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## Environnement Canada

Urban Wet-weather flows: sources of fecal contamination  
impacting on redreational waters and threatening drinking  
water sources

By:

J. Marsalek & Q. Rochfort

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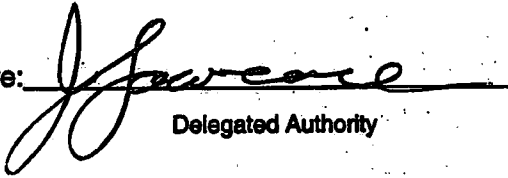
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## **Urban wet-weather flows: sources of fecal contamination impacting on recreational waters and threatening drinking water sources**

J. Marsalek and Q. Rochfort

### **ABSTRACT**

Fecal contamination is found frequently in urban waters as a result of discharges of wastewater treatment plant (WWTP) effluents, combined sewer overflows (CSOs), sanitary sewer overflows (SSOs), and urban stormwater. While the fecal contamination of WWTP effluents is well recognized and considered in the design of treatment and siting of effluent outfalls, wet-weather flow discharges (CSOs, SSOs and stormwater) have not been addressed so far to a similar extent. However, wet-weather flows often contaminate receiving waters and need to be considered in planning the protection of recreational waters and sources of drinking water.

During runoff, urban stormwater mobilizes and entrains solids, chemicals and bacteria from various sources, including cross-connections with sanitary sewers. Stormwater characterization data indicate that *E. coli* or fecal coliform bacteria counts in stormwater typically range from  $10^3$  to  $10^4$  units per 100 mL. Significantly higher counts ( $\geq 10^5$  units/100 mL) suggest the presence of cross-connections with sanitary sewers, which should be identified and corrected. Fecal contamination of stormwater may be attenuated prior to discharge into open waters by stormwater management measures, which typically remove suspended solids and attached bacteria. Exceptionally, stormwater discharges in the vicinity of swimming beaches are disinfected.

The levels of indicator bacteria in CSOs and SSOs (both represent diluted sanitary sewage) are much higher than in stormwater, and can be as high as  $10^6$  *E. coli* per 100 mL. Consequently, the abatement of fecal contamination of CSOs is now considered in the design of CSO control and treatment, as for example stipulated in the Ontario Interim Directive F-5-5 for CSO abatement. In some cases (e.g., the Toronto Waterfront), the abatement of fecal contamination of receiving waters is the primary driver behind the often-costly CSO abatement programs. CSO Abatement options comprise combinations of storage and treatment, in which the CSO treatment generally includes disinfection by UV irradiation.

Finally, indicator bacteria data from Sarnia (Ontario) are used to demonstrate some fecal contamination impacts of wet-weather flows. In wet weather, the microbiological quality of riverine water worsened as a result of activation of additional sources of fecal contamination (CSOs, stormwater discharges), and the recreational water guidelines for indicator organisms were exceeded much of the time. Local improvements in water quality were feasible by source controls and manipulation of transport of polluted water. Implications of differences between the federal and Ontario guidelines were also addressed. While the federal guideline uses two rules, a geometric mean (2000 *E. coli*/L) and a permissible maximum (4000 *E. coli*/L), the Ontario guideline specifies only the geometric mean (100 *E. coli*/100 mL). Depending on the number of collected samples, either guideline can become more rigorous.

## Débits pluviaux en milieu urbain : sources de contamination fécale des eaux récréatives et des sources d'eau potable

J. Marsalek et Q. Rochfort

### RÉSUMÉ

La contamination fécale se produit fréquemment dans les eaux en milieu urbain. Celle-ci est causée par : des rejets d'effluents provenant des stations municipales d'épuration des eaux usées (SMEEU), des trop-pleins d'égouts unitaires (TPEU) ou d'égouts sanitaires, et des eaux pluviales urbaines. Alors que le phénomène de la contamination fécale des effluents des SMEEU est bien connu et qu'on en tient compte lors de la mise au point de traitements et lors du choix de l'emplacement des émissaires d'effluents, les rejets des débits pluviaux (TPEU, trop-pleins d'égouts sanitaires et eaux pluviales) n'ont pas reçu la même attention jusqu'à présent. Toutefois, il faut noter que les débits pluviaux contaminent souvent les eaux réceptrices et doivent être pris en considération dans la planification de la protection des eaux utilisées à des fins récréatives ainsi que dans la protection des sources d'eau potable.

Au cours de leur écoulement, les eaux pluviales urbaines entraînent des matières solides, des composés chimiques et des bactéries provenant de diverses sources, dont entre autre des jonctions fautives avec des égouts sanitaires. Des données indiquent dans les eaux pluviales la présence de  $10^3$  à  $10^4$  unités d'*E.coli* ou de coliformes fécaux par 100 mL. Des taux significativement plus élevés ( $\geq 10^5$  unités par 100 mL) laissent supposer la présence de jonctions fautives avec des égouts sanitaires, qui doivent être localisées et corrigées. Il serait possible de diminuer la contamination fécale des eaux, avant que celles-ci soient rejetées dans les eaux libres, en adoptant des mesures de gestion des eaux pluviales qui permettraient d'éliminer les matières solides en suspension et les bactéries qui s'y fixent. Exceptionnellement, on procède à la désinfection des rejets d'eaux pluviales aux environs des plages publiques.

Les taux de bactéries indicatrices dans les TPEU et les trop-pleins d'égouts sanitaires (les deux représentent des eaux d'égout diluées) sont beaucoup plus élevés que dans les eaux pluviales, et peuvent atteindre  $10^6$  unités d'*E. coli* par 100 mL. Par conséquent, la réduction des contaminants fécaux des TPEU est maintenant envisagée dans la planification de mesures de dépollution et de traitement des TPEU, comme le stipule par exemple la Directive provisoire F-5-5 de l'Ontario, pour la réduction de la pollution des TPEU. Dans certains cas, (par exemple, le secteur riverain de Toronto), la réduction de la contamination fécale des eaux réceptrices est la principale motivation à la base des programmes, souvent coûteux, de réduction de la pollution des TPEU. Les options de réduction de la pollution des TPEU consistent en des combinaisons de stockage et de traitement, où les traitements comprennent généralement une désinfection par les rayons UV.

Finalement, nous avons utilisé des données de bactéries indicatrices provenant de Sarnia (Ontario) afin de démontrer un certain nombre d'impacts dus à la contamination fécale des débits d'eaux pluviales. Par temps pluvieux, la qualité microbiologique des eaux fluviales a diminué en raison de l'activation de sources additionnelles de

contamination fécale (TPEU, rejets d'eaux pluviales), et les limites de recommandations basées sur des organismes indicateurs dans les eaux utilisées à des fins récréatives ont été dépassées la plupart du temps. Des améliorations locales dans la qualité de l'eau étaient possibles par des mesures de réduction de la contamination à la source et des modifications au transport des eaux polluées. Les conséquences des différences entre la recommandation du fédéral et celle de la province de l'Ontario ont également été abordées. Tandis que la recommandation fédérale repose sur deux indicateurs, la moyenne géométrique (2000 *E. coli*/L) et le taux admissible maximal (4000 *E. coli*/L), la recommandation provinciale ne mentionne que la moyenne géométrique (100 *E. coli*/100 mL). Selon le nombre d'échantillons prélevés, il est possible de rendre l'une ou l'autre de ces recommandations plus rigoureuse.

## **NWRI RESEARCH SUMMARY**

### **Plain language title**

Fecal contamination in urban effluents and its impacts on recreational waters and sources of drinking water

### **What is the problem and what do scientists already know about it?**

When it rains, discharges of stormwater from storm sewers and overflows from combined sewers convey fecal bacteria to the receiving waters. Such discharges adversely impact on recreational waters (e.g., causing closures of public beaches) and potentially may contaminate sources of drinking water.

### **Who were our main partners in the study?**

The paper builds on the earlier studies of microbiological pollution in the Upper Great Lakes Connecting Channels. Those studies were requested and sponsored by Government of Canada's Great Lakes Sustainability Fund (GLSF), in support of remedial action in the Areas of Concern of the Great Lakes Basin.

### **Why did NWRI do this study?**

Stormwater and particularly combined sewer overflows (CSOs) are strong sources of fecal pollution of receiving waters and should be addressed in remedial activities. The impacts of both sources on recreational waters were clearly demonstrated. The analysis of results presented indicated a need for improving applications of recreational water quality guidelines with respect to microorganisms. Finally, effective remediation should include source controls (particularly removing sewer cross-connections), effluent treatment, and prevention of influx of contaminated waters to the areas used for recreation.

### **What were the results?**

The study results will be used in future NWRI and GLSF studies dealing with the management of stormwater and treatment of combined sewer overflows.

### **How will these results be used?**

The background studies were conducted in co-operation with the Great Lakes Sustainability Fund, and three universities - Queen's University, McMaster University and the University of Windsor.



## **Sommaire des recherches de l'INRE**

### **Titre en langage clair**

Contamination fécale des effluents en milieu urbain et ses impacts sur les eaux utilisées à des fins récréatives ainsi que sur les sources d'eau potable

### **Quel est le problème et que savent les chercheurs à ce sujet?**

Par temps pluvieux, les rejets d'eaux pluviales provenant des égouts pluviaux et les trop-pleins d'égouts unitaires acheminent des bactéries fécales vers les eaux réceptrices. De tels rejets peuvent avoir des impacts négatifs sur les eaux utilisées à des fins récréatives (par exemple, ils peuvent causer la fermeture des plages publiques) et contaminer des sources d'eau potable.

### **Pourquoi l'INRE a-t-il effectué cette étude?**

La communication repose sur des études faites antérieurement portant sur la contamination bactériologique des voies interlacustres des Grands Lacs d'amont. Le Fonds de durabilité des Grands Lacs du gouvernement du Canada (FDGL) a demandé et parrainé ces études afin de soutenir les mesures correctives dans les secteurs préoccupants du bassin des Grands Lacs.

### **Quels sont les résultats?**

Les eaux pluviales et plus particulièrement les trop-pleins d'égouts unitaires (TPEU) sont des sources importantes de pollution fécale des eaux réceptrices et doivent être pris en considération lors de l'élaboration de mesures correctives. Les impacts de ces deux sources sur les eaux utilisées à des fins récréatives ont été clairement démontrés. L'analyse des résultats présentés souligne l'importance d'améliorer la mise en application des recommandations sur la qualité des eaux utilisées à des fins récréatives en ce qui concerne les micro-organismes. Finalement, des mesures correctives efficaces doivent inclure des mesures de réduction de la contamination à la source (particulièrement l'élimination des jonctions fautives avec les égouts), le traitement des effluents et la prévention d'entrée d'eau contaminée dans les zones récréatives.

### **Comment ces résultats seront-ils utilisés?**

Les résultats de l'étude seront utilisés dans les prochaines études de l'INRE et du FDGL touchant à la gestion des eaux pluviales et au traitement des trop-pleins d'égouts unitaires.

### **Quels étaient nos principaux partenaires dans cette étude?**

Les études de base ont été menées en coopération avec le Fonds de durabilité des Grands Lacs ainsi qu'avec trois universités - l'Université Queen's, l'Université McMaster et l'Université de Windsor.

## URBAN WET-WEATHER FLOWS: SOURCES OF FECAL CONTAMINATION IMPACTING ON RECREATIONAL WATERS AND THREATENING DRINKING WATER SOURCES

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### ABSTRACT

*Fecal contamination is found frequently in urban waters as a result of discharges of wastewater treatment plant (WWTP) effluents, combined sewer overflows (CSOs), sanitary sewer overflows (SSOs), and urban stormwater. While the fecal contamination of WWTP effluents is well recognized and considered in the design of treatment and siting of effluent outfalls, wet-weather flow discharges (CSOs, SSOs and stormwater) have not been addressed so far to a similar extent. However, wet-weather flows often contaminate receiving waters and need to be considered in planning the protection of recreational waters and sources of drinking water.*

*During runoff, urban stormwater mobilizes and entrains solids, chemicals and bacteria from various sources, including cross-connections with sanitary sewers. Stormwater characterization data indicate that *E. coli* or fecal coliform bacteria counts in stormwater typically range from  $10^3$  to  $10^4$  units per 100 mL. Significantly higher counts ( $\geq 10^5$  units/100 mL) suggest the presence of cross-connections with sanitary sewers, which should be identified and corrected. Fecal contamination of stormwater may be attenuated prior to discharge into open waters by stormwater management measures, which typically remove suspended solids and attached bacteria. Exceptionally, stormwater discharges in the vicinity of swimming beaches are disinfected.*

*The levels of indicator bacteria in CSOs and SSOs (both represent diluted sanitary sewage) are much higher than in stormwater, and can be as high as  $10^6$  *E. coli* per 100 mL. Consequently, the abatement of fecal contamination of CSOs is now considered in the design of CSO control and treatment, as for example stipulated in the Ontario Interim Directive F-5-5 for CSO abatement. In some cases (e.g., the Toronto Waterfront), the abatement of fecal contamination of receiving waters is the primary driver behind the often-costly CSO abatement programs. CSO Abatement options comprise combinations of storage and treatment, in which the CSO treatment generally includes disinfection by UV irradiation.*

*Finally, indicator bacteria data from Sarnia (Ontario) are used to demonstrate some fecal contamination impacts of wet-weather flows. In wet weather, the microbiological quality of riverine water worsened as a result of activation of additional sources of fecal contamination (CSOs, stormwater discharges), and the recreational water guidelines for indicator organisms were exceeded much of the time. Local improvements in water quality were feasible by source controls and manipulation of transport of polluted water. Implications of differences between the federal and Ontario guidelines were also addressed. While the federal guideline uses two rules, a geometric mean (2000 *E. coli*/L) and a permissible maximum (4000 *E. coli*/L), the Ontario guideline specifies only the geometric mean (100 *E. coli*/100 mL). Depending on the number of collected samples, either guideline can become more rigorous.*

## 1.0 INTRODUCTION

In spite of continuing improvements in control of point source pollution, the water quality goals and designated uses of the receiving waters are unattainable without some advanced control of non-point source (NPS) pollution. In urban areas, the most significant source of NPS pollution is urban runoff, which may reach the receiving waters either as discharges of stormwater (SW) from storm sewers, or as combined sewer overflows (CSOs). Some sanitary sewers may also overflow in wet-weather, but not frequently. These three sources are then referred to as urban wet-weather pollution.

Urban wet-weather pollution (UWP) is recognized as a major source of impairment of water quality in many receiving waters, including a number of Areas of Concern (AOCs) in the Great Lakes region (Weatherbe and Sherbin, 1994). In 10 of the 17 Canadian AOCs, Weatherbe and Sherbin (1994) rated the urban wet-weather pollution of medium to very high significance. While wet-weather pollution can impact on receiving waters in many ways, the most difficult to control appears to be microbiological pollution, particularly in the case of CSOs. This follows from the fact that many water bodies in urban areas serve as recreational waters, which are subject to fairly rigorous microbiological water quality guidelines (100-200 *Escherichia coli* (*E. coli*)/100 mL) (Health and Welfare Canada, 1992; MOEE, 1994), and exceptionally, these waters may also serve as sources of raw drinking water. The typical levels of indicator bacteria in stormwater ( $10^3$ - $10^5$  *E. coli*/100 mL) and in CSOs ( $10^6$  *E. coli*/100 mL) greatly exceed the existing recreational water guidelines (Health and Welfare Canada, 1992) and make the control of wet-weather pollution rather challenging.

This situation is further exacerbated by the fact that wet-weather pollution is of a probabilistic nature, with respect to its occurrence in time, and the magnitude of flows and contaminant concentrations. In AOCs with strong wet-weather pollution, Toronto and Hamilton (Weatherbe and Sherbin, 1994), the abatement of microbiological pollution represents one of the greatest impediments to the delisting of these areas. In some AOCs, the upstream sources may strongly contribute to the observed microbiological pollution and remedial activities require an integrated approach addressing the entire contributing catchment (Murray et al., 2001; Pettibone and Irvine, 1996). Many studies indicate that microbiological pollution is the driving force behind ongoing wet-weather pollution control programs and contributes to the high costs of such efforts (Holler, 2001; Thackston and Murr 1999).

The main purpose of this review is to provide an overview of urban wet-weather flow pollution as a major source of microbiological pollution, examine recreational water quality guidelines, and address some pollution control measures. This discussion is supported by examples from the Upper Great Lakes Connecting Channels (UGLCCs) (Marsalek et al., 1996).

## 2.0 URBAN WET-WEATHER AS A SOURCE OF MICROBIOLOGICAL POLLUTION

During the past 30 years, numerous studies of indicator bacteria in stormwater and CSOs have been carried out in Canada (e.g., COA, 1978; Marsalek, 1979; James F. MacLaren, 1980; Marsalek et al., 1985; Marsalek and Ng, 1989; Marsalek et al., 1992; McCorquodale et al., 1992; Dutka and Marsalek, 1993; Kelly, 2002). In the early years, fecal coliforms were the indicator of choice, but more recently, *E. coli* was chosen according to the existing recreational water quality guidelines (Health and Welfare Canada, 1992; MOEE, 1994). In most locations, good correlation between both constituents exists (Health and Welfare Canada, 1992) and both sets of data are used in this discussion. A summary of microbiological data is given in Table 1.

Table 1: Mean *E. coli* or fecal coliform counts in Canadian stormwater.

Source (land use)	Location	Mean <i>E. coli</i> (EC) or fecal coliform (FC) units/100 mL	Reference
Residential	Barrhaven, Ottawa, ON	3,740 FC	COA (1978)
Residential	Brucewood (Toronto), ON	3,900 FC	James F. MacLaren (1980)
Residential	East York, ON	11,000 FC	COA (1978)
Residential	Guelph, ON	350 FC	COA (1978)
Residential	Malvern, Burlington, ON	3,600 FC	Marsalek (1979)
Residential	Mount Pearl, Nfld.	1,100 FC	Marsalek et al. (1985)
Residential	North York, ON	4,500 FC	COA (1978)
Residential	Sarnia, ON	820 EC	Marsalek and Ng (1989)
Commercial	Aldershot Plaza, ON	5,500 FC	Marsalek et al. (1992)
Combined	Etobicoke, ON	155,000 EC	Kelly (2002)
Combined	Sarnia, ON	6,140 EC	Marsalek and Ng (1989)
Combined	Sault Ste. Marie, ON	1,600 EC	Dutka and Marsalek (1993)
Combined	Toronto, ON	430,000 EC	Kelly (2002)
Combined	Windsor, ON	10,000 EC	McCorquodale et al. (1992)
Industrial	Scarborough, ON	1,140 EC	Kelly (2002)
Stormwater pond	Harding Park, Toronto, ON	2,300-8,400 EC	Kelly (2002)
Stormwater pond	Markham, ON	4,850 EC	Kelly (2002)
Highway	401 Highway, Toronto, ON	3,070 EC	Kelly (2002)

Bacteriological counts in Table 1 show a great variation ranging from about  $10^3$  to  $5 \times 10^5$  *E. coli* /100 mL. After excluding two large combined land use areas Etobicoke and Toronto in Table 1 (Kelly, 2002), the variation is reduced to 1,000 – 10,000 *E. coli*/100 mL. The lower range corresponds to small residential catchments and industrial land use, the higher values correspond to larger combined land use areas. All the stormwater sources listed exceed the recreational water quality guidelines 10 to 1000 times. Furthermore, even dry weather discharges from storm sewers may be contaminated by indicator bacteria, ranging from 20 to  $6 \times 10^5$  *E. coli*/100 mL (Kelly, 2002). There are two main

sources of dry weather flows in storm sewers – groundwater infiltration and sanitary sewer cross-connections. It appears that the low values would be associated with groundwater, the high values may represent sanitary sewage discharged illicitly into storm sewers. Storm sewer sediment also represents a source of indicator bacteria and pathogens; typical counts per gram of wet-weight sediment ranged from 20 fecal coliforms/g to 6000 fecal coliforms/g, and from 1.4 to 180 *Pseudomonas aeruginosa* units/g in relatively clean residential areas (COA, 1978).

The sources of bacteria in stormwater include domestic 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, accumulations of sediment in sewers, rodent habitation in sewers, land wash, and growth of bacteria in nutrient rich water standing in storm sewers between events (Olivieri et al., 1989). Besides indicator bacteria, other micro-organisms (*Pseudomonas aeruginosa*, *Salmonella*, total fungi, parasites) and a chemical indicator of bacteria, coprostanol, were also observed in stormwater (COA, 1978).

The levels of microbial populations in urban stormwater were considered high, similar to those observed in dilute sewage, and therefore constituted health hazards. The public health risks were further substantiated by the consistent recovery of pathogenic organisms at many sites studied (COA, 1978).

The levels of indicator bacteria in CSOs are higher than in stormwater, because CSOs represent a mixture of sanitary sewage, stormwater contaminated by bacteria and combined sewer sediment. A summary of limited data on CSOs appears in Table 2.

**Table 2: *E. coli* or fecal coliform counts in combined sewer overflows.**

Source	<i>E. coli</i> or fecal coliform units/100 mL	Reference
Toronto, mixed land use, ON	1,900,000 EC	Kelly (2002)
Sarnia, mixed land use, ON	944,000 EC	Marsalek and Ng (1989)
U.K. data	3,160,000 FC	Ellis (1986)
Sacramento, CA	7,900,000 FC	U.S. EPA (1974)

Data presented in Table 2 suggest that indicator bacterial counts in CSOs are higher than in stormwater, by as much as two orders of magnitude. Consequently, Ellis and Yu (1995) identified CSOs as a primary source with respect to fecal pollution indicator bacteria and pathogens in urban receiving waters. This was noted not only in the water column, but also in those in-stream sediments, which originated in sewers. Such sediments function as reservoirs of high bacterial concentrations over extended periods (> 9 days) following wet weather. Finally, since the main source of bacteria in CSOs is sanitary sewage (human waste), the presence of pathogenic organisms is to be expected, including bacteria, viruses, protozoa, and helminths (Metcalf and Eddy, 1991).

### 3. IMPACTS ON RECEIVING WATERS

Discharges of fecal pollution represent acute pollution, which manifests itself in receiving waters almost instantly. For pollutants causing acute impacts, frequency and duration of pollution discharge, and the resulting occurrence of pollutants in receiving waters at certain levels are of interest. Transport dynamics in receiving waters, including effluent mixing and dispersion, and pollutant decay (bacteria die-off), are important phenomena influencing the resulting concentrations in the receiving waters (Harremoes, 1988). The frequency of acute impacts is related to the frequency of rain events, which is governed by the local climate. The duration of such impacts exceeds the rainfall/runoff periods and includes the duration of wet-weather effects in receiving waters after rain cessation. After-effect duration may vary from several hours in well-flushed or stable receiving waters to 1-2 days in water bodies with limited circulation (Tsanis et al., 1995). Also, in the case of fecal bacteria, fecal pollution may be caused by resuspension of contaminated sediments in the near-shore lake zone (Palmer, 1987).

Microorganisms discharged into receiving waters are subjected to stressors such as temperature change, salinity (in coastal waters), nutrient deficiencies, sunlight and predation (Craig et al., 2001). The fastest decay occurs in the water column and at elevated temperatures (30° C), but bacteria survive particularly well in CSO sediment rich in organic carbon (Ellis and Yu, 1995).

Cause-effect relationships between the wet-weather discharges and impairment of recreational waters have been reported in many locations in the Upper Great Lakes Connecting Channels (Dutka and Marsalek, 1993; McCorquodale et al., 1992; Marsalek et al., 1996). However, the cases of contamination of drinking water sources by stormwater and CSOs are less well documented, because of a greater separation between wet-weather pollution discharges and drinking water sources. The impacts of wet-weather microbiological pollution on drinking water sources do occur in rivers, which may serve for pollution disposal in upstream communities and as a drinking water source in downstream communities (e.g., in some sections of the Upper Great Lakes Connecting Channels, UGLCC Study, 1988). Heath et al. (2002) studied this situation in the Ohio River, where indicator bacteria levels exceeded the recreational guidelines not only during wet weather, but also during dry weather, and also exceeded criteria for protection of human health for drinking water. Even with full control of CSO loads, the contact recreation criterion would be exceeded 5% of the time along the centre channel of the Ohio River, and 15% of the time along the banks, particularly below tributary confluences. The presence of *Giardia* and *Cryptosporidium* was not correlated with the occurrence of wet weather in this particular study.

Spatial considerations are also important for acute impacts, since their severity depends on the magnitude of discharges and the type and physical characteristics of the receiving waters. All receiving waters can tolerate some input loads without serious impairment of water uses (Harremoes, 1988). However, problems arise, when this capacity is exceeded. With respect to wet-weather pollution discharges, most significant impacts are found in streams and smaller rivers, and

harbours, estuaries and near-shore waters in lakes. The great numbers of stormwater and CSO outfalls, which are dispersed throughout the urban areas, also contribute to the severity of wet-weather pollution impacts.

Indicator bacteria concentrations were reported for many urban recreational waters, usually in connection with assessing the compliance with recreational water quality guidelines (Fuhs, 1975). Examples of such data are given below in Table 3 and refer to data collected in the early 1990s in the Upper Great Lakes Connecting Channels.

**Table 3: Summary of riverine bacteriological data (Marsalek et al., 1996).**

Assessment Parameter	<i>E. coli</i> Densities (EC/100mL)		
	Sault Ste. Marie	Sarnia	Windsor
Range of geometric means			
Dry weather	4-12	17-2046	49-395
Wet weather	4-162	62-5130	392-1929
Compliance with RWQG <sup>1</sup> (% of time)			
Dry weather	95.2-99.9	2-95	1.8-69.0
Wet weather	42.0-99.9	0.1-65.0	0.4-1.3

<sup>1</sup> RWQG = recreational water quality guideline = 100 *E. coli* units /100mL (MOEE, 1994).

The observed *E. coli* counts in Table 3 were found to follow the log-normal distribution. Such distributions were used to estimate compliance (% of the time during the swimming season) with the Ontario Recreational Water Quality Guideline (RWQG) of 100 *E. coli* units per 100 mL (MOE, 1994).

The data in Table 3 show large differences in microbiological pollution in the three study areas. The most upstream area, the St. Marys River in Sault Ste. Marie, is characterized by a high microbiological water quality resulting in high compliance with the RWQG in both wet and dry weather. The data from Sarnia show a greater microbiological pollution and much lower probabilities of compliance. As the range of values indicates, there are significant variations in the microbiological water quality in this area. The best values were found in the upstream section of the river, where recreational beaches are located (Marsalek et al., 1994). As one proceeds downstream through the urban area, the indicator bacteria counts increase not only in wet weather, but also in dry weather.

Finally, the results from Windsor show the same trends as those from Sarnia, but with greater severity. This may be explained by the large size of this urban area and the high number of CSO outfalls in the city (Marsalek et al., 1996). In both Sarnia and Windsor, the observed impacts of fecal pollution on the near-shore zones of the receiving waters were rather severe.

The integrated impacts of urban areas on microbiological riverine water quality were examined by comparing the data from the most downstream station to those from the most upstream station. In both Sarnia and Windsor, the indicator bacteria levels downstream from the study area exceeded those at the most

upstream station by an order of magnitude, in both wet and dry weather. In all areas, the microbiological water quality first worsened along the urban waterfront, but recovered downstream from the most populated section of the city through effluent mixing and dispersion (Marsalek et al., 1994; McCorquodale et al., 1992). In Sault Ste. Marie, such increases in fecal pollution along the river were not significant and the indicator bacteria counts at the downstream end were almost the same as at the upstream end. The local impacts of wet weather were observed in all three areas and could be characterized by bacterial count increases ranging from 1.5 times to more than 40 times, in the vicinity of sewer outfalls. After cessation of rain, runoff, and flushing (advection) of pollutants from the river reaches, the bacteria counts should return to the dry weather levels in less than 24 hours (Marsalek et al., 1992; McCorquodale et al., 1992).

While observations of bacterial concentrations in receiving waters represent the most reliable source of data, for practical reasons, field observations need to be extended by computer simulations, as described later.

#### 4.0 APPLICATION OF RWQGS IN RECEIVING WATERS

In recreational waters, the determination of the risk of disease or harm is based on such factors as environmental health assessment, epidemiological evidence, indicator organism limits (IOLs), and the presence of pathogens. While such factors can be determined for the existing state of waters, for remediation purposes, bacterial densities need to be predicted for various scenarios by modelling and compared to the existing RWQGs. In Canada, the federal guideline IOL may be superseded by more rigorous provincial guidelines.

The Health and Welfare Canada (federal) guideline (1992) requires that the geometric mean of at least 5 samples, taken during a period  $\leq 30$  days, should not exceed 200 *E. coli*/100 mL (the actual guideline specifies the count for 1 litre). When any sample exceeds 400 *E. coli*/100 mL, resampling should be performed. Thus, this guideline can be classified as a two-rule guideline. The Ontario Ministry of the Environment and Energy (provincial) water quality objective (1994) defines the IOL as 100 *E. coli*/100 mL, based on a geometric mean determined for a minimum of 5 samples per site taken within a given swimming area, within a one month period. This is a single rule guideline. Both guidelines were compared by El-Sharaawi and Marsalek (1999) by numerical simulations for a set of indicator bacteria data from the St. Clair River in Sarnia (just downstream of the city), characterized by  $\sigma = 0.61$  (the value of the standard deviation of log *E. coli* counts) and varying the number of samples. Using the 0.95 acceptance probability, for less than 15 samples, the provincial guideline was more difficult to meet; for 15 and more samples, the federal guideline was more conservative.

While the use of the geometric mean in calculating IOL is well established, Haas (1996) argued that this preference is based more or less on a simplified averaging issue, and that for microorganism densities in environmental media, the



arithmetic mean would be a better summary descriptor. Indeed, for a single rule guideline, in calculations of the geometric mean, high counts may be compensated for by low counts, but similar compensation does not apply to the risk of infection.

Considering the probabilistic nature of bacterial counts, the compliance with IOLs should be also specified at a certain level of probability, to avoid inherent non-compliance caused by wet-weather events. In other words, IOLs should be met during the swimming season for some specified minimum duration, typically ranging from 80 to 95% of the time (CEC, 1991). Lower limits may apply to waters not used extensively for recreation, higher limits may apply to waters used frequently for recreation. This probabilistic approach to IOL compliance is more realistic than the existing guidelines, and would ensure the possibility of full compliance with recreational water use guidelines.

Operational experience from many jurisdictions indicates difficulties in applying IOL guidelines. Perhaps the most apparent difficulty arises from the fact that guidelines do not differentiate between wet and dry weather, yet the bacteria sources and concentrations during those two weather regimes are quite different and the IOLs are hard to meet during wet weather. The distinction between both regimes is obscured by the after-effect period (Tsanis et al., 1995). In practice, the IOL is determined as a running mean of the  $N$  most recently collected samples ( $N \geq 5$ ). The choice of  $N$  will affect the calculated values of the IOL.

The last problem with applying IOLs in beach operation is the time delay in microorganism determination and the need to operate beaches in real time. Traditional analytical methods involve laboratory incubation and introduce a time delay of about 24 hours between sample collection and determination of bacteria counts. However, the decision whether to operate or close the beach should be done as soon as the exceedance occurs, rather than 24 hours later. Consequently, the decisions on beach closing are based on surrogate events, such as wet weather, which may be known as a primary cause of beach pollution. The beach may remain closed for some period after the rainfall cessation, to allow for any pollution after-effects. Significant improvement in this field should follow from new molecular biology methods for bacteria detection. Towards this end, Tryland et al. (2001) reported on the use of the Colifast Early Warning System, which is based on measuring  $\beta$ -galactosidase activity, and reduces the duration of *E. coli* measurements to 2-6 hours. Such a system can be used as an early warning indicator of fecal contamination.

Finally, it is of interest to note the European experience with bathing water surveillance, which is required under the EC Bathing Water Directive. Surveys of 14 bathing sites in Germany noted 5.5% non-compliance with respect to the existing microbiological standard; 6.1% non-compliance for the proposed Standard 2 (400 ECU/100 mL and 100 enterococci/100 mL), and 21% for the proposed Standard 3 (100 ECU/100 mL and 50 enterococci/100 mL (Holler, 2001). Potential costs of technical measures required to achieve compliance were

more than \$US 10 million per site. A shift from punishing non-compliance towards punishing inaction to improve water quality was noted.

## 5.0 MODELLING WET-WEATHER FLOW POLLUTION IMPACTS

Recognizing the complexity and dynamic nature of the fecal pollution in receiving waters, computer modelling is used extensively in analysis of such pollution. The modelling procedure comprises three steps - (a) developing source/loading models, (b) setting up receiving water models, and (c) modelling remedial effects on bacterial levels.

Two types of fecal bacteria sources are recognized, point sources (discharges from wastewater treatment plants) and non-point (diffuse) sources (storm sewer and CSO outfalls). The former sources can be readily modelled using plant records of discharges and bacterial counts. For modelling diffuse sources, existing urban runoff models can be used. For example, Schroeter (1991) used the STORM model in conjunction with a water quality rating curve to produce bacterial loads. The water quality rating curve was expressed as  $F = a Q^b$ , where  $F$  is a bacterial flux,  $Q$  is the source discharge, and parameters  $a$  and  $b$  were fitted to observed data. A similar approach was applied by Heath et al. (2002), who used the XP-SWMM model for load estimations.

For receiving water modelling, various models can be used. Tsanis et al. (1995) used a two-dimensional depth-averaged irregular finite-difference model (FDM) with two dynamic equations, a continuity equation and a transport equation describing two distinct mechanisms - advection and turbulent diffusion. The transport equation also included bacterial decay. McCorquodale et al. (1992) used the KETOX model to simulate a steady or quasi steady river system approximated by a link-node system. In each link, the hydrodynamics of two-dimensional non-recirculating flow was based on one of two options - friction and gravity forces equilibrium, or a momentum redistribution option that operated on a given upstream momentum distribution. The local eddy viscosity and lateral dispersion were approximated by the  $k-\epsilon$  model and a mixing component was also included. The model contained options for several kinetics processes (e.g. exponential decay of bacteria) as well as interaction with suspended and bed sediments. Both models were calibrated as much as the available data allowed. In the Ohio River study (Heath et al., 2002), two models were used; the U.S. Army Corps of Engineers hydrodynamic model for modelling river flows, and the U.S. EPA WASP5 water quality model for pollutant transport and fate.

In the St. Clair River in Sarnia (Tsanis et al., 1995), the main modelling results included the simulated persistence of elevated bacterial levels after the cessation of rainfall (flushing times) for various locations in the receiving waters, and the screening assessment of several remedial measures including the disconnection of outfalls, flushing of Sarnia Bay by unpolluted riverine water, and construction of a deflector barrier to prevent circulation from transporting sewer discharges into

the Bay. These results indicated that to achieve the RWQG value of 100 EC/100 mL, a combination of remedial measures would be needed (Tsanis et al., 1995).

In Windsor, the KETOX model was used to produce time series of bacterial counts along the river section studied (McCorquodale et al., 1992). During wet weather, the simulated data agreed fairly well with those observed. In dry weather, the model underestimated the observed bacterial levels, because of inputs from unexpected sources (i.e. malfunctioning sewer systems discharging in dry weather). To account for these sources, dry weather loadings equal to about 8% of the wet weather loadings had to be assumed (McCorquodale et al., 1992). The model also indicated that polluted waters may be detained in small embayments along the shoreline and contribute to elevated bacterial counts (after-effects) in dry weather. Among the remedial options, the elimination of five major CSO outfalls was considered and contributed to an increased probability of compliance with the Ontario RWQG (100 *E. coli*/100 mL) from the current 40% to about 70%, in model simulations.

## 6.0 REMEDIAL MEASURES

Remediation of fecal pollution requires an integrated approach applying controls at the source, in the transport network, and in the receiving waters. Source controls are generally policies and related structural measures (e.g., elimination of illicit sewer connections), which reduce or eliminate entry of fecal bacteria into stormwater and receiving waters. With respect to reducing fecal pollution of stormwater, main considerations include cleanup of pet feces, enforcement of sewer ordinances, proper housekeeping practices, and good maintenance of sewers and their appurtenances. Domestic pet pollution control is achieved through public education, awareness and participation; there is adequate guidance available in the literature on designing and implementing such programs (WEF and ASCE, 1998).

The enforcement of sewer ordinances is particularly important with respect to illicit connections to storm drains, often in the form of sanitary sewer cross-connections. To deal with these problems, a two-pronged approach is needed – educating the public about the harm caused by cross-connections, and instituting ordinances to detect and correct such connections. Municipal building and plumbing codes must prohibit connections of sanitary sewage to storm drains and establish penalties for violations. Codes are enforced by inspections, and where needed, common methods of tracking connections are used for verification (smoke, dye and TV testing) (WEF and ASCE, 1998). Housekeeping practices include proper collection of solid waste and prevention of rodent infestation. With respect to maintenance, effective domestic waste collection and recycling programs help reduce littering and illicit disposal (WEF and ASCE, 1998).

The need for regular and preventative maintenance also applies to the transport network conveying stormwater and combined sewage. In the case of stormwater, reduced fluxes of sediments and/or their removal may help reduce bacterial loads

carried by sediment. Furthermore, best management practices (BMPs) for stormwater control were also found effective in reducing bacterial loads in stormwater (Schueler, 1987). The most effective are those BMPs, which also reduce stormwater flows, such as infiltration trenches and basins, and porous pavement (Schueler, 1987). Among other BMPs, constructed wetlands were highly effective in retaining indicator organisms, 2-3 log per filter bed (Hagendorf et al., 2001), and wet ponds may also be effective, mostly through bacteria die-off during storage in shallow ponds exposed to solar radiation, as suggested by Schueler (1987). Hagendorf et al. (2001) found well-maintained constructed wetlands effective in removal of parasites, including *Cryptosporidium* and *Giardia*.

One of the most effective controls of fecal bacteria is disinfection (Metcalf and Eddy, 1991), which may be applied at various locations in the drainage system. Perhaps the first application of UV irradiation to stormwater disinfection was at the Longfields/Davidson Heights Stormwater Treatment Facility, operated by the City of Nepean (Tracy and Craig, 1993). This facility services a drainage area of 900 ha and discharges into the Rideau River, which is used for recreation. The pond provided for effective stormwater settling, with suspended solids below the limit of 25 mg/L. Such settled stormwater was disinfected by UV irradiation, with fecal coliform concentrations typically well below 100 units/100 mL, and most often less than 10. The cost of the UV facility was approximately \$1 million.

Disinfection of CSOs is required in Ontario in the areas upstream of recreational waters, under the Procedure F-5-5 (MOE, undated). The disinfected effluent concentrations of *E. coli* should be less than 1000 EC/100 mL (monthly average). The most common processes for CSO disinfection include calcium or sodium hypochlorite, chlorine dioxide, bromine chloride solution, ozone and UV light. The WPCF manual on CSO pollution abatement (WPCF, 1989) recommends use of shorter contact times but higher disinfectant doses and mixing in CSO disinfection. When using chlorination, dechlorination may be also required. For UV disinfection, it is important to substantially reduce suspended solids (say below 80 mg/L) to make this process effective (Metcalf and Eddy, 1991).

Finally, local improvements in bacteriological quality in receiving waters can be achieved by a combination of measures, which include source controls, re-routing of sewer discharges (e.g., by building an interceptor sewer conveying discharge to another location), and manipulating bacteria transport in rivers and preventing influx of contaminated waters to the areas used extensively for water-based recreation.

## 7.0 CONCLUSIONS

Urban wet-weather pollution, including CSOs, stormwater and sanitary overflows or bypasses, strongly contributes to the microbiological contamination of receiving waters and the resulting violations of recreational water quality guidelines. Such flows also impact on drinking water sources, where receiving

waters are used for water supply. Operation of public recreational waters is guided by recreational water quality guidelines, which use indicator organism limits to measure microbiological pollution. A number of difficulties exist in application of such guidelines, particularly in connection with wet-weather impacts and the need for fast or real time determination of indicator bacteria levels. For analysis of wet-weather impacts and the assessment of remedial measures, computer modelling is recommended. Among the remedial measures, the highest priority should be assigned to source controls, particularly in the case of dry weather sources. Local improvements in water quality can be obtained by re-routing sewer discharges, disinfection, and preventing influx of contaminated waters to the areas used extensively for water-based recreation.

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