Fisheries and Environment
Canada

Environmental Protection
Service

Pêcl
Can

Serv
de l'environnement

Municipal Wastewater Toxicity Program Summary, Pacific Region 1976

Manuscript Report
77-13

Pacific Region
December, 1977

MUNICIPAL WASTEWATER TOXICITY

PROGRAM SUMMARY, PACIFIC REGION

1976

by

T. W. HIGGS, P. ENG.

SIGMA RESOURCE CONSULTANTS LTD.

for the

ENVIRONMENTAL PROTECTION BRANCH

ENVIRONMENTAL PROTECTION SERVICE

PACIFIC REGION

MANUSCRIPT REPORT 77 - 13

DECEMBER 1977

ABSTRACT

Wastewater toxicity surveys were carried out by the Environmental Protection Service during the summer of 1976 at the following locations:

1) Annacis Island STP (77 - 3)
2) Iona Island STP (77 - 11)
3) Penticton WQCC (77 - 6)
4) Mission PCC (77 - 8)
5) Cache Creek STP (77 - 7)
6) Clinton Sewage Lagoons (77 - 10)
7) Williams Lake Sewage Lagoons (77 - 10)
8) Prince George STP (77 - 12)

Detailed survey results are contained in the individual manuscript reports.

This report contains:

1) a summary of the results from each survey,
2) a discussion of the strengths and weaknesses of the survey procedures,
3) a discussion of the overall results of the surveys,
4) recommendations for control of toxicity
5) suggestions for improvements in treatment plant design and operation
6) recommendations for further study.

TABLE OF CONTENTS Page

Page

LIST OF TABLES

LIST OF TABLES (cont'd)

LIST OF FIGURES

LIST OF ABBREVIATIONS

BOD_5	5 day biochemical oxygen demand
CFS	cubic feet per second
COD	chemical oxygen demand
DO	dissolved oxygen
GVS & DD	Greater Vancouver Sewage and Drainge District
hr	hour(s)
Imp GPD	Imperial gallons per day
Imp MGD	million Imperial gallons per day
l	liter(s)
LAS	linear alkylate sulfonate
LC_{50}	50th percentile lethal concentration
mg/l	milligrams per liter
NFR	non-filterable residue
PCB	polychlorinated biphenyls
PCC	pollution control center
SRT	solids retention time

LIST OF ABBREVIATIONS (cont'd)

STP	sewage treatment plant
Tc	toxicity concentration $Tc = \frac{100\%}{96\ hr\ LC_{50}(\%)}$
TOC	total organic carbon
TRC	total residual chlorine
WQCC	water quality control center

1 INTRODUCTION

Wastewater toxicity surveys were carried out on eight sewage treatment systems as listed in the Abstract. The purposes of these surveys were as follows:

1) to investigate different treatment processes and to determine the degree of toxicity reduction achieved with each type,
2) to document the increase in toxicity associated with the practice of chlorination,
3) to relate the toxicity of the influent and effluent to the concentrations of certain known toxic substances,
4) to determine the incidence and extent of removal of PCB, (this is discussed in the individual reports only),
5) to accumulate information pertaining to municipal discharges to assist Regional EPS personnel in making site specific judgements.

These surveys basically involved sample collection over a short period (2 or 4 days), bioassay determinations, and chemical analysis. The results of the chemical analyses were used to interpret the results of the bioassay determinations. The results obtained are only representative of conditions at the sewage treatment plants during the time of the survey.

A summary of each survey is contained in chapters 2.0, 3.0, and 4.0.

A discussion of the factors involved in carrying out these stated objectives appears in the following sections.

1.1 Sampling Procedures

To establish wastewater toxicity concentrations and the toxicants involved, 24 hour time proportional composite samples were collected. There are several inherent weaknesses in this procedure.

1) Fish in the receiving environment respond to peak concentrations of toxicants rather than the average concentrations.
2) The wastewater discharge from small communities can contain mostly ground water for long segments of a 24 hour period, thereby diluting the sample.
3) Time proportional composite samples do not compensate for changes in flow but in fact give equal weight to the aliquots collected at different times. Flow proportional composites would be difficult to collect due to the problems of producing a signal from various types of flow measurement devices and then transmitting that signal to the sample point location.
4) The toxic effect of a particular analytical parameter could be reduced significantly by storage during the 24 hour sampling period. This phenomena was readily apparent in attempting to determine the toxicity of chlorinated samples.
5) Unless composite sampling is conducted for an extended period, the results of a sampling program may not represent the plants overall performance.

Time proportional composites do however have several advantages over the alternative of taking single grab samples.

1) The peaks of toxicant discharge could be missed completely by a single grab. A number of grab samples collected at random intervals would be required to replace the composite. This would increase significantly the resources required to collect samples and perform analyses.
2) The toxicity of a wastewater as determined using a composite sample represents a conservative estimate of the actual toxicity.
3) The results obtained from a composite sampling program may be more reliable for comparison of various treatment processess and locations.

1.2 Bioassay Evaluation and Interpretation

The LC_{50} test involved determination of the wastewater concentration required to kill the 50th percentile of test fish over a 96 hour period. The main criticism of this test was that samples were aerated for a period up to 24 hours prior to the start of the test so as to increase the DO to a pre-determined level. The toxicity associated with parameters such as chlorines, NH_3 and dissolved gases, could be greatly reduced by aeration for an extended period. It is suggested that DO levels be raised by aerating with oxygen instead of air to shorten the aeration period.

On the average, however, the bioassay results are fairly consistent with the expected results, e.g. toxicity increases with surfactant concentration.

In addition, it was difficult to produce reliable values for LC_{50} in some situations due to the high control mortalities encountered. It is the author's understanding that these problems were generally caused by poor water supply quality and not by the test procedure itself.

1.3 Chlorine Toxicity

As mentioned in chapters 2.0, 3.0 and 4.0, a correlation can not be drawn between toxicity and a detectable chlorine residual using a static fish bioassay procedure. In some cases, however, there was a correlation between increased toxicity and the process of chlorination itself, e.g. Penticton WQCC, Iona Island STP, Annacis Island STP.

In some cases there was no measureable increase in toxicity due to the chlorination, for several possible reasons.

1) low chlorine dosage
2) low effluent ammonia concentration
3) high chlorine demand
4) test procedures

The influence of low chlorine dosage is self-explanatory.

Regarding low effluent ammonia, there appears to be a relationship between ammonia and chlorine induced toxicity without the presence of a measureable TRC. Ammonia appears to influence the persistence of toxic chlorinated compounds. High chlorine demand could influence chlorine induced toxicity in discharges of low quality effluent (high NFR). In other words, the chlorine applied to a wastewater could be absorbed completely by suspended solid material.

The determination of TRC was done using a Wallace and Tiernan Amperometric Titrator series A - 790013. The detection limit is stated as being 0.02 mg/l. This low a limit is questionable with the field procedure used by EPS personnel. The accuracy of the procedure could be improved by using microliter syringes for the titrations instead of pipets.

1.3.1 Chlorine Residual Control

As evident from the results of the chlorine residual monitoring programs, it can be concluded that neither manual nor flow proportional chlorine feed systems effectively control TRC. Compound loop systems using chlorine residual controllers and flow proportional devices are fairly reliable in maintaining a set TRC (e.g. Annacis Island STP).

Flow proportional devices cannot compensate for changes in chlorine demand. In addition, flow proportional chlorinators have limited response accuracy under the widely varying flow conditions experienced at sewage treatment plants. They cannot compensate for changes in the retention time of the chlorine contact chamber which influences the TRC.

The results of the chlorine residual monitoring programs indicated that some plants are chlorinating at levels much higher than that required by the regulatory agencies.

1.4 Ammonia Toxicity

Ammonia toxicity has been directly related to the amount of un-ionized ammonia in solution. Domestic sewage generally contains a high enough ammonia concentration to cause toxicity. In some cases the raw sewage ammonia levels are lower than expected due to dilution by groundwater infiltration and stormwater. Factors other than un-ionized ammonia, such as alkalinity, may be associated with the toxicity of ammonia. For this reason it is difficult to draw a direct correlation between ammonia concentration and toxicity.

1.4.1 Nitrification

Nitrification is the oxidation of ammonia to nitrite and in turn nitrite to nitrate. In situations where nitrification is taking place, there is a definite reduction in toxicity. The Williams Lake and Clinton lagoons systems and the Prince George STP accomplished nitrification and in turn produced non-toxic effluents, even after chlorination.

The degree of nitrification accomplished by a treatment system depends on solids retention time, dissolved oxygen, pH and temperature. These conditions are easily attainable in lagoon systems but somewhat difficult to maintain in activated sludge systems. A general relationship for activated sludge exists between solids retention time and degree of nitrification (assuming favourable D O and temperature). Unfortunately, with the activated sludge systems investigated, it was very difficult to calculate a reliable solids retention time due to varying flow rates, return sludge concentrations and sludge wasting rates.

1.5 Surfactant Toxicity

The primary toxic agent in detergent formulas is LAS (linear alkylate sulfonates), an anionic surfactant. The toxicity of LAS tends to increase in hard water. Activated sludge and lagoon treatment are fairly effective in reducing anionic surfactant concentrations to non-toxic levels. Primary treatment reduced surfactant levels somewhat, but a corresponding decrease in toxicity did not take place. The explanation is that the test fish would tend to react to the dissolved surfactant fraction and not to that portion associated with suspended solids.

1.6 Industrial Effluents

Annacis Island and Iona Island STP's both treat combined domestic and industrial effluent, however it is difficult to relate toxicity to any particular parameter common to industrial discharges such as CN, phenol and heavy metals. Parameters other than those investigated may have been responsible for a significant part of the toxicity. Ammonia and surfactant levels were not sufficiently high enough to explain the amount of toxicity observed. In addition, a synergistic effect could be taking place between different chemical substances.

2.0 PRIMARY SEDIMENTATION PLANTS

Primary sewage treatment implies the removal of floatable and settleable material from wastewater. To accomplish this, the two primary plants investigated as part of the Municipal Wastewater Toxicity Program utilized the processes of grit removal, screening, pre-aeration, sedimentation and disinfection.

2.1 Annacis Island Sewage Treatment Plant

The Annacis Island STP is a primary treatment plant with a design average dry weather flowrate of 100 CFS. The design maximum wet weather flowrate is 315 CFS. The actual average daily flow from November 1975 to October 1976 was 54.4 CFS. This low flow was due to the fact that the New Westminster and Burnaby South Slope Interceptors plus some major industries were not connected to the plant until after the survey was completed.

A flow sheet of the plant showing treatment components and the sample point locations is given in Figure 1. The operational characteristics are listed in Table 1.

The sewage treated by the plant could be classified as mixed domestic and industrial. Based on data provided by GVS & DD the treatment plant accomplished a 29.6% reduction in BOD_5, a 60.8% reduction in NFR and a 38.4% reduction in COD over a one year period.

A summary of the chemical and bioassay results from the field survey is presented in Table 2. For the purposes of this discussion the results obtained on the first day will be ignored because of the control mortalities. The remainder of the results indicate that primary sedimentation does not reduce toxicity. The raw sewage mean toxicity concentration (Tc) was 1.61 toxic units while the primary effluent mean Tc was 1.74 (a slight increase). Un-ionized ammonia and anionic surfactants were assumed responsible for the toxicity.

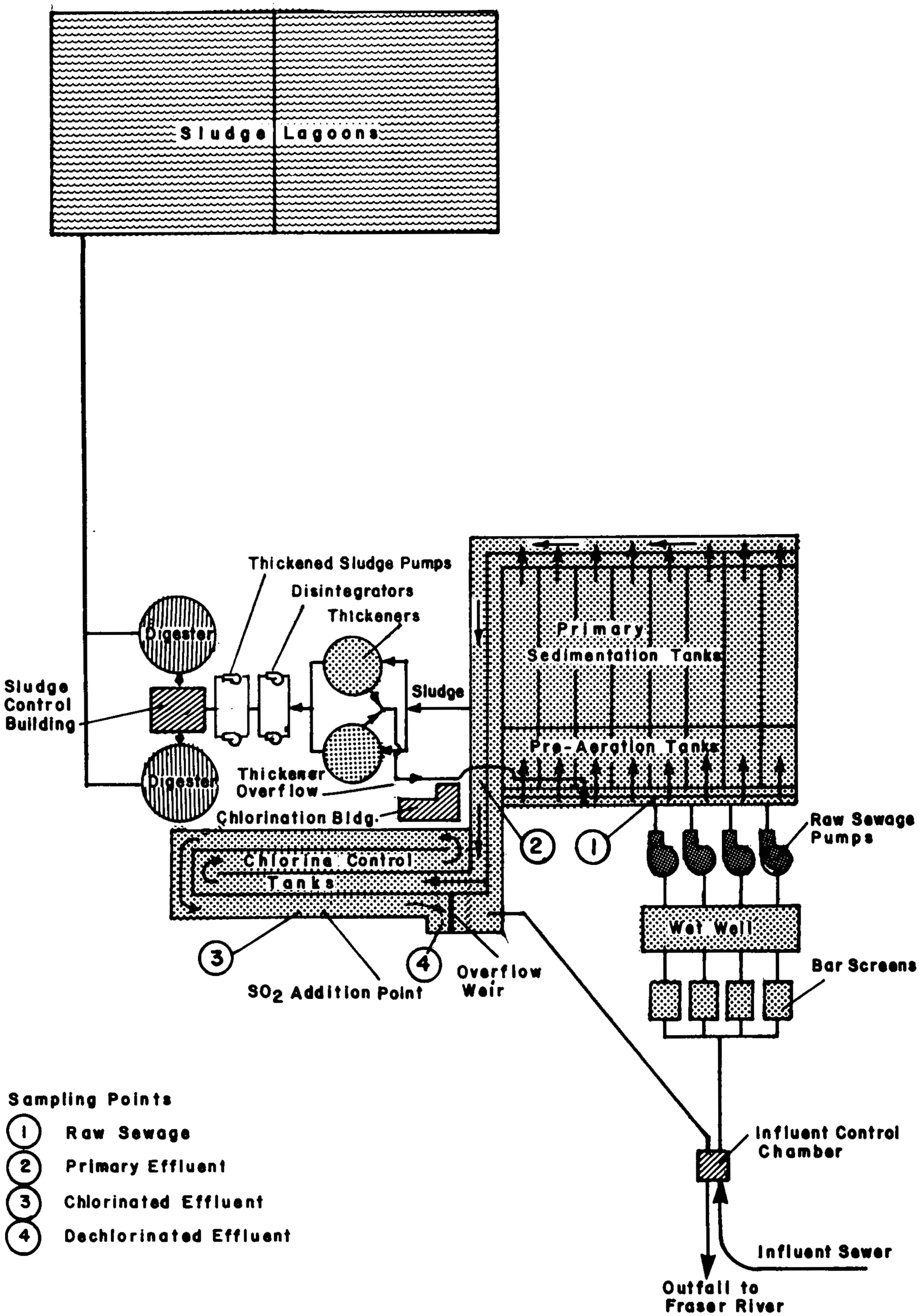

FIGURE I ANNACIS ISLAND SEWAGE TREATMENT PLANT-
FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

TABLE 1 OPERATIONAL CHARACTERISTICS OF ANNACIS ISLAND SEWAGE TREATMENT PLANT

Design Average Dry Weather	100 CFS
Design Peak Dry Weather	155 CFS
Design Maximum Wet Weather	315 CFS

Treatment Components

1) Bar Screens 4 Parallel
2) Raw Sewage pump 4 Parallel
3) Pre-aeration Tanks 8 Parallel
4) Primary Sedimentation Tanks 8 Parallel
5) Chlorine Contact Tank 4 Series
6) Sulfur Dioxide Addition

Average Flow (November 1975 - October 1976) = 54.4 CFS
(October 1976) = 56.9 CFS

Detention Times (at D. W. F.)

Pre-aeration Tanks	= 0.6 hr
Sedimentation Tanks	= 1.9 hr
Chlorine Contact Tanks	= 1.0 hr
Total Detention	3.5 hr

Sedimentation Tank Overflow (at D. W. F.) = 700 gal/ft^2/day

Raw Sewage Average	BOD	= 162 mg/l	Final Effluent Average BOD	= 115 mg/l
	NFR	= 148 mg/l	NFR	= 58 mg/l
	COD	= 331 mg/l	COD	= 204 mg/l

Sludge Treatment Components

1) Raw sludge pumps 4 parallel
2) Sludge thickeners 2 parallel
3) Disintegrators 2 parallel
4) Thickened sludge pumps 2 parallel
5) High rate anaerobic digesters 2 parallel
6) Sludge lagoons

TABLE 2 ANNACIS ISLAND STP
COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

Sample Points	Date	LC_{50}	Tc	NH_3	Un-ionized* NH_3	pH	Anionic Surfactants	Control Mortalities
	October	%	TU	mg/l N	mg/l N		mg/l LAS	%
Raw Sewage	5	56	1.79	40	0.17	7.2	4.5	20
	6	52	1.92	27	0.023	6.5	4.6	0
	7	78	1.28	21	0.046	6.9	4.6	0
	8	61	1.64	20.5	0.077	7.1	4.5	0
Primary Effluent	5	60	1.67	24	0.066	7.0	3.7	20
	6	45.5	2.20	28	0.048	6.8	2.7	0
	7	59.5	1.68	21	0.036	6.8	3.9	0
	8	75	1.33	20.5	0.056	7.0	3.4	0
Chlorinated Effluent	5	43	2.33	25	0.054	6.9	3.7	20
	6	58	1.72	28	0.069	6.9	2.8	0
	7	53	1.89	22	0.036	6.8	3.8	0
	8	37	2.70	21.5	0.059	7.0	3.5	0
Dechlorinated Effluent	5	26	3.85	21	0.046	6.9	3.7	20
	6	51	1.96	21	0.036	6.8	4.0	0
	7	75	1.33	20	0.034	6.8	4.2	0
	8	78	1.28	20	0.043	6.9	3.5	0

*According to Emmerson et al

Parameters other than those investigated may have influenced the bioassay results. Primary treatment reduced the anionic surfactant concentration by approximately 27%, but did not reduce the ammonia level. The reduction in the anionic surfactant concentration did not, however, cause a corresponding decrease in toxicity.

Chlorination increased the mean Tc to 2.10 toxic units. However, the chemical composition of the primary effluent and the chlorinated effluent were similar (except for the presence of chlorine). Composite samples analyzed for TRC prior to the bioassay test indicated the absence of a detectable residual. The process of chlorination was responsible for the increase in toxicity. Therefore, this chlorine induced toxicity was not related to a detectable residual. The actual chlorinated compounds involved could not be determined.

Dechlorination (SO_2) decreased the mean Tc to 1.52 toxic units. This would indicate that dechlorination using SO_2 was effective in eliminating chlorine induced toxicity. Dechlorination also caused a reduction in un-ionized ammonia from a mean of 0.055 mg/l N for the chlorinated effluent samples to a mean of 0.038 mg/l N for the dechlorinated samples (possibly due to ammonia stripping by SO_2). This would also result in a decrease in toxicity.

2.2 Iona Island Sewage Treatment Plant

The Iona Island STP treats domestic sewage, industrial sewage, and stormwater from the City of Vancouver and from part of the Municipality of Burnaby. The design average dry weather flow is 130 CFS and the design peak wet weather flow is 625 CFS. The actual average daily flow from September 1975 to August 1976 was 155 CFS.

The operational characteristics of Iona Island STP are listed in Table 3 and a flow diagram is presented in Figure 2. A summary of the chemical and bioassay results from the field survey is presented in Table 4. The results obtained on the last day will be ignored because the sample received excessive dilution from stormwater and also because the sample was stored 48 hours prior to the start of the bioassay test. The samples collected on the other three days also contained some surface runoff as evident by the low ammonia and surfactant concentrations.

The results obtained on August 17, 18, and 19, indicated that primary treatment did not reduce toxicity. The raw sewage mean toxicity concentration (Tc) was 1.46 toxic units while the primary effluent mean Tc was 1.45.

Un-ionized ammonia and anionic surfactants were assumed responsible for the toxicity of the raw sewage and primary effluent samples. However, parameters other than those investigated may have influenced the bioassay results. Primary treatment was responsible for a 59% reduction in the anionic surfactant concentration; this reduction did not, however, cause a corresponding decrease in toxicity as discussed in section 1.5.

Chlorination increased the mean Tc to 1.99 toxic units. The chemical compositions of the primary and chlorinated effluent were similar.

The process of chlorination was responsible for the increase

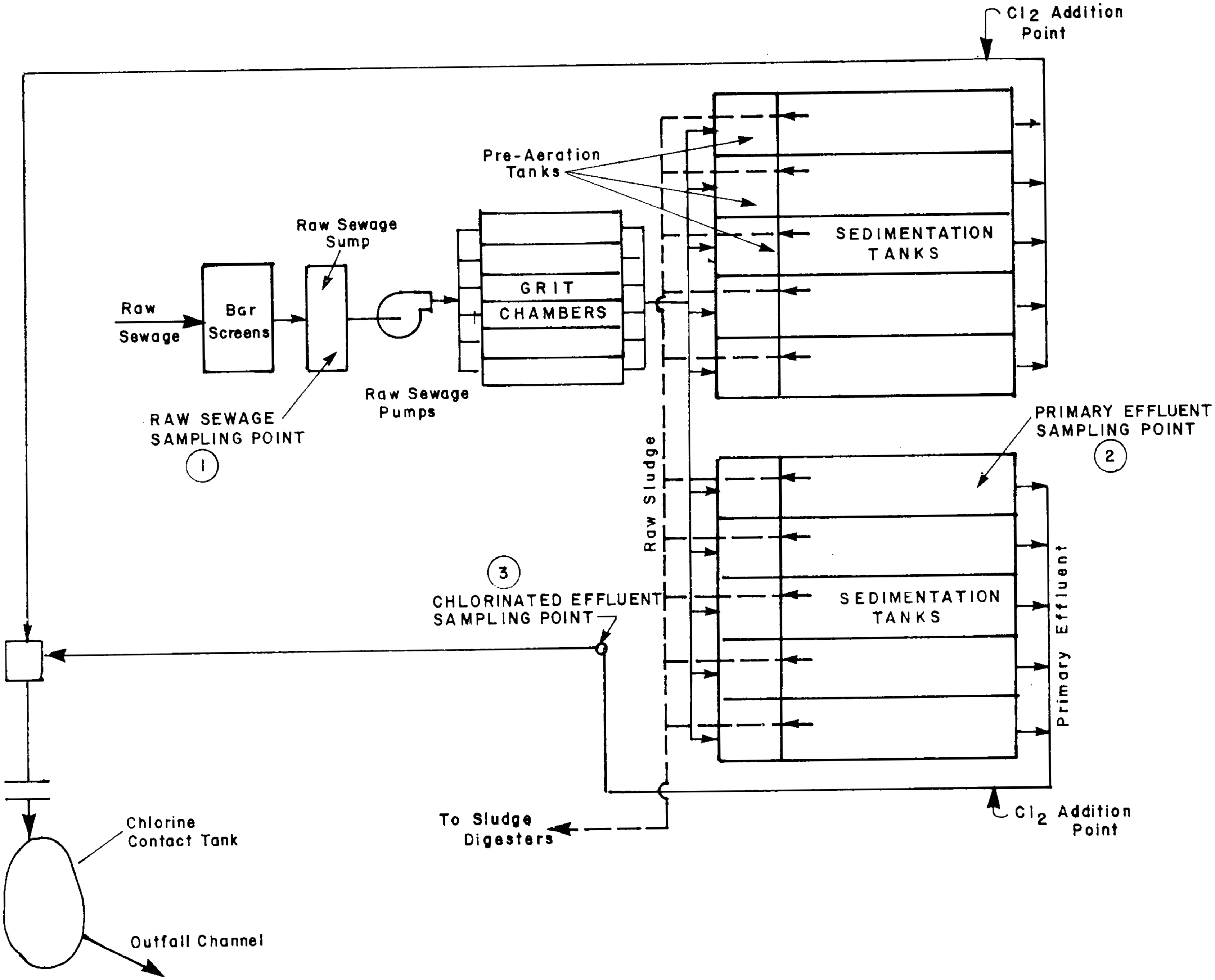

FIGURE 2 IONA ISLAND STP FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

Table 3 OPERATIONAL CHARACTERISTICS OF IONA ISLAND STP

Type of Treatment - Primary Sedimentation

Treatment Components:

1) Comminuting Units (2) Parallel
2) Bar Screens (4) Parallel
3) Raw Sewage (6) Parallel
4) Grit Chambers (6) Parallel
5) Pre-Aeration Tanks (10) Parallel
6) Sedimentation Tanks (10) Parallel
7) Chlorine Contact Tank (1)

Average Dry Weather Flow	=	130 CFS
Peak Dry Weather FLow	=	200 CFS
Peak Wet Weather Flow	=	625 CFS

Average Daily Flow (September 1975 to August 1976)	=	155 CFS
Average Daily Flow August 1976	=	109.6 CFS
Peak Daily FLow October 29, 1975	=	391 CFS
Peak Instantaneous Flowrate December 24, 1975	=	490 CFS

Detention Times at DWF

Grit Chambers	= 0.20 hr
Pre-Aeration Tanks	= 0.55 hr
Primary Sedimentation Tanks	= 1.60 hr
Chlorine Contact Tank	= 1.0 hr
Total	3.35 hr

Sedimentation Tank Overflow (at DWF) = 857 gal/ft^2/day

Raw Sewage Average	BOD	=	133 mg/l
	NFR	=	118 mg/l
	COD	=	230 mg/l

Table 3 (cont'd)

Effluent Average	BOD	=	97 mg/l
	NFR	=	48 mg/l
	COD	=	167 mg/l

Sludge Treatment Components

1) Raw Sludge Pumps 6 Parallel
2) Sludge Thickener 1
3) Disintegrators 2 Parallel
4) Thickened Sludge Pumps 2 Parallel
5) Primary Anaerobic Digesters 2 Parallel
6) Sludge Lagoons 4

TABLE 4 IONA ISLAND STP COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

Sample Points	Collection Date	LC_{50}	Tc	NH_3	Un-ionized NH_3	pH	Anionic Surfactants	Alkalinity	Start Date Bioassay Test
	August	%	TU	mg/l N	mg/l N		mg/l LAS	mg/l LAS	August
Raw Sewage	17	81.5	1.23	15	0.032	6.9	1.5	72	17
	18	62.5	1.60	11	0.029	7.0	2.6	93	18
	19	65	1.54	11	0.023	6.9	2.6	84	20
	20	NT[1]	-	2.4	0.004	6.8	1.9	38	22
Primary Effluent	17	48.5	2.06	10	0.021	6.9	0.57	62	17
	18	86.5	1.16	11	0.023	6.9	1.1	85	18
	19	89	1.12	12	0.025	6.9	0.97	100	22
	20	NT	-	4.4	0.009	6.9	0.49	50	22
Chlorinated Effluent	17	44	2.27	10	0.033	7.1	1.0	54	17
	18	58.5	1.71	11	0.036	7.1	1.1	79	18
	19	NT	-	12	0.031	7.0	0.93	90	22
	20	NT	-	3.6	0.012	7.1	0.63	40	22

1 NT Non-Toxic

in toxicity. As in the case of Annacis, the chlorine induced toxicity is not related to a detectable residual. Composite samples analyzed for TRC prior to the bioassay test indicated the absence of a detectable residual. The actual chlorinated compounds involved could not be determined.

3.0 ACTIVATED SLUDGE TREATMENT PLANTS

Many variations of the activated sludge process such as extended aeration, contact stabilization, high rate and step aeration are used in secondary sewage treatment plants. All basically involve the recirculation of a flocculated biological mass (activated sludge) which converts organic material to cell mass and carbon dioxide. The variations of the activated sludge process differ according to;

1) hydraulic retention time,
2) solids retention time,
3) organic loading,
4) type of mixing,
5) type of aeration,
6) sludge recycle ratio, and
7) method of wastewater introduction.

3.1 Penticton Water Quality Control Center

The Penticton WQCC is a conventional activated sludge sewage treatment plant including a phosphorous removal process utilizing iron salts. A flow sheet of the plant showing treatment components and the sample point locations is shown in Figure 3. The operational characteristics are listed in Table 5. The plant has a design dry weather flow of 1.83 Imp MGD. The actual average daily flow from July 1975 to July 1976 was 1.54 Imp MGD. The sewage is primarily domestic but includes food processing wastes on a seasonal basis. Pickling liquor containing 30% ferrous chloride ($Fe\ Cl_2$) is added to the aeration tanks to accomplish phosphate removal. Based on information provided by the City of Penticton, the treatment plant accomplished a 96% reduction in BOD_5, a 91% reduction in NFR and a 89% reduction in total phosphate over a one year period (July 1975-July 1976).

A summary of the chemical and bioassay results from the field survey is presented in Table 6. Based on these results, the

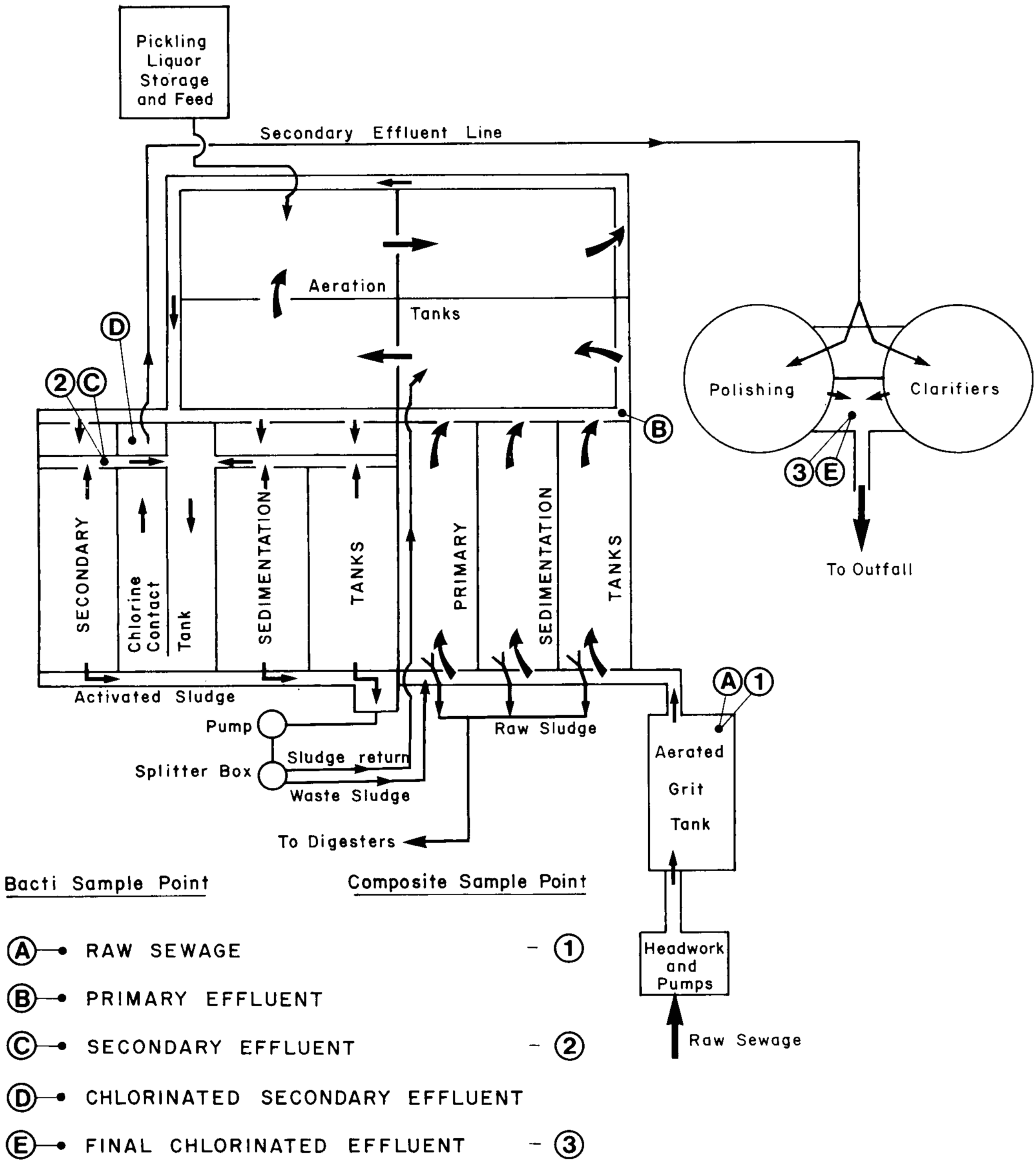

FIGURE 3 CITY OF PENTICTON WATER QUALITY CONTROL CENTER SIMPLIFIED FLOW DIAGRAM AND SAMPLE POINT LOCATION.

TABLE 5 OPERATIONAL CHARACTERISTICS OF PENTICTON WATER QUALITY CONTROL CENTER

Type of Treatment: Conventional Activated Sludge plus Phosphorous Removal and Polishing Clarifier

Treatment Components:
1) Barminutor (1)
2) Raw Sewage Pumps (3) Parallel
3) Aerated Grit Tank (1)
4) Primary Sedimentation Tanks (3) Parallel
5) Aeration Tanks (4) Series
6) Secondary Sedimentation Tanks (3) Parallel
7) Chlorine Contact Tank (1)
8) Polishing Clarifier (2) Parallel

Design Dry Weather Flow = 1.83 Imp MGD

Average Flow (July 1975 - July 1976) = 1.54 Imp MGD
Average Flow (July 1976) = 1.69 Imp MGD

Raw Sewage Average BOD_5 = 240 mg/ℓ
NFR = 180

Primary Effluent Average BOD_5 = 192 (est.)
NFR = 65

Average Mixed Liquor Suspended Solids = 1223 (July 1976)

Aeration Tank Volume = 400,000 Imp gal
= 64,100 cu ft

Food to Microorganisms Ratio F/M = 0.66 lb BOD_5/day·lb MLSS

Volumetric Loading = 50 lb BOD_5/1000 cu ft

Secondary Sedimentation Tank Overflow = 620 gal/ft^2/day

Average Retention Times (July 1976)

Primary Sedimentation	= 1.9 hr
Aeration Tank	= 4.4 hr (30% return sludge flow)
Secondary Sedimentation	= 1.9 hr (30% return sludge flow)
Chlorine Contact Tank	= 0.5 hr
Polishing Clarifier	= 3.5 hr
Total Retention	12.2 hr

Sludge Digestion Components
1) Primary Anaerobic Digester 50,900 cu ft
2) Secondary Anaerobic Digester 50,900 cu ft
3) Sludge Drying Beds 234,000 gal capacity

Chlorinator - Flow Proportional, checked twice daily

Point of Discharge - Okanagan River Channel, adjacent to plant

---

TABLE 6 PENTICTON WQCC COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

Sample Points	Date	LC_{50}	Tc	NH_3	*Un-ionized NH_3	Diss. Cu	Diss. Zn	Alkalinity	Anionic Surfactants
	July	%	TU	mg/ℓ N	mg/ℓ N	mg/ℓ	mg/ℓ	mg/ℓ $CaCO_3$	mg/ℓ LAS
Raw Sewage	20	65	1.50	21	0.24	0.11	0.17	181	4.80
	21	61	1.60	29	0.42	0.09	0.09	176	4.00
	22	57	1.75	22	0.32	0.08	0.20	184	4.30
	23	63	1.59	30	0.18	0.13	0.23	199	4.20
Secondary Effluent	20	87	1.15	21	0.12	0.03	0.19	140	0.70
	21	99	1.00	26	0.24	0.03	0.10	147	0.37
	22	78	1.28	22	0.16	0.03	0.20	154	0.44
	23	87	1.15	27	0.20	0.02	0.18	142	0.34
Final Chlorinated Effluent	20	51	1.96	21	0.12	0.03	0.18	138	0.70
	21	<32	3.13	23	0.17	0.01	0.10	144	0.36
	22	31	3.22	17	0.16	0.02	0.12	145	0.44
	23	49	2.04	24	0.14	0.02	0.37	138	0.54

*According to Emmerson, et al

toxicity concentration (Tc) was reduced from a mean of 1.61 toxic units in the raw sewage to mean of 1.15 toxic units in the secondary effluent, prior to chlorination. This reduction in toxicity was attributed to a decrease in the un-ionized ammonia and anionic surfactant concentrations and possibly to the decrease in copper levels.

The reduction of un-ionized ammonia was accomplished partially by nitrification but mainly by a reduction in pH. The anionic surfactant reduction was attributable to both suspended solids removal in the primary and secondary sedimentation tanks and biological degradation in the aeration tanks.

After chlorination and final clarification the mean toxicity concentration increased to 2.59 toxic units. The chemical composition of the secondary effluent and the final chlorinated effluent was similar. The process of chlorination was responsible for the increase in toxicity. However, the actual chlorinated compounds involved could not be determined as the chlorine residual was non-detectable. Composite samples analyzed for TRC prior to the bioassay test indicated the absence of a detectable residual. This would be expected since the samples were aerated for 24 hours prior to the test.

3.2 Cache Creek Sewage Treatment Plant

The Cache Creek STP is an activated sludge plant with a design capacity of 400,000 Imp GPD. The actual average daily flow from July 1975 to August 1976 was 146,000 Imp GPD. A flow sheet of the plant showing treatment components and the sample point locations is given in Figure 4; the operational characteristics are listed in Table 7. The sewage treated by the plant is primarily domestic. Based on data collected during the survey the treatment plant reduced raw sewage COD, TOC and NFR levels by 49%, 44% and 46% respectively.

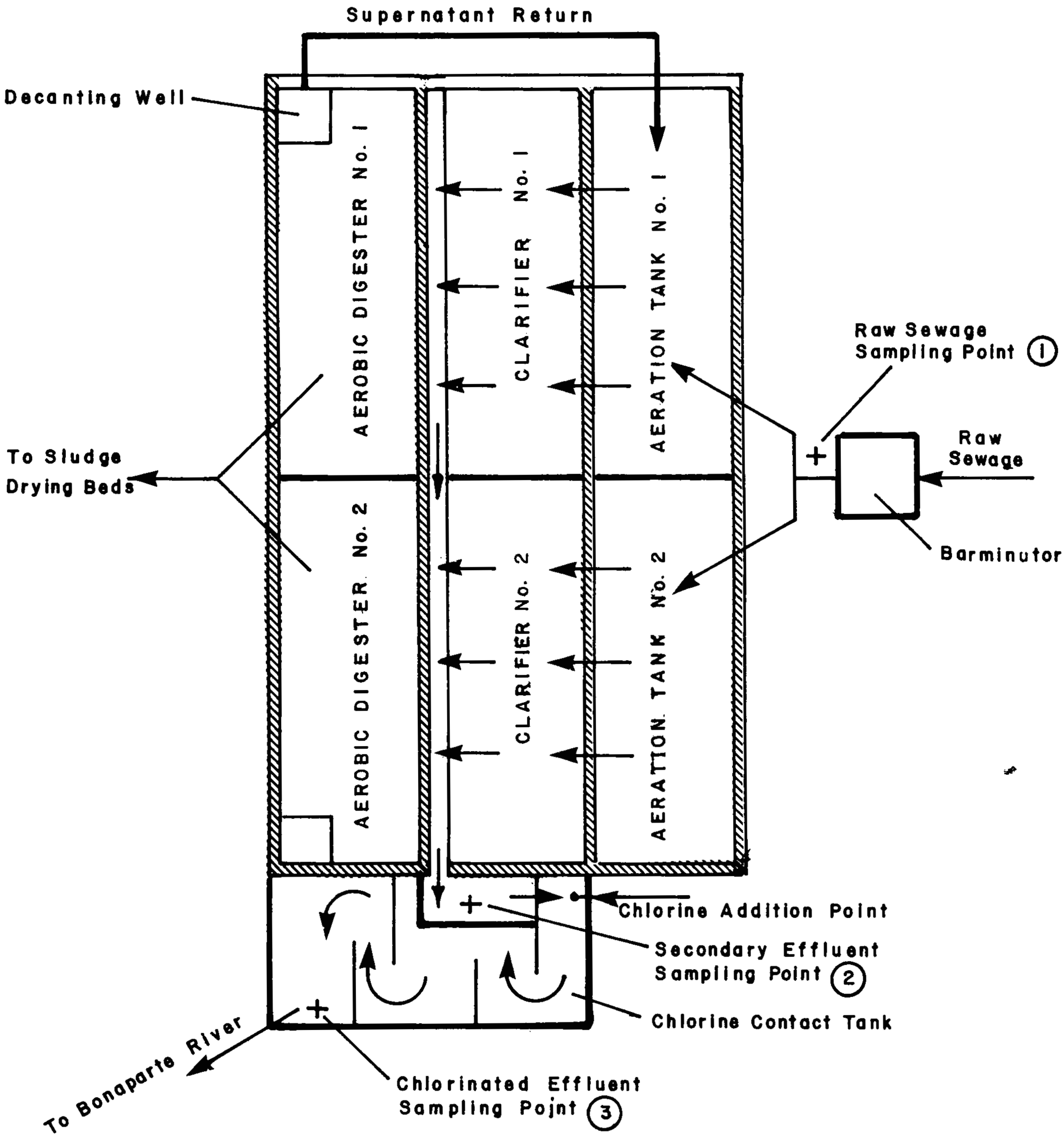

FIGURE 4 CACHE CREEK SEWAGE TREATMENT PLANT FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

TABLE 7 OPERATIONAL CHARACTERISTICS OF THE CACHE CREEK STP

Type of Treatment:		Activated Sludge
Treatment Components:	1.	Raw Sewage Pump
	2.	Barminutor
	3.	Aeration Tanks 2 Parallel
	4.	Clarifiers 2 Parallel
	5.	Chlorine Contact Tank
Design Flow	=	400,000 Imp GPD
Average Flow (July 75 - Aug. 76)	=	146,000 Imp GPD
Average Flow Aug. 76	=	158,900 Imp GPD
Clarifier Design Overflow Rate	=	400 gal/ft^2/day
Design Hydraulic Retention Time	=	3.0 hr (50% recycle)
Design Chlorine Contact Retention	=	20 min.
Aerobic Digesters Capacity	=	12,128 cu.ft.
Chlorinator	-	Manually adjusted checked daily
Point of Discharge	-	Bonaparte River

TABLE 8 CACHE CREEK STP COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

Sample Points	Date	LC_{50}	Tc	NH_3	*Un-ionized NH_3	Anionic Surfactants	Alkalinity	pH
		%	TU	mg/l N	mg/l N	mg/l LAS	mg/l Ca CO_3	
Raw Sewage	Aug 31	32	3.13	33	0.48	4.5	350	7.8
	Sept 1	46	2.17	26	0.48	5.2	320	7.9
	Sept 2	42.5	2.35	31	0.12	6.3	282	7.2
	Sept 3	39.5	2.53	45	0.42	5.1	330	7.6
Secondary Effluent	Aug 31	65	1.54	31	0.57	0.56	270	7.9
	Sept 1	74	1.35	30	0.35	0.53	350	7.7
	Sept 2	65	1.54	27	0.16	0.75	315	7.4
	Sept 3	52.5	1.90	36	0.33	0.18	350	7.6
Chlorinated Effluent	Aug 31	61	1.64	34	0.62	0.58	340	7.9
	Sept 1	87	1.15	36	0.42	0.64	320	7.7
	Sept 2	65	1.54	26	0.24	0.59	317	7.6
	Sept 3	52.5	1.90	37	0.34	2.0	360	7.6

*According to Emmerson, et al

A summary of the chemical and bioassay results from the field survey is presented in Table 8. These results show that the toxicity concentration (Tc) was reduced from a mean of 2.55 toxic units in the raw sewage to 1.58 toxic units in the secondary effluent prior to chlorination. This reduction was attributed to a reduction in the anionic surfactant concentration produced by biological degradation and sedimentation. Ammonia levels remained essentially unchanged by treatment.

Chlorination did not increase effluent toxicity. The chlorine dosage was relatively low averaging 4.3 mg/l during the survey. The low dosage resulted in a non-detectable chlorine residual for most of the 24 hour residual monitoring program. The high effluent solids level (approx. 63 mg/l) would also result in a high chlorine demand and consequently a low residual.

3.3 Mission Pollution Control Center

The Mission PCC is a high rate activated sludge plant with a design dry weather flow of 0.9 Imp MGD, and a design maximum wet weather flow of 3.0 Imp MGD. The actual average daily flow from June 1975 to May 1976 was 0.68 Imp MGD. There are no industrial discharges to the sewer system (the sewage is primarily domestic in origin). Based on data provided by the operator, the treatment plant accomplished BOD_5 and NFR reduction of 83 and 74% respectively over a one year period.

A flow diagram showing treatment components and sample point locations is presented in Figure 5. The operational characteristics of the treatment plant are listed in Table 9.

A summary of the chemical and bioassay results from the field survey is presented in Table 10. An average toxicity concentration

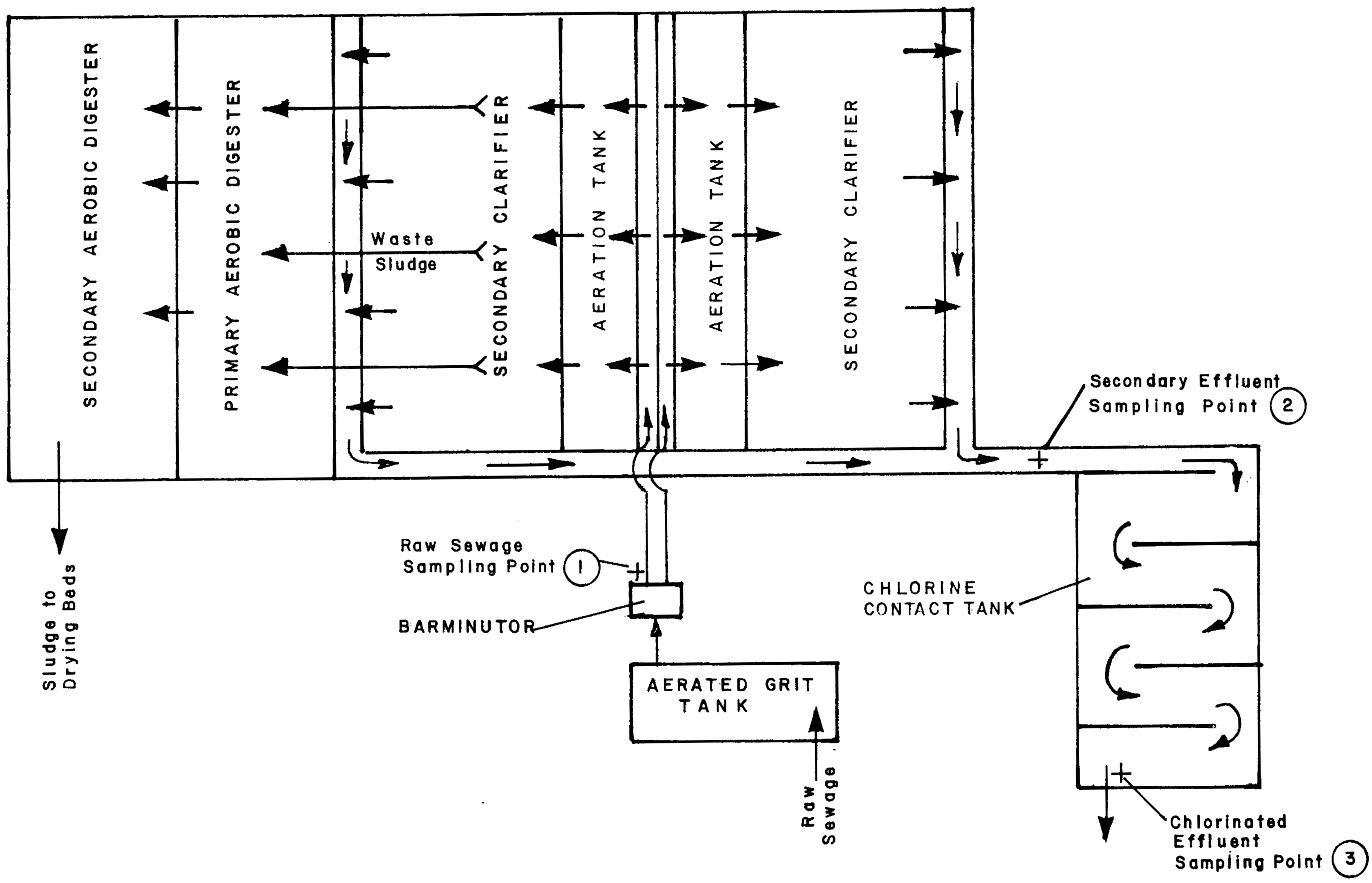

FIGURE 5 MISSION POLLUTION CONTROL CENTRE - FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

TABLE 9

OPERATIONAL CHARACTERISTICS OF THE MISSION PCC

Design Average Dry Weather Flow	0.9 Imp MGD
Design Peak Wet Weather Flow	3.0 Imp MGD

Treatment Components

a) Aerated Degritter
b) Barminutor
c) Aeration Tanks 2 Parallel
d) Secondary Clarifier 2 Parallel
e) Chlorine Contact Tank

Average Flow (June 1, 1975 - May 30, 1976)	=	0.68 Imp MGD
June , 1976	=	0.61 Imp MGD

RETENTION TIMES

	Average DWF	Average Flow (June, 1976)
Degritter Tank	5 min	7.4 min
Aeration Tanks	3 hours	4.4 (excluding recycle)
Secondary Clarifiers	5.8	8.5 (excluding recycle)
Chlorine Contact Tank	0.8	1.2
	9.7 hours	14.2 hours

Raw Sewage Average BOD_5 (June 1975-May 1976)	=	144 mg/l
Average Mixed Liquor Suspended Solids (MLSS)	=	2240 (June, 1976)
Aeration Tank Volume	=	17850 cu ft
Food to Microorganisms Ratio	=	0.35 lb BOD_5/day.lb MLSS

Sludge Digestion Components
1) Primary Aerobic Digester 23,000 cu ft
2) Secondary Aerobic Digester 23,000 cu ft
3) Sludge Drying Beds

Chlorinator - Flow Porportional Control - checked daily

Point of Discharge - Fraser River

TABLE 10 MISSION PCC COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

Sample Points	Date	LC_{50}	Tc	NH_3	Un-Ionized NH_3	Anionic Surfactants	pH	Alkalinity	Pretest Aeration
	July	%	TU	mg/l N	mg/l N	mg/l LAS		mg/l $CaCO_3$	hr
Raw Sewage	6	87	1.15	14	.028	3.9	6.9	130	19
	7	100	1.0	14	.045	2.9	7.1	120	24
	8	+	-	15	.048	3.2	7.1	119	17.5
	9	NT[1]	-	15	.038	3.5	7.0	110	25
Secondary Effluent	6	NT	-	10	.025	0.22	7.0	110	0
	7	NT	-	15	.060	0.11	7.2	130	0
	8	NT	-	14	.045	0.14	7.1	112	17.5
	9	NT	-	18	.057	0.25	7.1	111	25
Chlorinated Effluent	6	NT	-	12	.030	0.13	7.0	110	0
	7	NT	-	22	.110	0.13	7.3	125	0
	8	NT	-	15	.060	0.22	7.2	118	17.5
	9	NT	-	18	.057	0.29	7.1	107	24

\+ LC_{50} not established 33% mortality at 100% concentration

1 NT Non toxic at 100% concentration

cannot be calculated. The July 6 and 7 raw sewage samples exhibited LC_{50}'s of 87 and 100% respectively (Tc = 1.15 & 1.00). The July 8 raw sewage sample produced 33% mortality at the 100% concentration, in other words a Tc less than 1.00. The July 9 raw sewage sample was non-toxic at 100%. All the secondary effluent samples were non-toxic at 100%; attributable to a reduction in the anionic surfactant concentration from 3.38 to 0.18 mg/l LAS.

It is apparent that the raw sewage contains a significant amount of ground water from infiltration. This in turn has diluted the concentration of ammonia and surfactants in the raw sewage and produced results where the influent is only marginally toxic.

Chlorination did not influence the bioassay results. The TRC's of the chlorinated samples were non-detectable for 50% of the time during the chlorine residual monitoring program.

3.4 Prince George Sewage Treatment Plant

The Prince George STP is a high rate activated sludge plant with a design dry weather flow of 5.0 Imp MGD. The actual average daily flow from October 1975 to September 1976 was 3.2 Imp MGD. There are no major industrial discharges to the sewer system; the sewage is primarily domestic with an approximate 5% contribution from small service industries. Based on the results of a 24 hour sampling program conducted by the City of Prince George Engineering staff, the treatment plant accomplished an 87.5% reduction in BOD_5, a 83.3% reduction in COD and a 94.8% reduction in NFR over a 24 hour period just prior to the EPS survey. The operational characteristics of the treatment plant are listed in Table 11.

A summary of the chemical and bioassay results from the EPS field survey is presented in Table 12. A flow diagram showing treatment components and sampling points is given in Figure 6. The results

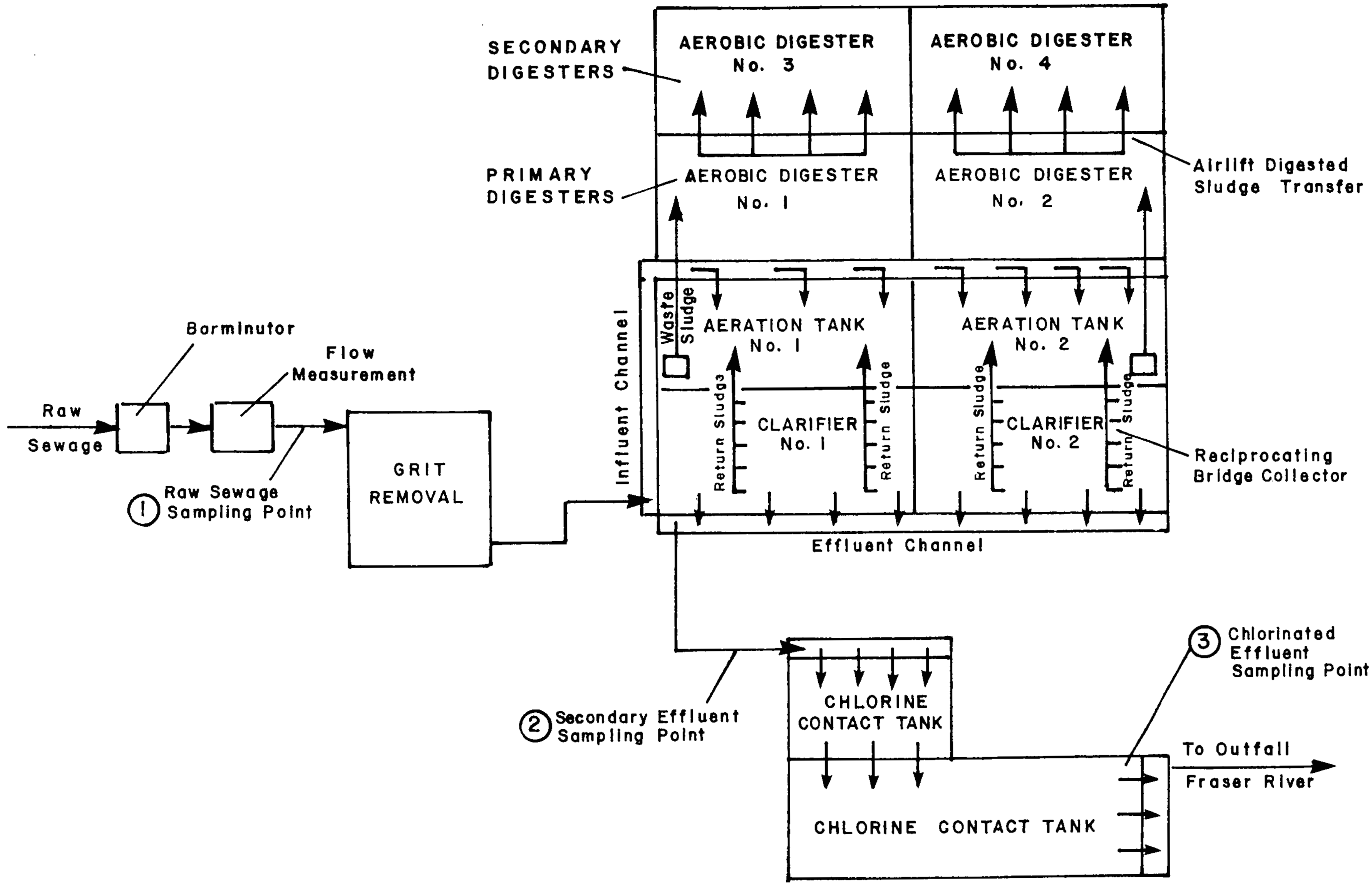

FIGURE 6 PRINCE GEORGE SEWAGE TREATMENT PLANT - FLOW DIAGRAM AND SAMPLE STATION LOCATIONS

TABLE 11 OPERATIONAL CHARACTERISTICS OF THE PRINCE GEORGE STP

Type of Treatment : High Rate Activated Sludge

Treatment Components :
1) Bar Screens
2) Barminutor (2) Parallel
3) Grit Removal Tank (1)
4) Aeration Tanks (2) Parallel
5) Clarifiers (2) Parallel
6) Chlorine Contact Tanks (2) Series

Average Design Flow = 5.0 Imp MGD

Average Flow (October 1975 - September 1976) = 3.20 Imp MGD
Average Flow (September 1976) = 3.19 Imp MGD

Raw Sewage BOD_5 = 132 mg/l
NFR = 137.5 mg/l

Average Mixed Liquor Suspended Solids	= 2800 mg/l (Sept 1976)
Aeration Tank Volume	= 84,000 cu.ft.
Food to Microorganisms Ratio F/M	= 0.29 lb BOD_5/day . lb MLSS
Volumetric Loading	= 50 lb BOD_5/1000 cu.ft.
Secondary Clarifier Overflow Rate	= 222 Imp gal/sq.ft./day
Return Sludge Rate, Percent of Flow	= 235%
Average Retention Times (Sept 1976)	
Grit Tank	= 0.30 hr
Aeration Tank	= 1.20 hr (includes recycle)
Secondary Clarifier	= 2.00 hr (includes recycle)
Chlorine Contact Tanks	= 1.50 hr
	5.00 hr

Sludge Digestion Primary Aerobic Digesters = 84,000 cu.ft.
Secondary Aerobic Digesters = 144,000 cu.ft.

Chlorination - Flow Proportional

Point of Discharge - Fraser River

TABLE 12

PRINCE GEORGE STP

COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

SAMPLE POINTS	DATE	LC_{50}	Tc	NH_3	Un-Ionized NH_3	Anionic Surfactants	Alkalinity
	Sept	%	TU	mg/1N	mg/1 N	mg/1 LAS	mg/1 $CaCO_3$
Raw Sewage	14	48.5	2.06	15	0.12	5.4	240
	15	65	1.54	25	0.25	4.5	250
	16	40 *	2.50 *	15	0.15	5.1	240
	17	32 *	3.13 *	20	0.10	5.1	230
Secondary Effluent	14	NT	-	5	0.002	0.38	60
	15	NT	-	17	0.108	0.22	150
	16	NT *	-	5.6	0.03	0.24	140
	17	- *	-	6	0.03	0.24	150
Chlorinated Effluent	14	NT	-	7	0.06	0.58	150
	15	NT	-	10	0.04	0.30	140
	16	NT *	-	4.8	0.03	0.36	140
	17	55 *	1.82 *	6	0.02	0.26	130

* Control Mortalities	Sept 16	40%
	Sept 17	60%

obtained from September 16 and 17 will be ignored because of the control mortalities. The remaining results indicate that high rate activated sludge treatment is capable of producing a non-toxic effluent. The mean toxicity concentration of the raw sewage was 1.80 toxic units while the secondary effluent and chlorinated effluent samples were non-toxic. Most of the toxicity associated with the raw sewage could be attributed to the anionic surfactant concentration (mean of 4.95 mg/l LAS). The un-ionized ammonia content (mean of 0.19 mg/l N) could also be expected to influence the toxicity. Activated sludge treatment reduced the anionic surfactant concentration to a mean of 0.30 mg/l LAS, this decrease is attributable to sedimentation and biological degradation. The treatment systems also reduced the total ammonia and un-ionized ammonia concentrations (20 to 14 mg/l N and 0.19 to 0.06 mg/l N respectively); which would result in a reduction of toxicity.

Chlorination did not result in any increase in toxicity. The chlorine dosage averaged 5.5 mg/l during the survey and the TRC of the chlorinated effluent average 0.82 mg/l during the chlorine residual monitoring program. The elimination of chlorine induced toxicity could be credited to the following factors:

1) the high quality effluent (NFR 10 mg/l, TOC 18 mg/l, NH_3 7 mg/l) could result in a reduced persistence of chlorine
2) the bioassay samples were aerated for 19 hours prior to the determination, insuring complete dissipation of chlorine and chloramines.

4.0 LAGOON TREATMENT SYSTEMS

Lagoon treatment processes depend upon the use of bacterial action to degrade organic material. Lagoon systems can either employ natural oxygenation through the growth of green algae and surface oxygen transfer or they can employ mechanical aeration using either surface aerators or submerged air diffusers. Lagoon processes utilize relatively long retention times to accomplish waste stabilization (1 - 3 months retention for some lagoon systems as compared to 4 - 6 hours for conventional activated sludge plants). Sewage lagoons are classified as being either aerobic, anaerobic, or facultative, depending on organic loading and the presence or lack of dissolved oxygen.

4.1 Williams Lake Sewage Treatment Lagoons

The Williams Lake sewage lagoons are comprised of two parallel anaerobic lagoons, an aerated lagoon, and a final settling lagoon. The anaerobic lagoons are operated alternately. At the average daily flowrate during July 1976 of 280,000 Imp GPD the retention times for the anaerobic, aerated and final settling lagoons were 13, 61, and 31 days respectively for a total of 105 days. Daily flowrates for the period of August 1, 1975 to July 31, 1976 had a range of 200,000 to 320,00 Imp GPD. Based on data collected during the survey the sewage lagoons accomplished a 64% reduction in COD, a 73% reduction in TOC, a 70% reduction in NFR and a 99% reduction in NH_3. The sewage treated by the lagoons was primarily domestic in origin. A flow diagram including the sampling points is given in Figure 7.

A summary of the chemical and bioassay results from the field survey is presented in Table 13. The results indicate that this lagoon treatment system produces a non-toxic effluent. The mean toxicity concentration of the raw sewage was 2.06 toxic units while the final effluent and the chlorinated final effluent samples were non-toxic.

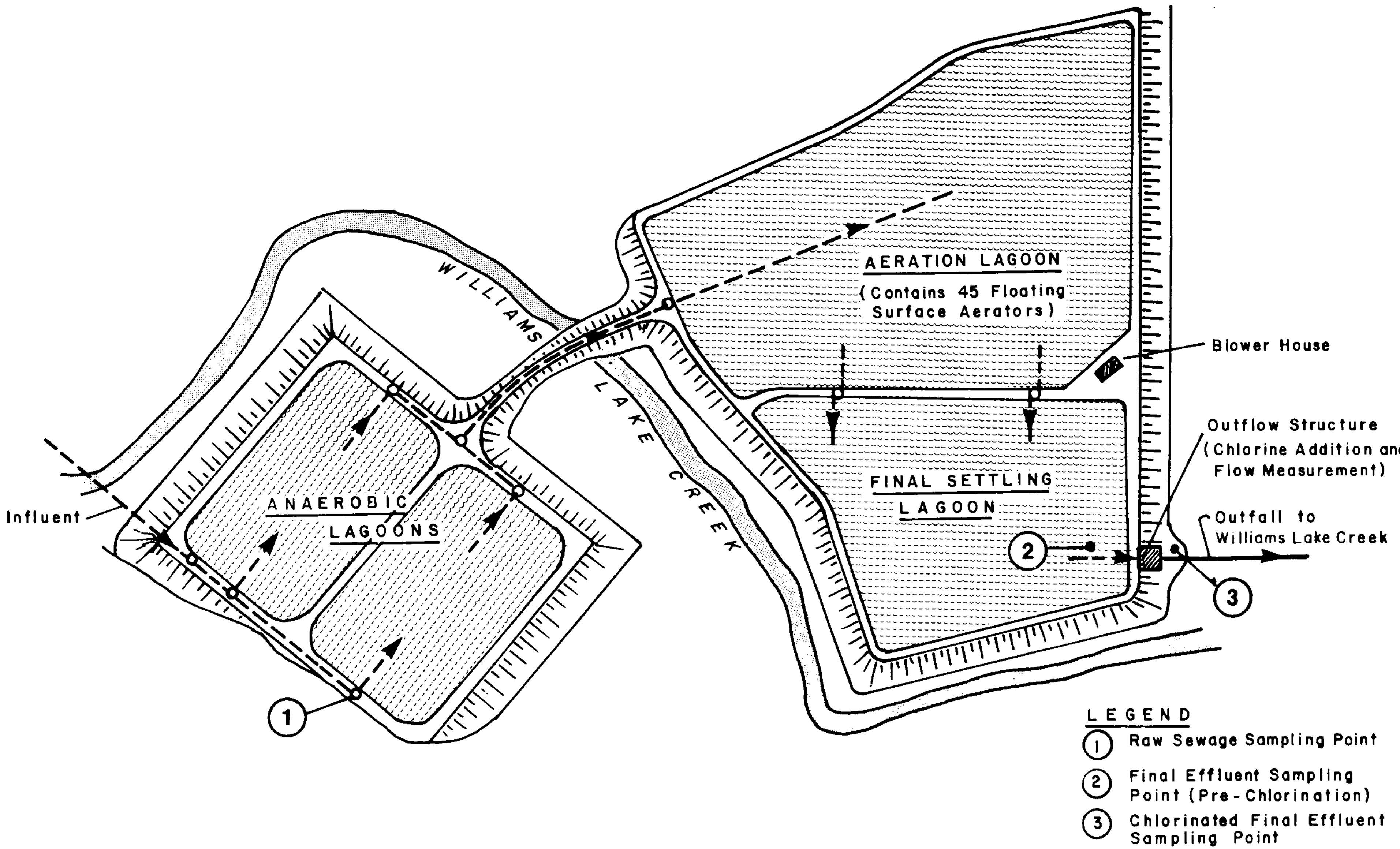

FIGURE 7 WILLIAMS LAKE-SEWAGE TREATMENT LAGOONS, FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

The toxicity of the raw sewage would be attributable to the anionic surfactant and un-ionized ammonia concentrations. The lagoon process reduced the anionic surfactant concentration to a mean of 0.2 mg/l LAS; attributable to sedimentation and biological degradation. The lagoons accomplished virtually complete nitrification (total ammonia 16.5 to 0.16 mg/l N) which would also result in a reduction in toxicity.

Chlorination did not result in any increase in toxicity.

However, during the chlorine residual monitoring program the TRC of the effluent was maintained at either a very low or non-detectable level. Chlorination in this case would not be expected to influence toxicity. The elimination of chlorine induced toxicity could be credited to:

1) the high quality effluent (NFR 22 mg/l, TOC 20 mg/l) should result in reduced persistence of chlorine
2) the bioassay samples were stored for between 48 and 72 hours prior to initiation of the test insuring complete dissipation of chlorine.

4.2 Clinton Sewage Treatment Lagoons

The Clinton sewage lagoons are comprised of two parallel anaerobic lagoons, a facultative lagoon and an aerobic lagoon. A flow diagram showing treatment components and sample point locations is given in Figure 8. At the design flowrate of 100,000 Imp GPD, the anaerobic, facultative and aerobic lagoons have retention times of 10, 43 and 84 days for total of 137 days. Flow records are not available. The actual flow was estimated at 45 - 50,000 during the survey. Sewage treated by the lagoons is primarily domestic in origin. Based on data collected during the survey, the sewage lagoons accomplished a 68% reduction in COD, and 69% reduction in TOC, a 90% reduction in NFR and a 82% reduction in ammonia.

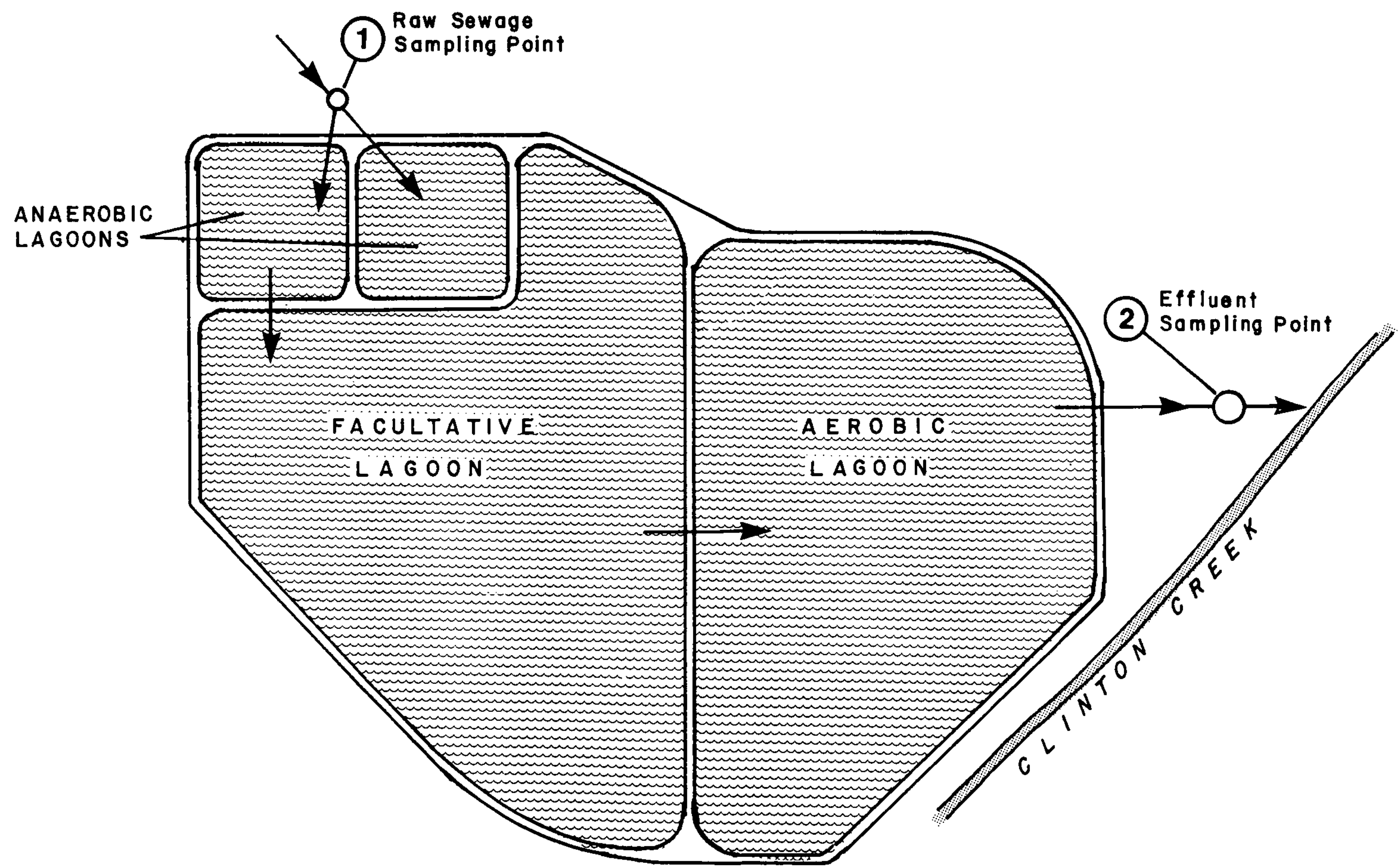

FIGURE 8 VILLAGE OF CLINTON - SEWAGE TREATMENT LAGOONS, FLOW DIAGRAM AND SAMPLE POINT LOCATIONS

A summary of the chemical and bioassay results from the field survey is presented in Table 13. The results indicated that this treatment system produced a non-toxic effluent. The mean toxicity concentration of the raw sewage was 2.22 toxic units; attributable to the anionic surfactant concentration and to some extent the un-ionized ammonia level. The lagoon process reduced the anionic surfactant concentration to a mean of 0.29 mg/l LAS and the ammonia concentration from 9.1 to 0.82 mg/l N.

TABLE 13 CLINTON AND WILLIAMS LAKE SEWAGE TREATMENT LAGOONS COMPARISON OF CHEMICAL AND BIOASSAY RESULTS

	Sample Points	Date	LC_{50}	T_c	NH_3	Un-Ionized NH_3	Anionic Surfactants	Total Alkalinity	pH	Pre-test Aeration
		August	%	TU	mg/l N	mg/l N	mg/l LAS	mg/l $CaCO_3$		hr.
Clinton Sewage Treatment Lagoons	Raw Sewage	4	60.5	1.65	9.7	0.13	3.5	330	7.7	18
		5	36.0	2.78	8.5	0.12	6.4	326	7.7	21.5
	Final Effluent	4	NT[1]	-	1.5	0.05	0.42	510	8.1	18
		5	NT	-	1.8	0.07	0.16	514	8.2	21.5
Williams Lake Sewage Treatment Lagoons	Raw Sewage	10	48	2.08	14.0	0.22	4.6	500	7.9	-
		11	49	2.04	19.0	0.15	6.4	500	7.6	-
	Final Effluent	10	NT	-	0.12	0.007	0.10	390	8.5	-
		11	NT	-	0.20	0.008	0.30	400	8.3	-
	Chlorinated Final Effluent	10	NT	-	0.12	0.007	0.11	390	8.5	-
		11	NT	-	0.17	0.007	0.15	390	8.3	-

NT[1] Non toxic (no mortalities at 100% concentration)

5 OBSERVATIONS

5.1 Control of Toxicity

The toxicity of municipal effluents can be reduced either through removal of toxic constituents at source, or by effective sewage treatment design and operation. Source control programs would not apply to domestic wastewater since the common toxic agents, ammonia and surfactants, are generally unavoidable. However, source control could reduce toxicity associated with a particular industrial discharge to a municipal system.

In regards to sewage treatment, it is obvious that primary sedimentation does not reduce toxicity. Biological treatment with activated sludge or lagoon systems can, however, produce non-toxic effluents. Lagoon systems are capable of reducing both ammonia and surfactants to non-toxic levels, whereas activated sludge systems are easily capable of reducing surfactant concentrations but may not necessarily accomplish nitrification. Of the activated sludge plants investigated, only the Prince George STP produced a significant degree of nitrification.

The process of chlorination generally adds toxicity to a wastewater. It would appear, however, that a relationship exists between chlorine induced toxicity and ammonia, in that reduced concentrations of ammonia result in a reduced persistence of chlorinated compounds and hence, reduced toxicity. This again points to need for a nitrified effluent. Chlorine induced toxicity could also be reduced in some cases by reducing the TRC level to that required by the effluent regulations.

5.2 Chlorination Design

Initial Mixing

Many investigators have shown that thorough mixing of chlorine solution in the bulk wastewater produces greatly enhanced disinfection. Extreme turbulence breaks up clumps of microorganisms - enabling more effective disinfection. In addition, good initial mixing is required to maximize the use of fresh chlorine residual and avoid residual "poisoning" from back mixing (Tonelli).

Detention Time

Chlorine contact tanks should be designed to develop plug flow characteristics. A length : width ratio of 40:1 or greater has been recommended to develop full plug flow characteristics.

Process Control

Manual control provides the crudest level of control and sometimes results in gross overdosing and underdosing some of the time.

Flow proportional devices offer the possibility of much better control. These devices cannot, however, compensate for changes in chlorine demand. If the control is based on peak demand some overdosing will occur.

The most complex system is compound loop control which utilizes one or more amperometric residual analyzer controllers and a flow proportional device. These systems are not generally suitable for small plants. Reliable chlorination control equipment should be developed for small plants. Many chlorine contact systems investigated in this report suffer from one or more of the design faults discussed above.

Therefore, in regard to chlorination it is suggested that:

1) the practice of chlorination should be eliminated where a health

hazard does not exist in the zone of influence of the discharge.

2) chlorine contact design should produce plug flow characteristics with good initial mixing.
3) consideration should be given to modifying existing chlorination facilities so as to improve disinfection and reduce chlorine consumption,
4) in site specific cases where both disinfection and protection of a fisheries resource is required, chlorinated effluent should be dechlorinated prior to discharge.

5.3 Bioassay Procedure

The determination of wastewater toxicity using LC_{50} measurements should be replaced with a simpler test such as the determination of a mean survival time. It would also be advantageous to use a test applicable to field situations to reduce delays in initiating the test. If, however, the LC_{50} measurement is retained, the length of time from sample collection to the start of the bioassay test should be reduced. Samples for chemical analysis should be taken from the same container and under the same conditions as the bioassay so as to produce a reasonable correlation between results.

5.4 Plant Operation and Process Reliability

Plants operating poorly and discharging high levels of solids and organic material are not necessarily producing toxic effluents. Surfactants are easily degraded by biological activity, plus other factors such as a dilute sewage can outweigh plant operation problems.

However, many existing activated sludge plants can reduce effluent toxicity through process modification and improved plant operation. As mentioned previously, nitrification is influenced by solids retention time; it is recommended, therefore, that existing treatment plants attempt to increase SRT to a maximum, depending on the limits imposed by clarifier solids handling capibility and on sludge recycle capacity.

5.5.1 Annacis Island STP

The 1976 EPS survey was conducted prior to connection of the Burnaby South Slope and the New Westminster Interceptors to the sewer system. A second survey is required to assess the influence of these discharges. In addition, due to problems with control mortalities it was difficult to determine the precise relationship between dechlorination and toxicity reduction. This relationship should be established by taking sufficient samples to make the results statistical valid.

5.5.2 Alternative Treatment Processes

The treatment processes of oxidation ditch, rotating biological contactor and extend aeration could be investigated to determine the degree of toxicity reduction involved with each type. Particular emphasize should be placed on processes capable of producing a nitrified effluent.

5.5.3 Cold Weather Operation

Consideration should be given to re-surveying some of the treatment plants covered in this report during cold weather periods. Since the biological reaction rates, responsible for the degradation of ammonia and surfactants, tend to decrease at low operating temperature conditions.

5.5.4 Chlorination

A thorough review of chlorination practices in the Pacific Region is required as to:

1) eliminate chlorination where not required for health protection,
2) investigate the degree of disinfection accomplished by different treatment processes,
3) promote dechlorination to protect fisheries resources,
4) improve chlorination systems design and operation, and
5) promote process modifications to improve disinfection, control residuals, and reduce chlorine consumption.

SELECTED REFERENCES

1. Emmerson, K., R. C. Russo, R. E. Lund, and R. V. Thurston, "Aqueous Ammonia Equilibrium Calculations: Effects of pH and Temperature", J. Fish. Res. Board Can. 32, 1975.

2. Mayo, R. D., P. B. Liao, and W. G. Williams, "A Study for Development of Fish Hatchery Water Treatment Systems", U.S. Bureau of Sport Fisheries and Wildlife, Seattle, 1972.

3. Notes on Water Pollution No. 63, Department of the Environment, UK, H.M.S.O., 1973.

4. Lloyd, R. and L. D. Orr, "The Diuretic Response by Rainbow Trout to Sublethal Concentration of NH_3", Water Research 3(5), 1969.

5. Esvelt, L. A., W. J. Kaufman and R. E. Selleck, "Toxicity Removal from Municipal Wastewater",SERL Rept. No. 71-7 San. Eng. Res. Lab., Univ. of California, Berkeley, 1971.

6. Water Quality Criteria. A Report of the Committee on Water Quality Criteria, Environmental Protection Agency, Washington, D.C., 1972.

7. Thatcher, T. O. and J. F. Santner, "Acute Toxicity of LAS to Various Fish Species", Purdue Univ. Eng. Bull. Ext. Ser. 121, 1966.

8. Dolan, J. M. and A. C. Hendricks, "The Lethality of an Intact & Degraded LAS Mixture to Bluegill Sunfish & a Snail", J. Water Pollut. Contr. Fed. 48(11), 1976.

9. Martens, D. W. and J. A. Servizi, "Acute Toxicity of Municipal Sewage to Fingerling Salmon", Int. Pac. Salmon Fish. Comm. Prog. Rept. No. 29, 1974.

10. Merkens, J. C., "Studies on the Toxicity of Chlorine and Chloramines to the Rainbow Trout", J. Water and Waste Treatment No. 7, 1958.

11. Tonelli, F. A., "Wastewater Disinfection", Technology Transfer Seminar on High Quality Effluents, Canada - Ontario Agreement on Great Lakes Water Quality, March, 1976.

12. Sutton, P. M. and B. E. Jank, "Design Considerations for Biological Carbon Removal - Nitrification Systems", Technology Transfer Seminar on High Quality Effluents, Canada - Ontario Agreement on Great Lakes Water Quality, March, 1976.

13. U.S.E.P.A., "Upgrading Existing Wastewater Treatment Plants", Process Design Manual, 1974.