.09	190.83							490
Acetate test--Poly-P***								0.26 %							
Dewatered sludge(mg/kg)**								32000	23900					38300	

Table A4.6: Laboratory Results; Pincourt

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
06/28/94																	
Influent--1 L composite	139.0	89.0															
Effluent--1 L composite	15.0	14.0	1.3	1.4	0.19			0.10									
Mixed liquor--2 x 1 L grab	5183.0	3500.0															
Dewatered sludge(mg/kg)**	159600	96600	18.6	32.7	29650												
06/29/94																	
Influent--1 L composite	121.3	94.0	1.5	2.0	1.84	0.92	50.0	0.82	44.4	0.10	5.6	0.92	50.0	0.00	0.0	0.92	50.0
Effluent--1 L composite	17.5	16.5	0.9	0.9	0.15	0.05	33.0	0.05	33.0	0.00	0.0	0.10	65.4	0.02	13.0	0.08	52.0
Mixed liquor--1 L composite	5193.3	3420.0	2.0	3.0	102.00	1.02	1.0	1.02	1.0	0.00	0.0	100.98	99.0	53.04	52.0	47.94	47.0
Dewatered sludge(mg/kg)**	169700	92800	23.0	42.0	39000												
06/30/94																	
Influent--1 L composite	106.3	59.0	1.4	2.5	1.48	0.82	55.2	0.61	41.4	0.20	13.8	0.66	44.8	0.07	4.7	0.59	40.1
Effluent--1 L composite	7.7	7.7	3.0	3.0	0.23	0.05	21.3	0.03	10.7	0.03	10.7	0.18	76.7	0.06	23.4	0.13	53.3
Mixed liquor--1 L composite	6046.7	4060.0	2.8	4.2	168.81	0.92	0.5	0.85	0.5	0.07	0.0	167.89	99.5	63.41	37.6	104.48	61.9
Dewatered sludge(mg/kg)**	134100	55300	26.7	64.7	35800												
07/01/94																	
Influent--1 L composite	35.7	30.3	3.5	4.1	1.23	1.12	90.9	0.63	51.2	0.49	39.7	0.11	9.1	0.01	0.8	0.10	8.3
Effluent--1 L composite	11.7	9.0	1.3	1.7	0.15	0.05	33.3	0.03	16.7	0.03	16.7	0.10	66.7	0.05	29.4	0.06	37.3
Mixed liquor--1 L composite	5030.0	3246.7	3.1	4.9	158.10	0.65	0.4	0.53	0.3	0.12	0.1	157.45	99.6	55.57	35.1	101.88	64.4
07/20/94																	
Influent--1 L composite	86.0	73.0	3.7	4.4	3.20	2.14	66.9	1.83	57.0	0.32	9.9	1.06	33.1	0.08	2.4	0.98	30.7
Effluent--1 L composite	15.7	11.3	2.1	3.0	0.34	0.07	21.2	0.05	15.2	0.02	6.1	0.27	78.8	0.09	26.7	0.18	52.0
Mixed liquor--3 x 330 mL grab	6766.5	4626.7	2.9	4.2	192.95	0.17	0.1	0.12	0.1	0.05	0.0	192.78	99.9	68.55	35.5	124.23	64.4
Acetate test--Poly-P					0.28%												
Dewatered sludge(mg/kg)**	167400	101300	18.6	30.7	31100												
07/21/94																	
Influent--3 x 330 mL grab	870.0	617.5	2.6	3.7	22.71	3.03	13.3	2.93	12.9	0.10	0.4	19.68	86.7	6.40	28.2	13.27	58.5
Effluent--3 x 330 mL grab	11.5	10.0	1.2	1.4	0.14	0.03	18.0	0.03	18.0	0.00	0.0	0.12	82.0	0.00	0.0	0.12	82.0
Mixed liquor--3 x 330 mL grab	6600.0	4553.3	2.9	4.2	190.83	0.09	0.0	0.05	0.0	0.04	0.0	190.74	100	81.30	43	109.44	57
Acetate test--Poly-P					0.26%												
Dewatered sludge(mg/kg)**	152500	90900	21.0	35.2	32000												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

Table A4.7 Laboratory Results; Victoriaville

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Fe(tot)	Alkalinity
	m3/d	mg Fe/L		'C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/05/94														
Influent--1 L composite	35294	3.5	7.23	16.5	1.72	2.43	2.30	3.16		60	159		1.33	214
Effluent--1 L composite			6.93	18.0	0.27	0.29	0.28	0.32		24	28		0.03	153
Mixed liquor--3 x 330 mL inst.					0.57	93.69	0.42	202.47		42	5641			295
Dewatered sludge(mg/kg)**								36200	31100				41100	
07/06/94														
Influent--1 L composite	33436		7.35	16.0	1.47	1.80	1.80	3.27		57	173	58	1.22	188
Effluent--1 L composite			7.24	18.0	0.32	0.34	0.34	0.37		32	34	<2	0.04	178
Mixed liquor--3 x 330 mL inst.					0.41	105.26	0.45	167.59		43	5584			320
Acetate test--Poly-P***								0.37 %						
Dewatered sludge(mg/kg)**								34100	20400				37500	
07/08/94														
Influent--1 L composite	32730		7.35	16.0	1.49	2.05	2.04	3.64		57	188(149)	49	<0.02	163
Effluent--1 L composite			7.24	18.0	0.28(0.27)	0.30	0.35	0.38(0.48)		20	22	<2	<0.02	175(164)
Mixed liquor--3 x 330 mL inst.					0.38	92.41	0.51	177.58		43	5915			330
Acetate test--Poly-P***								0.36 %						
Dewatered sludge(mg/kg)**								36200	33500				47000	

** mg/kg dry basis

*** g Poly-P released/g VSS (%)

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4 .8: Laboratory Results; Victoriaville

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/05/94																	
Influent--1 L composite	88.7	64.4	3.6	4.9	3.16	2.30	72.6	1.72	54.5	0.57	18.1	0.87	27.4	0.70	22.1	0.17	5.3
Effluent--1 L composite	2.0	0.7	15.8	45.2	0.32	0.28	87.1	0.27	83.9	0.01	3.2	0.04	12.9	0.02	6.3	0.02	6.6
Mixed liquor--3 x 330 mL inst.	5810.0	3783.3	3.5	5.4	202.47	0.57	0.3	0.57	0.3	0.00	0.0	201.90	99.7	93.12	46.0	108.78	53.7
Dewatered sludge(mg/kg)**	133600	79000			36200												
07/06/94																	
Influent--1 L composite	89.3	75.3	3.7	4.3	3.27	1.80	54.8	1.47	44.9	0.33	10.0	1.48	45.2	0.33	10.1	1.15	35.1
Effluent--1 L composite	4.3	4.3	8.5	8.5	0.37	0.34	91.7	0.32	86.1	0.02	5.6	0.03	8.3	0.02	5.4	0.01	2.9
Mixed liquor--3 x 330 mL inst.	5680.0	3656.7	3.0	4.6	167.59	0.45	0.3	0.41	0.2	0.04	0.0	167.14	99.7	104.86	62.6	62.28	37.2
Acetate test--Poly-P ***					0.37%												
Dewatered sludge(mg/kg)**	118700	64200			34100												
07/08/94																	
Influent--1 L composite	107.7	82.7	3.4	4.4	3.64	2.04	55.9	1.49	40.9	0.55	15.0	1.60	44.1	0.56	15.4	1.04	28.7
Effluent--1 L composite	3.5	3.0	10.9	12.7	0.38	0.35	91.3	0.28	73.7	0.07	17.6	0.03	8.7	0.02	5.3	0.01	3.5
Mixed liquor--3 x 330 mL inst.	5466.7	3566.7	3.2	5.0	177.58	0.51	0.3	0.38	0.2	0.13	0.1	177.07	99.7	92.03	51.8	85.04	47.9
Acetate test--Poly-P ***					0.36%												
Dewatered sludge(mg/kg)**	126100	86700			36200												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

*** g Poly-P released/g VSS (%)

Table A4.9: Laboratory Results; St-Jean-Baptiste

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Al(tot)	Alkalinity
	m3/d	mg Al/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
06/28/94														
Influent--1 L composite	2865	4.3	7.10	17.0						161	724		7.90	198
Effluent--1 L composite			7.10	18.0						29	62		0.81	179
Dewatered sludge(mg/kg)**								37200	22400				56600	
06/29/94														
Influent--1 L composite	2107	5.9	7.14	18.0	5.79		6.07	9.54		251	660	278	5.00	210
Effluent--1 L composite			6.98	21.0	0,29(0,26)	0.35	0.32	0.51(0.56)		37(<15)	40(<15)	2	<0.20	182(130)
Dewatered sludge(mg/kg)**								35750	31800				55100	
06/30/94														
Influent--1 L composite	2803	4.4	7.17	18.0	4.57	5.85	5.01	9.30		201	524	193	4.40	199
Effluent--1 L composite			7.03	19.0	0.16	0.31	0.19	0.57		56	82	6	0.54	176
Dewatered sludge(mg/kg)**								36050	31500				57300	
07/01/94														
Influent-1 L composite	2143	5.8	7.53	16.5	5.66	6.16	5.93	8.52		188	349	135	1.1	197
Effluent--1 L composite			6.99	19.0	0.20	0.35	0.22	0.63		50	65	6	0.92	178

** mg/kg dry basis

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.10: Laboratory Results; St-Jean-Baptiste

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
06/28/94																	
Influent--1 L composite	410.8	305.8															
Effluent--1 L compos	20.7	17.7															
Dewatered sludge(mg/kg)**	115600	76800			37200												
06/29/94																	
Influent--1 L composite	273.6	212.0	3.5	4.5	9.54	6.07	63.6	5.79	60.7	0.28	2.9	3.47	36.4				
Effluent--1 L composite	14.3	11.0	3.6	4.6	0.51	0.32	62.0	0.29	56.9	0.03	5.1	0.19	38.0	0.06	11.8	0.13	26.2
Dewatered sludge(mg/kg)**	133600	76300			35750												
06/30/94																	
Influent--1 L composite	245.6	186.7	3.8	5.0	9.30	5.01	53.8	4.57	49.1	0.44	4.7	4.29	46.2	1.28	13.8	3.01	32.4
Effluent--1 L composite	18.7	16.7	3.1	3.4	0.57	0.19	33.9	0.16	28.6	0.03	5.4	0.38	66.1	0.14	24.5	0.24	41.6
Dewatered sludge(mg/kg)**	124400	84100			36050												
07/01/94																	
Influent--1 L composite	133.9	101.7	6.4	8.4	8.52	5.93	69.6	5.66	66.5	0.27	3.2	2.59	30.4	0.50	5.9	2.09	24.5
Effluent--1 L composite	25.3	20.7	2.5	3.1	0.63	0.22	35.5	0.20	32.3	0.02	3.2	0.41	64.5	0.14	22.1	0.27	42.4

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

Table A4.11: Laboratory Results; Marieville

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg)	COD(F)	COD(N-F)	BOD5(tot)	Fe(tot)	Alkalinity
	m3/d	mg Al/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/12/94														
Influent--1 L composite	3983	0	7.48	22	1.52	3.14	1.96	4.55		134	261	127	0.70	298
Effluent--1 L composite			7.29	21	<0.05	0.06	<0.05	0.18		29	32	5	0.41	189
Mixed liquor--1 L inst.					0.06	33.35	0.12	93.30			4683			294
Acetate test--Poly-P***								0.14 %						
Dewatered sludge(mg/kg)**								25900	14700				64800	
07/13/94														
Influent--1 L composite	3799	0	7.25	21.5	2.45	2.52	2.81	3.80		167	436	188	1.25	219
Effluent--1 L composite			7.30	22.5	0.05	0.12	0.12	0.19		34	35	6	0.31	204
Mixed liquor--1 L inst.					0.09	51.97	0.13	106.29		64	1144			285
Acetate test--Poly-P***								0.14 %						
Dewatered sludge(mg/kg)**								26300	16500				60800	
07/15/94		mg Fe/L												
Influent--1 L composite	3670	14.7	7.72	21.5	1.35	3.41	3.52	5.52		164	415	176	0.68	261
Effluent--1 L composite			7.10	22.5	<0.05	0.7(<0.10)	<0.05	0.21(0.24)		23	40(30)	5	1.21	176
Mixed liquor--1 L inst.					<0.05	31.14	0.05	84.32		36	4199			308
Acetate test--Poly-P***								0.18 %						
Dewatered sludge(mg/kg)**								25200	16200				65400	

** mg/kg dry basis

*** g Poly-P released/g VSS (%)

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.12: Laboratory Results; Marieville

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L.	mg/L.	%	%	mg/L.	mg/L.	%	mg/L.	%	mg/L.	%	mg/L.	%	mg/L.	%	mg/L.	%
07/12/94																	
Influent--1 L composite	82.6	65.3	5.5	7.0	4.55	1.96	43.1	1.52	33.4	0.44	9.7	2.59	56.9	1.62	35.6	0.97	21.3
Effluent--1 L composite	10.7	10.7	1.7	1.7	0.18	0.03	13.9	0.03	13.9	0.00	0.0	0.16	86.1	0.04	19.4	0.12	66.7
Mixed liquor--1 L grab	4753.3	3046.7	2.0	3.1	93.30	0.12	0.1	0.06	0.1	0.06	0.1	93.18	99.9	33.29	35.7	59.89	64.2
Acetate test--Poly-P ***					0.14%												
Dewatered sludge(mg/kg)**	164200	91700			25900												
07/13/94																	
Influent--1 L composite	129.2	121.7	2.9	3.1	3.80	2.81	73.7	2.45	64.3	0.36	9.4	1.00	26.3	0.07	1.8	0.93	24.4
Effluent--1 L composite	6.0	6.0	3.2	3.2	0.19	0.12	63.2	0.05	26.3	0.07	36.8	0.07	36.8	0.07	36.8	0.00	0.0
Mixed liquor--1 L grab	5360.0	3780.0	2.0	2.8	106.29	0.13	0.1	0.09	0.1	0.04	0.0	106.16	99.9	51.88	48.8	54.28	51.1
Acetate test--Poly-P ***					0.15%												
Dewatered sludge(mg/kg)**	148600	44900			26300												
07/15/94																	
Influent--1 L composite	162.5	115.0	3.4	4.8	5.52	3.52	63.8	3.35	60.6	0.17	3.1	2.00	36.2	0.06	1.1	1.94	35.1
Effluent--1 L composite	12.0(<5)	10.0(<5)	1.8	2.1	0.21	0.03	11.9	0.03	11.9	0.00	0.0	0.19	88.1	0.05	21.4	0.14	66.7
Mixed liquor--1 L grab	4333.3	3000.0	1.9	2.8	84.32	0.05	0.1	0.03	0.0	0.03	0.0	84.27	99.9	31.12	36.9	53.16	63.0
Acetate test--Poly-P ***					0.18%												
Dewatered sludge(mg/kg)**	147800	83100			25200												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

*** g Poly-P released/g VSS (%)

Table A4.13: Laboratory Results; Châteauguay

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(sol)	BOD5(tot)	Al(tot)	Alkalinity
	m3/d	mg Al/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg O2/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/18/94															
Influent--1 L composite	35187	2.3	7.47	19.0								49	91	<0.20	
Effluent--1 L composite			7.17	19.0	0.35	0.47	0.37	0.56		16	22	<2	3	<0.20	194
Backwash sludge--1 L comp.***					0.24	7.17	0.30	14.85		21	484				237
Acetate test--Poly-P ##								0.02 %							
Dewatered sludge(mg/kg)**								28800	25100					46200	
07/19/94															
Influent--1 L composite	35566	2.5		18.0	0.45	0.96	0.54	1.67		12	114	16	27	<0.20	223
Effluent--1 L composite				19.5	0.18	0.32	0.21	0.54		10	24	4	4	<0.20	200
Backwash sludge--1 L inst.****					0.55	35.90	0.61	62.95		65	2254				311
Acetate test--Poly-P ##								0.03 %							
Dewatered sludge(mg/kg)**								30400	24300					39200	
07/20/94															
Influent--1 L composite	32285	2.6	7.44	18.6	0.91	1.08(1.2)	1.02	1.91(2.1)		30	105(171)	16	30	<0.20	219(165)
Effluent--1 L composite			7.46	19.2	0.19	0.31	0.17	0.48		17	30	4	5	<0.20	194
Backwash sludge--1 L inst.****					0.22	5.51	0.29	8.47		18	391				204
Dewatered sludge(mg/kg)**								33800	26500					40100	
07/21/94															
Influent--1 L composite	33258	2.4	7.71	18.4	0.86	1.00	1.01	1.79		28	100	19	33	<0.20	216
Effluent--1 L composite			7.76	18.9	0.18	0.35	0.21	0.54		15	26	4	6	<0.20	197
Dewatered sludge(mg/kg)**								31900	22000					33200	

** mg/kg dry basis

*** 6 grabs samples taken during the biofilter backwash cycle, combined and analyzed

**** grabs samples taken at the beginning of the biofilter backwash July 19, and towards the end of the backwash July 20

g Poly-P released/g VSS (%)

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.14: Laboratory Results; Châteauguay

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/18/94																	
Influent--1 L composite																	
Effluent--1 L composite	8.3	6.7	6.7	8.4	0.56	0.37	66.1	0.35	62.5	0.02	3.6	0.19	33.9	0.12	21.4	0.07	12.5
Backwash sludge--1 L comp.***	427.5	315.0	3.5	4.7	14.85	0.30	2.0	0.24	1.6	0.06	0.4	14.55	98.0	6.93	46.7	7.62	51.3
Acetate test--Poly-P ##					0.02%												
Dewatered sludge (mg/kg)**	352200	147800			28800												
07/19/94																	
Influent--1 L composite	56.7	55.0	2.9	3.0	1.67	0.54	32.3	0.45	26.9	0.09	5.4	1.13	67.7	0.51	30.5	0.62	37.1
Effluent--1 L composite	12.5	7.5	4.3	7.2	0.54	0.21	38.9	0.18	33.3	0.03	5.6	0.33	61.1	0.14	25.9	0.19	35.2
Backwash sludge--1 L grab****	2066.7	1506.7	3.0	4.2	62.95	0.61	1.0	0.55	0.9	0.06	0.1	62.34	99.0	35.35	56.2	26.99	42.9
Acetate test--Poly-P ##					0.03%												
Dewatered sludge(mg/kg)**	221600	94300			30400												
07/20/94																	
Influent--1 L composite	61.7(28)	52(24)	3.1	3.7	1.91	1.02	53.6	0.91	47.6	0.11	5.9	0.89	46.4	0.17	8.9	0.72	37.5
Effluent--1 L composite	14.0	8.7	3.4	5.5	0.48	0.19	39.6	0.19	39.6	0.00	0.0	0.29	60.4	0.12	25.0	0.17	35.4
Backwash sludge--1 L grab****	565.0	430.0	1.5	2.0	8.47	0.29	3.4	0.22	2.6	0.07	0.8	8.18	96.6	5.29	62.5	2.89	34.1
Dewatered sludge(mg/kg)**	365500	162500			33800												
07/21/94																	
Influent--1 L composite	60.5	48.5	3.0	3.7	1.79	1.01	56.4	0.86	48.0	0.15	8.4	0.78	43.6	0.14	7.8	0.64	35.8
Effluent--1 L composite	13.0	9.5	4.2	5.7	0.54	0.21	38.9	0.18	33.3	0.03	5.6	0.33	61.1	0.17	31.5	0.16	29.6
Dewatered sludge(mg/kg)**	284500	125600			31900												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

*** 6 grabs samples taken during the biofilter backwash cycle, combined and analyzed

**** grabs samples taken at the beginning of the biofilter backwash July 19, and towards the end of the backwash July 20

g Poly-P released/g VSS (%)

Table A4.15: Laboratory Results; Rigaud

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(sol)	COD(tot)	BOD5(sol)	BOD5(tot)	Fe(tot)	Alkalinity
	m3/d	mg Fe/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg CaCO3/L
07/25/94															
Influent--1 L grab	1845	4.8	7.50	20.0	13.54	13.91	13.97	15.75		508	816		380	0.68	373
Effluent--1 L grab			7.51	27.0	0.26	0.61	0.24	0.68		37	44		<2	2.00	258
Intermediate--1 L grab			7.67	26.5	2.46	2.82	2.36	2.85		41	87				277
07/26/94															
Influent--1 L composite	1814	4.8	7.47		0.52	3.21	0.43	3.60		98	283		76	0.63	339
Effluent--1 L grab					0.23	0.58	0.22	0.62		41	65		<2	1.90	253
Intermediate--1 L grab			7.44		2.28	2.85	2.21	2.94		60	117				272
Sedimented sludge(mg/kg)**								13700	9900					155500	
07/27/94															
Influent--1 L composite	1690	5.2	7.84		2.64	2.75	2.70	3.76		80	217(390)		77	0.44	360
Effluent--1 L grab			7.75		0.22	0.59	0.26	0.68		37	47		<5	2.10	256
Intermediate--1 L grab			7.72		2.27	2.50(2.70)	2.31	2.85		48	89				270
Sedimented sludge(mg/kg)**								36800	31500					259600	
10/25/94															
Influent--1 L composite	1512	5.8			3.50	4.00	3.60	5.10		130	420	130	380	0.78	380
Effluent--1 L grab				11.0	0.26	0.72	0.44	1.10		50	65	13	230	1.70	230
Intermediate--1 L grab				11.0	2.50	2.80	2.80	3.50		42	88	17	250	0.24	250
10/26/94															
Influent--1 L composite	1532	5.8			3.50	4.30	4.50	5.30		81	420	52	194	0.62	400
Effluent--1 L grab				11.0	0.33	1.10	1.00	1.90		15	65	9	19	1.70	230
Intermediate--1 L grab				11.0	2.50	3.20	2.80	3.50		15	96	13	20	0.10	250

** -composite of 7 samples of the bottom sludge in the third lagoon

-mg/kg dry basis

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.16: Laboratory Results; Rigaud

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/25/94																	
Influent--1 L grab	158.3	133.8	9.9	11.8	15.75	13.97	88.7	13.54	85.9	0.44	2.8	1.77	11.3	0.38	2.4	1.39	8.9
Effluent--1 L grab	15.0	4.3	4.5	15.8	0.68	0.26	38.2	0.26	38.2	0.00	0.0	0.42	61.8	0.35	51.5	0.07	10.3
Intermediate--1 L grab	38.3	30.5	7.4	9.3	2.85	2.46	86.3	2.46	86.3	0.00	0.0	0.39	13.7	0.36	12.6	0.03	1.1
07/26/94																	
Influent--1 L composite	112.9	92.4	3.2	3.9	3.60	0.52	14.4	0.52	14.4	0.00	0.0	3.08	85.6	2.69	74.7	0.39	10.8
Effluent--1 L grab	14.3	7.3	4.3	8.5	0.62	0.23	37.1	0.23	37.1	0.00	0.0	0.39	62.9	0.35	56.5	0.04	6.5
Intermediate--1 L grab	36.3	26.0	8.1	11.3	2.94	2.28	77.6	2.28	77.6	0.00	0.0	0.66	22.4	0.57	19.4	0.09	3.0
Sedimented sludge(mg/kg)**	67300	25000			13700												
07/27/94																	
Influent--1 L composite	91.3	80.0	4.1	4.7	3.76	2.70	71.7	2.64	70.1	0.06	1.6	1.06	28.3	0.11	2.9	0.95	25.3
Effluent--1 L grab	55.7	12.3	1.2	5.5	0.68	0.26	38.2	0.22	32.4	0.04	5.9	0.42	61.8	0.37	54.4	0.05	7.4
Intermediate--1 L grab	40.3	28.0	7.1	10.2	2.85	2.31	81.1	2.27	79.6	0.04	1.4	0.54	18.9	0.23	8.1	0.31	10.9
Sedimented sludge(mg/kg)**	27000	8700			36800												
10/25/94																	
Influent--1 L composite	168.0	143.0	3.0	3.6	5.10	3.60	70.6	3.50	68.6	0.10	2.0	1.50	29.4	0.50	9.8	1.00	19.6
Effluent--1 L grab	35.0	23.0	3.1	4.8	1.10	0.44	40.0	0.26	23.6	0.18	16.4	0.66	60.0	0.46	41.8	0.20	18.2
Intermediate--1 L grab	39.0	32.0	9.0	10.9	3.50	2.80	80.0	2.50	71.4	0.30	8.6	0.70	20.0	0.30	8.6	0.40	11.4
10/26/94																	
Influent--1 L composite	186.0	156.0	2.8	3.4	5.30	4.50	84.9	3.50	66.0	1.00	18.9	0.80	15.1	0.80	15.1	0.00	0.0
Effluent--1 L grab	50.0	36.0	3.8	5.3	1.90	1.00	52.6	0.33	17.4	0.67	35.3	0.90	47.4	0.90	47.4	0.00	0.0
Intermediate--1 L grab	46.0	36.0	7.6	9.7	3.50	2.80	80.0	2.50	71.4	0.30	8.6	0.70	20.0	0.70	20.0	0.00	0.0

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

** -composite of 7 samples of the bottom sludge in the third lagoon

Table A4.17: Laboratory Results; St-Georges

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(hyd)(F)	P(hyd)(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Al(tot)	Alkalinity
	m3/d			°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/11/94																
Influent--1 L composite	11645	Alum	7.56	17.0	0.85	1.30			1.11	2.39		49	200	50	1.00	124
Effluent--1 L composite		sludge	7.40	18.0	0.31	0.59			0.36	0.96		40	71	8	0.30	132
Mixed liquor--1 L inst.***					0.18	13.83			0.22	31.76		40	1923			161
Acetate test--Poly-P ##										0.23 %						
Sedimented sludge(mg/kg)**										20200	11100					
07/13/94																
Influent--1 L composite	15793	Alum	7.37	17.0	0.52(0.60)	0.92	0.16	0.59	0.70	2.00(1.80)		88	184(138)	39	1.60	122(123)
Effluent--1 L composite		sludge	7.63	17.5	0.18	0.23	0.03	0.08	0.24	0.39		61	72	3	<0.20	123
Mixed liquor--2 x 500 mL inst.***					0.15	20.84	0.04	19.50	0.22	48.67		69	2918			159
Acetate test--Poly-P ##										0.30 %						
07/15/94																
Influent--1 L composite	15670	Alum	6.92	17.0	0.80	1.22	0.00	0.76	0.89	1.87		68	201	63	2.90	121
Effluent--1 L composite		sludge	7.17	18.0	0.05	0.19	0.00	0.23	0.07	0.53		42	52	6	0.30	123
Mixed liquor--2 x 500 mL inst.****					0.32	17.48	0.02	16.85	0.36	43.06		54	2586			172
Acetate test--Poly-P ##										0.32 %						
Sedimented sludge(07/14)(mg/kg)**										20100	10600				28200	
Dewatered sludge(07/15)(mg/kg)**										20900	11400				27500	

** mg/kg dry basis

*** sample taken after 2 000 seconds of a 7 200 second mixing cycle had elapsed

*** sample taken after 3 000 seconds of a 7 200 second mixing cycle had elapsed

g Poly-P released/g VSS(%)

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.18: Laboratory Results; St-Georges

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/11/94																	
Influent--1 L composite	123.8	74.6	1.9	3.2	2.39	1.11	46.6	0.85	35.5	0.27	11.1	1.28	53.4	0.45	18.9	0.83	34.6
Effluent--1 L composite	28.0	19.7	3.4	4.9	0.96	0.36	37.2	0.31	32.3	0.05	4.9	0.60	62.8	0.28	29.2	0.32	33.6
Mixed liquor--1 L grab***	1866.7	1143.3	1.7	2.8	31.76	0.22	0.7	0.18	0.6	0.04	0.1	31.53	99.3	13.65	43.0	17.88	56.3
Acetate test--Poly-P ##					0,23%												
Sedimented sludge(mg/kg)**	12200	6700			20200												
07/13/94																	
Influent--1 L composite	97,9(84)	64.1(27)	2.0	3.1	2.00	0.70	35.2	0.52	26.0	0.18	9.2	1.30	64.8	0.92	46.0	0.38	18.8
Effluent--1 L composite	10.0	10.0	3.9	3.9	0.39	0.24	61.5	0.18	46.2	0.06	15.4	0.15	38.5	0.05	12.8	0.10	25.6
Mixed liquor--2 x 500 mL grab***	2740.0	1790.0	1.8	2.7	48.67	0.22	0.5	0.15	0.3	0.07	0.1	48.45	99.5	20.69	42.5	27.76	57.0
Acetate test--Poly-P ##					0.30%												
07/15/94																	
Influent--1 L composite	108.0	70.1	1.7	2.7	1.87	0.89	47.5	0.80	42.6	0.09	4.9	0.98	52.5	0.43	23.0	0.55	29.4
Effluent--1 L composite	23.0	15.0	2.3	3.5	0.53	0.07	13.2	0.05	9.4	0.02	3.8	0.46	86.8	0.14	26.4	0.32	60.4
Mixed liquor--2 x .5 L grab****	2500.0	1550.0	1.7	2.8	43.06	0.36	0.8	0.32	0.7	0.04	0.1	42.70	99.2	17.16	39.9	25.54	59.3
Acetate test--Poly-P ##					0.32%												
Sedimented sludge(mg/kg)**	10600	6000			20100												
Dewatered sludge(mg/kg)**	184400	95300			20900												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

*** sample taken after 2 000 seconds of a 7 200 second mixing cycle had elapsed

**** sample taken after 3 000 seconds of a 7 200 second mixing cycle had elapsed

g Poly-P released/g VSS (%)

Table A4.19: Laboratory Results; Haute-Bécancour

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg)	COD(F)	COD(N-F)	BOD5(tot)	Fe(tot)	Alkalinity
	m3/d	mg Fe/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/12/94														
Influent--1 L composite	25568	3.5	7.84	14.0	1.09	1.15	1.19	1.76		39	64	28	0.21	235
Effluent--1 L composite			7.36		0.05	0.31	0.09	0.52		48	56	8	1.87	223
Mixed liquor--1 L inst.							0.17	13.40		53	1236			235
07/13/94														
Influent--1 L composite	22011	4.1	7.36		1.06	1.13	1.22	1.79		76	180	19	0.31	234
Effluent--1 L composite			7.18		<0.05	0.22	0.07	0.44		74	95	8	1.76	214
Mixed liquor--1 L inst.					0.22	4.21	0.23	9.72		79	1167			234
Acetate test--Poly-P***								0.03 %						
Sedimented sludge(mg/kg)**								9500	5300				31500	
07/15/94														
Influent--1 L composite	20079	4.5	7.76	14.5	1.09(1.10)	1.19	1.21	1.98(1.70)		50(60)	149	42	0.38	121
Effluent--1 L composite			7.13	15.0	<0.05	0.14	<0.05	0.40		32	50	6	2.00	123
Mixed liquor--1 L inst.					0.06	9.12	0.14	18.39		38	1968			172
Acetate test--Poly-P***								0.01 %						
Sedimented sludge(mg/kg)**								10000	7100				34200	

** mg/kg dry basis

*** g Poly-P released/g VSS (%)

Note: Figures in brackets correspond to quality control performed by Proserco for McGill University

Table A4.20: Laboratory Results; Haute-Bécancour

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/12/94																	
Influent--1 L composite	51.4	44.3	3.4	4.0	1.76	1.19	67.6	1.09	61.8	0.10	5.9	0.57	32.4	0.06	3.4	0.51	29.0
Effluent--1 L composite	15.5	15.0	3.4	3.5	0.52	0.09	17.3	0.05	9.6	0.04	7.7	0.43	82.7	0.26	50.0	0.17	32.7
Mixed liquor--1 L grab	1220.0	765.0	1.1	1.8	13.40	0.17	1.3					13.23	98.7				
07/13/94																	
Influent--1 L composite	87.1	64.1	2.1	2.8	1.79	1.22	68.2	1.06	59.2	0.16	8.9	0.57	31.8	0.07	3.9	0.50	27.9
Effluent--1 L composite	14.5	14.5	3.0	3.0	0.44	0.07	15.9	0.03	5.7	0.05	10.2	0.37	84.1	0.23	51.1	0.15	33.0
Mixed liquor--1 L grab	991.3	587.5	1.0	1.7	9.72	0.23	2.4	0.22	2.3	0.01	0.1	9.49	97.6	3.99	41.0	5.50	56.6
Acetate test--Poly-P					0.03%												
Sedimented sludge(mg/kg)**	15700	7400			9500												
07/15/94																	
Influent--1 L composite	75.0(48.0)	58.6(37.0)	2.6	3.4	1.98	1.21	61.1	1.09	55.1	0.12	6.1	0.77	38.9	0.10	5.1	0.67	33.8
Effluent--1 L composite	13.5	12.0	3.0	3.3	0.40	0.03	6.3	0.03	6.3	0.00	0.0	0.38	93.8	0.12	30.0	0.26	63.8
Mixed liquor--1 L grab	2250.0	1350.0	0.8	1.4	18.39	0.14	0.8	0.06	0.3	0.08	0.4	18.25	99.2	9.06	49.3	9.19	50.0
Acetate test--Poly-P					0.01%												
Sedimented sludge(mg/kg)**	16900	8500			10000												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

Table A4.21: Laboratory Results; Mont-St-Grégoire

Sample	Flow	Dose	pH	Temp	Ortho(F)	Ortho(N-F)	P(tot)(F)	P(tot)(N-F)	P(inorg.)	COD(F)	COD(N-F)	BOD5(tot)	Al(tot)	Alkalinity
	m3/d	mg Al/L		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg CaCO3/L
07/25/94														
Influent--1 L composite	112	8.2	7.88	20.5	3.28	4.04(4.20)	3.51	5.36(6.00)		114(51)	319	75	1.00	357
Effluent--1 L composite			7.41	21.5	0.41	2.18	0.43	2.53		25	77	7	1.60	201
Intermediate--1 L composite			7.66	22.0	1.56	2.92	1.64	3.41		41	145			314
Sedimented sludge(mg/kg)**								40600	30900				38400	
07/26/94														
Influent--1 L grab	182	8.2	7.98		2.71	3.02	2.71	3.39		57	127	63	<0.20	360
Effluent--1 L composite			7.25		0.53	2.57	0.53	2.97		28	85	11	2.10	221
Intermediate--1 L composite			7.64		1.87	2.86	1.75	3.33		57	133			328
Sedimented sludge(mg/kg)**								40500	31700				39600	
07/27/94														
Influent--1 L composite	183	8.2	7.82		6.16	6.95	6.32	8.77		149	429	71	0.70	382
Effluent--1 L composite			7.54		0.95	2.84	0.99	3.43		37	89	5	1.80	242
Intermediate--1 L composite			7.76		2.79	3.69	2.87	4.62		55	127			348
Sedimented sludge(mg/kg)**								42000	30600				39300	

** mg/kg dry basis

Note: Figures in brackets correspond to quality control performed b [illegible] oserco for McGill University

Table A4.22: Laboratory Results; Mont-St-Grégoire

Sample	TSS*	VSS*	P-tot/TSS	P-tot/VSS	P-TOTAL	SOLUBLE PHOSPHORUS						PARTICULATE PHOSPHORUS					
						Total		Ortho		Non-Ortho		Total		Ortho		Non-Ortho	
	mg/L	mg/L	%	%	mg/L	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%	mg/L	%
07/25/94																	
Influent--1 L composite	162.9	108.4	3.3	4.9	5.36	3.51	65.5	3.28	61.3	0.22	4.2	2.08	38.7	0.76	14.2	1.32	24.5
Effluent--1 L composite	51.3	41.3	4.9	6.1	2.53	0.43	17.0	0.41	16.2	0.02	0.8	2.10	83.0	1.77	70.0	0.33	13.0
Intermediate--1 L composite	88.3	58.0	3.9	5.9	3.41	1.64	48.1	1.56	45.8	0.08	2.3	1.77	51.9	1.36	39.9	0.41	11.9
Sedimented sludge(mg/kg)**	45100	27300			40600												
07/26/94																	
Influent--1 L grab	44.7	37.8	7.6	9.0	3.39	2.71	80.0	2.71	80.0	0.00	0.0	0.68	20.0	0.31	9.2	0.37	10.8
Effluent--1 L composite	61.2	36.2	4.9	8.2	2.97	0.53	17.9	0.53	17.9	0.00	0.0	2.44	82.1	2.04	68.7	0.40	13.4
Intermediate--1 L composite	74.2	54.3	4.5	6.1	3.33	1.87	56.2	1.87	56.2	0.00	0.0	1.46	43.8	0.99	29.8	0.47	14.0
Sedimented sludge(mg/kg)**	44500	26850			40500												
07/27/94																	
Influent--1 L composite	183.3	132.0	4.8	6.6	8.77	6.32	72.1	6.16	70.2	0.16	1.9	2.61	29.8	0.79	9.0	1.82	20.8
Effluent--1 L composite	54.9	33.0	6.2	10.4	3.43	0.99	28.9	0.95	27.7	0.04	1.2	2.44	71.1	1.89	55.1	0.55	16.0
Intermediate--1 L composite	73.2	52.4	6.3	8.8	4.62	2.87	62.0	2.79	60.5	0.07	1.5	1.75	38.0	0.90	19.5	0.85	18.5
Sedimented sludge(mg/kg)**	44500	26600			42000												

* TS and TVS instead of TSS and VSS for the sludge

** mg/kg (dry basis) except for TS and TVS

APPENDIX B

COMPUTER PROGRAMS

Disclaimer

These computer models are based on a summary model and are non-exhaustive. They were not developed for the purpose of design and should not be used for this. At no time shall Dessau Inc. be held responsible for results or decisions taken from the use of this model or these programs, except when used during work on "Volet 1 and 2" of the project "Déphosphatation des eaux usées au Québec".

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Primary Clarifier - Alum

BILAN DE MASSE: CLARIFICATEUR PRIMAIRE-ALUN

AFFLUENT À TRAITER

Données:

Débit (m^3/d)	15298	
	mg/L	kg/d
MES	80.6	1233
MVES	79.3	1213
DBO5(T)	30.0	459
DBO5(S)	29.0	444
P total	3.4	53

% de P soluble	59
% de P particulaire	41
% de P ortho dans la fraction soluble	97
% de P non-ortho dans la fraction soluble	4
% de P ortho dans la fraction particulaire	14
% de P non-ortho dans la fraction particulaire	86

0.78	=MVES(D)/MVES	0.56	=MIES(D)/MIES
0.22	=MVES(ND)/MVES	0.44	=MIES(ND)/MIES

Sommaire: affluent à traiter

	kg/d	mg/L
MVES(D)	946	61.9
MVES(ND)	267	17.4
MIES(D)	11	0.7
MIES(ND)	9	0.6
MES	1233	80.6
MVES	1213	79.3
DBO5(T)	459	30.0
DBO5(S)	444	29.0
DBO5(P)	15	1.0
P total	53	3.44
P soluble	31	2.02
P particulaire	22	1.42
P soluble ortho	30	1.95
P soluble non-ortho	1	0.07
P particulaire ortho	3	0.20
P particulaire non-ortho	19	1.22

FLOCULATEUR

Données:

	Al	P
Rapport molaire Al/P total (dosage non-stoechiométrique) à l'affluent du floculateur:	2.0	1
% de P particulaire non-ortho --> P soluble ortho	10	
% de P soluble ortho qui réagit avec Al :	93	
% de P soluble ortho qui ne réagit pas avec Al:	7	
% de P soluble non-ortho qui est adsorbé:	58	
% d'alun en excès qui réagit avec l'alcalinité:	84	

Phosphore qui réagit (mg P/L):	1.9

Dosage d'alun:

mg Al/L	6.1
mg alun/L	67.0
kg alun/d	1,025

Boues d'alun produites:

Quantité de AlPO4 formée (mg/L):	7.6
(kg/d):	116
Quantité de Al(OH)3 formée (mg/L):	10.7
(kg/d):	163
Boues d'alun totales formées (mg/L):	18.2
(kg/d):	279

DÉCANTATION:

Données:

-% décantation des MVES(D):	90
-% décantation des MVES(ND):	18
-% décantation des MIES(D):	90
-% décantation des MIES(ND):	15
-% décantation des boues chimiques:	92
-% décantation de DBO5(P):	82
-% décantation de P particulaire ortho	60
-% décantation de P particulaire non-ortho	48
-% décantation de DBO5(S):	46

-Siccité des boues décantées (%)	3
-% de P particulaire non-ortho (effluent)-->P sol ortho (effluent)	0

Calcul de l'efficacité du décanteur:

		MES	Enlèvement	
		kg/d	%	kg/d
MES affluent	MVES(D)	946	90	852
	MVES(ND)	267	18	48
	MIES(D)	11	90	10
	MIES(ND)	9	15	1
	Total:	1233	74	911
MES boues chimiques:		279	92	257
Total:		1512	77	1168

L'efficacité du décanteur est de	77 %

Boues du décanteur:

Débit Q (m^3/d)		39
	kg/d	mg/L
MES	1168	30000.0
MVES	900	23111.1
DBO5 (T)	218	5598.9
DBO5(S)	205	5276.6
DBO5(P)	13	322.2
P soluble	0	0.0
P Particulaire	38	988.5
P particulaire ortho	29	743.5
P particulaire non-ortho	10	245.0
P total	38	988.5

Effluent du décanteur:

Débit Q (m^3/d)		15259
	kg/d	mg/L
MES	344	22.6
MVES	313	20.5
DBO5 (T)	241	15.8
DBO5 (S)	238	15.6
DBO5(P)	3	0.2
P soluble	3	0.18
P soluble ortho	2	0.15
P soluble non-ortho	0	0.03
P particulaire	11	0.75
P particulaire ortho	4	0.23
P particulaire non-ortho	8	0.52
P total	14	0.93

Primary Clarifier - $FeCl_3$

BILAN DE MASSE: CLARIFICATEUR PRIMAIRE-FeCl3

AFFLUENT À TRAITER

Données:

Débit (m^3/d)	2130630	
	mg/L	kg/d
MES	118.7	252906
MVES	94.0	200279
DBO5(T)	79.0	168320
DBO5(S)	47.4	100992
P total	2.15	4581

% de P soluble	36
% de P particulaire	64
% de P ortho dans la fraction soluble	65
% de P non-ortho dans la fraction soluble	35
% de P ortho dans la fraction particulaire	8
% de P non-ortho dans la fraction particulaire	92

0.87	=MVES(D)/MVES	0.72	=MIES(D)/MIES
0.13	=MVES(ND)/MVES	0.28	=MIES(ND)/MIES

Sommaire: affluent à traiter

	kg/d	mg/L
MVES(D)	174243	81.8
MVES(ND)	26036	12.2
MIES(D)	37891	17.8
MIES(ND)	14735	6.9
MES	252906	118.7
MVES	200279	94.0
DBO5(T)	168320	79.0
DBO5(S)	100992	47.4
DBO5(P)	67328	31.6
P total	4581	2.2
P soluble	1631	0.8
P particulaire	2950	1.4
P soluble ortho	1058	0.5
P soluble non-ortho	572	0.3
P particulaire ortho	236	0.1
P particulaire non-ortho	2714	1.3

FLOCULATEUR

Données:

	Fe	P
Rapport molaire Fe/P total (dosage non-stoechiométrique) à l'affluent du floculateur:	2.8	1
% de P particulaire non-ortho --> P soluble ortho	10	
% de P soluble ortho qui réagit avec Fe :	94	
% de P soluble ortho qui ne réagit pas avec Fe:	6	
% de P soluble non-ortho qui est adsorbé:	52	
% de FeCl3 en excès qui réagit avec l'alcalinité:	77	

Phosphore qui réagit (mg P/L):	0.59

Dosage de FeCl3:

mg Fe/L	11.0
mg FeCl3/L	31.9
kg FeCl3/d	67,890

Boues de FeCl3 produites:

Quantité de FePO4 précipitée	(mg/L):	2.9
	(kg/d):	6,104
Quantité de Fe(OH)3 précipitée	(mg/L):	14.6
	(kg/d):	31,118
Boues de Fer totales formées	(mg/L):	17.5
	(kg/d):	37,222

DÉCANTATION:

Données:

-% décantation des MVES(D):	90
-% décantation des MVES(ND):	35
-% décantation des MIES(D):	95
-% décantation des MIES(ND):	30
-% décantation des boues chimiques:	75
-% décantation de DBO5(P):	90
-% décantation de P particulaire ortho	60
-% décantation de P particulaire non-ortho	68
-% décantation de DBO5(S):	75

-Siccité des boues décantées (%)	3.0
-% de P particulaire non-ortho (effluent)-->P sol ortho (effluent)	0.0

Calcul de l'efficacité du décanteur:

		MES	Enlèvement	
		kg/d	%	kg/d
MES affluent	MVES(D)	174243	90	156819
	MVES(ND)	26036	35	9113
	MIES(D)	37891	95	35997
	MIES(ND)	14735	30	4421
	Total:	252906	82	206349
MES boues chimiques:		37222	75	27917
Total:		290128	81	234265

L'efficacité du décanteur est de 81 %

Boues du décanteur:

Débit Q (m^3/d)		7809
	kg/d	mg/L
MES	234265	30000.0
MVES	165931	21249.2
DBO5 (T)	136339	17459.6
DBO5(S)	75744	9699.8
DBO5(P)	60595	7759.8
P soluble	0	0.0
P Particulaire	3151	403.5
P particulaire ortho	1082	138.6
P particulaire non-ortho	2069	264.9
P total	3151	403.5

Effluent du décanteur:

Débit Q (m^3/d)		2122821
	kg/d	mg/L
MES	55863	26.3
MVES	34348	16.2
DBO5 (T)	31981	15.1
DBO5 (S)	25248	11.9
DBO5(P)	6733	3.17
P soluble	351	0.17
P soluble ortho	76	0.04
P soluble non-ortho	275	0.13
P particulaire	1079	0.51
P particulaire ortho	408	0.19
P particulaire non-ortho	672	0.32
P total	1430	0.67

Activated Sludge - Alum

BILAN DE MASSE: BOUES ACTIVÉES-ALUN

EFFLUENT DÉSIRÉ

	mg/L	kg/d
MES	13.2	106
MVES	11.4	91
DBO5(T)	3.5	28

AFFLUENT À TRAITER

Données:

Débit (m^3/d)	8000	
	mg/L	kg/d
MES	113.0	904
MVES	79.0	632
DBO5(T)	51.0	408
P total	2.2	17

% de P soluble	57
% de P particulaire	43
% de P ortho dans la fraction soluble	83
% de P non-ortho dans la fraction soluble	17
% de P ortho dans la fraction particulaire	9
% de P non-ortho dans la fraction particulaire	91

Conditions de départ:

Charges provenant du système de traitement des boues	%
(exprimées en pourcentage des charges à l'affluent)	5.0

	Affluent (kg/d)	Traitement des boues (kg/d)	Total (kg/d)	Total (mg/L)
MES	904	45	949	119
MVES	632	32	664	83
DBO5(T)	408	20	428	54
P total	17.4	0.9	18.2	2.28
P soluble	10.0	0.5	10.5	1.31
P particulaire	7.4	0.4	7.8	0.97
P soluble ortho	8.3	0.4	8.7	1.09
P soluble non-ortho	1.7	0.1	1.8	0.22
P particulaire ortho	0.7	0.0	0.7	0.09
P particulaire non-ortho	6.7	0.3	7.1	0.88

CALCUL DES BOUES BIOLOGIQUES

Données:

Volume du bassin d'aération (m^3)	1500.0
Concentration des MES dans la liqueur mixte (mg/L) *	5500.0
Coefficient de biomasse Y **	0.80
Coefficient de respiration endogène Kd (d^-1) ***	0.025

notes:

* Concentration des MES dans la liqueur mixte sans ajout de coagulants

** Y = kg MVES produites/kg DBO5(T) enlevées
Valeurs typiques Y: 0.4-0.8 (le plus souvent utilisé: 0.5)

*** Valeurs typiques Kd: 0.025-0.075 (le plus souvent utilisé: 0.06)

Quantité de MVES produites(net) (kg/d)	176.1
Quantité de MIES enlevées (kg/d)	271.2
Quantité de boues "biologiques" produites (kg/d)	447.3

MVES dans la liqueur mixte (mg/L)	3845.1
Temps de rétention (hr)	4.50
F/M (d^-1)	0.08
Age des boues (d)	18.44

Phosphore au point de dosage chimique:

	kg/d	mg/L
P total	11.8	1.48
P soluble	4.1	0.51
P soluble ortho	3.4	0.42
P soluble non-ortho	0.7	0.09
P particulaire	7.8	0.97
P particulaire ortho	0.7	0.09
P particulaire non-ortho	7.1	0.88

CALCUL DES BOUES CHIMIQUES

Données:

	Al	P
Rapport molaire Al/P total (dosage non-stoechiométrique) au point de dosage chimique:	1.9	1
% de P particulaire non-ortho --> P soluble ortho	20	
% de P soluble ortho qui réagit avec Al :	95	
% de P soluble ortho qui ne réagit pas avec Al:	5	
% de P soluble non-ortho qui est adsorbé:	80	
% d'alun en excès qui réagit avec l'alcalinité:	100	

Phosphore qui réagit (mg P/L):	0.6

Dosage d'alun:

mg Al/L	2.5
mg alun/L	27.3
kg alun/d	219

Boues d'alun produites:

Quantité de AlPO4 formée (mg/L):	2.2
(kg/d):	18
Quantité de Al(OH)3 formée (mg/L):	5.7
(kg/d):	46
Boues d'alun totales formées (mg/L):	8.0
(kg/d):	64

DÉCANTATION:

Boues chimiques produites (kg/d)	64
Boues "biologiques" produites (kg/d)	447
Total des boues produites (kg/d)	511

Boues "biologiques" volatiles produites (kg/d)	313

MES liqueur mixte (mg/L)	6284.5

Message:
OK : MES liqueur mixte < 6500 mg/L

% décantation des MES (calculé)	99.79
% décantation des boues chimiques	95
% décantation de P part Ortho	40
% décantation de P part Non-Ortho	70

% de P particulaire non-ortho --> P soluble ortho	10

Effluent du décanteur:

	kg/d	mg/L
MES	105.6	13.20
MVES	91.2	11.40
DBO5(T)	28.0	3.50
P total	1.3	0.17
P soluble	0.4	0.05
P soluble ortho	0.2	0.03
P soluble non-ortho	0.1	0.02
P particulaire	1.0	0.12
P particulaire ortho	0.2	0.03
P particulaire non-ortho	0.7	0.09

Activated Sludge - $Fe_2(SO_4)_3$

BILAN DE MASSE: BOUES ACTIVÉES-SULFATE FERRIQUE

EFFLUENT DÉSIRÉ

	mg/L	kg/d
MES	10.0	340
MVES	9.0	306
DBO5(T)	4.0	136

AFFLUENT À TRAITER

Données:

Débit (m^3/d)	34000	
	mg/L	kg/d
MES	95.0	3230
MVES	75.0	2550
DBO5(T)	54.0	1836
P total	3.4	116

% de P soluble	55
% de P particulaire	45
% de P ortho dans la fraction soluble	76
% de P non-ortho dans la fraction soluble	24
% de P ortho dans la fraction particulaire	29
% de P non-ortho dans la fraction particulaire	71

Conditions de départ:

Charges provenant du système de traitement des boues	%
(exprimées en pourcentage des charges à l'affluent)	5.0

	Affluent (kg/d)	Traitement des boues (kg/d)	Total (kg/d)	Total (mg/L)
MES	3230	162	3392	100
MVES	2550	128	2678	79
DBO5(T)	1836	92	1928	57
P total	115.6	5.8	121.4	3.57
P soluble	63.6	3.2	66.8	1.96
P particulaire	52.0	2.6	54.6	1.61
P soluble ortho	48.3	2.4	50.7	1.49
P soluble non-ortho	15.3	0.8	16.0	0.47
P particulaire ortho	15.1	0.8	15.8	0.47
P particulaire non-ortho	36.9	1.8	38.8	1.14

CALCUL DES BOUES BIOLOGIQUES

Données:

Volume du bassin d'aération (m^3)	14000.0
Concentration des MES dans la liqueur mixte (mg/L) *	5600.0
Coefficient de biomasse Y **	0.90
Coefficient de respiration endogène Kd (d^-1) ***	0.010

notes:

* Concentration des MES dans la liqueur mixte sans ajout de coagulants

** Y = kg MVES produites/kg DBO5(T) enlevées
Valeurs typiques Y: 0.4-0.8 (le plus souvent utilisé: 0.5)

*** Valeurs typiques Kd: 0.025-0.075 (le plus souvent utilisé: 0.06)

Quantité de MVES produites(nette) (kg/d)	993.7
Quantité de MIES enlevées (kg/d)	680.0
Quantité de boues "biologiques" produites (kg/d)	1673.7

MVES dans la liqueur mixte (mg/L)	4421.1
Temps de rétention (hr)	9.88
F/M (d^-1)	0.03
Age des boues (d)	46.84

Phosphore au point de dosage chimique:

	kg/d	mg/L
P total	89.1	2.62
P soluble	34.5	1.01
P soluble ortho	26.2	0.77
P soluble non-ortho	8.3	0.24
P particulaire	54.6	1.61
P particulaire ortho	15.8	0.47
P particulaire non-ortho	38.8	1.14

CALCUL DES BOUES CHIMIQUES

Données:

	Fe	P
Rapport molaire Fe/P total (dosage non-stoechiométrique) au point de dosage chimique:	0.6	1
% de P particulaire non-ortho --> P soluble ortho	20	
% de P soluble ortho qui réagit avec Fe :	82	
% de P soluble ortho qui ne réagit pas avec Fe :	18	
% de P soluble non-ortho qui est adsorbé:	95	
% de $Fe_2(SO_4)_3$ en excès qui réagit avec l'alcalinité:	100	

Phosphore qui réagit (mg P/L):	0.8

Dosage de sulfate ferrique:

mg Fe/L	3.0
mg sulfate ferrique/L	9.9
kg sulfate ferrique/d	335

Boues de $Fe_2(SO_4)_3$ produites:

Quantité de $FePO_4$ formée	(mg/L):	4.0
	(kg/d):	136
Quantité de $Fe(OH)_3$ formée	(mg/L):	2.9
	(kg/d):	98
Boues de sulfate ferrique totales formées	(mg/L):	6.9
	(kg/d):	233

DÉCANTATION:

Boues chimiques produites (kg/d)	233
Boues "biologiques" produites (kg/d)	1,674
Total des boues produites (kg/d)	1,907

Boues "biologiques" volatiles produites (kg/d)	1,321

MES liqueur mixte (mg/L)	6380.6

Message:
OK : MES liqueur mixte < 6500 mg/L

% décantation des MES (calculé)	99.84
% décantation des boues chimiques	95
% décantation de P part Ortho	40
% décantation de P part Non-Ortho	70

% de P particulaire non-ortho --> P soluble ortho	10

Effluent du décanteur:

	kg/d	mg/L
MES	340.0	10.0
MVES	306.0	9.0
DBO5(T)	136.0	4.0
P total	11.3	0.33
P soluble	5.6	0.16
P soluble ortho	5.1	0.15
P soluble non-ortho	0.4	0.01
P particulaire	5.7	0.17
P particulaire ortho	1.4	0.04
P particulaire non-ortho	4.3	0.13

Biofiltration - Alum

BILAN DE MASSE: BIOFILTRE-ALUN

AFFLUENT À TRAITER

Débit (m^3/d)	33000	
	mg/L	kg/d
MES	102.0	3366
MVES	82.0	2706
DBO5(T)	108.0	3564
DBO5(S)	64.8	2138
P total	2.30	76

AFFLUENT AU DÉCANTEUR PRIMAIRE (INCLUANT RECIRCULATION DES BOUES)

Débit (m^3/d)	35475	
	mg/L	kg/d
MES	199.5	7079
MVES	134.9	4785
DBO5(T)	159.4	5655
DBO5(S)	95.7	3393
P total	3.12	111

% de P soluble	50
% de P particulaire	50
% de P ortho dans la fraction soluble	80
% de P non-ortho dans la fraction soluble	20
% de P ortho dans la fraction particulaire	35
% de P non-ortho dans la fraction particulaire	65

0.80	=MVES(D)/MVES	0.88	=MIES(D)/MIES
0.20	=MVES(ND)/MVES	0.12	=MIES(ND)/MIES

Sommaire: affluent au décanteur primaire

	kg/d	mg/L
MVES(D)	3828	107.9
MVES(ND)	957	27.0
MIES(D)	2018	56.9
MIES(ND)	275	7.8
MES	7079	199.5
MVES	4785	134.9
DBO5(T)	5655	159.4
DBO5(S)	3393	95.7
DBO5(P)	2262	63.8
P total	111	3.12
P soluble	55	1.56
P particulaire	55	1.56
P soluble ortho	44	1.25
P soluble non-ortho	11	0.31
P particulaire ortho	19	0.55
P particulaire non-ortho	36	1.01

FLOCULATEUR

Données:

	Al	P
Rapport molaire Al/P total (dosage non-stoechiométrique) à l'affluent du décanteur.	1.0	1
% de P particulaire non-ortho --> P soluble ortho	10	
% de P soluble ortho qui réagit avec Al :	72	
% de P soluble ortho qui ne réagit pas avec Al:	28	
% de P soluble non-ortho qui est adsorbé:	65	
% d'alun en excès qui réagit avec l'alcalinité:	96	

Phosphore qui réagit (mg P/L):	1.0

Dosage d'alun:

mg Al/L	2.8
mg alun/L	31.1
kg alun/d	1,103

Boues d'alun produites:

Quantité de AlPO4 formée (mg/L):	3.8
(kg/d):	135
Quantité de Al(OH)3 formée (mg/L):	5.5
(kg/d):	195
Boues d'alun totales formées (mg/L):	9.3
(kg/d):	330

DÉCANTEUR PRIMAIRE

Données:

-% décantation des MVES(D):	90
-% décantation des MVES(ND):	18
-% décantation des MIES(D):	90
-% décantation des MIES(ND):	32
-% décantation des boues chimiques:	73
-% décantation de DBO5(P):	82
-% décantation de P particulaire ortho	43
-% décantation de P particulaire non-ortho	11
-% décantation de DBO5(S):	46

-Siccité des boues décantées (%)	3
-% de P particulaire non-ortho (effluent)-->P sol ortho (effluent)	0

Calcul de l'efficacité du décanteur primaire:

		MES	Enlèvement	
		kg/d	%	kg/d
MES affluent	MVES(D)	3828	90	3445
	MVES(ND)	957	18	172
	MIES(D)	2018	90	1816
	MIES(ND)	275	32	88
	Total:	7079	78	5522
MES boues chimiques:		330	73	241
Total:		7409	78	5763

L'efficacité du décanteur est de	78 %

Boues du décanteur primaire:

Débit Q (m^3/d)		192
	kg/d	mg/L
MES	5763	30000.0
MVES	3617	18831.1
DBO5 (T)	3426	17834.6
DBO5(S)	1571	8178.3
DBO5(P)	1855	9656.2
P soluble	0	0.0
P Particulaire	43	222.0
P particulaire ortho	33	174.1
P particulaire non-ortho	9	47.9
P total	43	222.0

Effluent du décanteur primaire:

Débit Q (m^3/d)		35283
	kg/d	mg/L
MES	1646	46.6
MVES	1168	33.1
DBO5 (T)	2229	63.2
DBO5 (S)	1822	51.6
DBO5(P)	407	11.5
P soluble	17	0.49
P soluble ortho	13	0.38
P soluble non-ortho	4	0.11
P particulaire	51	1.44
P particulaire ortho	20	0.58
P particulaire non-ortho	30	0.86
P total	68	1.92

BIOFILTRES

Affluent des biofiltres:

Débit Q (m^3/d):	35283	
	(mg/L)	(kg/d)
MES :	46.6	1646
MVES :	33.1	1168
DBO5 (T) :	63.2	2229
DBO5 (P) :	11.5	407
DBO5 (S) :	51.6	1822
P total:	1.92	68
P sol-O:	0.38	13
P sol-N.O.:	0.11	4
P part-O:	0.58	20
P part-N.O.:	0.86	30

Données:

Nombre de filtres:	12
Superficie d'un lit filtrant (m^2):	49.0
Volume d'un lit filtrant (m^3):	98.00
Volume de boues produites par lavage(m^3/m^3 lit filtrant):	5.1
Capacité de rétention d'un filtre avant lavage (kg MES/m^3 lit filtrant):	2.9
% en DBO5 (P) dans les MVES (B) des boues:	95
Coefficient A *	0.75
Coefficient B *	0.43

notes:

* MVES(boues de lavage) = A (MVES affluent - MVES effluent)
+ B (DBO5 affluent - DBO5 effluent)

Les coefficients obtenus lors d'essais-pilotes aux stations d'épuration de la CUQ sont :
A = 0,75 et B = 0,43.

Nombre de lavages/jour de chaque filtre (théorique):	0.531
Durée du cycle d'opération avant de débuter un lavage (d):	1.884

Vitesse de filtration (m^3/m^2-h) :	2.50
Charge massique (kg MES/m^3-d) :	1.40
Charge massique (kg DBO5(T)/m^3-d) :	1.90
Charge massique (kg DBO5(S)/m^3-d) :	1.55

Volume total des boues de lavage des biofiltres de tous les filtres en prenant le nombre théorique de lavages/jour par filtre:	3184

Boues de lavage des biofiltres

Débit Q (m^3/d):	3184	
	(kg/d)	(mg/L)
MES :	1810	568.6
MVES (B) :	1426	447.9
DBO5 (T) :	1426	447.9
DBO5 (P) :	1355	425.5
DBO5 (S) :	71	22.4

Effluent des biofiltres

Débit Q (m^3/d):	32099	
	(kg/d)	(mg/L)
MES :	322	10.0
MVES (B) :	229	7.1
DBO5 (T) :	182	5.7
DBO5 (P) :	38	1.2
DBO5 (S) :	144	4.5
P total:	17.4	0.54
P sol-O:	5.8	0.18
P sol-N.O.:	1.7	0.05
P part-O:	4.0	0.12
P part-N.O.:	5.9	0.19

Aerated Lagoons - $Fe_2(SO_4)_3$

BILAN DE MASSE: ÉTANGS AÉRÉS-SULFATE FERRIQUE

AFFLUENT À TRAITER

Données:

Débit (m^3/d)	1800
Température de l'affluent aux étangs (C)	20.0
Température de l'atmosphère (C)	25.0

	mg/L	kg/d
MES	120.0	216
MVES	100.0	180
DBO5(T)	77.0	139
P total	3.7	7

% de P soluble	76
% de P particulaire	24
% de P ortho dans la fraction soluble	95
% de P non-ortho dans la fraction soluble	5
% de P ortho dans la fraction particulaire	50
% de P non-ortho dans la fraction particulaire	50

Sommaire: affluent à traiter

	kg/d	mg/L
MES	216.0	120.0
MVES	180.0	100.0
DBO5(T)	138.6	77.0
P total	6.7	3.70
P soluble	5.1	2.81
P particulaire	1.6	0.89
P soluble ortho	4.8	2.67
P soluble non-ortho	0.3	0.14
P particulaire ortho	0.8	0.44
P particulaire non-ortho	0.8	0.44

LES ÉTANGS AÉRÉS

Données:

Taux d'enlèvement K de la DBO5 @ 20 C (d^-1):	0.37
Coefficient de biomasse Y:	0.50

Note: Y = kg MVES produites/kg DBO5 enlevées
valeurs typiques Y: 0.4-0.8

Etang no.	Volume (m^3)	Profondeur (m)	tr (d)	Superficie (m^2)	Temp. (C)	K = f(temp) (d^ -1)
1	18000	4.0	10.0	4500	22.8	0.45
2	18000	4.0	10.0	4500	24.0	0.48
3	18000	4.0	10.0	4500	24.5	0.50
4	0	0.0	NA	NA	NA	NA
Total:	54000		30.0	13500		

Note: s'il n'y a pas 4 étangs, inscrire "0" dans les cases ombrées correspondantes

-% enlèvement de P particulaire ortho avant dosage	10
-% enlèvement de P particulaire non-ortho avant dosage	10

Conditions au point de dosage chimique:

	kg/d	mg/L
MES	282.7	157.1
MVES	246.7	137.1
DBO5(T)	5.2	2.9
P total	5.2	2.87
P soluble	3.7	2.07
P particulaire	1.4	0.80
P soluble ortho	3.5	1.97
P soluble non-ortho	0.2	0.10
P particulaire ortho	0.7	0.40
P particulaire non-ortho	0.7	0.40

ADDITION DE Fe2(SO4)3 ET CALCUL DES BOUES CHIMIQUES

Données:

	Fe	P
Rapport molaire Fe/P total (dosage non-stoechiométrique)à l'affluent de l'avant-dernier étang	1.0	1
% de P particulaire non-ortho --> P soluble ortho	20	
% de P soluble ortho qui réagit avec Fe :	85	
% de P soluble ortho qui ne réagit pas avec Fe:	15	
% de P soluble non-ortho qui est adsorbé:	0	
% de Fe2(SO4)3 en excès qui réagit avec l'alcalinité:	0	

Phosphore qui réagit (mg P/L):	1.7

Dosage de Fe2(SO4)3

mg Fe/L	5.0
mg Fe2(SO4)3/L	33.3
kg Fe2(SO4)3/d	59.9

Boues de fer produites:

Quantité de FePO4 précipitée (mg/L):	8.5
(kg/d):	15
Quantité de Fe(OH)3 précipitée (mg/L):	0.0
(kg/d):	0
Boues totales de fer formées (mg/L):	8.5
(kg/d):	15

EFFLUENT

Données:

-% enlèvement des MES non-chimiques pour les 4 étangs	90
-% enlèvement des MES chimiques du dernier étang	90
-% enlèvement de P particulaire ortho du dernier étang	50
-% enlèvement de P particulaire non-ortho du dernier étang	50

-% P particulaire non-ortho (effluent)-->P soluble ortho (effluent)	20

Effluent du dernier étang:

Débit Q (m^3/d)		1800
	kg/d	mg/L
MES	30.0	16.7
MVES	24.9	13.8
DBO5 (T)	0.9	0.5
P soluble	0.7	0.41
P soluble ortho	0.6	0.31
P soluble non-ortho	0.2	0.10
P particulaire	0.8	0.47
P particulaire ortho	0.7	0.37
P particulaire non-ortho	0.2	0.10
P total	1.6	0.88