Wat. Res. Vol. 20, No. 1, pp. 105–112, 1986
Printed in Great Britain. All rights reserved

0043-1354/86 $3.00 + 0.00
Copyright © 1986 Pergamon Press Ltd

BATCH COAGULATION OF A LAGOON FOR FECAL COLIFORM REDUCTIONS

GORDON R. FINCH and DANIEL W. SMITH
Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G7

(*Received June 1985*)

Abstract—The research examined the factors affecting fecal coliform removal from lagoon wastewater by batch treatment with aluminum sulphate. Laboratory experiments based on factorial designs and jar tests were used to determine the statistically significant factors controlling the removal of fecal coliform bacteria. Temperature, chemical dose, pH, rapid mixing and flocculation were examined at two different laboratory scales. The results indicated that alum dose and pH were the only significant parameters. A design chart was developed for the wastewater tested enabling dose determination for a desired fecal coliform reduction. This chart was used to select the dose for a full scale field trial to reduce fecal coliforms to < 10 per 100 ml. The design dose was 300 mg l^{-1} $Al_2(SO_4)_3 \cdot 18\ H_2O$ and a final pH of 6.4 was predicted.

The field trial used liquid alum ($Al_2(SO_4)_3 \cdot 14.2\ H_2O$) delivered by tanker truck and distributed by motor boat. The treatment reduced fecal coliforms by 99.9%, total phosphorus by 97%, total suspended solids (TSS) by 90% and 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) by 35%.

The cost of treatment for labour and materials was $CDN 0.07 m^{-3}.

Key words—alum, coagulation, cold regions, experimental design, fecal coliforms, lagoon, scale-up, upgrading, wastewater treatment

INTRODUCTION

Lagoons have found widespread use for disposal of wastewater from small, cold climate communities since they are relatively inexpensive to construct and maintain in addition to requiring minimal operating expertise (Smith and Christensen, 1982).

Various design approaches have been used with mixed degrees of success, the lagoon often failing to perform as expected (U.S. EPA, 1983). One design method commonly used in cold regions has been the use of controlled discharges. This approach takes advantage of the dilution capacity afforded by spring runoff and the high degree of treatment found after the summer months (U.S. EPA 1979). Dawson and Grainge (1969) advocated the use of 180 day retention lagoons for these reasons. One problem with this design approach is a poor quality spring effluent which is discharged to the receiving environment. Often these discharges do not coincide with the peak dilution capacity of spring runoff and may contain levels of coliforms and $CBOD_5$ higher than acceptable. Furthermore, phosphorus levels can be higher than desired. New design criteria may require 365 days retention to help overcome some of these deficiencies (Alberta Environment, 1977).

Potential upgrading techniques for systems with a spring discharge include chlorine disinfection, chemical precipitation, chemical coagulation, land application of effluent and construction of expanded or more sophisticated facilities (Middlebrooks *et al.*, 1982). Chlorine disinfection is not considered effective by some authors (Coulter, 1982; Feachem *et al.*, 1983) and residual chlorine is detrimental to fish stocks (Osborne *et al.*, 1981). Chemical precipitation for phosphorus removal from lagoons has been investigated by some researchers with good results. Graham and Hunsinger (1974) batch treated a seasonal discharge lagoon in Ontario with alum achieving excellent reductions in phosphorus and some reduction in coliform bacteria. Bacteria removals were not the primary objective of the study and results were inconclusive. Hanaeus (1984) used lime in continuous flow lagoons in Sweden to remove phosphorus. He also tested one lagoon system for coliform removals and found good reductions in bacteria. Other researchers (Freedman *et al.*, 1983; Sproul, 1980) have studied the effect of coagulation on the removal of bacteria and viruses from water and wastewater concluding it was a viable technique. No specific investigations were found in the literature which systematically determined and confirmed through scale-up techniques the factors which affect the removal of fecal coliform bacteria from lagoon wastewater.

The research reported here was designed to systematically determine the physical and chemical factors which affect the removal of fecal coliform indicator organisms from lagoon wastewater by coagulation, flocculation, and sedimentation prior to drawdown.

Study location

The lagoon used for the study serves the Town of Gibbons, Alberta, a 3000 person community 40 km northeast of Edmonton, Alberta. The lagoon system consists of four short retention, anaerobic cells

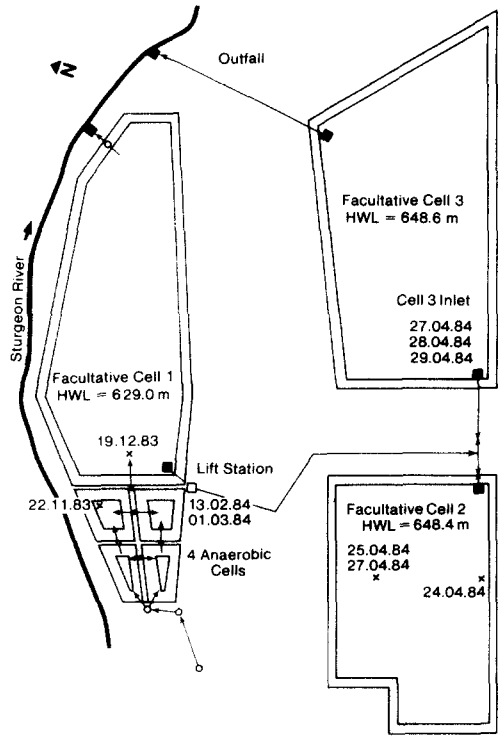

Fig. 1. Gibbons lagoon system and sampling locations.

followed by three long retention, facultative cells (Fig. 1). System storage provides for 180-day retention which requires discharge twice per year; once in the spring and once in the autumn. Only facultative cells 2 and 3 are discharged at these times. Lagoon effluent enters the Sturgeon River at a point approx. 20 km from its confluence with the North Saskatchewan River.

Facultative cell 2 was chosen as the test site since it has the smallest volume, approx. 35 Ml, and offered some flexibility with respect to time of discharge since it could be isolated from the rest of the system.

Sampling and wastewater composition

Grab sampling was performed at a variety of locations in the lagoon system. Samples were collected from anaerobic cell 4, facultative cell 1, facultative cell 2, and the wet well of the lift station (Fig. 1). Following spring break-up in April 1984, additional samples were collected from the centre of cell 2 where both a mixed and a stratified vertical sample of the water column were taken.

Samples were stored in the dark at 4–6°C and kept closed to the atmosphere. This handling attempted to simulate conditions in cell 2 where 200 mm of ice cover and 250 mm of snow cover were observed in January and February, 1984. This was necessary because large volumes of wastewater were collected and used over periods of several days. Therefore it was desirable to simulate the natural die-off of fecal coliforms during storage.

Table 1 summarizes selected wastewater characteristics from the lagoon system (Fig. 1) over the 6 month study period from November 1983 to April 1984. These were analysed following procedures outlined in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1981).

EXPERIMENTAL DESIGN, PROCEDURES AND ANALYSIS

Experimental design

Jar tests are commonly used when evaluating coagulation and flocculation processes. Combining jar tests with a systematic experimental design allows the experimenter to efficiently extract information regarding the influence of a large number of variables and their interactions on the performance of the processes. The technique of factorial experimental design permits the independent analysis of variables and their interactions using a minimum number of trials or jars.

A brief description of factorial designs with two levels and n factors (2^n) follows which will provide the basis for understanding the analysis methods. A complete description of factorial designs was given by Box and Hunter (1961a,b) or Davies (1979). Each variable or factor is tested in combination with all other factors resulting in (2^n) trials, or jars in this case. If many factors are being evaluated the number of trials become large and impractical to perform. Fortunately, many of the higher order (3 or 4 factor) interactions are often negligible and can be confounded with additional factors. This allows the experimenter to reduce the number of trials required to determine the main effect of each variable. These are called fractional factorial designs and are of the general form, 2^{n-m} where m is the fraction, $1/2^m$, of the factorial. The use of this type of design is efficient in extracting information on the main effects at the expense of information regarding the interactions.

Apparatus, reagents and procedure

A Phipps & Bird Inc. six place stirring apparatus was used throughout the bench scale testing. Maximum impeller speed was 100 rpm. The standard 75 mm dia by 25 mm high

Table 1. Lagoon wastewater composition 22.11.1983 to 25.04.1984

Parameter	Units	22.11.83	19.12.83	13.02.84	01.03.84	25.04.84	Standard method
$CBOD_5$	$mg\,l^{-1}$	185	108	—	104	54	507
TSS	$mg\,l^{-1}$	98	70	29	31	51	209D
PO_4^{3-}-P	$mg\,l^{-1}$	9.2	17	9.0	9.2	8.7	424C,D
SO_4^{2-}	$mg\,l^{-1}$	60	76	60	60	72	426C
Alkalinity (to pH 4.5)	$mg\,CaCO_3\,l^{-1}$	358	320	321	311	293	403
Temperature	°C	—	1	1	3	10	212
Ionic strength		0.0140	0.0144	0.0147	0.0147	0.0130	205 (Sawyer and McCarty, 1978)
pH		7.5	7.6	6.8	6.7	7.2	423
Fecal coliforms	No. per 100 ml	1.2×10^5	3.2×10^5	2.8×10^5	5.6×10^5	4.8×10^3	909C

two-bladed paddle was used to mix 1.0 l. samples in each 95 × 95 mm square jar. Cornwell and Bishop (1983) evaluated the velocity gradients for a similar Gator jar at various mixing speeds. Their jar was slightly larger, 115 × 115 mm, but their results were assumed to be adequate for the present investigation. A Fisher Accumet 156 pH meter was used to measure wastewater pH before and after treatment. Coagulant and polyelectrolyte feed solutions were prepared from 16 to 24 h in advance of the experiment. The cationic polyelectrolyte was activated according to the manufacturer's recommendations. Final pH was adjusted using approx. 6 N HCO_3 and 1 N NaOH solutions. Media and dilution water for membrane filtration determination of fecal coliforms was prepared according to Method 909C (APHA, 1981). Initial fecal coliform counts were determined prior to each set of trials.

Each trial was treated using the combination described by the experimental design matrix for each run. The final pH was adjusted to the desired value during the flocculation period. Following 30 min of sedimentation, an aliquot was extracted from the jar using a syringe or syphon and was stored at 4–6°C until it was analysed for remaining fecal coliforms on the same day.

Analysis

The response of each trial was recorded in the design matrix for each series. The statistical software package MIDAS (Fox and Guire, 1976) was used to perform a multivariate least squares regression of the design matrix on the response. The main effects and interactions were calculated from the resulting regression coefficients (β) by the relation:

$$\text{effect} = 2 \times \beta.$$

The fecal coliform count per 100 ml was subject to a $\log_{10}$ transformation to account for the dependence of variance on the number of coliforms counted (Draper and Smith, 1981).

Each factor and interaction was evaluated by the Yates method of analysis of variance (ANOVA) summarized in Davies (1979). The mean square of each term was calculated from the total effect:

$$\text{total effect (TE)} = \beta \times 2 \times 2^{n-m-1}$$

and

$$\text{mean square (MS)} = (\text{TE})^2/(\lambda \cdot 2^{n-m})$$

where

λ = degree of freedom of factor = 1.

An estimate of experimental error allows discrimination of real effects from null effects. The error mean square (MS_d) is an estimate of the error variance and may be calculated from the mean square of insignificant interactions and effects. Half-normal probability plots of the total effects of each factor and interaction provide a graphical technique for separating real effects from null effects (Daniel, 1959). They are constructed using half of the normal probability scale on probability paper. Starting at 50%, the scale is changed by the relationship:

$$P' = 2P - 100$$

where

P = full-normal probability.
P' = half-normal probability.

P' value for each factor and interaction is calculated by the rank of the effect, the highest rank being for the largest effect. The equation is:

$$P' = (\text{RANK} - \tfrac{1}{2})/2^{n-m-1}$$

Insignificant terms lie on a line through the origin. The average of the mean square of these factors approximates the error variance. The ratio of MS/MS_d for each term produces a statistic which may be compared to the F-statistic, $F\alpha(\lambda_1, \lambda_2)$, the degrees of freedom being for factor mean square and the error mean square, respectively. Those factors and interactions exceeding the tabulated F-statistic at α level have statistically significant effects. For these experiments, α was selected as 0.05.

LABORATORY INVESTIGATION

Screening experiment

A screening experiment was initially conducted to evaluate the impact of various physical and chemical parameters which were reported to influence the processes of coagulation and flocculation. Eight different factors were assessed in the screening process: primary coagulant dose; coagulant aid dose; pH; temperature; rapid mixing velocity gradient; flocculation velocity gradient; rapid mixing duration; and flocculation time.

Previous work by Al-Layla and Middlebrooks (1975), McGarry (1970) and Shindala and Stewart (1971) used alum ($Al_2(SO_4)_3 \cdot 18\,H_2O$) as a coagulant because it was economical, easy to use, and produced good results. On the basis of these past experiences, alum was selected as the primary coagulant. McGarry (1970) reported enhanced removals of algae using alum in combination with a cationic polyelectrolyte. Therefore a high molecular weight, cationic polymer was investigated as a coagulant aid.

The design chosen for the screening experiment was based on a one sixteenth fractional factorial of a 2^8 design (2^{8-4}). In this design, the three factor interactions were confused with four additional main factors. The resulting design is shown in Table 2. The source of this design was Davies (1979), Appendix 10A and Table M. Samples collected on 19 December 1983 (Fig. 1) contained 3.6×10^5 fecal coliforms per 100 ml at the time of testing. The stock alum and polyelectrolyte solutions were fed as 1% solutions. The different levels of temperature necessitated blocking the experiment based on temperature (factor G). The low temperature block was conducted in the cold room at 5°C and the other at a room temperature of 16°C.

Using the method of Daniel (1959), Fig. 2 presents the half-normal plot of the total effects and interactions. It clearly illustrates the importance of A and F, alum dose and pH. The error variance was estimated from the lower seven points on the line through the origin resulting in an estimate of 0.0110 with 7 degrees of freedom. The F-statistic for $F_{0.05}(1,7)$ was 5.59. Comparing the MS/MS_d ratio, Table 3 reveals that A and F were highly significant followed by C, D, E, G and AC as marginally significant effects. The ABCD interaction was significant.

The outcome of this run was consistent with the theory of hydrophilic colloid stability where chemical influences are known to be important (Stumm and Morgan, 1981). Mixing duration, flocculation time and flocculation G were found to be marginally

Table 2. (a) Screening experiment: design and results

Jar No.	Main effects and interactions															Results log FC per 100 ml
	A	B	C	D	E	F	G	H	AB	AC	AD	BC	BD	CD	ABCD	
1	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	4.86
2	+	−	−	−	+	−	+	+	−	−	−	+	+	+	−	4.20
3	−	+	−	−	+	+	+	−	−	+	+	−	−	+	−	5.11
4	+	+	−	−	−	+	−	+	+	−	−	−	−	+	+	4.90
5	−	−	+	−	+	+	−	+	+	−	+	−	+	−	−	5.08
6	+	−	+	−	−	+	+	−	−	+	−	−	+	−	+	4.89
7	−	+	+	−	−	−	+	+	−	−	+	+	−	−	+	4.85
8	+	+	+	−	+	−	−	−	+	+	−	+	−	−	−	3.75
9	−	−	−	+	−	+	+	+	+	+	−	+	−	−	−	5.18
10	+	−	−	+	+	+	−	−	−	−	+	+	−	−	+	4.86
11	−	+	−	+	+	−	−	+	−	+	−	−	+	−	+	4.32
12	+	+	−	+	−	−	+	−	+	−	+	−	+	−	−	4.23
13	−	−	+	+	+	−	+	−	+	−	−	−	−	+	+	4.52
14	+	−	+	+	−	−	−	+	−	+	+	−	−	+	−	3.72
15	−	+	+	+	−	+	−	−	−	−	−	+	+	+	−	5.00
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	4.65

Table 2. (b) Screening experiment: factors and levels

Factors	Levels (−)	(0)	(+)
A—Alum dose (mg l^{-1})	50	74	100
B—Polyelectrolyte dose (mg l^{-1})	0	1.75	3.5
C—Rapid mix duration (s)	10	25	40
D—Flocculation time (s)	60	120	180
E—Flocculation G (s^{-1})	10	25	40
F—pH	5	6.5	8
G—Temperature (°C)	5	10.5	16
H—Rapid mix G (s^{-1})	40	55	100

significant in both runs suggesting alum dose, pH, mixing time, flocculation time and flocculation G should be examined further. This conclusion was supported by the effect of the four factor interaction of alum dose, polyelectrolyte dose, mixing time and flocculation time. Polyelectrolyte dose was not significant over the experimental region examined, and since it was more difficult to prepare and handle than alum, it was not considered further.

Quadratic experiment

To this point it has been assumed that the response surface (remaining fecal coliforms) was planar which may not necessarily be true. Davies (1979) introduced orthogonal composite designs based on full or fractional factorial designs which allows the experimenter to investigate a quadratic response surface. A half fractional factorial design was used to examine four factors: alum dose; pH; rapid mixing duration; and flocculation time. This design left all main effects clear but confounded two factor interactions with one another. This was acceptable since alum dose and pH had consistently been the most important factors. In this case, nine extra points were required. Axial points were calculated from the centre points to maintain orthogonality using Table 11.6 from Davies (1979) where $a = \pm 1.414$. The complete design is shown in Table 4.

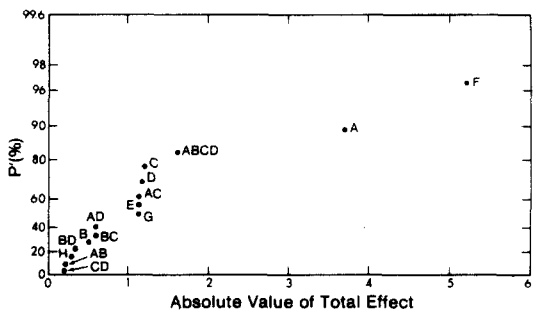

Fig. 2. Screening experiment: half-normal plot.

The wastewater collected on 19 December 1983 (Fig. 1) contained 5.0×10^4 fecal coliforms per 100 ml when this experiment was conducted. A 5% solution of alum was used as the feed stock to treat each jar. The 7°C wastewater was mixed at 100 rpm ($G = 100\ s^{-1}$) after the alum was added. As in the earlier experiments, a 30 min sedimentation period followed flocculation. The results are tabulated in Table 4.

This design did not readily lend itself to analysis by the Yates method. However, Draper and Smith (1981) discussed the use of step-wise regression analysis as a method of deciding which variables were significant in describing a response surface. In their opinion, the method of adding factors to the regression equation on a step by step basis was the best approach and recommended its use.

Using MIDAS (Fox and Guire, 1976) and the forward step-wise regression routine, SELECT, the

Table 3. Screening experiment ANOVA

Factor	β	TE	MS	MS/MS$_d$	Significant $\alpha = 0.05$	Rank
A	−0.232	−3.712	0.861	78	Highly	14
B	−0.031	−0.493	0.015	1.4	No	5
C	−0.075	−1.204	0.091	8.2	Yes	12
D	−0.073	−1.173	0.086	7.8	Yes	11
E	−0.071	−1.144	0.082	7.4	Yes	9
F	0.326	5.213	1.698	154	Highly	15
G	0.071	1.142	0.082	7.4	Yes	8
H	−0.019	−0.310	0.006	0.5	No	3
AB	0.012	0.195	0.002	0.2	No	2
AC	−0.073	−1.163	0.084	7.6	Yes	10
AD	−0.039	−0.621	0.024	2.2	No	7
BC	0.036	0.582	0.021	1.9	No	6
BD	0.021	0.340	0.007	0.6	No	4
CD	−0.012	−0.188	0.002	0.2	No	1
ABCD	0.100	1.597	0.159	14	Yes	13

Table 4. (a) Quadratic experiment: design and results

Jar No.	Main effects and interactions																Results log FC per 100 ml
	A	B	C	D	A^2	B^2	C^2	D^2	AB	AC	AD	BC	BD	CD	ACD	BCD	
1	−	−	−	−	+	+	+	+	+	+	+	+	+	+	−	−	1.11
2	+	−	−	+	+	+	+	+	−	−	−	+	+	+	+	−	1.54
3	−	+	−	+	+	+	+	+	−	+	+	−	−	+	−	+	0.48
4	+	+	−	−	+	+	+	+	+	−	−	−	−	+	+	+	2.90
5	−	−	+	+	+	+	+	+	+	−	+	−	+	−	+	+	0.70
6	+	−	+	−	+	+	+	+	−	+	−	−	+	−	−	+	3.20
7	−	+	+	−	+	+	+	+	−	−	+	+	−	−	+	−	0.95
8	+	+	+	+	+	+	+	+	+	+	−	+	−	−	−	−	1.81
9	$-a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	0	0	1.30
10	$+a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	0	0	2.51
11	0	$-a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	0	1.34
12	0	$+a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	0	2.00
13	0	0	$-a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	1.34
14	0	0	$+a$	0	0	0	a^2	0	0	0	0	0	0	0	0	0	1.40
15	0	0	0	$-a$	0	0	0	a^2	0	0	0	0	0	0	0	0	2.59
16	0	0	0	$+a$	0	0	0	a^2	0	0	0	0	0	0	0	0	1.70
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.70

Table 4. (b) Quadratic experiment: factors and levels

Factors	Levels				
	$(-a)$	$(-)$	(0)	$(+)$	$(+a)$
A—pH	4.8	5	5.5	6	6.2
B—Rapid mix duration (s)	36	60	120	180	204
C—Flocculation time (s)	108	180	360	540	612
D—Alum dose (mg l^{-1})	180	200	250	300	320

first order pH and alum dose terms were found to be the only significant variables. This was consistent with the earlier findings and confirmed that the responses of alum dose and pH were essentially linear.

It was possible to plot the experimental data gathered from the jar tests on a contour graph with fecal coliform removal as a function of pH and alum dose. The dimensionless number, N/N_0 where N was the number of microorganisms remaining and N_0 was the initial number present, was used in Fig. 3 to illustrate the interdependence of pH and alum dose. A sharp improvement in removals was observed when pH dropped below 5.5 and the alum dose was greater than 200 mg l^{-1}. This diagram was useful in estimating the alum dose and pH to achieve a desired level of bacteria removal. It should be stressed that if pH control is not practical in a full scale application, jar tests are essential in determining the response of the system to treatment, particularly final pH.

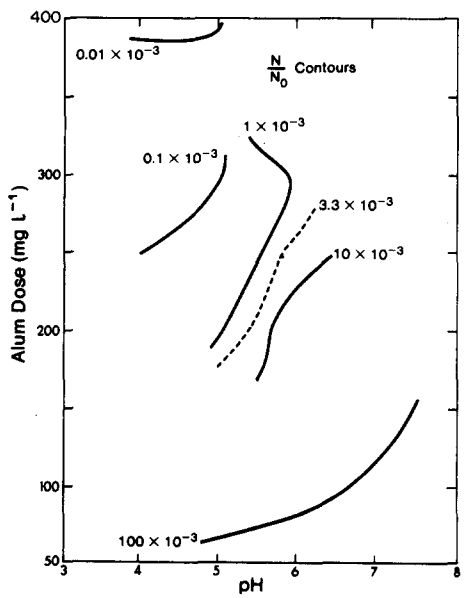

Fig. 3. Fecal coliform removal as a function of pH and alum dose.

Laboratory scale-up

It is evident that chemical factors play an important role in removing fecal coliforms from the water column. Physical parameters involving fluid motion, particle transport, and duration of mixing were found to play a relatively minor part in reducing fecal coliform numbers. Though the physical parameters are somewhat insignificant, it is desirable to know if this will remain the case when a somewhat larger volume of wastewater is treated. The objectives of this experiment were to confirm that chemical factors predominate through a 135-fold scale-up and that scale factors were not present.

Oldshue (1983) noted that chemical reactions involving particles <0.5 mm dia were independent of impeller size, therefore power input per unit volume was a suitable scale-up parameter. Design of scaled-up mixing processes involved the choice of power input and impeller speed which were interrelated by the Reynolds number, R, and the Power number, Φ, defined by:

$$R = \frac{D^2 S}{v}$$

where

D = diameter of impeller (m)
S = impeller speed (RPS)
v = kinematic viscosity ($m^2 s^{-1}$)

Table 5. (a) Scale-up: experimental design and results

Jar No.	Main effects A	B	C	Results: Jar test log FC per 100 ml	pH	Tank test log FC per 100 ml	pH
1	–	–	+	3.89	5.8	3.83	5.7
2	+	–	–	4.79	6.3	4.52	6.2
3	–	+	–	4.74	6.3	4.76	6.2
4	+	+	+	3.76	5.9	3.82	5.7

Table 5. (b) Scale-up: factors and levels

Factors	Levels (–)	(0)	(+)
A—Rapid mix Gt*	400	11,000	18,000
B—Flocculation Gt†	600	30,300	60,000
C—Alum dose (mg l^{-1})	200	300	400

*Rapid mix duration: (–) 40 s (+) 180 s.
†Flocculation duration: (–) 60 s (+) 600 s.

and

$$\Phi = \frac{P}{\rho S^3 D^5}$$

where

P = power input (W)
ρ = bulk density (kg m^{-3}).

A third equation of interest in flocculation was the relationship between G and power developed by Camp and Stein (1943):

$$P = \mu G^2 V$$

where

G = mean velocity gradient (s^{-1})
μ = absolute viscosity (N·s m^{-2})
V = volume of flocculation basin (m^3).

The scaled up experiment was carried out using the factorial design shown in Table 5. Jar tests and the scaled-up tests were conducted simultaneously to ensure ready comparison of the results. As seen in Tables 6 and 7, there was essentially no difference in the outcomes. It was concluded that pH and alum dose were significant at both scales and that no scale factors were present.

A more comprehensive account of the scale-up laboratory work is found elsewhere (Finch and Smith, 1984).

Table 6. Scale-up: jar test ANOVA

Factor	β	TE	MS	MS/MS$_d$	Significant $\alpha = 0.05$
A	−0.0174	−0.069	0.0012	0.1	No
B	−0.0451	−0.180	0.0081	0.7	No
C	−0.4692	−1.877	0.8808	80	Yes

Table 7. Scale-up: tank test ANOVA

Factor	β	TE	MS	MS/MS$_d$	Significant $\alpha = 0.05$
A	−0.0637	−0.255	0.016	1.5	No
B	0.0573	0.229	0.014	1.2	No
C	−0.4100	−1.640	0.673	61	Yes

FIELD INVESTIGATION

Objectives

Results of the laboratory research indicated that:

(1) alum dose and pH principally controlled the removal of fecal coliform bacteria;

(2) some mixing and flocculation was necessary but bacteria removals were insensitive to these parameters; and

(3) no factors of scale were present.

Therefore, the field trial was planned on the following basis:

(1) reduce fecal coliforms to < 10 per 100 ml;

(2) determine the initial number of bacteria present prior to treatment to enable calculation of the N/N_0 value;

(3) estimate the alum dose and final pH level from Fig. 3 to achieve the N/N_0 value without adjusting lagoon pH by means other than alum addition; and

(4) perform a jar test at this dose to confirm the design based on Fig. 3 and to indicate the likely outcome of the full scale trial.

The trial was conducted on 26 April 1984. The weather was generally sunny with an air temperature of 8°C, and a light, northeasterly wind.

Procedure

Wastewater sampled on 24 April 1984 contained approx. 3000 fecal coliforms per 100 ml (Table 8). Fecal coliform levels less than 10 per 100 ml corresponds to an N/N_0 ratio of 0.0033. From Fig. 3, it appears that an alum dose of 300 mg l^{-1} and a final pH of 6.4 would provide the desired removal of bacteria. The experience of previous experiments indicated that this alum dose would drop the pH to approximately the desired level.

A jar test was conducted using the same apparatus as in earlier tests. Rapid mixing was carried out for 30 s at a G of 100 s^{-1} and flocculation was done for 600 s at a G of 10 s^{-1}. Undiluted liquid alum (available as a 48.5% solution of $Al_2(SO_4)_3 \cdot 14.2\ H_2O$) was used in the jar test. Figure 3 was based on technical grade alum ($Al_2(SO_4)_3 \cdot 18\ H_2O$) therefore a correction must be made for liquid alum (1.11 mg l^{-1} technical grade alum = 1.0 mg l^{-1} liquid alum). The final pH

Table 8. Fecal coliform analysis: before and after treatment

Sample date	Location	FC per 100 ml
25.04.84 (before)		
1700 h	Cell 2 centre, mixed	4800
	Cell 2 centre, 0.5 m	3000
	Cell 2 centre, 1.0 m	1800
	Cell 2 centre, 1.5 m	2200
27.04.84 (after)		
1700 h	Cell 2 centre, 0.5 m	7
	Cell 2 centre, 1.0 m	11
	Cell 2 centre, 1.5 m	23
1800 h	Cell 3 inlet	33
28.04.84 (after)		
1000 h	Cell 3 inlet	7
1700 h		4
29.04.84 (after)		
1500 h	Cell 3 inlet	1

was 6.1. Following 30 min of sedimentation, a sample was analysed for fecal coliform bacteria. No fecal coliform bacteria were recovered using the membrane filtration method.

Liquid alum was ordered following completion of the jar tests using an estimated lagoon volume of 34.5 Ml. The delivered amount of liquid alum was 19430 kg resulting in a calculated dose of 304 mg l^{-1} as $Al_2(SO_4)_3 \cdot 18\,H_2O$.

Two 4.9 m aluminum boats equipped with 25 h.p. outboard motors were used to distribute alum, mix the lagoon and induce flocculation. Each boat had a 200 l. drum for storing alum. The alum was delivered over the stern of the boat using an 11.4 l s^{-1} gasoline pump. A 4 m long wharf facilitated the transfer of alum from the shore to the boats. Alum was transferred from the tanker truck to the boats by gravity through an 8 m long, 75 mm dia hose supplied by the hauler.

Each boat was assigned to cover approximately half of the lagoon surface area, distributing the alum uniformly around each sector. Rapid mixing was accomplished by directing the liquid alum into the propeller wash of the boat followed by two or three extra passes with the boat to promote good mixing. Near the end of the operation, one boat systematically traversed the entire lagoon at a speed which maximized bulk fluid motion. This speed was determined by the boat operator.

The lagoon was allowed to settle for 27 h prior to sampling and draining the cell.

Sampling

Grab samples were obtained at the end of the clarification period at two locations (Fig. 1). A vertical profile of the water column was taken in the centre of cell 2 at 0.5, 1.0 and 1.5 m. The outfall of cell 2 was the inlet to cell 3. This was also sampled (Fig. 1).

A small aluminum dinghy and controlled depth sampler was used to collect samples from the centre of cell 2. Temperature and pH were measured on site. Temperature ranged from 10°C at 0.5 m to 8°C at 1.5 m. pH was consistently 6.4. Fecal coliforms were determined the following day after storing samples in the dark at 4°C.

Sampling was continued for the next 2 days at the inlet to cell 3 since this was felt to be representative of the contents of cell 2.

Observations

Shortly after the operation started floc particles were clearly discernable in the treated water column. As the operation wore on, the entire lagoon contained similar sized floc particles, approx. 6 mm dia. The particles were observed to be moving constantly which contributed to their agglomeration. The motion was attributed to residual boat action and the light northeasterly wind.

The lagoon colour changed from black to milky white in the immediate vicinity of the alum addition followed by a rapid progression to a pale green which persisted for the duration of the trial. Clear water was observed in the shallows following 60 min of sedimentation after alum addition was completed.

Overnight sedimentation had little apparent effect, the lagoon appearing turbid and having a pale green colour. However, examination of a 1.0 l. beaker of supernatant obtained at various depths revealed that the water was very clear suggesting that the turbidity and pale green colour resulted from refraction of sunlight by a finely divided colloidal suspension, likely an aluminum precipitate. The draining of cell 2 commenced 27 h after the alum application ceased. Considerable foaming was observed at the inlet to cell 3. Subsequent discharge of cell 3 into the Sturgeon River also produced foam posing aesthetic problems for a short distance downstream.

Following drawdown of cell 2, the lagoon side slopes and bottom were observed to have accumulated insignificant amounts of sludge. The residual supernatant in cell 2, approx. 450 mm deep, remained clear a week after treatment.

Results and analysis

Overall reductions in $CBOD_5$, suspended solids, and phosphorus were good as shown in Table 9. Final pH was equal to that predicted by Fig. 3 but slightly higher than the jar test results. It is postulated that a minor change in the buffering capacity associated with the grab sample was responsible for the lower final pH in the jar tests whereas the entire lagoon contents were representative of the wastewater used to establish Fig. 3.

Results of the fecal coliform sampling program over the 72 h period following sedimentation are tabulated in Table 8. The highest value observed was at the cell 3 inlet, 30 min after opening the drain valve from cell 2. This may have been due to scouring of fecal coliforms from the walls of the interconnecting asbestos cement pipe. As cell 2 drained over the ensuing 46 h, the bacteria count dropped to 1 per 100 ml.

The low fecal coliform count in the final effluent was attributed to enmeshment and adsorption of

Table 9. Full-scale treatment performance

Parameter	Units	1700 h	1700 h
$CBOD_5$	mg l^{-1}	54	35
TSS	mg l^{-1}	15	1.5
PO_4^{3-}–P	mg l^{-1}	8.7	0.3
SO_4^{2-}	mg l^{-1}	72	185
Alkalinity (to pH 4.5)	mg $CaCO_3$ l^{-1}	293	183
Temperature	°C	10	10
Ionic strength		0.0130	0.0132
pH	—	7.2	6.4
Fecal coliforms	No. per 100 ml	4800	4
Al^{3+}	mg l^{-1}	*	1

*Undetectable using flame atomic absorption.

coliforms in the sweep floc of $Al(OH)_3$, $AlPO_4$ and other destabilized colloidal materials. The sludge remaining in the lagoon following drawdown was presumed to contain viable fecal coliforms and presumably pathogenic microorganisms. It is expected that natural die-off would be enhanced by the increased ultraviolet radiation and warmer water temperatures associated with the clear, shallow supernatant.

The estimated operating cost of the treatment was approximately \$CDN 0.07 m^{-3} of wastewater comprised of \$CDN 0.06 for delivered alum and \$CDN 0.01 for labour. Renting boats, motors, and pumps would likely be the most economical approach for these capital cost items unless a large number of applications were anticipated.

CONCLUSIONS

pH and alum dose were highly significant factors in removing fecal coliforms from the lagoon wastewater tested.

Rapid mixing and flocculation were marginally implicated in fecal coliform reductions, suggesting that only a minimum of mixing was required.

No factors of scale were observed.

The alum dose obtained from a pH–alum dose diagram which used N/N_0 as a measure of fecal coliform removal efficiency, produced removals in accordance with those predicted by the diagram at the measured final pH value.

Reduction of fecal coliforms by 99.9% was accompanied by a suspended solids reduction of 90% and a phosphorus reduction of 97%. $CBOD_5$ was reduced by 35%.

The operating cost of this upgrading technique was \$CDN 0.07 m^{-3} of wastewater. Boats, motors and pumps were the only capital investment items. The impact of the capital cost on the overall treatment cost depends on the amount of wastewater treated annually. In some cases, it may be very economical to rent the equipment for the occasion.

REFERENCES

Alberta Environment (1977) Recommended guidelines for design, approval, and operation of sewage lagoons for small municipalities and private developments. Standards and Approvals Division, Edmonton, Alberta.

Al-Layla M. A. and Middlebrooks E. J. (1975) Effect of temperature on algal removal from wastewater stabilization ponds by alum coagulation. *Water Res.* **9,** 873–879.

APHA (1981) *Standard Methods for the Examination of Water and Wastewater*, 15th edition. American Public Health Association, Washington, D.C.

Box G. E. P. and Hunter J. S. (1961a) The 2 $(k-p)$ fractional factorial designs, Part I. *Technometrics* **3,** 311–351.

Box G. E. P. and Hunter J. S. (1961b) The 2 $(k-p)$ fractional factorial designs, Part II. *Technometrics* **3,** 449–458.

Camp T. R. and Stein P. C. (1943) Velocity gradients and internal work in fluid motion. *J. Boston Soc. civ. Engrs* **30,** 219–237.

Cornwell D. A. and M. M. Bishop M. M. (1983) Determining velocity gradients in laboratory and full-scale systems. *J. Am. Wat. Wks Ass.* **75,** 470–475.

Coulter J. B. (1982) Don't chlorinate sewage. *Proceedings of the Second National Symposium on Municipal Wastewater Disinfection*, pp. 1–12. EPA 600/9-83-009.

Daniel C. (1959) Use of half-normal plots in interpreting factorial two-level experiments. *Technometrics* **1,** 311–341.

Davies O. L. (1979) *The Design and Analysis of Industrial Experiments*, 2nd edition. Longman, New York.

Dawson R. N. and Grainge J. W. (1969) Proposed design criteria for wastewater lagoons in arctic and sub-arctic regions. *J. Wat. Pollut. Control Fed.* **41,** 237–246.

Draper N. S. and Smith H. (1981) *Applied Regression Analysis*, 2nd edition. Wiley, New York.

Feachem R. G., Bradley D. J., Garelick H. and Mara D. D. (1983) *Sanitation and Disease. Health Aspects of Excreta and Wastewater Management*. Wiley, New York.

Finch G. R. and Smith D. W. (1984) Effect of chemical coagulation on the removal of fecal coliforms from a seasonal discharge sewage lagoon. Environmental Engineering Technical Report 84-1, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

Fox D. J. and Guire K. E. (1976) Documentation for MIDAS, 3rd edition. Statistical Research Laboratory, University of Michigan, Ann Arbor, Mich.

Freedman D., Koopman B. and Lincoln E. P. (1983) Chemical and biological flocculation of purple sulphur bacteria in anaerobic lagoon effluent. *J. agric. Engng Res.* **28,** 115–125.

Graham H. J. and Hunsinger R. B. (1974) Phosphorous removal in seasonal retention lagoons by batch chemical precipitation. Ontario Ministry of the Environment, Research Report No. 13. Information Canada Catalogue No. En 43-11/13.

Hanaeus J. (1984) Swedish field experiences with chemical precipitation in stabilization ponds. *Proceedings of the Third International Specialty Conference on Cold Regions Engineering*, pp. 547–564.

McGarry M. G. (1970) Algal flocculation with aluminum sulphate and polyelectrolytes. *J. Wat. Pollut. Control Fed.* **42,** R191–R201.

Middlebrooks E., Middlebrooks C., Reynolds J., Watters G., Reed S. and George D. (1982) *Wastewater Stabilization Lagoon Design, Performance, and Upgrading*. Macmillan, New York.

Oldshue J. Y. (1983) Perspectives on the scale-up of impeller mixers. *Scale-up of Water and Wastewater Treatment Processes* (Edited by Schmidtke N. W. and Smith, D. W.), pp. 31–54. Butterworth, Toronto, Ontario.

Osborne L., Iredale D., Wrona F. and Davis R. (1981) Effects of chlorinated sewage effluents on fish in Sheep River, Alberta. *Trans. Am. Fish. Soc.* **110,** 536–540.

Shindala A. and Stewart J. W. (1971) Chemical coagulation of effluents from municipal waste stabilization ponds. *Wat. Sewage Wks* **118,** 100–103.

Smith D. W. and Christensen V. (1982) Innovative approaches to sewage collection, treatment, and disposal: practices in northern Canada. *Can. J. civ. Engng* **9,** 653–662.

Sproul O. J. (1980) Critical review of virus removal by coagulation processes and pH modifications. United States Environmental Protection Agency Report No. EPA 600/2-80-004, NTIS PB80-221252, Cincinatti, Ohio.

Stumm W. and Morgan J. J. (1981) *Aquatic Chemistry*, 2nd edition. Wiley, New York.

U.S. EPA (1979) Cold climate utilities delivery design manual. Report No. EPA 600/8-79-027, Washington, D.C.

U.S. EPA (1983) Design manual: municipal wastewater stabilization ponds. Report No. EPA 625/1-83-015, Washington, D.C.