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International Seminar on Control of Nutrients in Municipal Wastewater Effluents

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Proceedings
Volume I: Phosphorus

CONTROL OF NUTRIENTS

IN MUNICIPAL WASTEWATER EFFLUENTS

VOLUME I: PHOSPHORUS

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September 9-11, 1980

Seminar Convener:

E. F. Barth
Wastewater Research Division
Municipal Environmental Research Laboratory

Speakers:

Dr. N. W. Schmidtke, Burlington, Canada
Dr. J. V. DePinto, Potsdam, New York
Mr. W. L. Morley, Gladstone, Michigan
Dr. B. G. Hultman, Stockholm, Sweden
Mr. T. Annaka, Tokyo, Japan
Mrs. D. VanDam, Grand Haven, Michigan
Mr. C. Heim, Tonawanda, New York

Municipal Environmental Research Laboratory

and

Center for Environmental Research Information
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

AGENDA FOR
INTERNATIONAL SEMINAR
ON
CONTROL OF NUTRIENTS IN WASTEWATER EFFLUENTS

SEPTEMBER 8, 1980

7:30 to 9:00 p.m.   RECEPTION/EARLY REGISTRATION

SEPTEMBER 10, 1980   NITROGEN CONTROL TECHNOLOGY

NUTRIENT REMOVAL TECHNOLOGY -- THE CANADIAN CONNECTION

N.W. Schmidtke, Ph.D., P. Eng.
Director, Wastewater Technology Centre
Environmental Protection Service, Environment Canada

INTRODUCTION

Man-initiated acceleration of eutrophication of large and small bodies of water has received attention from the public because of dramatic and rapid, visible changes in water quality. This not only results in undesirable changes in water use patterns such as restricted use of pleasure craft, swimming, fishing, but also more subtle effects such as clogging of water intakes, increased turbidity, taste and odor problems and general interferences with water treatment processes. These effects are caused by algae blooms which in most instances are a manifestation of a biological response to excessive nutrient input to the water column.

Even though Canada has 1/3 of the world's fresh water, deterioration in water quality such as previously noted exists. More specifically 4 major areas (Figure 1) where significant evidence of water quality impairment has been identified are:

1.   The Okanagan Basin - British Columbia

2.   The Qu'Appelle River Basin - Saskatchewan

3.   The Saint John River Basin - New Brunswick

4.   The Great Lakes Basin - Ontario

Phosphorus has been implicated as a limiting or key nutrient in the eutrophication of many natural or man-made bodies of water throughout the industrialized world (1).
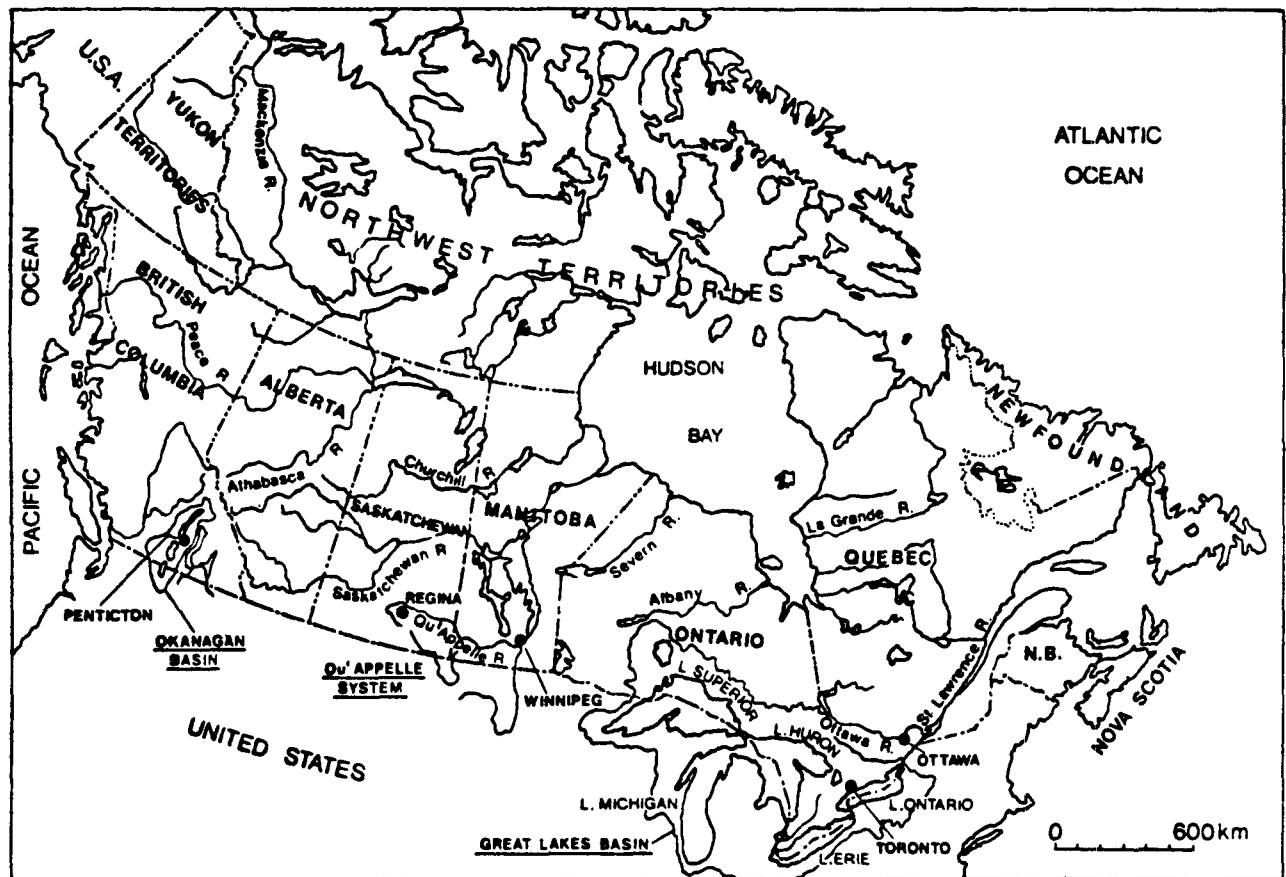
FIGURE 1. MAJOR AREAS OF WATER QUALITY CONCERN .

Detergents, human waste, agricultural run-off, atmospheric transport and industrial activities are all major sources of phosphorus being discharged to receiving bodies of water. An additional phosphorus reservoir exists in the bottom sediments of lakes and rivers.

An obvious solution to the problem consists of reducing the input of phosphorus to the environment. This is a relatively simple problem if dealing with point sources. One of the main point sources of phosphorus is the effluent from municipal waste treat-

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ment plants. Removal of phosphorus contained in domestic and industrial wastewaters is recognized as an essential step in decelerating and eventually reversing the extent of eutrophication in receiving waters.

The water management studies (2) conducted in the Okanagan Basin, the Qu'Appelle River Basin and the Saint John River Basin all confirm that reduction in nutrient inputs, especially phosphorus, will result in a decrease in the rate of water quality deterioration and will ultimately lead to improvement of existing water quality. In these three areas, activities related to the construction of new treatment plants and installation of phosphorus removal facilities are in progress.

This paper will provide an overview of the numerous activities undertaken by the Canadian government and the Province of Ontario in a concerted effort to control nutrient inputs (phosphorus) to the Great Lakes.

A POINT SOURCE PHOSPHORUS CONTROL STRATEGY

The International Joint Commission (IJC) Report (3) completed in 1969 after a six year study of pollution in the Lower Great Lakes drainage basin, recommended that all phosphorus discharges to the Lower Great Lakes be reduced to the lowest practical level, calling for an effluent objective of 1.0 $mg.L^{-1}$ total phosphorus.

To meet this challenge, Canada opted for a double-pronged attack on eutrophication, relying on legislative as well as technical means to reduce phosphorus concentrations in wastewater discharges.

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Thus, the Canadian Government, under the provisions of the Canada Water Act (1970), legislated a policy calling for a staged reduction in the phosphorus content of detergents to a limit - by weight as P_2O_5 - of 20% by August 1970 and 5% by December 31, 1972. Establishment and support of the framework for developing the technical means to reduce the nutrient content of municipal waste-water discharges to the Great Lakes system was recognized to be a joint Federal-Provincial responsibility.

A FEDERAL-PROVINCIAL ACCORD

As a prelude to the Canada-United States Agreement which was signed between the United States and Canada in 1972, the Governments of Canada and Ontario signed an Agreement (4) in August 1971, to implement and accelerate programs of pollution control in the Lower Great Lakes to meet the recommendations of the IJC. The Agreement secured funding for a $250 million capital works program aimed at upgrading sewage collection systems and treatment works. This included the installation of phosphorus removal equipment at an estimated cost of $40 million. An additional $6 million over the 5 year term of the Agreement was provided for related research studies. Phosphorus removal technology and treatability studies were given top priority in the research program.

The $6 million research fund was jointly shared and administered by the Governments of Canada and Ontario. The Agreement was subsequently extended for an additional 2 year period with a further $1 million allocation of research funding.

Largely as a result of this research funding, a program of integrat-

ing chemical treatment with existing plant processes was designed. This program consisted of jar testing followed by treatability studies at each plant. The success of this strategy is evident in that the deadlines for implementation of phosphorus removal at existing plants as established by Ontario in 1970 were largely met. Figure 2 illustrates the Ontario phosphorus removal program with scheduled compliance dates.

LEGEND

Dec.31,1973	All plants
Dec 31,1973	Plants larger than 1 mgd or where local problems demonstrated.
Dec.31, 1975	Plants larger than 1 mgd
Future	Studies required to determine need
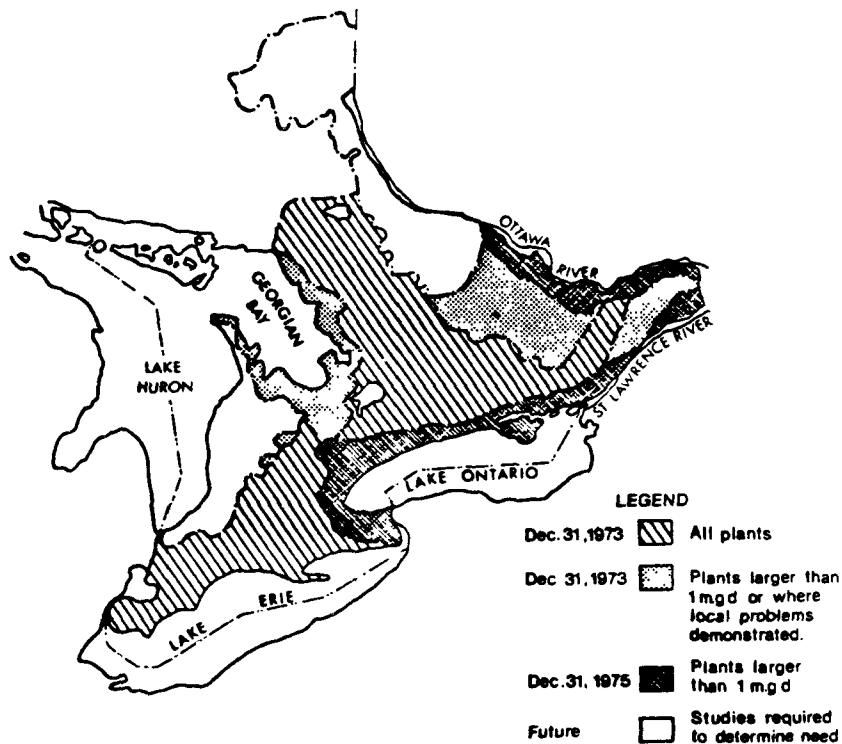
FIGURE 2. PROVINCE OF ONTARIO-SOUTHERN SECTION PHOSPHORUS REMOVAL PROGRAM SCHEDULED COMPLIANCE DATES. (8)

Even though the emphasis of phosphorus removal has been placed on point-source reduction at municipal treatment plants, other sources are not ignored. Specifically:

1. *Ontario policy calls for an effluent objective for industrial phosphorus discharges of 1 mg.L^{-1} maximum total phosphorus.*

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2. *Urban Drainage Sub-Committee of the Canada-Ontario Agreement in their Proposed Model Policies for Urban Drainage Management (5) suggests that "each municipality shall formulate and implement a comprehensive pollution control strategy related to its own particular land use, drainage and run-off characteristics."*

3. *The Province has recently adopted sewage sludge utilization guidelines (6) which include provisions for phosphorus control.*

4. *PLUARG in its summary report to the IJC (7) recommends that phosphorus reduction through non-point as well as point source control programs be implemented. This would include control of soil erosion, strengthening of the areas of reducing water pollution problems from animal manures, and improving fertilizer application practices.*

EFFECT OF DETERGENT PHOSPHORUS CONTROL

Before the Canadian Government imposed controls on detergent phosphorus levels, the phosphorus content of laundry detergents averaged approximately 25% (as P_2O_5). Influents to municipal sewage treatment plants had typical phosphorus concentrations of around 10 $mg.L^{-1}$.

Following the introduction of the first control regulations in August 1970 (limiting the laundry detergent phosphorus concentrations to 20% as P_2O_5) the raw sewage phosphorus concentration decreased to around 8.8 $mg.L^{-1}$.

Further legislative controls imposed December 1972 (laundry detergent phosphorus concentration to 5% as P_2O_5) saw influent phosphorus concentration decrease to approximatly 7 $mg.L^{-1}$.

The phosphorus concentration continued to decrease through 1974 to a low value of about 5.6 $mg.L^{-1}$ but has since increased to the current level of about 6.8 $mg.L^{-1}$ (9). Figure 3 illustrates the phosphorus influent concentrations over the period 1967 to 1977 for the province of Ontario.

```
  10
   9        STEP 1 (AUG. 1970)
   8          20% CRITERIA
   7                    STEP 2 (DEC.1972)
   6                      5% CRITERIA
   5
   4
   3
   2
   1
      67 68 69 70 71 72 73 74 75 76 77
```
PHOSPHORUS CONCENTRATION - MG/L

YEAR
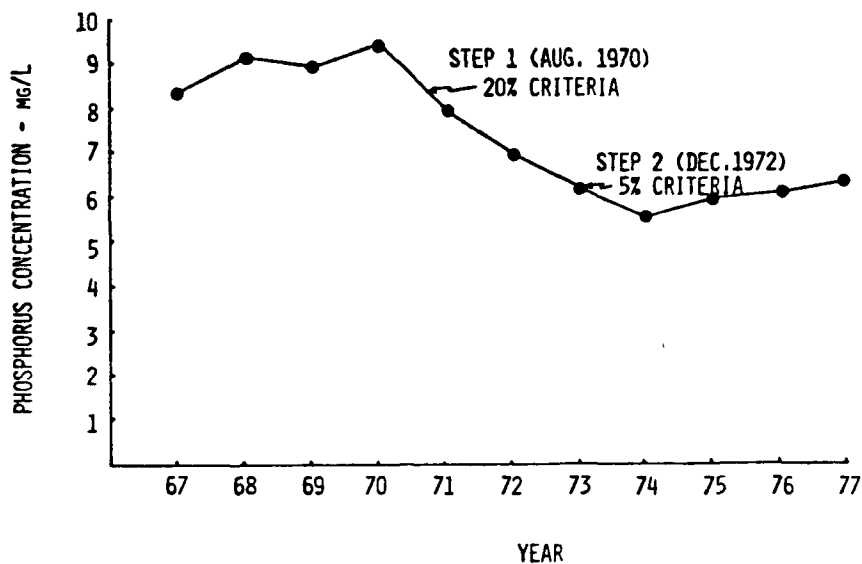
FIGURE 3. PHOSPHORUS CONCENTRATIONS IN RAW SEWAGE. (11)

The impact of legislated phosphorus detergent reductions was best illustrated in a ten-month long full-scale study of the activated sludge plant at the Canadian Forces Base in Uplands (10).

Figures 4 and 5 highlight these effects. Figure 4 illustrates the average diurnal variations of influent phosphorus for the 1972-1973 period, before and after reformulation. Each data point in Figure 4 is the mean of hourly samples collected on at least seven different days.

Figure 5 shows the average weekly data for total phosphorus and plant flow and clearly indicates that the reduction in total phosphorus concentration was not due to dilution by increased flows.

The data show that influent phosphorus loadings dropped from an average of 126 kg.d^{-1} in 1972 to an average of 55 kg.d^{-1} in 1973; a 56% reduction.
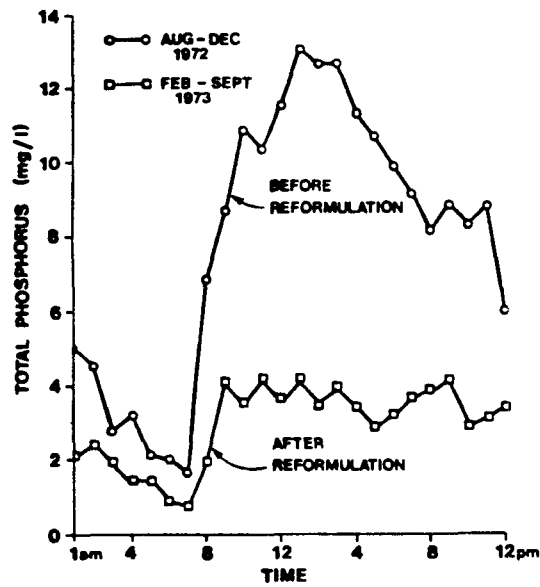
FIGURE 4. DIURNAL VARIATION OF TOTAL
PHOSPHORUS IN RAW WASTE-
WATER AT C.F.B. UPLANDS. (10)
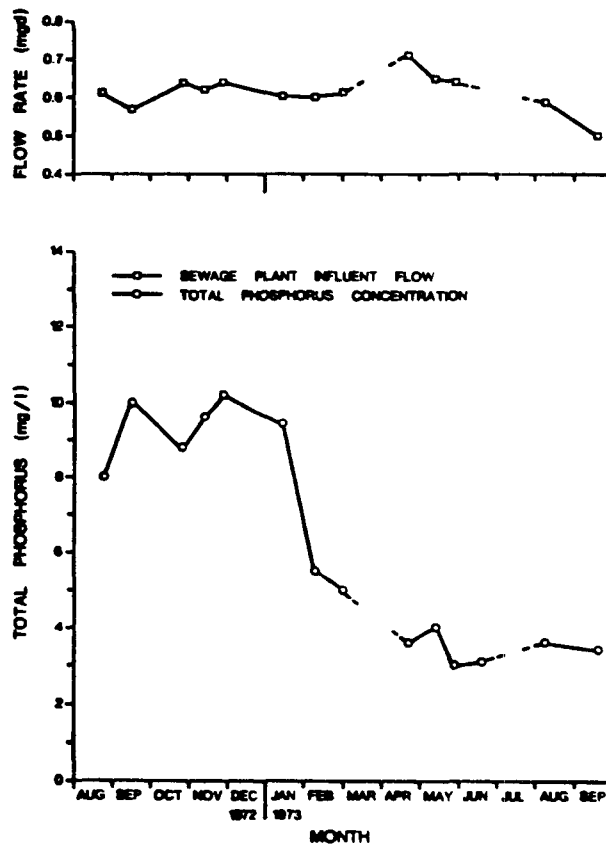
FIGURE 5. INFLUENT TOTAL PHOSPHORUS AND
FLOW TRENDS DURING DEMONSTRATION
STUDY AT C.F.B. UPLANDS. (10)

In another study (12) available Ontario phosphorus influent data were summarized over the bre-ban and post-ban periods. The data, based on approximately 35 plants, showed that the influent total phosphorus concentration had decreased from approximatly 7.1 mg.L^{-1} to 5.7 mg.L^{-1}. This represents a 20% reduction in wastewater phosphorus loading directly attributable to laundry detergent reformulation (Table 1).

TABLE 1. IMPACT OF DETERGENT REFORMULATION ON WASTE-
WATER PHOSPHORUS LEVELS (12)

	Before Reformulation (Prior to January 1973)[a]	After Reformulation (1973 to Date)[a]	Percent Reduction
Raw wastewater total phosphorus (mg/l as P)	7.1 (n[b] = 38)	5.7 (n = 35)	20
Secondary effluent total phosphorus (mg/l as P)	4.5 (n = 31)	3.4 (n = 25)	24

[a]Average value.
[b]n = number of observations.

When using iron or aluminum salts for phosphorus precipitation, a very strong correlation between chemical dosage and influent phosphorus concentration exists. Figure 6, for example, illustrates the quantity of aluminum required to attain an effluent phosphorus concentration of 1 mg.L^{-1} as a function of the influent phosphorus concentration. Clearly then, reduced total phosphorus influent concentrations will lead to reduced coagulant dosages, which is an operating cost saving. As well, the resulting smaller increases in sludge quantity represent additional reductions in plant operational costs.
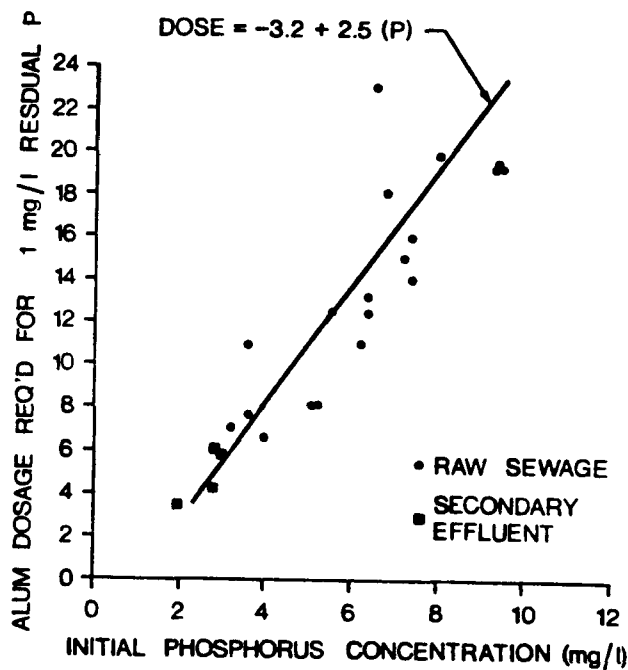
FIGURE 6. RELATIONSHIP BETWEEN ALUM DOSE REQ'D FOR 1MG/ℓ RESIDUAL P AND INITIAL PHOSPHORUS. (13)

Jar test data for coagulant dosage selection at Ontario treatment plants as summarized in Table 2 show dramatic reductions in coagulant dosage requirements between pre- and post- detergent legislation dates. By correcting the jar test dosages to full scale dosage requirements using the relationship developed in another investigation (13), it can be calculated that the reductions in chemical dosage requirements to achieve a 1 $mg.L^{-1}$ total phosphorus effluent are 7.6 $mg.L^{-1}$ as Fe^{3+} and 5.1 $mg.L^{-1}$ as Al^{3+} respectively.

Using chemical costs (1980) of \$0.558 kg^{-1} for $FeCl_3$ and \$0.134 kg^{-1} for alum it can be calculated that the saving in chemical cost

TABLE 2. AVERAGE JAR TEST DOSAGES OF ALUM OR FERRIC CHLORIDE REQUIRED TO ACHIEVE A 1 MG.L^{-1} TOTAL PHOSPHORUS RESIDUAL PRIOR TO 1973 (12)

Chemical	Raw Wastewater Addition			Mixed Liquor Addition		
	Pre-1973	1973-Present	Reduction (%)	Pre-1973	1973-Present	Reduction (%)
Ferric chloride	30.5	17.2	44	21.5	12.8	41
(mg/l) as Fe^{3+}	(n^a = 37)	(n = 36)		(n = 31)	(n = 26)	
Alum	19.4	13.1	32	12.8	6.9	46
(mg/l as Al^{3+}	(n = 38)	(n = 36)		(n = 31)	(n = 27)	

^{a}n = number of observations.

alone amounts to \$2.96 capita^{-1}yr^{-1} for FeCl$_3$ and \$1.82 capita^{-1}yr^{-1} for alum. In addition, available data permits one to calculate that if the laundry detergents had not been reformulated, sludge volumes would be approximatly 26% greater.

IMPLEMENTATION OF LOW COST TECHNOLOGY AT EXISTING PLANTS

A major component of the research program under the Canada-Ontario Agreement addressed the subject of treatability studies as a prelude to installing full-scale phosphorus removal facilities.

Ontario's successful experience in implementing the phosphorus removal program was to a large measure due to the two-phase approach used: initial jar testing studies followed by fairly long term full-scale studies. The data base thus developed and correlations obtained between jar test and full-scale data coupled with experience have given us sufficient confidence so that full-scale studies no longer need be conducted. At the initiation of the program the two-

phase approach gave us not only information on chemical and dosage selection but optimum point of chemical application and compatibility with the existing wastetreatment process type and operation.

Figure 7 is a summary of the Ontario treatability data when comparing jar test to full scale performance data. As shown, the
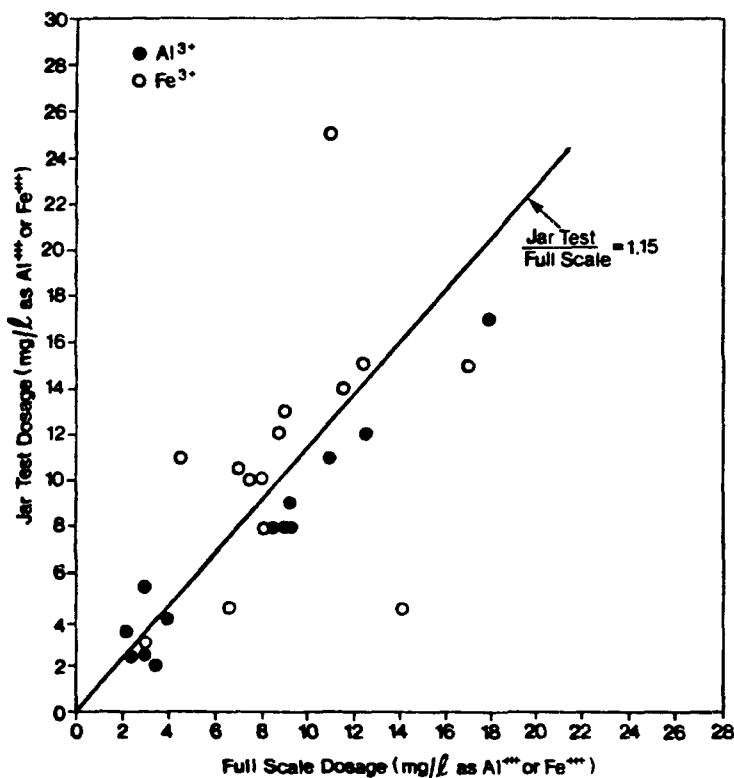
FIGURE 7. COMPARISON OF JAR TEST DOSAGES (FOR 1 MG/ℓ
P 50% OF THE TIME) TO FULL SCALE DOSAGES
(FOR 1 MG/ℓ P AVERAGE) AT PLANTS ADDING
ALUM OR FERRIC CHLORIDE TO THE MIXED LIQUOR. (12)

jar tests tended to overestimate the full-scale dosage requirements by about 15%. In one study (12) the Ontario treatability data was standardized and regression analyses were carried out to develop predictive equations for chemical phosphorus removal. The equations so developed were capable of predicting chemical

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dosages for a particular wastewater to $\pm 30\%$. The implication of this is that in future treatability programs the scope of the jar testing phase can be reduced. Some consultants have already used this approach successfully (14). An attempt was also made (15) to refine the predictive capability of the equations by including parameters additional to influent phosphorus concentrations, such as hardness, alkalinity, conductivity, etc. Even though the resultant equations now allowed one to predict chemical dosage requirements to within $\pm 20\%$ as opposed to the earlier $\pm 30\%$, it was concluded, that based on this marginal degree of improvement, the extra time and expense required cannot be justified.

Jar test and full-scale treatability cost data are summarized in Tables 3 and 4 respectively (11). The cost is not only a

TABLE 3. JAR TESTING TREATABILITY COSTS (11)

Type of Facility	Average Cost ($) 1974	
	Plant Staff	Outside Contractor
Primary	964	5020
Secondary	817	5877
Lagoons	588	

function of the type of waste treatment facility but more importantly whether the study was contracted out or conducted by the plant operations staff. Chemical costs are excluded. The wide

TABLE 4. FULL-SCALE TEMPORARY STUDY COSTS (11)

Type of Facility	Cost ($) 1974		
	Maximum	Minimum	Average
Primary	62,000	7,000	19,100
Secondary	83,000	1,000	13,100
Lagoons	8,000	800	4,100

variations shown in the full-scale treatability costs reflect whether chemical feed equipment had to be purchased or whether it was available on loan from the Ontario Ministry of the Environment.

The numerous phosphorus removal studies conducted at Ontario treatment plants have resulted in the development of a massive data base. Figure 8 is another example showing correlations for the molar effectiveness of $FeCl_3$ or alum on the removal of soluble phosphorus. As shown, the molar effectiveness is similar
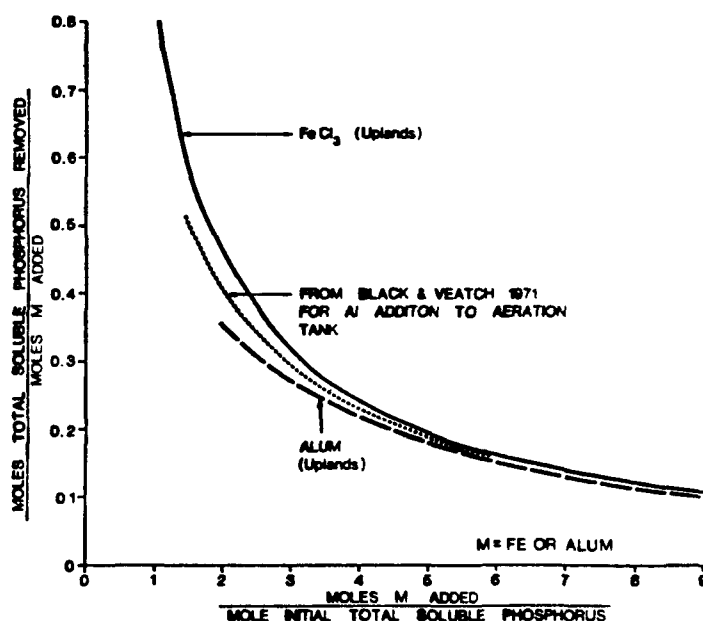
FIGURE 8. COMPARISON OF THE MOLAR EFFECTIVENESS OF FE CL_3 AND ALUM AT C.F.B. UPLANDS. (10)

for each chemical and agrees with the relationship reported by others (16) for alum addition to the secondary clarifier. What this means, is that if both chemicals were compared under identical total soluble phosphorus conditions, their performance on a molar basis would be similar.

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Hydraulic overloading of secondary clarifiers is one cause of poor effluent total phosphorus quality which is associated with suspended solids carryover. Data from the one study (10) illustrates the effluent total phosphorus/suspended solids dependence (Figure 9). The effect of plant flow and thus overflow rate
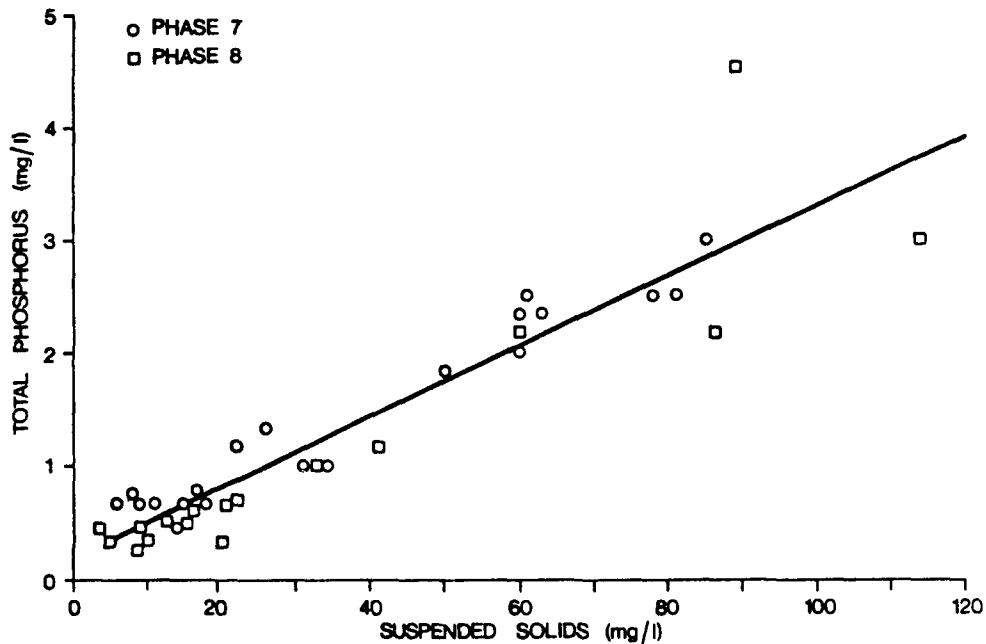
FIGURE 9. CORRELATION BETWEEN EFFLUENT TOTAL-P AND SUSPENDED SOLIDS. (10)

(OR) of the secondary clarifier on total phosphorus removal is illustrated in Figure 10 which shows data during the alum addition phases of a long term study. A trend line has been drawn using the average total phosphorus removals and flow rates for the various addition phases. The trend line shows that phosphorus removals in excess of 80% were obtained when plant flows were at or below the design flow or OR of less than 1.4 mh^{-1}. There was a

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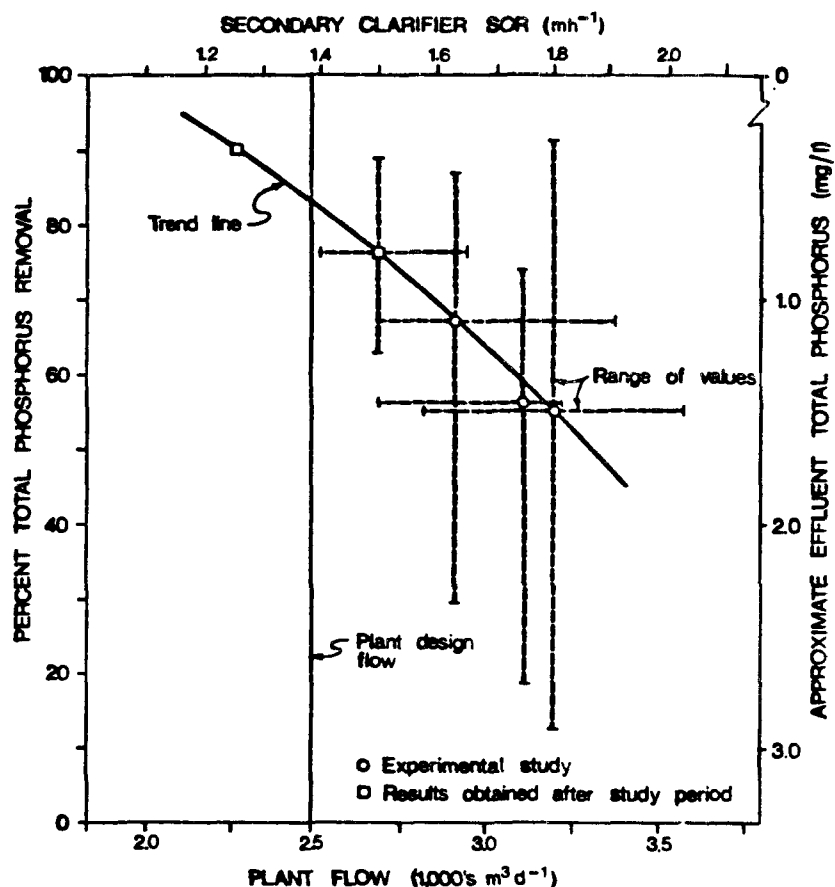
FIGURE 10. EFFECT OF PLANT FLOW AND SOR ON TOTAL PHOSPHORUS REMOVAL DURING ALUM ADDITION. (10)

decided increase in the variability of the effluent phosphorus concentration above the design flow.

Figure 11 also illustrates the effect of hydraulic load on secondary clarifier performance (17). Once the hydraulic load increased beyond 1.5 mh^{-1} effluent quality steadily deteriorated. In all cases chemicals were added to the aeration tank discharge.

Experience has shown that phosphorus removal efficiency is very closely related to solids removal efficiency. No matter how much chemical is added, unless the suspended solids level can be

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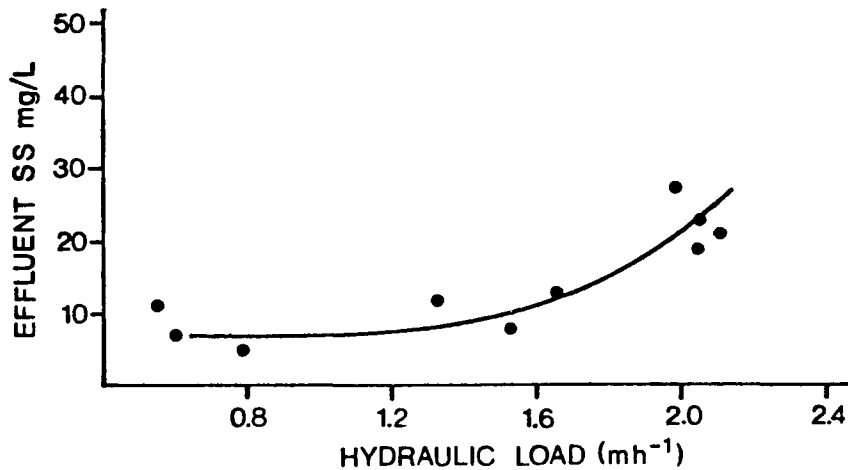
FIGURE 11.   EFFECT OF HYDRAULIC LOAD OF SECONDARY CLARIFIER
CHEMICAL ADDITION TO AERATION SECTION.   (17)

reduced to less than 15 mg.L^{-1}, it will be impossible to achieve an

effluent total phosphorus concentration of less than 1 mg.L^{-1}, even

though the soluble phosphorus may be as low as 0.1 mg.L^{-1}.

Extremely low levels of effluent total phosphorus of <0.3 mg.L^{-1}

are only attainable through tertiary filtration.

PHOSPHORUS REMOVAL FROM LAGOONS

The requirement of phosphorus removal from some 80 lagoons in

Ontario is dependent upon location and/or size of facility. It

has been Ontario's experience that high levels of phosphorus re-

moval can be attained at all types of lagoons. The approach to

implementing a phosphorus removal scheme depends considerably upon

the lagoon type.

AERATED LAGOONS

Sewage pumping stations are ideal locations for adding alum or

ferric chloride to the influent of aerated cells. A high degree of

mixing prior to reaching the lagoon is ensured. As with activated

sludge plants the successful and quick implementation of phosphorus control depends on following the typical jar test procedures.

While several aerated lagoons are successfully removing phosphorus using alum and ferric chloride, Ontario's experience has been that lime is not effective (18,19).

CONVENTIONAL STABILIZATION PONDS

Phosphorus removal is achieved by the continuous addition of alum or ferric chloride to the influent (18). Jar testing, excluding lime, should be conducted to determine optimum chemical and approximate dosage requirements. Unless there is concern over inadequate mixing, full-scale tests are unnecessary.

SEASONAL RETENTION PONDS

Ontario's experience in phosphorus removal from seasonal retention ponds favors batch treatment prior to discharge (20). Jar tests again provide valuable information but the dosage selected should be the one which reduced the phosphorus concentration to approximately 0.5 $mg.L^{-1}$. Batch treatment should be carried out by having the chemical in its liquid state contained in a 600-700 ℓ plastic tank mounted amidships in a 5 m, 70 HP outboard motorboat. Chemical dispersal occurs through a 50 mm siphon discharging into the prop wash while traversing the lagoon. Even, rapid chemical distribution and good mixing are prerequisites. This type of treatment has been extremely successful.

Effluent quality after treatment is usually less than 10 $mg.L^{-1}$ BOD and 20 $mg.L^{-1}$ SS with total phosphorus generally less than 0.5

$mg.L^{-1}$. It is desirable to complete the discharge of the lagoon contents within an 8-10 day period after treatment, otherwise a slight deterioration in effluent quality is experienced after about 2 weeks (20).

SLUDGE GENERATION AND HANDLING

The topic of sludge generation, handling and disposal at phosphorus control facilities was recently presented at the Cornell 1979 Conference (21). A few summary highlights have been extracted. Figures 12 and 13 illustrate the increase in sludge volume and mass for primary and secondary plants using metal salt addition. Figure 12 shows a 60% increase in sludge volume when metal salts are added to the primary plant to meet the 1 $mg.L^{-1}$ effluent total
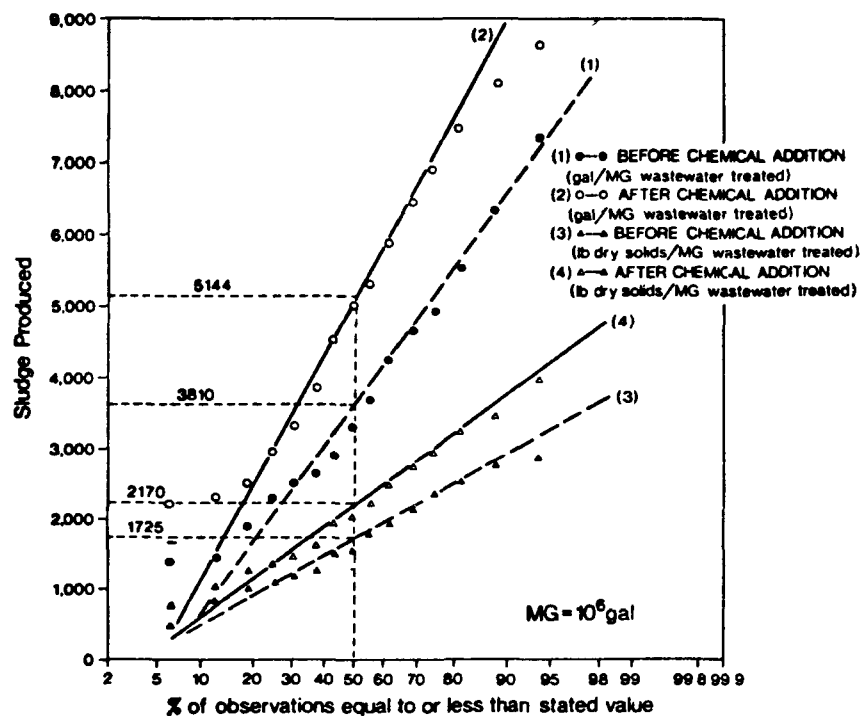
(lbs. dry solids/MG) ÷ 10 = kg/1000 m³

FIGURE 12.   PROBABILITY DISTRIBUTION FOR SLUDGE PRODUCED
            AT PRIMARY PLANTS WITH ADDITION OF METAL SALTS, (22)

phosphorus target. The sludge mass increased by 40%. Similarly, sludge volume and mass increased by 35% and 26% respectively for activated sludge plants where metal salts had been added to the aeration tanks (Figure 13).

(lbs. dry solids/MG) ÷ 10 = kg/1000 m³
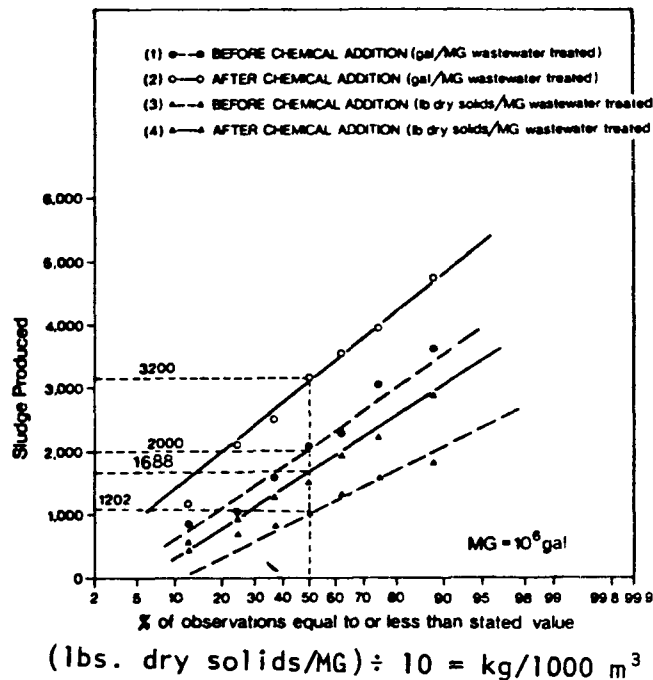
FIGURE 13. PROBABILITY DISTRIBUTION FOR SLUDGE PRODUCED AT SECONDARY (C.A.S.) PLANTS WITH ADDITION OF METAL SALTS TO AERATION TANK. (22)

Based on the results of the Ontario survey (22), some generalizations concerning sludge production are shown in Table 5. The rule-of-thumb that sludge volume approaches 0.5% of the influent hydraulic load to a conventional plant is a good approximation. By using this estimate, the apparent margin for safety would allow upgrading of a conventional plant to include chemical phosphorus removal to 1.0 mg.L^{-1} total phosphorus using metal salts without major expansion of sludge handling facilities.

TABLE 5.   SLUDGE PRODUCTION-SUGGESTED DESIGN
DATA (22)

System	Sludge Quantity		
	g capita^{-1}d^{-1}	Volume % of Influent	kg d.s./10^{3}m^3
Conventional Primary	77	0.20	120
Upgraded Primary	109	0.32	170
Conventional A.S.[b]	114	0.38	173
Upgraded A.S.[b]	145	0.51	218

[a]Based on Q = 658 ℓ capita^{-1}d^{-1}.   [b]Primary + waste activated.

d.s.   = dry solids.

SLUDGE DIGESTION

Before sludges can be disposed of in Ontario, they are digested.
In general, sludges from Ontario phosphorus removal facilities
have been found to be readily digestible in both existing aerobic
and anaerobic digesters. Initial problems which were experienced
could be related to the increase in sludge loading rather than the
nature of the sludge itself. This increased digester loading
has resulted in inadequate heat exchanger capacity which led to
operational problems caused by reduced digester temperature. Di-
gester (primary) foaming due to increased volatile solids loading
and inadequate gas/liquid separation has in some cases led to
further operational problems.

Inhibitive effects due to accumulated metal salts have never been
experienced. In one case (23), digester operation was completely
disrupted due to erratic lime dosing for phosphorus removal during
start-up. This resulted in periodic massive doses of high pH

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sludge being pumped to the digester until the digesters' buffer-

ing capacity was exceeded.

Later, under continuous operation, the digester was found to oper-

ate very effectively provided a sludge blanket of 0.3-0.5 m was

maintained in the clarifier. This partially neutralized the raw

sludge to a pH of 8.5-9.0.

Phosphorus resolubilization within the digester has been found to

be insignificant in relation to the total plant loading, regard-

less of the chemical used.

SLUDGE UTILIZATION AND DISPOSAL

As shown in Table 6, the most common method of sewage sludge dis-

posal in Ontario is land application of liquid digested sludge to

agricultural lands. The application of sludge to agricultural

lands is governed by Provincial Guidelines (6). Every effort is

made to dispose and at the same time utilize the sludge for its

TABLE 6. SLUDGE DISPOSAL METHODS PRACTICED IN ONTARIO(22)

Method of Disposal	No. of Plants	Percent of Total Plants	Wt of Sludge (dry tons/yr)	Percent of Total Wt
Application to Agricultural Lands	98	63.2	52,900	34.0
Incineration	3	2.0	62,000	39.8
Landfill Application	17	11.0	35,000	22.5
Dumpsite	14	9.0		
Storage Lagoon	7	4.5	5,800	3.7
Drying Beds	16	10.3		
TOTAL	155	100	155,700	100

potential nutrient value and soil builder characteristics. The

Guidelines take cognizance of this potential nutrient value but

at the same time ensure that no appreciable metal build-up in the

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soil will occur. Details concerning Ontario's experience have been reported on elsewhere (21).

FULL SCALE PHOSPHORUS REMOVAL COSTS

The costs depicted in Figures 14 and 15, are capital and operating cost data from 64 Ontario plants which had been practising phos-
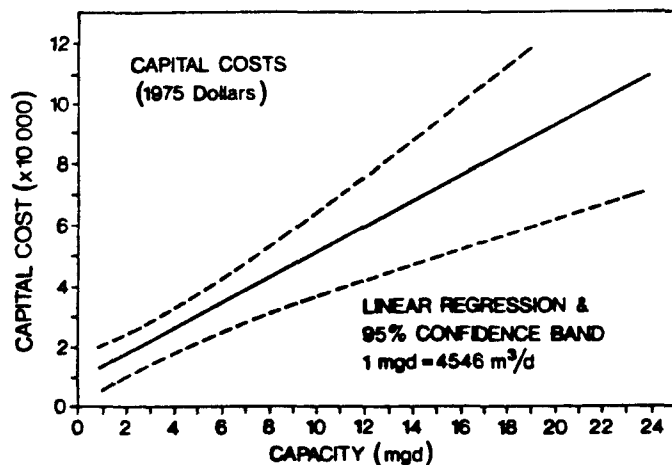
FIGURE 14. PHOSPHORUS REMOVAL EQUIPMENT-CAPITAL COSTS. (24)
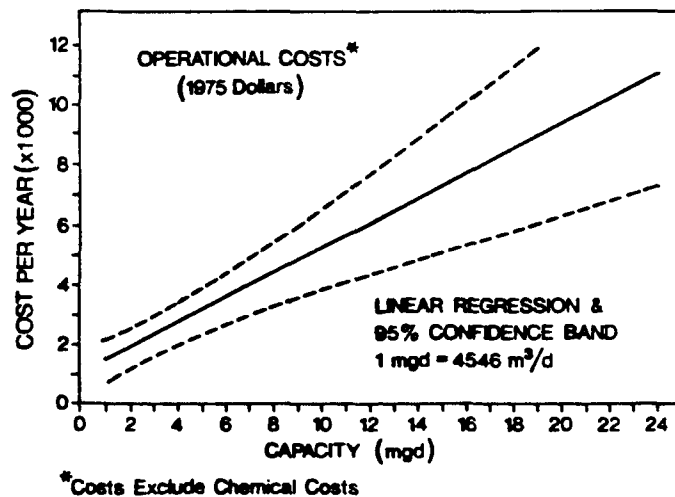
FIGURE 15. PHOSPHORUS REMOVAL-OPERATIONAL COSTS. (24)

phorus removal for 3-6 years prior to the survey (24). The cost data can be adjusted to 1979 dollars by using a multiplication factor of 1.38. This is based on the Marshall and Swift index of 451 for 1975 and 621 for 1979. The operational costs shown in Figure 15 exclude the cost of chemicals.

Chemical costs represent invariably the largest fraction of the total operating cost of the phosphorus removal facility component. Table 7 shows a percentage breakdown of the total annual costs for a 4500 m^3d^{-1} P-removal facility.

TABLE 7. TOTAL ANNUAL COSTS FOR A 4500 M^3D^{-1} P-REMOVAL FACILITY (25)

Process Option	Percentage of Total Annual Cost		
	Capital	Chemicals	Operation and Maintenance
Lime Primary	19	40	41
Metallic salt	19	70	11
Lime Tertiary	31	24	45

Actual chemical costs (1976) for operating facilities have ranged from $0.55 to $17. per 1000 m^3 of sewage treated in the plants surveyed. The average being $5. per 1000 m^3 treated.

CURRENT PICTURE

The initial and current distribution of chemical usage at Ontario phosphorus removal facilities is summarized in Table 8 (26). As

TABLE 8. CHEMICAL USAGE DISTRIBUTION (26)

Chemical	Initial (%)	1976 (%)	1979 (%)
Aluminum Sulfate	32	25	26
Iron Salts	60	64	70
Lime	5	6	2
None	3	5	2

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shown, the type of chemical used for phosphorus removal has changed little over the years. It should be noted, however, that the number of plants using lime has decreased dramatically. This in part is attributable to the fact that plant operators do not like lime and their bad experiences with lime feeding equipment.

Figure 16 summarizes the current status of phosphorus removal technology for Ontario's primary and secondary treatment plants. Since 1973 the total number of plants practicing phosphorus removal has increased from 111 to 272 in 1979, out of a total of 340 plants. This represents 87% of the total hydraulic plant capacity in Ontario.
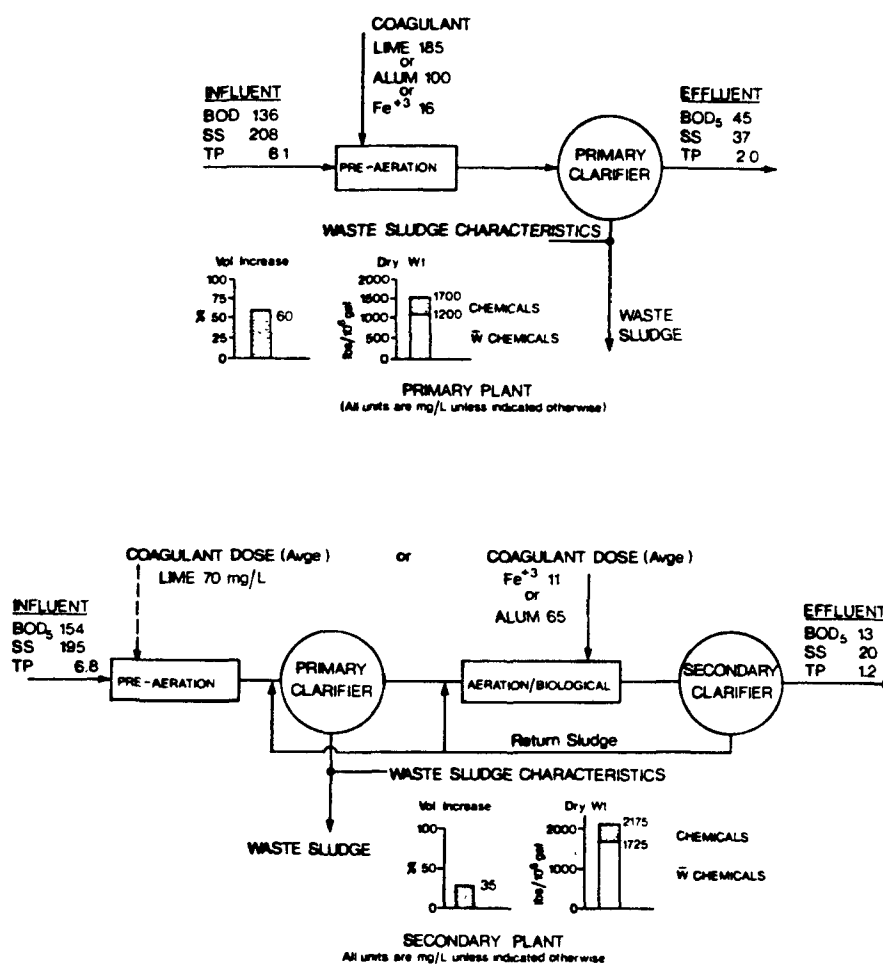
FIGURE 16. TYPICAL PHOSPHORUS REMOVAL PROCESSES. (27)

Having removed all this phosphorus over the years, the obvious question is raised: "Are we seeing any response by improved lake water quality?" Data summarized (28) recently as shown in Figure 17 does indeed show an encouraging decreasing trend in both total
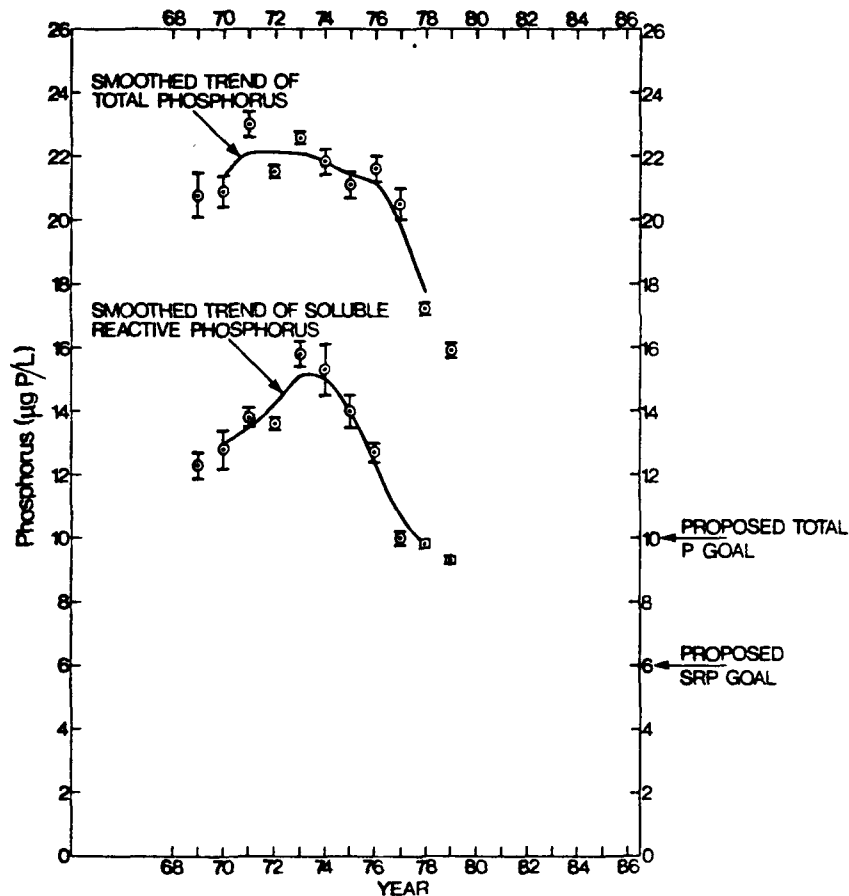
FIGURE 17. LAKE ONTARIO PHOSPHORUS IN SPRING 1969 TO 1979. (28)

and soluble reactive phosphorus in the offshore waters of Lake Ontario.

This paper paper has focused on phosphorus control even though nitrogen has in some cases been found to be nutrient limiting.

In Ontario several municipal and industrial treatment plants

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nitrify their effluents. In these instances local water quality
requirements dictate that nitrification be practiced. In general
though, nitrogen removal is not required in Ontario.

FUTURE DIRECTIONS

The new Canada-United States Agreement signed in 1978 reaffirms
among other things the objectives outlined in the 1972 Agreement.
As far as nutrients are concerned lower targets of 0.5 mg.L^{-1} for
point-discharges from municipal plants in the Lower Great Lakes
are advocated.

Before embarking on this course of action the question of other
phosphorus management strategies to meet the loading targets for
the various Great Lakes has to be examined. The IJC Task Force on
Phosphorus Management Strategies has recently addressed this aspect
and has now (July 1980) delivered its final report to the IJC's
Great Lakes Water Quality Board and Great Lakes Science Advisory
Board.

It would seem reasonable though that regardless of any other new
phosphorus management strategy or strategies, every effort be made
that the initial target of 1.0 mg.L^{-1} total effluent phosphorus
concentration be met. Larger plants may also be in a position to
produce effluents with lower than 1.0 mg.L^{-1} total phosphorus con-
centration at little extra expense.

The question of phosphorus availability, its significance vis-a-vis
waste treatment processes and impact on phosphorus management
strategies remains to be resolved.

Promising new technologies which require no or reduced amounts of chemical precipitants for phosphorus are under development and demonstration, which, once proven will be implemented.

SUMMARY

This paper outlined the phosphorus control program embarked on by Canada and specifically identified the highly successful joint venture between the Governments of Canada and the Province of Ontario in this regard.

Some technical points of significance which should be of interest to others are:

1. Reductions in laundry detergent phosphorus concentrations resulted in at least 20% lower influent phosphorus centrations to treatment plants, hence lower precipitant chemical dosage requirements, and less sludge volume generated.

2. A program of treatability studies is a prerequisite to successful low-cost implementation of chemical precipitation technology for phosphorus removal at existing wastewater treatment plants.

3. The metal salts of iron and aluminum are equally popular as a choice of precipitant if found to be equally effective in removing phosphorus at a treatment plant.

4. Lime is not a popular choice of precipitant.

5. Simultaneous precipitation at existing activated sludge plants has been found to be the most effective low-cost solution for the removal of phosphorus.

6. The application of chemical precipitation technology to various types of lagoon treatment processes did not present any problems.

7. Secondary clarifiers must be designed for overflow rate of <1.4 mh^{-1} at peak flow in order to ensure that an effluent objective of 1.0 mg.L^{-1} can be achieved.

8. Sludge volumes increase by 60% and 35% for primary and secondary plants (simultaneous precipitation) when adding metal salts to achieve an effluent objective of 1.0 mg L^{-1} total phosphorus.

9. Sludge digestion problems (aerobic or anaerobic) were not encountered.

REFERENCES

1. O.E.C.D., "Eutrophication in Large Lakes and Impoundments." (Proceedings of a Symposium held at Uppsala, Sweden, May 1968).

2. Canada Water Year Book, Environmental Management Service, Fisheries and Environment Canada, 1976.

3. International Joint Commission, "Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River," Vol. 1, Summary (1969).

4. "Canada-Ontario Agreement on the Lower Great Lakes Water Quality." (August 1971.)

5. Urban Drainage Subcommittee of the Canada-Ontario Agreement on Great Lakes Water Quality, "Manual of Practice on Urban Drainage."

6. Ontario Ministry of Agriculture and Food - Ontario Ministry of the Environment, "Guidelines for Sewage Sludge Utilization on Agricultural Lands," (April, 1978).

7. International Reference Group on Great Lakes Pollution from Land Use Activities (PLUARG), "Environmental Management Strategy for the Great Lakes System." Final Report to the International Joint Commission (July 1978).

8. Van Fleet, G.L., "Phosphorus Removal in Ontario," Phosphorus Design Seminar, Canada-Ontario Agreement Conference Proceedings No. 1, (1973).

9. Ministry of the Environment, "Operating Summary - Water Pollution Control Projects," (1978).

10. Stepko, W.E. and E.E. Shannon, "Phosphorus Removal Demonstration Study Using Ferric Chloride and Alum at C.F.B. Uplands," Environment Canada, Environmental Protection Service Report EPS 4-WP-74-5.

11. Black, S.A., "Experience with Phosphorus Removal at Existing Ontario Municipal Wastewater Treatment Plants," Chapter 13, Phosphorus Management Strategies for Lakes, Loehr, Martin and Rast, editors, Ann Arbor Science, publishers (1980).

12. Prested, B.P., et al., "Development of Prediction Models for Chemical Phosphorus Removal, Volume 1," Canada-Ontario Agreement Research Report No. 68 (1977).

13. Shannon, E.E. and R.J. Rush, "Phosphorus Removal Treatability Studies at C.F.B. Borden, Petawawa, Trenton and Uplands," Environment Canada, Environmental Protection Service Report EPS 4-WP-73-5.

14. Shannon, E.E. "Physical-Chemical Phosphorus Removal Processes," presented at the Nutrient Control Seminar, Calgary, Alberta (February, 1980).

15. Prested, B.P., E.E. Shann and R.J. Rush, "Development of Prediction Models for Chemical Phosphorus Removal, Volume II," Canada-Ontario Agreement Research Report No. 78, (1978).

16. Black and Veatch, Consulting Engineers, "Process Design Manual for Phosphorus Removal," Report to U.S. Environmental Protection Agency, Program #170.0GNP (1971).

17. Boyko, B.I. and J.W.G. Rupke, "Phosphorus Removal Within Existing Wastewater Treatment Facilities," Canada-Ontario Agreement Research Report No. 44 (1976).

18. Graham, H.J. and R.B. Hunsinger, "Phosphorus Reduction from Continuous Overflow Lagoons by Addition of Coagulants to Influent Sewage," Canada-Ontario Agreement Research Report No. 65, (1977).

19. Ahlberg, N.R., "Phosphorus Removal in a Facultative Aerated Lagoon - Grimsby WPCP," Ontario Ministry of the Environment, Research Branch, (July 1973).

20. Graham, H.J. and R.B. Hunsinger, "Phosphorus Removal in Seasonal Retention Lagoons by Batch Chemical Precipitation," Canada-Ontario Agreement Research Report No. 13, (1971).

21. Schmidtke, N.W., "Sludge Generation, Handling and Disposal at Phosphorus Control Facilities," Chapter 15, Phosphorus Management Strategies for Lakes, Loehr, Martin and Rast, editors; Ann Arbor Science, publishers, (1980).

22. Antonic, M., M.F. Hamoda, D.B. Cohen and N.W. Schmidtke, "A Survey of Ontario Sludge Disposal Practices", Project No. 74-3-19, Canada-Ontario Agreement Research Report (in press).

23. Black, S.A., "Anaerobic Digestion of Lime Sewage Sludge," Canada-Ontario Agreement Research Report No. 50, (1976).

24. Archer, J., "Summary Report on Phosphorus Removal", Canada-Ontario Agreement Research Report No. 83, (1978).

25. Schmidtke, N.W., "Coagulation and P-Removal," Lecture presented at the IAWPR Post-Conference Continuing Education Course, University of Melbourne, Australia,(October 23-26, 1976).

26. Rupke, J.W.G., "Operational Experience in Phosphorus Removal," Chapter 14, Phosphorus Management Strategies for Lakes, Loehr, Martin and Rast, editors; Ann Arbor Science, publishers, (1980).

27. Schmidtke, N.W. and D.B. Cohen, "Municipal Sludge Disposal on Land, A Down-to-Earth Solution," presented at the 29th Annual Convention of the Western Canada Water and Sewage Conference, Edmonton, Alberta, September 29-30, 1977.

28. Dobson, H., "Observed Phosphorus in Lake Ontario," Great Lakes Focus on Water Quality, 6(1), April 1980. International Joint Commission, Windsor, Ontario.

Appendix A to this paper summarizes the many phosphorus related studies conducted in Ontario, over the past 8 years.

Appendix B identifies nitrogen conversion/removal studies conducted under the Canada-Ontario Agreement.

PHOSPHORUS RELATED STUDIES

Project Title	Report Number*
TOPIC - 1. Phosphorus Removal - Primary and Secondary Treatment Plants	
Phosphorus Removal at the Sarnia Water Pollution Control Plant	14
The Use of Lime in the Treatment of Municipal Wastewaters	21
Phosphorus Removal Treatability Studies at CFB Borden, Petawawa, Trenton and Uplands	EPS 4-WP-73-5
Full Scale Phosphorus Removal at CFB Petawawa (Primary Plant)	EPS 4-WP-74-3
Phosphorus Removal Demonstration Study Using Ferric Chloride and Alum at CFB Uplands	EPS 4-WP-74-5
Phosphorus Removal Within Existing Wastewater Treatment Facilities	44
Phosphorus Removal Demonstration Studies at CFB Trenton Phase I Phase II	EPS 4-WP-74-9 EPS 4-WP-76-4
Phosphorus Removal Demonstration Studies Using Lime, Alum and Ferric Chloride at CFB Borden	EPS 4-WP-78-2
Phosphorus Removal Design Seminar, Toronto, 1973	1 (Conf. Proc.)
Integration of Physico-Chemical and Biological Wastewater Treatment Processes	7
TOPIC - 2. Phosphorus Removal - Lagoons	
Nutrient Control in Sewage Lagoons Volume I Volume II	8 23
Phosphorus Removal in Seasonal Retention Lagoons by Batch Chemical Precipitation	13
Spray Runoff Disposal of Waste Stabilization Pond Effluent	22
Phosphorus Reduction from Continuous Overflow Lagoons by Addition of Coagulants to Influent Sewage	65
TOPIC - 3. Process Control	
Chemical Control for Phosphorus Removal	4

* Individual numbers refer to reports published in the Canada-Ontario Agreement Research Report and Conference Proceedings (Conf. Proc.) Series.
  EPS numbers are reports published in the Environmental Protection Service, Environment Canada, Report Series.

PHOSPHORUS RELATED STUDIES (CONT'D.)

Project Title	Report Number*
TOPIC - 4. Prediction Models	
Development of Prediction Models for Chemical Phosphorus Removal Volume I Volume II	68 78
TOPIC 5. Sources of Chemicals	
Use and Production of Iron Salts for Phosphorus Removal	5
Utilization of Industrial Wastes and Waste By-products for Phosphorus Removal: An Inventory and Assessment	6
Utilization of Aluminized Red Mud Solids (ARMS) for Phosphorus Removal	EPS 4-WP-75-2
TOPIC 6. Chemical Aids	
Assessment of Polyelectrolytes for Phosphorus Removal	37
TOPIC 7. Process Studies	
Design and Performance Criteria for Settling Tanks for the Removal of Physical Chemical Flocs Volume I Volume II	10 56
TOPIC 8. Polishing Processes	
Effluent Polishing by Filtration Through Activated Alumina Volume I Volume II	39 40
Tertiary Phosphorus Removal and Limiting Nutrient Studies at CFS Lac St. Denis	EPS 4-WP-74-1
The Welland Canal Water Quality Experiments	EPS 4-WP-74-10

* Individual numbers refer to reports published in the Canada-Ontario Agreement Research Report and Conference Proceedings (Conf. Proc.) Series.
EPS numbers are reports published in the Environmental Protection Service, Environment Canada, Report Series.

Project Title	Report Number*
TOPIC - 9. Detergent Substitution Studies	
Effect of Citrate and Carbonate Based Detergents on Wastewater Characteristics and Treatment	61
A Study of NTA Degradation in a Receiving Stream	EPS 4-WP-74-7
Detergent Substitution Studies at CFS Gloucester	EPS 4-WP-73-3
Impact of Nitrilotriacetic Acid (NTA) on an Activated Sludge Plant	91
Activated Sludge Degradation of Nitrilotriactic Acid (NTA) - Metal Complexes	EPS 4-WP-78-5
TOPIC 10. Sludges	
a) Dewatering/Conditioning	
Sludge Dewatering Design Manual	72
b) Digestion Processes	
Aerobic Digestion of Organic Sludges Containing Inorganic Phosphorus Precipitates	
Phase I	3
Volume I	58
Anaerobic Digestion of Lime Sewage Sludge	50
c) Application to Land	
Land Application of Sewage Sludge	1
Heavy Metals in Agricultural Lands Receiving Chemical Sewage Sludges	
Volume I	9
Volume II	25
Volume III	30
Volume IV	51
Land Disposal of Sewage Sludge (Field Studies)	
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Volume II	24
Volume III	35
Volume IV	60
Volume V	73
Volume VI	90
Volume VII	98
Land Application of Digested Sludge Under Adverse Conditions	53
Air-Dried Chemical Sewage Sludge Disposal on Agricultural Land	
Volume I	EPS 4-WP-78-3
Phosphate Fertilizer and Sewage Sludge Use on Agricultural Land - The Potential for Cadmium Uptake by Crops	EPS 4-WP-79-2
Chemical Sewage Sludge Disposal on Land (Lysimeter Studies)	
Volume I	67
Volume II	79

*Individual numbers refer to reports published in the Canada-Ontario
 Agreement Research Report and Conference Proceedings (Conf.Proc.) Series

EPS numbers are reports published in the Environmental Protection
Service, Environment Canada, Report Series.

Project Title	Report Number*
d) Heat Processes	
Wet Air Oxidation of Chemical sludges	12
Evaluation of the Barber-Coleman Wetox Process for Sewage Sludge Disposal	20
Sludge Incineration and Precipitant Recovery	
Volume I	31
Volume II	74
Volume III	75
e) Recovery of Materials from Process Residuals	
Recycling of Incinerator Ash	19
Removal of Phosphates and Metals from Sewage Sludge	28
The Removal and Recovery of Metals from Sludge and Sludge Incinerator Ash	33
Reuse of Waste SO_2 and Phosphate Sewage Sludge by Solidification with Lime and Fly Ash	69
f) Health Hazards	
Examination of Sewage and Sewage Sludge for Enteroviruses	
Volume I	27
Volume II	52
g) Computer-aided Planning of Regional Sludge Disposal Systems	46
h) Analysis	
The Analysis of Chemical Digester Sludges for Metals by Several Laboratory Groups	EPS 4-WP-78-1
Development of an Efficient Sampling Strategy to Characterize Digested Sludges	71
i) Sludge Handling and Disposal Seminar, Toronto, 1974 and 1978	2 & 6 (Conf.Proc.)

* Individual numbers refer to reports published in the Canada-Ontario Agreement Research Report and Conference Proceedings (Conf. Proc.) Series.
EPS numbers are reports published in the Environmental Protection Service, Environment Canada, Report Series.

APPENDIX B

NITROGEN RELATED STUDIES

Project Title	Report Number*
TOPIC - 1. Nitrification	
Reliability of Nitrification Systems with Integrated Phosphorus Precipitation	64
TOPIC - 2. Denitrification	
Continuous Biological Denitrification of Wastewater	EPS 4-WP-74-6
Evaluation of Industrial Waste Carbon Sources for Biological Denitrification	EPS 4-WP-79-9
TOPIC - 3. Nitrification-Denitrification	
Nitrogen Removal from Municipal Wastewater	17
Nitrification-Denitrification of Wastewater Using a Single Sludge System Volume I Volume II	 86 96
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PHOSPHORUS REMOVAL IN LOWER GREAT LAKES MUNICIPAL TREATMENT PLANTS

Joseph V. DePinto
Michael S. Switzenbaum
Thomas C. Young
James K. Edzwald
Department of Civil and Environmental Engineering
Clarkson College of Technology

INTRODUCTION

The North American Great Lakes contain approximately 20 percent of the world's supply of surface freshwater and, as such, are indispensible resources worthy of every effort possible to protect and preserve their quality. With respect to eutrophication control, it has been determined that reducing and restricting phosphorus inputs is the best approach for the Great Lakes. The International Joint Commission (IJC) of Canada and the United States recognized the need for phosphorus control in its 1978 Great Lakes Water Quality Agreement. This agreement called for, among other things, the achievement by all plants discharging more than one million gallons per day of "effluent concentrations of 1.0 milligram per litre total phosphorus maximum for plants in the basins of Lakes Superior, Michigan, and Huron, and 0.5 milligram per litre total phosphorus maximum for plants in the basins of Lakes Ontario and Erie." (IJC,1978).

The 1978 Agreement also provided for an eighteen month review to confirm the cited phosphorus load limitation, followed by the

establishment of load allocations and compliance schedules.
The purpose of this study was to provide information that might
be useful in making recommendations regarding phosphorus load
reduction requirements for municipal treatment plants in the
lower Great Lakes basins.

There are several questions related to the efficacy and desira-
bility of a 0.5 mg/L lower lakes municipal effuent phosphorus
standard which were addressed in this study. The current
status of municipal treatment plant activities in the lower
lakes with respect to phosphorus removal has been evaluated.
Such questions as "what are the prevalent approaches being taken
to reduce phosphorus effluent concentrations to 1.0 mg/L" and
"what technological needs would the treatment plants have to
reduce total phosphorus effluent levels to 0.5 mg/L or any point
below 1.0 mg/L" have been addressed. Also, there is a need to
know the reliability with which full scale treatment operation
can operate at the various phosphorus reduction performance
levels.

In addition to the technological aspect of establishing a phos-
phorus treatment regulation for the lower lakes treatment
plants, prudent use of the taxpayer's money requires systematic
evaluation of the relationship between costs incurred and phos-
phorus effluent performance. These costs could then be weighed
against the economic and environmental benefits of various
phosphorus effluent limitations below 1.0 mg/L. This type of

cost analysis at the individual treatment plant level is examined in this study. Costs data gathered in this study can provide crucial information and confirmation of assumptions necessary to make basin-wide cost projections for various municipal phosphorus management programs.

In order to address the questions posed in the above discussion, this study contained the following three-phase approach:

- A survey was made of all municipal treatment plants in the lower Great Lakes basins with effluent flows greater than 1 MGD. The purpose of the survey was to evaluate the phosphorus treatment approaches and plant performance and to confirm municipal phosphorus loads.

- A detailed field operation monitoring program was conducted at four treatment plants practicing phosphorus removal processes representative of lower Great Lakes basin plants. The performance of these plants was evaluated in terms of removal of various phosphorus fractions and the overall effluent quality as a function of the phosphorus removal process employed.

- A detailed analysis of costs incurred at the four selected treatment plants was made for the existing level of treatment. With these data as a base, estimates were made for costs associated with phosphorus removal.

SURVEY METHODS

In order to meet the objectives of the project, it was felt that several important pieces of information had to be gathered on every treatment plant in the Lake Erie and Lake Ontario basins with a discharge flow greater than 1 MGD. It was, therefore, determined that the following information be obtained for the plants in question:

Identification of the location of treatment plant in terms of lake basin, regulatory unit, county, city and receiving water body.

- Identification of type of treatment plant (eg. conventional activated sludge, extended aeration, trickling filter, primary treatment only, etc.)

- Identification of method of phosphorus removal, including point of chemical additions and any tertiary processes associated with P removal (such as filtration, sedimentation, etc.).

- Identification of annual average daily flow and design flow as well as total P concentrations in the raw sewage and plant effluent.

It was determined that there are 229 municipal treatment plants in the lower Great Lakes basins with a discharge greater than 1 MGD (3785 m^3/d). The above information was obtained for these plants primarily from a questionnaire, which elicited a 66 percent response. Although not all of the above information was obtained from every plant, a flow and effluent phosphorus concentration has been assigned to each of the 229 plants, either from the questionnaire data or from an independent IJC survey (IJC, 1979).

TREATMENT PLANT MONITORING PROCEDURES

Four different treatment plants were intensively monitored during the field study phase of this project, which was performed during July and August, 1979. Each of the four treatment plants was visited for a two-week period, during which time 12 to 15 eight-hour composite samples (24 hour composites at the Frank Van Lare plant) were collected from three key locations within each plant. The sampling points for each plant were selected in an effort to isolate the effect of the phosphorus removal procedure. Presented in Table 1 is a listing of the sampling locations which were used at each plant.

TABLE 1. SAMPLING LOCATIONS WITHIN MONITORED TREATMENT PLANTS

Plant Name	Sampling Location Name	Location Characteristics
Gates-Chili-Ogden	Raw Influent	Sample taken from aerated grit chamber
	Primary Effluent	Sample taken from weir of primary clarifier
	Secondary Effluent	Sample taken from weir of final clarifier
Frank Van Lare	Raw Influent	Sample taken from aerated grit chamber
	Alum Effluent	Sample taken from weir of primary clarifier after alum treatment
	Biological Effluent	Sample taken from weir of final clarifier
Big Sister Creek	Raw Influent	Sample taken from post-screening wet well
	Secondary Effluent	Sample taken from weir of secondary clarifier
	Filtered Effluent	Sample taken from sand filter effluent channel
Ely	Raw Effluent	Sample taken from aerated grit chamber
	Secondary Effluent	Sample taken from weir of secondary clarifier
	Filtered Effluent	Sample taken from dual media filter effluent channel

A flow chart of the analyses performed on the composite samples is presented in Figure 1. Each composite sample was analyzed on-site for chemical oxygen demand (COD), suspended solids (SS), pH, alkalinity, soluble reactive phosphorus (SRP), total phosphorus (TP), total particulate phosphorus (TPP), and "available phosphorus" (AP) as defined by NaOH extraction. Less frequently, on-site analyses were performed to determine total Kjeldahl nitrogen (TKN), nitrate and nitrite nitrogen (NO_x), and five-day biochemical oxygen demand (BOD_5). Phosphorus precipitation cations (Al^{3+} and Fe^{3+}) were measured off-site on sub-samples taken in connection with the less frequent series of on-site analyses.

For the most part the analytical methods used in this study were according to Standard Methods (APHA, 1975) and/or recommended by EPA (1976). Additionally, the determination of the total NaOH-extractable fraction of particulate phosphorus was made by an extraction method similar to that of Sagher, et al. (1975). Inasmuch as the particulates of interest in this investigation were from municipal wastewaters and, thus, contained relatively labile organic phosphorus, it was decided to measure the total phosphorus in the extracts (rather than inorganic P only) for comparison with bioassay tests of particulate phosphorus bio-availability to algae.

As a verification of the chemical analysis of phosphorus availability in the wastewaters, a bioassay of algal-available soluble and particulate phosphorus was conducted on selected

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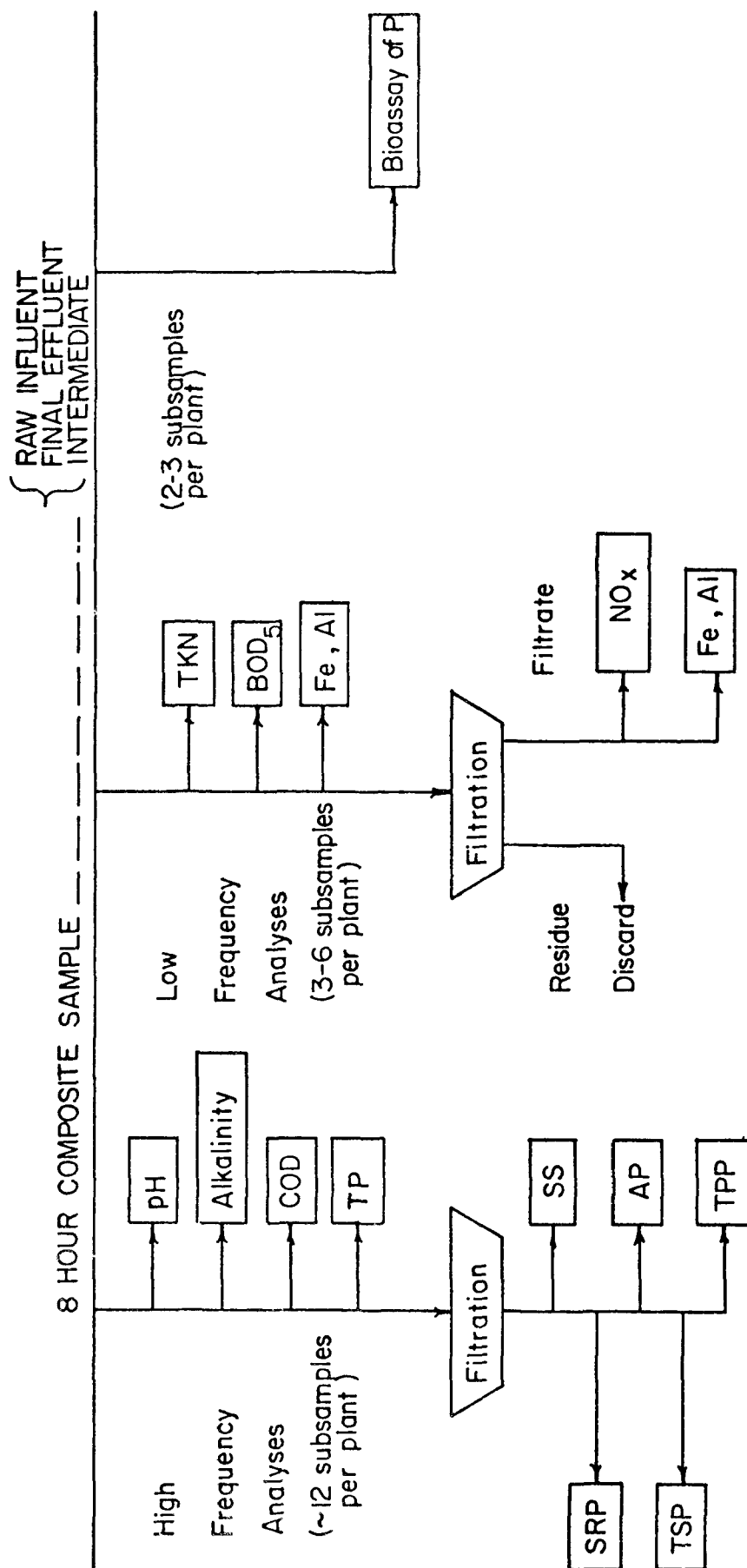
Figure 3. Flow Diagram of Analytical Work on Wastewater Samples

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samples from each plant (see Figure 1). While it is generally accepted that only a bioassay can be used to measure truly available phosphorus, the details of the experimental procedures vary widely (DePinto, 1978a). We have selected an approach which employs a direct measurement of phosphorus taken up by a test algal species, thus overcoming the problems associated with indirect estimates relating algal growth to phosphorus uptake. Furthermore, our approach provides for the separation of the assay algae from the particulate material in the plant effluent, which is a prerequisite for direct measurement of algal phosphorus.

Given the above considerations it was determined a dual culture approach similar to that currently being used in our laboratory (DePinto, 1978b) would circumvent many of the problems associated with bioassay determination of available phosphorus from particulates. The apparatus employed (hereafter referred to as a Dual Culture Diffusion Apparatus - DCDA) allows a suspension of particulate matter from a wastewater sample to be placed in one culture vessel (regeneration vessel) and the placement of a unialgal assay culture (with a known P content) in a separate assay vessel. The two vessels would be clamped together but the contents would be separated by a 0.4 µm membrane filter. This set-up permits repeated, routine sampling of the algae in the assay vessel without disturbing the particle-water system in the regeneration vessel. The membrane between the two vessels would prevent cross-contamination of

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particulates but would allow cross-diffusion of soluble material (including P released from the particle-water suspension). Any available phosphorus released by the material in the regeneration vessel will have a tendency to diffuse across the membrane to the assay vessel where it will be rapidly immobilized by the P-starved algae. By periodically sampling the phosphorus content of the assay vessel and performing a mass balance on the system one can determine the extent to which phosphorus is being released by the particulates. Details of DCDA operation and data analysis can be found in McKosky (1978).

In addition to the above analysis on the suspended solids in a sample, a bioassay of algal available P was performed on the soluble fraction. To bioassay the fraction of total soluble (less than 0.45 μm) phosphorus in these samples that is available for algal uptake, a simple sequential batch uptake experiment was performed. A filtered wastewater sample was inoculated with algae of a known phosphorus content and subsequently harvested after a 3-5 day growth period to measure the phosphorus taken up by the algae. This procedure was repeated until no further uptake occurred. The cumulative algal-uptake of phosphorus represented that portion of the total soluble phosphorus that was bioavailable.

WASTEWATER TREATMENT PLANT DESCRIPTIONS

Given below are general descriptions of the treatment methods employed at the four wastewater plants which were studied

intensively on-site during this investigation. Included in the descriptions are the approaches used for preliminary, primary, secondary, and tertiary wastewater treatment, and sludge treatment and disposal.

GATES-CHILI-OGDEN

At the Gates-Chili-Ogden facility, a 20 MGD plant located near Rochester, NY, raw municipal wastewater was given preliminary and primary treatment prior to biological treatment by a conventional activated sludge process. To remove phosphorus, alum was added in liquid form to the effluent of the aeration basin, upstream from the final clarifiers as illustrated in the process schematic (Figure 2). The secondary sludge, which consisted of biological and aluminum-phosphorus solids, was partially recycled to the aeration basin and partially wasted. By recycling alum with the return activated sludge, the contact period between alum and phosphorus in the wastewater was increased, which would permit kinetically-limited precipitation reactions to approach equilibrium more closely than could occur without alum recycle. Waste secondary sludge was conditioned for flotation thickening with a polymer and combined after thickening with primary sludge. The combined sludges were dewatered by vacuum filtration and incinerated or composted on-site.

FRANK VAN LARE

The Frank Van Lare wastewater treatment plant is located in Rochester, NY. It has an average daily flow of approximately 100 MGD. During the monitoring studies, treatment consisted of

GCO-PROCESS SCHEMATIC
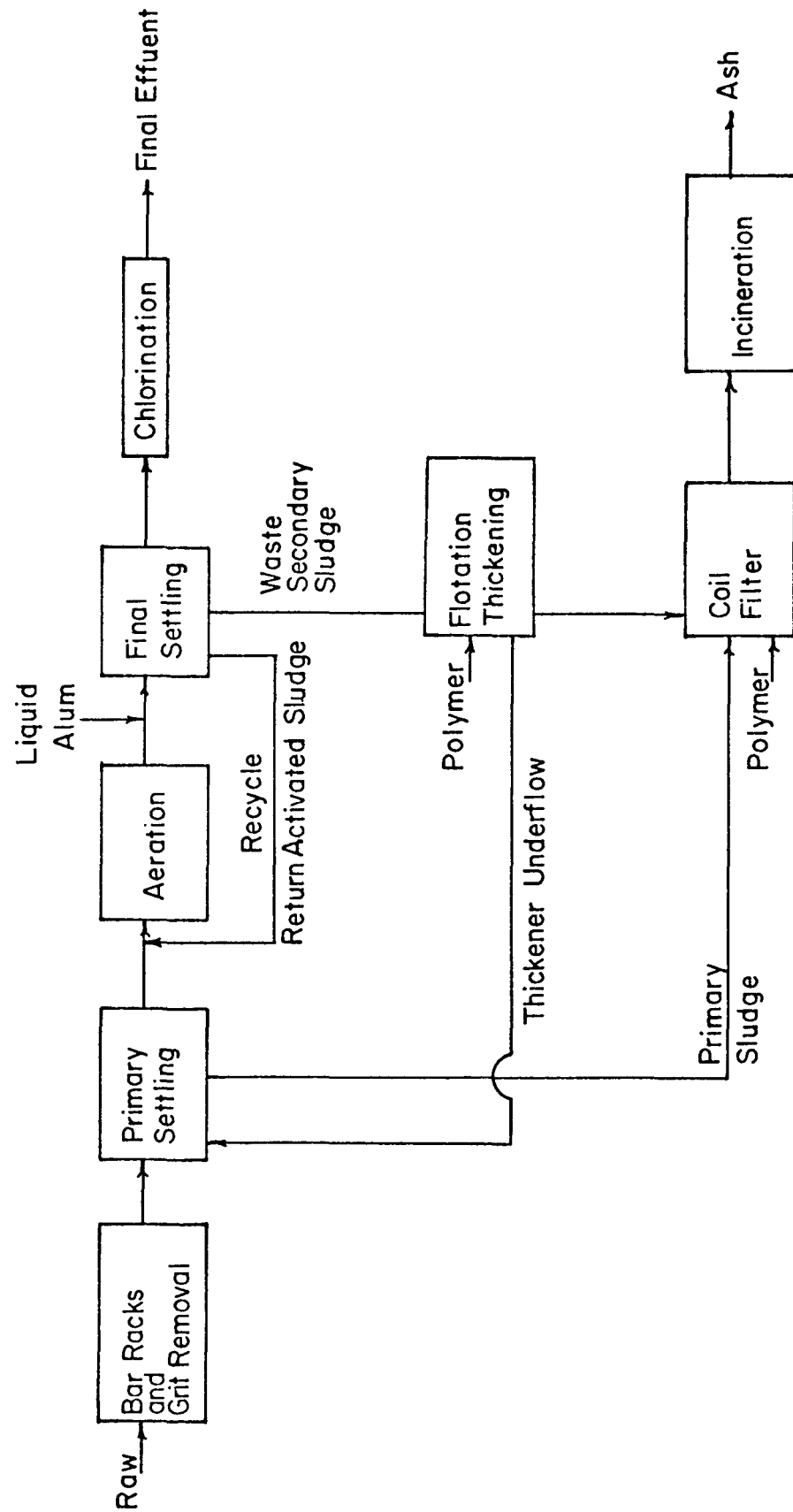
Figure 2. Process Schematic for Gates-Chili-Ogden Plant

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two main streams, as shown in the process schematic (Figure 3). Raw wastewater received preliminary screening and degritting and was then split for primary sedimentation and further treatment. To 20 percent of the total flow, liquid alum and a polymer were added just upstream from the primary clarifiers to enhance phosphorus removal during primary sedimentation. The remainder of the flow was given primary treatment, without alum addition, and biological treatment by conventional activated sludge. The clarified secondary effluent and alum-treated primary effluent were combined for chlorination prior to discharge. The primary sludges from both treatment streams were combined with wasted biological sludge for treatment by gravity thickening, vacuum filtration, and incineration.

BIG SISTER CREEK

The Big Sister Creek wastewater treatment plant, a 3.1 MDG plant located near Angola, NY, was upgraded in 1978 from a primary treatment facility to a tertiary treatment system. As shown in the process schematic for the Big Sister Creek plant (Figure 4), screened and degritted raw wastewater was sent without primary sedimentation to an aeration basin for biological treatment by an extended aeration activated sludge process. Effluent from the aeration basin is clarified by sedimentation and 70 percent of this flow was dosed with ferric chloride and a polymer for phosphorus removal in a solids contact clarifier. Effluent from the solids contact clarifier was applied to a sand filter, after which the filtrate was chlorinated for discharge. A portion of

VAN LARE-PROCESS SCHEMATIC
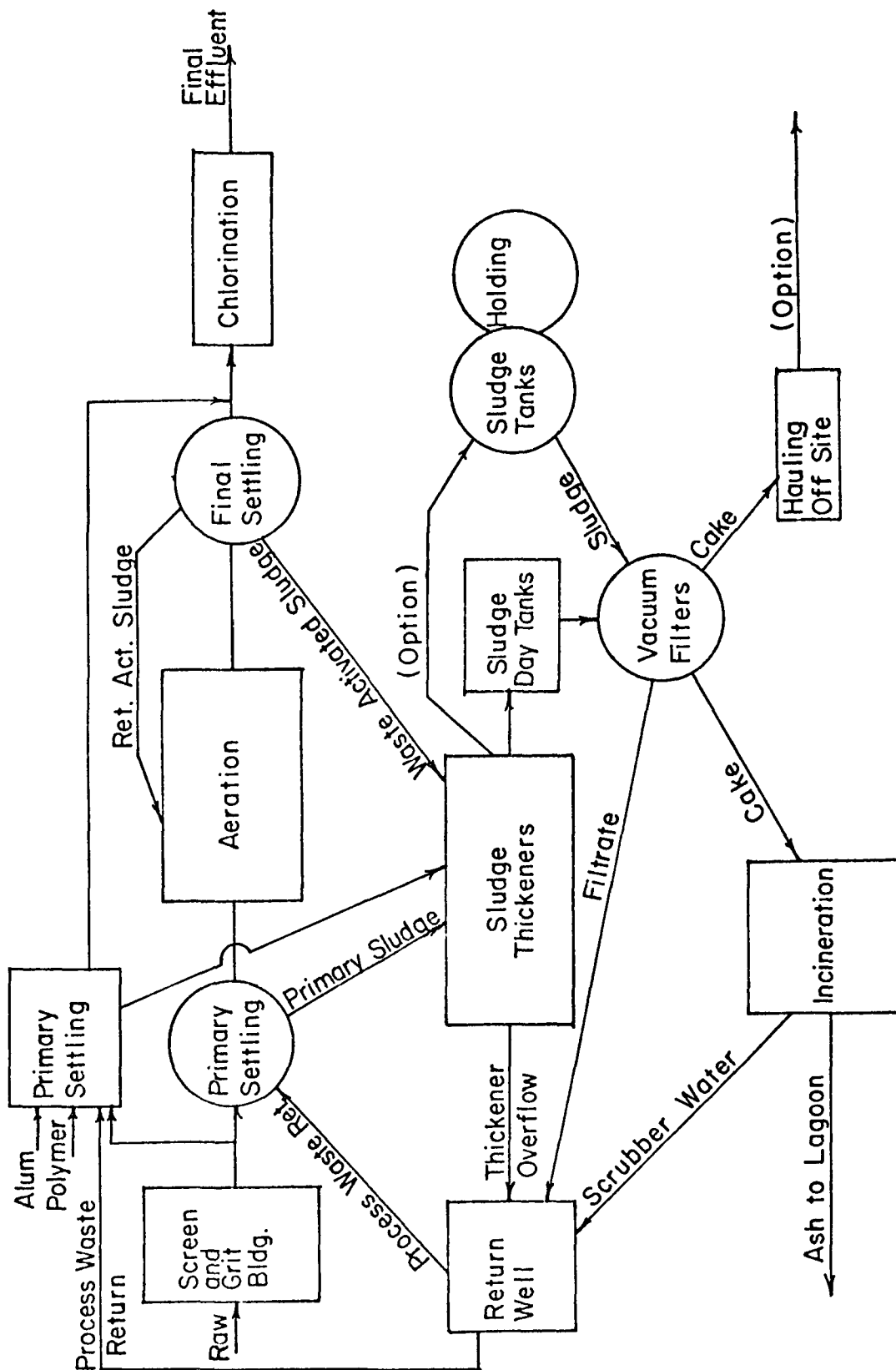
Figure 3. Process Schematic for Frank Van Lare Plant

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ANGOLA-PROCESS SCHEMATIC
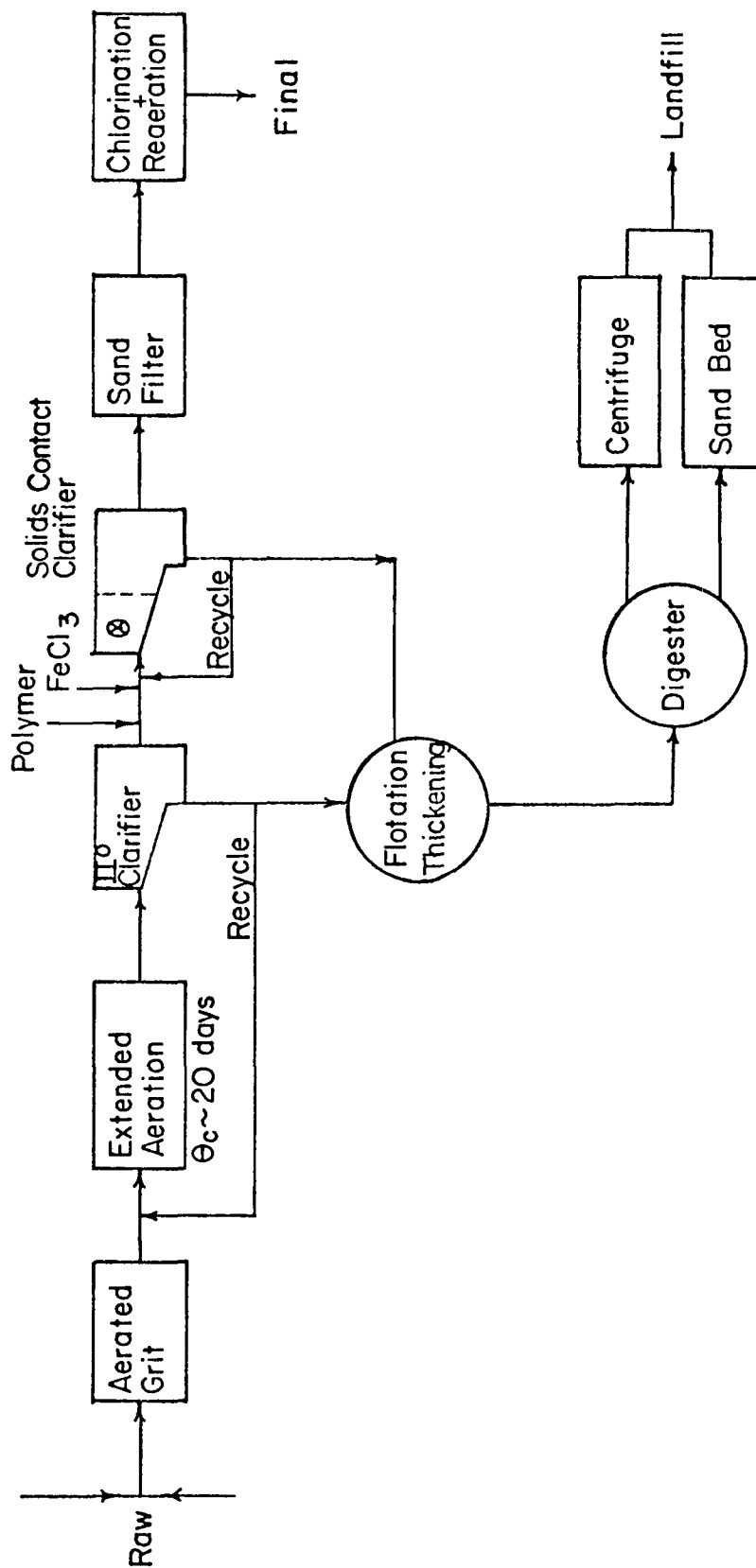
Figure 4.   Process Schematic for Big Sister Creek

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the iron-phosphorus sludge from the solids contact clarifier was recycled back to the clarifier influent. The sludge recycle provides an increased contact period between iron and wastewater phosphorus, which permits a closer approach to precipitation equilibrium, than would occur in the absence of solids recycle. Both secondary and iron-phosphorus sludges were thickened by flotation and combined for storage in an aerobic digester. Centrifugation and sand bed drying were employed for sludge de-watering. Dewatered sludge was trucked to an adjacent land fill for disposal.

ELY

As illustrated in the process schematic for the Ely, MN waste-water treatment plant (Figure 5), screened and degritted raw wastewater was given primary settling before biological treat-ment, which consisted of a single-stage trickling filter. Liquid alum and a polymer were added to the trickling filter effluent to enhance phosphorus removal during secondary clarification. All biological solids and alum-phosphate sludge which collected in the final clarifiers were recycled to the influent of the primary sedimentation tanks, which served to increase the time of contact between the alum, wastewater solids, and phosphorus. The secondary effluent was chlorinated, held briefly in non-functional solids contact tanks, and passed through a dual media filter prior to discharge from the plant. Sludge from the primary clarifier was thickened by gravity and conditioned with lime prior to vacuum filtration. A landfill

ELY-PROCESS SCHEMATIC
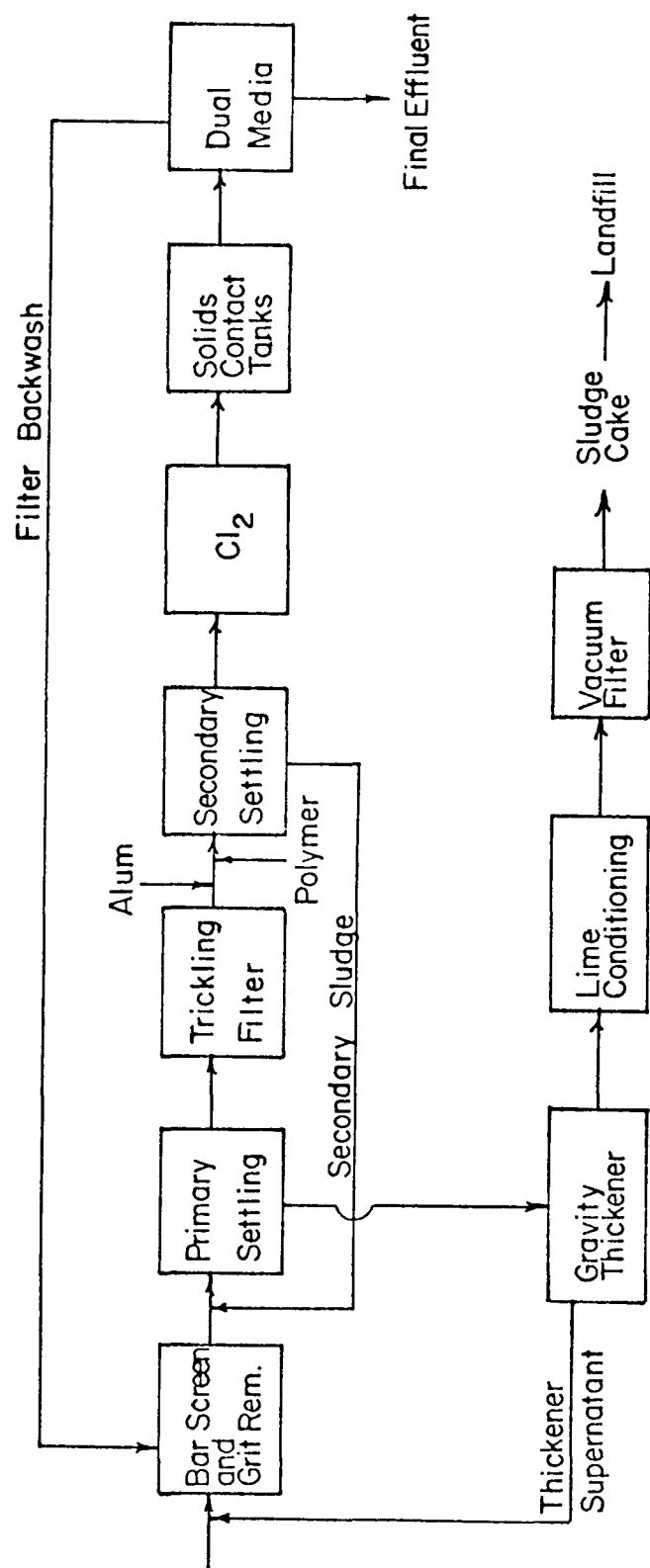
Figure 5.   Process Schematic for Ely Plant

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was used for disposal of the vacuum filter cake.

SURVEY RESULTS

The distribution of municipal treatment plants in the lower Great Lakes basins by state and Canadian province is presented in Table 2. Note that for the Lake Ontario basin the distribution of plants is relatively equal between U.S. and Canada; however, 77 percent of the Lake Erie basin plants are located in the U.S. These 229 plants range in annual phosphorus discharge from 0.6 to 2000 metric tons/yr, with effluent total phosphorus concentrations ranging from 0.3 to 17.5 mgP/L.

PHOSPHORUS REMOVAL APPROACHES

Based on the results of the questionnaire, an estimate of the relative distribution of treatment approaches for phosphorus removal at wastewater plants in the lower Great Lakes vicinity can be made. Of the 154 plants responding to the questionnaire, 104 indicated that phosphorus removal was being practiced while 30 were not practicing phosphorus removal. An additional 20 plants were eliminated from those who responded since they were later determined to be located outside the lower lakes basins or abandoned. Thus, from the questionnaire responses approximately 80 percent of the plants in the survey practiced phosphorus removal.

A summary of the major chemicals used for phosphorus removal and their point of addition in the treatment process (i.e. primary, secondary or tertiary) is shown in Table 3. Of the 104 plants

TABLE 2.   NUMBER OF PLANTS IN SURVEY

Lake Ontario

New York	48	U.S.	48
Ontario	43	Canada	43
	91		

Lake Erie

New York	10	U.S.	106
Pennsylvania	1	Canada	32
Indiana	3		
Michigan	23		
Ohio	69		
Ontario	32		
	138		

Totals:	U.S.	154
	Canada	75
		229

practicing phosphorus removal, 53 used an iron salt (one more

than shown in Table 6 as one respondent listed iron but did not

specify where), 49 used an aluminum salt, and only two used

lime. One plant used both iron and alum. The frequency of use

of the precipitation cations (aluminum or iron) is compared by

country in Table 4. In comparison, Fe or Al are used with about

the same frequency. Lime is now seldom used, based on our

survey.

In regard to the point in the treatment scheme where the majority

of phosphorus removal takes place, the data are summarized in

Table 5. At this point in time a relatively small percentage of

the plants are actually using a tertiary process to accomplish

phosphorus removal. A summary of the data suggests that

approaches for phosphorus removal include aluminum addition to

the secondary process, iron addition to primary, and iron addi-

tion to the secondary process, in order of decreasing frequency

of use.

PHOSPHORUS REMOVAL ACCOMPLISHMENTS

In spite of the fact that very few truly tertiary processes are

employed in the lower lakes area, those plants practicing phos-

phorus removal appear to be consistently achieving a 1.0 mgP/L

effluent total phosphorus goal. A frequency distribution,

developed for 30-day average effluent phosphorus concentrations,

is presented in Figure 6. Note that more plants (112) are

achieving a 1.0 mgP/L standard than the number which indicated

that they were practicing phosphorus removal (104). Of the

TABLE 3. TREATMENT APPROACHES BY CHEMICAL
(PRECIPITATION CATION) AND LOCATION

	Number of Plants								
	U.S.			Canada			Total		
	Al	Fe	Total	Al	Fe	Total	Al	Fe	Total
Primary	1	16	17	2	20	22	3	36	39
Secondary	26	6	32	17	8	25	43	14	57
Tertiary	2	2	4	1	0	1	3	2	5
Total	29	24	53	20	28	48	49	52	101

TABLE 4. FREQUENCY OF PRECIPITATION CATION USAGE

	Percent		
Metal	U.S.	Canada	Total
Al	54	41	48
Fe	44	57	50
Lime	2	2	2

TABLE 5. SUMMARY OF LOCATION OF PHOSPHORUS REMOVAL TREATMENT
IN THE TREATMENT PLANT PROCESS

	Percent		
Process Location	U.S.	Canada	Total
Primary	32	46	39
Secondary	60	52	56
Tertiary	8	2	5
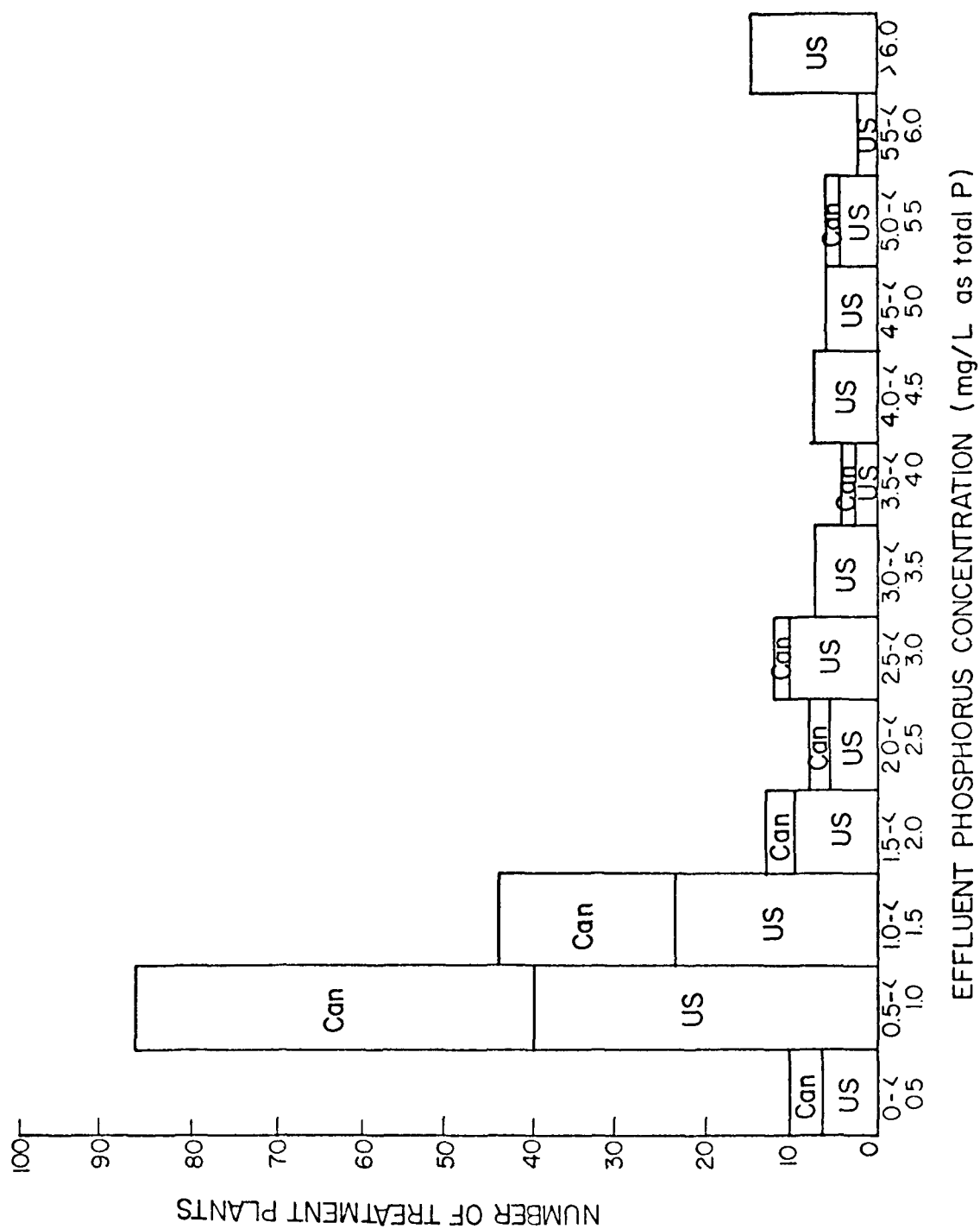
Figure 6. Histogram of Effluent Phosphorus Concentrations

plants for which effluent P data were available, 9 percent have an effluent total phosphorus concentration $\leq$ 0.5 mgP/L and 52 percent are discharging $\leq$ 1.0 mgP/L. These accomplishments are summarized by plant size and basin in Table 6.

Whether required or not, there are 19 plants in the basins currently meeting a 0.5 mgP/L standard. We received a questionnaire response, and therefore have treatment approach information, on 14 of these 19 plants. It is especially interesting to note that only 2 of the 14 plants are currently employing any tertiary treatment processes. Seven of the plants use $FeCl_3$ (some also use a polymer) or pickle liquor at some point in the treatment process; three of the plants use alum; and three plants claim to achieve 0.5 mgP/L with no chemical addition simply because the influent phosphorus is so low (1-2 mgP/L).

In order to get some feel for what percentage removals are currently needed to meet today's effluent phosphorus standards, a frequency distribution of removal percentage was prepared from our questionnaire data (Figure 7). It should be pointed out that only 117 plants made up the sample for this distribution, since both influent and effluent data were necessary to compile removal percentages. Recall that approximately 80 percent of the respondents to the survey were practicing phosphorus removal, yet only 63 percent of those reporting influent and effluent phosphorus levels were achieving 80 percent removal of total phosphorus through the plant. Virtually all (96 percent) of the

TABLE 6.   DISTRIBUTION OF PLANTS BY SIZE AND BASIN REACHING
1.0 and 0.5 mg P/L TOTAL PHOSPHORUS EFFLUENT
CONCENTRATIONS

Plant Size (mgd)*	No. of Plants in Size Range**	Plants Meeting 1.0 mg P/L Standard	Plants Meeting 0.5 mg P/L Standard
	Lake Erie		
<1	12	6	0
1-<10	94	47	8
10-<50	18	14	3
50-<100	5	1	0
≥100	2	1	0
Total	131	69	11
	Lake Ontario		
1	5	3	2
1-<10	60	29	5
10-<50	11	8	1
50-<100	4	1	0
≥100	3	2	0
Total	83	43	8

* 1.0 mgd = 3,785 m^3/d

** Phosphorus effluent data were not available for 7 plants in the Erie
basin and 8 plants in the Ontario basin
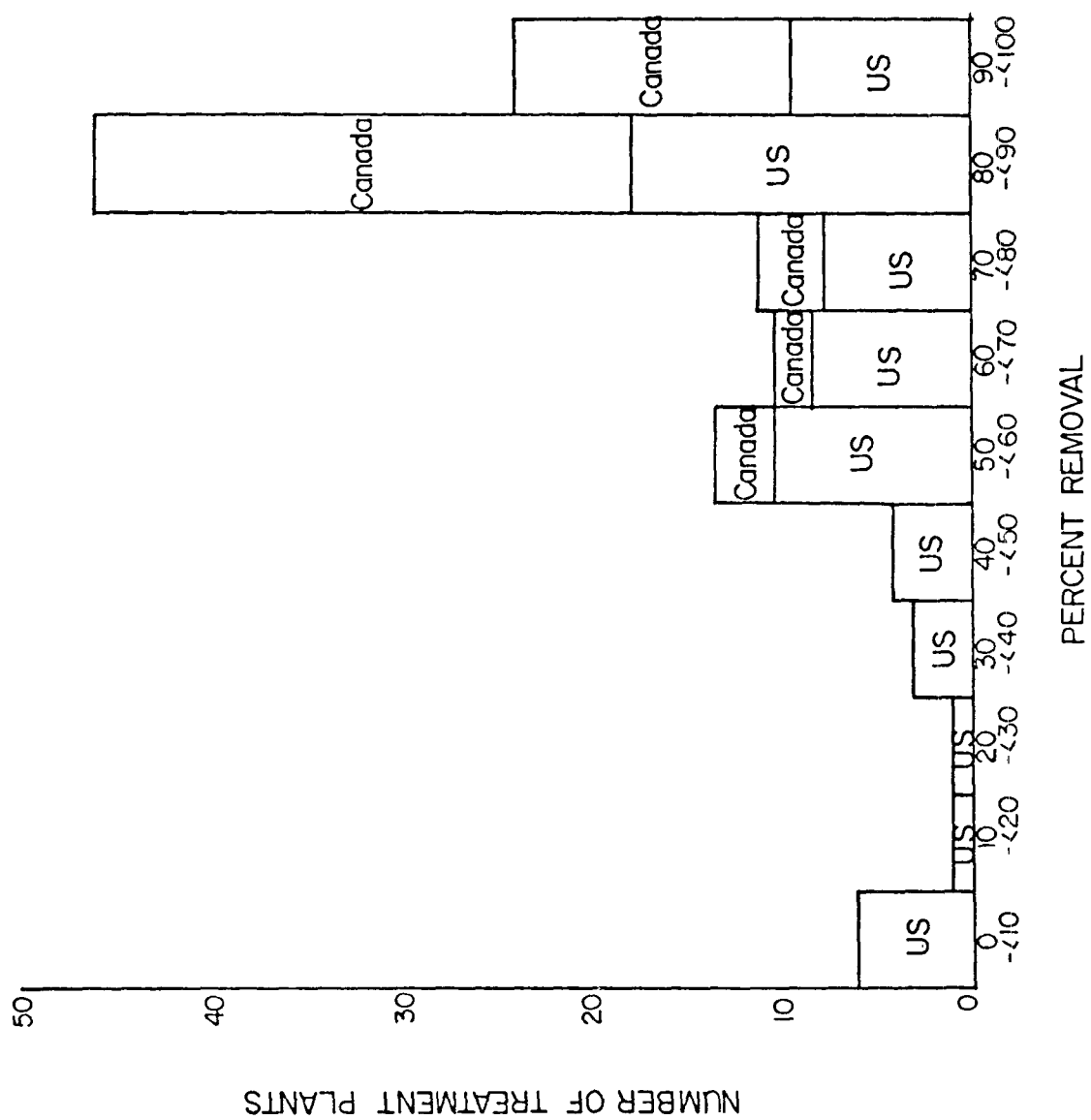
Figure 7. Histogram of Phosphorus Removal Percentages

plants which reported removal of 80 percent or more were using
iron or aluminum for precipitation during treatment. Conversely,
only 68 percent of all the plants which employed chemicals for
phsophorus removal were achieving removal of 80 percent or
better.

The above data suggest two possibilities: either the treatment
plants do not generally have to remove 80 percent of the phos-
phorus to meet 1.0 mgP/L effluent concentration, or there is
room for improvement in many plants as far as phosphorus removal
efficiency is concerned. For two reasons it seems likely that
the latter case is most prevalent. First, 47 percent of the
lower lakes plants are failing to meet a 1.0 mgP/L standard.
Also, according to our questionnaire the mean influent phos-
phorus concentration to plants in the lower lakes is 6.3 mgP/L.
This means that on the average 84 percent TP reduction through
plant would be necessary to achieve a 1.0 mgP/L effluent standard
and 92 percent TP reduction would be necessary to achieve a 0.5
mgP/L effluent concentration.

FIELD MONITORING RESULTS

OVERALL TREATMENT PERFORMANCE

In order to evaluate the performance of the four intensively
monitored plants with respect to phosphorus removal, it was
deemed necessary to also monitor the plant performance with
respect to the more conventional wastewater parameters. A
summary of the overall performance data during the monitoring
period for each plant is presented in Table 7.

TABLE 7. PERFORMANCE OF FOUR WASTETREATMENT PLANTS

Plant Name and Sampling Locations	Treatment Performance Parameters*					
	BOD_5 (mgO$_2$/L)	COD (mgO$_2$/L)	SS (mg/L)	Total P (mg/L)	TKN (mgN/L)	Total N** (mgN/L)
Gates-Chili-Ogden						
Raw Influent	187±14(3) (170-195)	385±74(12) (278-532)	165±54(12) (112-295)	6.3±1.5(12) (3.8-8.6)	24.8±5.2(6) (16.2-29.6)	-
Primary Effluent	-	290±37(3) (248-319)	69±8(3) (61-76)	5.5±0(3) (5.0-6.1)	25.2±3.5(2) (22.7-27.6)	
Secondary Effluent	16±1(3) (15-17)	50±18(12) (34-103)	9±3(12) (7-13)	0.8±0.3(12) (0.3-1.4)	4.0±1.8 (1.7-5.9)	
% Removal (Overall)	91	87	94	88	84	
Frank Van Lare						
Raw Influent	212±52(10) (149-295)	448±117(10) (337-735)	186±102(10) (127-470)	3.8±1.2(10) (2.8-6.9)	20.0±4.3(5) (16.9-27.5)	
Alum Effluent	151±27(10) (103-196)	238±37(10) (179-286)	53±14(10) (32.0-76)	1.3±0.4(10) (0.8-2.0)	13.9±1.3(5) (12.1-15.0)	
% Removal (Alum)	29	47	72	66	30	
Biological Effluent	30±19(10) (9-65)	88±32(10) (49-141)	53±32(10) (17-119)	1.5±0.9(10) (0.5-3.1)	4.4±2.3(5) (2.1-7.6)	
% Removal (Biological)	86	80	72	60	78	
% Removal (Overall)	74	74	72	61	68	
Big Sister Creek						
Raw Influent	130±4(2) (127-133)	446±215(13) (228-1062)	264±156(13) (111-670)	6.8±2.3(13) (4.01-10.2)	31.7±10.7(6) (21.8-44.9)	31.7±10.7(6)
Secondary Effluent	4±0(2) (3-4)	46±9(13) (28-58)	8±2(13) (5-12)	2.3±0.2(13) (1.8-2.6)	0.9±0.1(6) (0.8-1.1)	14.7±1.8(6) -
Filtered Effluent	2±0(2) (2)	29±6(13) (17-38)	2±1(13) (1-4)	0.9±0.1(13) (0.7-1.1)	0.4±0.1(5) (0.4-0.5)	13.9±3.5(6) -
% Removal (Overall)	98	93	99	86	99	56

TABLE 7. (continued)

Plant Name and Sampling Locations	BOD$_5$ (mgO$_2$/L)	COD (mgO$_2$/L)	SS (mg/L)	Total P (mg/L)	TKN (mgN/L)	Total N** (mgN/L)
Treatment Performance Parameters*						
Ely						
Raw Influent	181±120(2) (96-266)	270±86(12) (147-416)	123±42(12) (64-212)	3.8±1.3(12) (2.2-7.0)	19.0±8.4(5) (10.2-32.8)	19.1±8.4(5) –
Secondary Effluent	35±3(2) (33-37)	119±23(12) (79-154)	58±9(12) (42-68)	1.7±0.5(12) (1.0-2.6)	14.6±0.5(5) (14.0-14.9)	15.0±0.5(5) –
Filtered Effluent	15±2(2) (13-16)	68±12(12) (53-94)	13±3(12) (8-19)	0.6±0.2(12) (0.3-0.9)	12.0±.0(5) (10.9-13.2)	13.7±1.1(5) –
% Removal (Overall)	92	75	89	85	37	28

* Format of data: mean ± standard deviation (number of samples) (range of values observed)

** Total N = (TKN) + (NO$_3$-N) + (NO$_2$-N)

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The G-C-O, Big Sister Creek and Ely plants were all performing quite well with respect to secondary treatment. On the order of 90 percent or greater removal of BOD_5 and suspended solids was being accomplished during the monitoring periods. In these plants, therefore, adequate phosphorus removal was not being hampered by an inefficient secondary treatment system.

On the other hand, the Frank Van Lare plant, during our monitoring period, was less efficient than the other plants at removing conventional wastewater pollutants. The biological treatment stream was adequately removing BOD_5; however, the effluent suspended solids from the final clarifiers was erratic and averaged 53 mg/ℓ during the two-week monitoring. It should be pointed out that one of the final clarifiers and several primary sedimentation tanks were out of service at this time. As a result, the suspended solids removal facilities in the biological treatment stream were often overloaded. Phosphorus removal on this portion of the flow was as good as could be expected under the circumstances.

As might be expected, the BOD_5 removal was not good in the 20 percent of the flow receiving only the alum-enhanced primary sedimentation. The suspended solids removal in this process was slightly better than might be anticipated in a conventional primary sedimentation process, no doubt due to the use of alum in the system. However, it will become evident in later discussions that solids separation problems were the cause of lower total phosphorus removal efficiencies at the Van Lare plant.

PHOSPHORUS REMOVAL PERFORMANCE

Presented in Table 8 is a summary of data collected on phos-
phorus during the field monitoring studies. These data are
listed by plant and sampling location within each plant and
include the average values of total phosphorus as well as several
fractions of the total phosphorus in the wastewater.

Gates-Chili-Ogden

At the Gates-Chili-Ogden plant, the addition of alum to the
aeration tank effluent resulted in an excellent reduction of all
fractions of phosphorus analyzed (Figure 8). Soluble phosphorus
removal or conversion to particulate P was slightly more
efficient than particulate phosphorus removal, thus causing a
decrease in the relative total soluble P from 62 percent of the
total P in the raw influent to 45 percent of the total P in the
secondary effluent. As shown in Table 8, only a slight
reduction in particulate phosphorus (about 30 percent) occurred
during primary treatment, and virtually no change in soluble
phosphorus took place.

It was also noted that the relative contribution of the NaOH-
extractable phosphorus (EXP) to the total particulate P increased
through the plant. Particulate phosphorus which is formed during
alum precipitation would be likely to contribute directly to the
NaOH-extractable fraction, which probably explains the observa-
tion.

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TABLE 8. CONCENTRATION OF PHOSPHORUS FRACTIONS AND REMOVAL PERCENTAGES THROUGH FOUR WASTEWATER PLANTS

Plant Name and Sampling Locations*	Total P	Particulate (PP)		Soluble (SP)	
		Total PP	Total NaOH-PP	Total SP	SRP
Gates-Chili-Ogden					
Raw Influent (12)	6.28±1.50 (3.82-8.64)	2.17±0.72 (1.08-3.66)	1.70±0.55 (0.92-3.02)	3.89±1.13 (2.46-6.46)	2.54±0.54 (1.50-3.34)
Primary Effluent (3)	5.47±0.56 (4.98-6.08)	1.52±0.03 (1.47-1.56)	-	4.00±0.36 (3.60-4.28)	2.53±0.54 (1.92-2.94)
Secondary Effluent (12)	0.75±0.34 (0.32-1.36)	0.42±0.15 (0.21-0.76)	0.37±0.10 (0.22-0.61)	0.34±0.20 (0.14-0.74)	0.19±0.12 (0.10-0.42)
% Removal (Overall)	88	81	78	91	92
Frank Van Lare					
Raw Influent (10)	3.81±1.18 (2.85-6.90)	2.28±0.81 (1.53-4.15)	1.87±0.56 (1.44-3.13)	1.14±0.45 (0.42-2.01)	0.86±0.44 (0.18-1.75)
Alum Effluent (10)	1.31±0.39 (0.79-2.04)	1.06±0.36 (0.59-1.76)	0.96±0.31 (0.65-1.56)	0.11±0.05 (0.03-0.17)	0.03±0.04 (0.00-0.14)
% Removal (Alum)	66	54	49	90	96
Biological Effluent (10)	1.52±0.93 (0.49-3.06)	1.14±0.78 (0.37-2.78)	0.90±0.59 (0.30-2.06)	0.34±0.26 (0.09-0.63)	0.27±0.31 (0.01-0.85)
% Removal (Biological)	60	50	52	70	69
% Removal (Overall)	61	51	51	74	74
Big Sister Creek					
Raw Influent (13)	6.81±2.34 (3.98-11.07)	4.40±2.74 (1.81-11.84)	3.71±87 (1.28-7.34)	2.15±0.52 (1.43-3.27)	1.43±0.52 (0.75-2.47)
Secondary Effluent (13)	2.72±0.25 (1.83-2.65)	0.17±0.04 (0.12-0.25)	0.15±0.03 (0.11-0.24)	2.13±0.24 (1.75-2.53)	1.81±0.32 (1.32-2.28)
Solids Contact (4)	0.35±0.03 (0.32-0.39)	0.19±0.04 (0.14-0.23)	0.18±0.95 (0.12-0.23)	0.16±0.03 (0.13-0.19)	0.08±0.03 (0.06-0.12)

Phosphorus Concentration, mg P/L**
Phosphorus Fractions

TABLE 8. (continued)

		Phosphorus Concentration, mg P/L**			
		Phosphorus Fractions			
		Particulate (PP)		Soluble (SP)	
Plant Name and Sampling Locations*	Total P	Total PP	Total NaOH-PP	Total Sp	SRP
Filtered Effluent (13)	0.94±0.14 (0.68-1.12)	0.06±0.04 (0.02-0.13)	0.05±0.03 (0.02-0.13)	0.89±0.12 (0.65-1.07)	0.75±0.14 (0.50-0.92)
% Removal (Solids Contact)	95	96	95	93	94
% Removal (Overall)	86	99	99	59	48
Ely					
Raw Influent (2)	3.77±1.29 (2.20-6.97)	2.42±0.85 (1.52-4.78)	1.82±0.94 (0.96-4.56)	1.43±0.64 (0.37-2.72)	0.99±0.38 (0.30-1.61)
Secondary Effluent	1.72±0.45 (1.02-2.55)	1.62±0.41 (0.93-2.30)	1.40±0.36 (0.86-1.94)	0.03±0.01 (0.02-0.06)	0.01±0.01 (0.00-0.02)
Filtered Effluent (12)	0.56±0.19 (0.34-0.92)	0.49±0.17 (0.30-0.78)	0.47±0.17 (0.25-0.75)	0.04±0.02 (0.02-0.09)	0.01±0.01 (0.00-0.03)
% Removal (Overall)	85	80	74	97	99

* Number in parantheses signifies number of samples analyzed.

** Format of data: mean concentration ± standard deviation
(range of concentrations observed)

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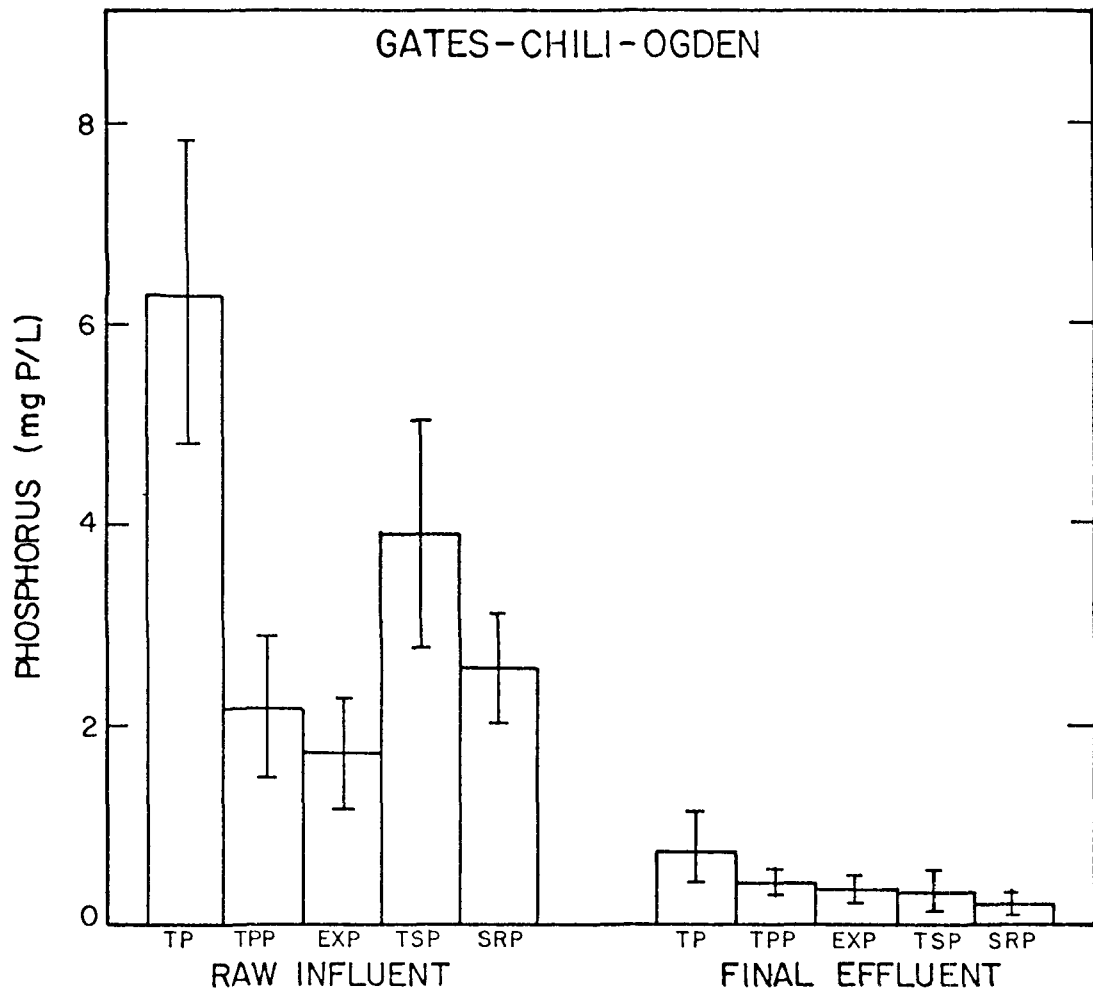
Figure 8. Mean Concentrations of Phosphorus and Phosphorus Fractions at the Gates-Chili-Ogden Plant. Error Bars Signify ± One Standard Deviation for the 12 Samples Analyzed.

<u>Frank Van Lare</u>

Reduction of total phosphorus at this plant was similar in both
the biological treatment stream (60 percent) and the alum-
primary settling stream (66 percent) (Figure 9). In both cases
soluble P reduction was sufficient, but particulate phosphorus
reduction was not effective enought to achieve a total P
standard of 1.0 mgP/L. The phosphorus removal in the biological
stream was typical for this treatment scheme. However,
relatively ineffective solids separation in the alum-primary
settling process accounted for a lower removal percentage than
might be expected. This ineffective capture of aluminum-
phosphorus precipitation solids resulted in a relatively large
fraction of the effluent particulate P from this process being
NaOH-extractable (91 percent).

<u>Big Sister Creek</u>

The performance of the Big Sister Creek plant for phosphorus
removal is illustrated in Figure 10. Figure 10 shows a near 70
percent reduction in total raw wastewater phosphorus from
biological treatment alone, due almost exclusively to removal of
particulate phosphorus. The effluent from the secondary
clarifier averaged 0.17 mgP/L of total particulate phosphorus,
compared with 4.40 mgP/L in the raw wastewater, while the total
soluble phosphorus concentration averaged 2.13 and 2.15 mgP/L on
samples taken from the two locations. The unusually low
particulate P in the secondary clarifier effluent was the result
of excellent solids separation in this phase of treatment.

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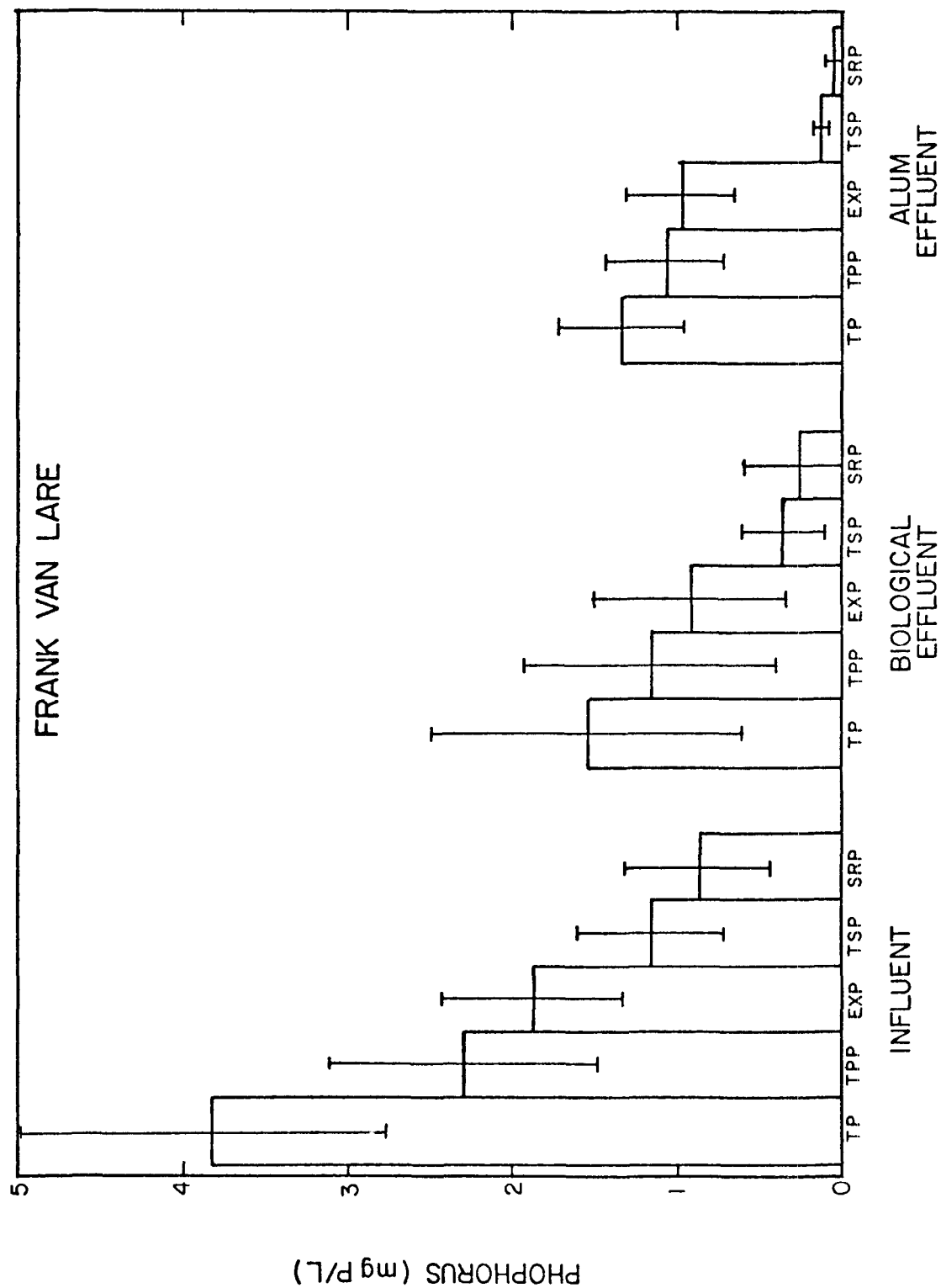
Figure 9.   Mean Concentrations of Phosphorus and Phosphorus Fractions at the Frank Van Lare Plant.   Error Bars Signify ± One Standard Deviation for 10 Samples Analyzed.
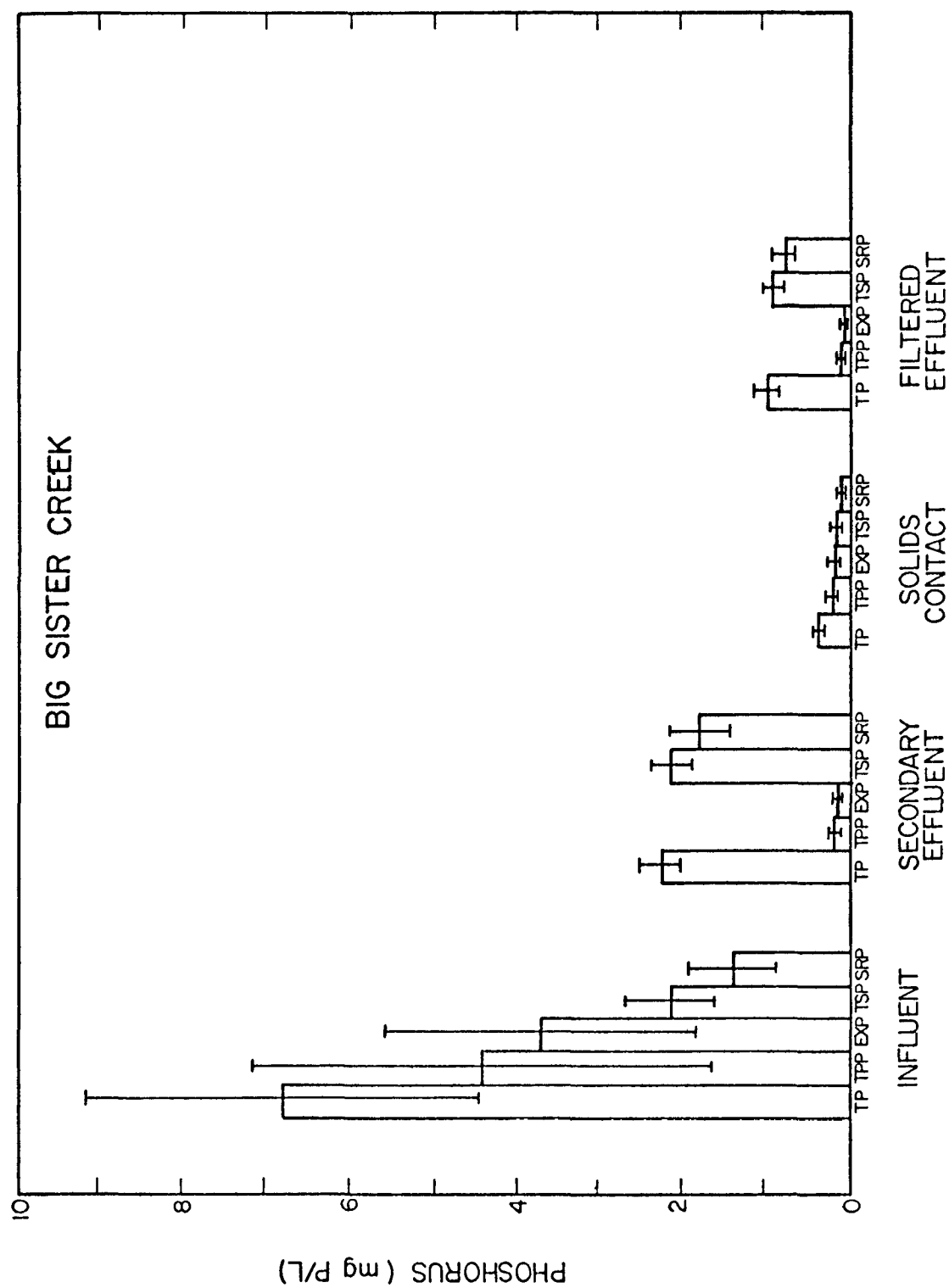
Figure 10.   Mean Concentrations of Phosphorus and Phosphorus Fractions at the Big Sister Creek Plant.   Error Bars Signify ± One Standard Deviation for the 13 Samples Analyzed.

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The data indicate that iron precipitation reduced the total soluble phosphorus from 2.13 mgP/L in the secondary effluent to 0.16 mgP/L in the solids contact clarifier effluent. Sand filtration was really unnecessary for phosphorus removal at this plant. The increased concentration of phosphorus observed in the filtered effluent, after iron precipitation, was due to routing of a portion of the secondary effluent around the solids contact clarifier for mixing with the iron treated effluent downstream from the clarifier and application to the sand filters.

ELY

Very good phosphorus removal was being accomplished at the Ely plant (Figure 11), with the filtered effluent very close to meeting a 0.5 mgP/L standard. The Ely plant has a permit requiring a 0.4 mg/L total phosphorus effluent level. Excellent reduction of soluble phosphorus was accomplished by alum addition to the trickling filter effluent; however, high suspended solids in the secondary clarifier effluent was again responsible for only a 33 percent reduction of particulate P to that point. Through the dual media filter, the extremely low concentrations of soluble phosphorus did not change, while the total particulate fraction was reduced to 20 percent of the raw wastewater particulate phosphorus.

An examination of the distribution of fractions of total phosphorus through the plant shows the approach to treatment at Ely favored removal of phosphorus from the soluble fraction to the
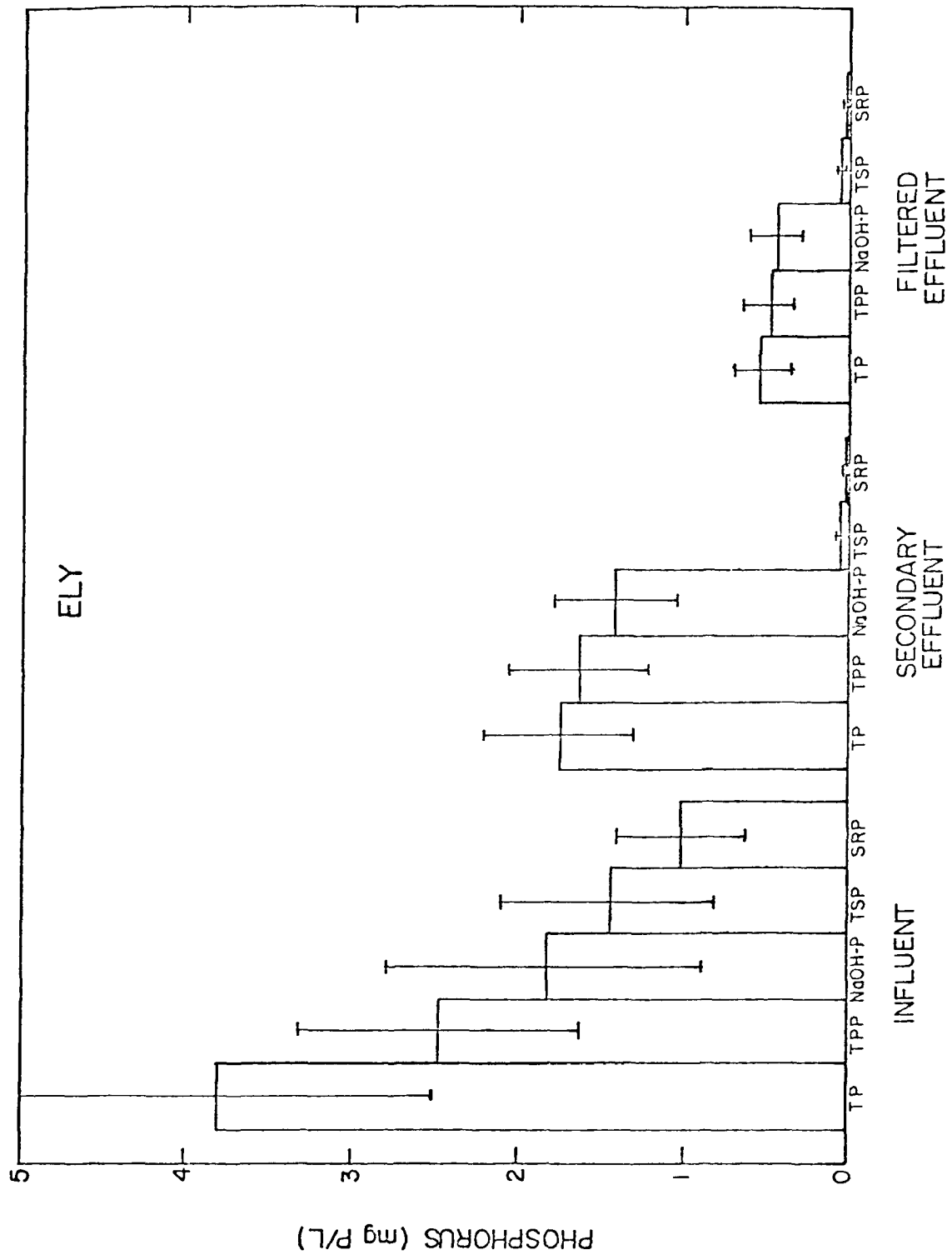
Figure 11. Mean concentrations total of phosphorus and phosphorus fractions at the Ely plant

extent that over 90 percent of the total phosphorus which
remained in the wastewater after alum treatment or filtration
occurred as particulate phosphorus (Table 8). Additionally, the
NaOH extractable fraction of the total particulate phosphorus
was an increasingly predominant component of that fraction,
relative to the total phosphorus that remained in the wastewater
at the stages of treatment which were sampled.

PHOSPHORUS BIOAVAILABILITY RESULTS

Algal bioassays were conducted on 22 samples of wastewater, taken
from various locations in each of four wastewater treatment
plants, to determine the availability of phosphorus, both soluble
and particulate, to aquatic organisms; and, to determine the
extent of relationship, if any, between analytically-defined
chemical fractions and bioassay-defined available phosphorus.
The results of these experiments are presented in Figures 12
through 15 for each of the four plants in our field study. A
comparison of available phosphorus fractions at the different
sampling points in each wastewater plant indicated that, at the
wastewater plants selected for study, the methods of treatment
had no major effect on the biologically available fraction of
either soluble or particulate phosphorus relative to the total
phosphorus content of those fractions (Table 9). Thus, with the
exception of the Van Lare plant, reductions of available phos-
phorus fractions through the plants corresponded quite closely
with the reductions in the analytically-defined chemical
fractions. Among the three plants behaving in this way, the
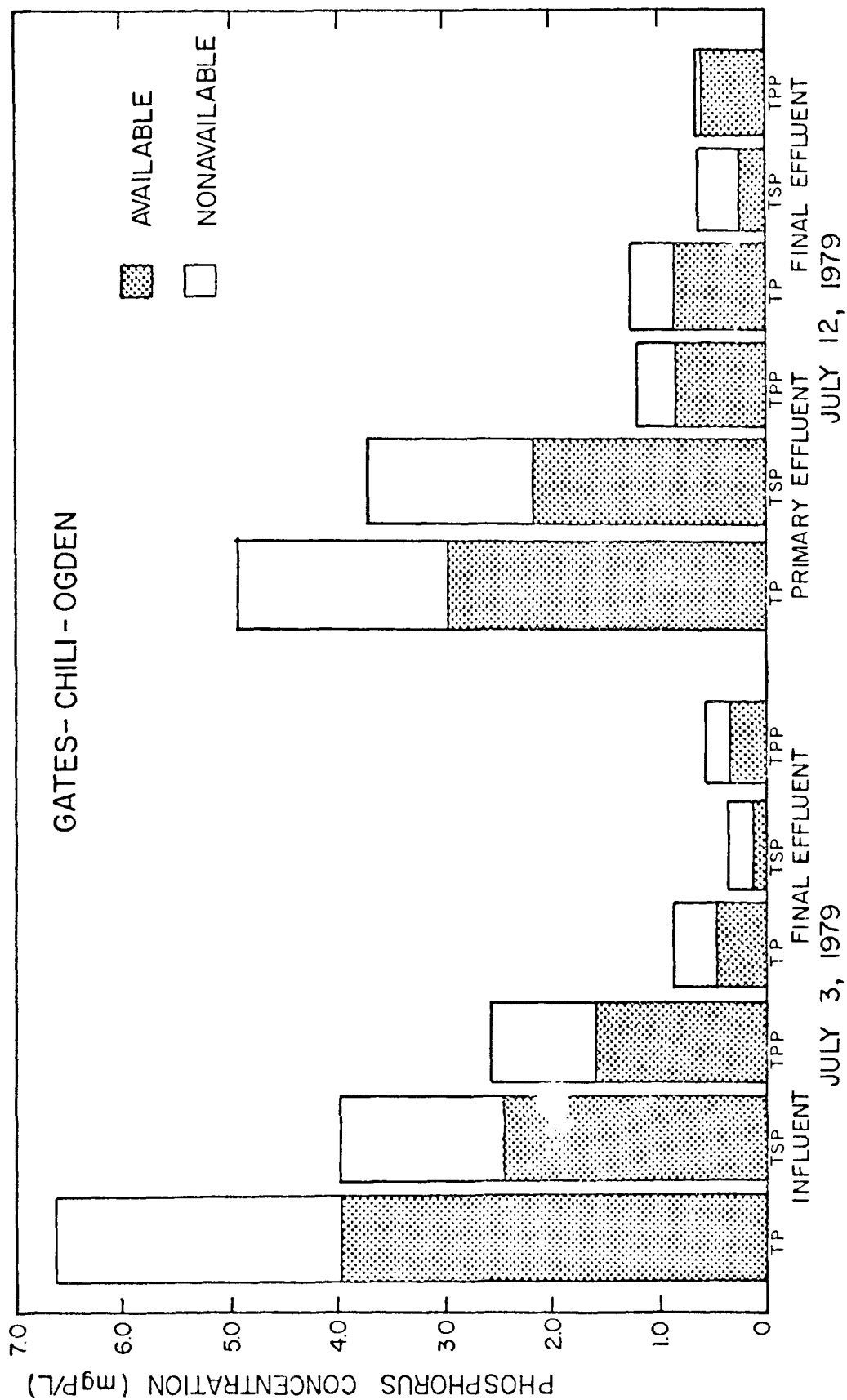
Figure 12. Biologically Available and Non-Available Phosphorus Fractions in Wastewater Samples From the Gates-Chili-Ogden Plant.
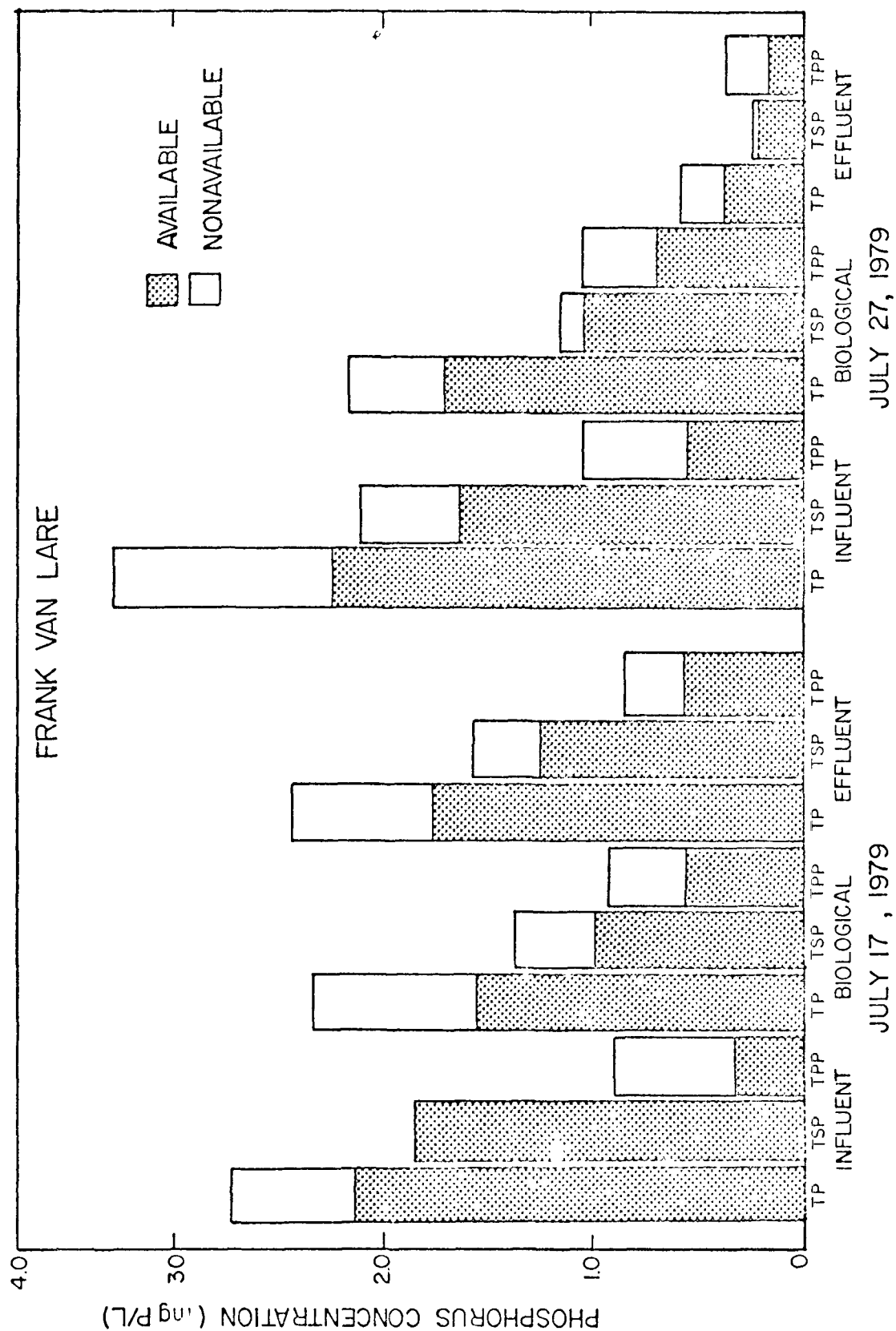
Figure 13. Biologically Available and Non-Available Fractions of Phosphorus in Wastewater Samples from the Frank Van Lare Plant.

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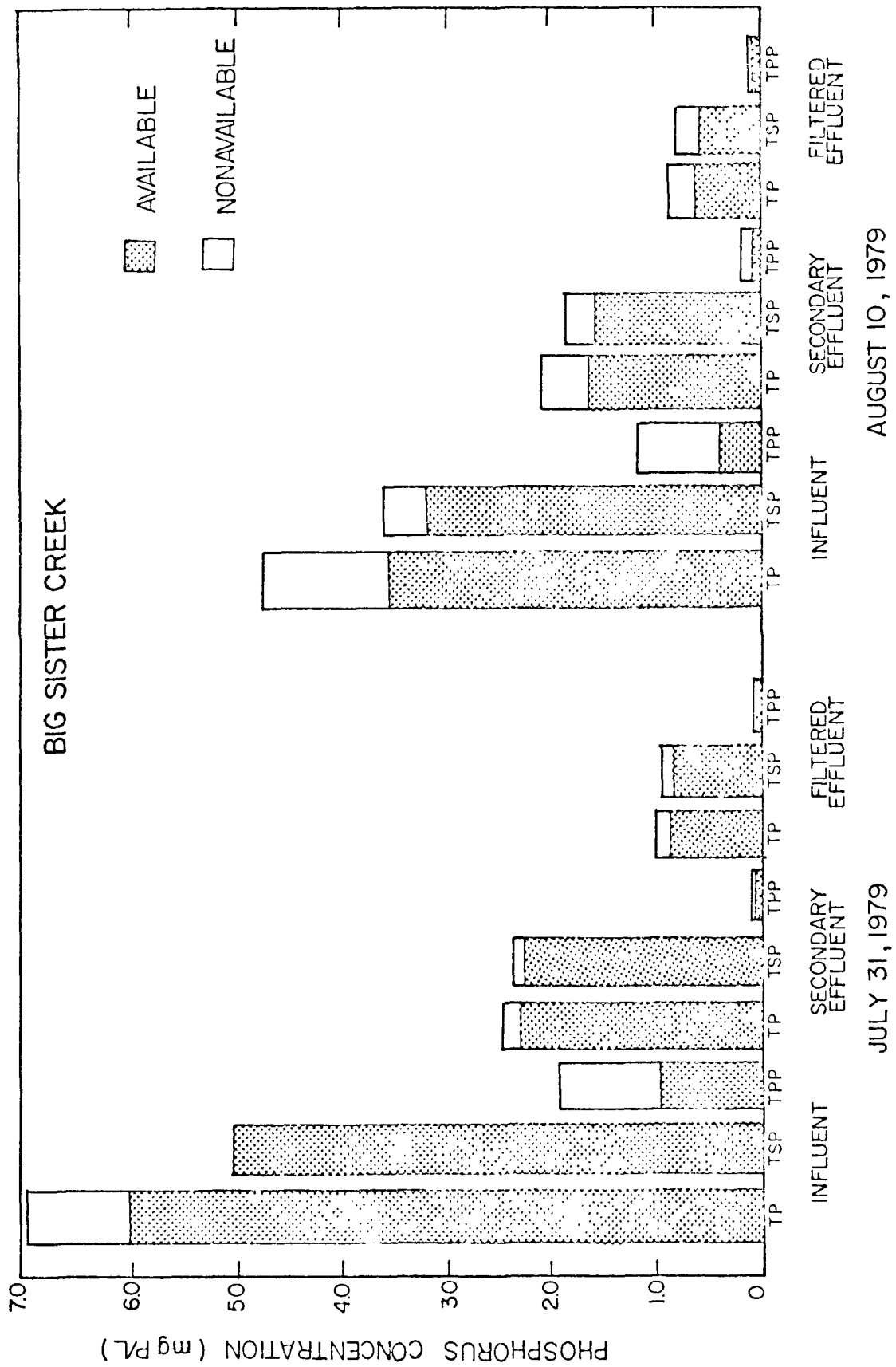
Figure 14. Biologically Available and Non-Available Fractions of Phosphorus in Wastewater Samples from the Big Sister Creek Plant.
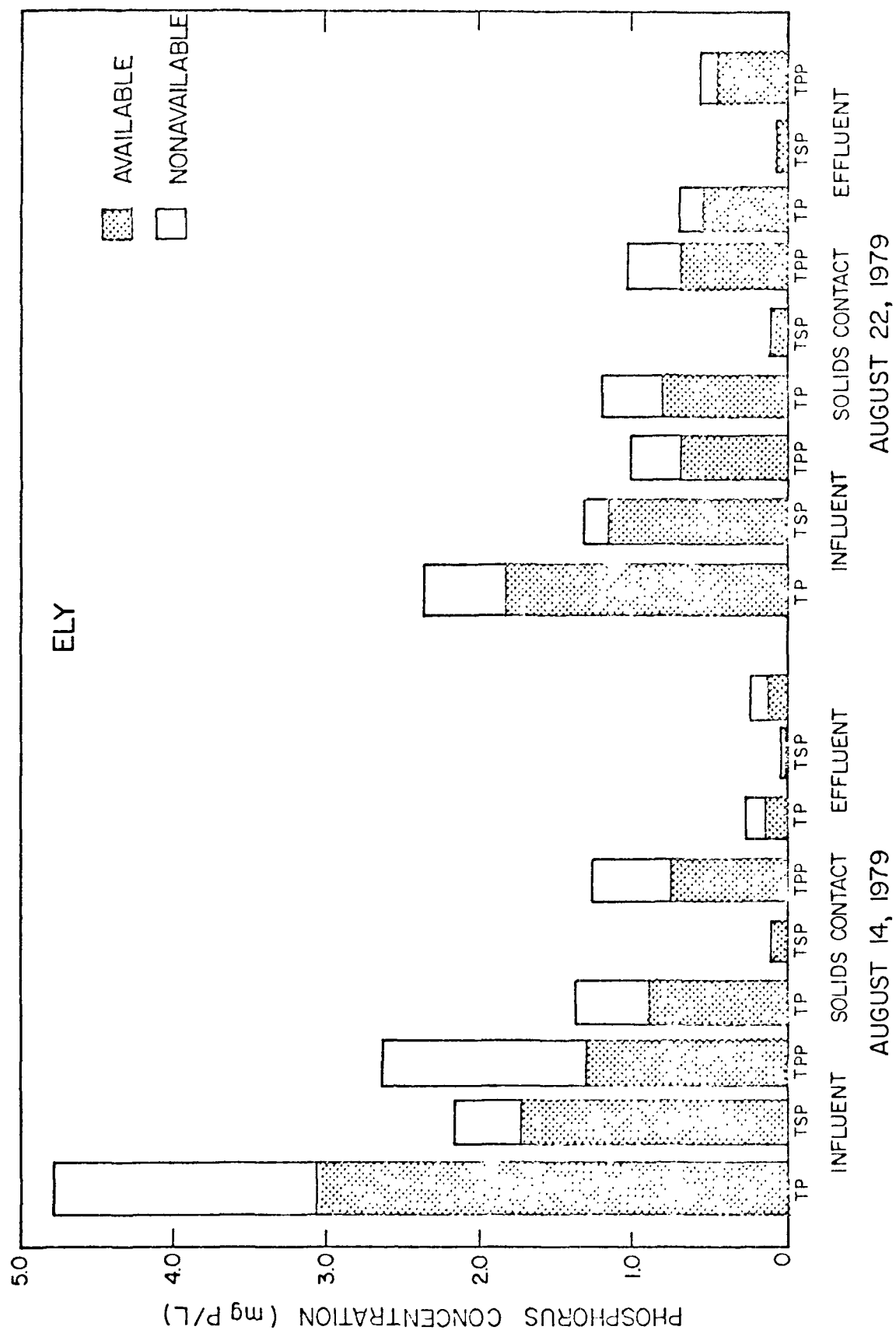
Figure 15. Biologically Available and Non-Available Fractions of Phosphorus in Wastewater Samples the Ely Plant.

TABLE 9.   PERCENTAGES OF BIOLOGICALLY AVAILABLE PHOSPHORUS AND
          REDUCTION IN BIOLOGICALLY AVAILABLE PHOSPHORUS AT
          MONITORED WASTEWATER PLANTS

| | Percent | | | | | |
| | Biologically Available Phosphorus | | | Reduction of Biologically Available Phosphorus Compared to Raw Influent | | |
Plant Name and Sampling Location*	$\frac{TBAP}{TP}$	$\frac{BAPP}{TPP}$	$\frac{BASP}{TSP}$	TBAP	BAPP	BASP
Gates-Chili-Ogden						
Raw Influent (1)	60	62	59	-	-	-
Primary Effluent (1)	60	68	57	-	-	-
Secondary Effluent (2)	58	74	40	88	79	94
Frank Van Lare						
Raw Influent (2)	72	44	88	-	-	-
Alum Effluent (2)	68	52	86	51	12	59
Biological Effluent (2)	73	62	82	26	38	41
Big Sister Creek						
Raw Influent (2)	80	40	94	-	-	-
Secondary Effluent (2)	88	48	91	58	90	53
Filtered Effluent (2)	76	40	79	85	96	83
Ely						
Raw Influent (2)	71	59	82	-	-	-
Secondary Effluent (2)	66	63	92	64	21	92
Filtered Effluent (2)	64	62	86	83	62	96

* Number of samples assayed is given in parentheses.

percentage removals of total phosphorus ranged from 85 to 88 percent (Table 8), while total available phosphorus (BAP) removal ranged from 83 to 88 percent (Table 9).

The results of these experiments could be summarized by noting that biologically available phosphorus averaged 72 percent of the total phosphorus. the available particulate fraction averaged 55 percent of the total particulate phosphorus, and the available soluble fraction averaged 82 percent of the total soluble phosphorus concentration in the wastewater samples. It should be noted that these fractions are based on relatively short-term (approximately 2 weeks) incubations; and, although accumulation of phosphorus by the DCDA assay cultures was slow towards the end of the incubation, a larger availability likely would have been measured with longer-term incubations.

Attempts to correlate biologically available phosphorus with various chemically-defined measures in the 22 samples assayed yielded several quite good correlations. Among the best was simply a correlation between total phosphorus and total bio-available phosphorus. This correlation is illustrated in Figure 16. The fact that the slope of the line in Figure 16 is identical to the average BAP/TP ratio for all the samples reflects the narrow range of values for that proportion among the treatment plants as well as between sampling locations within a plant.
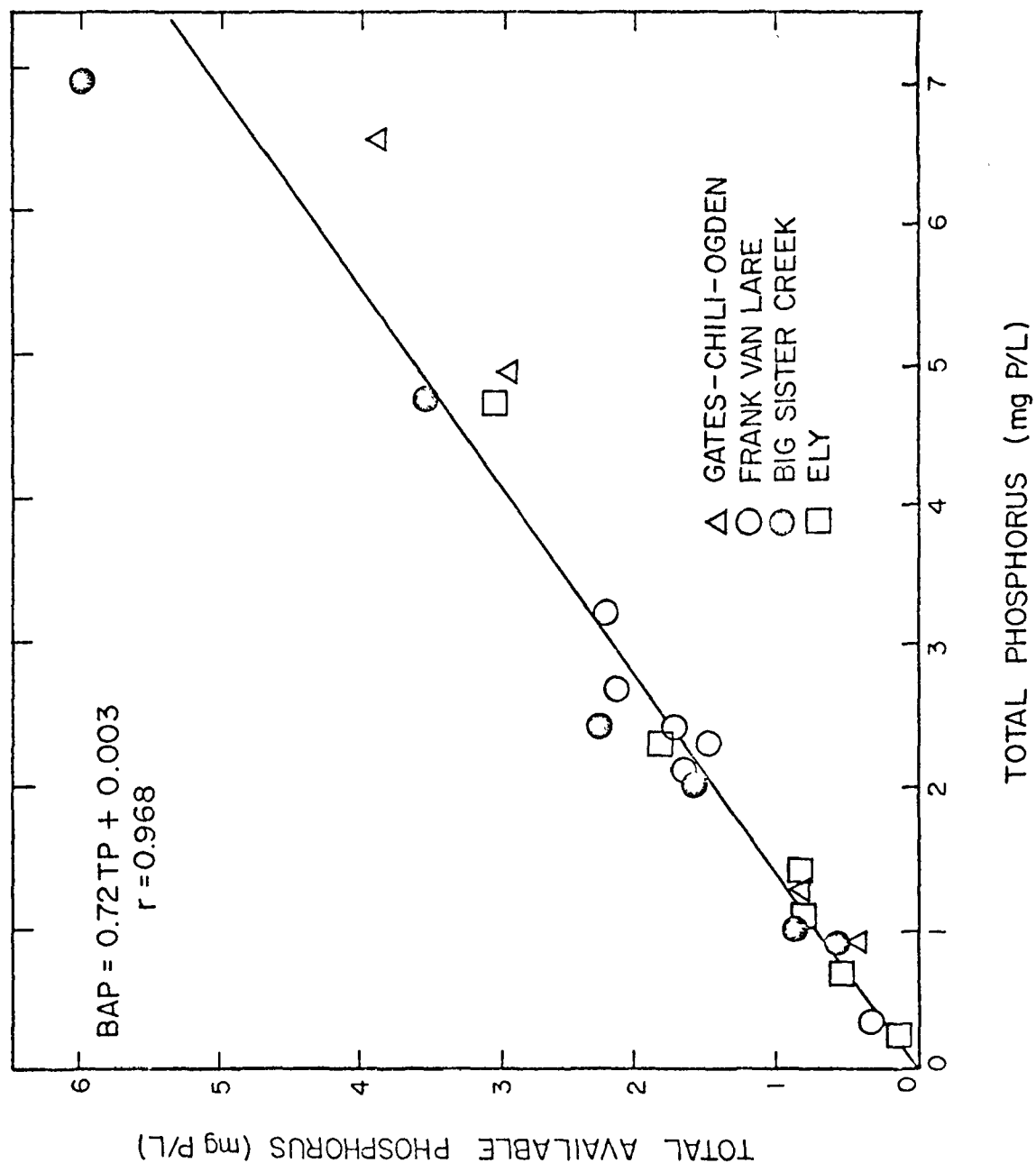
Figure 16. Total Biologically Available Phosphorus as a Function of Total Phosphorus in Wastewater Samples.

Legend (as shown in the figure):
- △ GATES-CHILI-OGDEN
- ◯ FRANK VAN LARE
- ◯ BIG SISTER CREEK
- ☐ ELY

BAP = 0.72 TP + 0.003
r = 0.968

X-axis: TOTAL PHOSPHORUS (mg P/L)
Y-axis: TOTAL AVAILABLE PHOSPHORUS (mg P/L)

COSTS FOR PHOSPHORUS REMOVAL

The proper evaluation of a given phosphorus effuent standard
requires the costs incurred as well as the benefits obtained.
As was stated previously, one of the goals of this study was to
analyze the costs incurred at the four selected treatment plants
associated with phosphorus removal. A summary of these costs is
presented in Table 10, comparing these costs to the total
operation and maintenance costs (O&M) at each of the four plants.
The data indicate a wide variation in both total and phosphorus
associated O&M costs for the four plants. On a $/1000 gallons
basis, the two plants with tertiary treatment had much higher
costs for phosphorus removal. The ratio of associated phos-
phorus removal costs to total O&M costs also varied widely
among the four plants.

A more detailed breakdown of the various fractions of the O&M
costs associated with phosphorus removal is presented in Table
11. In general the most sensitive item was chemical costs.
Labor and power costs were more significant at the plants with
tertiary treatment (Ely and Big Sister Creek) than those with
only secondary treatment (GCO and Van Lare). Sludge costs were
in general substantial but it should be pointed out that the
sludge production associated with phosphorus removal is generally
only a small fraction of the total sludge generated at these
treatment plants. This is shown in Table 12. It should be
pointed out, however, that the sludge generated from phosphorus
removal is more difficult to handle and process than typical

TABLE 10. TOTAL O&M COSTS AND O&M COSTS ASSOCIATED
WITH PHOSPHORUS REMOVAL AT FOUR
MONITORED TREATMENT PLANTS

| Treatment Plant | Total O&M Costs | | O&M Costs for P Removal | | % Total O&M |
	10^6 \$/Year	\$/1000 gal	10^6 \$/Year	\$/1000 gal	for P Removal
Gates-Chili-Ogden[2]	1.035	0.214	0.141	0.030	14.0
Ely[2]	0.301	0.916	0.035	0.107	11.7
Big Sister Creek[3]	0.569	0.482	0.121	0.109	22.6
Frank Van Lare[4]	9.015	0.243	0.407	0.011	4.5

[1]Base Period: Nov. '78-April '79

[2]Base Period: Summer '79; excluding sludge costs, which were unavailable because of recent changeover to alum treatment approach

[3]Base Period: 1978

[4]Base Period: Feb. '79-June '79

TABLE 11. BREAKDOWN OF ASSOCIATED O&M COSTS

	GCO[1]		Ely[2]	
Item	Unit Cost	$/1000 gallons	Unit Cost	$/1000 gallons
Labor	$7.00/hr	<0.001	$6.00/hr	0.038
Power	$0.031/Kw-hr	<0.001	$0.06/Kw-hr	0.019
Chemical	$0.059/lb liquid alum	0.025	Unavailable	0.050
Sludge Disposal	$71.40/ton dry solids	0.004	Unavailable	-

	Big Sister Creek[3]		Frank Van Lare[4]	
Item	Unit Cost	$/1000 gallons	Unit Cost	$/1000 gallons
Labor	$7.00/hr	0.081	$7.00/hr	0.0001
Power	Unavailable	0.004	$0.029/Kw-hr	0.0001
Chemical	FeCl₃ $0.0895/lb Polymer $1.40/lb	0.011	Alum $0.059/lb Polymer $1.32/lb	0.0007
Sludge Disposal	$223/ton dry solids	0.013	$158/ton dry solids	0.004

[1]Base Period: Nov. '79-April '79
[2]Base Period: Summer 1979
[3]Base Period: 1978
[4]Base Period: Feb. '79-June '79

TABLE 12. SLUDGE PRODUCTION AT THE FOUR
MONITORED TREATMENT PLANTS

	Total Sludge lbs/10^6 gallons	P Sludge lbs/10^6 gallons
GCO	1387	120
Ely	3415	82
Big Sister Creek	990	116
Frank Van Lare	1529	252

primary and secondary sludges generated at wastewater treatment plants. The costs shown in Table 11 for sludge disposal were calculated from stoichiometric relationships and then assigning that fraction of the unit cost to the phosphorus sludge. Therefore, they are probably on the liberal side.

CONCLUSION

The survey and field studies of phosphorus removal performance at municipal wastewater treatment plants in the lower Great Lakes basins were quite useful in revealing the current trends in full-scale phosphorus removal practice and the keys to successful phosphorus removal. Our survey showed that the basic approach most frequently employed to comply with present phosphorus effluent restrictions amounted to the addition of iron or aluminum to the wastewater at some point in a conventional secondary treatment system. Furthermore, both the survey and the field studies indicated that average final effluent total phosphorus concentrations of less than 1.0 mgP/L could be reliably attained without resorting to filtration.

Based on the field studies, achieving a low concentration and less available phosphorus effluent via chemical treatment could best be accomplished by converting as much of the wastewater phosphorus to a particulate form, followed by conservative design and operation of clarification facilities. In the four plants studied, phosphorus removal problems were the result of overloaded settling tanks. On the other hand, the G-C-O plant total phosphorus effluent averaged 0.75 mgP/L while operating the final

clarifier at overflow rates of 300-450 gpd/ft^2, conservative operation compared to the design rate of 650 gpd/ft^2. At Big Sister Creek, a tertiary plant, an effluent level of 0.5 mgP/L was consistently met by operating the solids contact clarifier for the iron + polymer treated secondary effluent at overflow rates ranging from 380-550 gpd/ft^2. The filtration step, although reducing the average particulate P solids contact clarifier effluent from 0.19 mgP/L to 0.06 mgP/L in the sand filter effluent, proved to be unnecessary for achieving a 0.5 mgP/L standard.

Consequently, in planning and designing for phosphorus removal at municipal facilities careful evaluation of less costly, alternative treatment approaches should be performed before resorting to a more expensive filtration process. Furthermore, more full-scale studies should be undertaken to optimize chemical addition at some point in a conventional secondary treatment system as a phosphorus removal alternative. Optimization of such operational parameters as point of chemical addition and dosage, clarifier overflow rates, and solids retention times should be the focus of these studies.

REFERENCES

1. APHA, Standard Methods. 1975. 14th Edition, American Public Health Association, Washington, D.C.

2. DePinto, J.V. 1978a. Phosphorus Availability of Aquatic Sediment Material: A Review. Environmental Engineering Technical Report. Clarkson College of Technology, Potsdam, N.Y. 24 pp.

3. DePinto, J.V. 1978b. Annual Progress Report of EPA Grant No. R-804937. November 1, 1976 - October 31, 1977.

4. IJC. 1978. Great Lakes Water Quality Agreement of 1978.

5. IJC. 1979. Inventory of Major Municipal and Industrial Point Source Dischargers in the Great Lakes Basin. Great Lakes Water Quality Board Remedial Programs Subcommittee.

6. McKosky, F.M. 1978. Laboratory Study of the Kinetics of Phytoplankton Decomposition and Subsequent Phosphorus Regeneration. M.S. Thesis. Clarkson College of Technology, Potsdam, N.Y. 99 pp.

7. Sagher, A., R.F. Harris, and D.E. Armstrong. 1975. Availability of sediment phosphorus to microorganisms. Technical Report WISWRC-75-01. Water Resources Center, University of Wisconsin, Madison.

8. USEPA. 1976. Methods for Chemical Analysis of Water and Wastes. U.S.E.P.A. Office of Technology Transfer, Cincinnati, Ohio.

EXPERIENCES AT GLADSTONE, MICHIGAN
UTILIZING ROTATING BIOLOGICAL CONTACTORS
FOR BOD-5, PHOSPHORUS, AND AMMONIA CONTROL

Willard Morley
Superintendent
Water & Wastewater Treatment
Gladstone, Michigan

INTRODUCTION

In March of 1974, the first federally funded municipal waste-
water treatment plant utilizing Rotating Biological Contactors
(RBC) was placed in operation in Gladstone, Michigan. The plant
was designed by Williams & Works of Grand Rapids, Michigan to
replace an existing primary treatment plant at the same site.
Because, in many respects, this plant was the first of its kind
in the United States, the performance of the system in a mod-
erately severe northern climate has received a relatively high
degree of scrutiny by engineers and manufacturers engaged in the
design of other RBC installations. The design considerations
for this plant, operating data for four years of operation, and
some general observations about RBC installations based on the
Gladstone experience will be presented in this paper.

DESIGN CONSIDERATIONS

Gladstone, Michigan is a predominantly residential community of
about 5,000 people located in the southern part of Michigan's
Upper Peninsula, on the shore of Lake Michigan, approximately 10
miles north of Escanaba. The climate in the area is character-
ized by cool, dry summers and cold, snowy winters. The mean

annual temperature is 42°F (5.5°C). Gladstone derives its water supply from Lake Michigan and wastewater temperatures are frequently in the mid 40's (°F) during winter months.

The 1.0 mgd (3,785 cu m/day) RBC plant was designed to provide secondary treatment and phosphorus removal on the site of an existing primary treatment plant. A system incorporating housed rotating biological contactors was selected on the basis of aesthetics, operational advantages, and data from successful pilot plant testing. The general design parameters are listed in Table 1.

Table 1
General Design Parameters

Population	10,000
BOD-5	1,670 lb/day (9758 kg/day)
TSS	2,000 lb/day (908 kg/day)
Average Daily Flow	1.0 mgd (3,785 cu m/day)
Peak Flow	2.88 mgd (10,000 cu m/day)
Effluent Quality Limitations:	
BOD-5	30 mg/l (30-day average)
Total Suspended Solids	30 mg/l (30-day average)
Total Phosphorus (TP)	20% of influent TP

General pilot plant tests of the RBC process were conducted at the University of Michigan in Ann Arbor in 1968-1969 under the supervision of Professor J.A. Borchardt. The pilot plant consisted of three stages in series, each with fifty, 4-foot

(1.22 m) diameter, 0.5-inch (1.27 cm) thick disks, with 0.75-in.
(1.90 cm) spacings between the disks. The pilot plant was
operated for approximately one year using raw wastewater and
primary effluent from the Ann Arbor municipal treatment plant.
Some results of the pilot plant tests are summarized in Table 2.
In general, this jpilot plant expeerience offered the following
design considerations:

Primary treatment is necessary to prevent accumulations of
debris on RBC shafts and to increase overall BOD-5
removals.

The RBC shafts must be rotated at a speed sufficient to
entrain sloughings and mixed liquor solids. At low speeds,
solids accumulations within the RBC tankage caused the
depletion of dissolved oxygen and created odor nuisances.

An average of 80 to 93 percent overall BOD-5 removals were
consistently achieved at hydraulic loadings of 1 to 4 gpd
per sq. ft. and at temperatures ranging from 48° to 63°F.

At similar hydraulic loadings, BOD-5 reductions through the
RBC process dropped about 1% for each 1°C drop in
wastewater temperature.

A schematic flow diagram of the treatment facility is shown in
Figure 1. The design parameters of the unit processes and
appurtenant equipment are summarized in Table 3. Raw wastewater
is screened and pumped to two grit chambers, then it is
comminuted and settled in a single, rectangular primary
clarifier, salvaged from the old plant. Primary clarifier
effluent is split to two parallel RBC paths, each with three
shafts and six stages. Mixed liquor within the RBC tanks flows
through 2-foot (0.61 m) diameter submerged openings to
subsequent stages. RBC efluent is dosed with liquid alum for
phosphorus precipitation prior to pumping to twin rectangular
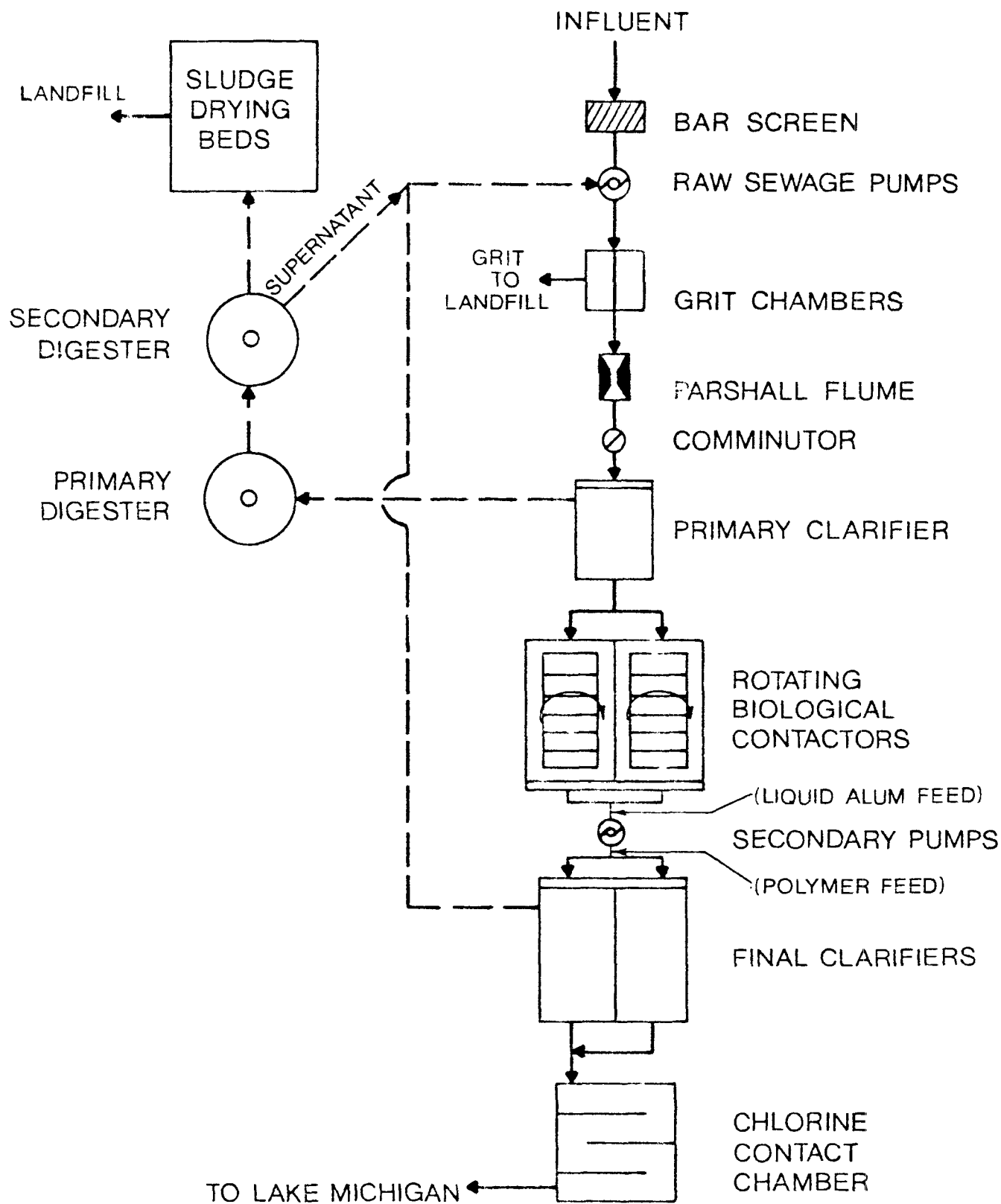
Figure 1. Wastewater Treatment System
Gladstone, Michigan

Table 2

Pilot Plant BOD-5 Removal Summary

Test Period	Hydraulic Loading gpd/sq.ft.	Estimated Detention (minutes)	Waste-water Temp. (°F.)	BOD-5, mg/l						Overall % Removal
				Raw	Prim. Effl.	1st Stage	2nd Stage	3rd Stage		
1/21-2/10/69	4.0 (1,500 gpd)	24	53-59 (56)	96-234 (159)	49-139 (100)	36-76 (59)	18-56 (39)	18-45 (31.9)		73.5-83.5 (80.0)
4/3-4/18/69	2.65 (10,000 gpd)	36	53-59 (56)	103-274 (156)	64-110 (85)	25-54 (42)	12-28 (19)	7-14 (13)		84.5-97.5 (91.6)
5/12-5/21/69	1.32 (5,000 gpd)	72	61-63 (62)	95-144 (116)	44-98 (62)	11-25 (19.2)	8-16 (11.5)	6-13 (8.6)		86.4-95.7 (92.6)
11/17-12/12/69	2.0 (7,500 gpd)	48	48-52 (50)	114-202 (162)	54-198 (111)	37-100 (52.5)	15-65 (32)	11-42 (21.4)		72.2-94.1 (86.8)

Average values are noted in parentheses

Table 3

Unit Process and Equipment Data

Equipment	Design Data
Raw Sewage Pumps	3@ 1,400 gpm (88.3 l/sec), 2 variable speed, 1 constant speed lag pump
Primary Clarifier	1 rectangular 70,000 gallon (265 cu m) capacity with 1.5 hr. detention and 895 gpd/sq ft (36.5 cu m/day/sq m) overflow rate
RBC Units	Bio-Surf by Autotrol. Two parallel paths with three shafts and six stages in each, 515,500 ft^2 (47,890 sq m) of media, 90 minutes retention and 1.94 gpd/sq ft (0.097) cu m/day/sq m) hydraulic loading rate
RBC Effluent Pumps	Same as raw sewage pumps
Secondary Clarifiers	2 rectangular, 2.75 hr detention and 620 gpd/sq ft (25.3 cu m/day/m^2) overflow rate
Chlorine Contact	2 baffled tanks, 35 min retention
Primary Digester	1 fixed cover, 100,000 gal (378.5 cu m) capacity with 15.5 days detention at design loading, heated, mixed by gas recirculation
Secondary Digester	1 floating cover, 100,000 gallon (378.5 cu m) capacity with supernatant discharge to raw wastewater wet well
Tank Truck	1 2,500 gallon (9.4 m^3) capacity
Drying Beds	Adjoining sanitary landfill site, 600' x 200' (183 m x 61 m) without underdrains
Liquid Alum Storage	2 tanks, each 2,600 gallons (9.8 cu m) capacity

clarifiers. Secondary effluent is chlorinated prior to discharge to Lake Michigan.

Grit is manually cleaned from the grit chambers and disposed of at a sanitary landfill. Settled primary and secondary sludges are pumped to a primary anaerobic digester that is heated and equipped with gas recirculation and mixing apparatus. Settled, digested sludge from the secondary digester is withdrawn by tank truck to sludge drying beds off-site. Dried sludge is disposed of in a sanitary landfill. Supernatant from the secondary digester is drained by gravity to the raw wastewater wet well.

INITIAL OPERATING EXPERIENCE

The operation of the plant was begun on March 1, 1974. At the same time, an 18-month testing and shakedown program was begun to monitor the performance of the plant and to make operational improvements where necessary. During this period, wastewater flows averaged 0.755 mgd (2,875 cu m/day) and were influenced occasionally by sewer infiltration and inflows. At start-up, wastewater temperatures averaged 45°F (7.2°C), then gradually increased to the low 60's (°F) by mid-summer.

Influent BOD-5 concentrations ranged from 129 to 219 mg/l and influent total suspended solids concentrations ranged from 101 mg/l to 168 mg/l. The average influent BOD-5 and total suspended solids concentrations for the test period were 164 mg/l and 132 mg/l, respectively.

The results of the initial 18-month test period are summarized
as follows:

Because the influent wastewater temperatures were quite
cold at start-up, it took 18 days before heavy sloughings
of biomass were observed and several months to achieve a
steady state operation.

During the last 12 months of the testing period (September
1974 through September 1975) with the addition of 70 mg/l
of alum and 0.8 mg/l of polymer, effluent BOD-5's were
generally less than 10 mg/l; effluent suspended solids
averaged 15 mg/l; and effluent total phosphorus con-
centrations were less than 1.6 mg/l.

In January 1975, design flow conditions were simulated for
two weeks by shutting down one of the parallel RBC paths
and one of the final clarifiers. The effluent BOD-5 for
this two-week test period averaged 19 mg/l, while the
average wastewater temperature was 47°F (8.3°C).

Because of low hydraulic loadings (1.0 to 2.1 gpd/ft^2),
nitrification occurred; 50% to 60% reductions in ammonia
nitrogen occurred during the winter months and 85% to 95%
reductions occurred during summer months.

After one of the RBC paths was restarted in February 1975,
after being shut down for full scale tests, nitrifiers did
not re-establish dominant cultures on latter stages until
June, when wastewater temperatures approached 60°F
(15.6°C).

Excellent BOD-5, suspended solids and ammonia nitrogen
removals permitted reductions in effluent chlorine doses,
from 6-7 mg/l to 2-3 mg/l.

Recycling of secondary sludge through the primary clarifier
was required to thicken the combined sludges from 2% - 3%
solids to 4% - 5% solids content.

Slug releases of digester supernatant to the head end of
the plant were detrimental to overall nitrification
results. Controlled release of digester supernatant is
considered essential to achieve consistent ammonia
nitrogen reduction.

No significant differences were noticed in the digesti-
bility of sludges with or without alum addition. Phos-
phorus release, volatile solids reduction, or gas
production were not significantly affected by alum
addition. The average total sludge production was 0.83 lb
of total solids per pound of BOD-5 removed. This figure
takes into account chemical sludge production.

The measured power usage by the rotating biological contactor shafts ranged from 5.6 hp to 3.5 hp. The average running horsepower per shaft was 4.2 hp.

PLANT PERFORMANCE (1976-1979)

The overall performance of the plant, subsequent to the 18-month test program, is summarized in Table 4. The data covers the period from January 1976 through December 1979. Table 5 shows a comparison of plant performance under summer and winter conditions. Data for these tables was obtained from the monthly operating reports prepared by the plant operators.

This data shows that the plant is consistently removing over 90% of influent BOD-5 even under winter conditions and at hydraulic loading rates of between 1.0 and 1.4 gpd/ft^2. Wastewater strength is affected by increased infiltration and inflow during warm weather months. During winter months, effluent BOD-5 concentrations increase as wastewater temperatures decrease to lows of 45°F. Effluent dissolved oxygen concentrations are consistently above 7 mg/l.

Effluent total suspended solids concentrations remained fairly consistent throughout the period at an average of about 16 mg/l. The hydraulic profile of the plant is such that secondary solids are pumped twice prior to removal with settled primary solids. The addition of polymer assists secondary sedimentation, and lower suspended solids concentrations could probably be obtained in the final effluent if flocculants were not disturbed by the centrifugal pumps.

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Table 4

Performance Summary

Parameter	- - - - - Annual Averages - - - - - -			
	1976	1977	1978	1979
Flow (mgd)	.635	.725	.612	.712
Hyd. Loading (gpd/sq.ft.)	1.23	1.41	1.19	1.38
BOD-5 (mg/l)				
-Influent	182	143	155	129
-Effluent	6	7	7	12
-% Removed	97%	95%	95%	91%
TSS (mg/l)				
-Influent	135	122	139	118
-Effluent	15	16	17	16
VSS (mg/l)				
-Influent	111	95	112	92
-Effluent	8	7	8	9
Total Phosphorus (mg/l)				
-Influent	7.8	6.3	4.7	3.5
-Effluent	1.4	1.1	0.9	0.9
-% Removed	82%	83%	81%	74%
Ammonia-N (mg/l)				
-Influent		15.5	17.4	15.9
-Effluent		3.5	2.1	2.0
-% Removed		77%	88%	87%
Eff. Dissolved Oxygen (mg/l)	7.3	7.6	7.6	8.2
Raw Sludge Pumped (lb VSS/day)	576	544	512	544
Digester Gas Prod. (cu.ft./day)	4,307	3,981	3,954	3,718
Chemicals Used (lb/day)				
-Chlorine	13	19	12	12
-Alum	435	485	365	262
-Polymer	1.5	1.7	1.5	1.4

Table 5

Comparative Performance Summary

Winter vs Summer Operation

	Average Winter Values 1/	Average Summer Values 2/
Flow (mgd)	0.530	0.726
Hydraulic Loading (gpd/sq.ft.)	1.03	1.41
Waste Temperature (°F)	46	64
BOD-5 (mg/l)		
-Influent	181	128
-Effluent	10	9
-% Removed	94	93
TSS (mg/l)		
-Influent	140	130
-Effluent	16	16
Total Phosphorus (mg/l)		
-Influent	5.8	4.7
-Effluent	0.8	1.0
-% Removed	86	79
Ammonia-N (mg/l)		
-Influent	20.0	15.1
-Effluent	4.9	1.0
-% Removed	76	93
Effluent Dissolved Oxygen (mg/l)	8.1	7.3

1/ From January, February, March, 1977 through 1979 reported data.

2/ From July, August, September, 1977 through 1979 reported data.

More than 80% of influent total phosphorus concentrations are removed by the addition of alum (hydrated aluminum sulfate). Plant operators attempt to maintain a liquid alum dosage rate sufficient to provide 1.5 moles of aluminum to 1.0 mole of influent total phosphorus.

The plant was not designed to accomplish nitrification. However, because it is currently operated at hydraulic loadings of less than 2 gpd/ft^2, nitrification does occur. Ammonia analyses show that average influent ammonia concentrations of 16 mg/l to 18 mg/l are reduced to 2 mg/l to 4 mg/l through the plant. As might be expected, less nitrification occurs during winter months.

In 1979, an average of 710 pounds per day of sludge was pumped to the primary digester with an average solids content of 3.7% by weight. The volatile content of the sludge averaged 74% by weight. Total sludge production, including chemical sludges, averaged 1.14 pounds per pound of BOD-5 removed, or approximately 1,000 pounds per million gallons treated. Approximately 262 pounds per day of alum was added to remove an average of 2.6 mg/l of total phosphorus.

OVERALL OPERATIONS AND MAINTENANCE

The Gladstone plant is staffed by one superintendent and three shift operators. The plant is manned 16 hours per day, five days a week; eight hours per day on week-ends and holidays. The superintendent also has the responsibility of the water filtration plant, staffed by two operators. Most of the

operators are cross-trained to provide flexibility. All operators are state certified and operate shifts on a rotational basis.

All laboratory tests are conducted according to "Standard Methods", 14th edition.

Flows are measured weekly at the Parshall flume to check the flow meter. The chlorinator, sampler, alum and polymer feeders are regulated by the flow meter.

Secondary sludge is returned at least five times per day to the primary clarifier to thicken the combined sludges from 2%-3% to 4%-5% solids content. The combined sludge is then pumped to the primary anaerobic digester. Digesting sludges are monitored weekly for volatile acid/alkalinity relationships and volatile content. When the volatile percentage is less than 50% and the supernatant shows excessive solids, sludge is hauled by tanker to the drying beds. The digesters are cleaned and inspected at three year intervals.

The RBC units are greased at the main bearings twice per week with 5 to 6 shots of grease. The oil in the chain casings and speed reducers is changed yearly or more often if the oil should become diluted with water. The walkways and the area around the disks are scrubbed weekly. The tanks are drained and flushed yearly for a general inspection. Very little accumulation has ever been found. The three V-belts on the drive units are replaced about yearly upon breakage. One main shaft bearing failed in the six years of operation.

The plant staff also maintains the six lift stations throughout the 22 miles (35.4 km) of the collection system, which ranges in size from 4 inches (10.2 cm) to 30 inches (76.2 cm). Most of the collection system was installed during the 1920's and 1930's, and was a combined system until new storm sewers were installed in the late 1950's. This contributes at times, to excessive infiltration and inflow during snow melts, severe rains and high lake levels. Step I studies are presently being conducted to locate the problem areas of the system. Maintenance of the collection system other than the lift stations is performed by the Public Works Department.

PROBLEMS THAT DEVELOPED

During the first years of operation a few problems developed and were solved by the operators. These included changes in alum feed points, sampling equipment, digester piping, and sludge handling. The problems as well as the solutions we employed are explained below.

ALUM APPLICATION POINTS

It was found that during low flows the alum dosages needed to be increased considerably to remove the required amounts. Also, with low flows, concentrations of phosphorus increased, creating the need for an increase in alum application.

Feed points at the secondary wet well did not provide enough turbulance for proper mixing, so a temporary feed line was installed to the sixth stage of each RBC path. This provided enough dispersion for coagulation and flocculation, but after

passing over a weir, through the wet well, and being pumped to the secondary clarifier, the floc was broken up. By adding alum to the primary wet well, dosages could be reduced at times, but results were not consistent.

Temporary lines were installed in 1979 to the discharge side of the primary pumps. A 30% reduction in the feed rate was found to achieve the same results. Permanent feed lines were then installed to each of the primary pumps. This has proven effective during both low and high flows.

METHANE GAS UTLIZATION

The heating system of the building and the primary anaerobic digester was designed to use both methane and natural gas. Methane gas has a content of about 650 BTU per cubic foot, and the boiler needed a rate of 5090 cubic feet per hour. The gas pressure in the digester would raise a column of water 10 inches (25.4 cm). A 2-inch (5.1 cm) gas pipe had been installed from both digesters. The floating cover of the secondary digester can hold about 4,000 cubic feet of gas. A sufficient gas rate was not available to sustain the gas boiler, since the piping extends some 70 feet (21.5 m), plus the meter, check valve, flame arrester, and etc. By reducing the orifices of the burner, some gas could be burned at times.

With the cleaning of the digesters in 1977, the portion of 2-inch (5.1 cm) pipe inside the secondary digester was changed to 4-inch (10.2 cm) with the intent of changing all the piping to this larger size.

After temporarily connecting to clean the primary digester and
to burn off the gas, we found the boiler would operate at all
times. The remainder of the pipe has never been changed.

SLUDGE ODORS

Sludge, especially when controlling ammonia, must be removed at
intervals of 2 to 3 hours to eliminate bulking and its odors.
Sludge remaining at the bottom of the clarifiers will soon
become anaerobic and de-nitrify. Higher temperatures will also
accelerate bulking.

Secondary sludge must be removed manually. When the plant is
not manned on week-ends and holidays, we occasionally experience
rising sludge. An automatic sludge removal system would be
advantageous, as these clarifiers are uncovered and the odors
are readily noticed by our neighbors.

Combined sludges are pumped to the anaerobic digesters at two to
three hour intervals to assure proper utilization of digester
capacity and functions.

DIGESTER UPSET

In the six years of operations, only once were the digesters
upset. This happened in 1976, when gas production ceased and
the digesters went "sour". The nitrifiers on the RBC units were
disrupted as well.

The supernatant from the primary digester contained small
cellophane-type pieces of irregular shapes, somewhat resembling
bleached potato peelings. The volatile acid/alkalinity ratio
rose above 1.0 and the pH was dropping below 6.4.

To correct the problem, heat was maintained at 90°F in the digester and continuous mixing was was employed. About 300 pounds of soda ash were added over a 10-day period to hold the pH near 7.0. Within two weeks the digesters were back functioning normally.

The only explanation as to the cause of the upset was that the city fire department floor had been stripped of several layers of paint using paint remover which was flushed to the sanitary sewers.

SAMPLING EQUIPMENT INADEQUACIES

The original sampling equipment supplied with the plant did not provide representative samples. The three samples required were raw wastewater, primary effluent, and final effluent. Only the final effluent samples could be collected continuously.

The samplers had a small opening about the size of the lead in a pencil, and the raw and primary effluent samples soon clogged the orifice. The pumps for raw and primary effluent had 1 1/2-inch (3.8 cm) suction piping but only 1-inch (2.54 cm) discharges. The primary effluent would pass easily enough, however, the raw pump would plug at the 1-inch opening almost immediately.

In 1975, a dipper type three-stage sampler with refrigeration was purchased from "Sonford Products" of Minneapolis, Minnesota and installed by the plant operators. All piping to the sampler was increased to 1 1/2-inch (3.8 cm) with provisions provided

for backflushing with final effluent. A submersible raw sample pump was installed directly behind the bar screen. The pump delivers 15 gallons per minute to the sampler and seldom causes any problems. The new sampling system works well with very little maintenance and we are assured of representative samples.

ENERGY AND CHEMICAL COSTS

The energy and chemical uses and costs associated with the plant operation for 1978 are summarized in Table 6. The costs shown per million gallons reflect actual prices Gladstone paid for the respective commodities in 1978.

Electricity consumption is of primary interest and the table shows electrical power consumption in terms of raw sewage pumping, secondary (RBC) treatment, and anaerobic digestion. The power consumption for the RBC units actually includes power consumption by clarifier drives, intermediate pumps, lights, ventilating equipment, etc., and computes to an average of approximately 38 running horsepower at any given time. Of this, approximately 80 percent (30 hp), including power draw by the RBC units, could be considered independent of actual flows. Based on measured power consumptions by the six RBC drive units in 1975, the RBC system draws an average of 25-26 horsepower at any given time.

TOTAL FACILITY BUDGET

Table 7 begins with the total facility budget and is followed by some of the major operating expenses. The remainder of the budget incorporates items such as the collection system, audit, administration, engineering, insurances, and etc.

Table 6

1978 Energy and Chemical Use
Gladstone, Michigan

	Electricity KWH/MG	Fuel 1000 BTU/MG	Chemicals Lbs/MG	Total Cost $/MG
Secondary Treatment				
Raw Sewage Pumping	263	–	–	$ 11.12
RBC System	1,105	–	–	46.74
Chlorination	–	–	20	3.49
Phosphorus Removal				
Alum	–	–	596	27.00
Polymer	–	–	2.4	4.47
Sludge Treatment				
Anaerobic Digesters	40	3,173	–	8.26
Truck	–	105	–	0.52
Drying Beds	–	N	–	N
Miscellaneous				
Building Heat	–	1,923	–	4.00
TOTAL SYSTEM	1,408	5,201	618	$105.60

Average Daily Flow for Year was 0.612 MGD

N = Negligible

Table 7

1979 Fiscal Year Budget

Total Facility Budget $178,000.00

Power
        Lift Stations   32,607 KWH
        Plant   313,627 KWH

        Total Power Costs   14,781.97

Natural Gas   1,185,490 cu ft   2,861,87

Chlorine   4,550 lbs   827.25

Aluminum Sulfate   95,648 lbs   4,497.96

Polymer   501 lbs   1,005.52

Labor   7,136 man-hours   57,088.00

Plant Maintenance   3,000.00

Parts, Supplies, Miscellaneous   4,000.00

Equipment Rentals   3,000.00

REVENUE TO OPERATE

In 1972, water meters were installed in every home. The water plant staff maintains these meters. All meters larger than 1-inch are checked at three year intervals. Small household meters are checked to assure accuracy as needed. Ten percent of the meters have registered 1 million gallons since 1972 and a routine maintenance program is being initiated.

The water distribution system originally began in 1889 and at the present, approximately 72% of the water produced can be accounted for. 63% of the water treated at the wastewater plant comes from inflow and infiltration.

Prior to 1969, no wastewater charges were collected, with the system operating solely on taxes. Water charges prior to 1970 averaged $1.00 per month. Today, with the new water filtration plant and the upgraded wastewater facility, the average house-hold using 5,000 gallons of water pays $11.65 for water and $10.49 for wastewater per month.

SUMMARY

We believe the RBC treatment system is an ideal treatment process for the city of Gladstone, Michigan. Excellent treatment results are being obtained and plant effluent quality is well within design limits. Consistent nitrification at loading below 2 gpd/sq ft is being achieved as an added bonus toward high quality treatment.

The system has been very consistent in achieving wastewater treatment and permitting stable solids handling procedures. Few problems have occurred with the day-to-day operation of our RBC secondary treatment system.

ACKNOWLEDGEMENTS

CONTROL TECHNOLOGY FOR NUTRIENTS IN
MUNICIPAL WASTEWATER TREATMENT IN SWEDEN

Bengt G. Hultman
Research Engineer
Swedish Water and Waste Water Works Association
Regeringsgatan 86
S-111 39 STOCKHOLM
Sweden

NEED FOR NUTRIENTS CONTROL

Sweden is comparatively rich in lakes with more than 20,000 exceeding 0.1 sq. km in area. Most of them are fairly shallow. In their natural states the lakes and coastal areas are deficient in nutrients. This means that the lakes and coastal areas will react to artificial supply of nutrients from for instance urban areas.

At the end of the 1950´s limnologists began to warn about the deterioration of the water quality in lakes and coastal areas due to the increased rate of the growth of algae and other vegetation. Rodhe (1958) pointed out that the phosphorus in sewage could increase the productivity in natural waters as much as commersial fertilisers applied on land. Different investigations on lakes indicated a significant rise in the water's content of phosphorus and biomass.

During two weeks in August 1972 an extensive lake survey was carried out by the National Swedish Environment Protection Board and the County Administrations (Johansson and Karlgren, 1974). A total of 1250 minor and medium-sized lakes were examined. Although not being the primary aim of the study, an attempt was made to estimate the degree of nutritional influence on the lakes resul-

ting from human activities. It was found that the inorganic phosphate content in water showed similar regional variations as that of total phosphorus and of total nitrogen with low concentrations in the low-productive lakes in northern Sweden and parts of southern Sweden and high concentrations in the high-productive lakes of the plains.

Based on the lake survey and complementary studies Hannerz and Forsberg (1975) estimated that less than 10 % of the Swedish lakes were eutrophic. In south Sweden about 10 to 20 % of the lakes were eutrophic and the percentage of eutrophic lakes in the Stockholm county amounted to about 50 %.

Several substances such as phosphorus, nitrogen, carbon dioxide, iron and vitamins can stimulate algal growth. Of these substances only phosphorus and nitrogen have been considered as main factors for stimulating eutrophication. A strong emphasis has been laid on phosphorus removal as the method for control of eutrophication especially from the National Swedish Environment Protection Board, while nitrogen has been considered to be of minor importance. The reasons for this view seem to be:

- Phosphorus seems to be rate limiting for algal growth in most Swedish lakes based on values of the weight proportion of nitrogen to phosphorus, which is about 25:1 for natural or low polluted lakes.

- A large fraction of phosphorus comes from point sources which may be more easily controlled than diffusive sources.

- Algae have the possibility of taking up nitrogen from the atmosphere if nitrogen is a limiting growth factor.

-       In the end of the 1960´s phosphorus removal was a much
        more wellknown technique than nitrogen removal in Sweden.

For a total of about 900 samples from surface water from 20 waste
affected lakes in Sweden during August-October 1972 Forsberg et
al. (1975) found phosphorus to be the growth limiting nutrient
in waters having total-P values less than 0.05 mg/l. Above 0.1
mg P/l nitrogen played the principal role. Between these values
the growth was primarily limited by phosphorus or nitrogen or
chelating agents.

Nitrogen seems to be the primarily rate limiting factor for algal
growth in case of eutrophic lakes (Forsberg, 1977) and in some
coastal waters as the Stockholm archipelago (Lindahl and Melin,
1973). In this case the policy of the National Swedish Environ-
ment Protection Board has been to try to reduce the phosphorus
supply to the water body as much as possible in order to make
phosphorus the growth limiting substance (Anonymous, 1971).

IMPLEMENTATION OF NUTRIENTS CONTROL

LEGISLATION AND ADMINISTRATION
Legislation concerning discharge of waste water into lakes and
rivers has been in existence in Sweden since the end of the
1930´s. A new law, the Environment Protection Act, came into for-
ce in July 1969 and tightened up regulations considerably.

The Environment Protection Act applies to what are termed pollu-
ting activities, i.e. the discharge of effluent, solids or gas

from land, a building or an installation or the use of such property in a manner liable to cause water pollution, atmospheric pollution, noise, vibration, the emission of light etc., if the nuisance thus caused is more than temporary (National Swedish Environment Protection Board, 1979a).

The chief principle of the act is to prevent environmental disturbances as far as possible. The precautionary measures, such as effective methods of wastewater treatment, shall be "economically feasible" and "technically practible".

Sewage from locations with more than 200 inhabitants must not be emitted without a permit. A special board, the Franchise Board for Protection of the Environment, holds the responsibility for the granting of permits. The obligation to apply for a permit is however not compulsory. The National Swedish Environment Protection Board may after due examination exempt an applicant from the need to apply to the Franchise Board for a permit. In exemption cases, the Board attempts through negotiations to come to an agreement with the applicant as to the conditions to be applied to the activity. An exemption granted lacks formal legal validity - as opposed to a permit - and may be withdrawn (National Swedish Environment Protection Board, 1979a).

SOURCE CONTROL

The synthetic detergents which were introduced in Sweden during the 1950's have greatly improved laundry cleaning efficiency. Polyphosphates were totally dominating as complexing agents in the

detergents. In the end of the 1960´s the average phosphate con-
centration was about 35 % in cleaning agents and in some special
products the phosphate concentration could amount to more than
60 % (Kjellman, 1975).

In the middle of the 1960´s municipal sewage from urban areas
contained phosphorus corresponding to about 4 g P per person and
day. Approximately half of this amount originated from detergents
(Ahl et al., 1967). The general opinion that phosphorus was the
main agent causing eutrophication lead to investigations of dif-
ferent methods to reduce the phosphate concentration in detergents.
In order to comply with authorities different manufacturers dimi-
nished the amount of phosphates in their detergents. As can be
seen from Table 1 the use of phosphate in detergents diminished
from about $3.9 \cdot 10^6$ kg in year 1968 to about $2.65 \cdot 10^6$ kg in 1972,
corresponding to a decrease of 32 %. Due to the decrease of phos-
phate in detergents the phosphorus content in sewage diminished
to about 3.3 g P per person and day of which about 30 % originated
from detergents (Kjellman, 1975). The use of phosphorus in deter-
gents has increased a little after 1972.

The trisodium salt of NTA may be used as a partial substitute for
or a complement to sodium tripolyphosphate as builder in house-
hold detergents. NTA was introduced on the market at the end of
the 1960´s (see Table 1). Several studies were performed in order
to evaluate the biodegradability of NTA (Forsberg and Lindquist,
1967, Bouveng et al., 1968 and 1970, and Björndal et al., 1972).

The results obtained showed that aerobic biological processes are capable of degrading NTA fairly efficient under normal conditions of operation. However, different foreign reports, for instance the Epstein report, raised some doubts that NTA could be safely used without negative consequences on the environment. These doubts lead to a decreased interest in using NTA in detergents (National Swedish Environment Protection Board, 1970) and the use of NTA in detergents has decreased during the 1970´s.

CHOICE OF PROCESS TECHNOLOGY FOR NUTRIENTS CONTROL
The first sewage works with chemical precipitation was built in 1961 in Åker, a small municipality with about 2,000 persons connected to the sewage works. The treatment plant was equipped for primary sedimentation with subsequent chemical precipitation where the flocs were separated in a flotation unit. The chemical precipitation agent was aluminium sulphate.

The sewage works in Åker was built before any significant research had started in chemical precipitation. In the middle of the 1960´s several research projects started on combined biological and chemical treatment of sewage. At that time the two processes which were considered were simultaneous precipitation and post-precipitation. Studies were performed in a laboratory scale, pilot plant scale and as full scale experiments.

Early studies on the simultaneous precipitation process gave rather high effluent values of total phosphorus. Pilot plant studies with simultaneous precipitation with aluminium sulphate gave eff-

luent values of total phosphorus of about 2 mg P/l (Balmér et al., 1968). Full scale tests at Eolshälls sewage works in Stockholm during a short test period showed effluent values of total phosphorus of about 1-1.5 mg P/l. Addition of aluminium sulphate caused a lower reduction of the BOD-values due to separation problems in the final sedimentation basin (Cronholm, 1968). Ulmgren (1969) reports other full scale tests in which simultaneous precipitation were studied giving high effluent values of total phosphorus. Laboratory studies of the simultaneous precipitation process, however, showed that it was possible to reach effluent values of total phosphorus below 1 mg P/l (Ericsson, 1967).

Laboratory experiments with post-precipitation showed that an effluent value could be reached of total phosphorus below 1 mg P/l (Ericsson, 1967, and Weijman-Hane, 1968). Similar results were obtained in evaluation of the first built sewage works with post-precipitation (National Swedish Environment Protection Board, 1969).

Based on the rather few experimental studies performed in Sweden concerning chemical precipitation and foreign experiences for instance in Switzerland the National Swedish Environment Protection Board strongly recommended post-precipitation instead of simultaneous precipitation as the removal method of phosphorus. In 1968 the expansion period began with chemical treatment plants with the purpose of reducing as much as possible of the phosphorus content in wastewaters.

No significant interest was laid on nitrogen removal. However, some research started in the middle of the 1960´s concerning nitrogen removal, especially by use of biological methods (Hultman, 1973, and Ericsson, 1975).

DESIGN GUIDELINES

To guide those who prepare or scrutinize proposals for treatment plants the National Swedish Environment Protection Board (1971) prepared "Guidelines for design of sewage treatment plants". In the guidelines the following are given: design values for sludge loads on the activated sludge process, BOD loads on trickling filters, detention time in flocculating units, surface loads in sedimentation basins etc (Ulmgren, 1975a).

EMISSION CONTROL

Instructions for emission control in Sweden have been issued by the National Swedish Environment Protection Board (1973). The sampling frequency in relation to the required parameters total BOD_7, total COD and total phosphorus is given in Table 2. In addition local authorities may demand more extensive emission control and programs for recipient control.

STATE GRANTS

State grants are since 1st of July 1968 payable on certain conditions for the construction, enlargement or alteration of sewage purification plants, outfalls and, in some cases, intercepting mains as well (National Swedish Environment Protection Board, 1968).

TABLE 1. YEARLY CONSUMPTION OF RAW MATERIALS FOR WASHING,
DISH-WASHING AND OTHER CLEANING MATERIALS USED IN
HOUSEHOLDS IN SWEDEN 1968-1972 (The consumption
figures are given in thousand kilograms; 1 kg =
2.205 lb) (Kjällman, 1965).

Raw material	Year				
	1968	1969	1970	1971	1972
Soap	1377	2037	2624	2597	2766
Synthetic tensides	7500	7704	7450	7443	8483
Phosphates	3920	3644	2855	2797	2650
NTA	777	1019	1711	1525	1373
Other organic com-plexing agents	116	115	226	330	492

TABLE 2. FREQUENCY OF SAMPLING IN EMISSION CONTROL
(National Swedish Environment Protection Board, 1970)

Parameter	Person equivalents (p.e.) connected to treatment plant			
	200-2000	2000-5000	5000-20000	>20000
COD [a]	4/year	1/month	2/month	4/month
BOD_7 [b]	1/year	4/year	6/year	1/month
P_{tot} [a]	4/year	1/month	2/month	4/month

(a)   Each sample collected durinq 7 days

(b)   Each sample collected during 1 day

Grants are gauged according to degree of purification and are payable at rates between 30 and 50 per cent of approved construction costs (see Table 3). During the fiscal years 1971/72-1973/74 grants were payable 25 per cent in excess of those rates given in Table 3. This formed a part of a programme to create jobs (National Swedish Environment Protection Board, 1979a). Grants given for different types of treatment are exemplified in Table 4 based on rates in Table 3.

PRESENT SITUATION

The general policies for implementation of the Environment Protection Act on sewage treatment as developed in the end of the 1960´s has essentially been maintained. Thus, a combined biological and chemical treatment of municipal wastewater is normally prescribed. In certain relatively few cases, only biological or only chemical treatment may be allowed. In localities with poor recipient conditions in relation to the discharge complementary treatment (mainly post-filtration) is prescribed in addition to biological and chemical treatment. Recently, requirements of nitrification has been prescribed for a sewage works in the Stockholm area. The main reason for this requirement is to diminish the oxygen demand of the wastewater which may give rise to oxygen deficit at the bottom of certain parts of the Stockholm archipelago and thereby cause leakage of phosphorus from the bottom sediments. Thus, the requirement of nitrification is to prevent phosphorus leakage and thereby according to the general view decrease algal growth.

TABLE 3.   STATE GRANTS FOR MUNICIPAL WASTEWATER WORKS
           (National Swedish Environment Protection Board, 1968)

Percentage BOD_7 purification effect	Percentage phosphorus purification effect		
	<50	$50-89$	>90
	Percentage grant:		
60-74	30	35	40
75-89	30	35	45
>90	35	40	50

TABLE 4.   PERCENTAGE GRANTS FOR DIFFERENT PROCESS COMBINATIONS
           (National Swedish Environment Protection Board, 1969)

Process combination	Percentage grant
Simultaneous precipitation	35
Direct precipitation	40
Post-precipitation	45-50

Sewage purification facilities in Sweden have expanded very quickly during the last decade (see Figure 1). In the beginning of 1979 about 640 municipal wastewater treatment plants were operated with combined biological and chemical treatment corresponding to about 72 % of the total amount of wastewater from urban areas.

The dominating process combination is post-precipitation with a share of more than 80 % calculated on the number of treatment plants with chemical precipitation (see Table 5). However, some of the largest sewage works, for instance in the Stockholm region, use pre-precipitation or simultaneous precipitation.

Aluminium sulphate has been the dominating precipitation agent. During the last years especially larger sewage works have changed to iron salts (see Table 6). This depends on that the production of ferric chloride from waste products has considerably lowered the price of the chemical. Besides there are some benificial effects on the sludge properties in the use of iron salts compared with aluminium sulphate.

EVALUATION OF NUTRIENTS CONTROL MEASURES

OPERATIONAL RESULTS

Several papers have been written on experiences of full scale operations of chemical precipitation in Sweden (Eklund, 1974, Grönqvist et al., 1978, Hultman, 1978, Isgård and Ericsson, 1976, and 1978, and Ulmgren, 1975a and 1975b). These papers discuss
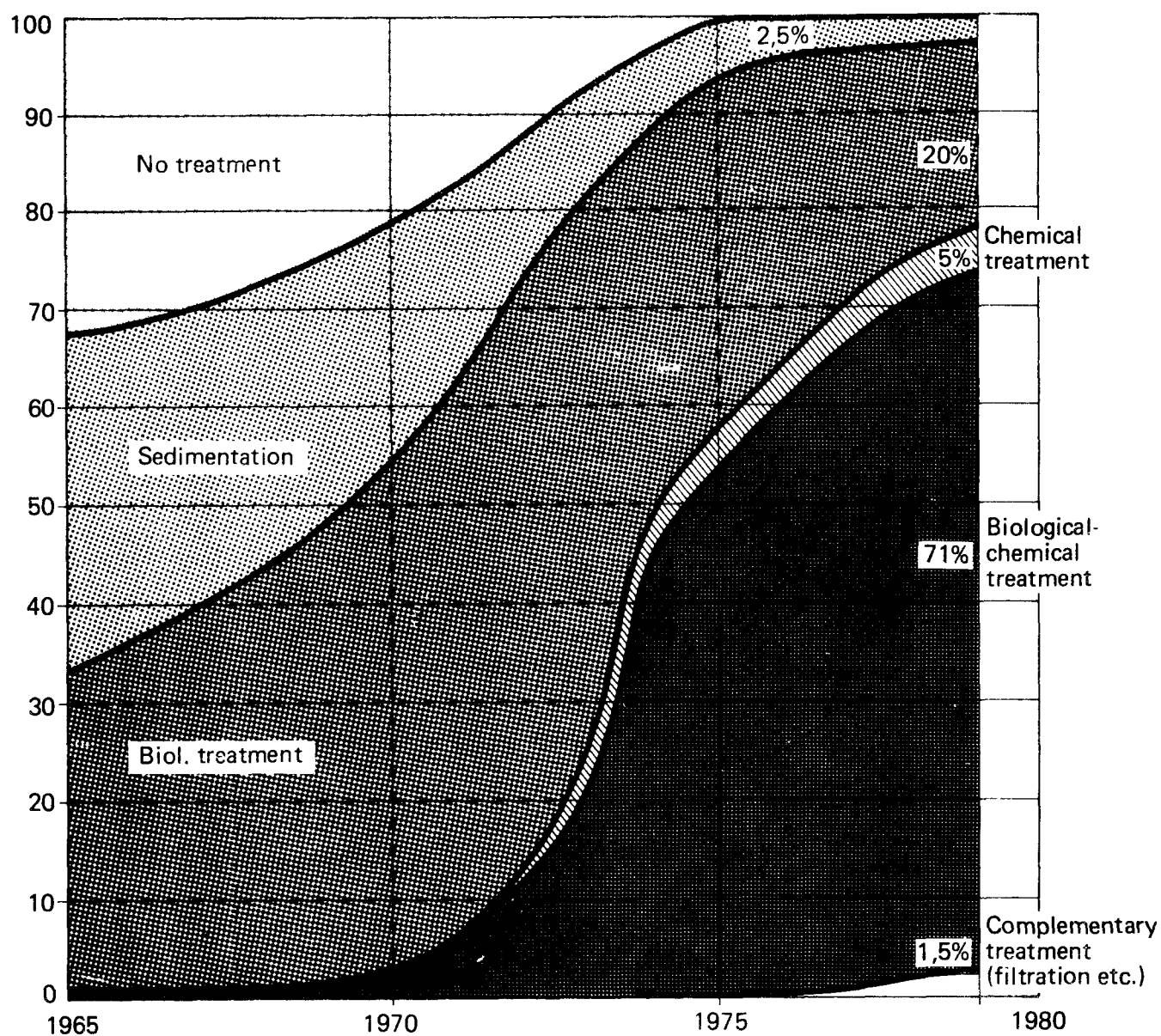
Type of sewage treatment	Number of treatment plants	Number of persons served
No treatment		7 000 (— 1 000)
Sedimentation	156 (—34)	181 000 (— 21 000)
Biological treatment	380 (—37)	1 398 000 (—110 000)
Chemical treatment	141 (+ 3)	324 000 (+ 22 000)
Bio. chemical treatment	625 (+ 18)	4 833 000 (+ 106 000)
Complementary treatment	18 (+ 2)	107 000 (+ 7 000)
	1 320 (—48)	6 850 000

The figures in brackets refer to the change since January 1 st, 1978

Figure 1.   Sewage Treatment in Sweden 1965–1979

TABLE 5. DIFFERENT TYPES OF SEWAGE WORKS WITH CHEMICAL PRECIPI-
TATION IN SWEDEN IN THE BEGINNING OF 1978
(National Swedish Environment Protection Board, 1979b)

PROCESS COMBINATION:	NUMBER OF PLANTS
Direct precipitation	138
Pre-precipitation	17
Simultaneous precipitation	35
Post-precipitation	554

Post-precipitation systems:

Trickling filters	49
Activated sludge	505
Separation of chemical flocs by contact filtration	11
Polishing by deep-bed filters	16

TABLE 6. USE OF DIFFERENT PRECIPITATION AGENTS AT MUNICIPAL SE-
WAGE WORKS IN SWEDEN IN THE BEGINNING OF 1977 AND 1979
(National Swedish Environment Protection Board, 1979b)

	TYPE OF CHEMICAL PRECIPITATION AGENT:				
	Aluminium sulphate	Ferric & ferrous iron	Lime	Iron salts & lime	Aluminium sulphate & iron salts
Number of plants	600 (578)	92 (60)	60 (48)	26 (22)	4 (3)
Percentage of connected po-pulation	49 (69)	42 (23)	5 (3)	2 (3)	2 (2)

Numbers from the beginning of 1977 are within brackets.

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different process configurations, the influence of different operational parameters such as dosage, pH-value in the flocculation step and type of chemical precipitation agent and the influence of separation methods.

Data from the emission control at municipal sewage works shall be sent to the National Swedish Environment Protection Board once a year. Compilations of such data have been published by the National Swedish Environment Protection Board (1977 and 1979b). Obtained results for different treatment systems are shown in Table 7. The results are compared in the table with expected results from treatment plants with a good operation and no significant disturbances based on results reported by Grönqvist et al. (1978).

A large fraction of the Swedish municipal sewage works do not operate reliably. Investigations of post-precipitation plants indicate that effluent values of BOD_7 are not below 15 mg/l (required limit) for about 30 % of the plants and effluent values of total phosphorus are not below 0.5 mg P/l (required limit) for about 40 % of the plants (National Swedish Environment Protection Board, 1977).

Full scale experiences of simultaneous precipitation plants in the Nordic countries have been put together by Grönqvist and Arvin (1979). It was shown that much better results could be obtained for the treatment plants than results shown in Table 7. The average concentration of total phosphorus from five simultaneous precipitation plants in the Stockholm area was 0.6 mg P/l.

TABLE 7. OPERATIONAL RESULTS BY USE OF DIFFERENT CHEMICAL PRECIPITATION METHODS

PROCESS COMBINATION	OPERATIONAL RESULTS IN 1977 (1)		EXPECTED RESULTS FOR PLANTS WITH NO SIGNIFICANT DISTURBANCES (2)
	BOD_7 mg/l	P_{tot} mg/l	P_{tot}, mg/l
Direct precipitation	39	0.70	-
Pre-precipitation	35	0.98	0.5-0.8
Simultaneous precipitation	28	1.48	0.5-0.8
Post-precipitation	10	0.53	0.5-1.2 (3) 0.2-0.4 (4)
Post-precipitation followed by deep-bed filtration	9	0.22	0.15-0.3 (5)

Notes: (1) Average values from different plants. Data from National Swedish Environment Protection Board (1979b).

(2) According to Grönquist et al. (1978).

(3) Post-precipitation with aluminium sulphate at pH 6.5-7.2 or lime in single stage at normal loaded plants.

(4) Post-precipitation with aluminium sulphate at pH 5.5-6.4, with ferric chloride and recirculation of sludge to the aeration basin or with lime in single stage at low loaded plants.

(5) Post-precipitation with aluminium sulphate at pH 5.5-6.4.

In order to elucidate the reasons of the unsatisfactory removal efficiencies of certain sewage works an enquiry was sent in spring 1979 to the County Councils. These were requested to give their opinion of the reasons for the unsatisfactory results of sewage works with effluent values of BOD_7 and total phosphorus above 15 mg/l and 0.5 mg P/l, respectively. Several explanations were given such as hydraulic problems, difficult industrial wastes and unreliable machinery equipment. The percentage distribution of reasons to unsatisfactory results is given in Table 8.

COSTS OF POST-PRECIPITATION PLANTS

The costs for post-precipitation plants based on average values from different Swedish reports are put together in Table 9. The capital costs are somewhat higher than the operating costs. Due to increasing treatment costs for diminishing sizes of the sewage works there is a tendency to centralize the wastewater treatment. The grant system has promoted this development. The use of complementary treatment by deep-bed filtration will increase the total costs for a post-precipitation plant 15-20 %. Different cost factors for the operating costs are shown in Table 10.

EFFECTS ON RECIPIENTS

In order to elucidate the effects of biological and chemical treatment on the water quality in the recipient the National Swedish Environment Protection Board started a program in 1972 for analyzing the conditions in a number of different recipient lakes (Forsberg et al., 1975).

TABLE 8.   CAUSES OF UNSATISFACTORY REMOVAL EFFICIENCIES OF POST-
PRECIPITATION PLANTS (Carlsson and Nordström, 1979)

CAUSE	PERCENTAGE DISTRIBUTION, %
Hydraulic problems	18
Industrial wastes	12
Machinary equipment	19
Process technology	17
Maintenance	2
Repairs, reconstruction	4
Unreliable analysis (1)	17
Unknown causes	12

Note: (1)   Probably depending on significant nitrification in
BOD-bottles during the BOD_7-measurement.

TABLE 9. APPROXIMATE COSTS FOR SEWAGE TREATMENT (1978).

Number of person equivalents (p.e.)	Costs for post-precipitation plants (including sludge treatment)		Additional costs for deep-bed filtration	
	Capital costs	Operating costs	Capital costs	Operating costs
	$\dfrac{Skr}{p.e.\cdot year}$	$\dfrac{Skr}{p.e.\cdot year}$	$\dfrac{Skr}{p.e.\cdot year}$	$\dfrac{Skr}{p.e.\cdot year}$
2,000	130	100	-	-
5,000	100	70	25	8
20,000	60	50	10	4
50,000	45	40	7	3

Notes: 1 Skr = 0.24 US dollars

In calculation of capital costs the annuity used is 10 % and 13 % for post-precipitation plants and deep-bed filters, respectively.

Average municipal water consumption is about 400 l per person and day in Sweden.

TABLE 10. OPERATING COSTS FOR POST-PRECIPITATION PLANTS (INCLUDING SLUDGE TREATMENT) (1978)

COST FACTOR	PERCENTAL COSTS, %
Labour and administration	30
Chemicals	25
For chemical precipitation	(15)
For sludge conditioning	(10)
Energy	20
Sludge transportation	10
Other costs factors	15
	100

From the experiences of phosphorus removal positive responses
have been reported from some water bodies. In other lakes delayed
recovery has been observed after nutrient reduction. In some la-
kes, where the phosphorus load was reduced by 30-40 %, no marked
improvements were noted. The results available indicate that a
comparatively great change in phosphorus load must occur in or-
der to get significant improvement in water clarity in the lakes.
As the phosphorus load from treatment plants is often the domi-
nant phosphorus source, reduction of phosphorus by advanced treat-
ment seems to be a good tool for controlling eutrophication in
many lakes (Ryding, 1978a and 1978b).

TRENDS IN IMPROVEMENT OF CONTROL OF NUTRIENTS

The operating costs have steadily increased at Swedish sewage
works. Therefore great interest has been directed towards biolo-
gical-chemical treatment methods which can reduce the operating
costs and which are more efficient. Such methods include the use
of counterflow of precipitated sludges, two-step precipitation,
regulation of the alkalinity and automatic control.

For a constant value of the suspended solids in the effluent it
is advantageous to have a low fraction of phosphorus in the sus-
pended solids in order to obtain low effluent values of phospho-
rus. If the effluent concentration of suspended solids is 10 mg/l
and the fraction of phosphorus in the suspended solids 6 % and 2
% the effluent concentration of suspended phosphorus will be 0.6
and 0.2 mg P/l, respectively.

A suitable way to diminish the fraction of phosphorus in the suspended solids is to decrease the influent phosphorus concentration before the precipitation step. This technique has been tried in full scale at several sewage works in Sweden. Different examples are:

- Two-step precipitation at Bälinge sewage works (Holmström, 1977) by use of the combination of simultaneous precipitation and contact filtration in which process combination the principal part of phosphorus removal occurs in the simultaneous precipitation step after which still more phosphorus is removed by the addition of low concentrations of ferric iron before a deep-bed filter.

- Two-step precipitation at Käppala (Isgård and Ericsson, 1978) and Bankeryd sewage works in which simultaneous precipitation is followed by post-precipitation.

- Recirculation of post-precipitated sludge to the aeration basin of the activated sludge process (Grönqvist et al., 1978). The phosphorus reduction in the biological step is hereby improved and the phosphorus concentration before the post-precipitation step will be much lower than if no recirculation takes place. Some preliminary results indicate, however, that nitrification may be inhibited by recirculation of aluminium containing post-precipitated sludges.

- Use of biological phosphorus reduction at Kristianstad sewage works by use of an anaerobic zone in the first part of the aeration basin. In this way the phosphorus concentration is diminished before the post-precipitation step.

These operational modifications of an existing post-precipitation plant have shown very promising results including better removal efficiencies of total phosphorus, lower total amount of chemical precipitation agents and better sludge properties. It therefore seems probable that a large fraction of the Swedish post-precipitation plants will change to a modified operating scheme.

The alkalinity of the effluent from a biological step is mainly determined by the influent alkalinity and the degree of nitrification and denitrification. In nitrification the produced amount of hydrogen ions reduces the alkalinity of the wastewater. This reduction often leads to reduced requirements of aluminium sulphate or lime in post-precipitation and several treatment plants are operated in this way in Sweden (Ericsson et al., 1976, and Grönqvist et al., 1978). Promising results have been shown by regulation of the alkalinity of the effluent from an activated sludge process by regulation of the degree of nitrification and denitrification by the supply of oxygen (Olsson, 1980).

SUMMARY

During the 1950´s observations were made and the conclusion drawn that the water quality in some lakes and coastal waters had deterioted. Different recipient studies indicated that phosphorus was the main factor which caused this deterioration. Some efforts were made to decrease the phosphate concentrations in the synthetic detergents and approximately a 30 % reduction of the phosphate amount in synthetic detergents was obtained between 1968 and 1972. In 1968 the expansion period began with chemical treatment plants and in the beginning of 1979 about 640 municipal wastewater treatment plants were operated with combined biological and chemical treatment corresponding to about 72 % of the total amount of wastewater from urban areas. At present a large interest has been directed towards modified operating schemes in order to get better removal efficiencies and savings in operating costs.

REFERENCES

Ahl, T., Karlgren, L., Olsson, E. and Tullander, V. (1967): Hushållsavloppsvattnet. Vatten, 23, 3, pp 178-204 (in Swedish).

Anonymous (1971): Eutrofieringsproblemet. Vatten, 27, 4, pp 463-465 (in Swedish).

Balmér, P., Blomquist, M. and Lindholm, M. (1968): Simultanfällning i en högbelastad aktivslamprocess. Vatten, 24, 2, pp 112-116 (in Swedish).

Björndal, H., Bouveng, H.O., Solyom, P. and Werner, J. (1972): NTA in sewage treatment. Part 3. Biochemical stability of some metal chelates. Vatten, 28, 1, pp 5-16.

Bouveng, H.O., Davidsson, G. and Steinberg, E.-M. (1968): NTA in sewage treatment. Vatten, 24, 4, pp 348-359.

Bouveng, H.O., Solyom, P. and Werner, J. (1970): NTA in sewage treatment. Part 2. Degradation of NTA in a trickling filter and an oxidation pond. Vatten, 26, 4, pp 389-402.

Carlsson, A. and Nordström, B. (1979): Orsaker till otillfredsställande reningsresultat vid kommunala avloppsreningsverk. National Swedish Environment Protection Board, SNV PM 1248 (in Swedish).

Cronholm, M. (1968): Fosforreduktion medelst aluminiumsulfat vid Eolshälls reningsverk, Stockholm. Vatten, 24, 2, pp 117-124 (in Swedish).

Eklund, L. (1974): Bearbetning av resultat från driftundersökningar vid kommunala reningsverk. National Swedish Environment Protection Board, SNV PM 556 (in Swedish).

Ericsson, B. (1967): Närsaltreduktion vid avloppsverk. Vatten, 23, 2, pp 92-102 (in Swedish).

Ericsson, B. (1975): Nitrogen removal in a pilot plant. J. Water Pollution Control Federation, 47, 4, pp 727-740.

Ericsson, B., Mård, G. and Åkesson, M. (1976): Drifterfarenheter med biologisk nitrifikation vid Örebro reningsverk. Vatten, 32, 3, pp 301-310 (in Swedish with an English summary).

Forsberg, C. (1977): Nitrogen as a growth factor in fresh water. Prog. Wat. Tech., Vol 8, Nos 4/5, pp 275-290.

Forsberg, C. and Lindqvist, G. (1967): Experimental studies on bacterial degradation of nitrilotriacetate, NTA. Vatten, 23, 4, pp 265-277.

Forsberg, C., Ryding, S.-O. and Claesson, A. (1975): Recovery of polluted lakes. A Swedish research program on the effects of advanced waste water treatment and sewage diversion. Water Research, 9, 1, pp 51-59.

Grönqvist, S. and Arvin, E. (1979): Simultanfällning - erfarenheter och FoU-behov. Nordforsk-prosjektet: Drift av renseanlegg, rapport 5 (in Swedish).

Grönqvist, S., Holmström, H., Hultman, B. and Reinius, L.-G. (1978): Experiences and process development in biological-chemical treatment of municipal wastewaters in Sweden. Prog. Wat. Tech., Vol 10, Nos 5/6, pp 701-713.

Hannerz, L. and Forsberg, C. (1975): Eutrofieringssituationen i Sverige. Tionde nordiska symposiet om vattenforskning. Nordforsk, Miljövårdssekretariatet, Publ. 1975:1 (in Swedish).

Holmström, H. (1977): Simultanfällning och kontaktfiltrering vid Bälinge reningsverk. Swedish Water and Waste Water Works Association, Rapport 1/77 (in Swedish with an English summary).

Hultman, B. (1973): Biological nitrogen reduction studied as a general microbiological engineering process. In "Environmental Engineering." G. Lindner and K. Nyberg (Eds.), D. Reidel Publ. Co., Dordrecht, Netherlands, pp 264-275.

Hultman, B. (1978): Chemical precipitation in Sweden - Present situation and trends in process improvement and cost reduction. Paper presented at 2nd International Congress of the Environment 4-8 Dec. 1978, Palais de Congrès, Paris, France.

Isgård, E. and Ericsson, B. (1976): Chemical and biological sewage treatment in Sweden. Effluent and Water Treatment Convention, Manchester 1976.

Isgård, E. and Ericsson, B. (1978): A review of the Swedish situation in combined wastewater treatment. Paper presented at "Colloque International 16-19 mai 1978, Traitement combiné des eaux usées domestiques et industrielles." Université de Liège - Section d'Environnement.

Johansson, K. and Karlgren, L. (1974): Tusen sjöar. Rapport från en inventering. National Swedish Environment Protection Board, Publ. 1974:11 (in Swedish).

Kjällman, A. (1975): Tvätt- och diskmedel som närsaltkälla. Tionde nordiska symposiet om vattenforskning. Nordforsk, Miljövårdssekretariatet, Publ. 1975:1 (in Swedish).

Lindahl, P.E.B. and Melin, R. (1973): Algal assays of archipelago waters. Quantitative aspects. OIKOS, 24, pp 171-178.

National Swedish Environment Protection Board (1968): Statsbidrag till avloppsreningsverk. Meddelande V 5 (in Swedish).

National Swedish Environment Protection Board (1969): Experience of chemical purification. Publ. 1969:10 E.

National Swedish Environment Protection Board (1970): Tvättmedel som miljöproblem. Publ. 1970:4 (in Swedish).

National Swedish Environment Protection Board (1971): Dimensionering av kommunala reningsverk (in Swedish).

National Swedish Environment Protection Board (1973): Utsläppskontroll vid kommunala avloppsanläggningar. Publ. 1973: 16 (in Swedish).

National Swedish Environment Protection Board (1977): Sewage treatment in built up areas in Sweden as at 1st January 1977. SNV PM 911 E.

National Swedish Environment Protection Board (1979a): Water Protection in Sweden. Bulletin, SNV PM 1153 E.

National Swedish Environment Protection Board (1979b): Avloppsrening – tätorternas avloppsförhållande den 1 januari 1979. Meddelande 4/1979 (in Swedish).

Olsson, G. (1980): Automatic control in wastewater treatment plants. Trib. Cebedeau, Vol 33, N° 436, pp 121-130.

Rodhe, W. (1978): Aktuella problem inom limnologin. Svensk Naturvetenskap, pp 55-107 (in Swedish).

Ryding, S.-O. (1978a): The significance of sewage effluent for the hydraulic and nutrient loads on lakes. Prog. Wat. Tech., Vol 10, Nos 5/6, pp 907-916.

Ryding, S.-O. (1978b): Research on recovery of polluted lakes. Loading, water quality and responses to nutrient reduction. Acta Universitas Upsaliensis, Abstracts of Uppsala Dissertations from the Faculty of Science, 459.

Ulmgren, L. (1969): Drifterfarenheter från några reningsverk för närsaltreduktion. Vatten, 25, 2, pp 140-145 (in Swedish).

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Ulmgren, L. (1975a): Experiences and results from chemical pre-
    cipitation of domestic waste water in full-scale
    plants. Prog. Wat. Tech., Vol 7, Nos 3/4, pp 409-416.

Ulmgren, L. (1975b): Swedish experiences in chemical treatment
    of wastewater. J. Water Pollution Control Federation,
    47, 4, pp 696-703.

Weijman-Hane, G. (1968): Närsaltreduktion. Vatten, 24, 2, pp 106-
    111 (in Swedish).

ECONOMICAL AND EFFICIENT PHOSPHORUS CONTROL
AT A DOMESTIC-INDUSTRIAL WASTEWATER PLANT

Doris Van Dam
Wastewater Treatment Plant Superintendent
Grand Haven - Spring Lake, Michigan Sewer Authority

INTRODUCTION

In 1968, the Michigan Water Resources Commission (MWRC) issued

orders for phosphorus and other pollutant reductions to commun-

ities and industries whose wastes were being discharged to the

waters or tributaries of the Great Lakes by December 1972. The

MWRC adopted its standard from the Federal State Conference on

the pollution of Lake Michigan and its tributary basin held in

Chicago, Illinois in March 1968.

The response at Grand Haven and Spring Lake, Michigan, located

on the sandy coast where the Grand River enters Lake Michigan,

was to form a combined sewer authority and build a new central

treatment plant. The plant was designed not only to process

domestic wastes, but also to receive a substantial contribution

from the Eagle Ottawa Leather Co., a chrome and vegetable tan-

ner of 12,000 hides per week and a principal employer in the

Grand Haven - Spring Lake area. (Figure 1).

It is the purpose of this paper to discuss the special challen-

ges the merged waste flow posed to design and subsequent opera-

tion of the treatment plant. How concentrated side streams,

such as heat treatment supernatants, must be considered in over-

all plant efficiency is discussed. The techniques used to control
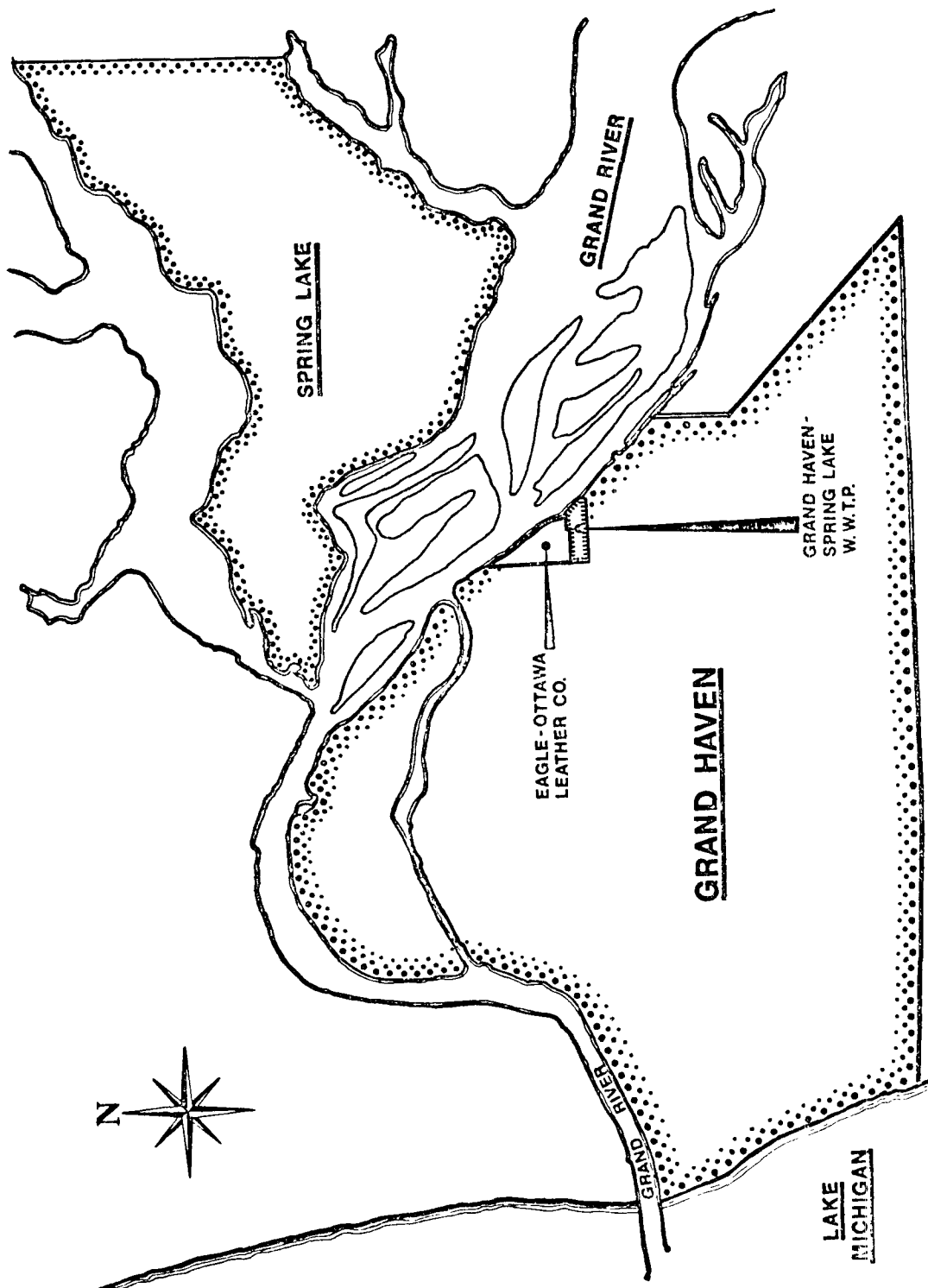
Figure 1. Grand Haven - Spring Lake
Wastewater Treatment Plant

phosphorus at a very low cost are presented. A summary of several years of plant efficiency and cost figures accompany the text.

BACKGROUND

The MWRC requirements called for an 80 percent removal of phosphorus for Grand Haven, Spring Lake, and the Eagle Ottawa Leather Co., as well as combined maximums from all three sources of 1,126 pounds per day (511.2 kg) of BOD, and 30 mg/l of suspended solids.

At the time, Grand Haven, population 10,500, was served by an outdated primary treatment plant, Spring Lake, population 3,034, employed an overloaded Imhoff tank, and Eagle Ottawa Tannery effluent was simply screened before discharge to the Grand River.

To meet the requirements, the newly-formed joint district constructed a single 5.0 mgd (18,925 cu m/day) activated sludge plant. The plant went on line in November, 1973, and 1978-1979 average contributions from the three sources were 2.1 mgd (7,759 cu m/day) from Grand Haven, 0.4 mgd (1,476 cu m/day) from Spring Lake, and 0.8 mgd (3,179 cu m/day) from Eagle Ottawa (Figure 2).

Although tannery wastes have amounted to just 26 percent of treatment plant flow, they represent 81 percent of total influent BOD, and 80 percent of influent suspended solids. The tannery waste contains in mg/l 60 sulfides, 34 chromium, 57 ammonia, 2911 COD, and a total nitrogen as N of 106 (Figure 2).

The treatment plant employs grit removal, phosphorus removal, primary clarification, activated sludge and chlorine contact; solids are conditioned thermally prior to vacuum filtration (Figure 3).

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YEARLY AVERAGES

GRAND HAVEN-SPRING LAKE, MI

	MGD	BOD	SS	COD
MUNICIPAL (GH-SL)	2.4 (9,235 cu m/day)	94 mg/l	119 mg/l	276 mg/l
TANNERY (EAGLE-OTTAWA)	0.8 (3,179 cu m/day)	1216 mg/l	1304 mg/l	2911 mg/l

TANNERY ONLY

SULFIDE	AMMONIA	TOTAL N
60 mg/l	57 mg/l	106 mg/l

pH RANGE	Cr RANGE	Cr AVERAGE
7.3-12.2	39-127 mg/l	34 mg/l

Figure 2. Influent Characteristics (1978-1979)
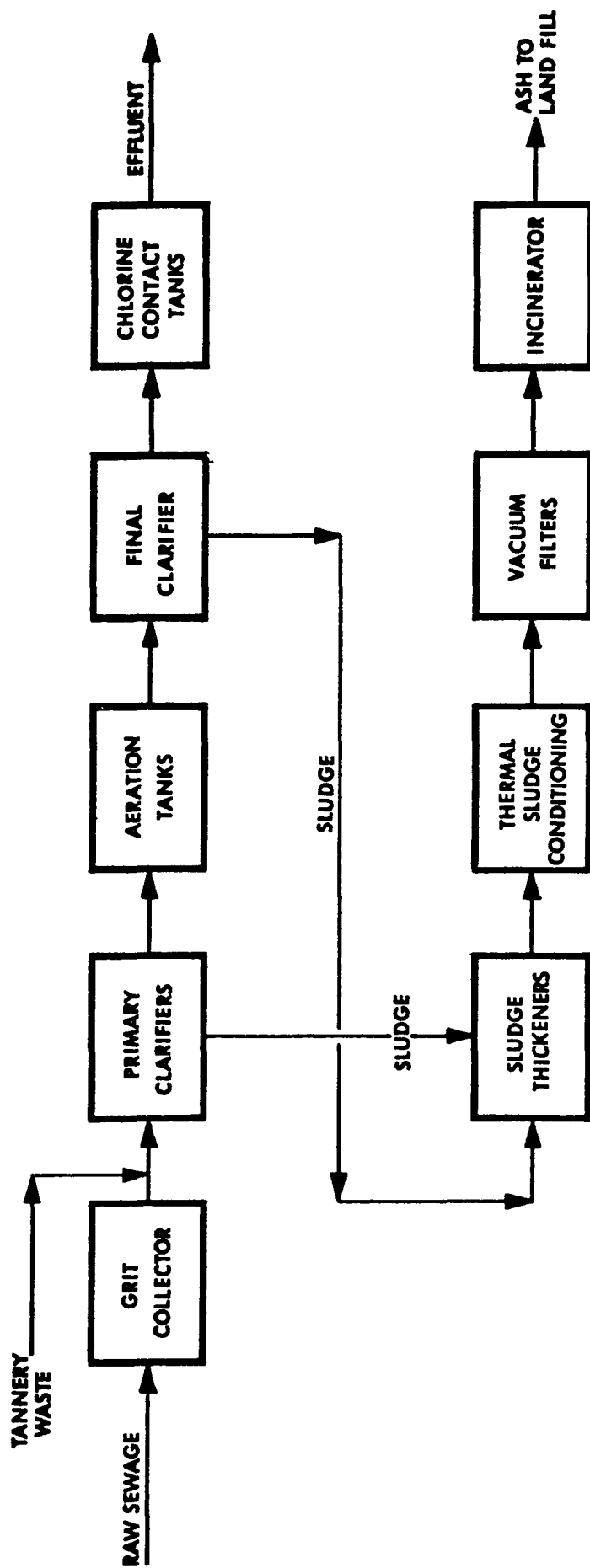
Figure 3. Grand Haven - Spring Lake, Michigan
Wastewater Treatment Plant

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All domestic flow is comminuted prior to reaching the grit tank. Eagle Ottawa wastes are screened at the tannery. Grit collected on the bottom of a square, aerated-type grit collector is removed by means of an air lift pump from the hoppered end of the tank. Grit is washed by means of a mechanical inclined screw mechanism.

Ferrous sulfate for phosphorus removal is added to the total flow in the rapid mix tank located in the grit building.

Air flocculcation is provided in the primary clarifiers for polymer flocculation.

The plant includes three 60-foot (18.29 m) diameter, primary clarifiers, 200,000 gallon (757 cu m) capacity each. The three aeration tanks have a total capacity of 1,700,000 gallons (6,434.5 cu m), and and are equipped with duo-spargers and coarse bubble diffusion. The aeration tanks are arranged so that the activated sludge process can be operated in one of four modes: conventional, complete mix, step aeration, or contact stabilization. Air is provided by four centrifugal blowers, each having a capacity of 5,200 cubic feet (145.6 cu m) per minute.

The three final clarifiers are the same size as the primaries, and are equipped with suction-type sludge removal mechanisms. The chlorine contact tank has been constructed to provide two separated tanks with gates so that either tank may be isolated for cleaning.

Effluent water is used for lawn sprinkling, the incinerator scrubber, filter belt wash, foam suppression, line flushing, thickener, and chlorinators.

Return sludge pumps are 20 hp (14.914 kw), and can provide 100 percent return sludge capacity. Sludge from primary clarifiers is drawn off from a sump at the center of the clarifier by means of positive displacement pumps, and pumped directly to two 45-foot (13.716 m) diameter, 20-foot (6.096 m) deep covered thickening tanks, with total capacity of 1,000,000 gallons (3,785 cu m), or 28,000 pounds (12,712 kg) per day of solids.

After thickening, sludge is processed through a wet oxidation unit where it is thermally conditioned at a rate of 68 gallons (257.38 liters) per minute. Sludge is first ground in one of two grinders which are piped in parallel to insure operation if one is out of service.

Air is supplied by a 50 hp (37.29 kw), 134 scfm (3.75 cu m/min) @ 500 spig (35.15 kg/sq cm) compressor, and the sludge-air mixture is pumped to reactor pressure of 306 psig (21.51 kg/sq cm) by a high pressure positive displacement ram-type pump. The material is fed through stainless steel heat exchangers to a stainless steel-clad reactor. A steam boiler maintains reactor temperature at 385°F (195.9°C). A standby boiler, and a second high pressure pump, provide backup capability.

Oxidized sludge is decanted in a separate tank and dewatered on one of two cloth-covered, 370 square foot (34.37 sq m) vacuum filters. When the incinerator is bypassed, sludge cake is hauled to landfill or used on agricultural land.

Plant performance has averaged 96 percent BOD removal, 76 percent COD removal, 96 percent suspended solids reduction, 88 percent

phosphorus removal, and chromium reduction of 96 percent (Figure 4).

SPECIAL PROBLEMS - LOCATION/ODORS

Inclusion of tannery wastes in the new treatment plant created conditions which required special consideration from the very first.

Because the hair, lime and grease in tannery wastes tend to clog sewer lines unless there is adequate sewer dilution or primary treatment prior to discharge into sewers, plant siting became a crucial decision. To minimize the anticipated difficulties in moving tannery effluent over longer distances, the new treatment plant was situated within the city limits of Grand Haven, immediately south of the Eagle Ottawa plant. The location is in a semi-residential neighborhood, and special provisions for odor control have had to be implemented.

In the original scheme, all usual odor-producing areas (grit and screening building, decant tank, thickeners, vacuum filters) were covered. The areas are vented and odors drawn off to the inlet of the aeration blowers and solubilized in the mixed liquor.

Because of equipment failures and the tannery contribution, however, odor problems unforeseen originally have required extraordinary odor control techniques.

TREATABILITY

Treatability of the tannery-domestic waste mixture was a second important question. Pilot studies verified the effectiveness of the activated sludge method, provided the chromium content of primary effluent could be reduced to approximately 5 mg/1 to avoid

GRAND HAVEN-SPRING LAKE, MI

	INFLUENT mg/l	EFFLUENT mg/l	% REMOVAL
BOD5 day	389	16	96
COD	920	228	76
SS	432	19	96
P	5.0	0.6	88
Cr	11.2	0.39	96

Figure 4.   Overall Plant Purification
Average 1978-79

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toxicity in the biological phase. This was achieved by blending lime from the tannery's beamhouse to aid in the precipitation of chromium hydroxide. The addition of sodium hydroxide to the tannery waste prior to its combination with the domestic flow is also possible. This has rarely been necessary, however, except for a period during a strike when the tannery was operating with limited staff and not using the beamhouse to full capacity.

Since the tannery wastes are discharged on a batch basis, with pH ranging from 3 to 12, an equalization tank was incorporated into the system to hold tannery efflyent and create an acceptable pH level of 8.5 to 9.0.

In addition, the system is designed so that all tannery wastes can be taken into one primary tank, exclusive of domestic wastes, and treated separately, should that become necessary.

SIDESTREAM RECYCLE

A great deal has been said about the supernatant decant liquor which is returned from thermally conditioned sludge to the treatment plant. Sidestream treatment should be studied in light of purpose and design of the total solids handling system and the fate of solids throughout.

Let us deal with solids first. While thermal conditioning is highly successful in making the difficult-to dewater sludge easily dewaterable, it also solubilizes a portion of the raw suspended solids. At the same time, a relatively small amount, approximately 5 percent, of oxidation of volatile solids occurs, due to the addition of air in the thermal conditioning system.

Supernatant recycle, of course, is another concern. After conditioning, the oxidized sludge flow enters the decant tank, where it thickens before it is sent to the vacuum filter for dewatering. The decant supernatant, a relatively clear liquid resulting from the thickening process, is decanted and returned to the aeration tanks for treatment. While its suspended solids concentration is only, 2460 mg/l, its COD, BOD_5, and P concentrations are 22, 320 mg/l, 9370 mg/l and 45 mg/l respectively, due to the solubilized dissolved volatile solids. It constitutes the major biological solids handling sidestream load on the plant. It also has some phosphorus load. Additional capacity and operational flexibility were designed into our secondary system to allow for adequate treatment of the solids handling recycle streams.

PHOSPHOROUS REMOVAL

A chemical mixing, feeding and distribution system was provided to provide chemical removal of phosphorous in the wastewater stream. It was planned that the chemicals used for phosphorous removal would include ferric chloride and polymer.

Ferric chloride would be delivered by truck and transferred to two 10,000 gallon (37,850 1) storage tanks located adjacent to the chemical feed room underground outside the control building.

Because the concentrations of ferric chloride delivered to the plant would vary from 38 percent to 45 percent during winter and summer months respectively, the operator had flexibility as to how to store and feed the ferric chloride. A dilution system was installed so that a constant dilution could be fed throughout the

year if desired. Non-potable water could be added to the storage tank along with air mixing from the bubbler system to provide the desired diluted concentration. Should the operator not desire to dilute the concentration, as is the case with waste pickle liquor currently used, the solution can be fed directly from the storage tanks to the plant.

A bubbler system was incorporated in the design to measure the level in both ferric chloride tanks.

Positive displacement metering pumps were provided to meter the iron solution to the various feed points which consisted of the rapid mix tank, inlet and outlet of primaries and aeration tanks, and inlet of the final settling tanks. Metering pumps were electronically paced from the main plant master flow meter. A standby iron solution pump was also included. The solution from the pumps flows to a rotameter distribution panel where it can be distributed throughout the plant.

It was designed for polymer to be delivered to the plant in dry form. An automatic mixer and dispenser were provided to meter the polymer solution to the various feed points. As in the case of the iron solution, the feed pumps were paced from an SCR controller which in turn was paced from the main plant master flow meter. The rotameter panel for polymer was also provided for distribution throughout the plant. This panel would split only the diluted polymer.

Numerous programs of varying chemical concentration and feed points for phosphorous removal were conducted (Figure 5). In March 1974

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1974	Fe APP-LIED mg/l	POLY-MER APP-LIED mg/l	INF. P mg/l	EFF. P mg/l	CHEM-ICALS COST	REMARKS:
MARCH	8.01	0.21	5.5	1.2	$1,181	FERRIC CHLORIDE ADDED AT PRIMARY TANKS. POLYMER APPLIED TO FINAL TANKS ONLY.
APRIL	8.63	0.17	5.2	1.3	$1,271	POLYMER TO FINAL TANKS ONLY. FERRIC CHLORIDE 60% TO PRI. TANKS, 40% TO INLET TO FINAL TANKS.
MAY	7.24	0.19	4.8	1.3	$1,293	DUPLICATED APRIL OPERATION.
JUNE	8.38	0.21	3.8	0.7	$1,989	SPLIT POLYMER AND Fe 2/3 TO PRI. TANKS, 1/3 TO FINAL TANKS. TANNERY ON LINE IN JUNE.
1975						
MARCH	4.1	0	4.6	0.9	$ 381	
APRIL	4.3	0	5.2	0.9	$ 352	STEEL MILL WASTE PICKLE LIQUOR, FERROUS SULFATE USED. ALL ADDED TO RAPID-MIX TANK PRIOR TO PRIMARY SEDIMENTATION.
MAY	4.8	0	5.8	1.1	$ 402	
JUNE	6.4	0	6.1	0.9	$ 542	

Figure 5. Phosphorus Removal Programs

ferric chloride was applied to the rapid mix tank, and polymer to the final sedimentation tank influent. Ferric chloride in the amount of 8.01 mg/l as Fe and polymer in the amount of 0.21 mg/l was applied at a cost of $1,181. Influent phosphorous was 5.5 mg/l and the final effluent 1.2 mg/l.

In April the polymer was again used in the influent to final sedimentation only, with the ferric chloride split, adding 60 percent to the rapid mix tank and 40 percent to the final sedimentation influent with no apparent improvement in phosphorus removal. Ferric chloride in the amount of 8.63 mg/l as Fe and polymer in the amount of 0.17 mg/l was applied at a cost of $1,271. Influent phosphorous was 5.2 mg/l and final effluent 1.3 mg/l.

This mode of operation was continued in May and again with no apparent improvement in phosphorus removal.

In June both the polymer and ferric chloride were split with two-thirds of the chemicals added to the rapid mix and one-third to the influent to final sedimentation. Although the final effluent phosphorous concentration was lower at 0.7 mg/l, it should be noted that the influent phosphorus was also lower at 3.8 mg/l. The amount of ferric chloride used was 8.38 mg/l as Fe and polymer applied was 0.21 for a total chemicals cost of $1,989. The diluted phosphorous concentration in the influent was due to heavy precipitaion and river water backflow. This condition was corrected shortly thereafter. Perhaps the impact of the tannery coming on line May 28, 1974 may also have helped in phosphorus removal. However, the tannery was on limited operation at that time and were

buying some of the hides in the blue, which reduced beamhouse lime waste.

It was apparent that neither split feed, nor chemicals added to the final sedimentation influent were as effective as adding the total iron solution to the rapid mix tank prior to primary sedimentation. Removals were excellent either with or without polymer addition. It would follow that polymer use was discontinued and the iron solution added to the rapid mix tank.

After several months of operation with ferric chloride we were contacted by several companies who were contracted to remove waste pickle liquor from the steel mills in Gary, Indiana. We were able to purchase the waste pickle liquor for less than the cost of commercial ferric chloride. This has been used for over five years to date. It has been equally as effective in phosphorus removal as was ferric chloride.

Also shown on the lower portion of Figure 5 is 1975 data for the same months as reported in 1974 for comparison. In March 1975 ferrous sulfate in the amount of 4.1 mg/1 as Fe at a cost of $381 was applied to the influent containing 4.6 mg/1 of phosphorus and resulted in a final effluent phosphorus content of 0.9 mg/1.

In April $352 was spent to apply 4.3 mg/1 of ferrous sulfate as Fe to an influent containing 5.2 mg/1 of phosphorous which resulted in a final effluent containing 0.9 mg/1 of phosphorus.

In May $402 spent for 4.8 mg/1 of Fe applied to an influent containing 5.8 mg/1 of phosphorus resulted in a final effluent of 1.1 mg/1 of phosphorus.

In June $542 was spent for 6.4 mg/l of Fe applied to an influent containing 6.1 mg/l of phosphorus resulting in an effluent containing 0.9 mg/l of phosphorus.

It would appear from the data shown in Figure 6 , which shows the iron used for phosphorus removal, that waste pickle liquor was actually more effective than ferric chloride in that the amount applied in milligrams per liter went from 9.3 in 1974-1975 to 6.6 in 1975-1976. We would propose, however, that the increasing load from the Eagle Ottawa Leather Co. resulted in much more lime from their beamhouse operations being discharged to the treatment plant, which aided in the decrease in the amount of iron required for phosphorus removal.

To support that theory, Figure 7 shows the amount of flow from the tannery and the amount of iron applied for phosphorus removal for the same period of time. As the amount of tannery waste increased, the amount of iron necessary to control phosphorus removal decreased. The tannery flow went form 190 mg (719,150 cu m) in 1974-1975 to 307 mg (1,161,995 cu m) in 1978-1979. The iron applied to the total plant flow decreased from 9.3 mg/l to 1.6 mg/l.

On May 18, 1978 the tannery discontinued the use of the million gallon equalization tank that had been in use prior to that time for equalizing the flow to the wastewater treatment plant. Following this, the tannery added more lime to their discharge during periods of dump from the tanhouse portion of their operation. In the tanhouse operation, a pickling process brings the hides to an acid condition in preparation for tanning. This waste has a low pH.

IRON USED FOR PHOSPHORUS REMOVAL
IRON AS Fe

	Fe POUNDS	Fe APPLIED mg/l	COST
74-75 TOTAL	104,390		$13,146.52
AVERAGE	8,699	9.3	$ 1,095.54
75-76 TOTAL	75,459		$ 7,182.55
AVERAGE	6,288	6.6	$ 598.55
76-77 TOTAL	65,966		$ 5,920.64
AVERAGE	5,497	6.7	$ 493.39
77-78 TOTAL	43,307		$ 3,681.14
AVERAGE	3,609	4.3	$ 306.76
78-79 TOTAL	14,767		$ 1,277.61
AVERAGE	1,231	1.6	$ 106.47

Figure 6. Iron Used for Phosphorus Removal

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EAGLE-OTTAWA TANNERY

	TOTAL FLOW M.G.	% OF TOTAL PLANT FLOW	Fe APPLIED mg/1 TO TOTAL PLANT FLOW
74-75 TOTAL	190.466	14.6	9.3
75-76 TOTAL	260.147	19.3	6.6
76-77 TOTAL	266.515	23.7	6.7
77-78 TOTAL	259.585	21.7	4.3
78-79 TOTAL	307.372	25.9	1.6*

*MAY 1978 EQUALIZATION TANK USE DISCONTINUED. THEREAFTER MORE LIME WAS USED TO CONTROL pH IN THE TANNERY DISCHARGE.

Figure 7. Eagle-Ottawa Tannery

Further documentation in regard to the relationship between volume of tannery flow and phosphorous removal at the treatment plant for January and February of 1979 as compared to 1980 is as follows: In January 1979 the tannery flow was 24.65 mg and 2.21 mg/l of Fe was fed resulting in final effluent phosphorus of 0.6 mg/l. To compare, in January 1980 the tannery flow was only 13.857 and 6.65 mg/l of Fe resulted in final effluent phosphorus being 0.6 mg/l. In February 1979 the tannery flow was 27.424 mg, no Fe feed was required, and the final effluent phosphorus was 0.5 mg/l. However, in February 1980 the tannery flow was only 18.494 mg and 4.89 mg/l of Fe was applied which resulted in final effluent phosphorus concentration of 0.7 mg/l.

SUMMARY

This domestic-industrial activated sludge wastewater plant with approximately 18 percent of the total flow emanating from a chrome tanner and 80 percent of the suspended solids and BOD, has achieved excellent purification. Suspended solids and BOD removals have consistently been above 90 percent. The final effluent phosphorus concentration has been under 1.0 mg/l with removal over 80 percent. This excellent phosphorus purification has been accomplished with pickle liquor, all added prior to primary sedimentation, and without a flocculating aid. Although phosphorus removal was successful with limited amounts of iron application when the tannery waste was present in considerable amount, it was necessary to add much larger amounts of iron solution when the tannery waste was limited or off entirely. Simple laboratory control has been practiced with analyses made on the daily composite sewage samples, and iron feed adjusted based on the prior day's operating results.

| | RAW INFLUENT | | PRIMARY EFFLUENT | | | FINAL EFF. | | TOTAL PLANT |
	mg/1	TOTAL POUNDS	mg/1	TOTAL POUNDS	REM %	mg/1	TOTAL POUNDS	% REM
74-75 AV.	5.6	5,160	3.7	3,424	33	0.9	804	84
75-76 AV.	5.5	5,135	3.7	3,384	33	0.9	891	82
76-77 AV.	5.5	4,426	3.4	3,001	32	0.8	641	85
77-78 AV.	5.5	4,641	3.3	2,750	41	0.7	586	88
78-79 AV.	5.0	4,156	2.9	2,437	41	0.6	499	88
FIVE YEAR AVERAGE	5.4	4,704	3.4	3,000	36	0.8	684	85

Figure 8. Total Phosphorus as P in Sewage

THE PHOSTRIP PROCESS FOR PHOSPHORUS REMOVAL

By

Mr. Carl J. Heim
Assistant Staff Engineer
Union Carbide Corporation
Linde Division
Tonawanda, New York

INTRODUCTION

The PhoStrip process is a combined biological-chemical process for the removal of phosphorus from wastewater. The process works by concentrating the phosphorus in the wastewater through biological means into a small substream, to which chemicals are added for precipitation of the concentrated phosphorus. Normally lime is used for phosphorus precipitation because the quantity of lime required is proportional to the flow being treated rather than the phosphorus concentration in that flow. Thus, if the phosphorus in the wastewater is concentrated into a substream that is 15% of the entering wastewater flow, the amount of lime required would be only 15% of the lime required to treat the entire wastewater flow.

In addition to drastically reducing the chemical requirement for phosphorus removal, the PhoStrip process also produces relatively small quantities of chemical sludge. Phosphorus is precipitated in a separate reactor in the process and the resulting chemical sludge does not contain significant biological solids. This sludge is inert and stabilization (such as digestion) is not required prior to disposal. When lime is used for phosphorus precipitation, a very easily dewatered sludge is produced. The net results are very substantial savings in both chemical costs and sludge disposal costs.

DESCRIPTION OF THE PHOSTRIP PROCESS

A flow schematic of the PhoStrip process is shown in Figure 1. In the process, return sludge is mixed with plant influent and aerated exactly as in a conventional activated sludge system. While under aeration, the microorganisms have the capability of removing essentially all of the soluble phosphorus from the wastewater because of special conditioning received in the PhoStrip process. The phosphorus removed in the aeration basin is incorporated into the sludge in the form of stored polyphosphates. The phosphorus content of the sludge leaving the aeration basin can be more than twice that of sludge from a conventional system. Removals of biological oxygen demand and suspended solids in the aeration system are unaffected by PhoStrip.

The phosphorus-laden sludge is separated from the phosphorus-free effluent in the secondary clarifier. The sludge withdrawn with the clarifier underflow is then either sent directly back to the aeration basin, wasted from the system (excess biological sludge quantities are not affected by the PhoStrip process) or sent to a stripper tank, where it is held under anoxic conditions for several hours. While under anoxic conditions, the microorganisms release their stored phosphorus in soluble form. The released phosphorus is "washed" from the sludge blanket by an elutriation stream and withdrawn as a supernatant from the stripper tank. This supernatant stream is then fed to a reactor-clarifier where the phosphorus is precipitated with lime. Typically, the supernatant flow is 10-20% of the influent flow. Therefore, as explained previously, lime requirements are reduced by

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Influent

Aeration
Basin

Clarifier

Effluent

Direct Recycle

Waste
Sludge

Stripper Feed

Supernatant

Reactor-
Clarifier

Anoxic
Stripper
Tank

Elutriation Stream

Waste Chemical Sludge

Stripper Underflow
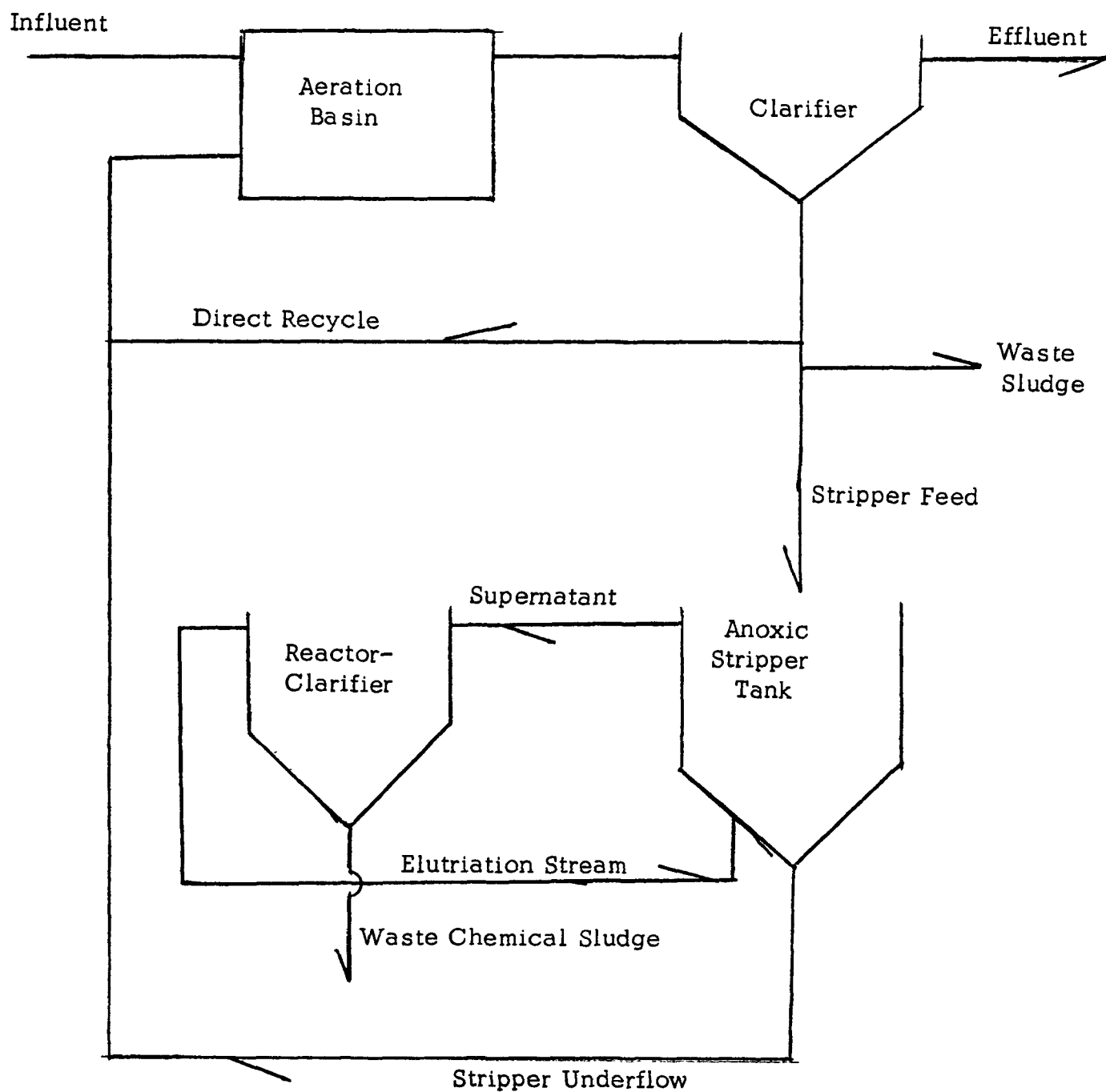
Figure 1. Phostrip System Flow Schematic

80-90% and chemical sludge quantities are also reduced. The inert chemical sludge is withdrawn from the bottom of the reactor-clarifier. The overflow from the reactor-clarifier, which has a relatively low phosphorus concentration, is used as the elutriation stream.

Sludge is withdrawn from the bottom of the anoxic stripper tank at the same rate as it is fed to the tank to avoid solids buildup. This sludge is returned to the aeration basin where phosphorus uptake is resumed.

The PhoStrip process typically produces an effluent with a total phosphorus concentration of 0.5-1.0 mg/l. The effluent soluble phosphorus concentration normally ranges from 0.1-0.5 mg/l. The PhoStrip process operates over the normal range of activated sludge system operating conditions and can be used with either air or oxygen activated sludge systems.

THEORY

Biochemical Aspects

The biochemical phenomemon responsible for the PhoStrip process has not been fully defined. Results of experimental work have led to the formulation of the following mechanisms for the observed phenomenon.

Organisms containing high intracellular phosphate concentrations have been isolated from wastewater treatment systems exhibiting high phosphorus removal rates. Typical of these isolates are organisms of the genus Acineto-bacter.[1] The organisms of this genus have demonstrated the ability to take

up and release phosphorus as a function of the aerobic-anoxic cycle, while in pure culture form. The interior of the cells have been characterized as containing very large volutin (polyphosphate) granules while under aerobic conditions. The size of these granules diminished as the culture was maintained in an anoxic environment. This indicates a transfer of phosphorus from the volutin granules into solution. These particular organisms are so abundant in activated sludge systems that the Water Research Centre Laboratory at Stevenage, England, has utilized pure cultures to simulate activated sludge systems. These organisms are also obligate aerboes preferring Krebs cycle intermediates and acetates as substrates for metabolism.

It is believed that the anoxic period of the PhoStrip process forces these strict aerobes to undertake a sequential series of reactions which result in their forming polyphosphate granules while in the aerobic period. This results in a set of aerobic organisms that can compete more effectively with facultative organisms in a cyclic aerobic-anoxic environment. The polyphosphate granules within the cell may provide phosphorus and energy to convert ADP to ATP during the anoxic period through the catalysis of the polyphosphokinase enzyme.[2,3] Substitution of polyphosphate for ATP in biochemical reactions during anaerobiosis is also possible.[4] (A third potential pathway of phosphorus release utilizing the phosphatase enzyme has not yet been delineated.)

In the first mechanism, conversion of ATP to ADP during the anoxic period results in the release of phosphorus from the cell as well as providing a source of energy. This energy is utilized by the obligate aerobes to continue some of their metabolic functions. The fact that the addition of acetates increases the

rate of phosphorus release suggests an interaction between these organisms and the facultative microbes present in activated sludge. Under anoxic conditions, the facultative aerobes produce acetates which enhance the rate of phosphorus release by the oligate aerobes. When the sludge leaves the anoxic environment and enters aerobic conditions, the ATP content within the cell is low because the reaction of $ATP \longrightarrow ADP + P$ is a high rate reaction relative to the formation of ATP from polyphosphates.

In the second, direct substitution mechanism, the energy of the poly-phosphate-phosphorus bond is utilized in place of the ATP bond energy. The phosphorus would be directly released to solution from the polyphosphate molecule. If direct substitution is the major means of phosphorus release, the above ATP to ADP reaction would also occur producing a low ATP/ADP ratio in the cell.

Under aerobic conditions, the strict aerobes oxidize stored metabolites and other substrates to provide energy to increase the ATP content of the cell. After a very short time, the ATP/ADP ratio in the cell becomes high enough to trigger the formation of polyphosphate via the reversible polyphosphokinase enzyme. This results in the formation of polyphosphate granules which are stable storage products in an aerobic environment.

The performance of the PhoStrip process is consistent with the theory. The theory implies a temperature dependency. In fact, an Arrhenius type relationship has been established. This theory also indicates that the rate of phosphorus release per unit mass of organisms is a function of the duration

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of the anoxic period, as well as the quantity and activity of facultative organisms. The activity of the facultative bacteria can be related to the Food-to-Microorganism ratio (F/M) of the activated sludge system, while quantity is related to the concentration of sludge in the stripper tank. Since strict aerobes are implicated in the above theory, too long an anoxic period relative to the aerobic period could cause the organisms to cease phosphorus uptake. Experimentally determined operating limits for such a response do exist. However, there is a broad spectrum of conditions under which good performance has been established.

The finite capacity of these organisms for phosphorus storage results in a loading requirement which must not be exceeded if a high degree of phosphorus removal is to be achieved. Different activated sludge systems have exhibited different maximum levels of phosphorus per unit mass of MLVSS. This maximum P/VSS ratio has been observed to be a function of the viable organism content of the volatile suspended solids. The P/VSS ratio observed in efficiently operating PhoStrip Systems depends on the phosphorus available in the feed, the maximum P/VSS ratio attainable, and the environmental conditions presented earlier.

Ideally, all the phosphorus in the feed would be incorporated into the cell mass and wasted from the system as biological sludge. This mode of operation would eliminate the need for chemical precipitation facilities and significantly reduce the operating cost of the process. However, there are factors which prevent this from being realized in all but a few instances.

First, effluent quality is a function of the soluble and particulate phosphorus

content. Even if an effluent soluble PO_4 level of $\leqslant .01$ mg/l were achieved,

a 20 mg/l VSS in the effluent would limit the phosphorus to VSS ratio to <0.05

in order to achieve an effluent < 1.0 mg PO_4-P/l. Second, for a given P/

VSS level, a specific quantity of sludge must be wasted as dictated by phos-

phorus mass balances in order to remove enough phosphorus to achieve the

desired effluent. The amount wasted generally depends on the F/M (SRT) of

the system. In most cases a high degree of phosphorus removal could only be

achieved at very high F/M (low SRT) values because of the low P /VSS levels

necessary to satisfy effluent criteria as presented above. Third, bio-chemical

sludges tend to release phosphorus when digested. If high P /VSS levels

are employed for phosphorus removal, large quantities of phosphorus could

return to the head end of the plant. This level of phosphorus return would

require a significant increase in sludge wasting unless some method of chemi-

cal precipitation were employed.

The PhoStrip System is normally designed for a phosphorus content of

0.03-0.04 lb. P/lb. VSS in the sludge in order to achieve effluents of less

than 1.0 mg PO_4-P/l. · The phosphorus that is not removed through wasting is

precipitated from the supernatant stream leaving the stripper tank. The

relative amounts of phosphorus removed through sludge wasting and precipi-

tation depend on the F/M (SRT) of the activated sludge system and the BOD_5 /P

level in the wastewater. The ratio of phosphorus removal by precipitation to

the overall phosphorus removal can range from 0 to 0.9+. Each wastewater will result in different values of this ratio depending on the design conditions of the activated sludge system and the method of waste sludge disposal.

Chemical Precipitation of Phosphorus

Lime was chosen as the precipitant because of its pH functionality. Unlike alum and ferric chloride, the gross quantity of lime required for precipitation of phosphorus in water is dependent only on the amount and alkalinity of the water not the concentration of phosphorus. Further reduction in chemical requirements can be achieved by precipitating phosphorus at lower pH levels (8.5 - 9.0). At these pH levels, the stripper supernatant after lime addition may typically contain 2-5 mg soluble PO_4-P/l. A lower ph will also result in substantially less chemical sludge to be handled because less calcium carbonate and no magnesium hydroxide are formed. The chemical sludge production will be typically less than 50 percent of that produced at a pH = 10.5. This material could be used as an agricultural fertilizer because of its high phosphate content.

FULL SCALE PERFORMANCE

The PhoStrip system has been demonstrated at two localities under full scale conditions and 9 pilot plant locations. These two full scale plants were Seneca Falls, NY and Reno/Sparks, Reno, Nevada.

The wastewater treatment facility at Seneca Fall, NY is an activated

sludge treatment plant with two trains and a total capacity of 3.5 MGD

(13,247 m^3/day). The plant consists of a bar screen, comminutor, two cir-

cular primary clarifiers, two completely mixed aeration basins with mechanical

aerators, two rectangular secondary clarifiers and a chlorine contact chamber. The

The wastewater is largely domestic in character with a BOD of approximately

160 mg/l; total dissolved solids of 680 mg/l and total phosphorus of 6.3 mg/l.

Conversion of the plant to the PhoStrip process was facilitated by the

fact that, at the time of the study, the raw wastewater flow was only 3800 m^3/d

(1 mgd). This enabled the plant to handle the full plant flow through one of

the two reactor trains, thus freeing a primary clarifier to provide the anoxic

environment required for the return sludge to release excess phosphorus.

The tank providing this anoxic zone has been labelled the "stripper tank".

The use of a single train to treat the entire wastewater flow also permitted

the test to be run on a system that was much nearer the design hydraulic loading

for the Seneca Falls plant. The use of the primary clarifier as the stripper tank

was expeditious; however, it was significantly oversized relative to the waste-

flow entering the aeration basins. Table 1 presents a concise summary

of the data obtained during the first thirty days of operation at Seneca Falls.

It is evident from this table that substantial savings have been demonstrated.

The amount of lime has been greatly reduced since the supernatant from the

Table 1.   Results of Phosphorus Removal Test
at Seneca Falls, N.Y.

Plant Flow, m^3/d (mgd)   3400 (0.9)

Return Flows, percent of raw flow:

    Sludge to Stripper   24

    Sludge to Aeration from Stripper   10

    Supernatant to Primary Clarifier   14

Total Suspended Solids, mg/l:

    Mixed Liquor   1,440

    Sludge to Stripper   7,840

    Sludge to Aeration from Stripper   15,910

Influent, mg/l:

    BOD_5 158

    Total Phosphorus   6.3

Effluent, mg/l:

    BOD_5 ~4

    Total Phosphorus   .6

Plant Performance:

    BOD_5 Removal, percent   98

    Total Phosphorus Removal, percent   91

Lime Dose, Stripper Supernatant, mg/l of supernatant   170
(as CaO)
Lime Dose, prorated to mg/l of raw flow (as CaO)   24

PhoStrip stripper is only fourteen percent of the incoming flow. Calculated on the basis of the incoming flow, the lime dose would be 24 mg/l as CaO. When compared to conventional lime requirements of 300-660 mg/l for post precipitation to obtain the same total phosphorus effluent concentration of less than 1 ppm (0.6 ppm), the savings are quite apparent. This represents the period of operation during which the performance of the process was intensively monitored. The recycle flow rates presented are typical of a system utilizing sludge thickening in the stripper tank to produce the phosphate-enriched supernatant. The data on plant performance indicates that very high removals of both BOD_5 and phosphorus were achieved. The lime dosage is reflective of the chemical requirements anticipated for many full scale systems.

RENO/SPARKS, RENO, NEVADA

The Reno/Sparks facility is designed to process an average flow of 76,000 m^3/d (20 mgd) and discharges into the Truckee River. The system consists of an aerated grit chamber, three primary clarifiers, three activated sludge trains and three secondary clarifiers. The PhoStrip System initially operated by Kennedy Engineers, San Francisco, California, on one third of the total average plant flow (25,000 m^3/d) by using the sludge recycle option of operation (Figure 2). In this option, the stripper is operated in a thickening mode and a portion of the stripper underflow is recycled back to the stripper feed. The reason for recycling the underflow is to increase the supernatant phosphorus by mixing high P/low P streams. (This mode of operation produced an elutriation efficiency of approximately 38%, where elutriation efficiency, E, is defined as the
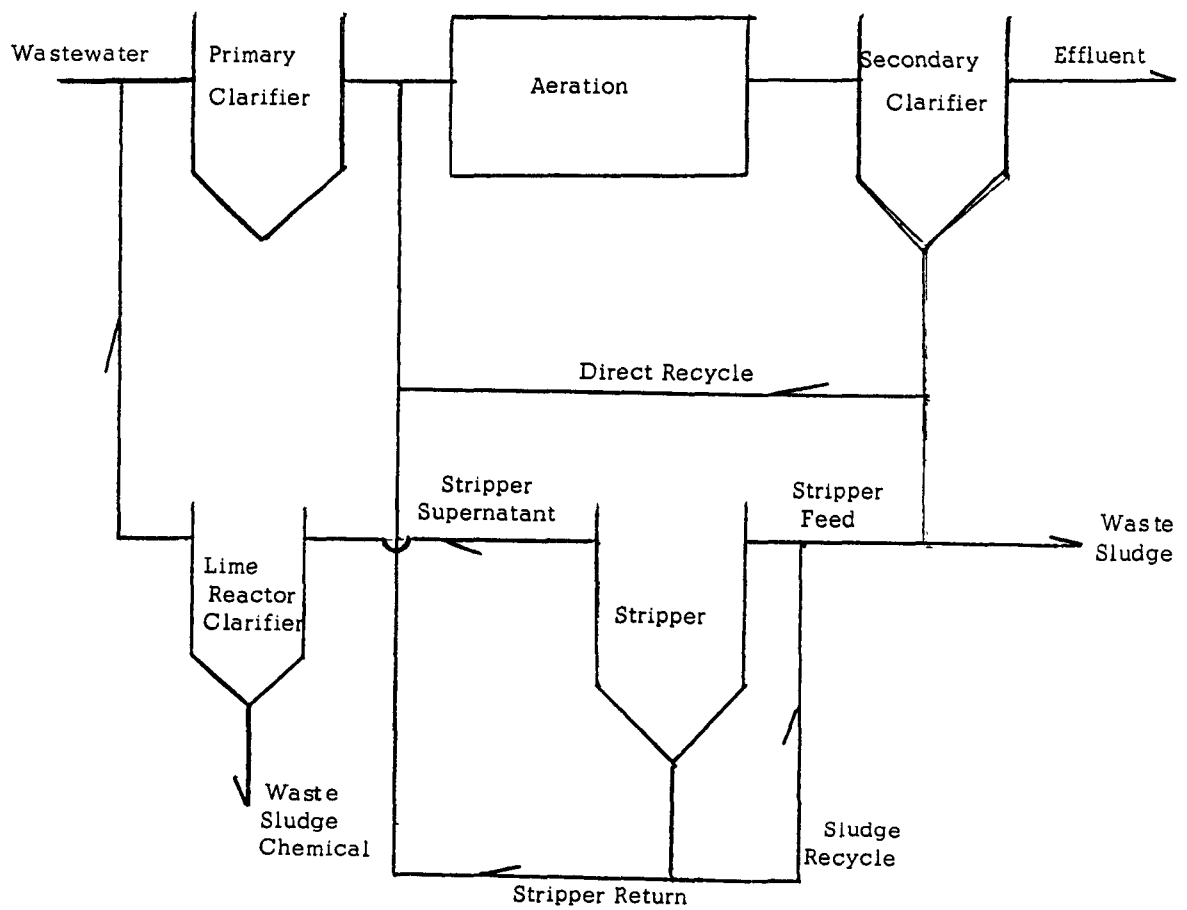
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Figure 2. Sludge Recycle Option

amount of phosphorus removed by the stripper overflow per day divided by the

– amount of phosphorus released in the stripper per day.)

On June 25, 1975, Union Carbide Corporation began its evaluation of the PhoStrip process on the full scale plant at Reno/Sparks, Nevada. A set of conditions was established on the full scale (Table 2) and the system was allowed to come to steady state. After steady operating conditions were achieved, a period of intensive evaluation followed. Table 3 presents the results of analyses performed at Reno/Sparks during this phase. Figures 3 & 4 present the influent and effluent phosphorus levels during the testing period and their variation with the flow to the plant. The system demonstrated excellent effluent quality in all respects, and as evident in the figures, total phosphorus levels were consistently 1 mg/l or less.

In an effort to improve the elutriation efficiency a low phosphorus elutriation (LPE) modification was employed. The cross sectional area requirement for the stripper as dictated by the limiting-flux theory is reduced relative to the sludge recycle system. Since the primary clarifier (stripper tank) at the Reno/Sparks plant had a fixed cross-sectional area, the solids flux considerations indicated that two-thirds of the plant flow (50,000 m^3/d) could be treated with the available area. As a result, the system was modified according to Figure 1, which was referred to earlier. Table 4 presents the operating conditions for this two week test period (Jan. 18-30, 1977) and Figure 5 graphically displays the influent and effluent phosphorus concentration. Again, the effluent total phosphorus levels were usually 1.0 mg/l of phosphorus or under.

Table 2. Operating Conditions for the Phostrip
Sludge Recycle System – Full Scale Testing
at Reno/Sparks, Nevada (9/13/75-9/27/75)

Parameter	Minimum	Maximum	Time Weighted Mean
Flow Rates (m^3/day)			
Feed, (Q)	14,690	25,060	22,460
Recycle to Stripper (R_1)	5,180	7,340	6,830
Stripper Underflow (R_3)	2,330	4,150	3,630
Stripper Supernatant	2,850	3,200	3,110
Recirculation Rate (R_2)	4,230	2,420	2,850
Waste Sludge Rate	639	639	639
Aeration Time, Hr. (based on Q)	10.2	6.0	7.1
Anoxic Period, Hr. (based on R_3)	16.	9.4	11.0
MLSS, mg/l	–	–	1,150
MLVSS, mg/l	–	–	900
R_1SS, mg/l	3,060	4,620	4,230
R_1VSS, mg/l	2,480	3,740	3,420
R_3SS, mg/l	9,620	9,120	9,250
R_3VSS, mg/l	7,700	7,300	7,340
TSS Stripper Supernatant, mg/l	65	90	84
VSS Stripper Supernatant, mg/l	50	69	64
D.O., End of Aeration, mg/l	–	1.5 (0.7-2.2)	–
D.O., R_1, mg/l	0.4	0.7	0.6
D.O., R_3, mg/l	0.3	0.3	0.3
pH, End of Aeration Basin	–	7.0	–
pH, R_1	6.8	6.8	–
pH, R_3	6.4	6.4	–
pH, Stripper Supernatant	6.6	6.5	–
Temperature, °C	23	23	23
F/M_a (kg COD/day/kg MLVSS)	–	–	0.96
Clarifier Overflow Rate, m/day	22.4	38.2	34.3
Clarifier Blanket Level, m.	0.08	0.09	0.09

Table 3. Analytical Results for the Phostrip
Sludge Recycle System Full Scale Testing
at Reno/Sparks, Nevada (9/13/75-9/27/75)

| Parameter	Minimum	Maximum	Flow Weighted Mean
COD, mg/l			
Influent	187	266	253
Effluent	40	37	37
Total Suspended Solids, mg/l			
Influent	–	–	113
Effluent	19	13	13
Effluent Volatile Suspended Solids, mg/l	13	10	10
Total Phosphorus, mg P/l			
Influent	9.6	9.1	9.2
Effluent (ortho)	1.0 (.3)	0.8 (.4)	0.8 (.4)
Stripper Supernatant	44	41	42
Stripper Underflow	257	240	247
Filtered Stripper Underflow	67	55	58
Filtered Aeration Effluent (ortho)	–	– (.04)	–
Secondary Clarifier Underflow	104	161	113
P/VSS			
Secondary Clarifier Underflow	0.042	0.043	0.043
Stripper Underflow	0.025	0.025	0.025

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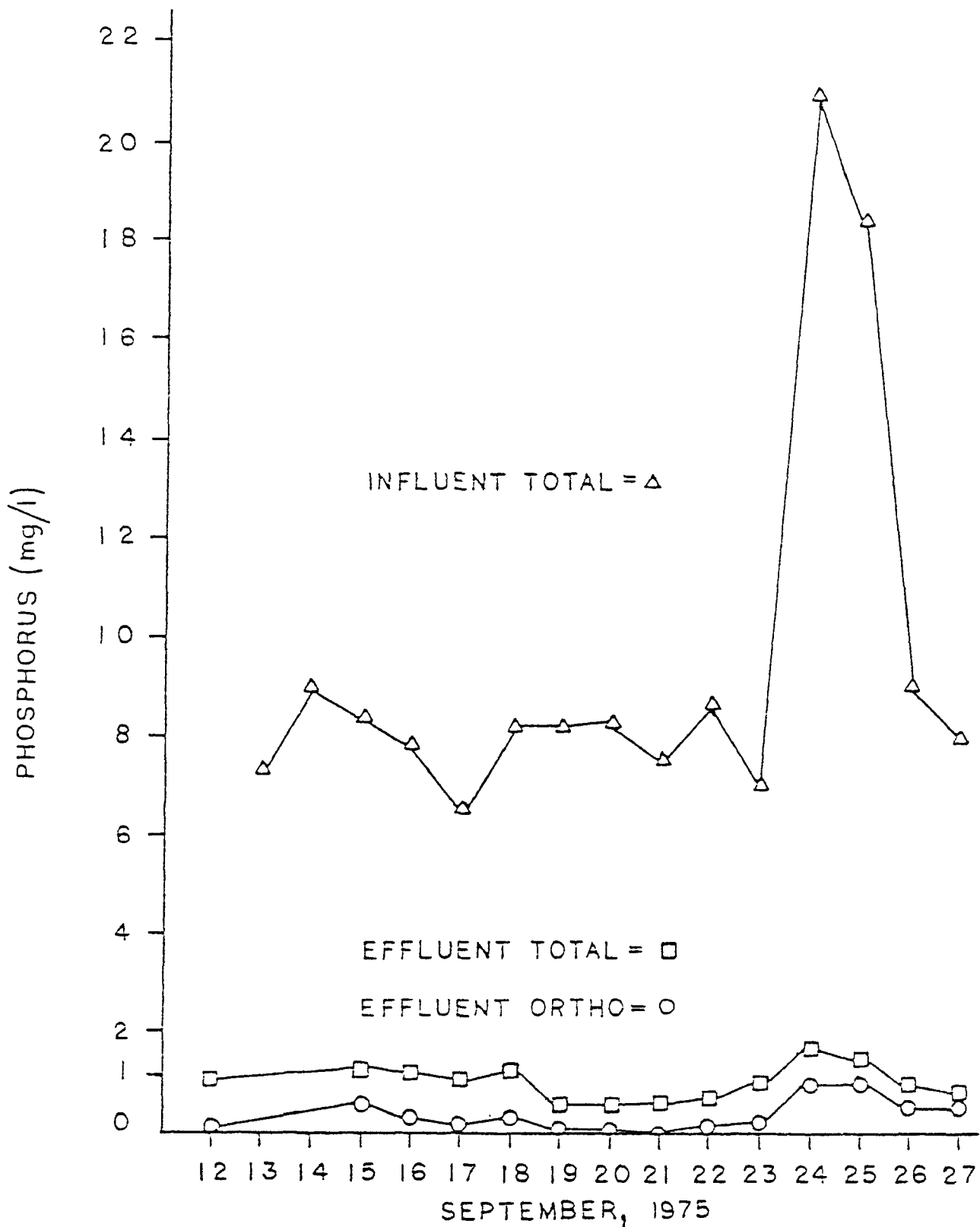
Figure 3. Reno/Sparks Full Scale Phosphorus Data Obtained
during Minimum Flow Period (16% of the Total
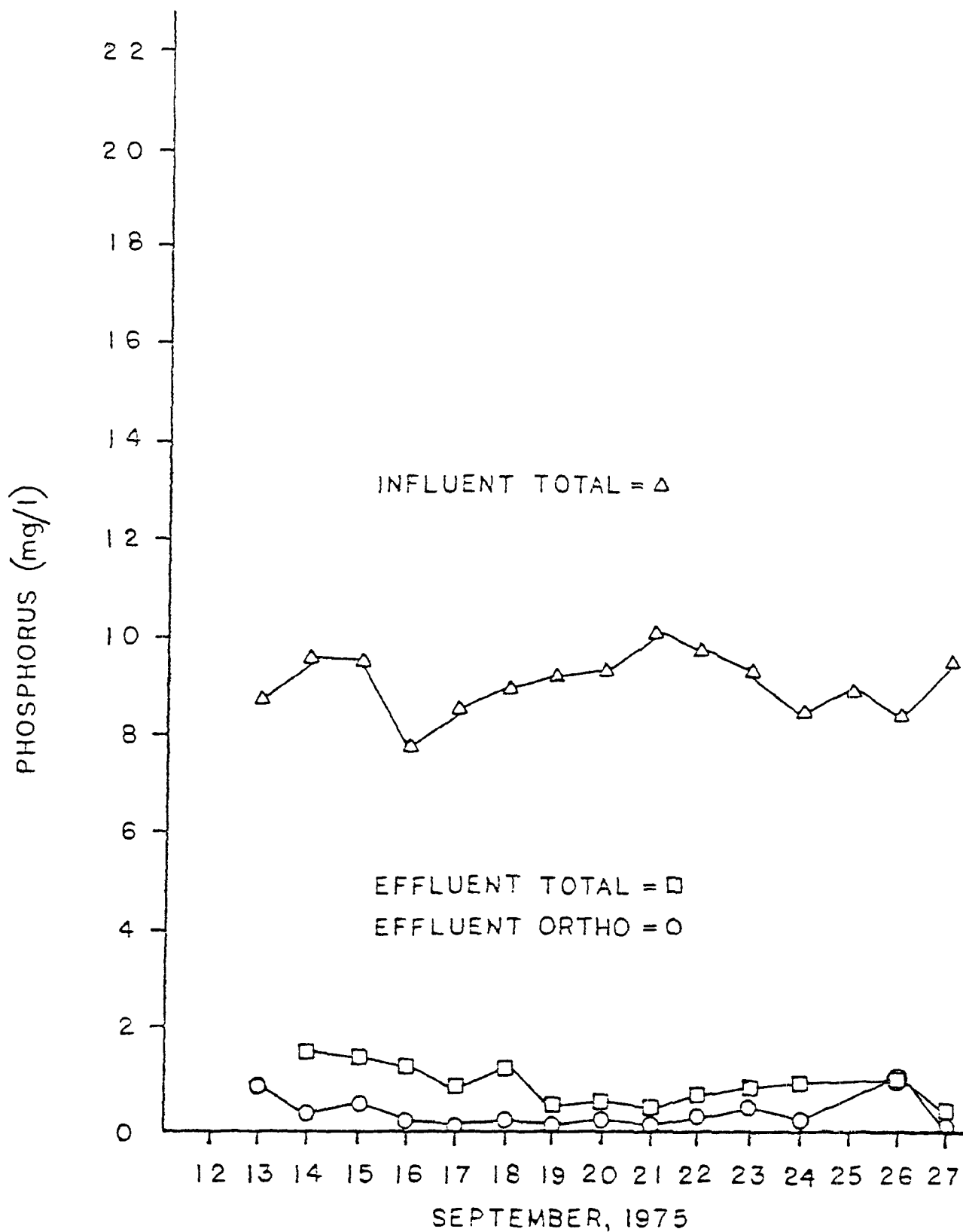Volume Treated by the Phostrip System)

Figure 4. Reno/Sparks Full Scale Phosphorus Data Obtained
during Maximum Flow Period (84% of the Total
Volume Treated by the Phostrip System)

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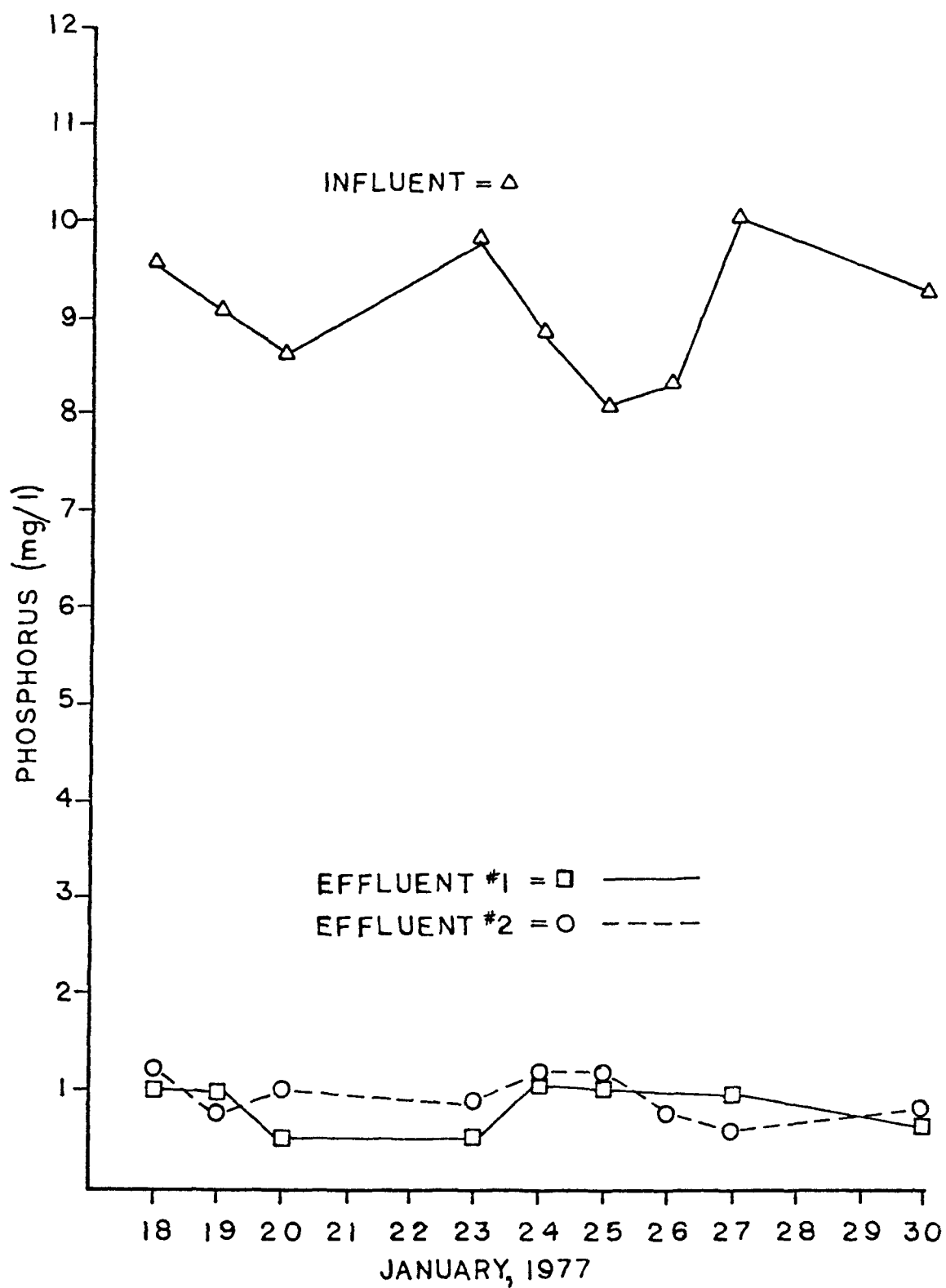
Figure 5. Reno/Sparks Full Scale Phosphorus Data for LPE System

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A comparison between the LPE and sludge recycle system indicates that the LPE System was capable of producing the same quality effluent while utilizing the same stripper, but handling twice the flow.

The main reason for this is an improvement in elutriation efficiency with the LPE System (ξ = 0.59 vs. ξ = 0.38). This improvement translates to a decrease in the initial capital cost due to the decrease in tankage.

ECONOMIC EVALUATION

COMPARISON OF OPERATING COSTS FOR PHOSPHORUS REMOVAL SYSTEMS

Table 4 shows a comparison of operating costs for various phosphorus removal systems. Included in the comparison are conventional chemical precipitation with lime, alum, ferric chloride and pickle liquor, as well as the PhoStrip process with lime or pickle liquor addition. The costs are based on an alkalinity of 250 mg/l, and an influent phosphorus concentration of 1 mg/l. Chemical requirements and costs for the conventional phosphorus removal systems were taken from the EPA Process Design Manual for Phosphorus Removal (1976) and have been adjusted to 1st quarter 1980. Chemical sludge disposal costs were assumed to be $100/ton of dry solids.

It is apparent from inspection of Table 5 that the use of the PhoStrip process drastically reduces the operating costs for phosphorus removal. For the example case shown, operating costs are reduced by approximately 40-55% compared to a conventional system using pickle liquor, which has the lowest operating cost of the conventional systems.

CASE STUDY

The following economic study has been taken verbatim from the EPA Bio-logical-Chemical Process for Removing Phosphorus at Reno/Sparks, NV publication, and is for illustrative purposes only.

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Table 4. Operating Conditions for Full Scale
Testing at Reno/Sparks, Nevada
Phostrip LPE System (January 18-30, 1977)

PARAMETER	MINIMUM TRAIN 1/TRAIN 2	MAXIMUM* TRAIN 1/TRAIN 2	FLOW WEIGHTED MEAN TRAIN 1/TRAIN 2
Flow Rates, m^3/day			
Feed Q, (each train)	17280/17280	29380/29380	22460/22460
Recycle to Stripper, R_1	1987/2160	3200/3370	2510/2680
Stripper Underflow, R_3	1210/1470	2250/2250	1640/1810
Stripper Supernatant, S	6570	7000	6740
Elutriation, EL	5270	5620	5440
Total Aerobic Recycle, R_1 + R_{direct}	-	-	4490/5530
Sludge Wasting	-	-	331/418
Aeration Time, Hrs. (based on Q)	9.0/9.0	5.1/5.1	6.8/6.8
Anoxic Period, Hrs. (based on R_3)	11.6	7.0	9.5
MLSS, mg/l	1230/1280	1110/1140	1170/1220
VSS/TSS	0.8	0.8	0.8
R_1SS, mg/l	5750/5460	6770/6720	6210/6030
VSS/TSS	0.78	0.78	0.78
R_3SS, mg/l	8930	8310	8650
R_3VSS, mg/l	7360	6590	7010
TSS Stripper Supernatant, mg/l	-	-	59
VSS Stripper Supernatant, mg/l	-	-	54
pH, Mixed Liquor, mg/l	7.1/7.0	7.0/7.0	-
Temperature (Influent), °C	13	13	13
F/M_a (kg BOD_5/day/kg MLVSS)	0.45	0.88	0.62
Secondary Clarifier Overflow Rate, m/day	26.4/26.4	44.8/44.8	34.3/34.3
Clarifier Blanket Level, m.	-	-	< 0.2

* duration at max. flow ≈ 11 hrs/day

Table 5. Comparison of Operating Costs
for Phosphorus Removal Systems

Chemicals and/or Process Used	Pounds of Chemical Per MGD	Cost of Chemical per MGD ($)	Pounds of Chemical Sludge per MGD (dry)	Cost of Chemical Sludge Disposal Per MGD ($)	Total O & M Cost per MGD ($)
High Lime Process	1880	41 ($42.5 per ton)	2460	125.0	166
CaO EPA Recommended Dose CaO/Alkalinity = 0.9 to obtain a pH of 10.5					
Alum Addition	1600	82 ($102 per ton)	540	27.00	109
$Al_2(SO_4)_3 \cdot 14 H_2O$ EPA Recommended Dose Mole Ratio Al:P					
Ferric Chloride Addition	790	61 ($150 per ton)	640	32.00	93
$FeCl_3$ EPA Recommended Dose Mole Ratio Fe:P = 1.8:1					
PhoStrip System with Lime (CaO)	125	2.7 ($42.5 per ton)	250	12.50	15.2
Dose = 150 mg/l					

ADRIAN, MICHIGAN

The proposed Adrian WWTP design is for a two-stage activated sludge system. The first stage will be used for carbonaceous removal and the second stage will convert ammonia to nitrate. The PhoStrip process will be operated in conjunction with the first stage aeration system. The main advantage of the PhoStrip System is dosing only 10-15% of the sewage flow with chemicals as compared to the conventional method of chemical treatment which uses addition of chemical to the entire flow of sewage. Most of the operating expenses of phosphorus removal is the chemical cost and the PhoStrip System significantly reduces this cost. (Tables 6 & 7)

An economic evaluation was made comparing PhoStrip against the traditional chemical addition methods using ferric chloride and alum. The cost-effective analysis included initial installment cost and total annual costs which includes capital cost amortized over 20 years at 6.125% interest; chemical cost; operating labor; maintenance and repair costs; and sludge disposal costs.

The PhoStrip costs were based on (chemical) treatment of 15% of the maximum plant flow of 7 mgd, or 1.0 mgd. The cost of the two traditional chemical processes were based on total plant flow of 7 mgd. The bench scale lime dosage test conducted during the pilot plant operation established a lime dosage of 250 mg/l to produce the desired treatment. The dosage required for treatment with the traditional chemicals were: 90 mg/l of ferric chloride and 135 mg/l of alum.

Design Flow = 7 mgd
Influent P = 10 mgd
Effluent P = 1 mg/l

Item	PhoStrip	Ferric Chloride	Alum
A. Installed Investment[1]	$520,000	$ 60,000	$ 65,000
B. Annual Costs			
1. Amortized Investment[2] (A x 0.08897)	46,265	5,338	5,783
2. Chemical Costs			
a. Lime[3]	20,000	---	---
b. Ferric Chloride[4]	---	105,500	---
c. Alum[5]	---	---	115,000
3. Operating Labor, Maintenance & Repair	8,000	3,000	3,500
4. Sludge Disposal Cost O&M	at 800 T/yr	at 835 T/yr	at 525 T/yr
a. Anaerobic Digestion at $5/ton	4,000	4,175	2,625
b. Transport of Liquid Sludge by Tank Truck at $15/Ton	12,000	12,525	7,875
TOTAL ANNUAL COST	90,265	130,538	134,783
$/mg	$33.50	$51.10	$52.75

[1] See Table 7   for cost breakdown.

[2] Assumes a 20-year equipment life and 6-1/8% capital cost.

[3] Based on a 250 mg/l lime dosage, 15% Q_t supernate flow, and a lime cost of $50/ton delivered. (where Q_t is the total influent flow to the plant.)

[4] Based on a 90 mg/l $FeCl_3$ dosage, 7 mgd flow, and a $FeCl_3$ cost of $110/ton delivered.

[5] Based on a 135 mg/l alum dosage, 7 mgd flow, and an alum cost of $80/ton delivered.

Table 7. PhoStrip Cost Comparison

Equipment Cost (PhoStrip)	Cost
1. Stripper Tank	
a. Concrete 65-ft. dia. at 20-ft. SWD	$150,000
b. Mechanism & Warranty (supplied by Union Carbide)	245,000
2. Lime-Mix Tank	
a. Concrete 9-sq. ft. at 12-ft. SWD	57,500
b. Mixer	2,500
3. Pumps	
a. Stripper supernatant Pumps	2,000
b. Anaerobic RAS Pumps	2,000
c. Stripper Waste Pumps	1,000
4. Lime Feed Equipment* (50 ton Bin, Feeder, Slaker)	60,000
Total Installed Cost	$520,000

* Cost taken from EPA Manual "Phosphorus Removal", p. 10-32

$$ENR = \frac{2520^{(1977)}}{1643_{(1971)}} = 1.53$$

Equipment Cost (Ferric Chloride)	Cost
1. Bulk Storage 2/8000 gal. tanks	$ 25,000
2. Pumps	
Transfer	15,000
Feed	
3. Dilution and Feed Tanks, Agitation, Piping	20,000
Total Installed Cost	$ 60,000

Equipment Cost (Alum)	Cost
1. Bulk Storage 4/8000 gal. tanks	$ 50,000
2. Pumps	
Transfer	15,000
Feed	
Metering	
Total Installed Cost	$ 65,000

The estimated total annual cost of increasing the capacity of the existing plant and adding the capability for phosphorus removal are: $85,565 per year using the PhoStrip process; $129,163 per year using the ferric chloride process; and $136,183 per year using the alum process.

REFERENCES

1) Fuhs, G. W., and Min Chen, "Microbiological Basis of Phosphate in Activated Sludge Process for Treatment of Wastewater," Microbial Ecology, 1976.

2) Kornberg, S. R., "Adhenosine Triphosphate Synthesis from Polyphosphate by an Enzyme from Eschericia Coli", Biochimica et Biophysica, Acta, 26, 294, 1957.

3) Buller, L., "A Suggested Approach to ATP Regeneration for Enzyme Technology Applications", Biotechnology and Bioengineering, 19, 591, 1977.

4) Fox, J. L., "Pyrophosphate Drives Biochemical Reaction", Chemical & Engineering News, 22, April 25, 1977.