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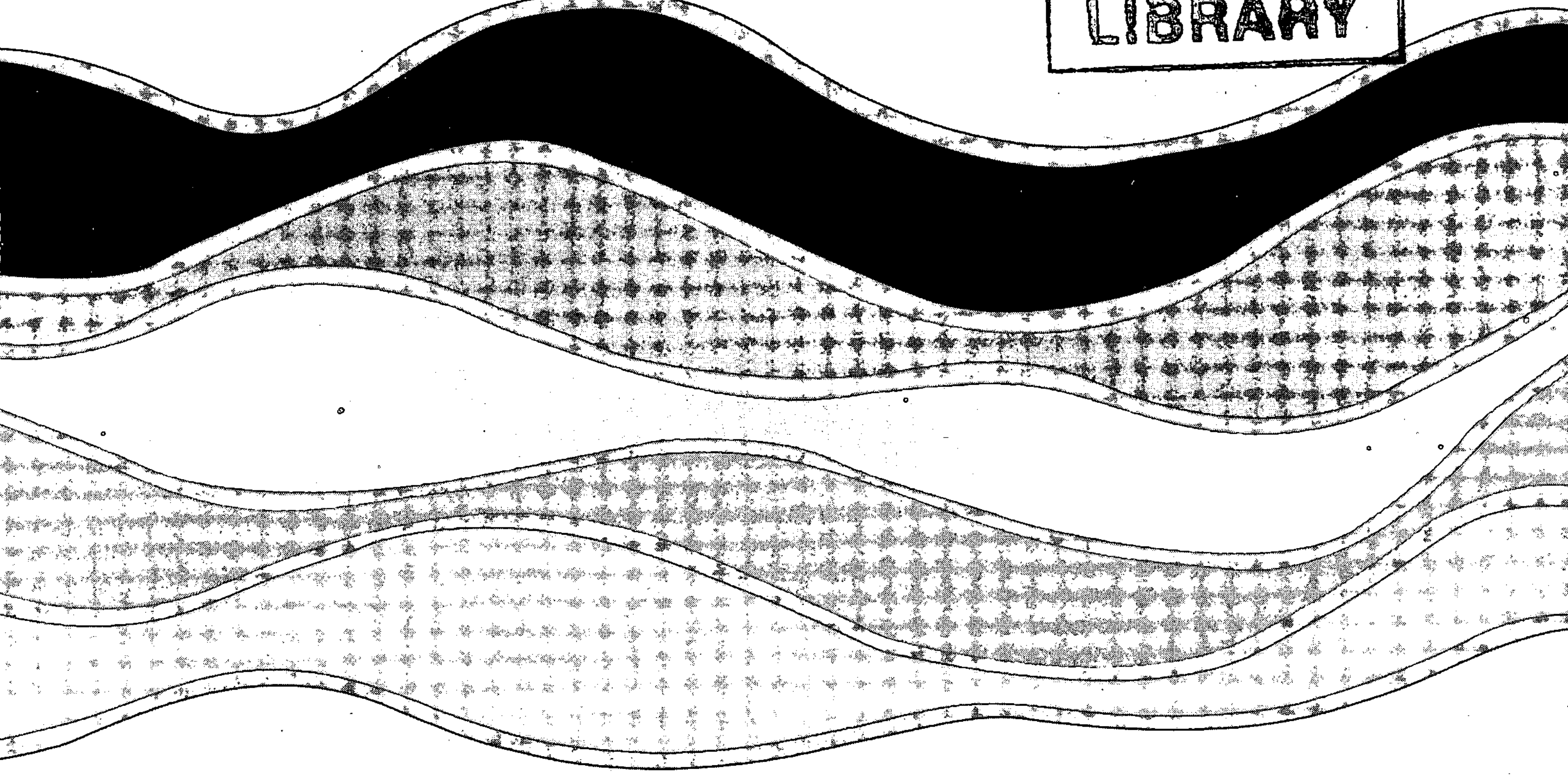

URBAN IMPACTS ON BACTERIOLOGICAL POLLUTION OF THE ST. CLAIR RIVER IN SARNIA: SOURCES AND CLEANUP

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Preface

The Cleanup Fund is one of three programs (the other two being Preservation and Health Effects) of the Federal Government's Great Lakes Action Plan. The Cleanup Fund provides resources to develop and demonstrate technologies and remedial programs to meet federal responsibilities in the Canadian Areas of Concern.

The report that follows was sponsored by the Great Lakes Action Plan Cleanup Fund and addressed water quality issues in one of the Canadian Areas of Concern, the St. Clair River in Sarnia, Ontario. Although the report was subject to technical review, it does not necessarily reflect the views of the Cleanup Fund or Environment Canada.

MANAGEMENT PERSPECTIVE

The closing of swimming beaches, caused by fecal bacteria contamination, is one of the most common water use impairments caused by urban pollution. Such incidents are particularly frequent in urban areas with combined sewer overflows. The report that follows addresses this problem in one of the areas of concern in the Great Lakes Basin, the St. Clair River in Sarnia, Ontario. The report presents a methodology proposed for the assessment of bacteriological contamination of the receiving waters, and evaluation of contamination sources and transport modes. This methodology comprises field observations of indicator microorganisms in the receiving waters and source discharges, simulation of bacterial loads by a loading model, and simulation of transport in the receiving waters.

This report will assist the St. Clair River Remedial Action Plan Team in their environmental planning and should be of interest to others dealing with the assessment of fecal bacteria pollution of receiving waters due to urban sources.

SOMMAIRE À L'INTENTION DE LA DIRECTION

La fermeture des plages à la baignade, par suite d'une contamination bactérienne fécale, constitue l'une des formes les plus courantes de perte d'utilité de l'eau attribuable à la pollution urbaine. Les problèmes de ce genre sont particulièrement fréquents dans les secteurs urbains où existent des égouts évacuateurs unitaires. Le présent rapport traite de ce problème dans l'un des secteurs préoccupants du bassin des Grands Lacs, soit la rivière Sainte-Claire à Sarnia, Ontario. Ce rapport fait état d'une méthode proposée d'évaluation de la contamination bactérienne des plans d'eau récepteurs et de l'évaluation des sources de contamination ainsi que des modes de transport. La méthode comprend des observations sur le terrain de micro-organismes indicateurs dans les plans d'eau récepteurs et les points de rejet, la simulation des charges bactériennes par un modèle et la simulation du transport dans les plans d'eau récepteurs.

Ce rapport aidera l'équipe responsable du plan de mesures correctrices de la rivière Sainte-Claire à planifier ses interventions environnementales; il devrait avoir de l'intérêt pour d'autres personnes concernées par l'évaluation de la pollution bactérienne fécale des plans d'eau récepteurs, qui est attribuable à des sources urbaines.

ABSTRACT

The urban impacts on fecal bacteria pollution of the near-shore zone of the St. Clair River in Sarnia were studied by means of field observations and computer modelling. Toward this end, 14 sampling stations were established in the study area and served for observing fecal coliform, fecal streptococci, E. coli, Pseudomonas aeruginosa and coliphage in the river and in discharges from several sources. Distributions of the observed microorganism densities were used to assess the levels of fecal bacteria pollution and to evaluate compliance with the Canadian Recreational Water Quality Guidelines recommending a limiting value of 100 fecal coliform/100 mL. The upper reach of the river exhibited good water quality with low fecal bacteria densities and probabilities of compliance with the guidelines greater than 80%. The worst fecal bacteria contamination was observed at the downstream end of the Sarnia Waterfront where the probability of compliance was about 1%. Below the waterfront, the water quality somewhat recovered probably by the mixing and dilution of sewer outfall plumes.

For modelling purposes, a fecal bacteria loading model was developed and interfaced with a receiving water model. The loading model comprised an urban runoff/combined sewer overflow (CSO) generator coupled with a water quality rating curve, which was fitted to the observed data on indicator bacteria. Simulations with the receiving water model indicated that in the main river channel, the advective transport clearly prevailed and led to a fast flushing of the channel, The Government Harbour and Sarnia Bay, different transport conditions were observed - much weaker advection and longer flushing times. Consequently, in these bodies, wet weather impacts may persist from 10 to 20 hours after the cessation of runoff.

A preliminary analysis of remedial measures indicated the need to prioritize such measures according to the water uses in various sections of the receiving waters and sources of bacterial contamination. In terms of recreational water uses, the highest

ranking was assigned to Sarnia Bay followed by the water front. Among the sources, the highest priority should be assigned to pollutional discharges occurring in dry weather, caused by cross-connections or malfunctions in the sewer systems, followed by combined sewer overflows, and stormwater.

RÉSUMÉ

Les effets de la pollution bactérienne fécale d'origine urbaine sur la zone riveraine de la rivière Sainte-Claire à Sarnia, ont été étudiés par observation sur le terrain et modélisation informatique. À cette fin, 14 stations d'échantillonnage ont été déterminées dans la région d'étude et ont servi à l'observation des concentrations de coliformes fécaux, de streptocoques fécaux, d'*E. coli*, de *Pseudomonas aeruginosa* et de coliphages dans l'eau de la rivière et dans les rejets provenant de différentes sources. La distribution des densités observées de micro-organismes a servi à l'évaluation de l'importance de la pollution bactérienne fécale et à l'évaluation du respect des recommandations au sujet de la qualité des eaux utilisées à des fins récréatives au Canada, dont la limite a été fixée à 100 coliformes fécaux par 100 mL d'eau. Dans le cours supérieur de la rivière, l'eau était de bonne qualité, la densité des bactéries d'origine fécale était basse et les probabilités du respect des directives étaient supérieures à 80 %. La pire contamination bactérienne d'origine fécale a été observée du côté situé en aval du secteur riverain de Sarnia, où la probabilité du respect des directives était d'environ 1 %. En aval du secteur riverain, la qualité de l'eau s'améliore quelque peu; cela est probablement attribuable au mélange et à la dilution de l'eau de l'exutoire.

Afin de pouvoir procéder à des modélisations, un modèle de charge bactérienne fécale a été mis au point et combiné à un modèle de plans d'eau récepteurs. Le modèle de charge comprend une source de ruissellement urbain et d'égouts évacuateurs unitaires, et il comprend une courbe représentant la qualité de l'eau qui a été ajustée aux données d'observation sur les bactéries indicatrices. Les simulations faites avec le modèle des plans d'eau récepteurs indiquent que dans le chenal principal de la rivière, le transport par advection constitue le mécanisme dominant et qu'il exerce une action de chasse. Dans le port du gouvernement et dans la baie Sarnia, des conditions différentes de transport ont été observées : il y avait beaucoup moins d'advection et le temps de renouvellement de l'eau était plus long. Par conséquent, dans ces plans d'eau, l'effet des précipitations peut persister dix à vingt heures après la fin des précipitations.

Une analyse préliminaire des mesures correctrices indique la nécessité de procéder à un établissement des priorités des mesures afin de tenir compte des utilisations de l'eau dans les différents secteurs des plans d'eau récepteurs et selon les sources de contamination bactérienne. Pour ce qui est des activités récréatives, la baie Sarnia obtenait la plus grande priorité; elle était suivie par le secteur riverain. Quant aux sources, la plus grande priorité devrait être attribuée aux rejets de matières polluantes par temps sec qui sont attribuables à des raccordements ou au mauvais fonctionnement des réseaux d'égout; viennent ensuite les égouts évacuateurs unitaires et le rejet des eaux de pluie.

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1. INTRODUCTION

1.1 Background

Environmental conditions in the Upper Great Lakes Connecting Channels were investigated in the Upper Great Lakes Connecting Channels Study (UGLCCS) from 1983 to 1988 (UGLCCS, 1988). The main objectives of this study were to assess the environmental quality of the Detroit, St. Marys and St. Clair Rivers, and Lake St. Clair; identify and assess the major sources of contamination of these waters; and, recommend actions to ensure the remediation and protection of these waters. In the assessment of contamination, the UGLCCS identified fecal pollution as one of the contaminants of concern contributing to the impairment of water uses of all the three rivers. These concerns are particularly serious in view of the ongoing use of these rivers for such purposes as drinking water supply, swimming, boating/sailing, and commercial and sport fishing (UGLCCS, 1988).

The UGLCC Study also identified the sources of contamination, including combined sewer overflows (CSOs) and urban runoff. While the CSOs were classified as major contaminant sources, urban runoff was classified as a locally significant source (UGLCCS, 1988). Such an assessment is in full agreement with the current understanding of fecal bacterial contamination of urban waters (Ellis, 1986).

Finally, the UGLCC Study recommended a management strategy to correct the impairment of water uses in the UGLCC area. Such a strategy includes detailed assessments of contributions of contaminant sources and the development and implementation of effective control measures. As a first step in the implementation of such measures, a long-term monitoring program was recommended. This program should focus, among others, on the monitoring of bacterial indicators of fecal pollution from municipal effluents, industrial discharges, CSOs and urban runoff (UGLCCS, 1988).

To initiate the implementation of the UGLCCS recommendations, the National Water Research Institute and Ontario Ministry of the Environment proposed a joint research project which would assess the near-shore fecal bacterial contamination of the St. Clair River in Sarnia, identify the sources of this contamination, and evaluate the feasibility of remediation. This proposal was accepted and jointly funded by the Cleanup Fund Program, the Ministry of the Environment and the National Water Research Institute. The report that follows describes the project findings.

1.2 Project Objectives

Objectives of the project on the assessment and remediation of the fecal bacterial pollution of the St. Clair River can be summarized as follows:

(1) Assess the levels of dry and wet weather fecal bacterial contamination of the near-shore zone of the St. Clair River in Sarnia using common indicator organisms and coliphage. The field sampling should be restricted to the shallow near-shore waters (2-3 m offshore) which are primarily used by bathers and seem to contain the highest bacterial counts.

(2) Characterize the selected sources of fecal bacteria including sanitary sewage, stormwater and combined sewer overflows.

(3) Assess the feasibility of modelling indicator bacteria levels in the St. Clair River in Sarnia.

(4) Assess the feasibility of controlling the fecal bacterial contamination in the St. Clair River in Sarnia.

As a further objective, outside of the scope of this study, the project team collected additional samples in order to

(5) Determine, coincident with bacterial sampling, the levels of heavy metals and organic contaminants occurring at the outfalls of storm and combined sewers, municipal sewage treatment plant effluent outfalls and in the near-shore zone of the St. Clair River. The results of this sampling have not been included in this study report, but should be reported as part of the Stage 1 Remedial Action Plan (RAP) for the St. Clair River (COA and MDNR, 1991).

1.3 Project Team

The project on the fecal bacterial contamination of the St. Clair River in Sarnia was executed by a large team involving government agencies, private contractors, and university researchers. The division of responsibilities among the co-operating parties is listed below.

Donna Stewart and Lesley Megson Cleanup Fund, Environment Canada, Toronto, Ontario	Development of project objectives, liaison between the Cleanup Fund and other agencies
Jiri Marsalek National Water Research Institute Burlington, Ontario	Project proposal, planning, management and reporting; preparation of the final report
Barney Dutka National Water Research Institute Burlington, Ontario	Advice on data collection, interpretation of bacteriological data, preparation of the final report
Frank Dunnett National Water Research Institute Burlington, Ontario	Collection of field data
Gary Johnson Ministry of the Environment (MOE) Sarnia, Ontario	Development of project objectives, project planning and management of the tasks conducted by MOE, final report review
Gary Palmateer London, Ontario Ministry of the Environment	Supervision of bacteriological analyses of field samples
Jacqueline Holik and Darcy Haggith Consultants London, Ontario	Collection of field data and analysis of field samples

Ioannis Tsanis McMaster University Hamilton, Ontario	Modelling of river hydrodynamics and bacterial populations
Kenneth Stevens The City of Sarnia Sarnia, Ontario	Liaison with the City, background information on drainage systems

2. STUDY AREA

The study area (Fig.1) comprised a 9.5 km reach of the St. Clair River in the City of Sarnia and the adjacent part of the City contributing drainage and wastewater effluents to the river. Detailed descriptions of the study area in terms of physiography, demography, water quality and sources of contamination had been presented earlier (Environment Canada and Ministry of the Environment, 1986; UGLCCS, 1988) and updated in the St. Clair River Remedial Action Plan (COA and MDNR, 1991). A brief summary of such descriptions follows.

2.1 The St.Clair River Characteristics

The study of fecal bacterial contamination in Sarnia focussed on the St. Clair River reach between the Blue Water Bridge and the south property line of the Suncor Sunoco Group. This reach is 9.5 km long and fully covers the urban and industrial shorelines in Sarnia. Most of the field work was done in the upper part of this reach, extending downstream from the Blue Water Bridge to the Canadian National Rail Yard (the total length = 3.75 km). This upper reach, which is commonly used for swimming and boating, has a potential for further expansion of water-based recreation. In the downstream reach, the potential for water-based recreation is rather limited, because of the industrial discharges into the river and the lack of public access to the shore. Basic characteristics of the St. Clair River, related to the transport of contaminants, are listed in Table 1.

Table 1. Characteristics of the St. Clair River

The Source of River Flow	Lake Huron
Total Land Drainage Area (km^2)	146,000
Man-Made Flow Controls	None
Study Reach Length (from the Blue Water Bridge to the Suncor Plant, in metres)	9,500
River Depth (m)	9-21
River Width (m)	230-770
Range of Average Flow Velocities (m/s)	1.1 - 2.1
Average time of travel through the study reach (minutes)	90
Discharges (m^3/s)	
Minimum	3,000
Average	5,200
Maximum	6,700

The data in Table 1 indicate that the St.Clair River conveys steady flows, characterized by small discharge variations. In the study area, the river width varies from 230m, at the Blue Water Bridge, to 770 m just south of Sarnia Bay. The river flow through the study reach is fairly swift, with average velocities ranging from 1.1 to 2.1 m/s. Such velocities result in fast transport through the study river reach, with average times of travel on the order of 90 minutes. The actual times of travel depend on local flow velocities which are the lowest along the shoreline. The fast river flow creates a counter-clockwise circulation in Sarnia Bay. This circulation may enhance contaminant transport from sewer outfalls into the Bay. The hydrodynamic modelling of the river flow indicated that contaminant plumes discharged from shore outfalls typically stayed within 100 m of the shore (Environment Canada and Ministry of the Environment, 1986).

2.2 Characteristics of the Adjacent Urban Area

In the upper part of the studied river reach, the river follows the west boundary of two municipalities - the Village of Point Edward and the City of Sarnia - which discharge urban runoff (stormwater), combined sewer overflows, and treated wastewater into the river. Such discharges are important sources of fecal bacterial pollution. Characteristics of sewerage and wastewater treatment in both municipalities are listed in Table 2.

Table 2. Sewerage and Wastewater Treatment in the Study Area (MOE, 1989)

Municipality	Point Edward	Sarnia
Type of Sewerage	Separate	Combined
Number of CSO Outfalls[1]	None	5[2]
Number of Storm Sewer Outfalls[1] into the St.Clair River	1	12
Wastewater Treatment Plant		
Name	Point Edward WPCP[3]	Sarnia WPCP[4]
Treatment	Primary, continuous phosphorus removal	Primary, continuous phosphorus removal
Design Capacity	2,590 m^3/day	65,910 m^3/day
Population Served	2,210	64,475
Effluent Discharge	Just downstream from Blue Water Bridge	5 km downstream from Blue Water Bridge

[1] Fifty cross-connections between storm and combined sewers have been reported for Sarnia (Greck, 1990). Consequently, storm sewer flows may be contaminated by sanitary sewage.

[2] As indicated in a map supplied by the City of Sarnia.

[3] WPCP = Water Pollution Control Plant

[4] There is also another small facility, Bright Grove Lagoon, a conventional seasonal lagoon, serving a population of 3,500 and discharging into Lake Huron via Perch Creek.

In view of numerous sewer cross-connections, some storm sewers carry combined sewage during wet weather. Greck (1990) identified 22 overflow structures in the Sarnia sewer system, some internal (i.e. between combined and storm sewers) and some external discharging to the river. The three overflows discharging almost 80% of the seasonal (May to October) overflow volume are referred to by the street names as the Exmouth, Cromwell and Devine overflows.

Thus, the principal sources of fecal pollution in the study area include wastewater discharges (treated and untreated) produced by the urban population and washoff of urban surfaces, containing bacteria and fecal bacteria from such sources as soils, plants and animals. Bacteria from these sources are transported with wastewater or runoff to the receiving stream, the St. Clair River, where they contribute to the impairment of water uses. One of such impairments is the closure of beaches during the swimming season, when the observed fecal pollution indicator bacteria concentrations exceed the water quality guidelines for recreational waters.

3.0 URBAN SOURCES OF BACTERIA

Sanitary sewage has long been recognized as a primary source of fecal pollution indicator bacteria and pathogenic bacteria, but an understanding of microbial contamination of stormwater runoff and combined sewer overflows has been attained only recently. Such an understanding has evolved from numerous studies which are summarized in the following sections.

3.1 Fecal Bacteria in Urban Stormwater

Urban runoff is recognized as a source of numerous contaminants, including fecal pollution indicator bacteria and pathogens. A pioneering study indicating the presence of microbial pollution in stormwater runoff was conducted by Weibel et al.(1964) and their findings were later confirmed and greatly expanded by many other researchers (Geldreich et al., 1968; Waller, 1971; Olivieri et al., 1977; Ellis, 1985). In Ontario, the issue of microbial pollution of urban stormwater was systematically addressed for the first time under the Canada-U.S. Agreement on Great Lakes Water Quality when three studies of stormwater pollution were done by Dutka and Rybakowski(1978), Dutka and Tobin (1978), and Qureshi (1978) and published in a summary report (COA, 1978). In general, studies of bacteria in urban stormwater can be divided into two categories - studies of sources of bacteria in stormwater and studies of microbial characterization of stormwater.

Urban stormwater discharges are a major source of microbial pollution originating from such sources as pet populations, urban wildlife (particularly birds), cross-connections between storm and sanitary sewers (human fecal pollution), lack of sanitation, deficient solid waste collection and disposal, accumulation of sediment in sewers, rodent habitation in sewers, land wash and growth of bacteria in nutrient rich standing water in storm sewers between events. Typical counts of indicator bacteria reported from some of these sources are shown in Table 3.

Table 3. Geometric Mean Concentrations of Indicator Bacteria From Various Sources (Olivieri et al. 1989)

Source	Total Coliform MPN[1]/g (wet weight)	Fecal Coliform MPN/g (wet weight)	Fecal Streptococci MPN/g (wet weight)
Vegetation	470	51	1,800
Soil	480	52	1,100
Street dirt	1,500	47	1,800
Uncovered Refuse	1,600	500	22,000
Rat Feces	1,400,000	520,000	29,000,000
Dog Feces	2,000,000	830,000	26,000,000

[1] MPN = The most probable number

Additional sources of fecal coliforms were studied by Palmer (1983) who reported that bird populations, resident in urban areas, were a very important source of fecal coliforms. In Ottawa, birds residing on bridges contributed between 0.88 and 1.3×10^{10} fecal coliforms/day to the receiving stream, the Ottawa River. Furthermore, bacterial levels in the receiving waters can be increased by resuspension of bacteria from sediments in the near-shore zone. Palmer (1987) estimated such loadings from 0 to 1410 fecal coliforms/(m^2.s)

Microbial characterization of urban stormwater reflects the mixtures of bacterial sources in a particular location. Source mixtures greatly vary and so do the resulting bacterial counts found in stormwater. Furthermore, bacterial densities in stormwater vary in time, as a result of environmental conditions. Storage of stormwater, which is often rich in nutrients, may lead to the growth of bacteria such as the pathogen <u>Pseudomonas aeruginosa</u>(Cabelli, 1978). On the other hand, the presence of toxicants may inhibit such a growth or lead to bacterial dieoff. Sewer sediment appears to be an important reservoir of bacteria and fluctuations in sediment transport rates are likely to contribute to fluctuations in bacterial densities during storm events (Ellis, 1985). In general, bacterial levels observed in stormwater discharges closely resemble diluted sanitary sewage and as such, may cause public health risks where the receiving waters are used for body contact recreation or similar purposes.

In Ontario, some of the most detailed data on characterization of indicator bacteria in stormwater were reported for five test catchments in Burlington (two sites - a residential area and a commercial plaza), East York, Guelph, and North York. The ranges of bacterial densities observed at these five sites and some additional data from Ottawa are presented in Table 4.

The data in Table 4 indicate high densities of indicator bacteria in storm runoff from relatively clean and well maintained urban areas in Southern Ontario. These densities are comparable to the data reported for the United Kingdom (Ellis, 1986) and the U.S.A. (U.S. EPA, 1983). Ellis (1986) reported the fecal coliform densities in urban stormwater as 6.4×10^3 (MPN/100mL) and the corresponding annual load as 2.1×10^9 fecal coliforms per impervious hectare per year. In the U.S. Nationwide Urban Runoff Program, the median count of fecal coliforms in stormwater from all the 16 U.S. sites was 2.1×10^4/100 mL, with the coefficient of variation of $C_v = 0.8$. Furthermore, distinct differences between cold and warm weather bacteriological counts were observed, with the latter one exceeding the former ones about 20 times (U.S. EPA, 1983).

Table 4. Bacteria in Urban Stormwater from Selected Ontario Catchments (COA, 1978)

Location/Site	Medium Sampled	Bacterial Densities by Membrane Filtration (counts per 100 mL of liquid samples, or counts per 10 g of wet-weight sediment samples)			
		Total Coliform	Fecal Coliform	Fecal Streptococci	<u>Pseudomonas aeruginosa</u>
Burlington I	SW	$1x10^{3}-6x10^{6}$	$1x10^{2}-3x10^{5}$	$2x10^{2}-7x10^{4}$	$1x10^{2}-1x10^{7}$
	DWD	$2x10^{2}-7x10^{3}$	$2x10^{1}-3x10^{3}$	$2x10^{2}-3x10^{3}$	$1x10^{1}-6x10^{2}$
	Sed.	$1.2x10^{4}$	$7.8x10^{2}$	$7.8x10^{2}$	$1.8x10^{3}$
Burlington II	SW	$1x10^{4}-1x10^{6}$	$5x10^{2}-5x10^{4}$	$1x10^{3}-6x10^{4}$	$1x10^{3}-2x10^{4}$
	DWD	$3x10^{3}-2x10^{7}$	$1x10^{2}-8x10^{3}$	$1x10^{2}-6x10^{3}$	$1x10^{1}-3x10^{3}$
North York	SW	$6x10^{3}-4x10^{4}$	$1x10^{3}-2x10^{4}$	$1x10^{3}-1x10^{4}$	$1x10^{2}-2x10^{5}$
	DWD	$1.5x10^{2}$	$2.7x10^{1}$	$5.2x10^{1}$	$2.0x10^{1}$
	Sed.	$1.0x10^{3}$	$2.0x10^{2}$	$4.0x10^{2}$	$1.4x10^{2}$
East York					
Fall	SW	$2x10^{5}-1x10^{6}$	$1x10^{4}-6x10^{5}$	$1x10^{4}-6x10^{5}$	No data
Winter	SW	$3x10^{3}-6x10^{4}$	$2x10^{2}-2x10^{4}$	$3x10^{3}-3x10^{4}$	$2x10^{1}-6x10^{2}$
Fall	Sed.	$9x10^{6}$	$6x10^{4}$	$5x10^{4}$	$<10^{3}$
Guelph	SW	$4x10^{3}-2x10^{4}$	$2x10^{2}-6x10^{2}$	$4x10^{3}-2x10^{4}$	$1x10^{0}-3x10^{1}$
	Sed.	$1x10^{5}$	$8x10^{3}$	$4x10^{3}$	$<10^{3}$
Ottawa (Barrhaven)	SW	$1x10^{4}-2x10^{5}$	$2x10^{3}-7x10^{3}$	$3x10^{1}-10^{4}$	

Legend: Burlington I = a commercial plaza; Burlington II = a residential area;
North York, East York, Guelph and Ottawa = all residential areas;
SW = stormwater; DWD = dry weather discharge from storm sewers;
Sed. = sediment, results recalculated per 10 g of wet weight sediment.

Even though the above studies focussed on indicator bacteria, such as total coliforms, fecal coliforms, and fecal streptococci, some work was also done on pathogenic bacteria, such as <u>Pseudomonas aeruginosa</u> and salmonellae, and other organisms including total fungi, parasites and the chemical indicator coprostanol (COA, 1978). Among the pathogenic microorganisms, <u>Pseudomonas aeruginosa</u> were the most numerous and consistently recovered. Salmonellae were detected less frequently (COA, 1978).

In the overall assessment, the levels of microbial populations in urban stormwater were found to be strikingly high, similar to those observed in dilute sewage, and therefore constituting health hazards. The asserted public health risks were further substantiated by the consistent recovery of pathogenic microorganisms at all the sites studied (COA, 1978).

When comparing the characteristic stormwater bacterial densities to the water quality guidelines for recreational waters, it is evident that nearly all stormwater data exceed the guideline's limiting value of less than 200 fecal coliform units per 100 ml (CCREM, 1987; an analogous value recommended by the Ontario Ministry of the Environment is 100 FCU/100mL), and the high stormwater values exceed this guideline by up to 3000 times. In many receiving waters, the dilution of stormwater discharges may be insufficient to prevent guideline exceedances. Even after the cessation of stormwater discharges, resuspension of sewer sediment deposited in the receiving waters, may lead to high bacterial densities in the water column (Palmer, 1987) and exceedance of the guideline for recreational waters quality.

3.2 Fecal Bacteria in Combined Sewer Overflows (CSOs) and Sanitary Sewage

In wet weather, combined sewers convey stormwater runoff and municipal sewage which are both recognized as significant sources of fecal bacteria (U.S. EPA, 1974). Furthermore, high wet-weather flows lead to the scouring of sewer sediment which constitutes a reservoir for various microorganisms including fecal bacteria (Ellis, 1986). Thus, the wet-weather flows in combined sewers are characterized by high fecal bacterial densities exceeding those in stormwater. When flows in combined sewers exceed the sewer pipe capacity, excessive flows escape sewers and are discharged into the receiving waters as CSOs. Such discharges contribute to bacterial contamination of the receiving waters and a severe impairment of water uses.

In the absence of local (Ontario) data on microbial pollution of CSOs, the preliminary assessment of such a pollution had to be based on the literature data from other regions or countries. The U.K. data, reported by Ellis (1986), indicate fecal coliform densities in CSOs in the range from 10^5 to 10^8 (MPN/100 mL). Similar U.S. data were characterized by total coliform densities which are presented in Table 5 (U.S. EPA, 1974).

The data in Table 5 indicate that fecal bacterial densities in municipal sewage and CSOs are one to two orders of magnitude higher than those in stormwater and, consequently, both sources can cause serious impacts on the bacteriological quality of receiving waters. Sewage treatment and disinfection reduce bacterial densities in treated effluents as also shown in Table 5.

Table 5. Indicator Bacteria in CSOs and Municipal Sewage (U.S. EPA, 1974)

Area	Source	Total Coliform (MPN/100 ml)	
		Average	Range
Atlanta, Ga.	CSOs	$1x10^7$	
Kenosha, Wis.	CSOs	$2x10^6$	
Milwaukee, Wis	CSOs	---	$1.5x10^5$ - $3.1x10^7$
Bucyrus, Ohio	CSOs	$1x\ 10^7$	$2x10^5$ - $5x10^7$
San Francisco, Ca.	CSOs	$3x10^6$	$2x10^4$ - $2x10^7$
Washington, D.C.	CSOs	$3x10^6$	$4x10^5$ - $6x10^6$
Sacramento, Ca.	CSOs	$5x10^6$	$7x10^5$ - $9x10^7$ (FC)
Roanoke, VA	CSOs	$7x10^7$	
Typical Raw Municipal Sewage[1]		$5x10^7$	$1x10^7$ - $1x10^9$
Treated Municipal Effluent			
Primary		$2x10^7$	$5x10^6$ - $5x10^8$
Secondary		$1x10^3$	$1x10^2$ - $1x10^4$

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[1] Raw Sewage, fecal coliform count = $6.3x10^6$, fecal streptococci count = $1.2x10^6$ (MOE, 1989)

3.3 Source Identification

Although the levels of indicator bacteria in the receiving waters can be easily determined, the identification of bacterial sources, without detailed and expensive coliform speciation, is rather difficult. Some techniques used in the public health practice, such as ratios of different species, can be helpful, but are not foolproof. For example, Geldreich and Kenner (1969) used a ratio of fecal coliform (FC) to fecal streptococcus (FS) ratio and suggested, that for FC/FS > 4.0, the source is likely of human origin; for FC/FS < 0.7, the source is probably of non-human origin; and, for the values in between, from 0.7 to 4.0, the source identification is indeterminate. These criteria apply to fresh samples collected within 24 hours of discharge. Similarly, Cabelli et al.(1976) suggested that for ratios of *Pseudomonas aeruginosa* (PA) to fecal coliform (FC) equal to about 0.001 and fecal coliform densities > 10^3, a probable source of bacteriological contamination is animal feces.

In view of the dynamics of bacterial loadings in urban stormwater as well as CSOs, and high variability of sources and their contributions during various phases of runoff, the usefulness of the FC/FS and PA/FS ratios in determining bacteria sources is questionable. Other approaches to source identification such as bacterial speciation from coliform isolates and bacterial gene probes (under development) may provide better identification.

In summary, the previous discussion of fecal bacterial sources indicates that discharges of stormwater, CSOs and sanitary sewage (both untreated and treated) are all significant sources of fecal bacteria. Consequently, it should be expected that numerous sewer outfalls in the study area (see Fig.2) discharge large quantities of fecal bacteria into the receiving water, particularly during wet weather when all outfalls are discharging. These sources and outfall locations need to be considered in the design of field bacterial surveys.

4.0 FIELD SURVEYS OF FECAL BACTERIA DENSITIES

The main purpose of field surveys was to assess indicator bacterial densities in source discharges and the receiving waters. Towards this end, samples were collected at a number of sampling stations and analyzed for several microbial parameters.

4.1 Sampling Stations

For the assessment of fecal bacterial sources and the contamination of the St. Clair River in Sarnia, 14 sampling stations were established in the study area. These stations are listed in Table 6 and their locations are shown in Fig.3.

The selection of these stations was driven by the need to evaluate fecal bacterial densities in the receiving water body, the St. Clair River, and in discharges from several sources. Station A, at the upstream end of the study reach, served as a reference (experimental control) station located upstream from all significant urban sources of fecal bacteria. Throughout the study period, fecal bacterial densities at this station were very low.

Table 6. Sampling Stations in Sarnia

Station Designation	Location	Source Sampled
A	At N-W Corner of Blue Water Bridge	River Water
B	Government Harbour, N-E Corner	River Water/Stormwater[1]
C	Government Dock, West End	River Water
D	South End, West Pier	River Water
E	Sarnia Bay, near Boat Ramp	River Water
F	Sarnia Bay, Foot of London St.	River Water/Stormwater[1]
G	Sarnia Bay, Foot of George St.	River Water/Stormwater[1]
H	CNR Ferry Dock	River Water
J	Opposite Sunoco Entrance	River Water
L	Point Edward WPCP Effluent	WPCP Effluent
M	Sarnia WPCP Effluent	WPCP Effluent[2]
W	Cromwell Street CSO	CSO
Y	Devine Street CSO	CSO
Z	Sarnia WPCP Influent	Raw Sewage

[1] Samples collected in front of a sewer outfall; in dry weather, these samples represented ambient water quality, in wet weather they represented stormwater discharges.

[2] Sampled before disinfection

Station B was located at the mouth of a large storm sewer outfall in the North-East corner of the Government Harbour and served for assessing stormwater quality in wet weather. In dry weather, Station B indicated bacterial densities in the harbour basin which is characterized by poor flushing by the river water.

Station C was located at the mouth of the Government Harbour and served for detecting transport of fecal bacteria from the harbour basin into the river. Station D was located well outside of the harbour in the river channel with flow velocities much higher than at Station C.

Stations E, F, and G were located in and near Sarnia Bay. Station E was the most remote one from the bay entrance, in a location with long residence times. The other two stations, F and G, were selected progressively closer to the bay entrance and were located immediately in front of storm sewer outfalls. In wet weather, bacterial densities observed at these stations should represent microbial characteristics of stormwater.

Station H was in the river channel, approximately 3.75 km downstream from the Blue Water Bridge. This was the most downstream station still accessible from public land. It was located downstream from nearly all municipal sewer outfalls, with the exception of one storm sewer and two CSO outfalls.

Station J was at the nearest publicly accessible location downstream from Station H. It was located about 6 km downstream from H. Between stations H and J, there are three municipal sewer outfalls, the Sarnia Water Pollution Control Plant effluent outfall, and 15 industrial sewer outfalls. Thus, Station H integrates all urban impacts on the upper river reach which has a potential for swimming and Station J reflects the impacts of all municipal and industrial fecal bacterial sources in Sarnia.

Sampling stations A-J were located in a shallow near-shore zone of the river, suitable for swimming, with water depths 1 - 1.5 m. This zone represents the most contaminated zone of the river, because the pollution plumes emitted from onshore sewer outfalls remain attached to the shore and disperse relatively slowly by vertical and lateral mixing. A complete cross-sectional mixing may require lengths in the order of 100 river widths (about 50 km). This estimate is supported by the MOE hydrodynamic studies indicating that at Port Lambton, which is about 45 km downstream from Suncor, only a small fraction of materials released along the Ontario shoreline has reached the Michigan shoreline.

The remaining stations L, M, W, Y and Z served for characterization of fecal bacterial sources. At station L, sewage effluent (before disinfection) was sampled at the Point Edward WPCP. At station M, sewage effluent (before disinfection) was sampled at the Sarnia WPCPs. At station Z, the influent to the Sarnia WPCP was sampled. Stations W and Y served for wet-weather sampling of CSOs at Cromwell and Devine Street outfalls, respectively. This sampling was done directly in the CSO outfall sewers.

4.2 Types of Sampling Surveys

Three different types of sampling surveys were conducted in the study area - dry weather, wet weather and an outfall plume sampling. The main objectives of such surveys were to establish bacterial densities in both dry and wet weather, and to determine whether the impact of the Point Edward WPCP effluent on bacterial densities in the St. Clair River can be detected.

Dry-weather sampling was done at all stations during the periods of dry weather. The frequency of such sampling varied from once to three times per week, depending on the weather and the available laboratory capacity. A complete sampling run was accomplished in less than two hours.

Wet-weather samples were collected during the periods of significant rain. Under such circumstances, the samples collected at stations B, F and G represented stormwater being discharged from sewer outfalls into the river. As discussed later in the section on bacteria modelling, at sampling stations with slow flushing (e.g. inside Sarnia Bay, station E), wet-weather impacts persisted after the cessation of rainfall and this caused difficulties in distinguishing between dry and wet weather results. To examine temporal variability during storm events, wet-weather sampling runs were repeated about every two hours during the rain storms.

In the last type of sampling, the detection of a fecal bacterial plume, caused by the discharge of the Point Edward WPCP effluent into the St. Clair River, was attempted. For this purpose, samples were collected at several depths along a series of traverses (extending 25 m offshore), starting at the outfall and moving up to 500 m in the downstream direction. Even the plume samples collected near the outfall showed very low bacterial densities and it was impossible to follow the plume in the river. Consequently, these surveys were abandoned. Similar sampling of the Sarnia WPCP plume would have been more interesting in terms of bacterial densities, but the lack of access to the plant outfall prevented undertaking such surveys.

4.3 Sample Collection

Sample collections and submissions to the Ministry of the Environment (MOE) Laboratory were done in accordance with the MOE guidelines (MOE, 1985). Samples were collected by quickly lowering pre-sterilized 250 mL sampling bottles, attached to a telescopic sampling pole (a maximum extension of 4 m), into the water with the mouth facing into the current. After pulling the bottle out of the water, the sample volume in the bottle was adjusted to keep the bottle about 3/4 full. To reflect the study concerns about bacterial densities and their impacts on swimming beaches, samples were collected in shallow waters (1- 1.5 m), typically 2-3 m from the shore, at depths about 0.3 m below the water surface. When filling up the bottles, precautions were taken to avoid skimming the water surface which is known to contain the highest bacterial densities. Samples were collected in moving water, away from stagnant zones caused by offshore structures.

After the collection of samples, bottles were placed in ice coolers and delivered to the Microbiological Laboratory of the Ministry of the Environment (MOE) in London, Ontario where the sample processing started immediately and all analyses were initiated within less than 24 hours of the start of sampling. The time lag between the collection of samples and their delivery to the laboratory was typically 5-6 hours and when the sampling extended over two days, samples were delivered each day.

4.4. Microbiological Parameters and Analyses

Field samples were routinely analyzed by the MOE Microbiology Laboratory for fecal coliforms (FC), fecal streptococci (FS), E. coli (EC) and Pseudomonas aeruginosa (PA) densities using the analytical and QA/QC procedures described in the MOE handbook (MOE, 1984a) and summarized below. All these parameters are used by the Ministry of the Environment in the assessment of bacteriological water quality and/or in the identification of bacterial sources. Pseudomonas aeruginosa warrants further attention, because it is a bacterial pathogen which causes ear, eye, nose and skin infections in swimmers (Gustafson et al., 1983; Havelaar et al., 1983; Seyfried and Cook, 1984).

All microbial densities were determined by membrane filtration using cellulose nitrate 0.45 um membranes and different incubation procedures. For fecal coliforms, m-Tec and m-Tec IG agar with a 24-hour incubation at 44.5 °C were used. In fecal streptococci measurements, m-Enterococcus agar with incubation at 41.5 °C for 48 hours were used. Finally, Pseudomonas aeruginosa densities were determined by using m-PAC agar with incubation at 41.5 °C for 48 hours.

On some samples, coliphage tests were also performed. Guelin (1948) was the first researcher to recognize the potential of bacteriophages as indicators of fecal pollution. Since Guelin's work, there have been several papers indicating the potential of bacteriophage/coliphage to act as indicators of bacterial water quality (Bosco, 1963; Kuznetsova and Ostrowskaja, 1963; Amin-Zade and Poultof, 1964; Kenard and Valentine, 1974; Zais, 1982; Wensel et al., 1982; Kennedy et al., 1985) and viral water quality (Vaughn and Metcalf, 1975; Grabow et al., 1984).

There is also sufficient evidence to suggest that the coliphage test has many advantages over traditional bacteriological and virological tests in that the procedure is economical, simple to perform and provides results within 6 hours. The speed with which results can be obtained indicates that the coliphage test is a definite asset where approximate or risk estimate data are required urgently.

Based on an international study of river, freshwater lake and marine beach, it was found that (a) within location FC and coliphages are positively correlated, (b) coliphage values can be indicated or predicted by using FC MPN, fecal streptococci and E. coli data, (c) it would be feasible to propose a quality guideline of 20 coliphage/100 mL for recreational waters (Dutka et al., 1987). Havelaar (1991) recommended to use somatic coliphages in the assessment of sewage pollution of fresh waters, using the classification shown in Table 7 below.

Table 7. Occurrence of Bacteriophages in Fresh Waters in Relation to the Degree of Sewage Pollution (Havelaar, 1991)

Degree of Pollution	BOD[1] (mg/L)	Total Coliform Bacteria/100 mL	Somatic Coliphages[2]/100 mL
1	< 3	$< 5x10^2$	< 0.1
2	3 - 10	$5x10^2 - 5x10^4$	$10 - 10^3$
3	10 - 20	$5x10^4 - 5x10^5$	$5x10^2 - 5x10^4$
4	> 20	$> 5x10^5$	$1x10^4 - 5x10^5$

[1] Biochemical Oxygen Demand (typically 5 days at 20°C)

[2] Enumeration on E. coli K12, B, C, of HfrH

In coliphage tests, the procedure detailed in the APHA Standard Methods (1989) was used. This procedure consists in adding 5mL of water to each of four test tubes containing 5.5 mL of molten agar (MTSA), followed by addition of 1 mL of frozen E. coli C host culture (thawed at 44.5 °C for 10 to 15 minutes). The contents of each tube are mixed, plated, incubated at 35°C and scored for PFU at approximately eight hours. The E. coli C host culture used was #13706 of the American Type Culture Collection.

5.0 RESULTS AND DISCUSSION

All bacterial survey results were entered into computer files and further processed by calculating geometric means presented in Table 8 and the corresponding probabilistic distributions were plotted in Figs.4-7. The number of coliphage samples was limited and consequently, data statistics could not be produced for all stations.

The data in Table 8 are classified into fours groups - the receiving waters (ambient river water quality) and three bacterial sources, stormwater, combined sewer overflows and wastewater treatment plant flows. Further discussion of results focuses on urban source impacts on fecal bacterial densities in the receiving waters, comparison of dry and wet weather impacts, and observations for individual sampling sites.

Table 8. Summary of Bacteriological Data

Station	Geometric Means (counts/100 mL)									
	Coliphage		Fecal Coliform		Fecal Streptococci		*Pseudomonas aeruginosa*		*E. coli*	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
River St.										
A	28	46	20	129	11	70	361	1570	17	96
B	59	-	221	5129[1]	79	2483[1]	973	3776[1]	133	6138[1]
C	26	106	50	689	23	375	893	3184	34	454
D	29	-	24	63	8	38	1002	1542	18	62
E	40	63	79	568	34	216	929	6714	71	406
F	36	-	297	1236[1]	94	839[1]	2173	4345[1]	286	818[1]
G	38	50	87	1560[1]	31	520[1]	1991	6776[1]	51	1138[1]
H	83	-	2547	8017	380	705	1574	4853	2046	5129
J	61	85	241	863	26	197	927	4560	197	590
Storm Sewers										
B		-		5129		2483		3776		6138
F		-		1236		839		4345		818
G		50		1560		520		6776		1138
CSOs										
W		5841		1900000		90600		17300		1140000
Y		529		1180000		162000		17000		810000
WPCPs										
L[2]	413	1006	8800	87700	7350	9420	1220	614	19300	72800
Z	--			4530000		195000		55000		2250000
M[2]	817	1130	970000	1120000	70300	140000	11900	6270	885000	1290000

[1] Stations B, F and G represent storm sewer discharges in wet weather

[2] Samples collected before disinfection (for comparison of fecal pollution in sewage and CSOs)

In evaluations of field data, probabilistic distributions of bacterial densities, illustrated by a data sample in Fig.4, were used. Probabilistic distributions of fecal coliform densities, fitted by the method of moments, are shown in Fig.5 for four river stations, in Fig.6 for stations in the Government Harbour and Sarnia Bay and, finally, distributions of various microorganisms studied are compared in Fig.7 for stations A and J. At this level of analysis, the confidence limits of the fitted distributions were not established, but the uncertainties associated with the data in Figs.4-7 should not be underestimated.

The data in Fig.5 were used to evaluate the impact of urban pollution on fecal bacterial densities in the main river channel. The data in Fig.6 served for similar evaluations in two water bodies connected to the main channel - the Government Harbour and Sarnia Bay. For simplicity, only fecal coliform density distributions are shown in Figs.5 and 6. As shown by samples of data for stations A and J in Fig.7, fecal streptococci and *E. coli* closely follow the trends exhibited by fecal coliform. Another reason for focussing on fecal coliform is the fact that this is the only microbial parameter for which some water quality guidelines are available.

5.1. Impacts of Urban Sources on Fecal Bacteria in the St. Clair River

For the overall assessment of the impacts of urban sources on fecal bacteria levels in the St.Clair River in Sarnia, the data from stations A, D, H and J can be used. The first station is a control station located upstream from all major urban sources discharging directly into the river (except two small storm sewers draining into Lake Huron). Station D is located downstream from the first three sewer outfalls. Station, H, is located on the Sarnia Waterfront, downstream from about 4/5 of all municipal sewer outfalls. The last station, J, is located downstream from all the municipal and industrial outfalls as far downstream as Suncor.

For evaluations of urban impacts, probabilistic distributions of bacterial densities at stations A, D, H, and J were compared in Fig.5. For all the microbial parameters studied in both dry and wet weather, bacterial densities at the mid-reach station (H) and the most downstream station (J) exceeded those at the control station (A) and the next downstream station (D).

Bacterial densities barely changed between the control station A and the next downstream station D, but then increased sharply when progressing in the downstream direction from station D to the mid-reach station H, and eventually declined between the mid-reach station and the most downstream station J. The same trend was exhibited by the coliphage data, though the changes in magnitudes were less pronounced. These observations indicate that the discharges from municipal sewer outfalls, most of which are located in the upper reach (A-H), are the most significant sources of fecal bacteria in the study area. High bacterial densities at Station H, even during dry weather, suggest occurrences of dry-weather discharges of sewage along the waterfront. Such discharges can be caused by sewer cross-connections, prolonged overflows caused by sewer infiltration (Greck, 1990), and malfunctioning controls in the sewer system. Comparisons of bacterial densities at the control station (A) and the most downstream, station (J), provide an evaluation of the upstream/downstream effects.

Reductions in bacterial densities in the lower reach can be explained by the mixing and dispersion of municipal pollutant plumes. No information was available on bacterial loadings in the industrial discharges typical for this reach.

The impacts of urban sources on fecal pollution of the St. Clair River were observed in both dry and wet weather. In dry weather, fecal coliform (FC) and E. coli densities downstream from the city exceed those upstream from the city by an order of magnitude; for coliphage, fecal streptococci and Pseudomonas aeruginosa (PA) such exceedances were much smaller, about 2 to 2.5 times. The sources of such bacteriological pollution are sewage treatment plant effluents, dry-weather discharges from both storm and combined sewers, and possibly after-effects of wet-weather bacterial contamination. It was noted that the geometric means of the fecal coliform data collected at river stations correlated well with those determined for fecal streptococci and E. coli data, with the resulting coefficients of correlation (r) equal to 0.987 and 0.999, respectively. A somewhat worse correlation was found between FC and coliphage geometric means for various stations, r = 0.80. A poor correlation between FC and PA was described by r = 0.296. These results are also supported by the data distributions shown in Fig.7.

Among the microbial parameters studied, Pseudomonas aeruginosa showed the highest densities at all the river stations monitored, but not necessarily in all the sources. This suggests a possibility of bacteria reproduction wherever water rich in nutrients is stored. Such storage includes submerged sewer pipes, regulated by backflow check valves, and possibly stagnant zones in the river, for example in Sarnia Bay. When these storages are emptied, the resulting bacteria levels may be unusually high. These results strongly suggest that, as a follow up to this study, bacterial levels in the submerged sewer pipe outfalls should be investigated.

In wet weather, bacterial densities downstream of the city still exceed the levels upstream of the city, but by slightly smaller margins. For fecal coliforms and E. coli , the densities at the control station were higher than those at the most downstream station about 6 times, for fecal streptococci and Pseudomonas aeruginosa, about three times, and for coliphage, about two times.

5.2 Dry vs. Wet Weather Data

In dry weather, the fecal bacterial concentrations observed at the river stations were relatively low. In wet weather, additional sources of bacteria in the form of storm sewer and CSO discharges become activated and contribute to bacteriological pollution of the river. Consequently, the bacterial densities observed directly in the river increased in the case of fecal coliforms, fecal streptococci, Pseudomonas aeruginosa, E. coli, and coliphage 2.6 to 6.5 times, 1.9 to 7.6 times, 1.5 to 4.9 times, and 2.5 to 5.6 times, and 1.4 to 4 times, respectively. Even higher increases in wet weather bacterial densities were found in the immediate vicinity of wet-weather sources, up to 46 times. Thus, during rainfall events generating surface runoff (typically storms with total precipitation over 2 mm), bacterial densities in the study area increase and these elevated densities may persist long after the cessation of rain. This is caused by two phenomena - prolongation of sewer discharges caused by high infiltration into sewers (Greck, 1990) and by relatively slow decline in fecal bacterial densities in the river at locations with slow flushing.

5.3 Compliance with Microbiological Recreational Water Quality Guidelines

The Canadian Water Quality Guidelines (CCREM, 1987) discuss several indicator organisms in connection with health risk for swimming areas. The most widely used guideline applies to fecal coliforms and recommends that the geometric mean of not less than five samples taken over a 30-day period should be less than 200 fecal coliforms per 100 mL. Resampling should be performed when any sample exceeds 400 fecal coliforms per 100 mL (Health and Welfare Canada, 1983). The exact risk associated with bathing in water of this quality cannot be established, but from epidemiological data, it was estimated as a 0.12-1.5% chance of contracting gastrointestinal illness (CCREM, 1987).

The Guidelines further note that no limits were set for total coliforms and fecal streptococci (Health and Welfare Canada, 1983), but some recommendations exist for enterococci (11/100 mL - IJC, 1983) and E. coli (126/100 mL, U.S.

EPA). Recent practice indicates that the fecal coliform guidelines, expressed as 100 or 200 organisms per 100 mL, have been used widely (CCREM, 1987). The compliance is determined by repeated testing, where up to five samples are collected, often during a relatively short time period, and their geometric mean is compared to the limiting value.

The Ministry of the Environment also recommends the use of bacteriological water quality indicators in the assessment of public health hazards (MOE, 1984b). Specifically, potential health hazard exists if the fecal coliform geometric mean density for a series of water samples exceeds 100 per 100 mL, and water quality is considered impaired when the total coliform geometric mean density for a series of water samples exceeds 1000 per 100 mL. A series of at least 10 samples per month per sampling location is recommended, but an increased sampling frequency is required when the water is used for recreational purposes or when the water is subjected to contamination or discharge (MOE, 1984b).

A similar water quality standard for the State of Michigan states that all waters of the State shall contain not more than 200 fecal coliforms per 100 mL as determined on the basis of a geometric average of any series of 5 or more consecutive samples taken over not more than a 30-day period. This concentration may be exceeded if such concentration is due to uncontrollable nonpoint sources. The State my suspend this limit from November 1 through April 30 upon determining that designated uses will be protected (COA and MDNR, 1991).

Among these three water quality criteria, the Canadian Water Quality Guidelines and the Michigan Water Quality Standards are almost identical, but the MOE objectives are more stringent in terms of acceptable fecal coliform concentrations and the number of samples required. The use of moving averages, common to all three documents, makes the assessment of guideline compliance difficult - a single sample exceedance of the limiting value does not necessarily constitute violation of the guidelines.

Considering bacterial densities as a probabilistic phenomenon, it is possible to examine the statistical distributions of fecal coliforms in the study area and the probabilities of non-exceedance of some limiting values during the swimming period. Using the notation presented below, the duration of non-exceedance of the limiting value of 100 FC/100 mL can be expressed as

$$D_{ne} = t_d \, P_{FC<100,\, d} + t_w \, P_{FC<100,\, w} \qquad [1]$$

where D_{ne} is the duration of non-exceedance (days), t_d and t_w are the numbers of days with dry and wet weather during the swimming period, respectively, $P_{FC<100}$ is the probability of FC densities less than 100/100 mL, and the subscripts d and w refer to dry and wet weather, respectively. For applications of eq.[1] the swimming period was defined as the period of 92 days from June 1 to August 31. The wet days were defined as calendar days with at least 2 mm of precipitation and the average number of wet days during this period, as determined from a 20-year rainfall record available for the Sarnia Airport station, was 31.

Using eq.[1], the probabilities of non-exceedance of the limiting values of 100 and 200 FC/100 mL were estimated and presented in Table 9. In these estimates, it was assumed that the fecal coliform density distributions, presented earlier in Figs. 5 and 6, were valid during the swimming season.

Since some of those data were collected after the swimming season, when water temperature and bacteria concentrations decrease, this assumption is somewhat conservative and may lead to overestimation of non-exceedance probabilities.

Table 9. Estimated Probabilities of Non- Exceedance of 100 FC/100mL and 200 FC/100 mL Concentrations in the Study Area

STATION	Probability of Non-Exceedance [%]					
	100 FC/100 mL			200 FC/100 mL		
	Dry	Wet	Dry + Wet	Dry	Wet	Dry + Wet
A	95	41	77	99	64	87
B	31	5	22	48	10	35
C	70	10	50	88	20	65
D	94	65	84	99	85	94
E	60	11	44	76	22	58
F	20	0.6	14	39	4	27
G	53	2	36	75	7	52
H	2	0.1	1	6	0.4	4
J	24	0.0	16	45	0.5	30

In Table 9, the most relevant data appear in the second column - applying the guideline of 100 FC/100 mL in dry weather, when the interest in recreational water use is the highest. Under such circumstances, the estimated probabilities of non-exceedance vary from the high of 95%, at the upstream control station, to the low of 2% at the mid-reach station H. The most downstream station, J, is characterized by a value of 24%. Combined (wet and dry) values indicate that during the swimming period of 92 days, the concentration of 100 FC/100 mL would not be exceeded during about 71-78 days upstream from the city, about 15 days at the downstream station J, and only about 1 day at the mid-reach station H. With the exception of station H, these durations would be about 10 to 14 days longer for a less stringent guideline of 200 FC/100 mL. By introducing confidence limits into these considerations, the probabilities of non-exceedance of the limiting values would be reduced.
The estimated probabilities of fecal coliform concentrations being less than 100 FC/100 mL are shown in Fig.8 to illustrate the impact of urban sources of fecal bacteria on the bacteriological quality of water in the St. Clair River in the study area.

5.4 Observations for Individual Sites

5.4.1 River Sites

Site A (Control site upstream from the city)
Even this site shows some signs of fecal pollution, as evidenced by occasional high densities (up to 85/100 mL) of coliphage which do not reproduce outside the mammalian gut. The mix of indicator bacteria is somewhat confusing, with *E. coli*, fecal coliform and fecal streptococci occurring at similar levels (certainly if statistical significance of results is considered). The levels of *Pseudomonas aeruginosa* are rather high. *P. aeruginosa*, a pathogen, is generally accepted as an indicator of sewage pollution and it is known to grow in organically rich natural waters. Notwithstanding the above concerns, this

was a site with a relatively high probability (77%) of fecal coliform concentrations being less than 100 FC/100 mL during the swimming season. In summary, this site shows minor to low fecal pollution fluctuating with precipitation. Storm sewers draining into Lake Huron and the lake water are suspected as major sources of this pollution.

Site C (the mouth of Government Harbour, 1.9 km downstream from site A)
Site C is not located directly in the main river channel, but in a channel extension at the mouth of the Government Harbour. It represents an intermediate point between several sources, storm sewer and CSO outfalls at site B, and the river. Bacterial densities at site C were 2 to 5 times higher than those at site A, but at least four times lower than those at site B, with the exception of *Pseudomonas aeruginosa*. Obviously, indicator bacteria discharged into the harbour basin at site B are diluted by water in the basin with one exception - *P. aeruginosa*, which persists at almost constant densities throughout the harbour. This strongly suggests *P. aeruginosa* regrowth in the nutrient rich waters of the harbour basin. Wet weather bacterial densities were substantially higher (4 to 13 times) than dry weather densities, but by smaller margins than at site B. At site C, wet weather discharges from sources are diluted not only by water from the harbour, but also by the river water.

Site D (just upstream from Sarnia Bay)
This appeared to be the least polluted river site with bacteriological water quality comparable to that at the control site A. Bacteria level patterns were similar as at site A; fecal coliform and *E. coli* densities were about the same and slightly greater than fecal streptococci counts. Again, *P. aeruginosa* densities exceeded those of other indicator bacteria. Coliphage counts, indicating fecal pollution, varied from <5 to 85/100 mL, and frequently exceeded the suggested recreation water guideline of 20 coliphage/100 mL. The upper values, observed infrequently, indicate significant fecal contamination. High *P. aeruginosa* densities indicate impacts of sewage discharges and/or nutrient loadings. Probable sources include Prince Edward WPCP effluent, sewer outfalls in the Government Harbour, Bridgewater Marina and possibly industries along the east bank of the river downstream from the Blue Water Bridge. The probability of fecal coliform concentrations being less than 100 FC/100 mL, during the swimming season, was estimated for this site as 84%. In summary, this site shows relatively low fecal pollution, which somewhat increases in wet weather. The sources of such pollution include upstream sewer outfalls and the loads carried by the river from the upstream section.

Site G (immediately downstream from Sarnia Bay)
This site is characterized by significantly higher levels of fecal pollution than the upstream sites, in both dry and wet weather. In comparison to site D, the increases in dry weather bacterial densities are moderate and described by factors ranging from three to five. However, in wet weather the corresponding range is four to 12 times. Dry weather coliphage densities, ranging from 15 - 100/100 mL, indicated a relatively weak ongoing fecal pollution. This was further confirmed by mean densities of fecal coliform (87/100 mL), fecal streptococci (31/100 mL) and *E. coli*(51/100 mL). *P. aeruginosa* densities (6776/100 mL) were again very high and indicated microorganism growth in the receiving waters. The probable sources of the observed fecal pollution are similar to those listed for site D, except for additional sources draining into Sarnia Bay (two storm sewers and a pleasure craft marina).

High bacterial densities observed in wet weather confirm the severe impacts of all wet weather discharges and a somewhat limited mixing in the river causes these elevated densities to persist even after the cessation of rainfall. The mix of microorganisms at this site suggests land runoff impacts as opposed to effluent impacts. The probability of fecal coliform concentrations being less than 100 FC/100 mL, during the swimming season, was estimated for this site as 36%. In summary, site G shows impacts of urban fecal pollution which increases in the downstream direction along the Sarnia waterfront. These impacts are particularly severe in wet weather, because of the proximity of several sewer outfalls and a limited flushing given by the distribution of flow in the river.

Site H (a mid-reach site at the CN Railroad Yard)
This is the most downstream river site with public access within the municipal boundaries. The site is located downstream from 14 storm sewer and CSO outfalls. Both dry and wet weather fecal bacterial densities are very high and indicate strong fecal contamination. Dry weather contamination was characterized by high mean densities of fecal coliforms (2550/100 mL), E. coli (2050/100 mL), P. aeruginosa (1570/100 mL), fecal streptococci ((380/100 mL), and coliphage (35-115/100 mL). The fecal coliform concentration of 100 FC/100 mL is exceeded at this site practically all the time (99%). During several rainfall events, P. aeruginosa and fecal streptococci were lower than E. coli and fecal coliform counts, which suggests that during some phases of runoff, sewer discharges may be diluting the near-shore bacterial contamination of the river at this site.

In raw sewage, fecal coliform and E. coli densities predominate P. aeruginosa and fecal streptococci densities. In at least one case, bacterial densities two days after a rain event still exceeded some wet weather bacteria levels, which suggests a continuous sewage output (e.g. through sewer cross-connections or by malfunctioning CSO controls) even during dry weather. In summary, this site is highly contaminated by fecal bacteria from urban sources. The observed fecal bacterial densities are very high during both dry and wet weather and completely impair any recreational use of the river in this section. The coliphage concentrations also were always greater than recreational water quality guidelines proposed in the literature as 20/100 mL.

Site J (downstream from the petrochemical industrial area)
This was the most downstream site located about 6 km downstream from site H. The water quality in the river at this site should reflect the additional sources of fecal pollution - two CSOs, 14 industrial outfalls and the Sarnia WPCP outfall - discharging into the river between sites H and J. Bacterial densities at site J, while greater than those at relatively clean sites upstream of the city, are significantly lower than those at the nearest upstream site, H, for all the microbial parameters studied. Thus, there is some recovery of the near-shore water quality in the river between sites H and J, but it is suspected that most of this recovery is caused by dilution within the river - by the continuing mixing of outfall plumes with the main river flow. Other processes affecting indicator bacterial densities, including bacterial dieoff and removal by sedimentation, were deemed to be of secondary importance in view of fast flows in the river.

Comparable mean densities of E. coli and fecal coliforms point to fecal material as the main contaminant source. Similar coliphage counts during both wet and dry weather suggest a continuous input of fecally contaminated discharges upstream of the site J and this assertion is also confirmed by the P. aeruginosa densities. The probability of fecal coliform concentrations being less than 100 FC/100 mL, during the swimming season, was estimated for this site as 18%. In summary, the most downstream river site indicates some recovery of the microbial quality in the near-shore zone of the river, largely caused by the mixing and dilution of urban effluents in the river. In spite of this partial recovery, the microbial quality at this site is rather poor and indicates persistent fecal pollution.

5.4.2 Sites in Sarnia Bay

Sarnia Bay represents a primary location for water recreation and, consequently, the water quality in this distinct water body is of great importance. Two sampling sites were established in Sarnia Bay.

Site E (northeast corner of Sarnia Bay)
This is a site most remote from the bay inlet. The relatively long time required for flushing this part of the bay is the result of water circulation patterns that develop in the bay under certain climatological conditions. For certain flow and wind conditions, a counterclockwise circulation develops in the bay and transports contaminants, discharged from sewer outfalls at sites F and G, into the more remote parts of the bay. Additional polluted water is discharged from one storm sewer (0.4 m in diameter) directly into the Bay. Thus, the sources of fecal contamination in the bay include several storm sewer outfalls discharging either directly into the bay or into the currents flowing into the bay, bathers (Sherry, 1986), bacterial growth, and grey waters from pleasure boats (MOE, 1991). Such grey waters, including household wastewater from sinks and showers, are contaminated by E. coli and Pseudomonas aeruginosa (Ministry of the Environment, 1991). While the volumes of grey water discharges are relatively small, they may contribute to fecal contamination of small sheltered water bodies, such as Sarnia Bay.

The microbial pollution at site E is relatively minor, but greater than at the upstream river sites A and D. Bacterial concentrations in dry weather were characterized by the mean densities of 79 fecal coliforms/100 mL, 34 fecal streptococci/100 mL, 71 E. coli/100 mL, and 930 P. aeruginosa/100 mL. In wet weather, these densities increased about seven times. It was noted with concern that the wet-weather densities of P. aeruginosa (maximum of 52000/100 mL) were even greater than those at the most contaminated site H. High P. aeruginosa levels may be caused by the microbial growth in nutrient rich waters during warm weather. Nutrient enrichment may be caused by small craft activities contributing nutrients from fuel leaks and grey water discharges and also by slowly draining sewers providing an influx of nutrients and bacteria. Furthermore, the process of nutrient enrichment is aided by low dispersion of nutrients, resulting from minimal water circulation in the bay.

It appears that at this site, wet weather effects may persist for one or two days, depending on the flow conditions. The probability of fecal coliform concentrations being less than 100 FC/100 mL, during the swimming season, was estimated for this site as 44%. In summary, the site E shows moderate signs of fecal pollution which further increases in wet weather. The relatively high levels of P. aeruginosa, a pathogen commonly infecting ears and skin surfaces, should be a major concern in view of the extensive use of this somewhat sheltered water body for swimming.

Site F (on the east shore of inlet to Sarnia Bay)
This site is located about 300m south of site E in front of a storm sewer outfall. During both dry and wet weather, bacterial densities at site F exceeded those at site E, from two to four times, with the exception of *P. aeruginosa*. Site F is impacted by more sources of fecal pollution than site E and this is reflected by the observed densities of indicator bacteria. In wet weather, *P. aeruginosa* densities at site F were somewhat lower (maximum 26000/100 mL) than at site E. This can be explained by an effective water exchange at site F and the reduced opportunities for microorganism growth in the receiving waters. The probability of fecal coliform concentrations being less than 100 FC/100 mL, during the swimming season, was estimated for this site as 14%. In general, site F shows significant impacts of fecal contamination originating from storm sewers with possible cross-connections. This observation was also supported by the observed elevated coliphage densities.

5.4.3. Fecal Bacteria Sources

Several urban sources of fecal bacteria were sampled, including storm sewers, CSOs and wastewater treatment plant flows. Such sites were designated as sites B, F, G, L, M, W, Y and Z.

Storm sewers
Three of the river sites were sampled in front of storm sewer outfalls and the data collected in wet weather therefore represented stormwater characteristics. These sites were B, F and G; among these F and G were already discussed earlier.

Site B (The northeast corner of the Government Harbour)
This site was characterized by exceptionally high bacteriological pollution and the largest differences between dry and wet weather bacterial densities. In fact, the mean wet-weather bacterial densities exceeded dry weather densities 46 times for *E. coli*, 31 times for fecal streptococci, 23 times for fecal coliform, four times for *P. aeruginosa* and two times for coliphage. The observed densities are comparable to those reported earlier for stormwater from other Ontario locations. Site B shows signs of long term fecal pollution impact persisting even after the cessation of rain. Because of the limited water circulation at this site, it is believed that a trickling inflow of bacteria enriched discharges from storm or combined sewers during dry weather could cause significant bacterial impacts. A relatively low ratio of *E.coli* to fecal coliforms, observed during wet weather, suggests a higher impact of street or land wash pollution as opposed to fecal pollution, certainly during the early phase of runoff. Later phases of runoff seem to be more characterized by fecal pollution than land wash pollution. High densities of *P. aeruginosa* indicate a potential of nutrient rich waters from sewers serving as growth media.

Combined Sewer Overflows
In wet weather, two CSO sewers were sampled at sites W (Cromwell Street) and Y (Devine Street), respectively. Since remarkably similar microbiological data were obtained from both sites, they will be discussed jointly. Bacterial densities for CSOs indicate a massive fecal contamination fully comparable to that of raw sewage. Both fecal coliforms and *E. coli* were consistently found in densities of 10^6/100 mL, fecal streptococci at about 10^5/100 mL, and *P.*

aeruginosa at about 2×10^4/100 mL. The exceedance of the P. aeruginosa densities by those of fecal coliforms and E. coli by about two orders of magnitude is consistent with general characteristics of municipal sewage and indicates that the other sites with excessive P. aeruginosa densities must be impacted by some non-fecal pollution sources of this pathogen or by its growth in the receiving waters.

The fecal coliform to fecal streptococci ratios, ranging from 7 to 21.1, strongly suggest that the fecal bacteria observed at this site are of the human origin. The observed data clearly indicate that CSOs are exceptionally strong sources of fecal pollution and the associated fecal bacteria. These sources discharge mostly during wet weather, but when the overflow regulators malfunction, such discharges may continue in dry weather as well. Where fecal bacterial pollution is of concern, CSO sources of bacteria have to be controlled.

Wastewater Pollution Control Plants

Two wastewater pollution control plants (WPCPs) are located in the study area - the Point Edward WPCP and the Sarnia WPCP. Both plants employ primary sewage treatment and discharge into the St. Clair River. The former plant has a very small discharge, about 0.030 m^3/s, and consequently, its impact on fecal bacterial densities in the river is minimal, certainly during the periods when disinfection is applied. The sampling of the discharge plume of this WPCP in the river did not produce any discernible increases in bacteria densities within this plume. The Sarnia plant is much larger and its impact on the river may be measurable, but the lack of public access to this outfall site prevented any sampling of the plant plume. For the assessment of CSOs bacterial loadings, it was of interest to obtain bacteriological characterization of municipal sewage, before disinfection.

In effluents from the Point Edward and Sarnia WPCPs (both sampled before disinfection), fecal coliform and E. coli densities were comparable and clearly exceeded those of P. aeruginosa, by one or two orders of magnitude. In dry weather, the FC/FS ratio in the Point Edward effluent was just 1.2 and increased to 9.3 in wet weather. The former small value may be just an artifact caused by some exceptionally scattered values. At both plants, bacteria densities in the effluent increased in wet weather, with an exception of P. aeruginosa, which would indicate some dilution in wet weather and the concomitant reduction of bacterial densities.

The Sarnia WPCP effluent (before disinfection) is characterized by bacterial densities typical for large municipal plants, with fecal coliform and E. coli densities about equal to 10^6/100 mL, the fecal streptococci density equal to about $1\text{-}2 \times 10^5$/100 mL, and the P. aeruginosa density ranging from 6×10^3 to 10^4/100 mL. The FC/FS ratios were approximately 8:1 and 14:1, for wet and dry weather, respectively. In wet weather, bacterial levels generally increased, with the exception of P. aeruginosa showing the signs of dilution.

The elevated coliphage densities observed at all the CSO and WPCP sampling sites cause concerns, because the presence of coliphage in the receiving waters implies a potential presence of human enteric viruses (Simkova and Cervenka, 1981) which are all considered to be pathogens.

6.0 MODELLING OF INDICATOR BACTERIA

Field observations provide the best data for the assessment of contamination of the receiving waters. Because of costs and operational difficulties, the scope and duration of field observations are often limited and, consequently, it becomes desirable to extend such limited observations by mathematical modelling. The same philosophy applies to the bacterial pollution of the receiving waters. In the case at hand, the duration of the field program was limited to about four months. Yet in the planning of water pollution controls, it is required to work with data records of much longer duration and such records can be produced by mathematical modelling. Consequently, one of the study objectives was to assess the feasibility of modelling fecal bacteria in the St. Clair River in Sarnia. This study task can be broken into two components - modelling the source loadings of fecal bacteria and modelling bacteria in the river itself.

6.1 Modelling of Urban Fecal Bacterial Loadings

Field observations indicate that the major urban sources of fecal bacteria in the study area include stormwater, CSOs, and wastewater treatment plant effluents. When focussing on the upper reach of the study area, within the City boundaries, both WPCP effluents can be omitted from the list of sources. The Point Edward WPCP effluent is insignificant in terms of loadings and the Sarnia WPCP effluent enters the river downstream from this reach.

The modelling of fecal bacterial loads in stormwater and CSOs represents a special case of modelling the urban runoff quantity and quality. While the literature on the modelling of urban runoff chemistry is fairly extensive, the experience with modelling bacterial characteristics is rather limited (U.S. Army, 1977; Palmer and Dewey, 1984; Huber and Dickinson, 1988). The modelling approaches use both deterministic descriptions of fundamental processes as well as systems approaches portraying the physical system as a black box which transforms inputs into outputs by some mathematical operation.

In this study, it was desirable to employ a planning-level model which would mimic the important responses of the urban drainage system and could be supported by the available data. Such a model has to simulate runoff flows and CSOs, and their bacterial characteristics. The first task, runoff flow modelling, can be achieved by using the STORM model of the U.S. Army (1977). It is a planning level model which simulates urban runoff in storm or combined sewers using such input data as descriptions of the catchment and its drainage network, hourly precipitation and hourly air temperature data. To reduce the requirements on input data, the modelling option used in this study for runoff simulation was based on the runoff coefficient method. Snowmelt can be also simulated by means of a degree-day method and the simulated snowmelt depths are added to the rainfall depths in runoff computations.

The physiographic input data include the catchment area, the distribution of land use within the catchment, and imperviousness of the individual land use types. Finally, three hydrologic process parameters, two runoff coefficients for impervious and pervious areas, C_{imp} and C_p, respectively, and the maximum depression storage, d_{max}, also need to be specified. All the three parameter values were adopted from an earlier model application in the study area (Marsalek and Ng, 1989).

In combined sewer systems, the STORM model requires some additional input data including the dry weather flow rate, the rate of infiltration into sewers, the volume of storage facilities, and the treatment rate. The model then calculates the combined flow comprising runoff, dry weather flow and infiltration. The combined flow fills the available storage which is continuously draining to the wastewater treatment plant at a rate equal to the treatment flow rate. Whenever the storage volume is exceeded, overflows occur and their volume and duration are calculated by the model.

The STORM model also simulates runoff quality in terms of six water quality constituents, including coliform bacteria. Such calculations are based on the rates of dust and dirt accumulations on the catchment surface, reductions of these accumulations by street sweeping, specifications of potency factors for individual constituents present in the accumulated dust and dirt, and washoff of such materials during rain storms. In combined sewers, the composition of combined flow is calculated from runoff characteristics and the dry weather flow composition which has to be specified as an input.

While the above modelling options may provide good results, with appropriate calibration, the results of comparable quality can be obtained by using simpler methods allowing direct calibration of the model outputs, without adjustments of intermediate process parameters. Among such methods, the so-called load rating curves show a great promise. The load rating curves have been used for some time in sediment transport, loading calculations (Betson and McMaster, 1973; Brown, 1987), and recently in urban runoff quality modelling (Huber and Dickinson, 1988). In this method, the contaminant load or concentration is assumed to be a function of the discharge. A power-law function is often used for this purpose and written as

$$L = a\, Q^{b} \qquad [2]$$

where L denotes the mass discharge (counts /s for bacteria), corresponding to the discharge Q [m^3/s], and 'a' and 'b' are the rating curve coefficient and exponent, respectively. Both 'a' and 'b' are determined by fitting the experimental data. In the application of this method in this study, recommended by Schroeter (1991), eq.[2] was fitted to the wet-weather field data for all four bacteriological parameters using site B as a representative site for stormwater, and sites X and Y as representative sites for combined sewer overflows.

After logarithmic transformations, a standard linear regression technique was used to estimate the parameters 'a' and 'b', providing the best fit of field data. The results of this fitting procedure are shown in Table 9 which lists the fitted values of 'a' and 'b' , and the correlation coefficient (r^2). It was noted that the values of 'b', listed in Table 10, were comparable to those reported by Betson and McMaster (1973) for some dissolved constituents.

In general, the goodness of fit, described by the correlation coefficient (r^2 = 0.39-0.88) in Table 10, is satisfactory in view of large uncertainties typical for bacterial data. In comparison of stormwater and CSO results, a better fit was obtained for CSOs characterized by the r^2 values ranging from 0.55 to 0.76. The best attainable goodness of fit is illustrated in Fig.9 showing samples of observed loads and the loads calculated from eq.[2].

Table 10. Bacteria Load Rating Curves: Summary of Regression Analysis Results[1] (Schroeter, 1991)

Site	Parameter	No. of Obs.	Fitted Coefficients a	Fitted Coefficients b	r^2
Sarnia B (storm-water)	Fecal Coliform	13	$6.86x10^4$	0.954	0.41
	E. coli	13	$3.72x10^4$	0.879	0.39
	Fecal Streptococci	13	$1.33x10^4$	0.850	0.44
	Pseudomonas aeruginosa	11	$1.05x10^6$	1.840	0.88
Sarnia X (CSO)	Fecal Coliform	14	$6.54x10^6$	0.798	0.77
	E. coli	14	$1.23x10^7$	1.030	0.70
	Fecal Streptococci	14	$7.81x10^5$	0.969	0.75
	Pseudomonas aeruginosa	14	$8.71x10^4$	0.857	0.69
Sarnia Y (CSO)	Fecal Coliform	12	$6.05x10^6$	0.707	0.68
	E. coli	12	$5.56x10^6$	0.859	0.76
	Fecal Streptococci	12	$1.52x10^6$	0.987	0.76
	Pseudomonas aeruginosa	12	$1.81x10^5$	1.210	0.55

[1] Fitted equation: $L = a Q^b$, where Q is in m^3/s, L is kilocounts/s.

The earlier experience with load rating curves indicates that this approach produced excellent results when the number of observations used in regression analysis ranged from 100 to 300 (Schroeter, 1991). Thus, it can be expected that a better fit would be obtained for a larger database which could be analyzed for a possible hysteresis in the rating curve.

In summary, the degree of accuracy allowed by the fitted load rating curves was deemed satisfactory, particularly at this stage of analysis which indicates high bacterial densities greatly exceeding the specified guideline limits. The costs of improvements in the accuracy of this procedure can be justified only if they lead to improved water management decisions, which does not seem to be the case at this time.

The fitted load rating curves were applied in conjunction with the simulated flow records for the selected sampling sites and hourly bacteria loads were produced for the period from August to November, 1990 using an equation (Schroeter, 1991)

$$C(t) = 0.1\ L(t)\ /\ Q(t) \qquad [3]$$

where C(t) is the estimated bacterial count (count/100mL) at time t(h), L(t) is the bacterial load (in kilocounts/s) and Q(t) is the simulated discharge. These bacterial loads were produced for all sewer outfalls from the Blue Water Bridge to the last municipal storm sewer, just south of Devine Street, about 0.75 km downstream from the mid-reach sampling station H. Industrial outfalls, downstream from the Devine street outfall, could not be accessed by the study team and had to be omitted from the modelling analysis.

The modelling of fecal bacterial loads, conducted in this study, represents a planning-level approximation with significant uncertainties. Such uncertainties are primarily caused by the complexity of the sewer system with numerous cross-connections and internal or external overflows, and high infiltration into sewers (Greck, 1990). Neither of these factors could be fully addressed within the limited scope of this study.

6.2 Modelling of Fecal Bacteria Densities in the St. Clair River

The modelling of fecal bacteria in receiving waters is made difficult by the complexity of the processes occurring in the nature. Even after simplification, the processes modelled should often include bacterial effluent mixing and dilution, bacteria dieoff or growth, and bacteria removal by sedimentation. In the case at hand, extensive simplifications are possible because of the special features of the receiving water body. In particular, the residence times in the main river channel are rather short, in the range from 45 to 90 minutes, and fast flows in the study reach preclude significant sedimentation. Consequently, it is safe to assume that in the river reach studied, the changes in bacterial densities caused by dieoff, growth and sedimentation are insignificant and can be neglected in the modelling analysis (Tsanis and Wu, 1991).

The same assumptions, however, may not be fully applicable in the water bodies connected to the main river channel and characterized by limited circulation. Such bodies include the Government Harbour and Sarnia Bay, but only the latter one is of interest in connection with water-based recreation. A detailed modelling of these water bodies would require extensive calibration data which were not available at this stage of study. Consequently, the main objective of the modelling work was to establish the feasibility of bacteria modelling in the study area with emphasis on recreational water uses and the relevant water quality guidelines.

6.2.1 Model Used

A two-dimensional horizontal (large width to depth ratio) depth-averaged irregular finite-difference model (FDM) was used to simulate the combined hydraulic and wind-induced circulation in the St. Clair River (Tsanis and Wu, 1991). The model was applied with two levels of discretization - an irregular grid encompassing the upper study reach (about 4.5 km long) and a regular grid discretization of Sarnia Bay and the adjacent section of the river. The former discretization allowed investigations of hydrodynamics and pollutant transport throughout the whole upper study reach, but the detail was too coarse for a good comprehension of flow conditions in the bay. Consequently, a second, finer discretization was introduced to allow a detailed analysis of flow conditions in the bay and its vicinity. Both levels of discretization are shown in Fig.10.

The flow components of the FDM model include two dynamic equations, with terms involving both depth-averaged velocities U and V, a Coriolis term, surface wind stresses and bottom friction stresses, and horizontal eddy viscosity terms. The third equation is a continuity equation. Transport of pollutants, described by a transport equation, includes two distinctive mechanisms - advection and turbulent diffusion. The first mechanism describes the entrainment of contaminants by the ambient flow and its transport in solution or suspension, at the ambient flow velocity. The second mechanism describes the entrainment of contaminants by turbulent eddies, thus effectively increasing the area occupied by the contaminant. The rate of diffusion in turbulent flow is described by a diffusion coefficient, which depends on the hydrodynamics of the river flow (Tsanis and Wu, 1991). In this analysis, it is desirable to distinguish between conservative and nonconservative contaminants. Bacteria were considered as nonconservative contaminants with a decay coefficient equal to 0.5 day^{-1}.

The reliability of modelling results can be greatly enhanced by model calibration and verification, which are commonly applied at advanced stages of analysis. During this study, only a partial calibration of the FDM model was possible, using the available river flow velocity measurements (U.S. Army, 1974) and estimates of dispersion coefficients D_x and D_y (McCorquodale et al., 1986).

6.2.2 Modelling Results

The modelling results are described in detail elsewhere (Tsanis and Wu, 1991); only the essential results required for further discussion in this report are summarized below. Two aspects of the modelling results are of particular interest in the study area - details of circulation in Sarnia Bay and the duration of after-effects of wet-weather bacterial inputs throughout the study area.

Flow Circulation in Sarnia Bay

Simulations of flow conditions in the study area indicate strong advective flows through the main river channel and these flows contribute to the generation of counter-clockwise eddies in two basins connected to the river channel, the Government Harbour and Sarnia Bay (see Fig.11). The resulting circulation can be enhanced by winds of favourable directions, as demonstrated in Fig. 12 for a 10 m/s westerly wind. The existence of these eddies, predicted by the hydrodynamic modelling, was confirmed by field observations.

Circulation patterns in the bay have important implications for the transport of contaminants discharged into the bay. Strong velocity gradients between the advective flow in the river channel and the eddies in the bay result in a limited interaction between the river and the bay. Thus, contaminants released in the bay will remain in the bay, at relatively high levels, for long time after the release, as confirmed by modelling results (Tsanis and Wu, 1991). These findings also apply to the Government Harbour.

The prevailing circulation, in the anti-clockwise direction, provides a mechanism for transport of pollutants, discharged from the shore in the vicinity of sampling stations F and G, into the other parts of the bay. This is demonstrated by the modelling results plotted in Fig. 13. In less than five hours after the start of a continuous contaminant discharge, the contaminant travelled to the northwest corner of the bay and attained concentrations equal to about 30% of the concentration released from the outfall. Thus, stormwater discharges along the east bay shore, characterized by the mean fecal coliform densities in the range from 1200 to 5000/100 mL, would be transported by the described circulation throughout the bay. About five hours after the start of continuous discharge, the bacterial densities in the bay would range from 400 to 1700 fecal coliforms/100 mL. For any contaminants discharged into the bay, the residence times would be rather long (10 - 20 hours).

Duration of the After-Effects of Bacteria Releases

The earlier discussion of field observations of bacterial densities showed great differences between dry and wet weather densities. The ability to distinguish between the dry and wet weather data in field surveys is impaired by the fact that the wet-weather impacts may extend into dry periods, long after the cessation of rain. Such after-effects can be caused by three factors - slow flushing of the receiving waters (or some zones of receiving waters), prolongation of wet-weather discharges due to infiltration into sewers (Greck, 1990), and malfunctions of sewerage systems allowing sanitary discharges even during dry weather. Only the first issue can be effectively addressed here, because the other two would require detailed surveys of all sewer outfalls in both dry and wet weather, extending beyond the scope of this study.

The duration of wet-weather after-effects in the receiving water can be studied by the hydrodynamic model used in this study. In such numerical experiments, high bacterial density inputs (10^4-10^5 organisms/100 mL) were introduced by the model and, after the cessation of such inputs, the times required to reduce bacterial densities to the 100 counts/100 mL level (equal to the water quality guideline for FC in recreational waters) were determined for various locations in the study area (see Figs.14 and 15). The durations of such after-effects are summarized in Table 11.

Table 11. Modelled Durations of Bacterial Densities Persisting Above the 100 Organisms/100 mL Limit after Cessation of Rainfall

Point No.	Location[1]	Duration (hrs)
1	River, 75 m in front of the mouth of the Gov. Harbour	0.5
2	Government Harbour, 250 m east of entrance, 50 m south of north pier	19.5
3	Sarnia Bay, 150 m south and 50 m east of NW corner	15.3
4	Sarnia Bay, 50 m south and 100 m west of NE corner	14.3
5	Sarnia Bay, 150 m south and 25 m west of NE corner	12.0
6	Sarnia Bay, 250 m south and 25 m west of NE corner	8.1
7	Sarnia Bay, sampling st. G, 25 m offshore	2.0
8	Sarnia Bay inlet, opposite Derby Lane, 175 m offshore	1.1
9	River, 125 m north of Cromwell St. CSO, 25 m offshore	1.0
10	River, 50 m south of Wellington St. CSO, 50 m offshore	1.3
11	River, 150 m south of Wellington St. CSO, 200 m offshore	1.2
12	River, 1 km downstream of site 11, 175 m offshore	1.6

[1] These locations are shown in Fig.14.

The results in Table 11 give a good indication of flushing times for various parts of the receiving water system. In the main river channel, the decline of bacterial densities after the rain cessation is very fast and points to strong advection transport. Any after-effects of wet-weather bacterial pollution inputs would disappear within 0.5 to 2 hours after the cessation of polluted discharges. Field observations indicating longer after-effects can be explained only by the continuation of pollutional discharges in dry weather, because of operational problems in the sewerage system.

The durations of after-effects in the basins with limited flow circulation, the Government Harbour and Sarnia Bay, are in the order of 10 to 20 hours. This slow flushing effectively extends the duration of wet weather impacts by these long periods. At the same time, the conditions in these basins, characterized by nutrient supply and favourable temperatures, may encourage the growth of Pseudomonas aeruginosa.

Finally, using bacterial fluxes in runoff and CSOs, described in Section 6.1, bacterial densities at selected river sites were simulated by the FDM model. A sample of such simulations is shown in Fig.16 for a storm of September 15, 1990. At the end of the storm, the fecal coliform densities along the Sarnia Waterfront were as high as 10^6/100 mL, with typical values ranging from $5x10^4$ to $1x10^5$/100 mL. In the bay, the peak density was about 10^3 FC/100 mL. After one hour, the densities in the river dropped to background values of 50 FC/100 mL and the same value was attained throughout the bay after about 11 hours.

The sensitivity of simulated results to the wind speed and direction (affecting circulation patterns) and the bacterial decay coefficient was tested in special simulation runs shown in Fig.17. The impacts of both factors on simulated results were deemed insignificant within the realm of modelling uncertainties.

When assessing the feasibility of modelling indicator bacteria, it appears that for recreational waters, the ability to reproduce the magnitude of peak bacterial densities is not critical at this stage of analysis. Obviously, large exceedances of the recreational water quality guidelines will occur in wet weather and the degree of exceedance is not critical when assessing the probability of noncompliance with the guideline. The speed of decline of these high bacteria densities is, however, of greater interest, because it indicates how long the wet-weather impacts persist in the receiving waters. The proposed modelling approach, based on a planning-level modelling of bacterial loads and a detailed modelling of the receiving waters is feasible for assessing the frequency and duration of noncompliance with the recreational water quality guidelines in wet weather. The difficulties with assessing the dry-weather conditions follows from the lack of knowledge of dry-weather fecal bacterial discharges into the river.

7.0 REMEDIAL MEASURES

The remediation of water contamination problems in the Areas of Concern is addressed in the local Remedial Action Plans (COA and MDNR, 1991). These plans deal with all the issues of water use impairment using an integrated approach with multiple purpose objectives. The same integrated approach is taken in the Pollution Control Plans required by the Ministry of the Environment to address both wet and dry weather pollution. A study preparing such a plan for the City of Sarnia is currently underway. Consequently, this section of the report should be viewed as a planning-level analysis suggesting some selected remedial measures to be considered in the future pollution control, in order to deal effectively with bacteriological contamination and impairment of recreational water use in the study area.

The discussion of limited remedial measures having a direct impact on bacteriological water quality is also useful for another reason - sizable investments required for implementation of the general pollution control plan will require a step-wise implementation addressing various issues according to their priorities. For such an implementation, some guidance for bacterial related tasks can be obtained from the discussion of bacterial control measures in this section.

Finally, it should be emphasized that before proceeding with any conceptual remediation measures discussed in this section, more detailed design/planning studies and public consultation would be required, including detailed modelling and model calibration/verification by field data. Also, the impacts of such measures on the river below the study area would have to be assessed.

7.1 Priorities Within the Study Area

Microbial contamination and/or contamination by other constituents is gradually increasing as the river passes through the urban core of the city and later through the petrochemical industrial area. Consequently, the costs of cleaning up individual reaches along the river will also increase in the downstream direction. It is therefore desirable to establish priorities for the restoration of water uses along the river shore, recognizing that in some (upstream) river reaches, the desired water uses can be restored faster and less expensively than in others. This is particularly true for swimming in the study area. Because the St. Clair river upstream from Sarnia Bay has a limited recreational (swimming) potential (fast currents, industrial land use), the main efforts should focus on Sarnia Bay and the Sarnia Waterfront which is a 600 m long reach of the river downstream from the Bay. Between these two prioritized areas, a higher priority should be given to Sarnia Bay which is already extensively used for recreational purposes.

Although the scope of this study was limited to the 9.5-km reach of the St. Clair River studied, the impacts of urban fecal bacterial pollution on the river below the study area must be recognized. Fecal coliform concentrations at the most downstream station J are rather high, as described by the geometric means of 240 and 860 FC/100 mL for the dry and wet weather, respectively. These concentrations will be further reduced downstream from the study area, mostly by the mixing of pollutant plumes following the shoreline and by bacterial dieoff. Improvements in the bacteriological water quality in the river below the study area will be achieved by the elimination of urban sources of fecal bacteria. Other remediation measures, enhancing the flushing in some recreational areas along the river or diverting pollutant discharges and plumes, do not reduce bacteriological loads entering the river and their usefulness for the improvement of downstream water quality is therefore limited.

7.2 Remedial Measures Studied

Conceptual remedial measures comprise source controls (removals of fecal bacterial sources), diversion of fecal bacterial discharges from the slow-flushing areas, and the dilution of fecal bacterial densities enhancing guideline attainment. Although various combinations of these three measures can be used to improve the microbial quality of water in the study area, source controls are preferable because they prevent contamination of the receiving waters and their beneficial impacts extend even downstream from the study area.

Microbial concentrations in stormwater runoff are barely controlled by non-structural (policy oriented) measures. It is recognized that a general cleanliness of urban areas contributes to reduced bacterial loadings, but the presence of indicator bacteria is unavoidable (U.S. EPA, 1983; Olivieri et al., 1989). The cleanliness and sanitation of urban areas can be improved by strict enforcement of pet control, anti-litter campaigns and public education, proper solid waste collection, and regular street sweeping and cleaning. The effectiveness of the above measures in reducing the bacterial loadings on the catchment surface is not known. On the other hand, structural measures, consisting in removal of cross-connections between storm and sanitary/combined sewers and discontinuation of dry weather discharges, are very effective in reducing fecal bacterial loadings (U.S. EPA, 1974). Even small numbers of cross-connections can severely contaminate flows in storm sewers.

The control of fecal bacterial sources should also be prioritized according to the source strength. In this connection, the first priority would be to address the dry-weather discharges of fecal bacteria, generally caused by sewer cross-connections, prolongation of discharges by high sewer infiltration, and possible malfunctioning of controls in combined sewers. In both cases, sanitary sewage with extremely high fecal bacterial densities is discharged into the receiving waters and the recreational water quality guideline is inevitably exceeded. The presence of these sources in the study area is documented by high dry-weather fecal bacterial densities in the river reaches with sewer outfalls. The control of these sources would improve water quality during both dry and wet weather.

7.2.1 Sarnia Bay

Field surveys indicated frequently occurring bacteriological contamination of the bay well in excess of the recreational water quality guideline (100 FC/100 mL). The sources of such contamination include one storm sewer discharging along the north shore and four storm sewers discharging along the east shore, grey waters from boats using the marina in the bay, possible growth of microorganisms in the bay, local drainage, and the river water entering the bay through the interface between the bay and the river.

Following the removal of dry-weather discharges of fecal pollution discussed in the preceding section, the next step would be to control stormwater discharges. A direct source of fecal pollution could be removed from the bay by redirecting the existing 0.4 m-diameter storm sewer from the bay to the harbour (Fig.18). This would require to extend this sewer by about 125 m, subject to any restrictions on the available head drop. The impact of the remaining four storm sewers, which contribute bacteria and viruses to the bay through eddy circulation, would need to be countered as well. Possible solutions include interception of these storm sewers and moving their outfall further downstream, at least to the vicinity of the George Street storm sewer. This would require construction of an interceptor, up to 0.5 km long and about 1.5 m in diameter. Other control measures would include storage of stormwater discharges from these four sewers and partial treatment by sedimentation and disinfection. All the above measures would reduce the incidence of wet-weather impacts on microbial water quality in the bay.

Another method of diversion of contaminated discharges consists in preventing the formation of the counter-clockwise eddy, which transports storm sewer discharges into the bay. This could be achieved by building a deflector barrier, extending in the westerly direction into the bay (see Fig.18).

The last source of fecal and indicator bacteria in the bay are the so-called grey waters discharged from pleasure boats operating in the bay. Improved controls of such waters would be beneficial for reducing bacterial inputs as well as for reducing the supply of nutrients required for bacterial growth in the bay (Ministry of the Environment, 1991).

A faster flushing of the bay and the prevention of growth of Pseudomonas aeruginosa would be accomplished by pumping river water into the northwest corner of the bay. By discharging this water along the northeast wall of the Sarnia Bay Marina, a circulation would be set in the clockwise direction and it should transport storm sewer discharges along the east shore of the bay and out into the river. The pipe connecting the bay with the river would be about 65 m long. Discharges in the order of 1 m^3/s were found insufficient to set up the desired circulation and, consequently, higher discharges would be required. The operation of this system does not have to be continuous, it could be operated in wet weather and/or when the bay needs flushing. Operation in wet weather would prevent stormwater from the four outfalls entering the bay and would thus prevent fecally oriented microorganisms and other pathogens, nutrient and other stormwater loadings from entering the bay.

The water pumped into the bay should be similar in microbiological quality to that observed at station D, which showed the lowest concentration of fecal indicator organisms and pathogens in the entire study area and indicated compliance with the recreational water quality guideline for almost 90% of the summer period. An improved bay flushing and loss of nutrient loads should lead to reduced risks of growth of Pseudomonas aeruginosa. On the adverse side, this flushing would have impact on the temperature of water in the bay and such impacts, as well as other impacts on the bay ecosystem, would have to be studied and fully assessed through public consultations.

To illustrate the potential impacts of the remedial measures discussed in this section, several remedial scenarios (see Fig.18) of increasing complexity (and costs) were simulated by the receiving water quality model. The results of such simulations, for a particular storm event, are shown in Fig.19(a)-(f).

Fig.19(a) is a reference simulation run, for the existing conditions and assumed absence of dry weather sources of fecal pollution. During the storm, the fecal coliform densities inside the bay (locations #2 and #4) ranged from 1,000 to 5,000, and along the waterfront the corresponding densities were about 100,000 FCU/100 mL. After the storm, the densities along the waterfront quickly subsided to the background levels. Inside the bay, the decline in FC densities was much slower and lasted from 7 to 17 hours.

Fig.19(b) shows the impact of disconnecting the storm sewer SS104 (see Fig.18). The only location showing any impacts of this measure is location #2 where FC densities were slightly reduced. Similarly, the impact of disconnecting storm sewer SS105, shown in Fig. 19(c), was manifested by reduced FC densities at locations #2 and 4, and by a faster decline of high FC densities. An addition of a deflector barrier upstream from the storm sewer SS105 (Fig.19.d) slightly reduced FC densities in the bay and contributed to their faster decline. The enhanced flushing of the bay, by pumped riverine water discharged close to location #2, led to slightly reduced FC densities at this location (Fig.19.e).

Finally, the impact of disconnecting storm sewers SS104 and 105, and building a deflector barrier upstream from SS105, to prevent the transport of fecal pollution into the bay by an anti-clockwise eddy, is shown in Fig.19.f. This measure reduced FC densities by 40 to 50 times and brought them to the levels comparable to the recreational water quality guideline of 100 FC/100 mL.

The simulation results presented in Fig.19 indicate that the microbial quality of water in Sarnia Bay can be improved by combinations of various remedial measures. The best results were obtained by source controls and prevention of fecal pollution transport into the bay by an eddy circulation. Depending on detailed costing and evaluations in a wider context of water pollution control planning for the study area, the remedial measures discussed in this section show a good potential for control of fecal bacterial contamination in Sarnia Bay.

7.1.2 Sarnia Waterfront

The fecal bacterial contamination along the Sarnia Waterfront is much more serious than in the Bay and calls for thorough controls of both dry and wet weather pollution. In this river reach, there are ten storm sewer and CSO outfalls, which contribute to excessive fecal bacterial pollution of the river along the shore. Field observations in this study indicate that some of these outfalls discharge even in dry weather and this further exacerbates the pollutional impacts.

A full remediation of wet-weather flow impacts may be hard to accomplish and seems to be less important than the remediation of water quality during dry weather with high demands on water-based recreation. Under the existing conditions, the poor bacteriological quality along the waterfront can be explained only by sewage discharges during dry weather. These discharges can be caused by cross-connections of storm and sanitary/combined sewers, prolonged discharge of CSOs caused by sewer infiltration, and slow drainage of sewer outfalls when river stage drops and backflow check valves at the outfalls open.

While the data collected in this study did not allow to estimate the magnitude of suspected dry weather discharges of sewage, potential impacts of such discharges can be demonstrated by the receiving waters model. An example of the impacts of sewage discharges on FC densities along the waterfront is shown in Fig.20. In this case, a steady discharge of sewage ($Q < 0.1$ m^3/s), with fecal coliform densities of 10^6 FCU/100 mL, was released from sewer outfall SS107 and produced FC densities ranging from 400 to 10^5 FCU/100 mL along the waterfront. Since the FC densities observed at the sampling station H sharply exceeded those at the next upstream station G, it was believed that these high FC densities were caused by sources in the immediate vicinity of station H.

As stated earlier, some reductions in bacterial loadings in stormwater and CSOs can be achieved by nonstructural measures, but their effectiveness is limited. After the implementation of such measures, structural remedies are required. In the order of priorities, dry-weather discharges and CSOs have to be addressed first using a variety of control options including source controls, collection system controls, and storage and treatment. It is expected that such options will be addressed in the forthcoming pollution control study of the city.

For storm sewers, some reductions in their bacterial loads can be achieved by elimination of sewer cross-connections and by the nonstructural measures discussed in Section 7.1.1. Needs for such measures and their priorities would have to be established by detailed surveys and sampling of individual pipes.

The control scenarios for the Sarnia Waterfront comprise a complete removal of dry weather pollution along the waterfront and removal of CSOs. The fast advective transport along the waterfront indicates that these measures should limit the bacterial pollution along the waterfront to the periods of wet weather. Because of strong advective transport along the waterfront, after-effects of wet-weather pollution would be limited and the river channel would be flushed in slightly more than an hour. The removal of fecal bacteria sources would have beneficial impacts on bacteriological quality of the river below the city.

8.0 SUMMARY AND CONCLUSIONS

Urban sources of fecal indicator bacteria and bacterial pathogens severely impact on bacteriological quality of water in the St. Clair River in Sarnia. These impacts are caused by both wet and dry weather sources of fecal bacteria and their severity increases along the river shore from the most upstream station at the Blue Water Bridge to the upstream end of the industrial shore. From here to the downstream end of the industrial area, a partial recovery of the bacterial water quality takes place.

Observations of common indicator bacteria were used to detect the fecal pollution of the St. Clair River and to estimate compliance with the recreational water quality guidelines. The concentrations of five indicators, fecal coliform, fecal streptococci, Pseudomonas aeruginosa, E. coli and coliphage all indicate fecal bacterial contamination of various degrees, ranging from minor at the upstream end of the area (at the Blue Water Bridge) to major, at the downstream end of the Sarnia waterfront. Furthermore, unusually high levels of Pseudomonas aeruginosa (a bacterial pathogen which causes ear, eye, nose and skin infections in swimmers) observed at some stations, may be caused by the known ability of this microorganism to grow in nutrient rich waters.

In the areas upstream from Sarnia Bay, the probability of fecal coliform concentrations being less than 100 FC/100 mL (i.e. the limiting value listed in the Ontario water quality objectives) was estimated at 80%, for the entire swimming season including both dry and wet days. At the CN Yard, about 0.5 km downstream from the City Hall, this estimated probability declined to 1% (equivalent to one day per the swimming season), and just downstream from the industrial shoreline, this estimated probability increased to about 16%. The sites inside the bay were characterized by intermediate probability values around 44%.

Fecal bacterial sources include stormwater runoff, combined sewer overflows (CSOs) and wastewater treatment plant effluents. These sources of contaminated discharges in turn receive bacteria from many primary sources. For stormwater, such sources include animal feces (from both wildlife and pets), human fecal pollution from cross-connections with sanitary sewers, urban garbage and litter, and catchment surface wash. The observed fecal pollution in stormwater resembled that typical for diluted sanitary sewage. In the case of CSOs, fecal bacteria originated from the stormwater sources and, most importantly, from sanitary and industrial sewage discharged into combined sewers. High bacterial densities are also found in the sewer sludge deposited in sewers in dry weather and washed out in wet weather. Concentrations of fecal bacteria in CSOs in Sarnia were fully comparable to those found in raw sewage. Sewage treatment plant effluents contain fecal bacteria from all the above sources, including human fecal pollution. Fecal bacteria are partly removed by treatment, e.g. the sedimentation of solids, but more effectively by disinfection. In the study area, the Point Edward WPCP effluent impact was undetectable. The impact of the Sarnia WPCP was not assessed because of the lack of access to the outfall site.

A planning-level runoff model was used to simulate fecal bacterial loads carried by urban runoff and CSOs, with modelling uncertainties adequate for the assessment of recreational water quality. This model also provided an input to the receiving water model, which simulated river hydrodynamics in the study area and transport of bacteria. The receiving water model reproduced the wet-weather fecal bacterial densities with acceptable accuracies. Difficulties with modelling the dry-weather conditions followed from the complexity of and operational problems in the municipal sewer system, indicated by high fecal pollution during dry weather. The fecal bacterial concentrations observed could be explained only by dry-weather discharges of fecal pollution.

Hydrodynamic simulations indicated a very fast advective transport in the main river channel, with a quick flushing. The pollutant discharges entering the river are quickly washed through, with the times of travel through the study reach in the order of 1.5 hours. Substantially different results were found in two basins with limited water circulation - the Government Harbour and Sarnia Bay. In these two water bodies, weak circulation currents are set by shear stresses along the interface with the main river flow and wind stresses on the water surface. Most attention focused on Sarnia Bay which is used widely for water-based recreation. A fast river flow sets a counter-clockwise circulation in the bay and this circulation transports contaminated discharges from the sewer outfalls along the east river bank into the bay. The exchange of water in the bay is rather slow and the decline of wet-weather pollutant levels to the levels characteristic for dry weather may take 12-24 hours after the cessation of rainfall. These times further extend the duration of pollutional impacts of rainfall events.

Remedies of fecal bacterial pollution have to be addressed in conjunction with the comprehensive planning of pollution controls for the City of Sarnia as well as the areas downstream from the city. Such a planning process can benefit from a preliminary assessment of the fecal bacteria controls and control priorities addressed in this study. In the assessment of local priorities, a higher ranking should be assigned to Sarnia Bay which is extensively used for water-based recreation, followed by the Sarnia waterfront. For both sites, the first remedial measure to be implemented is the control of dry weather discharges of fecal bacteria.

The remedial measures studied for Sarnia Bay included the removal and/or diversion of storm sewer discharges from the bay, prevention of the counterclockwise circulation which brings pollutants discharged from sewer outfalls into the bay, and the improvement of bay flushing by creating a clockwise circulation forced by river water pumped into the northwest corner of the bay. Although each of these measures brought about some improvement in the simulated bacteriological quality of water in the bay, a significant improvement in the probability of compliance with the recreational water quality guidelines was achieved only by removing all sources of fecal bacteria from the bay.

Remediation along the waterfront will require extensive structural measures including runoff controls, collection system controls and storage/and or treatment of wet weather flows. The planning of such control schemes should start by addressing the dry weather pollution whose control would significantly reduce the impairment of recreational water uses during the summer months. Preferred alternatives generally represent cost-effective combinations of various types of controls. The final assessment of the remedial measures would require a more robust data base than the one collected in this study, more detailed modelling with full model calibration/verification, and extensive public consultations.

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FIGURES

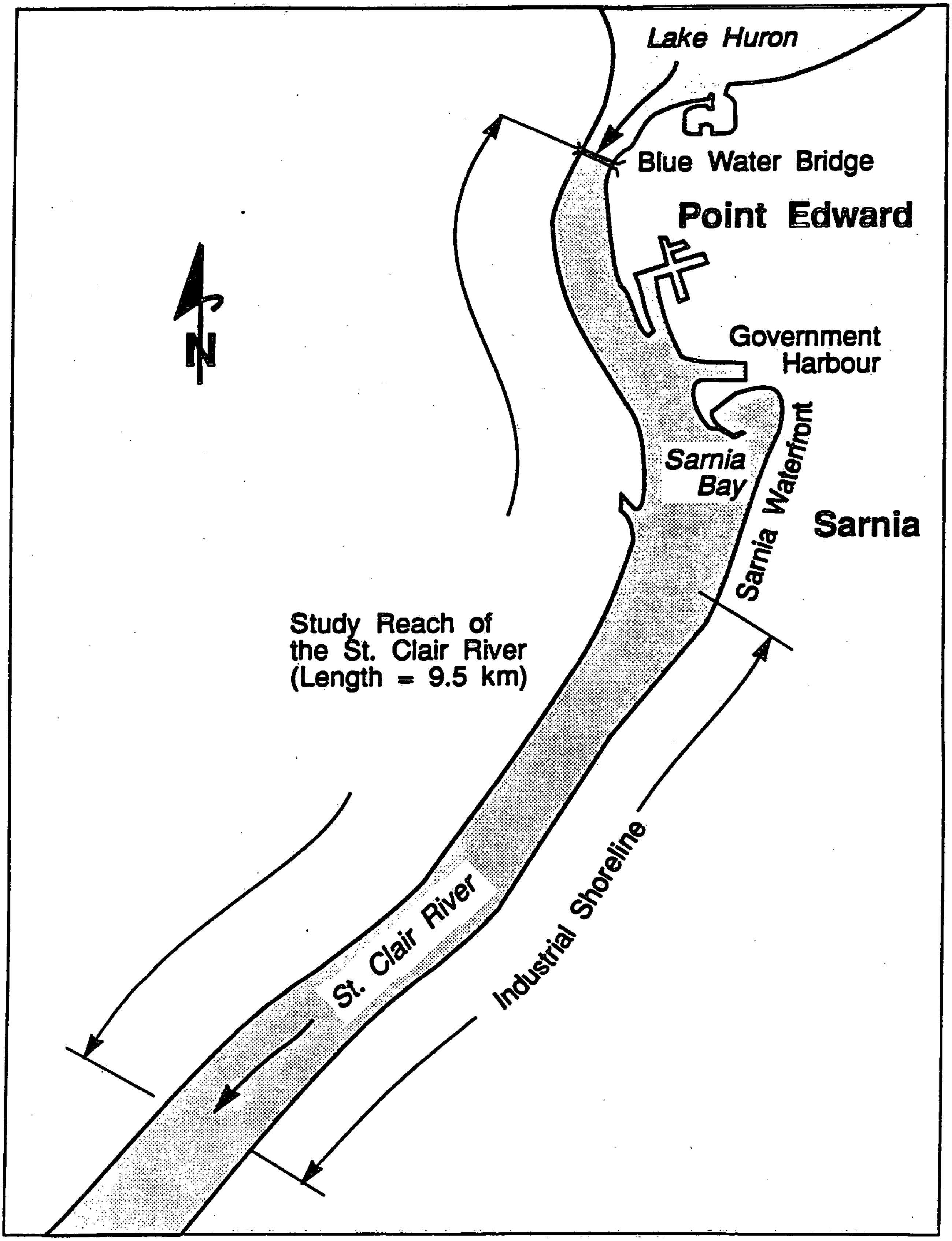


Figure 1. Study Area

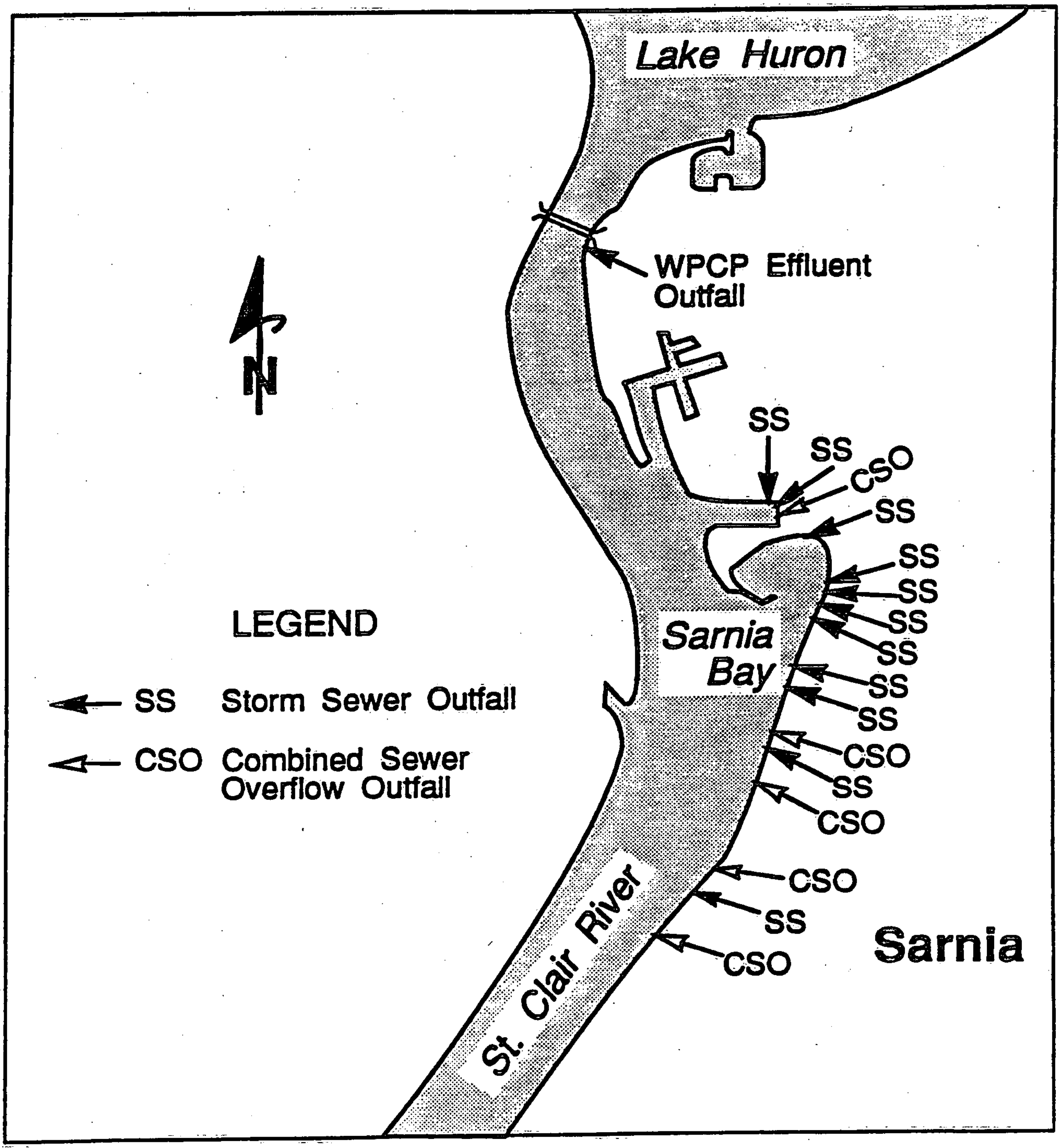


Figure 2. Municipal Sewer Outfalls in the Study Area.

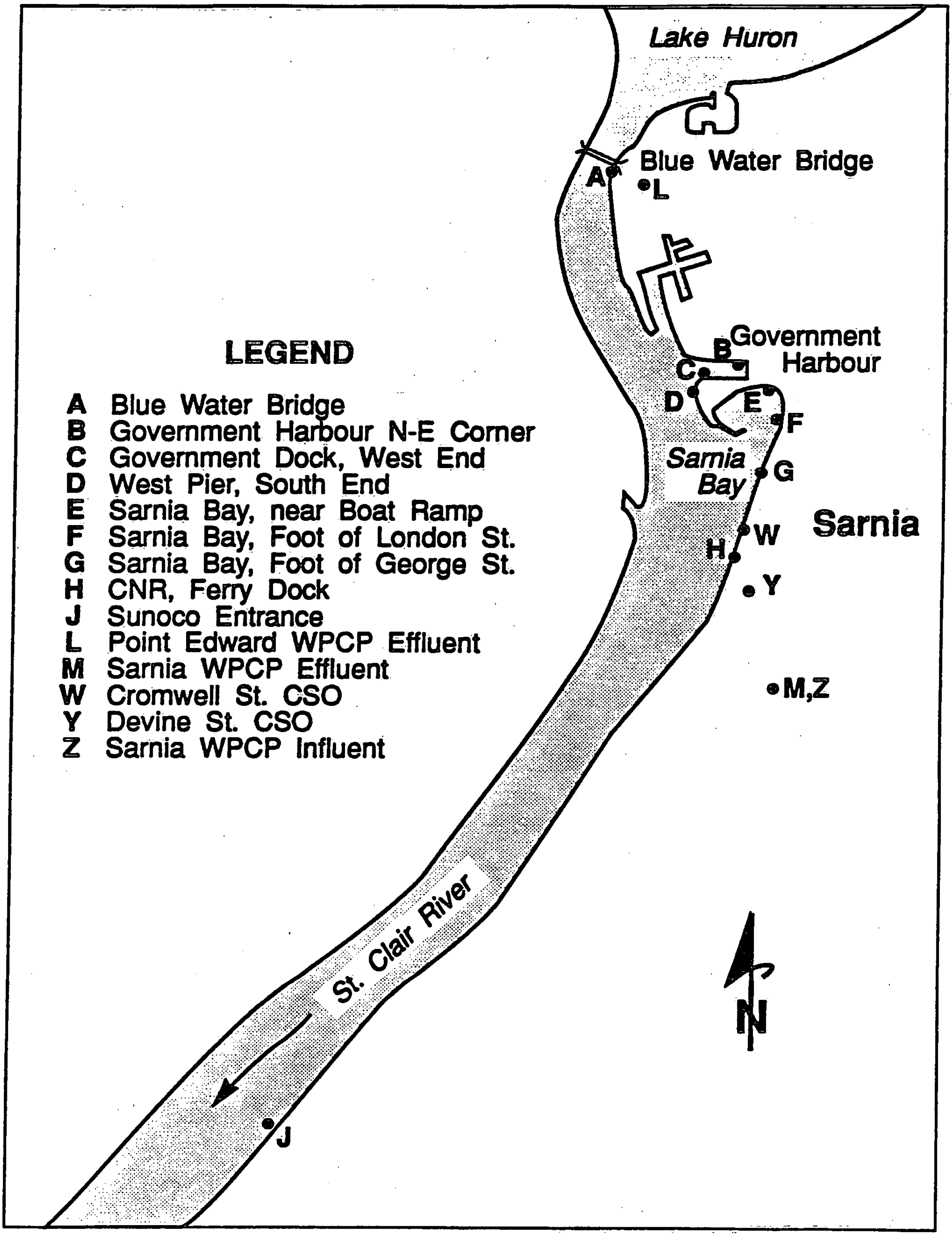


Figure 3. Sampling Locations.

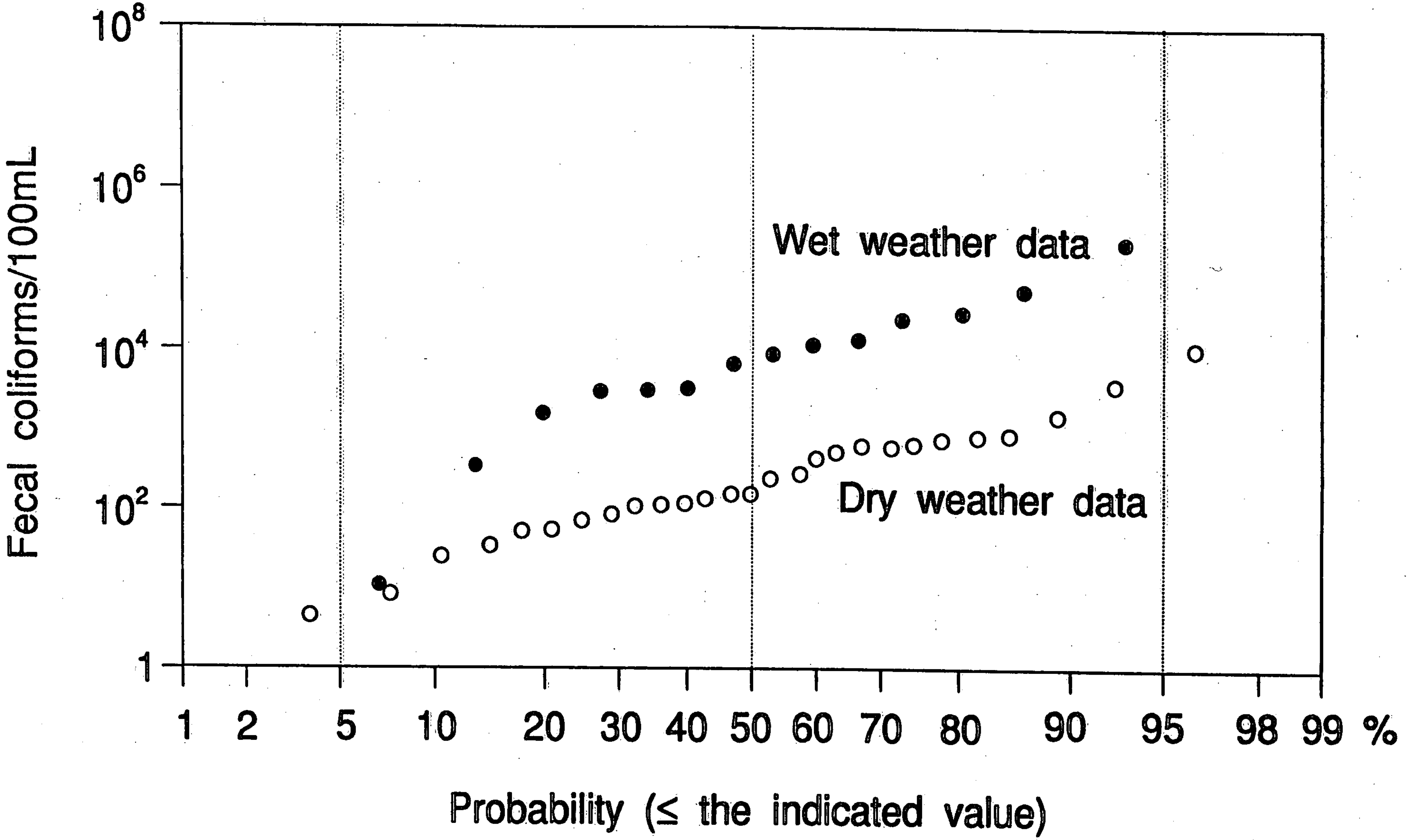


Figure 4. Sample of Bacterial Density Distributions (Station B - Government Harbour)

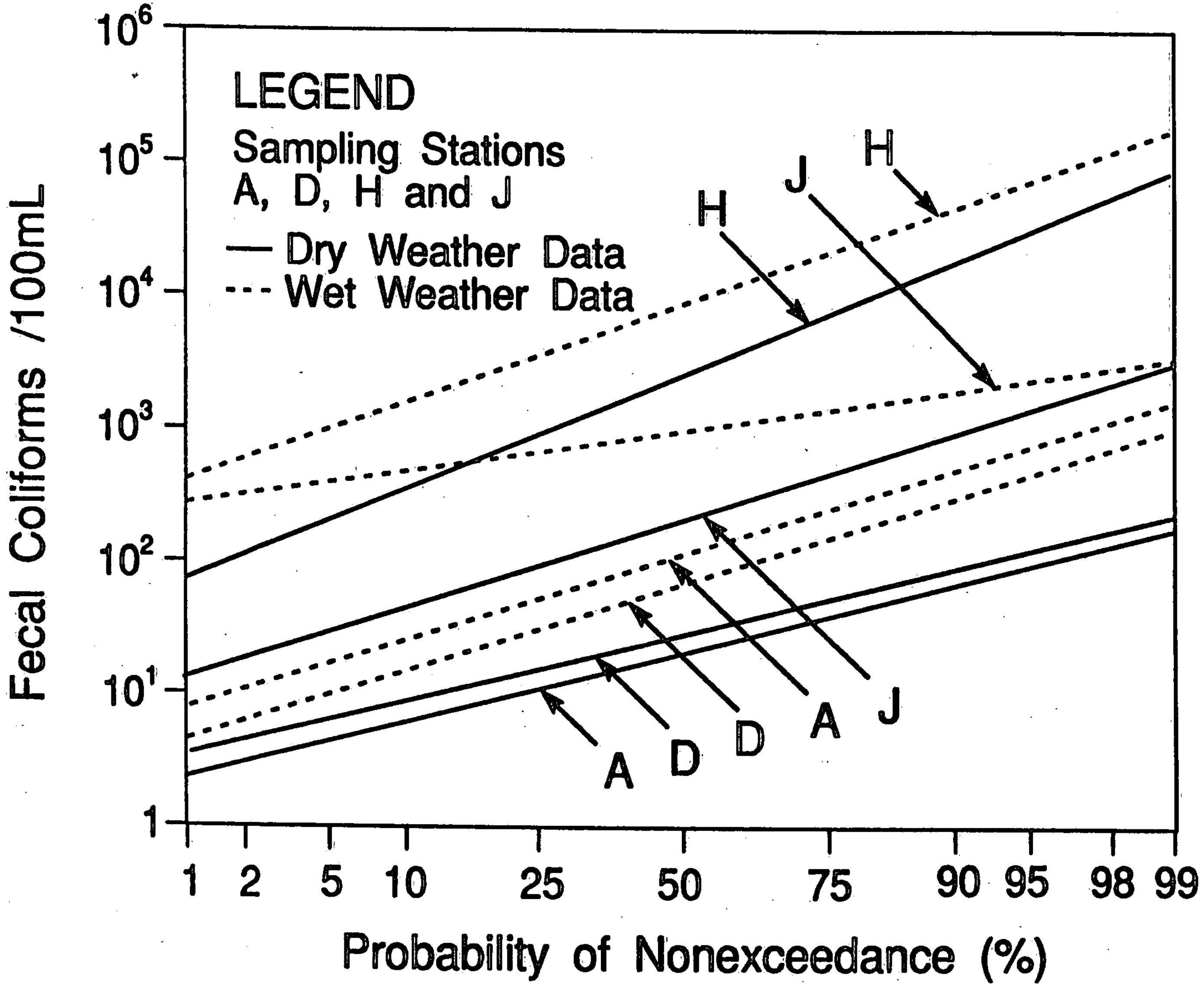


Figure 5. Fecal Coliform Density Distributions at River Stations.

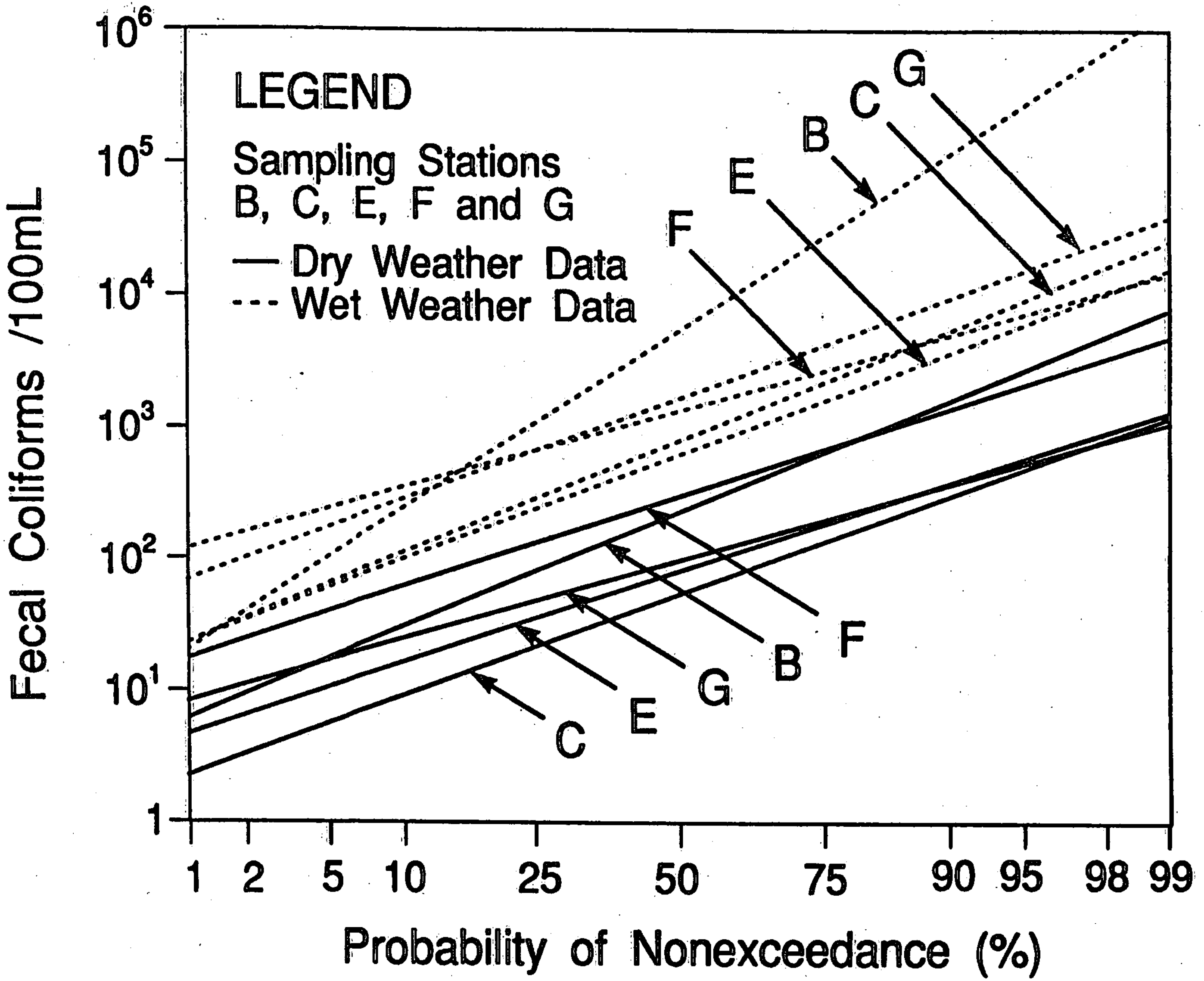


Figure 6. Fecal Coliform Density Distributions at Government Harbour and Sarnia Bay Stations.

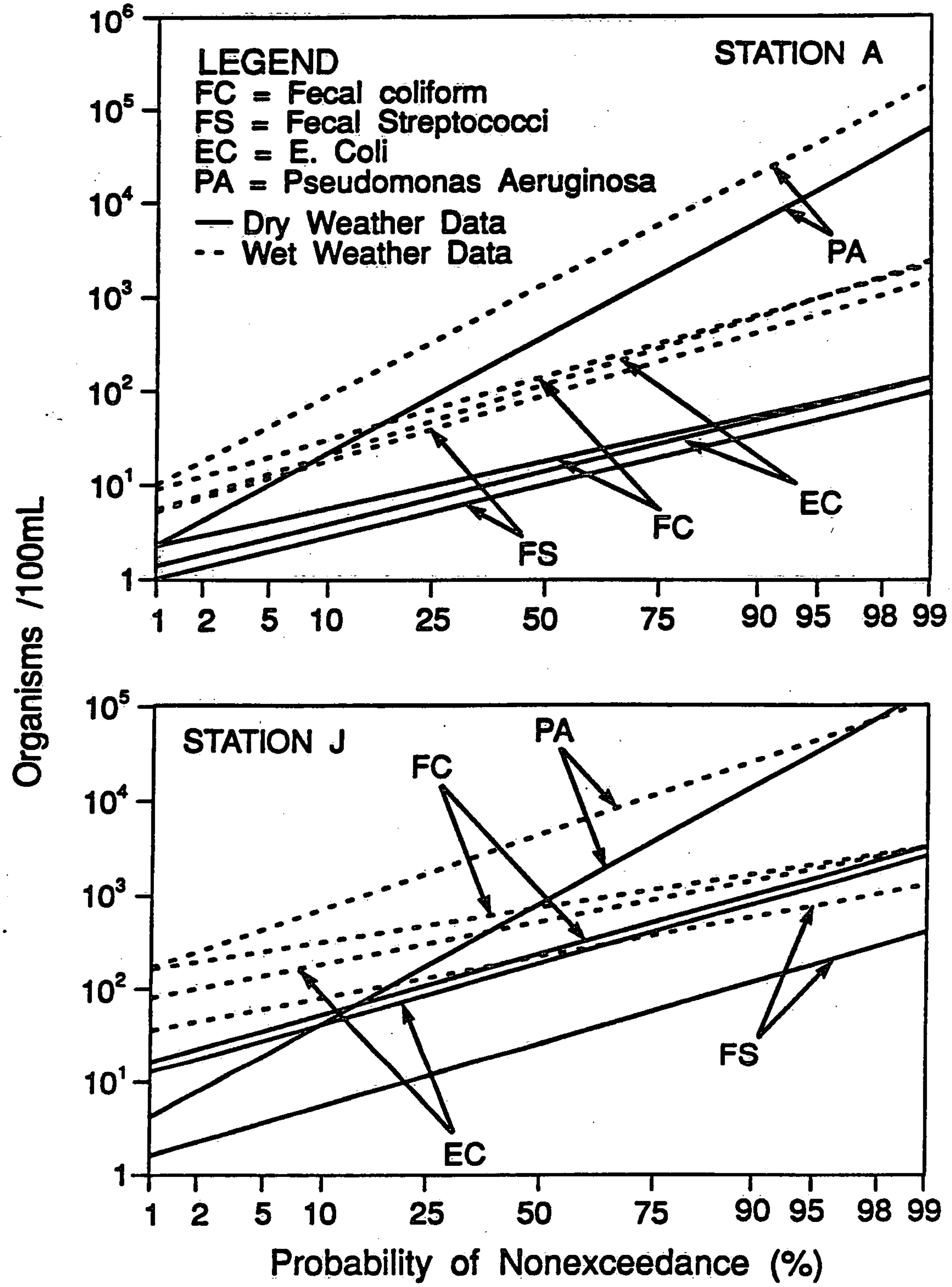


Figure 7. Distributions of Microorganism Densities at Stations A and J.

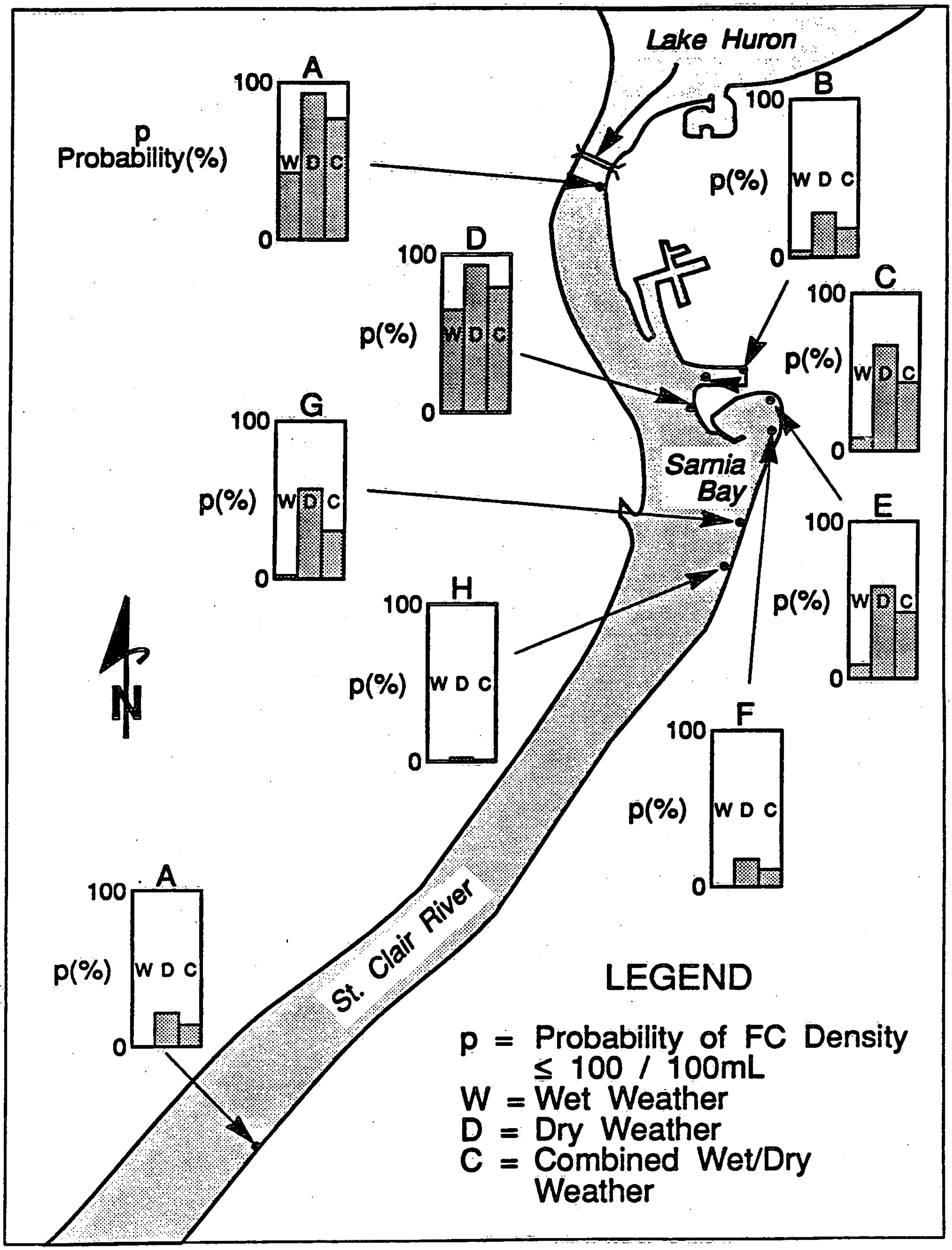


Figure 8. Estimated Probabilities of Fecal Coliform Densities ≤ 100 / 100 mL

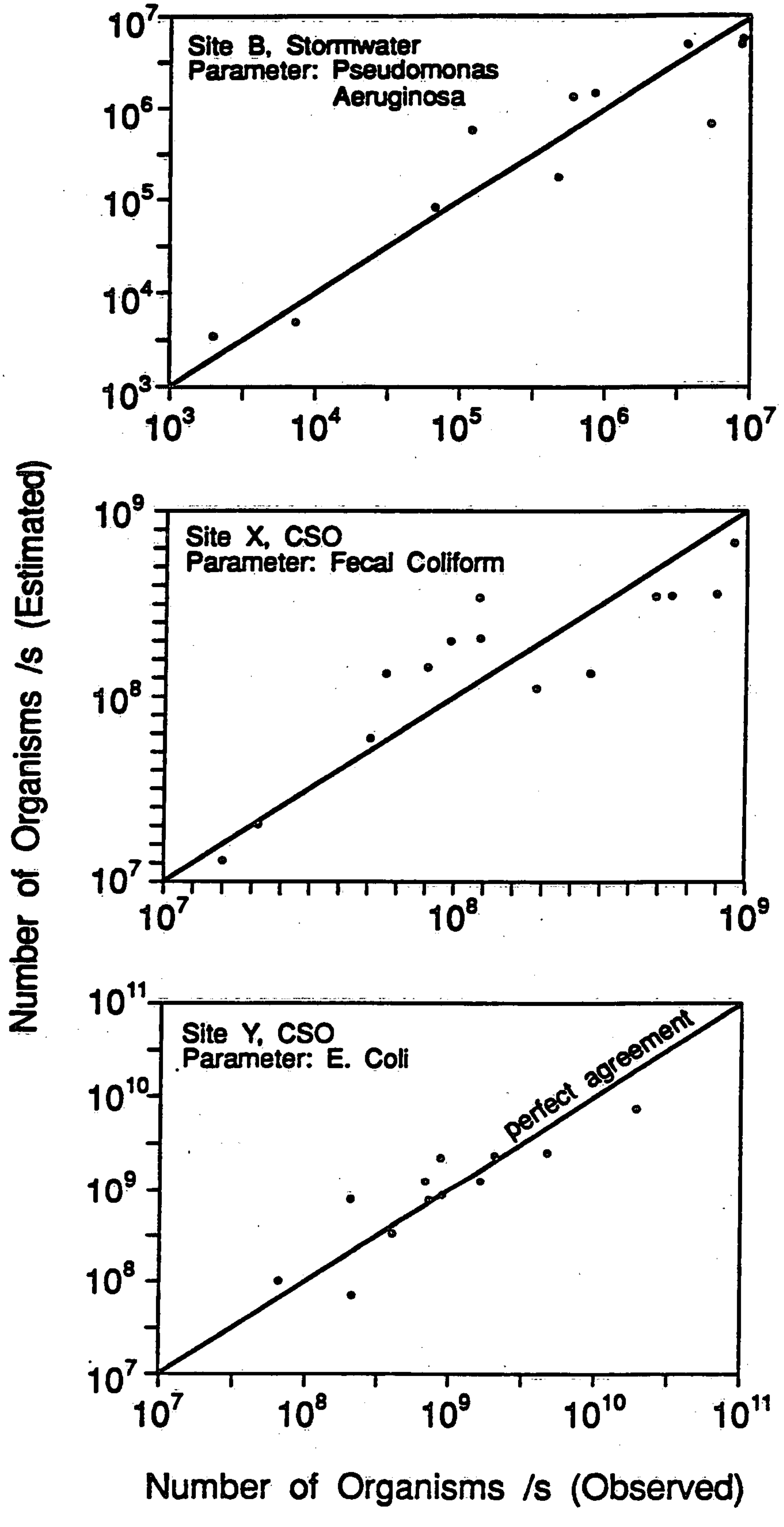
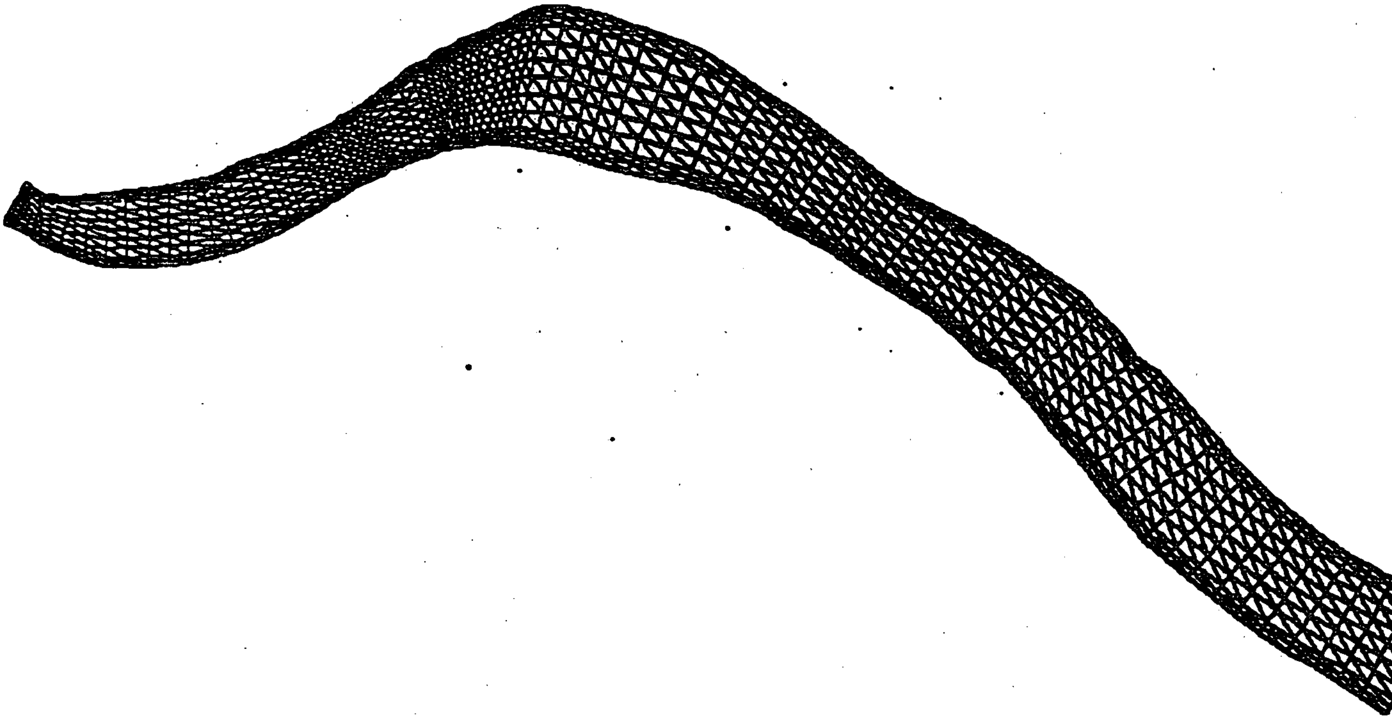


Figure 9. Examples of Bacterial Fluxes: Observed and Estimated.

(a) Irregular-Grid Discretization of the Upper St. Clair River Study Reach.



(b) Regular-Grid Discretization of the St. Clair River around Sarnia Bay.

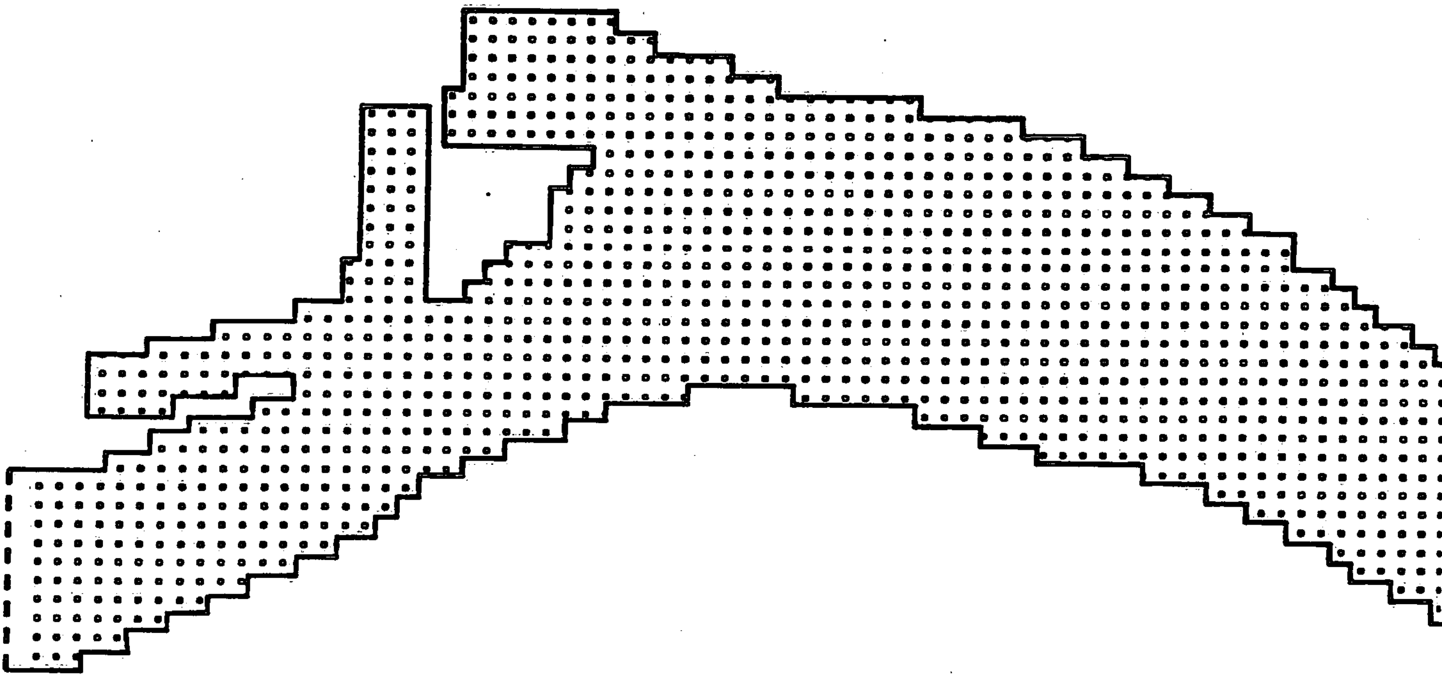


Figure 10. Two Levels of Discretization of the St. Clair River.

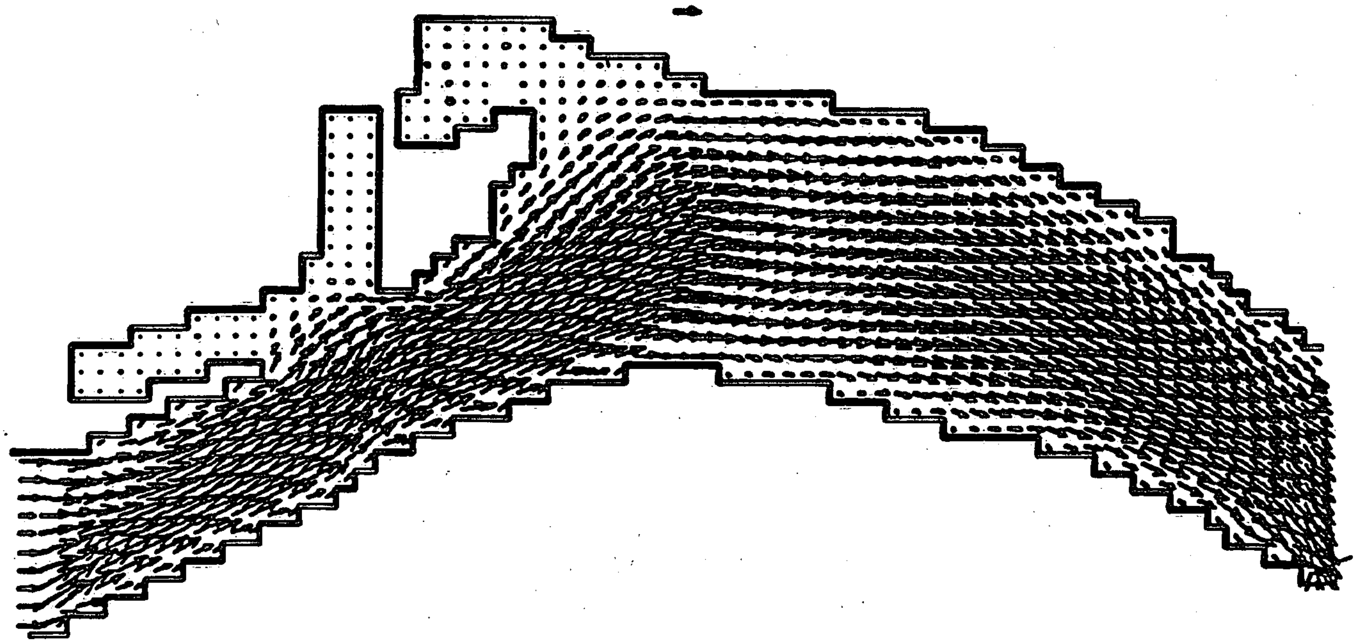
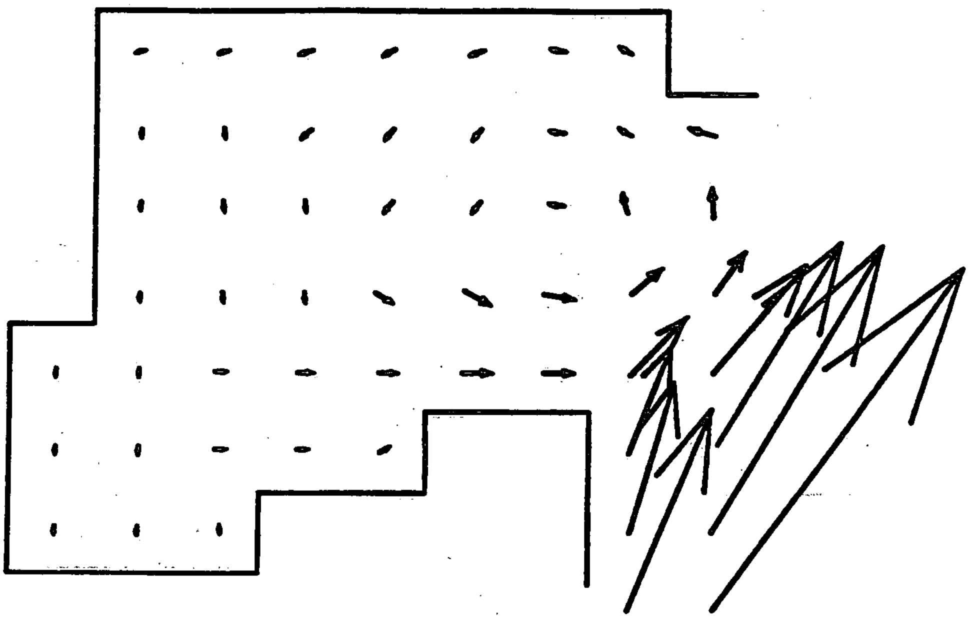


Figure 11. Simulated Velocity Field in the St. Clair River and Sarnia Bay.

(a) Bay Model



(b) Nested Model of Sarnia Bay.

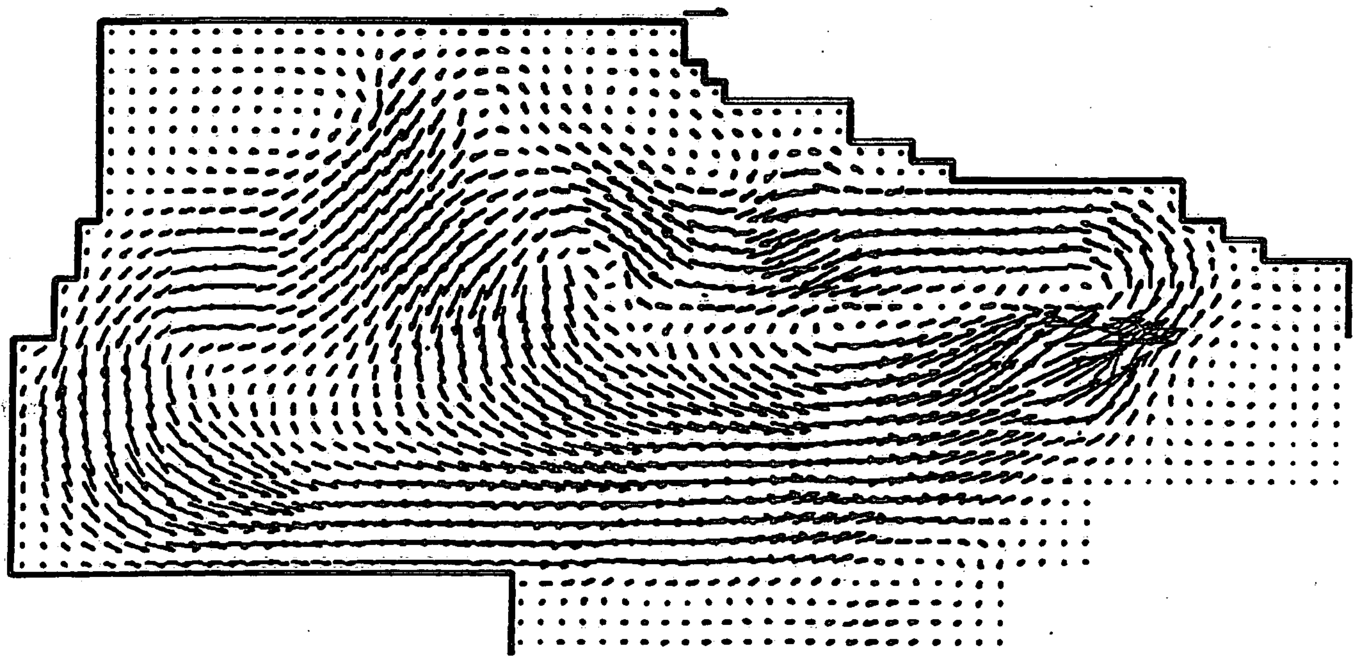


Figure 12. Effects of a 10 m/s West Wind on Velocity Field in Sarnia Bay.

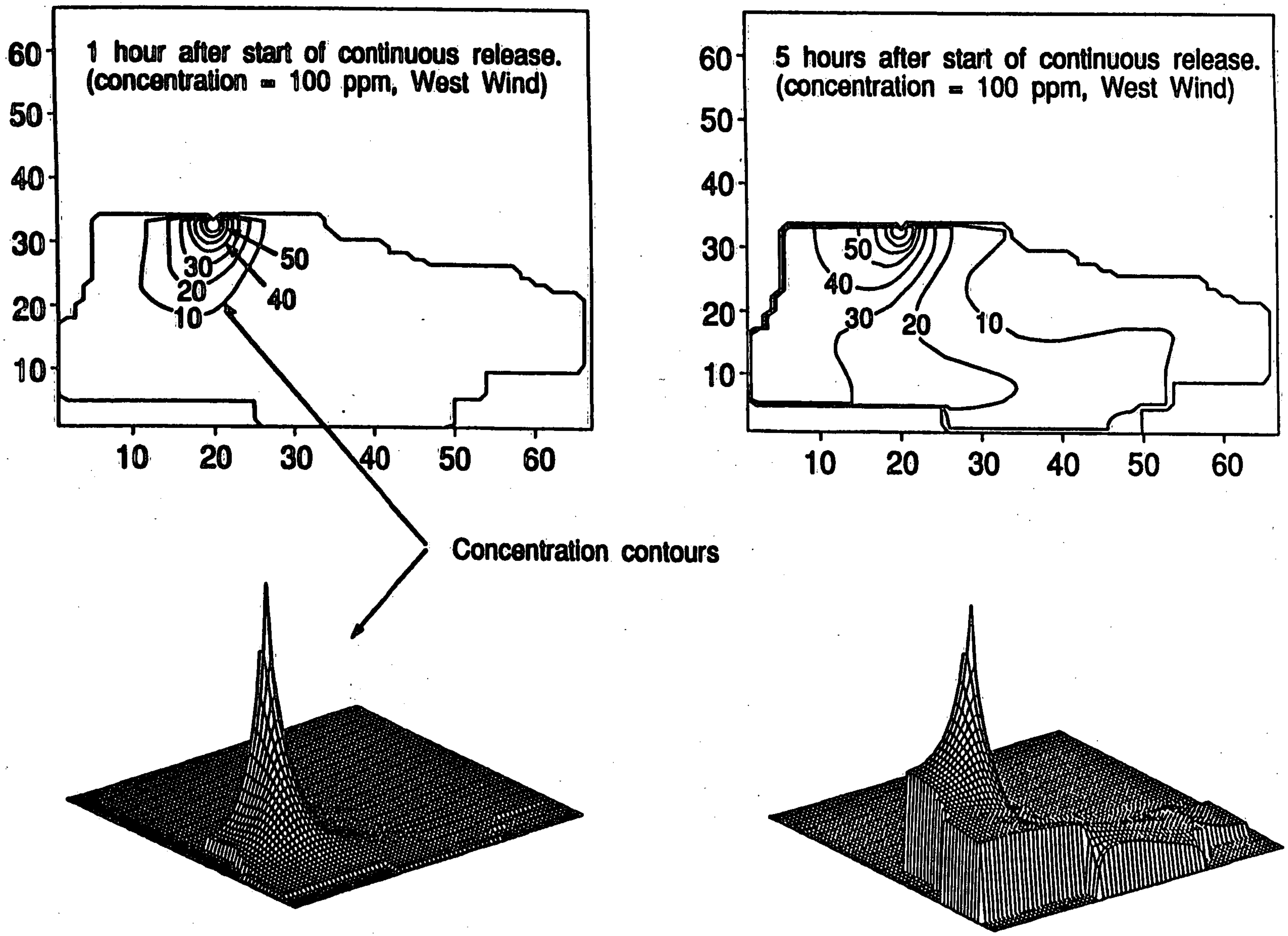


Figure 13. Spreading of Pollutants Released from East Shore of Sarnia Bay.

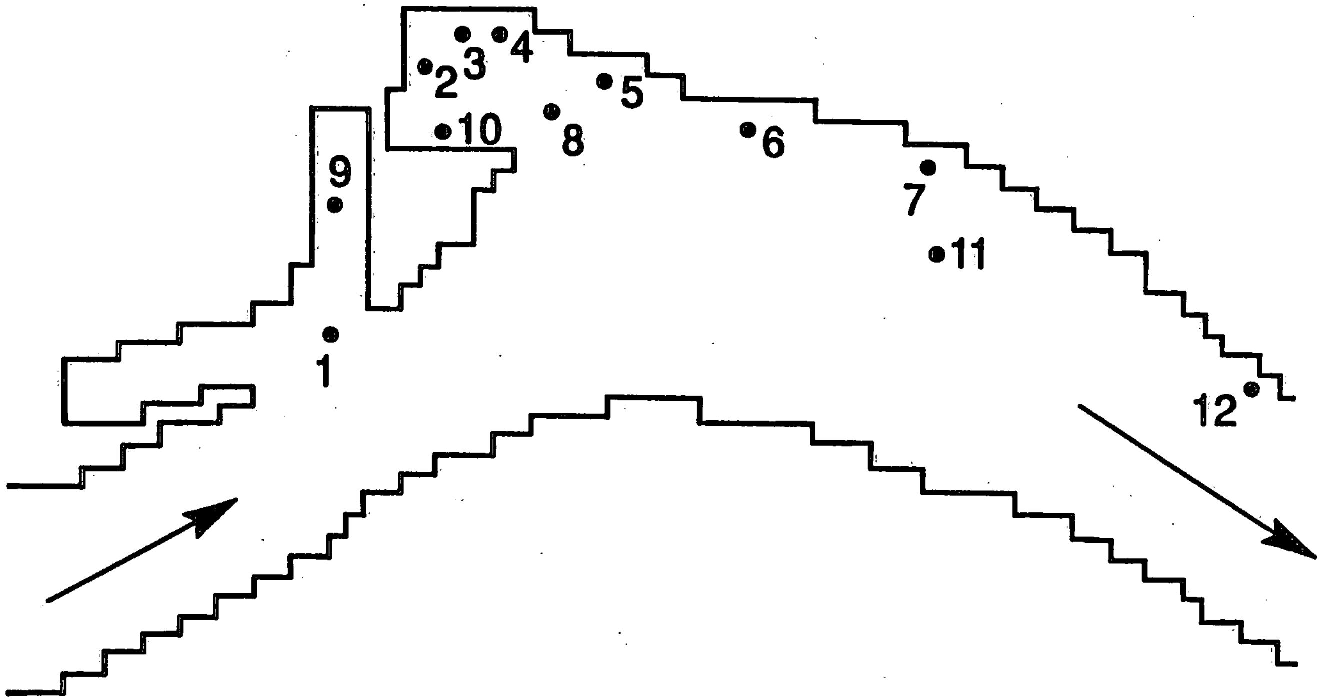


Figure 14. Locations of Points at which Temporal Variations of Bacterial Densities Were Simulated

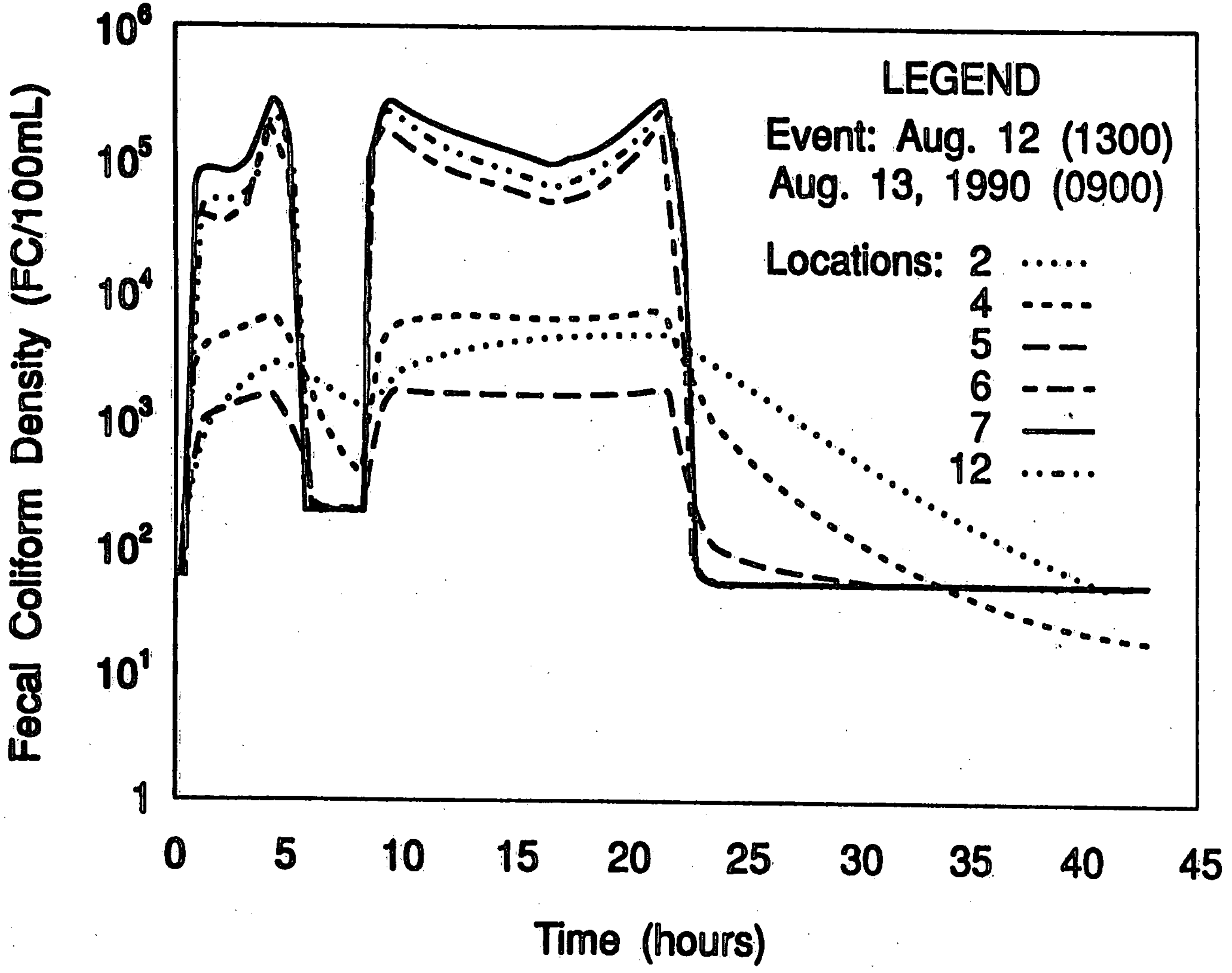
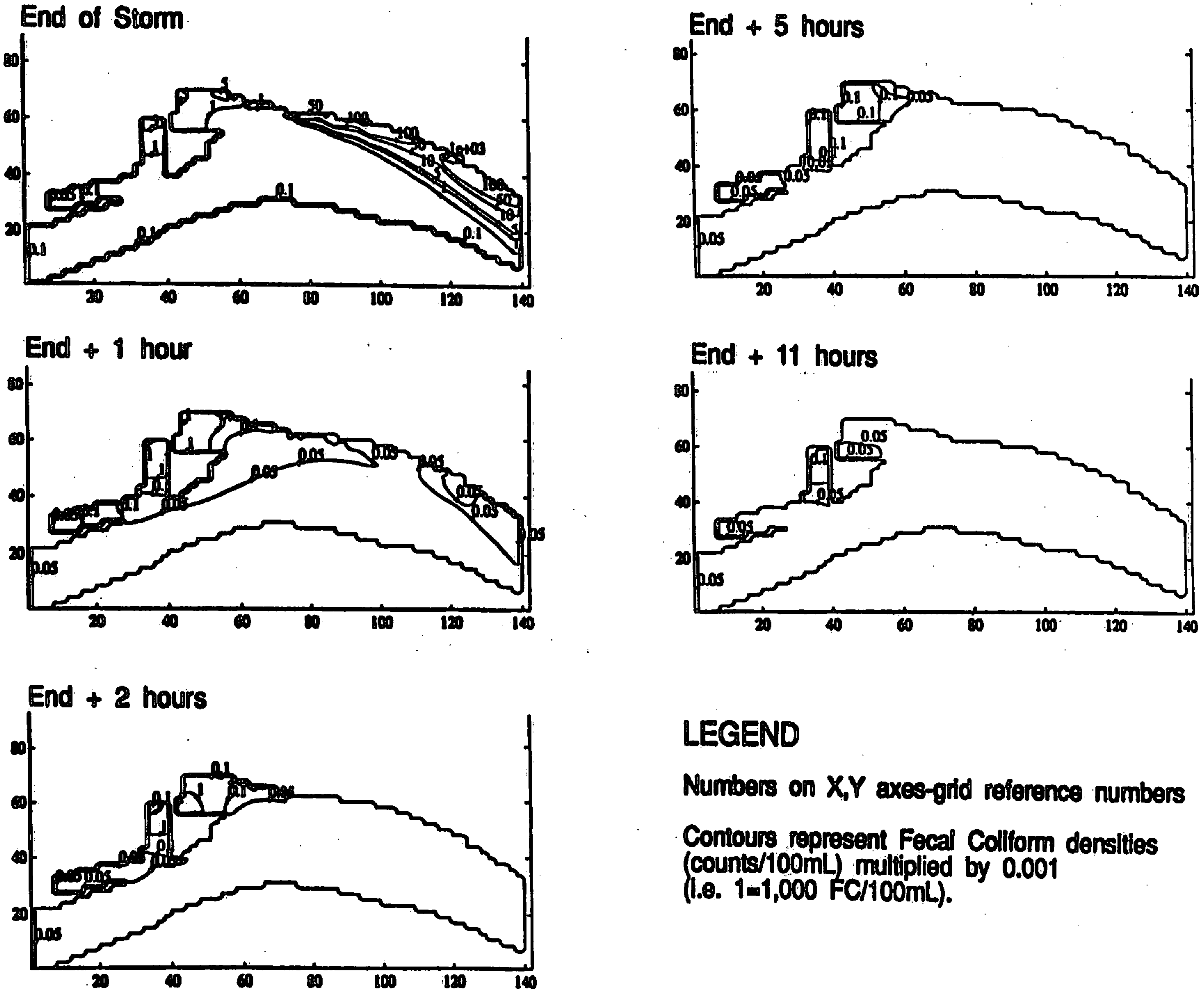


Figure 15. Simulation of Fecal Coliform Densities for Selected Locations. (Storm of August 12/13, 1990)

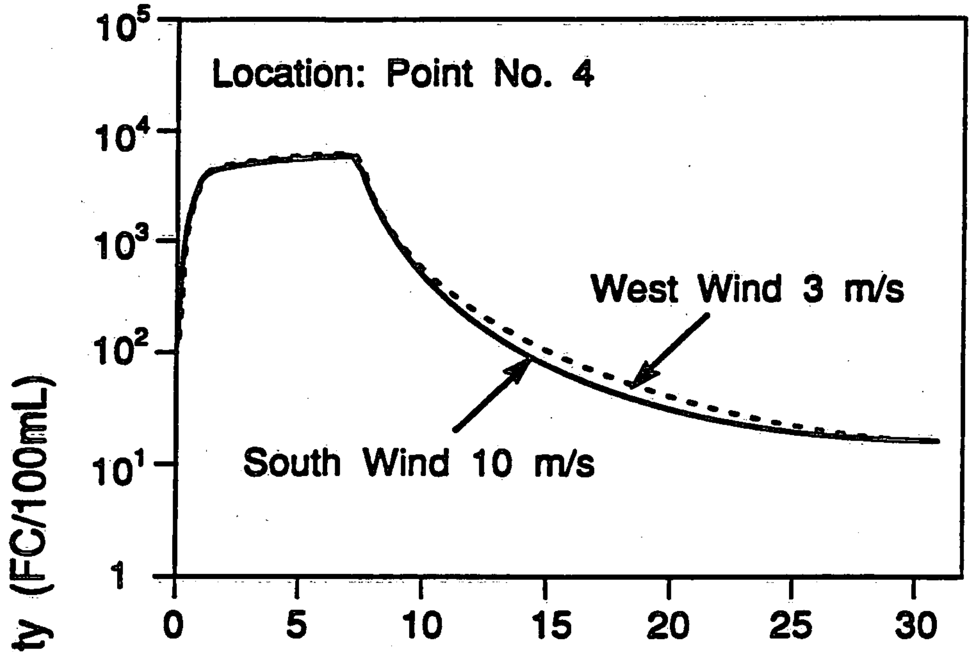


LEGEND

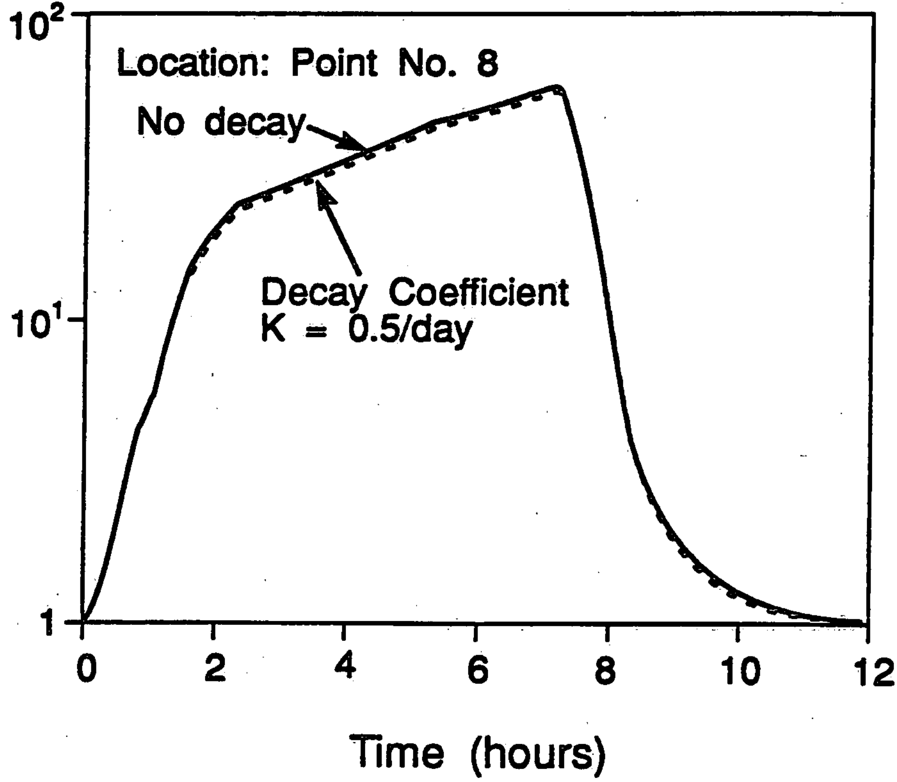
Numbers on X,Y axes-grid reference numbers

Contours represent Fecal Coliform densities
(counts/100mL) multiplied by 0.001
(i.e. 1=1,000 FC/100mL).

Figure 16. Decay of Fecal Coliform Densities After the



(a) Impact of Wind Speed and Direction.



(b) Impact of Bacterial Decay

Figure 17. Sensitivity of Modelling Results to Variations in wind and Bacterial Decay.

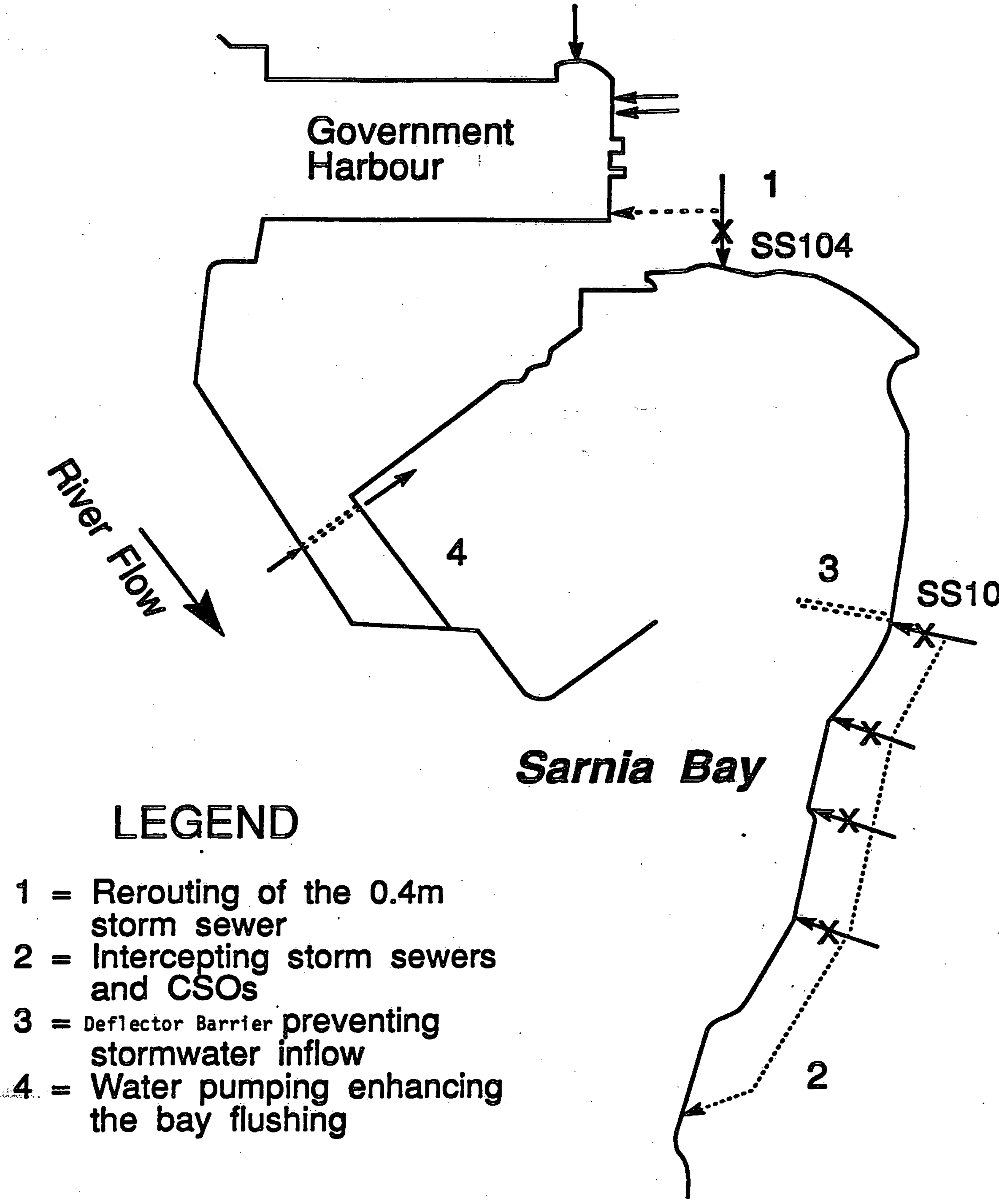


Figure 18. Remedial Scenarios

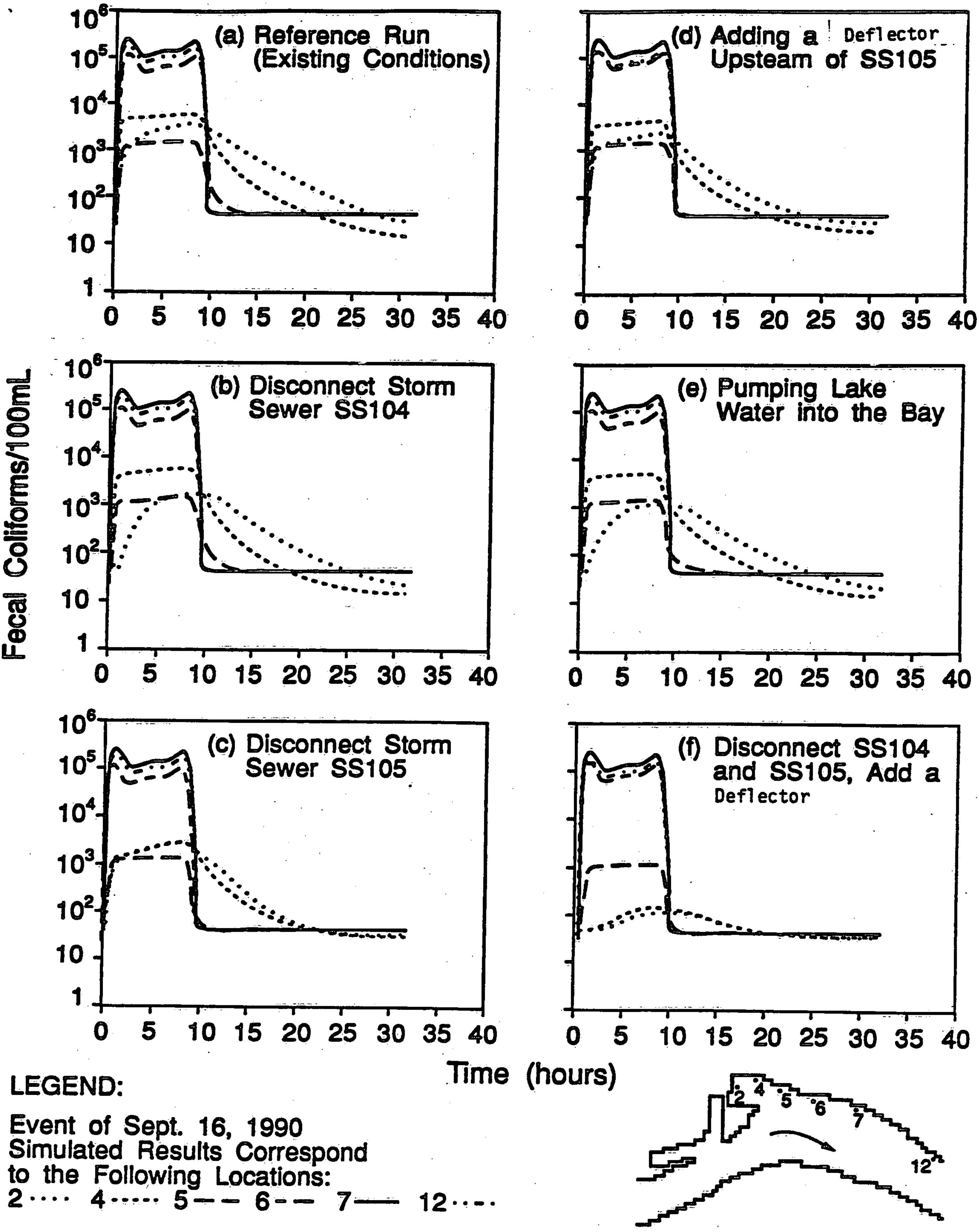


Figure 19. Comparison of Remedial Measures

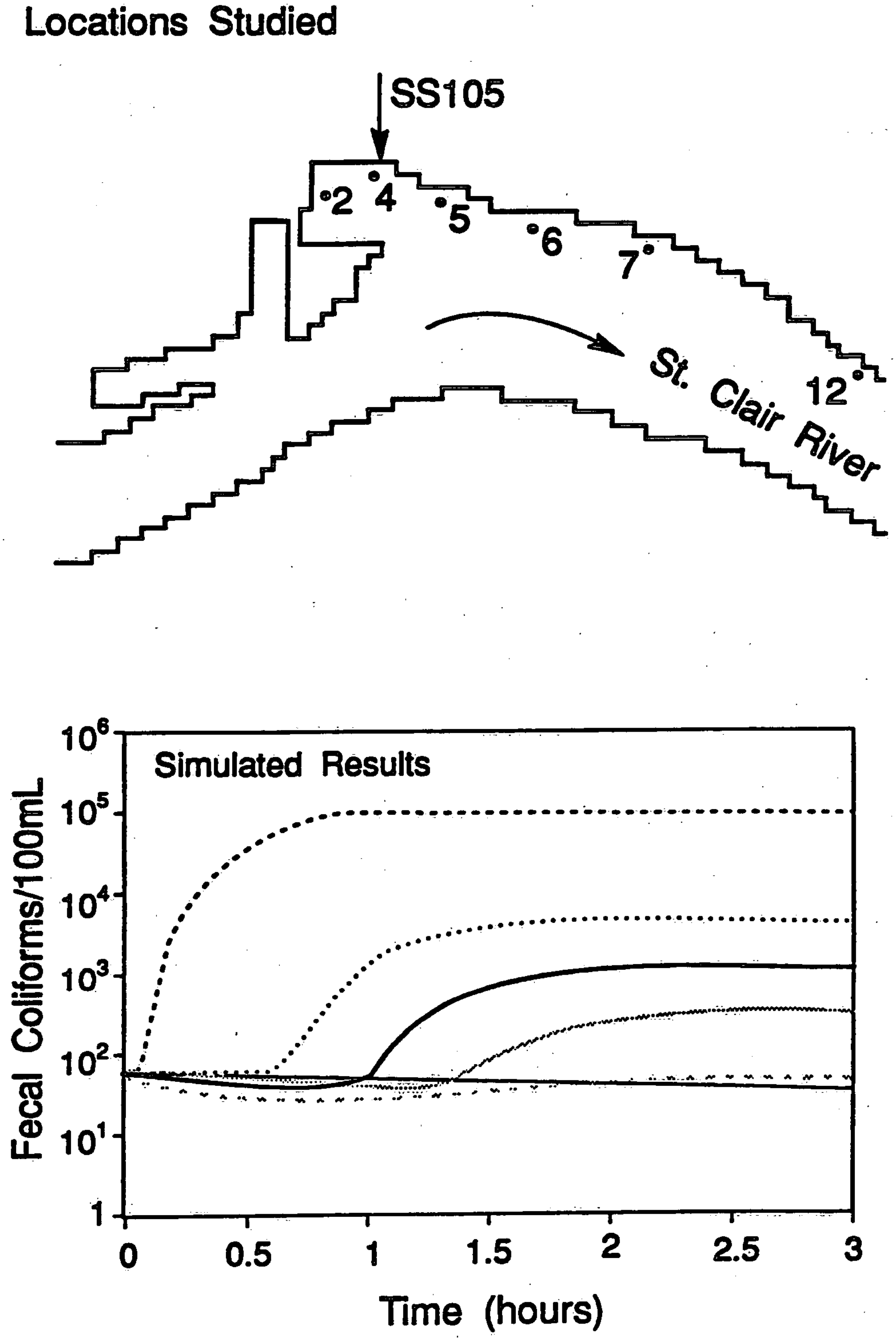
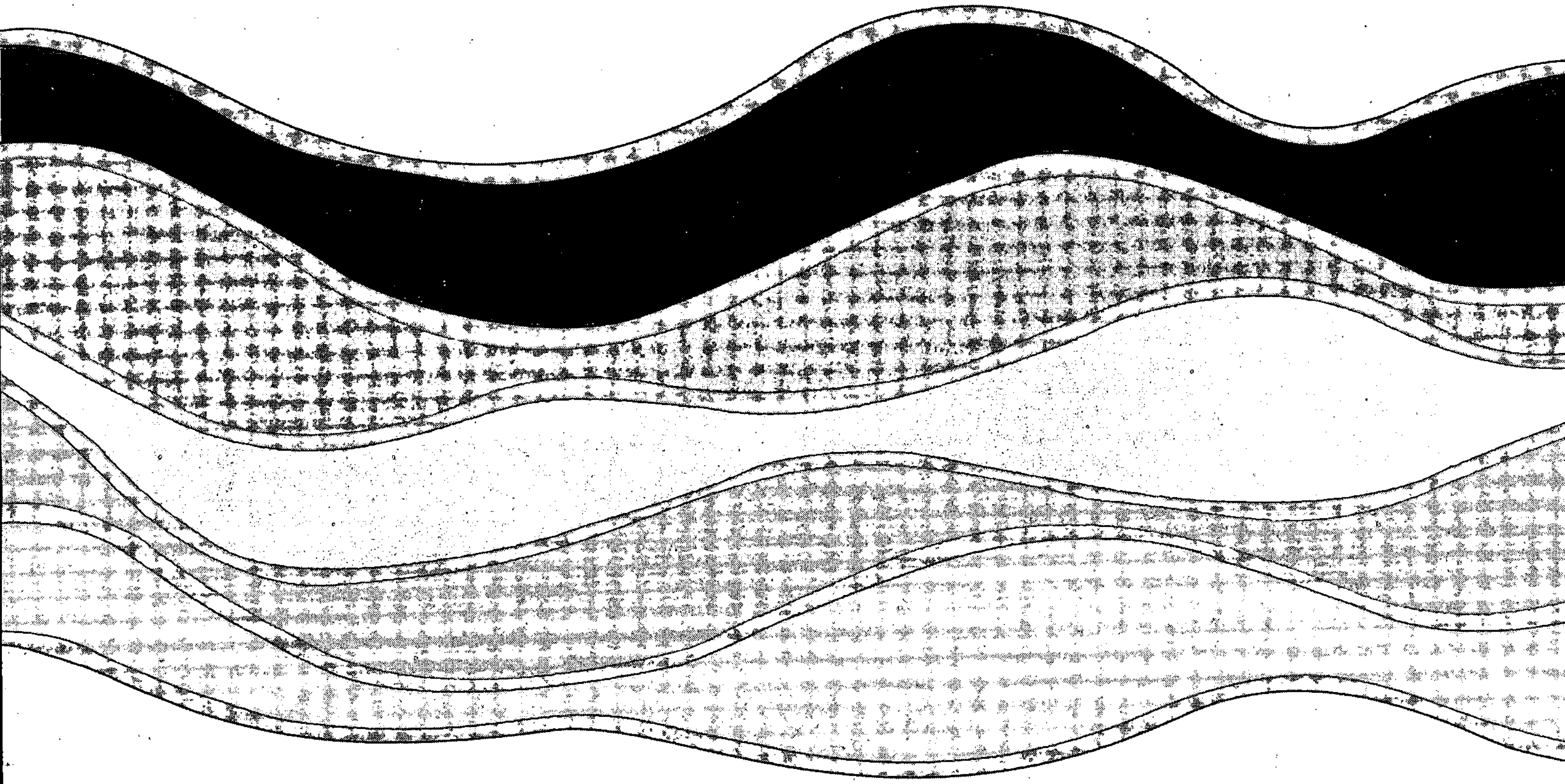


Figure 20. Impact of Fecal Pollution Discharge on Fecal Coliform Densities Along the Sarnia Waterfront



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