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Hydraulics Research
Wallingford

# BACTERIA IN URBAN DRAINAGE SYSTEMS

## LITERATURE REVIEW

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ABSTRACT

This report summarises available information on the behaviour of bacteria in urban drainage systems. The report has been prepared as a preliminary step towards the modelling of bacteria in MOSQITO and/or QUDOS, the sewer flow quality models currently under development at Hydraulics Research Limited in conjunction with the Water Research Centre as part of the UK River Basin Management Programme. It is anticipated that simulation of bacterial quality will be required to coordinate with receiving water impact models and recreational water quality standards such as the EC Bathing Beaches Directive.

The lack of data collected in the UK which would be suitable for model development is highlighted, and the difficulties associated with data collection are described. Data collected elsewhere are summarised in terms of sources of bacteria, likely bacterial populations in combined and separate sewer systems, and factors which affect bacterial behaviour.

Methods of modelling bacteria are described, and existing models which simulate bacteria counts in urban drainage systems are reviewed.

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# 1 INTRODUCTION

## 1.1 Background

MOSQITO I is the initial version of a sewer flow quality model being developed by Hydraulics Research Ltd. and the Water Research Centre as part of the UK River Basin Management programme.

The rationale behind the model, its development and its structure have been described in detail elsewhere (Moys et al, 1988).

MOSQITO simulates the time-varying behaviour of pollutants on catchment surfaces and in sewer systems, and produces discharge pollutographs which can be used as input to a river water quality model. Determinands simulated in the initial version of MOSQITO are:

suspended solids (SS)
biochemical oxygen demand (BOD)
chemical oxygen demand (COD)
ammoniacal nitrogen (Am-N)

The enhanced version of MOSQITO, due for release in 1990/91, will simulate the behaviour of additional determinands; possibly including metals and bacteria.

Before attempting to model the behaviour of bacteria in urban drainage systems (and possibly receiving waters), a review of current knowledge has been undertaken.

## 1.2 Objectives

The objectives of this exercise are as follows:

(1) Identify the sources of bacteria in urban drainage systems

(2) Determine the numbers of bacteria likely to be present in urban drainage systems

(3) Investigate the behaviour of bacteria in urban drainage systems

(4) Identify the factors influencing the behaviour of bacteria in urban drainage systems

(5) Review previous methods of modelling bacteria in urban drainage systems.

## 1.3 **Bacterial Indicators**

Many pathogenic and non-pathogenic microorganisms are present in storm sewage and urban runoff. Pathogens can enter streams and water bodies where they constitute a health hazard.

Monitoring for the presence of specific pathogens is impractical for routine samples. The most common approach for determining the possible presence of pathogens in water is the detection of an indicator organism. The presence of indicator organisms is indicative of faecal pollution, and therefore of the potential presence of intestinal pathogens. Indicator organisms are preferred primarily because they are more abundant and therefore easier to detect than the pathogens themselves.

The ideal indicator of an intestinal pathogen must always be present when the pathogen is present and absent when the pathogen is absent. It should be easy to detect and quantify. The only ideal indicator is the pathogen itself, as no organism can consistently meet all the criteria for the ideal indicator. The organisms used as indicators are widely accepted as adequate indicators in clean water.

Bacteria of the coliform group are the most frequently used indicators of faecal pollution. The total coliform group includes E. Coli, all other faecal coliforms, and many of non-faecal origin. Faecal streptococci are also commonly used. Faecal streptococci often die off less rapidly than E.Coli and in the absence of the latter their presence can indicate remote or intermittent faecal pollution. They can be used in conjunction with faecal coliform counts to determine the likely source of pollution (Geldreich, 1978), although this is not always reliable (Gameson, 1978).

The limitations of coliform bacteria as indicators of the presence of pathogens are recognised, and alternative indicators have been proposed. Despite this, coliform bacteria and faecal streptococci counts are the most commonly quoted indices of microbiological quality in water quality standards.

## 1.4 **Enumeration of Bacteria**

Numbers of indicator organisms are usually estimated either by the "Multiple Tube" or by the "Membrane Filtration" method.

In the multiple tube method, a selective enrichment medium is inoculated with serial dilutions of sample and then incubated.

Statistical tables are used to give the most probable number (MPN) of organisms per 100ml sample following their detection in the multiple tube method. The method is known to have a large sampling error. For example, in the 11-tube and 15-tube tests, the upper limit of the number of organisms likely to be present is about three times the MPN value, and the lower limit is between a third and a quarter of it (Standing Committee of Analysts, 1983).

Alternatively, the membrane filter technique, which involves separation of bacteria from suspension by filtration, can be used. The filtration is followed by incubation with a nutrient medium and counting of coliform colonies. Results from this method are reported as counts per 100ml sample.

Replicate membrane tests on samples do not yield identical results, but the range of counts obtained would lie within statistically calculated limits. Membrane filtration counts should therefore be regarded as estimates subject to statistical variation.

Both methods rely on bacterial growth. Coliform bacteria have the ability to ferment lactose and produce acid and gas. The production of acid and gas within 48 hours following incubation at 37°C indicates the presence of coliform bacteria. Coliform bacteria which have the same properties at 44°C are known as 'thermotolerant', and are usually referred to as 'faecal coliforms' although this is not strictly correct since not all thermotolerant coliform bacteria are of faecal origin. E. Coli are thermotolerant coliform organisms which produce acid and gas within 24 hours and which also form indole from tryptophan.

Because the methods used to enumerate bacteria are dependent on the ability of the bacteria to multiply, the results will depend on the conditions of the test (temperature, nutrient medium used etc.) and on the physiological state of the bacteria present. The accuracy of such methods is therefore difficult to assess and apparently slight procedural differences can significantly affect results.

Further problems are caused by the effect of delays between sampling and analysis. This may be particularly important where automatic samplers are employed and analysis is deferred. British data examined by Gameson (1978) indicate that coliform counts in sewage increase by a factor of approximately 2 during the first day of storage, and that there is an initial rise in count during the first few hours, followed by a decline. It follows that any delay in analysis is crucial. For drinking water, it is recommended that samples should be examined within six hours of collection (PHLS, 1952). For sewage samples, even this delay will affect results. Storage temperature also affects counts : Gameson found that storing sewage for four hours at 6°C resulted in a 40% decrease in coliform count whereas storage at 20°C resulted in a 60% increase.

The difficulties associated with the enumeration of bacteria must be considered in the collection and interpretation of data intended for use in model development and verification.

## 1.5 **Health Hazard and Water Quality Standards**

Indicator bacteria and pathogens are consistently detected in urban runoff, but in relatively low concentrations which are unlikely to cause disease unless large quantities are ingested (Olivieri, 1980). A possible threat exists from consuming contaminated shellfish in coastal areas, but the risk of infection from recreational contact with water is low.

In the case of combined discharges the risk is greater, although existing standards have not been supported by data on health effects. The WHO therefore recommend that individual countries develop their own health-related quality criteria to suit particular conditions (Cheung et al, 1988).

The EC bathing water directive (Council of the European Communities, 1976) requirement is for fortnightly sampling and analysis for total and faecal coliforms, and analysis for faecal streptococci, salmonellae and enteroviruses if quality deteriorates. The guide values for total and faecal coliform counts are 500 and 100 per 100ml respectively, and 80% of samples should conform to this standard. The mandatory limits set in the Directive are 10,000 total coliforms and 2000 faecal coliforms per 100ml. 95% of samples should conform to this standard.

No standards have yet been set for recreational river water quality, but it is likely that they will be based on the existing bathing water directive.

## 2 SURFACE WATER SYSTEMS

There is little information on the bacterial quality of urban runoff in the UK. Several studies have been carried out in the US and Canada which indicate that urban runoff contributes significantly to bacteria counts in sewerage systems.

### 2.1 Sources of Microorganisms in Surface Water Systems

Rainwater contains insignificant numbers of bacteria (Geldreich et al, 1968) so it follows that contamination with bacteria takes place on contact with the urban land environment.

Surface sources include contaminated soils, faeces of pets and rodents, and accumulations of domestic litter in streets (Olivieri, 1980).

Within surface water sewers, additional contamination from foul sewage can occur as a result of overflows from the foul system, illegal connections and spillages.

Geldreich et al (1968) related non-faecal coliforms in runoff to levels in soil, and faecal coliforms to cat, dog and rodent faeces on the catchment surface; based on the occurrence of different coliform types.

Qureshi and Dutka (1979) conducted a study on a 23.3 ha section of Burlington, Ontario which they describe as 100% separately sewered. Samples of infiltration water (presumably from contaminated groundwater and illegal connections) were collected and analysed for total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS). Counts up to 5600/100ml (TC), 1800/100ml (FC), and 900/100ml (FS) were recorded. Infiltration waters were concluded to be a continuous source of low-grade pollution. More detailed examination of the infiltration samples indicated 'faecal pollution with more regrowth within the system'.

Olivieri et al (1988) found low concentrations of indicators in runoff from areas with low population densities, and higher concentrations in high population density areas with poor sanitary conditions. The 'dirtiness' of the areas studied, and in particular the presence of uncovered rubbish, was concluded to have a significant effect on the bacteriological quality of the runoff.

## 2.2 **Bacterial Populations in Surface Water Systems**

### **2.2.1** Average Organism Densities

An extensive study of microorganisms in sewer systems was carried out in Baltimore, Maryland and has been reported by Olivieri (1980) and others (Olivieri et al, 1977). Samples were taken and analysed over a 12 month period from sites including 5 surface water storm sewer outfalls. Some characteristics of the catchments are given in Table 2.1.

TABLE 2.1 CHARACTERISTICS OF SAMPLED CATCHMENTS

| sampling station | catchment area (ha) | predominant land use | remarks |
|---|---|---|---|
| Stoney Run | 558 | residential | 3 overflows* |
| Glen Ave. | 80 | residential | 1 overflow* |
| Jones Falls | 253 | residential | 1 overflow* |
| Bush St. | 440 | residential /parkland | storm only |
| Northwood | 50 | residential /industrial /commercial | storm only |

* Intentional overflow from foul sewer to storm drainage system

The Stoney Run, Glen Avenue and Jones Falls systems were known to be contaminated with foul sewage from overflows from the foul system. Sewage contamination in the Bush Street system was also suspected. The Northwood system was believed to be storm only. The geometric mean densities of TC, FC and FS are given in Table 2.2, with data for raw sewage collected as part of the same study.

The reported figures suggest heavy contamination at each site, with organism densities approaching those found in raw sewage. The Northwood site, which was believed to be uncontaminated, contained consistently lower levels of indicators than the other sites.

TABLE 2.2 MEAN DENSITIES OF INDICATORS IN URBAN RUNOFF (after Olivieri, 1980)

| sampling station | total coliform MPN/100ml | faecal coliform MPN/100ml | faecal streptococci no./100ml |
|---|---|---|---|
| Stoney Run | $4.8 \times 10^4$ | $1.9 \times 10^4$ | $4.1 \times 10^4$ |
| Glen Ave. | 2.4 x 105 | $8.1 \times 10^4$ | $6.6 \times 10^5$ |
| Jones Falls | $2.9 \times 10^5$ | $1.2 \times 10^5$ | $2.8 \times 10^5$ |
| Bush St. | $3.8 \times 10^5$ | $8.3 \times 10^4$ | $5.6 \times 10^5$ |
| Northwood | $3.8 \times 10^4$ | $6.9 \times 10^3$ | $5.0 \times 10^4$ |
| Raw Sewage | $2.3 \times 10^7$ | $6.3 \times 10^6$ | $1.2 \times 10^6$ |

Similar studies have been reported by Geldreich et al (1968), Burns and Vaughn (1966), Benzie and Courchaine (1966), DeFilippi and Shih (1971), and Olivieri et al (1988). A summary of these results is given in Table 2.3. There is wide variation in reported counts, with marked seasonal effects as counts rise in summer and autumn. Seasonal effects are further discussed in section 2.3.

### **2.2.2** Variation Within Events

Qureshi and Dutka (1979) observed maximum bacterial populations in samples taken during the 60 to 105 minute period of most storms, although they do not relate these to flows.

DeFilippi and Shih (1971) observed a first flush effect for total coliforms, faecal coliforms and faecal streptococci. In one event the bacteria counts in the early part of the storm were 1.34 million, 1.3 million, and 31,000 per 100ml for TC, FC and FS respectively. In the remainder of the storm the average counts fell to 540,000, 160,000 and 17,400 per 100ml. Flows were measured in this study but the first flush effect was reported in terms of organism densities.

Blumberg and Bell (1984) found a first flush for total and faecal coliforms in runoff from a 29 acre residential catchment. The first flush was reported in terms of organism densities.

TABLE 2.3 INDICATOR ORGANISMS IN URBAN RUNOFF

| Catchment | Period | Total Samples | Total Coliform | Faecal Coliform | Faecal Streptococci | Remarks |
|---|---|---|---|---|---|---|
| Wooded hillside, Cincinnati | Spring | 278 | 2 400 | 190 | 940 | Organisms/100ml |
| | Summer | | 79 000 | 1 900 | 27 000 | Median values |
| | Autumn | | 180 000 | 430 | 13 000 | (Geldreich et al,1968) |
| | Winter | | 260 | 20 | 950 | |
| Street Gutters, Cincinnati | Spring | 177 | 1 400 | 230 | 3 100 | Organisms/100ml |
| | Summer | | 90 000 | 6 400 | 150 000 | Median values |
| | Autumn | | 290 000 | 47 000 | 140 000 | (Geldreich et al, 1968) |
| | Winter | | 1 600 | 50 | 2 000 | |
| Business District, Cincinnati | Spring | 294 | 22 000 | 2 500 | 13 000 | Organisms/100ml |
| | Summer | | 172 000 | 13 000 | 51 000 | Median values |
| | Autumn | | 190 000 | 40 000 | 56 000 | (Geldreich et al, 1968) |
| | Winter | | 46 000 | 4 300 | 28 000 | |
| Allen Creek, Ann Arbor | April | - | 340 000 | 10 000 | 20 000 | |
| | May | - | 510 000 | 51 000 | 200 000 | Organisms/100ml |
| | June | - | 4000 000 | 78 000 | 120 000 | (Benzie and Courchaine, |
| | July | - | 4000 000 | 120 000 | 390 000 | 1966) |
| | August | - | 1700 000 | 350 000 | 310 000 | |
| Good Hope Run, District of Columbia | April to September | - | 600 000 | 310 000 | 21 000 | Organisms/100ml Mean values (DeFilippi and Shih, 1971) |
| Homeland, Baltimore | November to June | 26 | 280 | 33 | 790 | MPN/100ml (n/100ml for FS) Mean values (Olivieri, 1988) |
| Bolton Hill, Baltimore | November to June | 26 | 1 000 | 170 | 3 600 | MPN/100ml (n/100ml for FS) Mean values (Olivieri, 1988) |
| Reservoir Hill, Baltimore | November to | 24 | 110 000 | 49 000 | 6 500 | MPN/100ml (n/100ml for FS) Mean values (Olivieri, 1988) |

FIGURE 2.1 PLOTS OF TOTAL COLIFORM, FAECAL COLIFORM AND FLOW EXHIBITING PATTERN-ONE POLLUTOGRAPHS

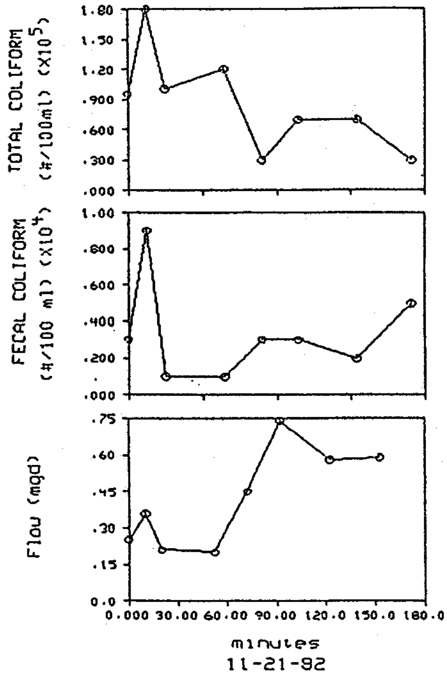



FIGURE 2.2 PLOTS OF TOTAL COLIFORM, FAECAL COLIFORM AND FLOW EXHIBITING PATTERN-TWO POLLUTOGRAPHS

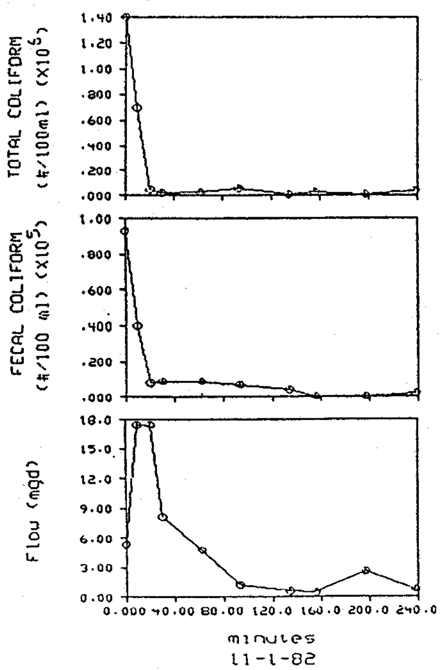
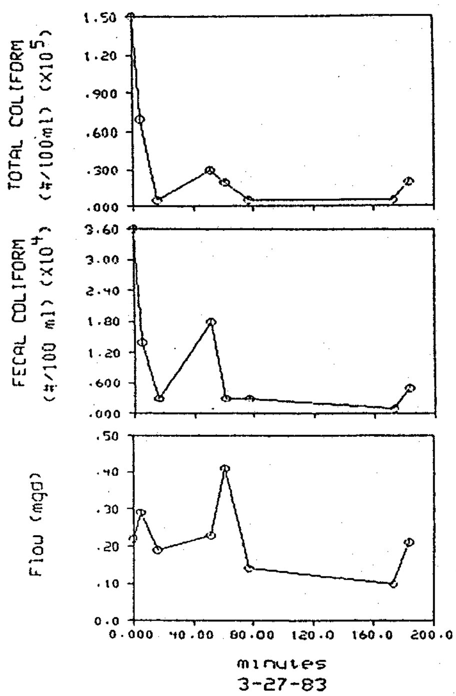


FIGURE 2.3 PLOTS OF TOTAL COLIFORM, FAECAL COLIFORM AND FLOW EXHIBITING PATTERN-THREE POLLUTOGRAPHS




Three general pollutograph patterns were identified (Figs 2.1 to 2.3). Total coliforms exhibited 7 pattern-one, 4 pattern-two and 13 pattern-three pollutographs. Faecal coliforms exhibited 6 pattern-one, 7 pattern-two, and 10 pattern-three. This was the only study which attempted to establish any pattern for bacterial discharge. No such patterns were reported by other studies.

### 2.2.3 Relationship to Other Parameters

In studies where chemical as well as bacteriological analyses were carried out, no correlation between indicator densities and other quality parameters has been reported. Collins and Ridgway (1980) pooled data from surface water system surveys and found that faecal coliform did not correlate with concentrations of suspended solids.

Schillinger and Gannon (1985) found no strong correlations between the bacteriological and other measurements made on the Allen Creek surface water system. A possible positive relationship was observed between faecal coliforms and suspended solids, but this was not always present.

The Detroit study (Benzie and Courchaine, 1966) looked for a relationship between bacteriological quality and total rainfall but none was found.

Olivieri (1977) failed to find any relationship between instantaneous discharge and faecal coliform levels. Similarly, counts were found to be independent of the antecedent dry weather period.

### 2.2.4 Indicator Ratios

Geldreich and Kenner (1969) suggested that the ratio of faecal coliform to faecal streptococci was an indication of the source of faecal contamination. An FC:FS ratio greater than 4.0 indicates human faecal matter, and a ratio less than 0.7 indicates faecal contamination from other animals. This ratio is used in some countries in an attempt to assess the nature of recent faecal pollution, although many variables such as time, temperature, and differential survival of organisms affect its validity.

Despite doubts over the applicability of the FC:FS ratio to urban situations, it can be used as a guide to the degree of contamination of surface water systems. Values of the ratio for the sites considered above are given in Table 2.4. The values are all low, as would be expected in storm only systems. The faecal coliform content of samples as a percentage of the total coliform population can be used similarly.

TABLE 2.4 INDICATOR RATIOS IN SURFACE WATER SYSTEMS

| catchment | period | FC/FS | FC/TC x 100 |
|---|---|---|---|
| Wooded hillside, Cincinnati | spring | 0.20 | 7.9 |
| | summer | 0.70 | 2.4 |
| | autumn | 0.30 | 0.2 |
| | winter | 0.02 | 7.7 |
| Street gutters, Cincinnati | spring | 0.07 | 16.4 |
| | summer | 0.04 | 7.1 |
| | autumn | 0.34 | 16.2 |
| | winter | 0.02 | 3.1 |
| Business district, Cincinnati | spring | 0.19 | 11.4 |
| | summer | 0.26 | 7.6 |
| | autumn | 0.71 | 21.6 |
| | winter | 0.15 | 9.4 |
| Allen Creek, Ann Arbor | April | 0.50 | 2.9 |
| | May | 0.30 | 10.0 |
| | June | 0.70 | 2.0 |
| | July | 0.30 | 3.0 |
| | August | 1.10 | 20.5 |

### 2.2.5 Summary

Similar conclusions were reached in most of the reported studies and these are summarised below.

a) Separate storm discharges contain considerable quantities of total coliforms, faecal coliforms, and faecal streptococci.

b) No relationships were observed between bacterial quality and chemical quality, total rainfall, flow in the sewer or antecedent dry weather period.

c) There was no predictable pattern for numbers of bacteria discharged within individual events.

d) Bacteria counts vary with discharge flow rates with a tendency for a first flush effect.

e) Marked seasonal effects were observed, with peak bacteria counts occurring in summer and autumn.

## 2.3 **Factors Affecting Bacterial Populations in Surface Water Systems**

The factors which have been identified as affecting the numbers of bacteria present in surface water systems are:

a) 'Dirtiness' of the catchment surface

b) Season, probably due to temperature

c) Degree of contamination by foul sewage

The dirtiness of catchments is difficult to assess, but an approximation can be made using the socio-economic group as a guide to the likely sanitary conditions.

Substantial seasonal variation in coliform count was observed at sites participating in the US EPA's Nationwide Urban Runoff Program (US EPA, 1983). Warm-weather counts are reported as approximately 20 times higher than cold-weather counts, and this is attributed to temperature and non-faecal sources of coliform.

Geldreich et al (1968) conducted bacterial survival studies on 52 samples of runoff collected over a two-year period. These samples had widely differing chemical characteristics. No relationship was found between survival rate of bacteria and chemical composition of the runoff, but a positive correlation was found between survival and water temperature (Figs. 2.4 and 2.5). Organism persistence was generally higher for winter samples kept at 10°C than for summer samples kept at 20°C.

Schillinger and Gannon (1985) investigated adsorption of bacteria to suspended sediment surfaces in urban runoff. They found that retention and settling was of sufficient magnitude to warrant further study for modelling applications. They also reported lower adsorption of faecal coliforms than other bacteria, and suggested that faecal coliforms may not be the best indicators of pathogen adsorption and sedimentation.

FIGURE 2.4 PERSISTENCE OF SELECTED ENTERIC BACTERIA IN STORMWATER STORED AT 10°C

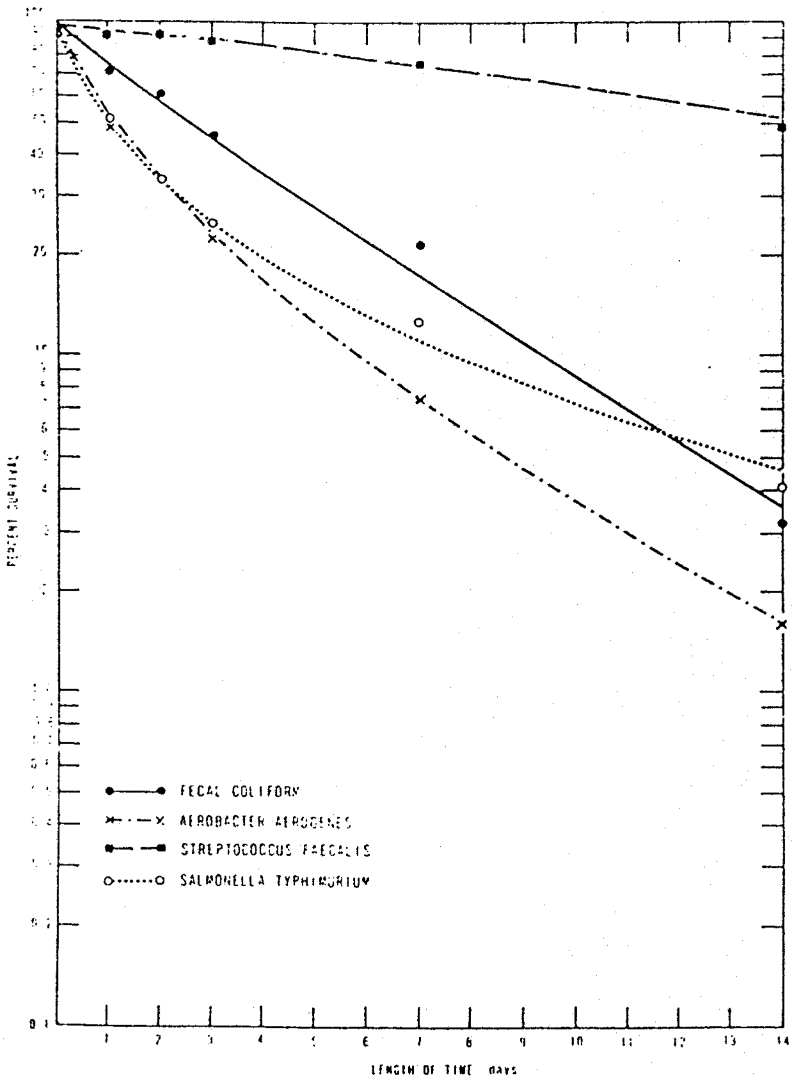
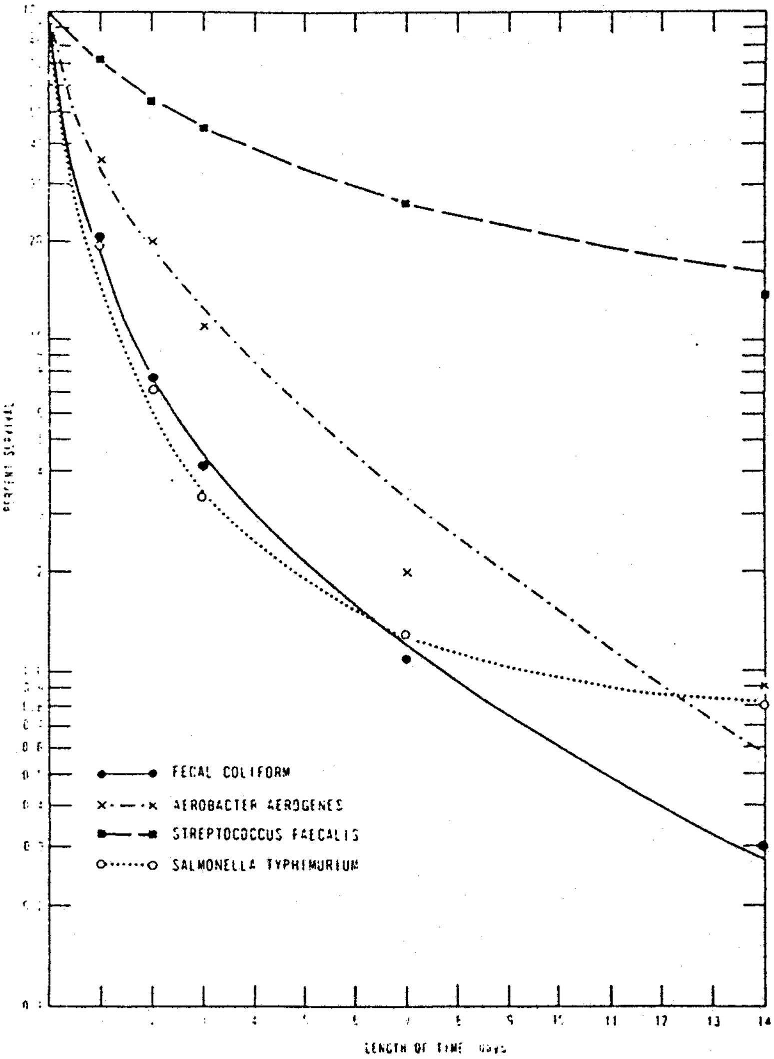


FIGURE 2.5 PERSISTENCE OF SELECTED ENTERIC BACTERIA IN STORMWATER STORED AT 20°C



## 3 COMBINED SYSTEMS

The majority of published data from combined systems is from American studies. Some British data have been reported by Gameson (1978) which relate to coastal discharges.

### 3.1 Foul Sewage

Most of the coliform bacteria in foul sewage are derived from the faeces of the human population. Additional sources are domestic and commercial kitchen and laundry wastes, which have been shown to contain high numbers of coliforms (Kitrell and Furfari, 1963).

E. Coli is the most abundant coliform organism in the human intestine, and is present in fresh faeces in numbers approaching 1000 million per gram. Other coliform organisms and faecal streptococci are present in faeces in smaller numbers, typically up to one million per gram (Standing Committee of Analysts, 1983).

The numbers of coliform bacteria in sewage are far greater than would be expected if human faeces were the only source. This is a direct result of multiplication within the system. Raw sewage from large US cities is reported to have a coliform count of 15 to 30 million per 100ml in summer and 5 to 10 million in winter (Kitrell and Furfari, 1963). Counts are lower in small towns where the sewer systems do not provide long detention times for multiplication.

Factors which affect the density of bacteria in sewage include the size of the community served, the prevalence of disease, physical and chemical characteristics of the sewage, retention time in the system, season, and time of day (Gameson, 1978). Discharge of industrial wastes also affects bacterial populations - some wastes are toxic to bacteria and others are rich in nutrients and promote multiplication.

Gameson reported total coliform counts rising from approximately 5 million per 100ml in winter to 50 million at the end of August for British coastal sites. This was attributed to temperature variations and tourist population increases. An inland site exhibited a similar but less pronounced summer increase, probably due to temperature variation alone.

## 3.2 **Bacterial Populations in Combined Systems**

### **3.2.1** Average Organism Densities

Three American studies have looked at indicator organisms in combined systems. A summary of the organism densities observed is given in Table 3.1.

Conner Creek, a 8500ha area of Detroit, was sampled at two overflows to the Detroit River (Benzie and Courchaine, 1966). Land use in the Conner Creek district was as follows:

| | |
|---|---|
| streets | 28.0 % |
| commercial | 3.4 % |
| recreational | 10.3 % |
| industrial | 19.0 % |
| residential | 39.3 % |

The system was monitored from May 1963 to October 1964 and 727 samples were collected during 45 periods of overflow.

The Howard Park drainage area in Baltimore is a 31.6ha site with a population density of 738 persons/ha. The catchment is mostly residential, with a golf course which occupies almost one quarter of the total area. Samples were taken over a 12 month period.

The B4 and G4 sewer districts of the District of Columbia serve areas of 45 and 107ha respectively, with population densities of 107 and 130 persons/ha. The catchments were monitored from April to September 1969, during which time data were collected on seven storms in district B4 and 17 storms in district G4.

Comparison of organism densities in combined sewage and urban runoff is difficult because of the wide variation in both and because of differences in sampling and reporting of results. The highest reported total coliform count in combined sewage is 37,000,000 (Conner Creek, July). This is almost ten times the highest count in urban runoff of 4,000,000 which was also measured in July. In general, urban runoff contains total coliform populations of approximately 10% of those in combined sewage.

TABLE 3.1 INDICATOR ORGANISMS IN COMBINED SEWAGE

| **Catchment** | **Period** | **Total Coliform** | **Faecal Coliform** | **Faecal Streptococci** | **Remarks** |
|---|---|---|---|---|---|
| Conner Creek, Detroit | April | 2,400,000 | 890,000 | - | Organisms/100ml (Benzie and Courchaine, 1966) |
| | May | 4,400,000 | 1,500,000 | 320,000 | |
| | June | 12,000,000 | 2,700,000 | 740,000 | |
| | July | 37,000,000 | 7,600,000 | 350,000 | |
| | August | 26,000,000 | 4,400,000 | 530,000 | |
| Howard Park Baltimore | 12 months | 1,200,000 | 450,000 | 240,000 | MPN/100ml (n/100ml for FS) Mean values (Olivieri, 1980) |
| B4 & G4 | April to September | 2,800,000 | 2,400,00 | 17,200 | Organisms/100ml Mean values (DeFilippi and Shih, 1971) |

### 3.2.2 Variation Within Events

DeFilippi and Shih (1971) found that total coliform, faecal coliform and faecal streptococci counts varied with the flow rate during each storm, with a first flush observed in all storms (Fig. 3.1).

Coliform counts from one of the British coastal sites for a 24 hour period during which heavy rainfall occurred are given in Fig. 3.2. During the first part of the storm, coliform counts increased with flow; but by the end of the storm the coliform counts had fallen even though the flow was still high. It is suggested that this first flush is due to resuspension of faecal material deposited in the system or to the introduction of coliforms from sources other than sewage.

### 3.2.3 Relationship to Other Parameters

No flows were reported by the study of the Conner system in Detroit. Bacteriological quality of samples was compared with storm characteristics, and no relationship was found with intensity, duration, or total rainfall. Example spring and summer storms are shown in Figs. 3.3 and 3.4.

## 3.3 Factors Affecting Bacterial Populations in Combined Systems

The factors which have been identified as affecting the numbers of bacteria present in combined systems are:

a) Temperature

b) Detention time in the system

c) Time of day

A limited amount of data collected during the winter from the Conner system showed a marked decline in coliform levels compared with other times of the year. Fig. 3.5 shows data for a winter storm. The air temperature on the day of the storm ranged from -1.7°C to 4.4°C. The median total and faecal coliform counts were about one to two and four to eight percent respectively of the corresponding July values. The proportion of total coliforms accounted for by faecal coliforms also differed - in July approximately 22% of coliforms were faecal coliforms, whereas in January the figure was 75%.

Gameson observed seasonal differences in coliform counts for dry weather flows at British coastal sites. The rise in coliform levels in summer was attributed to higher temperatures and increases in population during holiday periods. The retention period of sewage within the system, as well as the temperature, is likely to affect counts.

Gameson also reports diurnal variations in total coliforms (Fig. 3.6). Counts tended to be higher in the early afternoon. After 1800-2100hrs samples were kept for analysis the following morning, and rises at these times may be due to growth of bacteria during storage. Diurnal variations observed for faecal streptococci and faecal coliforms are illustrated in Figs. 3.7 and 3.8.

Van Donsel and Geldreich (1970) studied the survival of total coliform, faecal coliform, and faecal streptococci in mud samples at 20°C. Survival rates after seven days were 25% (TC), 10% (FC) and 40% (FS). These figures are considerably higher than those in runoff waters, suggesting that indicators may persist in sediments within sewers. This could account for the first flush observed in studies where bacterial densities were monitored for individual events.

Irving (1977) reported increased survival of enteric bacteria in sea water when silt was present, due to reduced penetration of solar radiation. Although bacteria were observed to accumulate in sediments, the bacteria counts in the overlying water were also high and it was concluded that resuspension of sediment was unlikely to further impair the water quality at this location.

Adsorption and settling lead to high concentrations of bacteria in sediments, which may be of concern in receiving streams where sediment-associated bacteria are protected from the destructive action of sunlight and from predators, with the effect that their survival is enhanced.

FIGURE 3.1 BACTERIOLOGICAL DATA VERSUS STORM TIME FOR COMBINED WASTEWATER
(Gpm x 0.0631=l/s; in. x 2.54=cm)

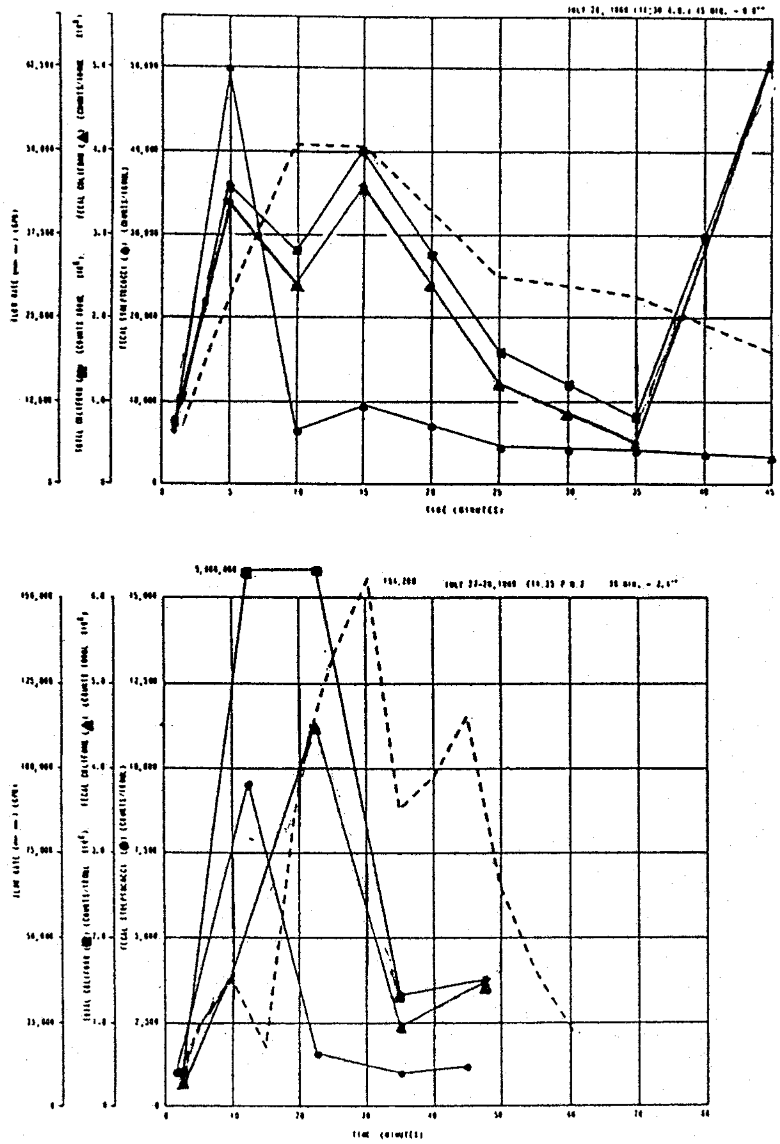


FIGURE 3.2 TOTAL COLIFORMS IN STORM SEWAGE AT WEST BAY PUMPING STATION

Bars and circles (coliform counts) and broken curve (flow) refer to 1-2 March 1971. Continuous curve (coliform counts) and dotted curve (flow) refer to 16 February - 4 March 1971.

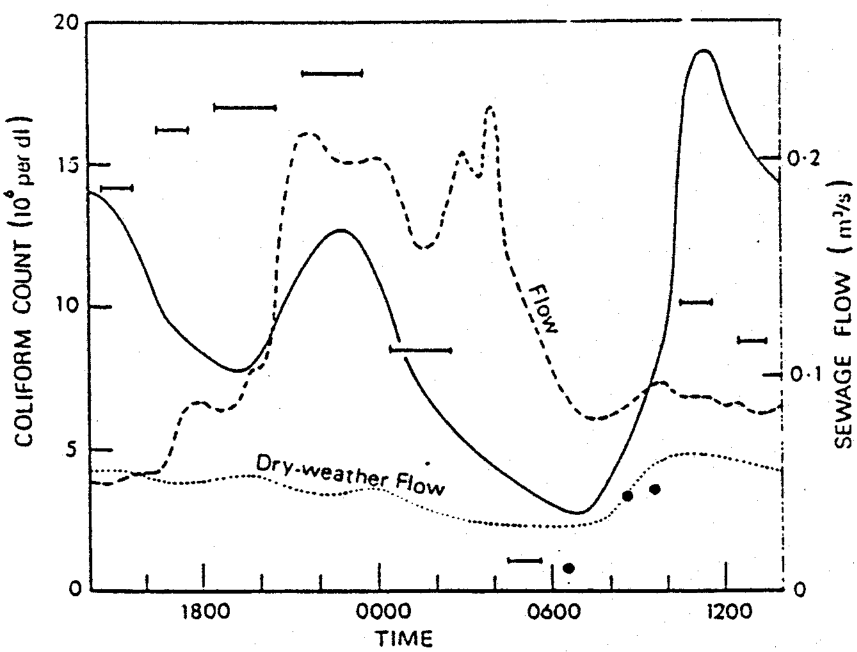


FIGURE 3.3 RAINFALL AND BACTERIA COUNTS DURING SUMMER STORM, CONNER CREEK

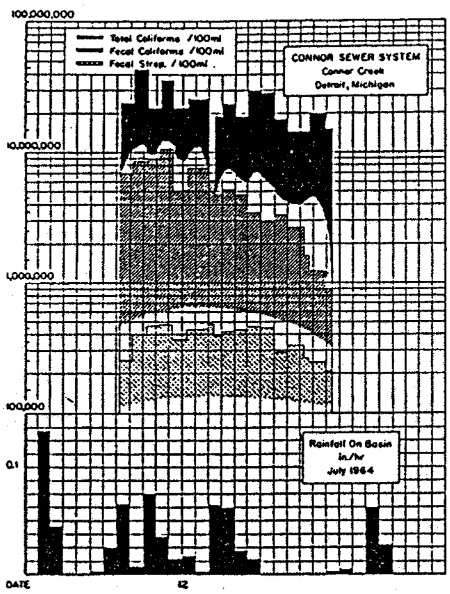



FIGURE 3.4 RAINFALL AND COLIFORM COUNTS DURING SPRING STORM, CONNER CREEK

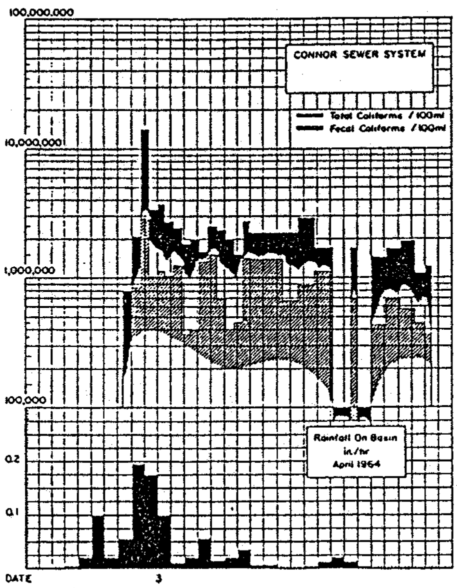


FIGURE 3.5 RAINFALL AND BACTERIAL COUNTS DURING WINTER STORM, CONNER CREEK

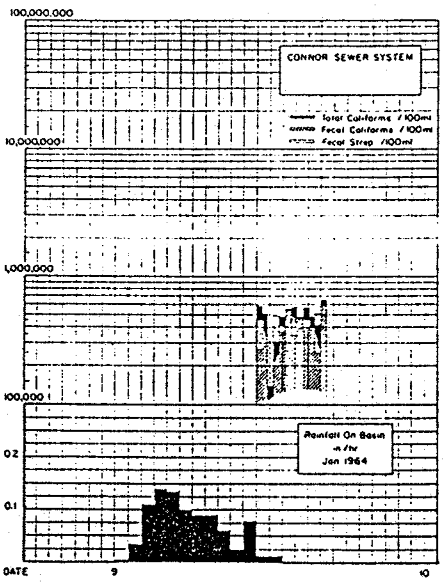


FIGURE 3.6 DIURNAL VARIATIONS IN TOTAL COLIFORMS IN COMMINUTED SEWAGE SAMPLED AUTOMATICALLY

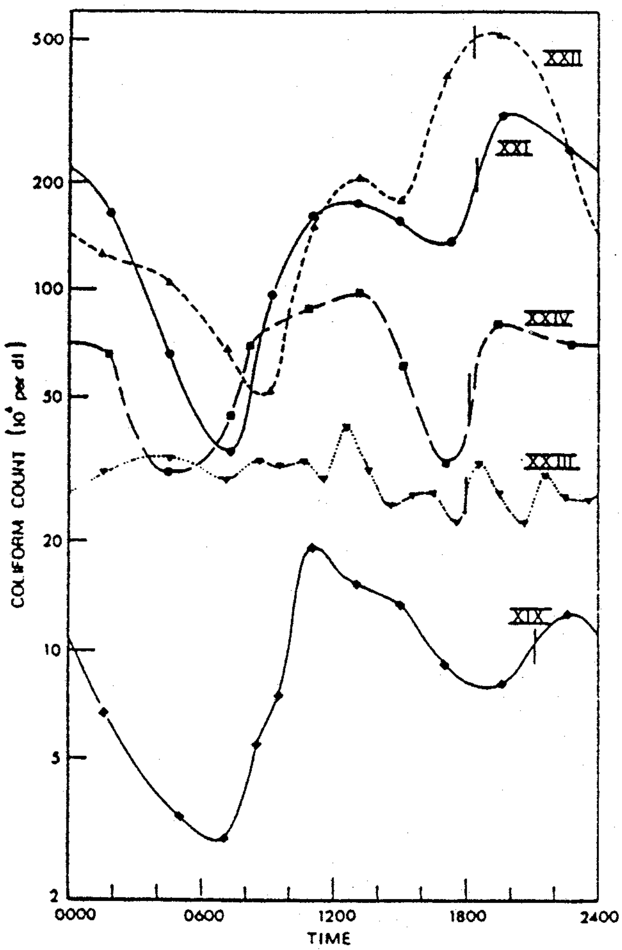


FIGURE 3.7 DIURNAL VARIATIONS IN COUNTS OF FAECAL STREPTOCOCCI AT THREE COASTAL SITES

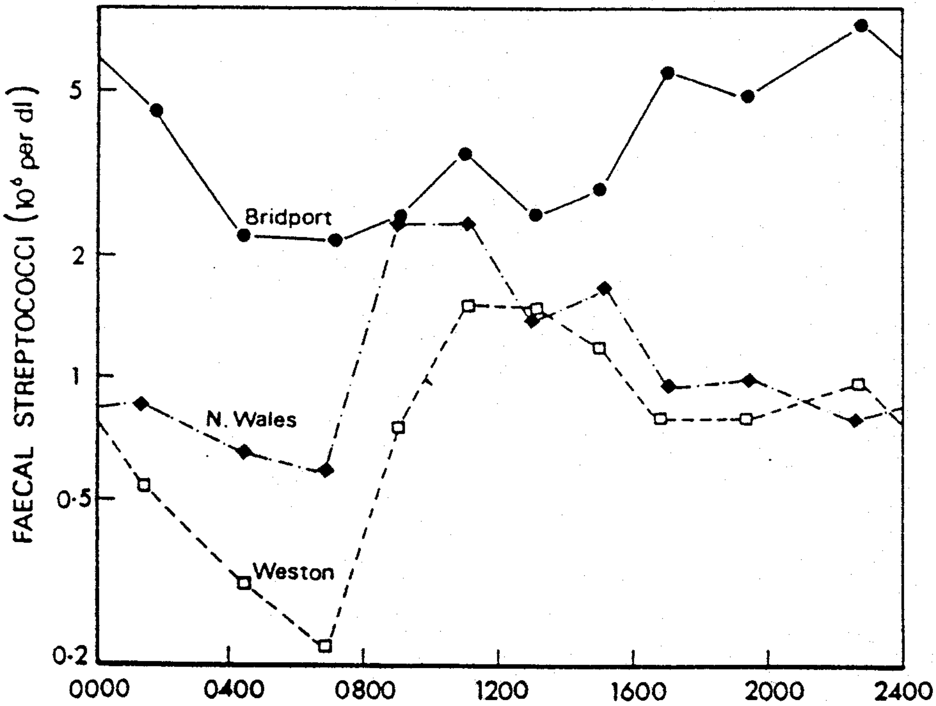
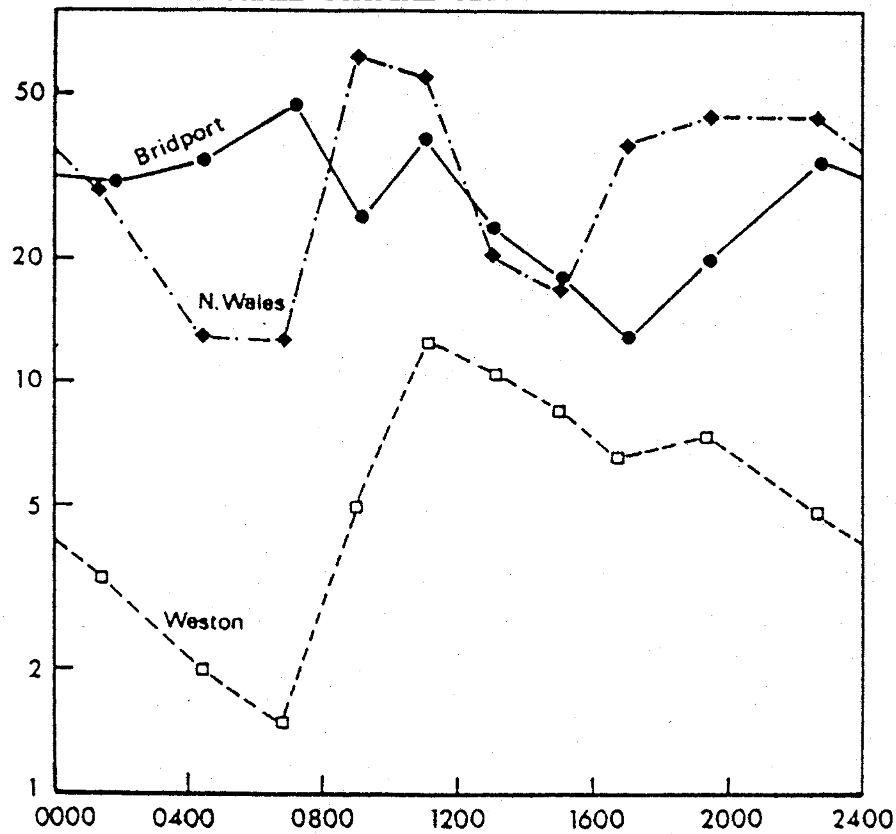



FIGURE 3.8 DIURNAL VARIATIONS IN FAECAL COLIFORM COUNT OF SEWAGE AT THREE COASTAL SITES



## 4. MODELLING THE BEHAVIOUR OF BACTERIA IN URBAN DRAINAGE SYSTEMS

There has been little work concerned with the modelling of bacteria in urban drainage systems. Of the various operational water quality models, four (SWMM3, QQS, STORM and SAMBA; Huber, 1983; Geiger and Dorsch, 1980; US Army Corps of Engineers, 1977; Johansen, 1985) appear capable of predicting bacterial discharges from urban systems. These models differ markedly in the complexity with which they describe processes operating within the catchment, but differ little in usage. The following paragraphs discuss an appropriate approach for modelling bacterial discharges from urban catchments.

### 4.1 Mathematical Approaches for Predicting Pollutant Discharges

The models mentioned above are all deterministic models, in that for a given set of input conditions model predictions will remain constant. Furthermore, in use each model is similar as a continuous simulation approach is followed. However, the models do differ significantly in the complexity with which they represent the behaviour of pollutants within the catchment and over the time-scale at which predictions are made. On this basis a broad subdivision can be recognised.

First, models in which the major sources of pollutants (catchment surfaces, foul inflows and sediments in sewers) are lumped together. These models are also commonly event-based; no attempt is made to predict time-varying pollutant response. This 'black-box' approach has been used in the SAMBA model which applies a constant concentration at the outfall irrespective of the ambient hydrological and hydraulic conditions. Different concentrations are applied dependent on whether the system is separate or combined. A similar approach has been devised for use in the U.K. in conjunction with the WASSP simulation model. This method, known as the 'WRc Interim Procedure' (WRc, 1986), also uses a constant concentration at the outfall but can only be applied at present to combined systems which are differentiated on the basis of average catchment slope. With the availability of more data from a variety of catchment types it can be envisaged that multivariate statistical techniques will be used to allocate a particular concentration to a particular catchment type. This approach could be logically extended to include the discharge of bacterial indicators such as total coliforms, faecal coliforms and faecal streptococci. Data would be required to derive appropriate constant concentrations from a range of catchment types.

The second class of models are those which attempt to consider the source or sources of pollutants within urban catchments. Typically these models will attempt to produce pollutographs, or time-varying pollutant behaviour within an event. Included in this category are the SWMM3, QQS and STORM models. Generally, these models consider the input of pollutants from catchment surfaces, foul water and infiltration into the drainage system. Less emphasis is placed on the processes operative in the drainage system itself. STORM is the simplest of the three models as no hydraulic or pollutant routing calculations are carried out (this model does not therefore predict pollutographs but event loadings). QQS routes pollutants through the drainage system but in-sewer sediment deposits are largely ignored (it is advised, somewhat quixotically, to include these influences as part of the sediment washoff). SWMM3 allows sediment and associated pollutants to be deposited and re-entrained within the drainage system during a storm event. In all of the models, however, there are no routines dealing explicitly with bacterial discharges nor is the influence of sediment deposits present before the onset of the storm event considered in detail. It is also assumed that bacteria behave largely as a conservative pollutant during their passage through the drainage system.

## 4.2 Build-up and Washoff of Bacteria from Catchment Surfaces.

A number of different relationships have been used in urban water quality models to represent the buildup and washoff of bacteria from catchment surfaces. In all cases these relationships were derived using data for pollutants such as suspended solids and BOD; none of them have been developed using data of bacteria build-up or washoff.

Five different functions have been used to represent bacteria buildup on catchment surfaces (Fig.4.1):-

i) linear build-up (STORM, SWMM3);

ii) linear build-up to a threshold (SWMM3);

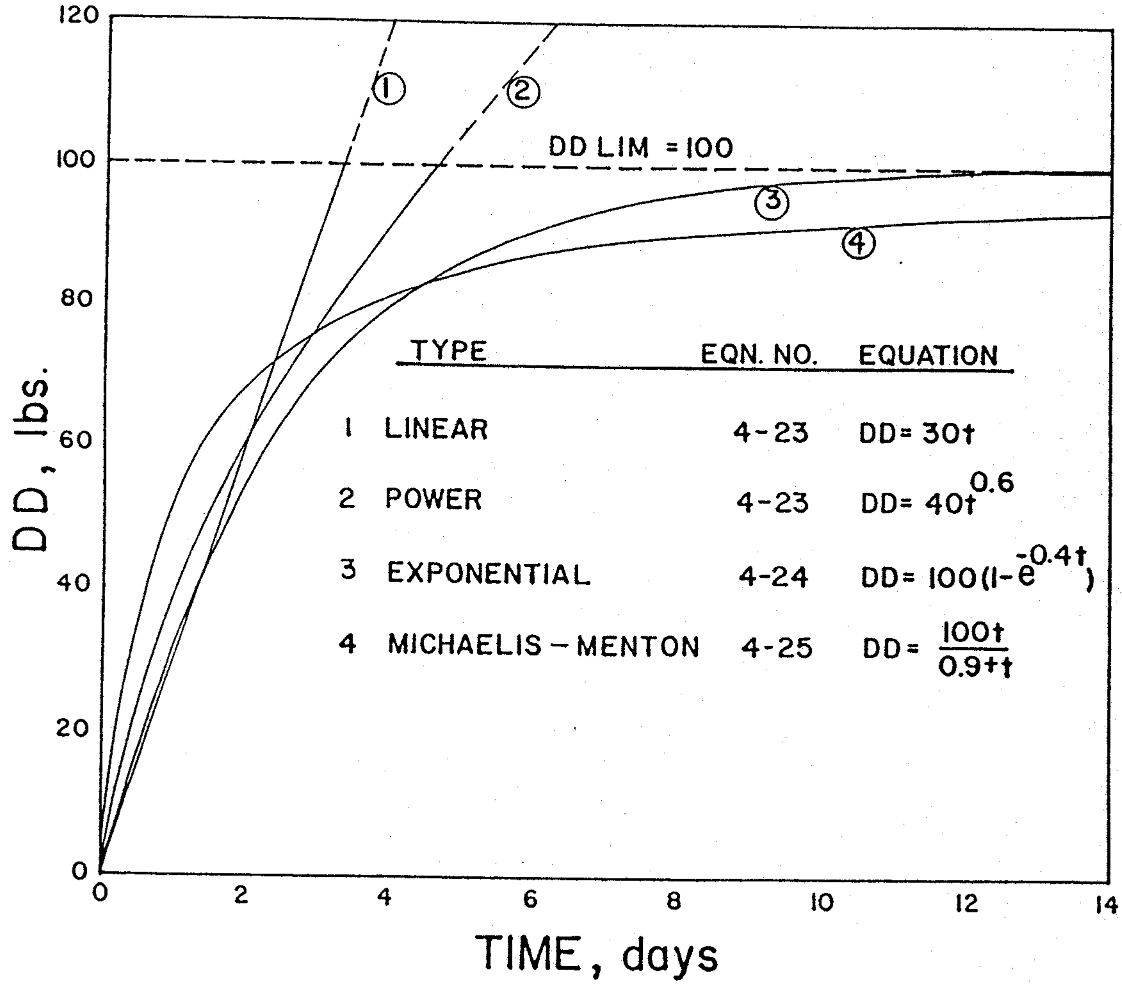
iii) exponential build-up (SWMM3);

iv) Monod build-up (SWMM3);

v) polynomial build-up (QQS).

There have not been any direct studies justifying the use of any of the above relationships. The growth of bacteria in laboratory environments has been modelled using Monod kinetic functions (Mitchell and Chamberlin, 1978). Hence, this might justify the use of this form of function for representing bacterial build-up on catchment surfaces. However, build-up on catchment surfaces does not just reflect the growth of bacteria, but also reflects their initial deposition and redistribution within the catchment.

FIGURE 4.1 BACTERIAL BUILDUP ON CATCHMENT SURFACES



In a similar manner to build-up, attempts to model the washoff of bacteria from catchment surfaces have relied upon approaches developed for suspended sediments and pollutants such as BOD. Two typical examples are provided by the SWMM3 and QQS models. SWMM3 uses an exponential washoff equation to represent removal from impervious catchment surfaces. This model has only been strictly validated for use with suspended solids and always predicts high concentrations at the start of a storm with concentrations falling off as material is removed from the catchment surface. The 'unit pollutograph' approach used in QQS is more versatile in that different distributions of concentration can occur during a storm. Both of these conceptual approaches rely upon pollutant observations with which to calibrate model parameters.

A major deficiency in using either of these approaches is the assumption that bacteria are not linked to any other pollutant parameter. It is well known that bacteria can adhere to particles dispersed in water and wastewater (LaBelle et al., 1980; Schillinger and Gannon, 1985). The adsorption of bacteria to sediments may not be important in the prediction of bacterial discharges from urban catchments, but may be of extreme importance in the prediction of bacterial impacts within the receiving water due to settling processes. Hence, for impact modelling it is essential to represent the linkage of bacteria to sediments in some manner.

## 4.3 Changes in bacterial populations in drainage systems

Bacterial die-off rates vary with species type and environment. Reported values of die-off rate within stormwater vary from 0.1 to 1.5 per day for faecal streptococci (Geldreich and Kenner, 1969). Expressed in terms of the 90% mortality time, $t_{90}$, this gives a range of 23 to 1.5 days. If we assume a time of concentration for a catchment of 1 hour then for a bacteria with a die of rate of 1.5/day then 93% of the bacteria will remain after passage through the drainage system assuming no deposition of the bacteria. It may therefore not be necessary to include bacteria die-off within the transport equations due to its relatively minor influence. However, this conclusion depends heavily on the die-off rate which may vary markedly from the values quoted above.

## 4.4 Conclusions

This brief review of urban water quality models in relation to bacterial pollution illustrates the simplicity of the approaches thus far adopted. This reflects not only the lack of basic knowledge concerning the behaviour of bacteria in urban drainage systems, but also, the problems in calibrating and verifying a complex model due to the errors implicit in bacteria enumeration.

If a pollutograph model is to be used then it is clear that current models are deficient in their ignorance of the possible influences of contaminated sewer sediments. If a simple event loading model, with event mean concentrations applied at the outfall, is required then the current models are sufficient - the problem then resolves into a data collection exercise in order to define appropriate outfall concentrations in relation to influencing factors such as system type and characteristics.

## 5 CONCLUSIONS

1. There is very little published information on the bacterial quality of urban runoff or combined storm discharges in the UK.

2. Studies in the US and Canada have found total coliform densities of 1 to 37 million per 100ml in combined storm discharges. Densities in urban runoff are approximately 10% of those in combined systems.

3. There is a tendency for a first flush effect for the common indicator organisms (total coliforms, faecal coliforms and faecal streptococci) in combined and separate sewer systems.

4. No reliable relationships have been established between bacterial quality and chemical quality or storm event characteristics, for combined or separate sewer systems.

5. There are marked seasonal differences in bacteria counts in both separate and combined systems. Peak values occur in summer and autumn and differences have been attributed to temperature variation.

6. Bacterial survival is enhanced in sediments where organisms are protected from the destructive action of sunlight (in receiving waters) and from predators.

7. The simplicity of the treatment of bacteria in existing water quality models reflects a lack of knowledge of bacterial behaviour in urban drainage systems.

8. A major problem in the development of a model to simulate the behaviour of bacteria is the difficulty of obtaining reliable data. This arises because of the problems associated with the enumeration of bacteria.

9. Although a receiving water impact model may not require bacterial pollutograph inputs, event loadings are unlikely to be sufficient in a model which is to be used to assess the effects of rehabilitation measures. This is particularly true if there is a first flush of bacteria which is to be controlled.

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