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The effect of wind speed and direction on the distribution of sewage-associated bacteria

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P. SMITH, C. CARROLL, B. WILKINS, P. JOHNSON, S. NIC GABHAINN AND L.P. SMITH. 1999. A study of the relationship between wind and the distribution of sewage-associated bacteria was undertaken at a location where the sewage was discharged into the sea adjacent to the mouth of a river. The numbers of presumptive *Escherichia coli* were determined in 149 sea-water samples taken from three locations at distances of 1·9, 2·4 and 4·3 km from the outfall. On each sampling occasion, data on the wind speed and direction in the 3 h prior to collection of the samples were also collected. Analysis of these data demonstrated a significant role for wind speed and direction. With respect to wind direction, the numbers of presumptive *E. coli* present in a sample were significantly higher when the sample site lay downwind of the outfall. Wind speed was shown to have an influence on the numbers of presumptive *E. coli* only when the sample site was downwind of the outfall. In an analysis of 61 samples, an inverse correlation ($r^2 = 0{\cdot}73$) between salinity and log presumptive *E. coli* numbers was demonstrated. These data demonstrate that wind speed and direction at the time of sampling significantly influence the numbers of presumptive *E. coli* detected in any sea-water sample. It is argued that failure to pay sufficient attention to these parameters in the design of monitoring programmes may result in the generation of data that could provide a seriously distorted picture of the microbiological status of a water body.

INTRODUCTION

In the European Union, the microbial quality of inshore marine waters is governed by a number of directives, including 76/160/EEC (CEC 1976) and 79/923/EEC (CEC 1979), which concern the quality of water used for primary contact recreation and shellfish production, respectively. Both directives require regular measurement of the number of faecal coliforms as sewage indicator bacteria. Although they make recommendations as to the frequency of analysis for these parameters, the directives make no recommendations as to the range of meteorological or hydrographic conditions that should be encompassed in any sampling programme. Prokopenko *et al.* (1974) demonstrated that the numbers of sewage-associated bacteria determined at two sites 3 km either side of a sewage outfall were significantly ($P < 0{\cdot}01$) influenced by the wind direction. Krstulovic and Solic (1991) demonstrated that the results of faecal indicator bacteria analyses of waters were significantly influenced by the dominant winds at the time of sampling.

The work presented in this paper was undertaken to provide sufficient data to allow for a statistical analysis of the influence of wind direction and speed on the numbers of presumptive *Escherichia coli* which could be determined in water samples at sites where raw sewage was discharged into the sea.

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MATERIALS AND METHODS

Sample sites

Galway city, which lies to the north-east of Galway Bay (53°16′N, 09°03′W), is situated on the mouth of the River Corrib and has a population of approximately 50 000. The flow of the River Corrib is controlled by a weir and can vary between 10 and 250 $m^3 s^{-1}$ (unpublished data, Aquafact International Services). Upstream of the city, the river passes through extensive bogland which supports only a low human population density and no intensive agriculture. At the time of the survey, the city sewage was not treated and the majority was discharged, without comminution or diffusion, into the sea by a short pipe extending to immediately below the low water mark at a site within the mouth of the River Corrib. A number of minor outfalls were also discharging sewage but the majority were either within the river system, or within 100 m of the river mouth. During the period of the collection of samples reported here, a number of minor outfalls were also in operation but the majority of these were either discharging directly into the river or were situated between the main outflow and the river mouth. Three sample sites were used. Site 1 was at Salthill on a major tourist beach and lay 2400 m to the west of the major outfall. Site 2 was situated at Ballyloughan on a minor bathing beach to the east of the mouth of the Corrib and was 1900 m from the major outfall. Site 3 was in the open sea off Tawin Island and was 4300 m to the south-east of the outfall (Fig. 1).

Sample collection

At sites 1 and 2, samples were collected at low tide in hand-held 500 ml bottles immersed in the sea by operatives standing at the shoreline. When the sea was calm, samples were collected at about 0·25 m below the surface in water that was about 0·5 m deep. When these conditions prevailed, samples were only collected after the majority of the sand, resuspended by the sampling procedure, had resettled. Under rough sea conditions, samples were collected when possible. At site 3, samples were collected in 500 ml bottles immersed by hand in the sea from the side of a small boat at or around high tide. All samples were placed in insulated containers and taken to the laboratory. Those from sites 1 and 2 were analysed within 1 h of collection, those from site 3 within 3 h of collection. Dates of sample collection were not random but were occasionally selected, on the basis of weather forecasts, to provide a reasonable number of samples collected under the types of wind conditions required for the analysis presented in this paper. For this reason the data generated in this study cannot be taken as providing a representative picture of the microbiological status of the sites surveyed.

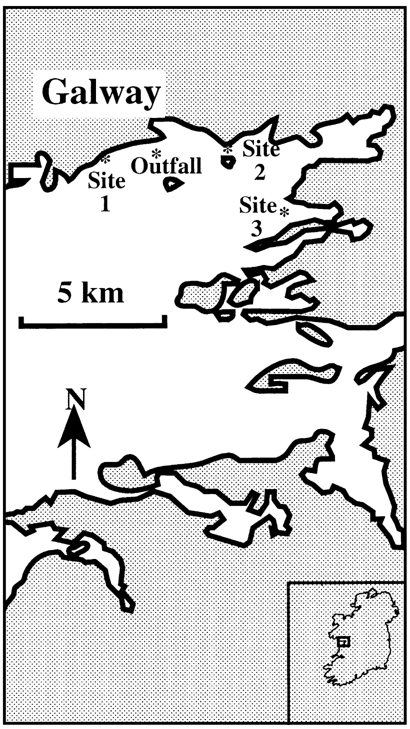

Fig. 1 Map showing sampling sites in Galway Bay, Ireland

Analytical methods

The numbers of presumptive *E. coli* were determined by the methods specified in Report 71 (1983). The salinity of a number of samples was determined by the argentometric titration method (Rand *et al.* 1976).

Wind data

Hourly data on wind speed and direction for the sampling days were obtained from the Irish Meteorological Office at a weather station 4·5 km to the east of the outfall.

Data processing

The coast line at Galway city lies in an approximate east–west direction and this influenced the method of analysis of data obtained from sites 1 and 2. At these sites, the samples were divided into three groups depending on the prevailing wind direction and speed in the 3 h prior to sample collection. The first group consisted of those samples collected when the wind direction was offshore (> 270° and < 90°). When the wind was onshore, the samples were divided into two groups depending on whether the site was downwind or upwind of the major outfall. Thus, samples taken at site 2, which lay to the east of the outfall, were grouped as onshore–upwind when the wind was in the sector 90° to 180°, and onshore–downwind when the wind came from the sector 180° to 270°. At site 1, which lay to the west of the outfall, samples taken when winds were from the sector 90° to 180° were grouped as onshore–downwind and those taken when the wind came from the sector 180° to 270° were grouped as onshore–upwind.

Site 3 lay 110° south-east of the outfall. Samples taken at this site were placed into four groups depending on the wind direction. When the wind was between 245° and 335°, samples were placed in the downwind group. Conversely, when the wind direction was 65° to 155°, samples were placed in the upwind groups. The two crosswind groups were those collected when the winds were either 335°–65° or 155°–245°.

On any occasion when the extent of the change in wind direction, in the 3 h prior to sampling, rendered the above groupings ambiguous, the data obtained from those samples were discarded. Equally, data collected on a sampling day on which the wind speed was not consistently above or below 10 knots, during the 3 h period prior to sample collection were not used in the analysis of the effects of wind speed.

Statistical methods

In order to analyse the differences between the presumptive *E. coli* counts obtained under different conditions, it was necessary to transform all the dependent variables to their $\log_{10}$ values. When transformed in this way, the distribution of the data approximated to normal and the skew value (−0·34) was not significant. Each hypothesis was dealt with sequentially employing students *t*-test to determine the significance of differences between independent sample sets.

RESULTS

Table 1 shows the results of the analysis of the presumptive *E. coli* counts obtained at sites 1 and 2 with respect to wind direction. At both sites, the geometric mean counts were higher when the wind was from the onshore–downwind sector and were significantly ($P < 0{\cdot}01$) different from those obtained when the wind was offshore or when the wind was onshore but the sites were upwind of the outfall. At neither site was there any significant ($P > 0{\cdot}05$) difference between the data sets obtained when the wind was offshore and when it was onshore but upwind.

Table 2 shows the effect of wind speeds over 10 knots on the counts obtained at sites 1 and 2. Due to the limited data for some conditions, this table compares the effect of wind speed when the wind was from the onshore–downwind direction with its effect on the counts when it was coming from all other directions. Again, the data from both sample sites reveal the same picture. Wind speed only influenced the counts when its direction was onshore and the sample site was downwind of the outfall. Wind speed had no detectable effect on the counts when its direction was from any other sector. The data obtained from site 3 were too limited to allow any statistical analysis of the effect of wind speed.

A comparison of the salinity of 61 samples collected at sites 1 and 2 and the numbers of thermotolerant coliforms detected in the samples revealed a statistically significant ($r^2 = 0{\cdot}73$) inverse linear relationship between these parameters.

Table 3 shows the data obtained from site 3 analysed with respect to wind direction. The geometric mean of the counts ($n = 13$) determined when the site was downwind of the outfall was 77 *E. coli* 100 ml^{-1}. The sets of counts obtained when the wind was from all other sectors (geometric means 1·5–3·6 presumptive *E. coli* 100 ml^{-1}) were significantly lower ($P < 0{\cdot}01$).

DISCUSSION

These results clearly show that there is a significant correlation between the numbers of presumptive *E. coli* counted in samples and the direction of the wind recorded 3 h before the sample was collected. These data suggest that wind plays a significant role in the distribution of sewage-borne bacteria in the inshore area, and the data from site 3 further show that this effect is clearly demonstrable up to 4·3 km from an outfall. In addition, the data demonstrate an inverse correlation between the salinity of samples and their bacterial content. Local hydrographic data can provide a model that allows an understanding of the mechanism by which the wind exerts this effect. The dominant current flow in the sea in Galway Bay is anti-clockwise. However, Lei (1995) demonstrated that in the vicinity of Galway city there was a significant halocline with a body of fresh water derived from the River Corrib lying over the more saline waters derived from the Atlantic Ocean. Further, he demonstrated that the distribution of this body of fresh water was significantly

Table 1 Counts of presumptive *Escherichia coli* in samples taken from site 1 and site 2 analysed with respect to wind direction

	Presumptive *E. coli* 100 ml^{-1}					
	Site 1			Site 2		
Wind direction	*n*	Range	Geometric mean	*n*	Range	Geometric mean
Off-shore	20	10–600	93	24	10–900	131
On-shore upwind	18	0–350	23	27	10–2300	85
On-shore downwind	16	33–3800	758	12	150–4900	1150

Table 2 Counts of presumptive *Escherichia coli* numbers at site 1 and site 2, analysed with respect to wind speed and direction

		Wind speed				*t* test*
		Over 10 knots		Under 10 knots		
Site	Wind direction	*n*	Geometric mean	*n*	Geometric mean	*p*
1	Downwind <90°–<180°	8	2100	6	190	0·001
	Other <180°–<090°	19	50	14	74	0·584
2	Downwind <180°–<270°	15	1860	12	632	0·001
	Other <270°–<180°	17	98	19	138	0·368

*An unpaired student *t* test was used to investigate the significance of the difference between $\log_{10}$ presumptive *E. coli* numbers determined when the wind was over and under 10 knots.

Table 3 Counts of presumptive *Escherichia coli* in samples taken from site 3 analysed with respect to wind direction

	Presumptive *E. coli* 100 ml^{-1}		
Wind direction	*n*	Range	Geometric mean
245°–335°	13	17–250	77
335°–065°	5	0–47	1·7
065°–155°	6	0–11	1·5
155°–245°	8	0–35	3·6

influenced by wind. Sewage-associated bacteria will enter the marine environment suspended in fresh water and it is probable that a significant fraction will associate with the river-derived fresh-water layer. For the period that these bacteria remain suspended in the fresh or low salinity water layer, their movement will be governed primarily by the wind rather than by the underlying east to west currents.

The significance of these observations for the design of sampling programmes employed in the determination of inshore water quality clearly depends on the extent to which they are generally applicable. It could be argued that specific and local hydrographic factors in Galway Bay have a necessary role in determining the relationships demonstrated in this work. *A priori* considerations would, however, suggest a general applicability of the observations. It is reasonable to postulate that the major, local hydrographic factors are those related to the presence of an outfall in the vicinity of a river discharging into an embayment. Such an association of seaside towns with river estuaries discharging into a bay must be considered to be the norm rather than the exception. The fact that wind has been identified as a major factor in the movement of sewage-associated bacteria in studies in Russia (Prokopenko *et al.* 1974) and Greece (Krstulovic and Solic 1991) suggests that the relationships demonstrated in this work are not limited in their relevance to the specific conditions that pertain in the north-east of Galway Bay.

The effect of wind speed on the numbers of bacteria in the water column has not, to our knowledge, been reported before. In theory, the wind speed might be expected to exert an effect through increased turbulence at the shore line. This would result in an increased resuspension of bacteria from the sediments and would therefore lead to an apparent increase in presumptive thermotolerant coliform counts in the water samples. The data presented in Table 2, however, demonstrate that the speed of the wind has a significant role only when the sample site lies downstream of the outfall. This suggests that the major effect of wind speed is exerted through its influence on the rapidity of the movement of low salinity surface waters.

Demonstration that wind speed and direction play a significant role in the distribution of sewage-associated bacteria has significant consequences for the design of sampling programmes for monitoring water quality. It is clear that the apparent status of any area, with respect to Directives 76/160/EEC (CEC 1976) and 79/932/EEC (CEC 1979), could be significantly altered by judicious choice of sampling conditions. This issue can be illustrated by reference to the data collected at sample site 1, the major bathing beach in Galway. If sampling was confined to days on which the wind blew from the outfall towards the beach (90°–180°), the water at the beach would not meet the mandatory standards set in directive 76/160/EEC (CEC 1976). If, on the other hand, sampling was confined to days when the beach was upwind of the outfall (180°–170°), the beach would easily meet the more stringent guide concentrations set out in this directive. With regard to Galway, it should be noted that over a year south-west winds occur, on average, on 48% of days while winds from the south-east sector (90°–180°) are relatively uncommon (20%).

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