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Development of Prediction Models for Chemical Phosphorus Removal

Volume II

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These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Fisheries and Environment Canada, and the Ontario Ministry of Environment, and contracts with municipalities, research institutions and industrial organizations.

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DEVELOPMENT OF PREDICTION MODELS FOR CHEMICAL PHOSPHORUS REMOVAL
VOLUME II

by

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RESEARCH PROGRAM FOR THE ABATEMENT
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ABSTRACT

In Volume 1 of this report, results of Canada-Ontario phosphorus removal treatability studies were summarized and regression equations for predicting chemical requirements for phosphorus removal based on influent phosphorus levels were developed.

The second phase of the study, as reported herein, was carried out to determine whether improved prediction equations could be derived by considering several wastewater characteristics, in addition to influent phosphorus. To this end, a multi-parameter jar testing program was carried out on 20 different raw municipal wastewaters. A wastewater strength index (WSI) was developed which was used to rank and classify wastewaters by simultaneously considering six common parameters (hardness, total phosphorus, suspended solids, total alkalinity, conductivity and total organic carbon). Multiple regression relationships, expressing alum, iron salt and lime dosages as a function of raw wastewater characteristics were derived for three wastewater strength (weak, medium, strong) categories.

The equations obtained for lime were inconsistent and had little predictive value. However, a good linear regression relationship between alkalinity and lime required to reach a given pH was developed. Jar tests, in conjunction with such a relationship, remain the best way to estimate lime requirement for a given wastewater.

The predictive value of the Al and Fe equations was somewhat better than that of the simpler equations developed in the first phase of the study, based on the influent phosphorus concentration only (i.e., ± 20% compared to = ± 30%). However, this degree of improvement would not warrant the extra time and expense normally required for sample collection and analysis for several wastewater characteristics. Unless the additional information required for these equations is readily available, the simpler equations developed in Volume 1 should be used to assist in the selection of the chemical and dosage for full scale application.

RÉSUMÉ

Dans le premier volume du présent rapport, nous avons résumé les résultats des études conjointes Canada-Ontario sur la maniabilité du procédé de déphosphatation. On y trouve également des équations de régression élaborées en vue de prévoir la dose de produits chimiques requis pour la déphosphatation en fonction de la teneur en phosphore des effluents à l'arrivée.

La deuxième étape, commentée ici, vise à préciser la valeur prévisionnelle des équations en tenant compte, en plus, de différents paramètres des eaux usées en outre des taux de phosphore à l'arrivée. A cette fin, une série de tests en éprouvettes, avec 20 types d'eaux brutes urbaines, a servi à établir l'indice de concentration des eaux usées (I.C.E.U.). Elles ont ensuite été classées en fonction de six paramètres communs (dureté, phosphore total, matières en suspension, alcalinité totale, conductivité et carbone organique total). Des équations de régression multiple exprimant les doses d'alun, de sel ferreux et de chaux, en fonction des caractéristiques des eaux à traiter, ont été élaborées à partir de trois degrés de concentration des eaux usées (faible, moyen et fort).

Les équations obtenues pour la chaux étaient inconséquentes et n'avaient que peu de valeur prévisionnelle. Par contre, on a réussi à déterminer une régression linéaire valable entre l'alcalinité et la dose de chaux requise pour obtenir un pH donné. Des tests en éprouvette, conjugués avec une telle relation, constituent le meilleur moyen d'évaluer les besoins en chaux d'un type donné d'eau usée.

La valeur prévisionnelle des équations pour l'Al et le Fe était quelque peu supérieure à celle des équations plus simples de la première étape de notre étude s'appuyant seulement sur le taux de phosphore à l'arrivée (par exemple, ~ ± 20 p. 100 comparativement à± 30 p. 100). Toutefois, cette amélioration ne justifie pas les fonds et le temps additionnels d'échantillonnage et d'analyse pour déterminer différentes caractéristiques des eaux usées. A moins que les données supplémentaires qu'exigent ces équations ne soient immédiatement accessibles, il y a avantage à utiliser celles du volume I, qui sont plus simples, pour choisir les produits chimiques et des doses à utiliser à l'échelle urbaine.

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Data collected from a multi-parameter jar test program carried out on 20 different raw municipal wastewaters were statistically analyzed and a methodology was derived for predicting chemical dosage requirements for phosphorus removal. Major features of the methodology included:

(i) Derivation of a wastewater strength index (WS!) which was capable of classifying wastewaters by simultaneously considering six commonly measured parameters (hardness, total phosphorus, alkalinity, suspended solids, conductivity and total organic carbon).

(ii) Wastewaters with a WSI less than 8 were classified as weak; wastewaters with a WSI between 8 and 10 were classified as medium strength and those with a WSI greater than 10 were classified as strong.

(iii) Cluster analyses of the wastewaters confirmed that the WSI classification system was representative.

(iv) Multiple regression equations, derived for the three wastewater strength categories relating alum and iron salt dosages to selected wastewater characteristics, were statistically significant and capable of predicting actual chemical dosage requirements to within approximately ± 20%.

(v) Multiple regression equation values obtained for lime dosage requirements were inconsistent and had little predictive value. However, a strong correlation between alkalinity and amount of lime required to reach a given pH was developed.

The major conclusion of this study was:

The predictive value of the Al and Fe equations developed in this part of the study was somewhat better than that of the equations developed in Volume 1 (Prested *et al* , 1977), (i.e., ± 20% compared to = ± 30%). However, this degree of improvement does not warrant the extra time and expense normally required for sample collection and analysis for several wastewater characteristics. Unless the additional information required for these equations is readily available, the simpler equations developed in Volume I should be used to assist in the selection of the proper chemical and dosage for full scale testing.

1 BACKGROUND AND STUDY OBJECTIVES

1.1 Background

The Canada-Ontario Agreement on Great Lakes Water Quality (Prince and Bruce, 1972) stipulated that phosphorus be removed at all municipal wastewater treatment plants in the Lake Erie watershed by 1974, and in the Lake Ontario watershed, by 1976. Over 200 primary and secondary treatment plants in these watersheds were involved and will have full scale phosphorus removal facilities operational by the completion of the program. An integral part of the Canada-Ontario Agreement was a two-phase treatability study program administered by the Ontario Ministry of the Environment. To determine the optimum chemical and dosage, individual jar test and full scale studies were carried out at each treatment facility. Van Fleet (1972) has provided complete details on the treatability study program.

During this program, a great deal of data was collected from the jar test and full scale treatability studies and a data bank has been established at the Wastewater Technology Centre of the Environmental Protection Service in Burlington. A review and analysis of these data was described by Prested *et al* (1977).Using this large data base, simple and useful regression equations relating Al^{3+} and Fe^{3+} dosage requirements to influent wastewater phosphorus levels were derived. A summary of the equations developed in Volume 1 is presented in Table 1.

Other models for phosphorus removal have been proposed by numerous investigators [e.g., Schmid (1968), Pöpel (1971), Ferguson and King (1974), Menar and Jenkins (1970) and Black and Veatch (1971)]. The utility of all these models for predicting optimum chemical dosage for a particular wastewater is limited, in that they do not account for all the influencing variables and they usually have a very narrow range of application. Even the equations derived from the large data base in Volume 1 of this study [Prested *et al* , 1977] were capable of predicting chemical dosage to only ±30% of the actual full scale requirement. It was hoped that this error could be further reduced by categorizing wastewaters according to their strength and developing regression equations based on several wastewater characteristics (instead of only influent phosphorus concentration as in Volume 1).

TABLE 1. Summary Of Regression Relationships Between Chemical Requirements And Influent Wastewater Phosphorus Levels (Prested *et al* 1977).

Chemical		Raw Wastewater Addition	Mixed Liquor Addition
Iron* (mg/L as Fe^{3+})	Jar Test Data **	Fe^{3+} = 2.8 +3.3 (TP) -- (1) r = 0.653 n = 71	Fe^{3+} =2.4 + 3.8 (TP)-- (3) r= 0.650 *n* = 57
	Full Scale Data **	Insufficient data for regression n = 7	Fe^{3+}=0.5 +1.4 (TP) -- (5) r = 0.689 n =15
Alum (mg/L as Al^{3+})	Jar Test Data **	Al^{3+} = 0.6 + 2.4 (TP)-- (2) r = 0.689 n= 72	Al^{3+}= 1.5 +2.2(TP)--- (4) r = 0.553 n= 57
	Full Scale Data **	Insufficient data for regression n = 5	Al^{3+} =-0.3 +1.3 (TP) -- (6) r =0.642 n =15

* Iron was added as $FeCl_3$ except at two plants where pickle liquor was used.
** To achieve 1 mg/L TP.
TP = Average Total Phosphorus (mg/L as P) in the raw wastewater when chemical added to raw wastewater.
= Average Total Phosphorus (mg/L as P) in the secondary when chemical added to mixed liquor.
r = Correlation coefficient (the r's for ail equations are significant at the 95% confidence level).
n = Number of observations,

1.2 Study Objectives

The overall objective of this part of the study was to derive regression equations for predicting chemical requirements based on several wastewater characteristics and to compare their predictive value with the simpler equations developed in Volume 1. This information would be useful for future treatability studies and, at best, eliminate the need for jar testing and/or full scale treatability studies. Specific objectives included:

(i) Determination of, in a statistical sense, the significant wastewater variables that influence alum, ferric chloride and lime, phosphorus removal systems.

(ii) Development of a wastewater strength index (WSI) capable of describing the concept of wastewater strength on a continuous numerical scale and an investigation of the relationship between the index and chemical phosphorus removal requirements.

(iii) Development of a method for classifying wastewaters into different strength (weak, medium, strong) categories.

(iv) Development and testing of the predictive capabilities of regression relationships between chemical dosages required for phosphorus removal and wastewater characteristics.

2. STUDY METHODOLOGY

A flow chart depicting the project methodology is shown in Figure 1. Briefly, the study consisted of carrying out multi-parameter wastewater characterizations and jar testing on 20 different raw municipal wastewaters. The resultant data were then compiled and statistically analyzed to formulate predictive models for chemical phosphorus removal. Each phase of the project methodology is described in the following sections.

2.1 Selection of Wastewaters

Twenty representative municipal wastewaters in the Province of Ontario (see listing in Table 2 and Figure 2 for locations) were selected for the multi-parameter studies. Criteria used in selecting the municipalities include:

(i) The sample size must be large enough so that statistically significant relationships can be derived.
(ii) Wastewater strengths should range from strictly domestic to domestic with heavy industrial influence.
(iii) Wastewaters should be representative of the geographically different water supply regions.
(iv) Treatment plants ranging from <4,550 to 818,100 m^3/d (<1.0 to 180 mgd) should be represented.

2.2 Wastewater Characterization and Jar Testing

At each of the 20 municipal wastewater treatment plants, 10 separate jar test runs were conducted over a five-day period. One run was carried out in mid-morning and the other in the afternoon of each day on 25-litre grab samples of the raw degritted wastewater. Each wastewater sample was characterized with respect to the 26 parameters shown in Table 3. Some critical analyses were performed in the field, whereas the remainder were carried out on samples that were transported to the Wastewater Technology Centre laboratory. Most analyses were done in accordance with Standard Methods (APHA *et al*,1971).

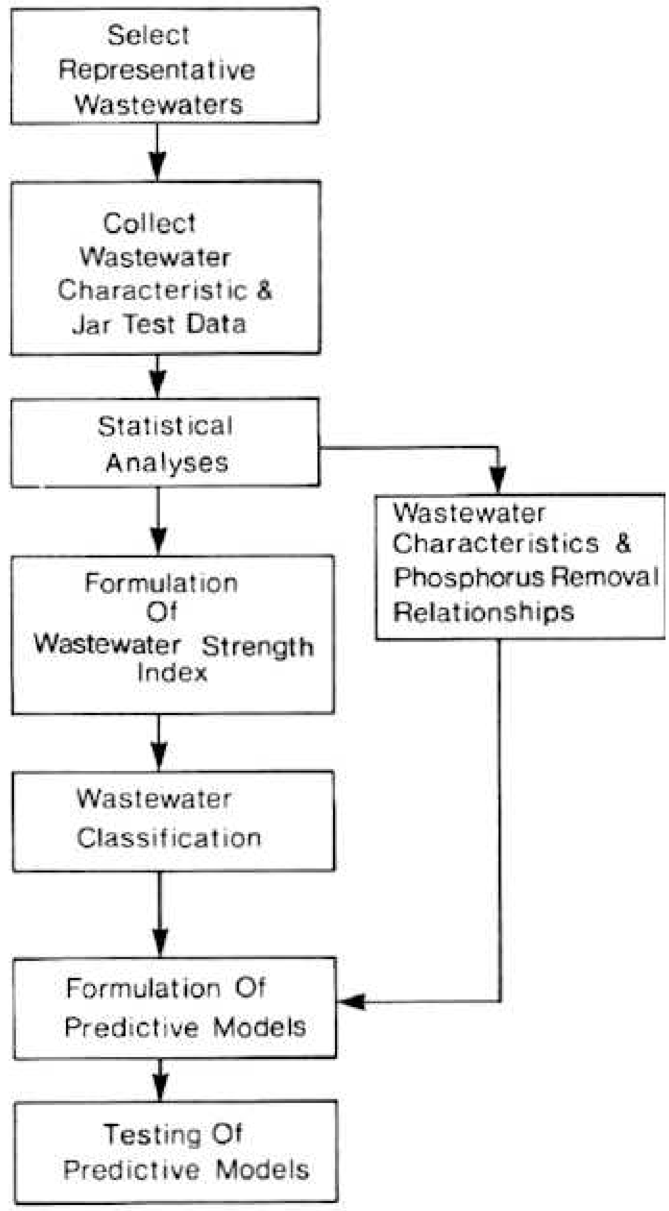

FIG.1. Flow Chart Of Project Methodology.

TABLE 2. Municipalities Selected For Multi-Parameter Studies.

Location	Plant Type	Industrial Influence	Size Water (mgd)	Supply
Burlington Skyway	Ext. Aeration	Medium	9.0	Lake Ontario
Burlington Drury Lane	Act. Sludge	Light	2.5	Lake Ontario
C.F.B. Borden	Primary	None	1.5	Wells
Chatham	Act. Sludge	Medium	4.5	Lake St. Clair
Guelph	Act. Sludge	Medium	1.5	Wells
Hamilton	Act. Sludge	Heavy	80.0	Lake Ontario
Kitchener	Act. Sludge	Medium	13.5	Wells
London Greenway	Act. Sludge	Medium	18.0	Lake St. Clair
Midland	Primary	Light	1.3	Wells
Mississauga Lakeview	Act. Sludge	Heavy	10.0	Lake Ontario
C.F.B. Petawawa	Primary	None	1.6	Ottawa River
Point Edward	Primary	None	0.6	St. Clair River
Preston	Act. Sludge	Heavy	1.8	Wells
Oakville--Southeast	Act. Sludge	Light	2.0	Lake Ontario
Ottawa--Greens Creek	Primary	Light	40.0	Ottawa River
Sarnia	Primary	Light	8.0	St. Clair River
Toronto -- Highland Creek	Act. Sludge	Medium	16.0	Lake Ontario
Toronto--Main	Act. Sludge	Heavy	180.0	Lake Ontario
Waterloo	Act. Sludge	Medium	6.0	Wells
Windsor--West	Primary	Medium	25.0	Detroit River

* mgd x 4545 = m^3/d.

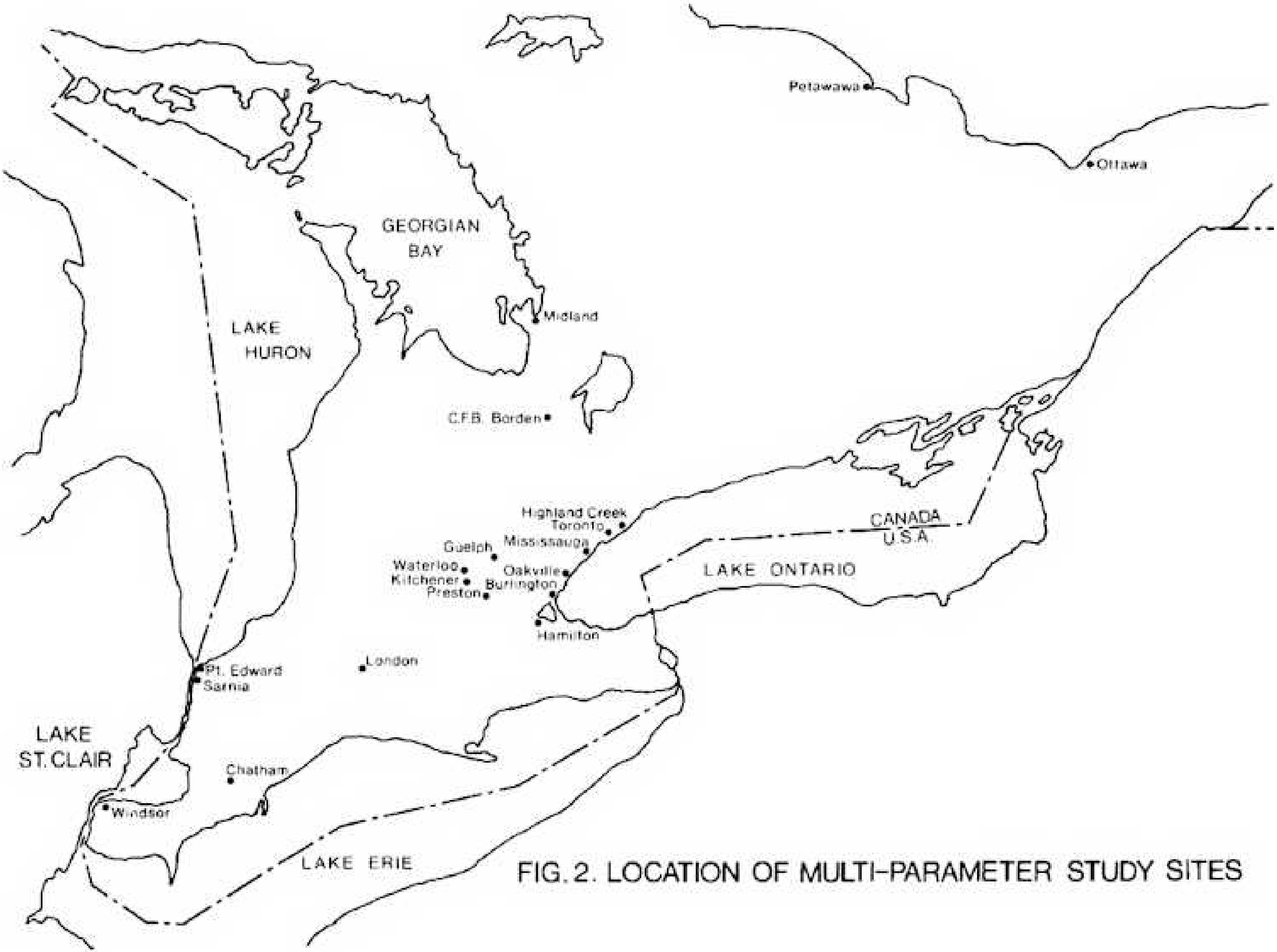

FIG. 2. LOCATION OF MULTI-PARAMETER STUDY SITES

TABLE 3. Wastewater Characteristics Measured During Multi-Parameter Studies.

Characteristic	Comments		
	Field	Lab.	Calculated
Total Hardness	*		
Calcium	*		
Magnesium			✔
Sodium		†	
Potassium		†	
Fluoride		†	
Total Aluminum	filtered	†	
Soluble Aluminum	filtered	†	
Total Iron		†	
Soluble Iron	filtered	†	
Total Phosphorus		†	
Soluble Phosphorus	filtered	†	
Ortho Phosphorus	*		
Suspended Solids		†	
Total Dissolved Solids		†	
Sulphate		†	
Chloride		†	
Dissolved Reactive Silica	filtered	†	
Turbidity	*		
Total Organic Carbon	acidified	†	
Hydroxyl Alkalinity			✔
Carbonate Alkalinity			✔
Bicarbonate Alkalinity			✔
Total Alkalinity	*		
Carbon Dioxide			✔
pH	*		
Temperature	*		

* Analyses performed at the field site.
† Analyses performed in the WTC laboratory.
✔ Values determined by calculation.

Turbidity measurements were carried out with a Hach Turbidimeter. Metals, silica, cations and anions were analyzed according to Traversy (1971). Soluble aluminum, iron and phosphorus were measured on a filtered (0.45 µ) sample. Fluoride was measured with an Orion specific ion electrode. Carbon dioxide and alkalinity values were calculated from total alkalinity, pH, temperature and dissolved solids data. Total organic carbon analyses were substituted for the more common, but time consuming, BOD_5 analyses.

Three sets of jar tests were carried out simultaneously on each wastewater sample (one each for ferric chloride, alum and lime). Chemical dosages for ferric chloride and alum were 0, 5, 10, 15, 20 and 30 mg/L as Fe^{3+} and Al^{3+} and for lime 0, 25, 50, 100, 150 and 200 mg/L as Ca^{2+}. The jar test procedures were:

(i) Addition of chemicals to one litre aliquots of the wastewater.
(ii) Rapid mixing at 100 rpm for five minutes.
(iii) Twenty minutes flocculation at 40 rpm.
(iv) Ninety minutes settling at 10 rpm followed by five minutes quiescent settling.
(v) Supernatant decanting and analysis for total and soluble phosphorus and pH.

2.3 Statistical Methods

Jar test data were plotted for each chemical in each run and the chemical dosage required to achieve a 1 mg/L residual total phosphorus was extrapolated for the plot. These data, together with the wastewater characteristic data, were coded for computer analysis. An example of a complete data set is shown in Table 4. The data were then examined to eliminate any values which did not fall within ± three standard deviations of the mean for the particular parameter of interest. Once outliers were eliminated a new mean and standard deviation were calculated. The mean values from each of the twenty studies (Appendix A) comprised the basic data set for subsequent statistical analyses and model derivations.

TABLE 4. A Typical Multi-Parameter Data Set.

			Multi-Parameter Study No.1 Burlington Skyway Treatment Plant													
RUN	HARD	Ca	Mg	Na	K	F	Al-TOT	Al -DISS	Fe-TOT	Fe-DISS	TP	DP	Ortho -P	SS	TDS	pH
1	280.0	184.0	86.0	62.0	6.6	0.64	1.00	0.050	0.29	0.120	2.60	0.70	1.30	142.0	786.0	7.70
2	204.0	152.0	52.0	191.0	8.6	0.74	8.25	0.090	1.81	0.080	7.20	0.60	0.82	438.0	946.0	7.80
3	270.0	192.0	78.0	81.0	7.1	0.49	1.90	0.030	0.93	0.050	2.10	1.20	2.10	154.0	610.0	7.83
4	200.0	154.0	46.0	89.0	8.3	0.80	0.50	0.030	0.65	0.110	4.70	3.10	2.48	374.0	670.0	7.70
5	268.0	212.0	54.0	133.0	7.1	0.45	5.40	0.135	1.21	0.070	1.50	0.05	0.13	202.0	790.0	7.52
6	208.0	156.0	52.0	152.0	8.2	0.70	3.22	0.040	1.07	0.090	5.30	2.70	1.85	180.0	804.0	7.98
7	276.0	194.0	80.0	100.0	7.3	0.60	3.12	0.050	0.84	0.050	2.10	1.10	1.46	96.0	656.0	7.96
8	216.0	152.0	64.0	126.0	8.2	0.65	2.58	0.040	0.91	0.090	3.90	1.70	1.70	170.0	714.0	7.85
9	236.0	150.0	86.0	93.0	9.6	0.72	1.80	0.050	1.82	0.140	6.00	4.30	4.30	202.0	578.0	7.72
10	220.0	168.0	52.0	98.0	10.4	0.59	1.50	0.050	1.25	0.470	6.10	4.20	4.20	138.0	618.0	7.60
Mean	237.8	172.4	65.0	112.5	8.1	0.64	2.93	0.057	1.08	0.127	4.23	1.97	2.03	209.6	717.2	7.77
Std Dev	32.4	23.2	15.9	38.2	1.2	0.11	2.33	0.032	0.40	0.124	2.10	1.52	1.34	109.3	113.0	0.15

TABLE 4 (Continued)

RUN	ALK-TOTAL	SO_4	Cl	Si	TURB	COND	TEMP	TOC	ALK - OH	ALK - CARB	ALK-BICARB	CO_2	Fe DOSE	Al DOSE	Ca DOSE
1	214.0	90.0	86.3	2.9	35.0	0.75	16.5	19.3	0.015	1.05	212.9	2.26	2.0	1.2	8.0
2	216.0	340.0	107.5	6.2	100.0	1.16	17.0	14.5	0.019	1.32	214.7	7.33	6.0	1.2	0.0
3	220.0	110.5	97.5	2.9	45.0	0.83	17.0	12.2	0.020	1.47	218.5	7.14	3.3	1.3	10.0
4	244.0	83.5	113.0	4.7	52.0	0.71	17.5	14.5	0.016	1.21	242.8	10.65	16.0	7.8	48.0
5	190.0	322.5	102.0	3.0	28.0	1.04	17.0	13.6	0.010	0.62	189.4	12.45	0.0	0.0	0.0
6	244.0	305.0	100.5	4.1	80.0	1.01	17.5	25.8	0.030	2.27	241.7	5.51	12.5	6.0	110.0
7	254.0	280.0	100.0	3.0	34.0	0.90	18.0	14.0	0.030	2.28	251.7	6.07	1.1	1.4	0.0
8	242.0	101.0	122.5	3.0	55.0	0.98	18.0	36.8	0.023	1.68	240.3	7.43	6.5	3.0	116.0
9	314.0	80.5	109.0	5.2	44.0	0.89	17.0	51.0	0.016	1.64	312.3	13.18	18.3	10.0	150.0
10	322.0	78.5	108.5	5.7	52.0	0.93	19.0	54.3	0.014	1.27	320.7	17.78	33.0	10.0	113.0
Mean	246.0	179.1	104.7	4.1	52.5	0.92	17.4	25.6	0.019	1.48	244.5	8.98	9.9	4.2	55.6
Std Dev	42.5	115.6	9.8	1.3	22.1	0.14	0.7	16.1	0.007	0.52	42.3	4.52	10.3	3.9	60.0

All values as mg/L except conductivity(mmho/cm); turbidity (FTU) and pH.
All alkalinities, hardness, calcium and magnesium are in mg/L as $CaCO_3$. However, note that Ca DOSE is the lime dosage as Ca^{2+}.

Three multi-variable statistical methods were employed in the data analyses. Details on each method are provided in Appendix B. Each of the three was used for a specific purpose. Briefly, they may be described as:

(i) Cluster analysis: to form wastewater groups with similar characteristics.

(ii) Principal component analysis: to formulate a wastewater strength index (WSI) from wastewater characteristics data.

(iii) Stepwise regression analysis: to derive relationships (Models) between wastewater characteristics and chemical requirements for phosphorus removal.

These statistical methods have been applied in various other fields. An application similar to that in this study has been presented by Shannon and Brezonik (1972) who investigated the statistical relationship between lake water quality and watershed land-use conditions.

3. RESULTS AND DISCUSSION

3.1 General

This study was of an analytical nature. Basic jar test and wastewater characteristic data were compiled (Appendix A) for twenty different raw municipal wastewaters. Multi-variable procedures were then employed to analyze these data to:

(i) formulate a wastewater strength index;

(ii) develop a wastewater classification system; and

(iii) develop regression models relating chemical phosphorus removal requirements to wastewater characteristics.

Because a large number of statistical analyses were undertaken, to present all the results here would be confusing and also beyond the scope of this report. The methodology shown in Figure 1 was followed for several combinations of variables, including all variables, at one extreme, down to only four variables, at the other. The best result from the standpoint of practicality (e.g., using a few easily measured parameters), which at the same time provided significant statistical relationships, was achieved for the combination of the following variables:

(i) hardness;

(ii) total phosphorus;

(iii) suspended solids;

(iv) total alkalinity;

(v) conductivity; and

(vi) total organic carbon.

Results for these six variables are presented in the following sections.

3.2 Formulation of a Wastewater Strength Index (WSI)

The first principal component extracted from the correlation matrix of the six wastewater characteristics (Table 5) was designated as the Wastewater Strength Index (WSI).

TABLE 5. Means, Standard Deviations And Correlation Matrix For The Six Wastewater Characteristics Used In The WSI*.

Means and Standard Deviations

Parameter	Mean	Standard Deviation
Hardness (mg/L as $CaCO_3$)	256.7	90.5
Total Phosphorus (mg/L as P)	6.5	3.5
Suspended Solids (mg/L)	149.3	65.1
Alkalinity(mg/L as $CaCO_3$)	240.8	80.1
Conductivity (mmho/cm)	0.9	0.4
TOC (mg/L)	50.0	21.9

Correlation Matrix

	Hardness	Total P	SS	Alkalinity	Cond.	TOC
Hardness	1.000	0.406	0.358	0.759	0.660	0.385
Total P		1.000	0.350	0.322	0.136	0.511
SS			1.000	0.567	0.394	0.529
Alkalinity				1.000	0.821	0.337
Conductivity					1.000	0.335
TOC						1.000

* For 20 Ontario wastewater treatment plants (Appendix A).

This principal component is simply a linear combination of the six characteristics with a weighting factor placed on each characteristic. The first principal component explained 50% of the variation in the correlation matrix. The weighting factors cannot be interpreted directly as a measure of the relative importance of the particular characteristic since the values in parenthesis [see Equation (7)] are standardized values (i.e., the actual raw data value of the characteristic minus its mean value and divided by its standard deviation). The appropriate means and standard deviations for standardizing the six variables are also shown in Table 5. A constant has been added to the principal component so that the WSI would always be greater than zero. This constant was derived by substituting zero values for all six parameters into the principal component (i.e., a hypothetical pure water with zero ions, SS or organics). The resultant WSI is presented in Equation (7) as:

$$\begin{aligned} WSI = {} & 0.77\ (\text{Hardness})^{*} + 0.57\ (\text{Total P})^{*} + 0.60\ (\text{SS})^{*} \\ & + 0.86\ (\text{Alkalinity})^{*} + 0.79\ (\text{Cond})^{*} + 0.63\ (\text{TOC})^{*} + 9.29 \end{aligned} \qquad (7)$$

Table 6 summarized a typical WSI calculation using the Borden wastewater for illustration. Raw values consisting of the mean of a particular parameter for 10 grab samples are obtained from Appendix A for the location under consideration. The mean values and standard deviations as shown in Table 5 refer to the particular parameter of all 20 waste treatment plants studied (Appendix A). The standardized value is then calculated as the difference between raw and mean value divided by the standard deviation. The sum of each standardized value multiplied by its appropriate component coefficient, as shown in equation (7) plus the equation constant of 9.29 is the WSI. In this example, for Borden the WSI is 6.87 (or =6.9).

Similarly, the WSI for the remaining 19 wastewaters was calculated using equation (7) from the data in Appendix A. The wastewaters ranked according to their WSI are shown in Table 7.

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* Standardized values.

TABLE 6. Example Calculation For The WSI for CFB Borden.

Wastewater † Characteristics	Raw Value (Borden Appendix A)	Mean Value (Table 5)	Standard † Deviation (Table 5)	Standardized Value	WSI Calculation	
				Raw - Mean / Standard Deviation	Component Coefficients	Component Contribution
Hardness	190.2	256.7	90.5	-0.74	0.77	-0.57
Total P	4.76	6.5	3.5	-0.50	0.57	-0.29
SS	127.7	149.3	65.1	-0.33	0.60	-0.20
Alkalinity	240.2	240.8	80.1	-0.01	0.86	-0.01
Conductivity	0.48	0.9	0.4	-1.05	0.79	-0.83
TOC	31.8	50.0	121.9	-0.83	0.63	-0.52
					Constant	+9.29
					WSI	+6.87*

* See Table 7.

† Absolute value of standard deviation.

† All units are expressed As mg/L, except conductivity(millimho/cm).

TABLE 7. Twenty Wastewaters Ranked According to the WSI.

Wastewater	WSI	Cluster Group	(Figure 3)
C.F.B. Petawawa	3.0	-	
Ottawa– Greens Creek	6.1	Weak	Weak Group
Windsor	6.3	Weak	used in
Sarnia	6.3	Weak	Regression
Oakville– Southeast	7.3	Medium	Analyses
C.F.B. Borden	6.9	Weak	
Hamilton	8.0	Weak	
Toronto--Main	8.3	Weak	
Burlington- Drury Lane	8.6	Medium	Medium Group
Burlington- Skyway	8.7	Medium	used in
Midland	8.9	Medium	Regression
Point Edward	9.0	Weak	Analyses
Toronto– Highland Creek	9.2	Medium	
Mississauga– Lakeview	10.7	Medium	
London– Greenway	11.9	Medium	Strong Group
Guelph	12.3	Medium	used in
Chatham	12.5	Medium	Regression
Waterloo	12.8	Medium	Analyses
Preston	14.6	Strong	
Kitchener	15.1	Strong	

The ranking in Table 7 is an arrangement of the wastewaters from the weakest (Petawawa) to the strongest (Kitchener), considering the six variables simultaneously. The inclusion of additional variables did not change the ranking. Probably a seasonal change in wastewater characteristics (e.g., infiltration during spring) could change a wastewater's relative rank. However, the relative range of the wastewaters, based on their average characteristics (over one year), would probably not change significantly from that in Table 7.

3.3 Wastewater Classification

Another step in the study involved the determination of wastewater groups with similar characteristics. This was accomplished by performing Q-type cluster analyses (Appendix B) on the six wastewater characteristics. The results of a cluster analysis are generally expressed in a dendrogram (or clustering diagram) showing the manner in which the objects (wastewaters) were joined. The dendrogram for the six wastewater parameters is shown in Figure 3. In the clustering procedure, wastewaters with the greatest similarity are joined first. The scale on the abscissa of the dendrogram is a measure of relative similarity. The smaller the value at which a junction is made between the wastewaters (or groups) the more similar they are.

The wastewaters clustered into three groups which could be interpreted as varying degrees of wastewater strength: (i) strong, (ii) medium and (iii) weak. One wastewater, Petawawa, was dissimilar enough (weaker) from even the weak group that it was not linked with any group.

A comparison of cluster groupings and WSI's in Table 7 shows that the WSI ranking and the natural groups formed by the cluster analyses are in good agreement. For classification purposes and subsequent statistical analyses, the following WSI breakdown was employed:

$$WSI \leq 8 = \text{weak}$$

$$8 < WSI \leq 10 = \text{medium}$$

$$WSI > 10 = \text{strong}$$

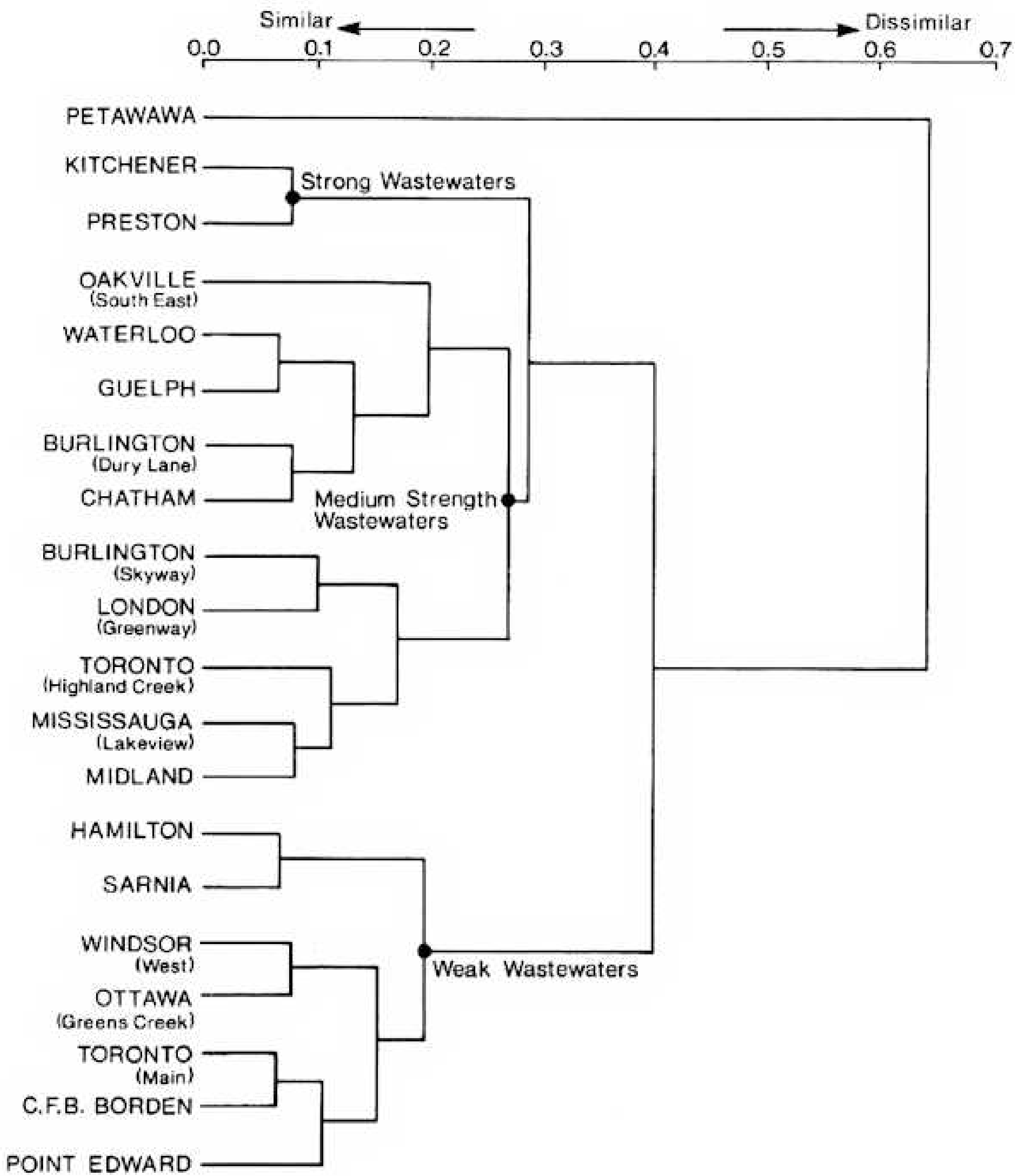

FIG. 3. Dendrogram of 20 Wastewaters Clustered With Respect to Hardness, Total Phosphorus, Alkalinity, Conductivity Suspended Solids And Total Organic Carbon.

3.4 Regression Analyses of Chemical Dosage Required for Phosphorus Removal Versus Wastewater Characteristics

The next step in the study was the derivation of regression relationships expressing chemical dosages (Fe, Al or Ca) required to achieve a 1 mg/L residual total phosphorus, as a linear function of wastewater characteristics. Separate regressions were run for each of the three strength categories. A summary of the predictive equations derived, based on the six wastewater characteristics (hardness, total P, SS, alkalinity, conductivity, and TOC), is presented in Table 8.

Examination of regression equations (8) to (16) indicates that the most important variable in predicting alum and iron salt dosages was the initial total phosphorus content of the wastewater. This was not unexpected because numerous other investigations including (Prested *et al*, 1977) have observed strong relationships between Fe and Al requirements and influent phosphorus. Conductivity appeared to be of secondary importance.

All regression relationships were significant at the 99% level. However, the stronger relationships were for iron and alum and a closer look at the three lime equations (10), (13) and (16) shows these to be inconsistent and uninterpretable. Alkalinity had no effect in the first case, a large positive effect in the second, and a negative effect in the third. For example, when equation (16) for strong sewage was used, the estimated lime requirement decreased as the wastewater alkalinity increased, (i.e., at alkalinity = 618 mg/L the estimated Ca = 0).Since lime is consumed primarily by its reaction with alkalinity, a good positive relationship between lime requirement and wastewater alkalinity would be anticipated. This is not evident from these equations. Apparently the traditional approach to estimating Time dosage, based on experimentally established relationships between pH, lime and alkalinity, remains the most reliable method of estimating lime requirements for a given wastewater.

Experience has shown that there is no simple method for estimating the pH required to achieve the desired level of phosphorus removal. Jar testing is the best method, but rough estimates can be made from a knowledge of the type of water.

TABLE 8. Regression Equations Predicting Chemical Requirements For Phosphorus Removal to 1 mg P/L.

Type of Wastewater	Precipitant	Equation		Correlation Multiple Coefficient
	Iron	Fe = 2.5 + 3.9 (TP) -12.5 (COND)	(8)	0.795*
Weak	Alum	Al = 0.77 +1.76 (TP)	(9)	0.802*
	Lime	Ca = 30.9 - 0.32 (HARD)+21.9 (TP)	(10)	0.831*
	Iron	Fe = 11.4+ 3.0 (TP)+ 0.046 (ALK)	(11)	0.916*
Medium	Alum	Al = 1.2+1.8 (TP)+0.0I9(SS)	(12)	0.817*
	Lime	Ca = 100.1+ 0.51 (ALK)+ 1.2 (TOC)	(13)	0.676*
	Iron	Fe = -7.3+ 1.8 (TP)+ 11.6 (COND)	(14)	0.637*
Strong	Alum	Al = -5.8+1.2 (TP)+ 0.13 (TOC)	(15)	0.739*
	Lime	Ca = 160.7 - 0.26 (ALK)	(16)	0.418*

* Denotes significance at 99% confidence level.
Fe = Ferric chloride dosage (mg/L as Fe^{3+}).
Al = Alum dosage (mg/L as Al^{3+}).
Ca = Lime dosage (mg/L as Ca^{2+}).
TOC = Total organic carbon (mg/L).
SS= Suspended solids (mg/L).
TP= Total phosphorus (mg/L).
HARD = Hardness (mg/L as $CaCO_3$).
ALK = Alkalinity (mg/L as $CaCO_3$).
COND = Conductivity (millimhos/cm).

For example, about 90% phosphorus removal would be expected at pH 10 in a hard water with a moderate magnesium content (> 10 mg/L) whereas a pH of 11 or more may be required in a softer water with low magnesium content (< 5 mg/L).

For each of the 20 wastewaters examined in this study, the lime dosages required for pH 10 and 11 were correlated with wastewater alkalinity. Good regression relationships were obtained between alkalinity and lime requirements for both pH levels as illustrated in Figures 4 and 5. These are in excellent agreement with similar relationships developed by Stamberg *et al* (1970) and Farrell (1975).However, it should be pointed out that Figure 5 consistently predicts about 25% lower lime requirement to reach pH 11 than does a much used relationship presented by Tchobanoglous (1970). In any case, if caution is exercised, these empirical relationships should be useful for obtaining rough estimates of lime requirements for low and high lime systems (pH 10 and 1I).

3.5 Application of Prediction Models

To ascertain the accuracy of the derived methodology for predicting chemical requirements, three additional jar test studies were carried out on the raw municipal wastewaters from Simcoe, Galt and Elmira. The study conditions and experimental methods were identical to those described previously except only six wastewater parameters (hardness, total phosphorus, suspended solids, alkalinity, conductivity and TOC) were determined and lime was no longer evaluated. The mean parameter values for the three test municipalities as well as the average precipitant dosages required to achieve a 1 mg/L total phosphorus residual are summarized in Table 9.

Wastewater strength indices (WSI) were calculated for each wastewater using Equation (7). Simcoe had a WSI of 9.9 placing it in the medium strength category. Galt and Elmira had respective WSI's of 15.4 and 12.0, placing them in the strong wastewater category. The appropriate regression relationships from Table 8 were then used to predict the Al^{3+} and Fe^{3+} dosage requirements. Comparing the predicted and experimental dosages (Table 10) indicated that the average percent errors between measured and predicted values were -10% for Fe and -24% for Al.

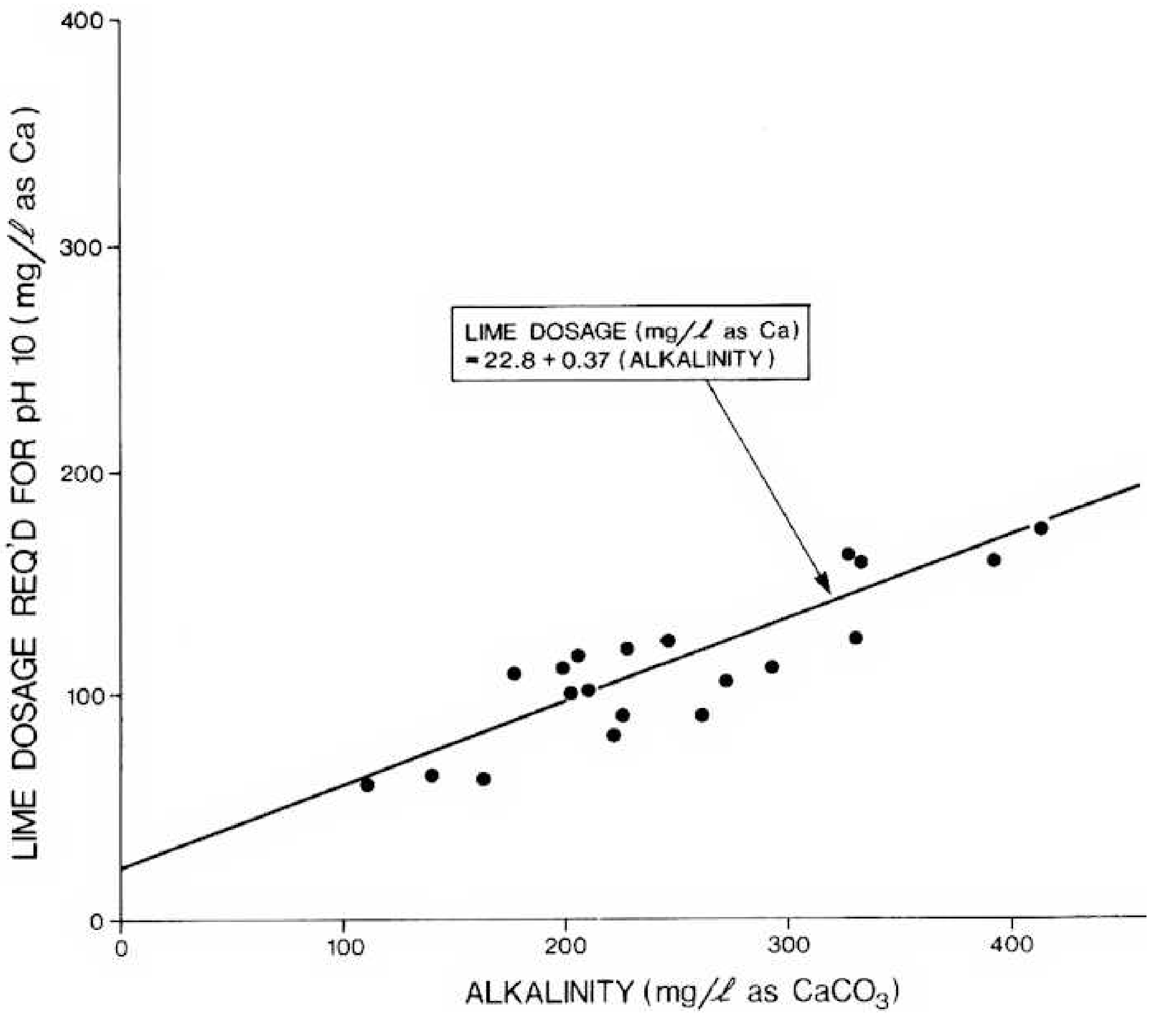

FIG. 4. Lime Dosage Required To Obtain pH 10 vs. Wastewater Alkalinity.

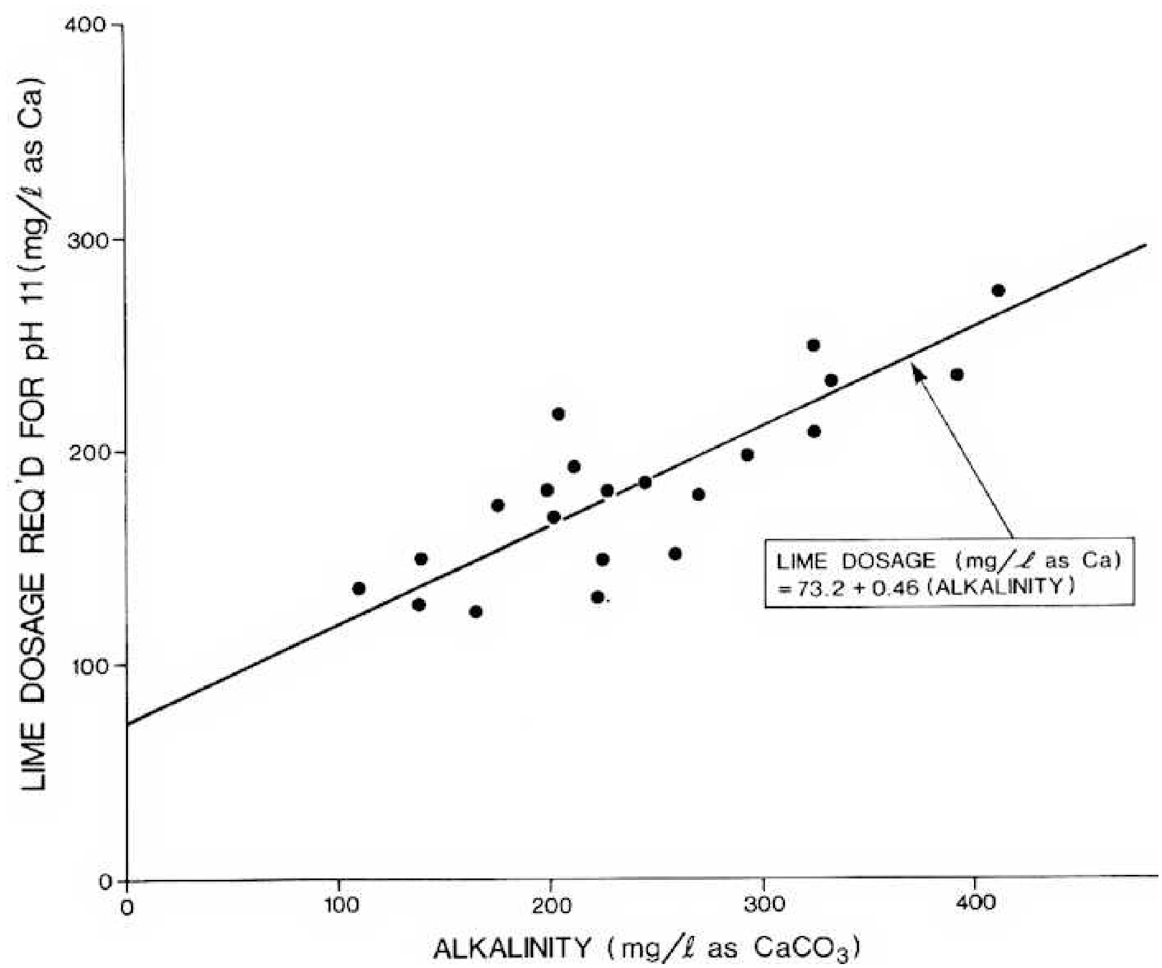

FIG. 5. Lime Dosage Required To Obtain pH 11 vs. Wastewater Alkalinity.

In other words, the prediction equations using six wastewater characteristics (Table 8) tended to slightly underestimate iron and alum dosage requirements. Table 10 also shows the Fe^{3+} and Al^{3+} dosage requirements predicted using the equations developed by (Prested *et al* , 1977) based only on the influent phosphorus content of the wastewater. The average percent errors between experimental and predicted values using these simpler equations (shown in Table 1) were24% and ± 32% for Fe^{3+} and Al^{3+} dosages, respectively.

TABLE 9. Mean Wastewater Characteristics For Simcoe, Galt And Elmira Studies.

Parameter	Simcoe	Galt	Elmira
Hardness (mg/L as $CaCO_3$)	295	500	491
Total P (mg/L)	6.9	5.2	8.8
SS (mg/L)	150	149	147
Alkalinity (mg/L as $CaCO_3$)	284	332	246
Conductivity(millimhos/cm)	0.85	1.35	0.91
TOC (mg/L)	41.0	60.3	55.0
Fe dose req'd. *(mg/L)	27.3	18.0	21.0
Al dose req'd. *(mg/L)	22.6	11.8	13.6

* Dosage required for 1 mg/L residual P.

It is emphasized that additional verification of the derived models will be required to provide a statistically reliable estimate of the overall percent error, using any of these equations. From this brief comparison the prediction capability of the equations developed in this part of the study appeared to be somewhat better than when using the equations developed in Volume 1, based simply on influent phosphorus (i.e., -17% compared to ±28%).

However, this degree of improvement would not warrant the extra time and expense normally involved in collecting and analyzing several wastewater characteristics.

TABLE 10. Comparison Of Experimental And Predicted Chemical Dosage Requirements For 1 mg/L Residual Total Phosphorus.

			Experimental	Predicted							
Location	WSI	Precipitant	Jar Tests	Equations, (Prested *et al*, 1977) (Table 1)				Equations, This Study (Table 8)			
			Dosage (mg/L)	Equation No.	Dosage (mg/L)	Absolute % Error	Ave. % Error	Equation No.	Dosage (mg/L)	% Error	Ave. % Error
Simcoe	9.9	Fe^{3+}	27.3	(1)	25.6	- 6		(11)	22.4	-18	
Elmira	12.0	Fe^{3+}	21.0	(1)	32.8	+56		(14)	19.1	- 9	
Galt	15.4	Fe^{3+}	18.0	(1)	20.0	+11		(14)	17.7	- 2	
						Ave.	± 24			Ave.	-10
Simcoe	9.9	Al^{3+}	22.6	(2)	17.2	- 24		(12)	16.5	- 27	
Elmira	12.0	Al^{3+}	13.6	(2)	21.7	- 60		(15)	11.7	-15	
Galt	15.4	Al^{3+}	11.8	(2)	13.1	+11		(15)	8.2	-31	
						Ave.	± 32			Ave.	-24
Ave. Error For All Equations							± 28				-17

Unless the additional information required for these equations is readily available, the simpler equations based only on influent phosphorus should be used.

The results of this study suggest that, in future phosphorus removal treatability programs, the jar testing phase could be reduced or even eliminated. The application of some of the empirical relationships derived herein should be of considerable assistance in selecting the proper chemical for full scale testing.

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LIST OF ABBREVIATIONS

Abbreviation	Variable	Units
HARD	Hardness (as $CaCO_3$)	mg/L
Ca	Calcium (as $CaCO_3$)	mg/L
Mg	Magnesium (as $CaCO_3$)	mg/L
Na	Sodium	mg/L
K	Potassium	mg/L
Fl	Fluoride	mg/L
Al-TOT	Total Aluminum	mg/L
Al-DISS	Dissolved Aluminum	mg/L
Fe-TOT	Total Iron	mg/L
Fe-DISS	Dissolved Iron	mg/L
TP	Total Phosphorus	mg/L
DP	Dissolved Phosphorus	mg/L
ORTHO-P	Ortho-Phosphorus	mg/L
SS	Suspended Solids	mg/L
TDS	Total Dissolved Solids	mg/L
ALK	Total Alkalinity (as $CaCO_3$)	mg/L
SO_4	Sulphate	mg/L
Cl	Chloride	mg/L
Si	Silica	mg/L
TURB	Turbidity	FTU
COND	Conductivity	millimhos/cm
TEMP	Temperature	°C
TOC	Total Organic Carbon	mg/L
ALK-OH	Hydroxide Alkalinity (as $CaCO_3$)	mg/L
ALK-CARB	Carbonate Alkalinity (as $CaCO_3$)	mg/L
ALK-BICARB	Bicarbonate Alkalinity (as $CaCO_3$)	mg/L
CO_2	Carbon Dioxide	mg/L
Fe DOSE	Fe^{3+} Dose Required for 1 mg/L Residual P	mg/L
Al DOSE	Al^{3+} Dose Required for 1 mg/L Residual P	mg/L
Ca DOSE	Ca^{2+} Dose Required for 1mg/L Residual P	mg/L

APPENDIX A

SUMMARY OF MULTI-PARAMETER STUDY MEAN VALUES

TABLE A-I - Summary Of Multi-parameter Study Mean Values.

Parameter \ Study	Borden	Burlington Drury Lane	Burlington Skyway	Chatham	Guelph	Hamilton	Kitchener	London Greenway	Midland	Mississauga Lakeview	Oakville South East	Ottawa Greens Creek	Point Edward	Petawawa	Preston	Sarnia	Toronto Highland Creek	Toronto Main	Waterloo	*Windsor West*
Alkalinity (Carbonate)	2.1	1.0	1.5	1.1	2.9	1.5	7.6	8.1	1.4	0.7	1.8	1.6	2.8	0.4	3.0	1.3	0.4	3.9	3.6	0.7
Alkalinity (Bicarbonate)	238.1	222.2	244.5	260.5	332.1	177.5	419.8	283.5	194.8	183.3	241.2	158.4	255.2	108.7	369.6	197.9	192.5	205.1	337.5	144.6
Alkalinity (Hydroxide)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Alkalinity	240.2	223.2	246.0	261.6	335.0	179.0	427.5	291.7	196.2	184.0	243.0	160.0	258.0	109.1	372.6	199.2	192.9	209.1	341.1	145.3
Aluminum (Dissolved)	0.006	0.044	0.057	0.054	0.013	0.048	0.150	1.184	0.037	0.044	0.639	0.033	0.053	0.142	0.045	0.131	0.279	0.263	0.044	0.023
Aluminum (Total)	0.13	0.70	2.93	3.16	0.14	0.44	0.35	3.56	3.19	1.27	0.16	0.28	0.46	0.47	0.76	0.77	1.12	1.04	0.43	0.27
Calcium	147.1	234.5	172.4	161.3	239.4	144.4	290.5	160.8	149.4	141.5	239.3	134.4	128.0	20.8	225.0	101.5	134.1	150.0	220.0	107.1
Chloride	28.1	120.6	104.7	93.5	141.6	128.5	310.3	71.7	75.0	109.2	130.2	113.8	44.9	16.0	153.4	38.9	133.1	116.4	531.8	58.5
CO_2 (Free)	6.4	10.7	9.0	16.8	12.9	5.5	4.9	2.5	21.1	15.8	8.5	3.7	5.8	7.9	10.5	8.0	19.5	3.3	7.3	17.0
conductivity	0.48	0.77	0.92	0.85	1.20	0.94	1.91	0.77	0.64	0.82	0.87	0.64	0.70	0.27	1.08	0.55	0.93	0.90	1.61	0.53
Fluoride	0.55	0.48	0.64	0.24	0.59	0.53	0.36	0.86	0.73	0.91	0.53	0.75	0.98	0.60	0.37	0.33	0.94	0.88	2.20	0.98
Hardness	190.2	342.0	237.8	336.7	416.7	161.7	361.3	259.2	277.2	278.5	314.7	228.9	240.0	28.6	363.6	151.5	199.5	216.3	322.0	207.1
Iron (Dissolved)	0.080	0.086	0.127	0.135	0.093	0.745	0.157	0.139	0.094	0.781	0.070	0.114	0.375	0.157	0.130	1.575	0.277	0.147	0.198	0.112
Iron Total)	0.59	1.06	1.08	2.41	1.57	6.63	1.65	3.34	1.93	9.07	0.32	0.73	1.86	0.69	2.41	5.8	1.11	1.33	0.90	1.08
Magnesium	43.1	108.8	65.0	175.3	177.2	17.3	70.8	98.5	127.9	137.0	92.0	94.4	112.0	7.8	138.6	50.0	65.4	66.3	102.0	100.0
pH	7.93	7.66	7.77	7.57	7.85	7.89	8.27	8.43	7.51	7.38	7.82	7.98	8.02	7.49	7.89	7.77	7.35	8.21	8.02	7.66
Phosphorus (Dissolved)	2.97	3.55	1.97	12.30	3.69	1.10	3.28	1.02	7.61	3.58	2.95	2.21	6.45	2.83	4.42	2.78	3.02	2.56	2.64	2.59
Phosphorus (Ortho)	2.23	2.82	2.03	10.40	2.42	0.92	2.86	1.90	6.99	2.39	2.50	1.69	3.76	2.10	4.19	2.49	2.30	2.04	2.36	1.99
Phosphorus (Total)	4.76	4.61	4.23	17.2	5.78	3.46	8.02	9.69	11.20	9.04	3.48	3.40	9.01	4.10	7.90	4.37	4.55	5.14	6.16	3.78
Potassium	4.9	7.8	8.1	17.2	9.1	7.5	21.5	13.8	7.8	16.7	5.9	5.2	8.6	6.2	16.7	8.3	16.8	14.7	11.8	8.3
Silica	6.9	2.7	4.1	3.5	4.0	5.7	7.7	3.5	5.6	4.9	1.8	3.2	3.0	3.9	6.1	2.1	2.8	*2.9*	4.9	2.6
Sodium	37.6	67.8	112.5	90.7	206.0	63.2	244.2	78.5	78.8	110.1	91.0	63.4	59.6	39.1	124.1	38.1	85.9	84.1	223.2	186.0
Sulphate	45.9	118.8	179.1	105.3	28.2	107.8	51.7	82.5	71.3	65.8	79.2	92.2	62.2	43.4	45.6	43.4	30.7	87.2	115.8	68.6
Suspended Solids	127.7	114.9	209.6	140.0	128.2	107.0	232.7	261.5	156.3	202.6	57.8	84.9	89.0	75.2	310.2	145.0	172.8	126.9	133.2	110.3
Total Dissolved Solids	412.8	696.1	717.2	713.3	897.6	554.6	1304.	682.0	511.7	687.4	679.5	95.6	578.5	292.4	936.7	396.5	674.7	613.7	1100	413.7
Total Organic Carbon	31.8	38.5	25.6	75.1	60.7	83.3	46.2	68.3	34.8	87.0	12.5	34.9	55.6	27.5	81.4	29.0	81.5	53.1	72.2	50.4
Turbidity	43.1	46.9	52.5	60.0	64.1	47.7	83.7	97.6	59.7	78.0	25.0	34.3	54.9	39.9	70.0	52.4	96.3	111.6	60.2	56.0

* mg/L except conductivity (mmho/cm); turbidity (FTU) and pH
All alkalinities, hardness, calcium and magnesium are in mg/L as $CaCO_3$. However, note that Ca Dose is the lime dosage as Ca^{2+}.

APPENDIX B

MULTIVARIATE STATISTICAL PROCEDURES

APPENDIX B

Multivariate Analysis

Multivariate analysis as defined by Kendall (1961) is that branch of statistical analysis which is concerned with the relationships of sets of dependent variates (as in the case of multiple regression analysis, where one variate is regressed on the remaining variates) or with interdependence (as is the case of principal component analysis) where the interrelationships of the variates are being studied. It describes statistical techniques concerned with analyzing data collected for p difference variables on N objects. In this study the variables are chemical characteristics of wastewaters determined at 20 sewage treatment plants (objects) across Ontario.

Cluster Analysis

Cluster analysis consists of splitting a large number of multivariate observations into a smaller number of relatively homogeneous groups. Each individual of a multivariate sample may be represented by a point in a multidimensional space. Cluster analysis attempts to group these points into disjoint sets corresponding to marked features of the sample.

There are many techniques of cluster analysis and it is difficult to judge their relative merits and demerits because a cluster is not a well defined concept. Different methods of cluster analysis of the same sample may assume different geometrical distribution of the points or may employ different clustering criteria or may differ in both respects. The program used in this study was developed at the Canada Centre for Inland Waters by E. Pickett, and yielded results for seven methods of clustering, six of which produced very similar results. One of these six (furthest neighbour)was chosen and used throughout the study. The clustering of objects is referred to as a Q-type analysis whereas the R-type is the cluster analysis of variables. In this study the primary concern was the clustering of sewage treatment plants and therefore only the Q-type of analysis was used.

Principal Component Analysis

Principal component analysis is used for analyzing the dependence structure of multivariate data. The method offers a means of reducing the dimensionality of multivariate data by expressing the original variables in terms of fewer component variables which are linear functions of the observation variables. In this study principal component analysis was used in deriving the wastewater strength index from wastewater characteristics.

Computational methods for calculating the principal components of the correlation matrix are presented in Kendall (1961) and Morrison (1967). The program BMD 03M from the Biomedical Computer Program Library (Dixon, 1968) was used for the principal component analyses.

Multiple Regression Analysis

Multiple regression analysis is the prediction of the value of one variable from the values of other given variables. The general model of multiple linear regression may be written as:

$$y = b_o + b_i x_i + b_2 x_2 + \ldots\ldots\ldots\ldots + b_P x_P$$

where y is the dependent variable and x_1, x_2 ...., x_P may be raw data or may be transformed values of the raw data. Draper and Smith (1966), describe computation procedures for multiple regression.

In this study, the program used was a stepwise multiple regression analysis program (BMD 02R) from the Biomedical Computer Programs Library (Dixon, 1968). One variable is added to the regression equation at each step in the calculation. The variable added is the one that makes the greatest reduction in the error sum of squares terms. The number of terms (variables) in this final equation was determined by examining the significance of the contribution that each term made to the equation.