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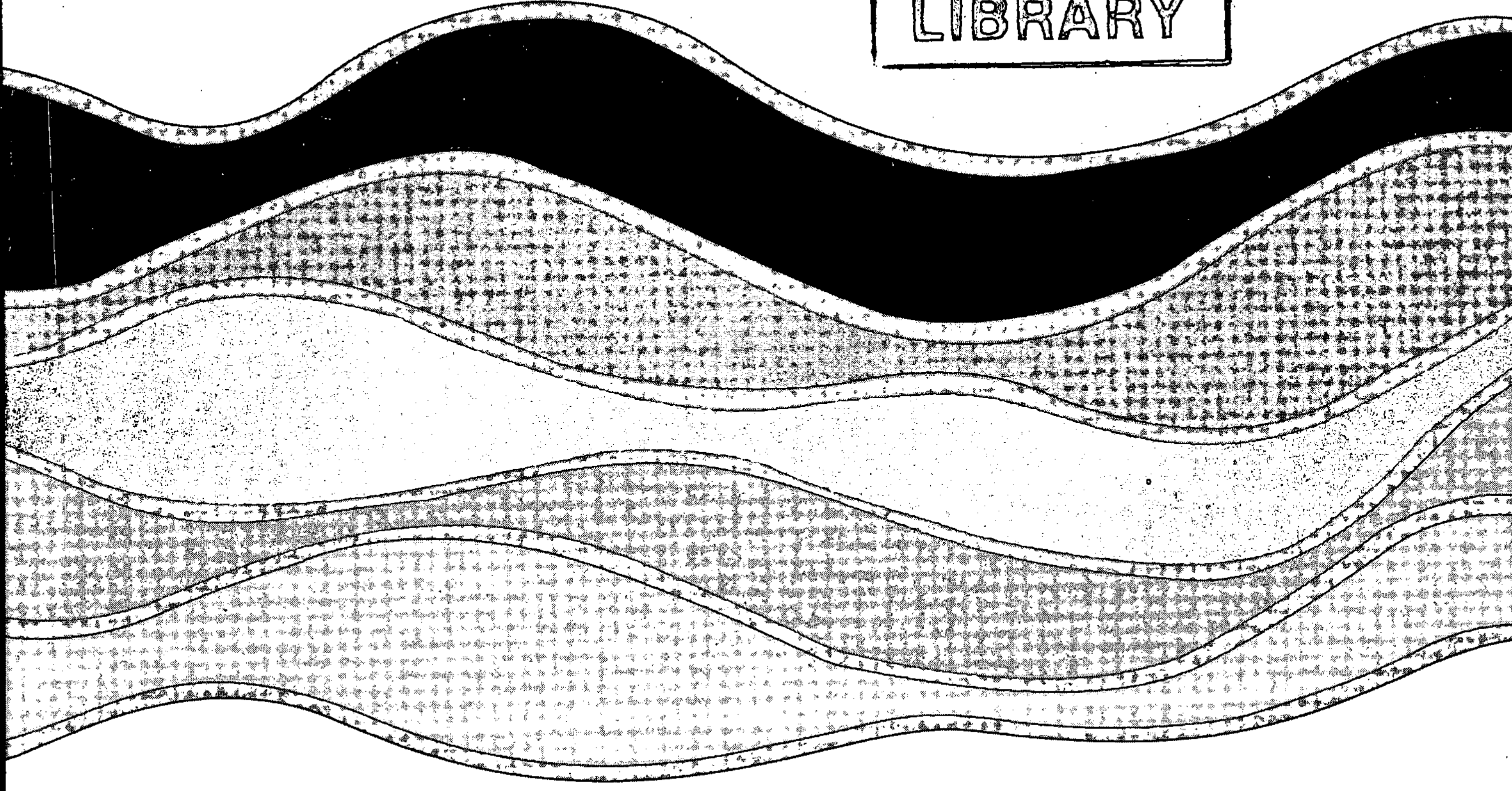

URBAN IMPACTS ON MICROBIOLOGICAL POLLUTION OF THE ST. CLAIR RIVER IN SARNIA, ONTARIO

J. Marsalek, B.J. Dutka and I. Tsanis

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J. Marsalek, B.J. Dutka and I.K. Tsanis*

Aquatic Ecosystem Protection Branch
National Water Research Institute
Burlington, Ontario L7R 4A6

*McMaster University
Hamilton, Ontario L8S 4L7

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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 is 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.

The 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 by urban sources.

SOMMAIRE À L'INTENTION DE LA DIRECTION

La fermeture des plages servant à la baignade en raison de leur contamination par les bactéries fécales constitue l'une des altérations des utilisations de l'eau les plus courantes imputables à la pollution urbaine. De tels incidents sont particulièrement fréquents dans les zones urbaines où il y a des trop-pleins d'égouts unitaires. Le rapport qui suit traite de ce problème dans l'un des secteurs de préoccupation du bassin des Grands Lacs, la rivière St. Clair à Sarnia (Ontario). On y présente la méthodologie proposée pour évaluer la contamination bactérienne des eaux réceptrices et déterminer les sources de contamination et les voies de transport. Cette méthodologie comprend l'observation sur le terrain de micro-organismes indicateurs dans les eaux réceptrices et les rejets à la source, la simulation de la charge en bactéries à l'aide d'un modèle de calcul de la charge et la simulation du transport dans les eaux réceptrices.

Le rapport aidera l'équipe du Plan de redressement de la rivière St. Clair dans ses travaux de planification environnementale et devrait intéresser également tous ceux qui doivent évaluer la pollution des eaux réceptrices par les bactéries fécales d'origine urbaine.

ABSTRACT

Urban impacts on faecal bacterial pollution of the near-shore zone of the St. Clair River in Sarnia were studied by means of field observations and computer modelling. Towards this end, water samples were collected at various sources of faecal pollution and at nine sampling stations in the river, and analysed for faecal coliform, faecal streptococci, *Escherichia coli*, *Pseudomonas aeruginosa* and coliphage. Probabilistic distributions of the observed microorganism densities were used to assess the levels of faecal bacteria pollution, describe the impacts of urban sources on faecal bacteria concentrations in the river, and make inferences about compliance with the recreational water quality guidelines. Relatively high probabilities of guideline violations ($p > 30\%$, at most sites, in dry weather) indicated the need for remedial measures. The screening of such measures was accomplished by preliminary modelling of indicator bacteria in the receiving waters, using a bacteria loading model interfaced with a receiving water model.

KEYWORDS

Combined sewer overflows (CSOs), storm drainage, microbiological pollution.

RÉSUMÉ

Les incidences urbaines de la pollution par les bactéries fécales sur la zone littorale de la rivière St. Clair à Sarnia ont été étudiées par le biais d'observations sur le terrain et de modélisations par ordinateur. À cette fin, on a prélevé des échantillons d'eau à différentes sources de pollution fécale et en neuf points d'échantillonnage dans la rivière afin de procéder à la numération des coliformes fécaux, streptocoques fécaux, *Escherichia coli*, *Pseudomonas aeruginosa* et coliphages. On a utilisé la distribution des densités de microorganismes observées pour évaluer les niveaux de pollution par les bactéries fécales, décrire les incidences des sources urbaines sur les numérations bactériennes dans la rivière et en tirer des conclusions en ce qui concerne le respect des lignes directrices relatives à la qualité de l'eau utilisée à des fins récréatives. Les probabilités relativement élevées de non-respect des lignes directrices calculées (p > 30 % dans la plupart des sites, par temps sec) ont permis de conclure à la nécessité de prendre des mesures de redressement. L'évaluation de telles mesures s'est faite par le biais d'une modélisation préliminaire des bactéries indicatrices dans les eaux réceptrices à l'aide d'un modèle de calculs de la charge en bactéries conjugué à un modèle des eaux réceptrices.

MOTS-CLÉS

Trop-plein d'égouts unitaires (TPÉU), évacuation des eaux pluviales, pollution d'origine microbiologique.

INTRODUCTION

Microbiological pollution represents one of the most widespread impairments of water uses caused by such urban discharges as effluents or bypasses of wastewater treatment plants (WTP), combined sewer overflows (CSOs) and urban stormwater (House *et al.*, 1993). While the microbiological pollution of WTP discharges is well recognized and considered in locating effluent outfalls downstream from sensitive sections of receiving waters, the discharges of CSOs and stormwater occur throughout urban areas and impact on the receiving water uses (Ellis, 1991).

Urban runoff, in the form of CSOs or stormwater discharges, is a significant source of faecal pollution indicator bacteria and pathogens (Dutka and Tobin, 1978; Olivieri *et al.*, 1989). Major sources of such pollution include pet populations, urban wildlife (particularly birds), cross-connections between storm and sanitary sewers, lack of sanitation, deficient solid waste collection and disposal, accumulation of sediment in sewers and receiving waters, rodent habitation in sewers, land wash and growth of bacteria in nutrient rich standing water in storm sewers between events (Ellis, 1985; Olivieri *et al.* 1989). In general, bacterial levels observed in stormwater discharges resemble those in diluted sanitary sewage (House *et al.*, 1993).

While the determination of microbial pollution in the receiving waters is a routine task, the choice of suitable parameters and the potential public health risks are not well established (House *et al.*, 1993). In spite of these uncertainties, concerns about the spread of waterborne diseases in such waters led to the promulgation of recreational (bathing) water guidelines which specify the permissable concentrations of various microorganisms. Most commonly, the primary guidelines deal with indicator bacteria (e.g. faecal coliforms, *Escherichia coli*) which indicate the potential presence of pathogens (Health and Welfare Canada, 1992; CEC, 1991).

An earlier study of the Upper Great Lakes Connecting Channels (UGLCCS, 1988) recommended to assess the microbiological pollution of the St. Clair River in Sarnia. The methodology developed for, and the results of, this assessment are presented in this paper. To reduce the frequency of violations of microbiological water quality guidelines, remedial measures are needed. A modelling procedure for screening of such measures is also presented.

STUDY AREA AND METHODS

The study area comprised a 8.6 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 (see Fig.1). The upper part of this reach, between the stations A and H, is used for swimming and boating, and there is potential for further expansion of such activities. Consequently, most of the field work focused on this upper section of the river. In the downstream reach, the potential for water-based recreation is rather limited, because of industrial pollution and the lack of public access.

In the study area, the river conveys an average discharge of 5,200 m^3/s, its width varies from 230 to 770 m, the depth ranges from 9 to 21 m, and the average velocities vary from 1.1 to 2.1 m/s. The river receives discharges from two WTPs, five combined sewer overflow outfalls and 13 storm sewer outfalls. In view of numerous sewer cross-connections, some of the storm sewers may carry combined sewage during wet weather. Just downstream from station A, the disinfected primary effluent from the Point Edward WTP is discharged into the river. Plume studies indicated that this small effluent ($V = 2{,}600$ m^3/day) had no measurable impact on faecal bacteria levels in the river (Marsalek et al., 1992). The effluent from the main Sarnia WTP (treated volume $V = 66{,}000$ m^3/day) is discharged 4.5 km below the sensitive upstream river reach and may impact on observations at station J at the downstream end of the study area.

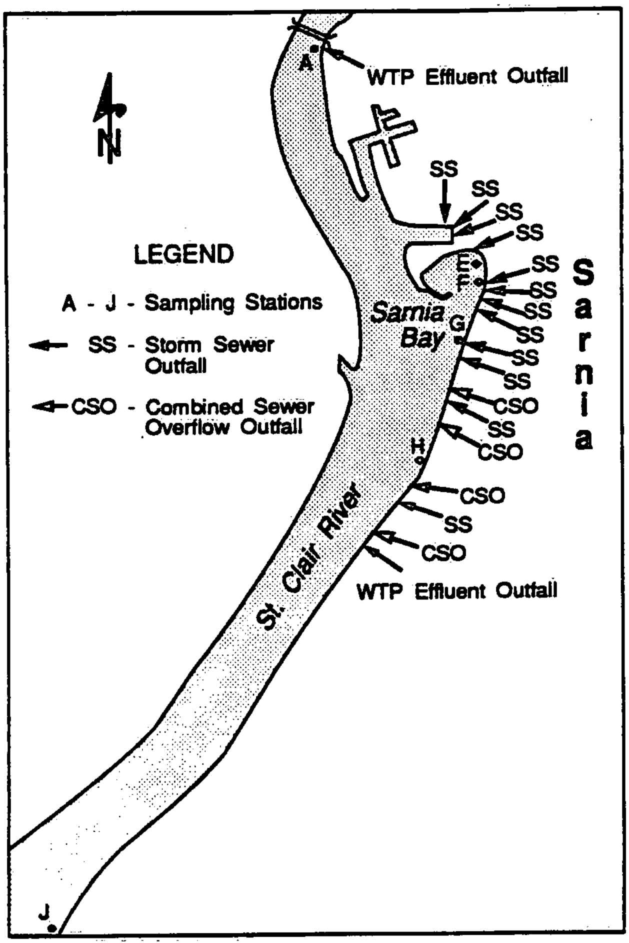

Fig. 1. Study area

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). An interesting flow feature was noted at the mouth of Sarnia Bay - the fast river flow creates a counter-clockwise circulation in Sarnia Bay and this circulation may enhance transport of faecal bacteria from sewer outfalls into the Bay.

For the assessment of faecal bacterial sources and the pollution of the St. Clair River in Sarnia, 14 sampling stations were established in the study area. The locations of six of these stations are shown in Fig.1. Station A served as a reference station located upstream from all significant urban sources of faecal bacteria.

To reflect the study interest in bathing waters, 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. Samples were collected in moving water by lowering pre-sterilized 250 mL sampling bottles into the river, with the mouth facing into the current. After the collection of samples, bottles were placed in ice coolers and delivered to the microbiological laboratory, where the sample processing started immediately and all analyses were initiated within less than 24 hours of the sample collection.

Field samples were routinely analyzed for faecal coliform (FC), faecal streptococci (FS), *E. coli* (EC), *Pseudomonas aeruginosa* (PA), and coliphage densities (Marsalek *et al.*, 1992). All these parameters, except coliphage, are used in the Province of Ontario 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). While coliphages allow more economical and faster (within 6 to 8 hours) determinations of faecal pollution than the conventional parameters, and may provide alternative evaluations of viral pathogen loadings (IAWPRC Study Group, 1991), further research is required to provide scientific and operational bases for their use as reliable indicators of faecal pollution (House *et al.*, 1993).

All microbial densities were determined by membrane filtration using cellulose nitrate 0.45 μm membranes and different incubation procedures. For faecal coliforms, m-Tec and m-Tec IG agars with a 24-hour incubation at 44.5 °C were used. In faecal streptococci measurements, m-Enterococcus agar with incubation at 41.5 °C for 48 hours was used, and *Pseudomonas aeruginosa* densities were determined by using m-PAC agar with incubation at 41.5 °C for 48 hours. Coliphages were determined by the APHA Standard Methods (1989) procedure consisting in adding 5 mL of water to each of four test tubes containing 5.5 mL of molten agar (MTSA), followed by addition of 1 mL of overnight culture of *E. coli* C. host culture. 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.

RESULTS AND DISCUSSION

All microbial densities were processed by calculating geometric means (Table 1) and the corresponding probabilistic distributions (examples are given in Fig.2). Table 1 contains three sets of microbiological data - from the river sites and two pollution sources, stormwater and CSOs. For completeness, all five microbiological parameters are presented in Table 1, but detailed discussion focuses mostly on three parameters - EC, FC and coliphage, dealing with such aspects as urban impacts on faecal bacterial densities in the receiving waters, comparison of dry and wet weather impacts, and compliance with water quality guidelines. Further details and data interpretation can be found elsewhere (Marsalek *et al.*, 1992).

The geometric means of the faecal coliform *E. coli* data, collected at river stations, correlated well with those determined for faecal streptococci (r = 0.987) and coliphage (r = 0.8). A poor correlation between FC and PA was described by r = 0.296. 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 with backflow check valves, and stagnant zones in the river, for example in Sarnia Bay. When these storages are emptied, the resulting bacteria levels may be unusually high.

TABLE 1 Summary of Microbiological Data

Station	Geometric Means (counts/100 mL)									
	Coliphage		Faecal Coliform		Faecal Streptococci		*Pseudomonas aeruginosa*		*E. coli*	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
A	28	46	20	129	11	70	361	1570	17	96
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
CSO$_W$	5841		1.9x10^6		90600		17300		1.14x10^6	
CSO$_Y$	529		1.18x10^6		1.62x10^5		17000		8.1x10^5	

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

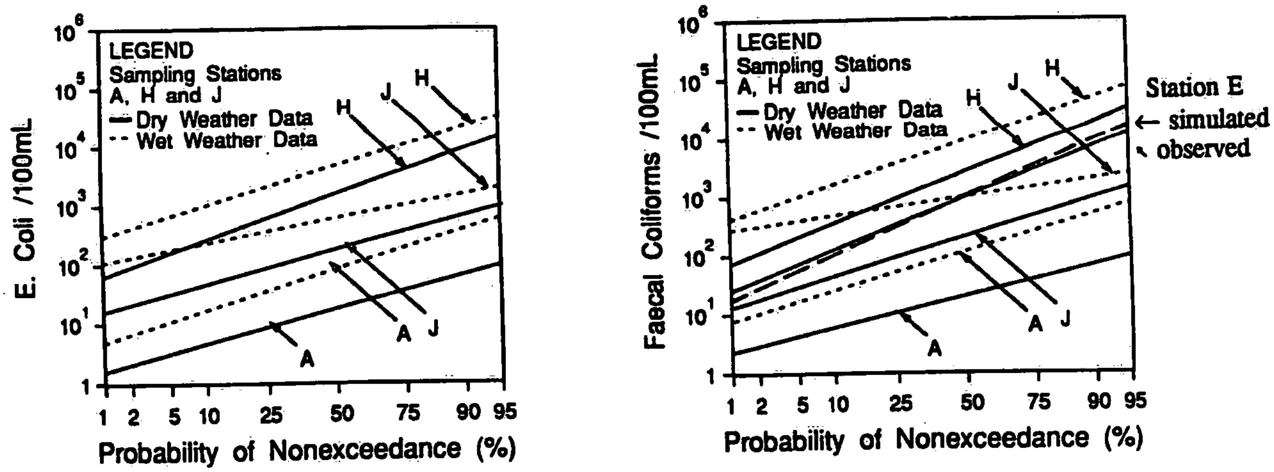

Fig. 2. Statistical distributions of observed microbiological data

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

For the overall assessment of the impacts of urban sources on faecal bacteria levels in the St. Clair River in Sarnia, the probabilistic distributions of bacterial densities at stations A, H and J can be used (Fig.3). The first station (A) is located upstream from all major urban sources discharging directly into the river, station H is located on the Sarnia Waterfront, downstream from about 4/5 of all municipal sewer outfalls, and station J is located downstream from all the municipal and industrial outfalls in the study area. For all the microbial parameters studied, in both dry and wet weather, bacterial densities at the mid-reach station H were greater than at the most downstream station J, and both significantly exceeded those at the control station A.

For all the parameters studied, microbiological densities increased sharply when progressing from station A to the mid-reach station H, and eventually declined between the mid-reach station and the most downstream station J. These observations indicate that the discharges from municipal sewer outfalls, most of which are located in the upper reach (A-H), are significant sources of faecal bacteria in the study area. High bacterial densities at Station H, even during dry weather, suggest dry-weather discharges of sewage along the waterfront. Such discharges may be caused by sewer cross-connections, prolonged discharges caused by infiltration into sewers, and malfunctioning overflow controls in the sewer system. Reductions in bacterial densities in the lower reach (between H and J) can be explained by the mixing and dispersion of municipal pollutant plumes. Comparisons of microbiological densities at the control station A and the most downstream station J provide an evaluation of the overall upstream/downstream effects.

The impacts of urban sources on faecal pollution of the St. Clair River were observed in both dry and wet weather. In dry weather, faecal coliform (FC) and *E. coli* densities downstream from the city exceeded those upstream from the city by an order of magnitude; for coliphage, faecal streptococci and *Pseudomonas aeruginosa* such exceedances were much smaller, about 2 to 2.5 times. These impacts were caused by such urban sources of bacteriological pollution as sewage treatment plant effluents, dry-weather discharges from both storm and combined sewers, and possible after-effects of wet-weather bacterial contamination.

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

Dry vs. Wet Weather Data

In dry weather, the faecal bacterial concentrations observed at some river stations were relatively low. In wet weather, additional sources of bacteria in the form of storm sewer and CSO discharges became activated and contributed to faecal pollution of the river. Consequently, the bacterial densities observed directly in the river increased in the case of faecal coliforms, faecal 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, 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 and by relatively slow decline in faecal bacterial densities in the river at locations with slow flushing.

Compliance with Microbiological Recreational Water Quality Guidelines

The Canadian Water Quality Guidelines (Health and Welfare Canada, 1992) discuss several indicator organisms in connection with health risk in bathing waters. The most widely used guideline applies to *E. coli* and recommends that the geometric mean of not less than five samples taken over a 30-day period should be less than 200 *E. coli*/100 mL. The exact risk associated with bathing in water of this quality cannot be established, but from U.S. EPA epidemiological data, it was estimated as a 1-2% chance of contracting a seasonal gastrointestinal illness (Health and Welfare Canada, 1992). A proposed U.S. EPA guideline for freshwater beaches is 126 *E. coli*/100 mL. In the study area, a more stringent (Ontario) provincial guideline, defined as a geometric mean of 10 samples not exceeding 100 *E. coli*/100 mL, takes precedence.

Considering the probabilistic nature of microbiological bacterial densities, it is possible to use the probabilistic distributions of microbial parameters in the study area to determine the probabilities of non-exceedance of average limiting values during the swimming period. Such estimates were produced for EC and FC in the study area and presented in Table 2. The former value (EC) represents the current Ontario provincial guideline, the latter value (FC) represents the former Ontario provincial guideline, which was identical to the current EC Guide value (CEC, 1991). To expand this discussion, the U.S. EPA proposed guideline (126 *E. coli*/100 mL) and the EC Mandatory value (2,000 FC/100 mL - CEC, 1991) were also included in Table 2.

TABLE 2 Probabilities of Non-Exceedance of Indicator Bacteria Guidelines in the Study Area

STATION	Probability of Non-Exceedance [%]							
	100 EC/100 mL			126 EC	100 FC/100 mL			2000 FC
	Dry	Wet	Dry+Wet	Dry	Dry	Wet	Dry+Wet	Dry
A	95	52	81	97	95	41	77	>99.99
E	61	17	46	69	60	11	44	99.8
F	20	3.5	14	25	20	0.6	14	95
G	72	5.5	50	79	53	2	36	99.94
H	2	0.1	1.4	3	2	0.1	1.4	49
J	29	1.4	20	35	24	0.1	16	98

In Table 2, the most relevant data appear in the second column - applying the guideline of 100 EC/100 mL in dry weather, when the interest in recreational waters 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 29%. The corresponding FC probabilities are slightly lower as expected. A slightly better degree of compliance would be obtained for the proposed EPA guideline of 126 EC MPN/100 mL. In this procedure, as described by House *et al.* (1993), the recommended probabilities of compliance are 82%, 90% and 95% for light (e.g. at stations A, F, G), moderate and frequent body (at station E) contact, respectively. Among these stations, only A would meet the EPA guideline in dry weather. In practical terms, the EC mandatory value (2,000 FC/100 mL) is complied with at stations A, E and G.

Using the IAWPRC Study Group's classification (1991), the coliphage data, characterized by the geometric means ranging from 26 to 83 units/100 mL (Table 1), indicate at all sites the second degree of pollution described by the coliphage concentrations in the range from 10 to 10^3 units/100 mL. Referring to an earlier proposal of a recreational water quality guideline of 20 coliphage units/100 mL (Dutka *et al.*, 1987), on the average, none of the study sites would comply.

Regardless of the guidelines used, practically all the sites, except the control station A, show significant signs of faecal bacterial pollution and violations of guidelines. The best microbiological quality is found at site A which is not suitable for bathing (fast currents). Site E, in Sarnia Bay, is used extensively for bathing. Observations of microbiological water quality at this site indicate that relatively frequent violations of recreational water guidelines will occur at this site and result in beach closures. Consequently, the probabilities of compliance should be improved by remedial measures discussed in the next section.

MODELLING OF REMEDIAL MEASURES

For the development of remedial options, it is advantageous to screen various options by modelling (Linde-Jensen *et al.*, 1993). A modelling package used should include a loading model, simulating fluxes from faecal bacteria sources, and a receiving water model. In this study, the loading model was devised by combining the STORM model with a water quality rating curve in the form of $F = a\ Q^b$, where F is the bacteria flux (i.e. units/second), $Q(m^3/s)$ is the source discharge, and the parameters a and b were fitted to the observed data (Marsalek *et al.*, 1992). For EC/FC in CSO and stormwater discharges, the fitted rating curves were described by r^2 values of 0.68 and 0.77. This degree of uncertainty was deemed acceptable for the screening of remedial measures. A better fit may be possible with larger numbers of measurements.

Flow conditions in the river were simulated by a two-dimensional depth-averaged irregular finite-difference model, comprising two dynamic equations, a continuity equation and a transport equation (Tsanis and Wu, 1991). The dynamic equations included terms involving both depth-averaged velocities (i.e. longitudinal and lateral velocities), a Coriolis term, surface wind stresses and bottom friction stresses, and horizontal eddy viscosity terms. The transport equation described two distinct mechanisms - advection and turbulent diffusion, where the first mechanism refers to the entrainment of contaminants by the ambient flow and their transport at the ambient flow velocity, and the second mechanism describes the entrainment of contaminants by turbulent eddies. This equation also included bacterial decay. The river model was calibrated using river flow velocity measurements (U.S. Army, 1974), estimates of dispersion coefficients D_x and D_y (McCorquo-dale *et al.*, 1986), and faecal coliform concentration distribution at station E (see Fig.2).

The main modelling results included the persistence of elevated bacterial densities after cessation of rainfall at various locations in the receiving waters, and a screening assessment of several remedial measures. In the river channel, contaminants were transported primarily by advection and wet-weather loads were flushed out in less than 2 hours. The situation in sheltered water bodies (e.g. Sarnia Bay) connected to the river channel was quite different. In this case, the predominant mode of transport was turbulent diffusion and the elevated bacteria concentrations, caused by wet-weather discharges, persisted as long as 20 hours after the cessation of rainfall (Marsalek *et al.*, 1992). Thus in such areas, the closing of beaches in wet weather can be expected and should extend about 24 hours after the cessation of rainfall.

Several remedial options have been proposed and tested in simulation experiments, including the disconnection of storm sewer outfalls, the flushing of Sarnia Bay by pumped riverine water, and a deflector barrier preventing circulation transporting sewer discharges into the Bay (Marsalek *et al.*, 1992). The modelling results indicated that water pumping would be ineffective, and that to achieve the guide value (100 EC or FC/100 mL), a remedial scenario, comprising redirection of two storm sewer outfalls (SS 104 and 105 in Fig.3) and construction of a deflector barrier, would be needed. An example of simulation results for the existing and remediated conditions is given in Fig.3 (Tsanis and

Wu, 1991). By implementing this scenario, it should be feasible to reduce the faecal pollution in Sarnia Bay and achieve EC/FC densities in the order of 100 units/100 mL at site E. Before proceeding with remediation activities, it would be desirable to expand the existing microbiological database, refine calibration of the model package, and conduct public consultations to test the acceptance of remedial measures proposed.

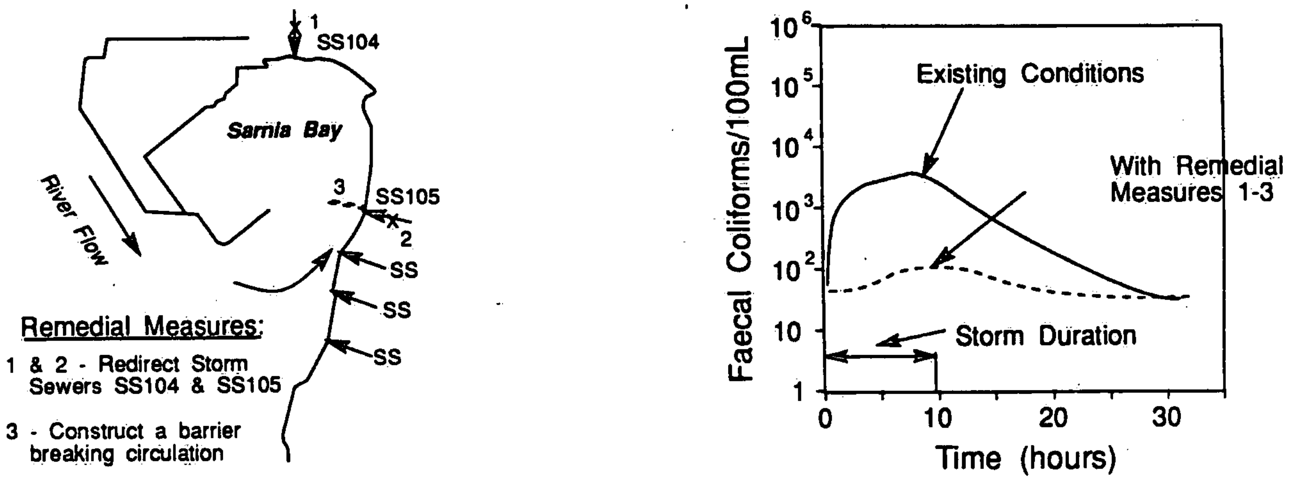

Fig. 3. Simulation of faecal coliform for the existing and remediated conditions

CONCLUSIONS

Urban sources of faecal pollution, including CSO and stormwater discharges, strongly impact on the near-shore bacteriological quality of the St. Clair River in Sarnia. The severity of such impacts increases along the river shore from the most upstream station to the downstream end of Sarnia Waterfront, below which a partial recovery of water quality takes place. The assessment of such impacts was accomplished by comparisons of probabilistic distributions of five microbiological parameters at various sampling sites. These distributions also indicated significant probabilities of violation of a recreational water guideline defined as 100 *E. coli*/100 mL. To reduce the frequency of guideline violations and beach closures, remedial measures are needed and can be developed by the demonstrated methodology - statistical interpretation of observed microbiological data, simulation of bacterial fluxes with a loading model, and examination of bacterial transport and levels simulated by the receiving waters model. Planing-level modelling indicates that the microbiological quality in Sarnia Bay could be significantly improved by redirection of two storm sewer outfalls and the use of a barrier preventing the influx of faecal pollution along the east bay shore.

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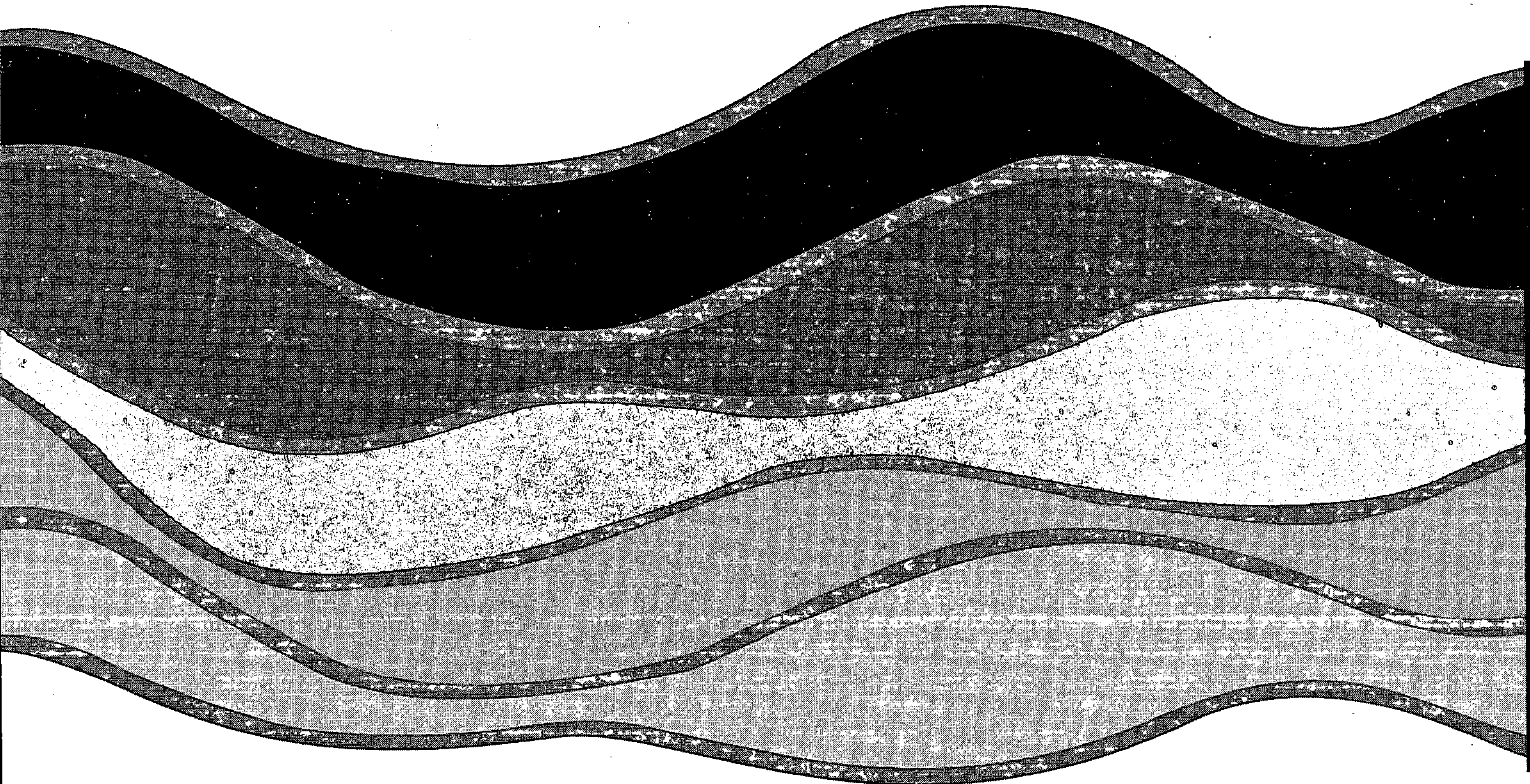

NATIONAL WATER RESEARCH INSTITUTE
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