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Variations in microbial indicator densities in beach waters and health-related assessment of bathing water quality

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SUMMARY

Daily and hourly variations in microbial indicators densities in the beach-waters of Hong Kong have been described. The levels of *Escherichia coli* at a number of beaches was observed to be influenced by tide, and for staphylococci, by bather numbers. The tidal influence was most obvious during spring tides; and for the effect of bathers, during neap tides. Both organisms are present in high densities in external sources of faecal pollution of bathing beaches, with the average staphylococci to *E. coli* ratios being 0·04–3. Staphylococci may serve as an indicator of bather density and the risk of cross-infection amongst bathers (rather than as another indicator of faecal contamination) when the average staphylococci to *E. coli* ratio for a bathing beach is considerably higher than 3. The variability of microbial indicator densities means the routine sampling of bathing beaches should be carried out on weekend days with maximum numbers of swimmers exposed to the water, and spread throughout the bathing season.

INTRODUCTION

The levels of microbial indicators in beach-waters are important for indexing the health risks associated with swimming. Enterococci were found to be the best indicator relating bathing water quality to gastroenteritis symptoms among bathers at the marine beaches of USA [1]; and both *Escherichia coli* and enterococci were good indicators for such perceived symptoms at US freshwater beaches [2]. In a study of Canadian freshwater beaches, staphylococci appeared to correlate well with total morbidity rates among swimmers [3]. Both *E. coli* and staphylococci were found to be good indicators of different health effects due to swimming in the coastal beaches of Hong Kong [4]. *E. coli* was the best indicator for predicting gastroenteritis and skin symptoms. Staphylococci were related to other perceived symptoms among bathers, namely ear, respiratory and total illness, but could not be used for predicting swimming-associated health risks.

Previous studies have indicated that an understanding of the time-related variations in microbial indicator densities in beach-waters is essential for properly assessing the microbiological quality and swimming-associated health risk levels of bathing beaches [5–7]. The purpose of this paper is to (*a*) describe the daily and hourly variations in microbial indicator densities at Hong Kong beaches; (*b*)

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evaluate the importance of tide and bather numbers in causing such fluctuations; and (*c*) explain some of the observations by elucidating the sources of the indicator microorganisms in bathing waters. Emphasis is placed on *E. coli* and staphylococci, as these two indicators have been used for setting new water quality standards for the bathing beaches in Hong Kong [4]. The implications of the findings in designing health-related beach sampling programmes and interpreting microbial indicator data are discussed.

METHODS

Beaches under study

The nine beaches for which microbiological data were obtained are Repulse Bay, Deep Water Bay, Stanley Main, Shek O, Clear Water Bay, Lido, Butterfly, and Old and New Cafeteria. Their location and pollution sources have already been described by Cheung and colleagues [4].

Water sampling

Subsurface water samples were collected from three sampling points (50–150 m apart and 1 m deep) at each beach, in locations with high densities of bathers. This was carried out every 2 h over a 8 h period from 9 a.m. to 5 p.m. on weekend days. Overnight sampling at 3 h intervals was also undertaken at every beach. This, together with daytime sampling in the two weekend days before and after, gave a picture of the fluctuation of microbial indicator levels in beach-water over a 32 h period.

Microbiological analysis

A total of nine microbial indicators were tested. They included faecal coliforms, *E. coli*, *Klebsiella* spp., faecal streptococci, enterococci, staphylococci, *Pseudomonas aeruginosa*, total fungi and *Candida albicans*. The membrane filtration methods for enumerating these microorganisms in environmental samples have been described previously [4, 8].

Study on tidal effects

The tidal height on each sampling occasion was derived from a tide table [9]. A preliminary examination of the relationship between hourly fluctuation of microbial indicator densities in beach-waters and tidal height indicated that the logarithm of microbial counts tended to vary sinusoidally with the tidal state. The appropriate form of equation to relate the microbial densities at a beach with tidal height is thus: $y = A + B\sin(\theta - \alpha)$, where y is the logarithm of the microbial indicator density in beach-water; A, the logarithm of the daily geometric mean density of the microbial indicator at a beach; B, the amplitude of the variation in tidal height; θ, the tidal state (high water being 90° and low water being 270°); and α, the phase shift.

Expected microbial indicator densities (y) were derived using this equation, based on the geometric mean microbial density for each sampling period (8 or 32 h) and the tidal height data. Correlation between the densities derived from the equation and the corresponding actual counts measured in each sampling period was analysed.

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Table 1. *Daily geometric mean densities of nine microbial indicators at two Hong Kong beaches, 1987*

	Repulse Bay	Old Cafeteria
	Range over 5 sampling days	Range over 7 sampling days
Faecal coliforms	160–1900* (0·3)†	680–11000 (0·3)
E. coli	100–1200 (0·4)	500–7700 (0·3)
Klebsiella spp.	20–390 (0·4)	70–2000 (0·4)
Faecal streptococci	60–140 (0·1)	100–680 (0·3)
Enterococci	60–140 (0·1)	80–740 (0·4)
Staphylococci	240–2800 (0·4)	540–3200 (0·3)
Pseudomonas aeruginosa	5–40 (0·3)	20–290 (0·4)
Total fungi	100–800 (0·3)	50–2000 (0·5)
Candida albicans	4–20 (0·2)	2–60 (0·4)

* Geometric mean counts per 100 ml for 15 samples, collected at bihourly intervals from 3 sampling points at the beach on a sampling day.

† Figures in parentheses are log standard deviation of the daily geometric mean microbial densities.

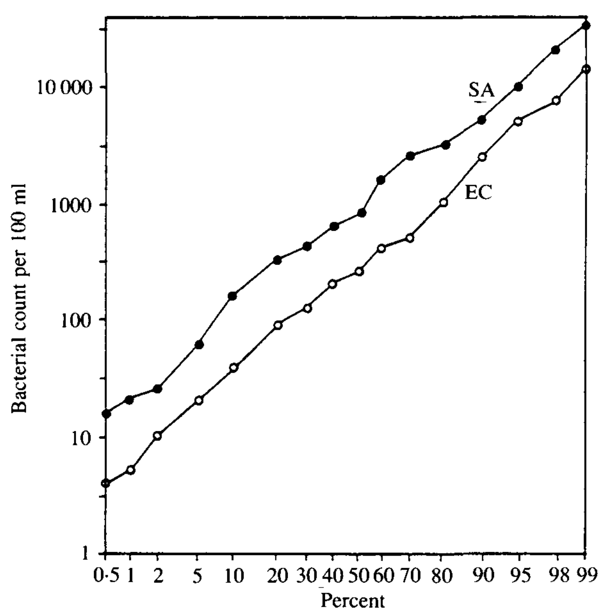

Fig. 1. Frequency distributions of *E. coli* and staphylococci at nine Hong Kong beaches, 1987. EC, *E. coli*; SA, staphylococci.

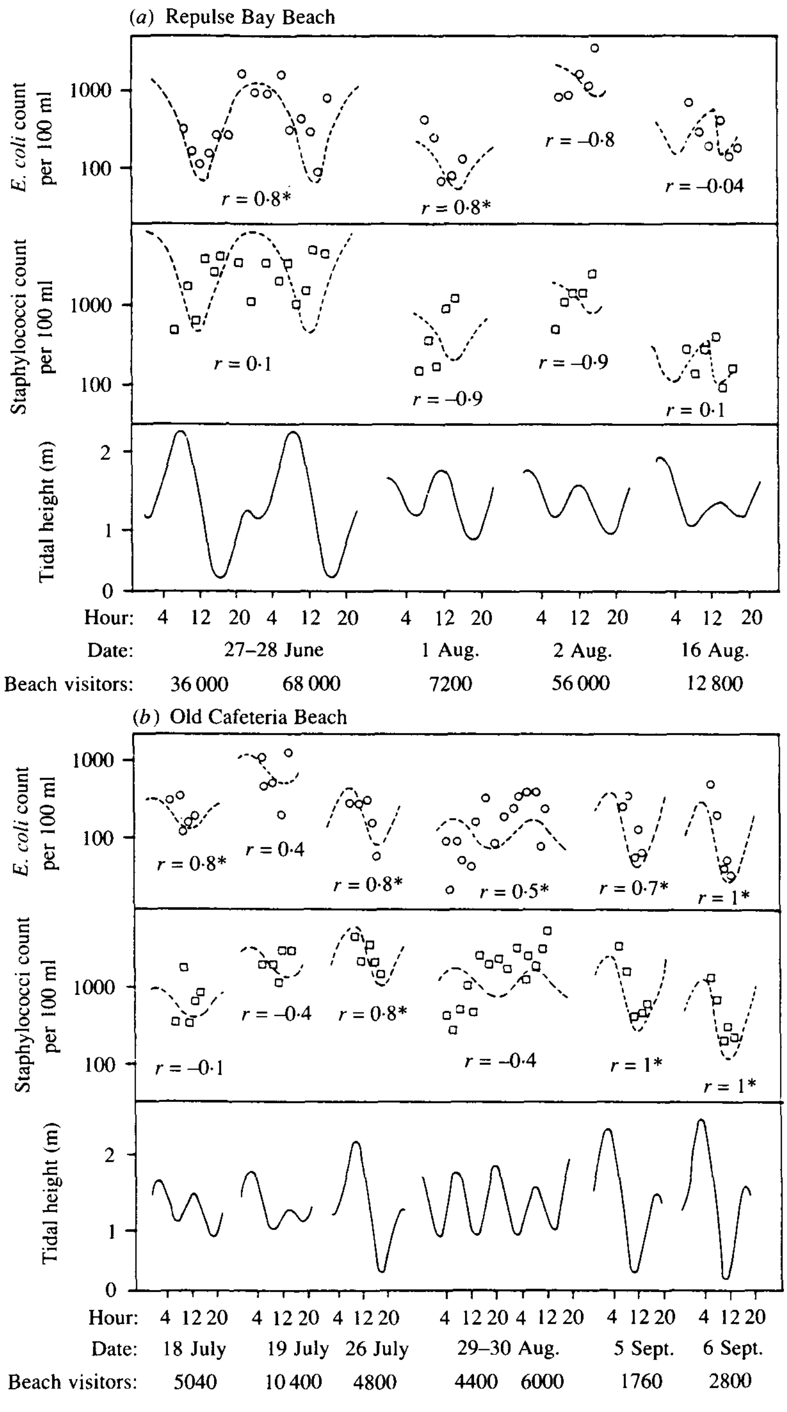

Fig. 2. For legend see opposite.

Studies on bather effects

The effect of bather numbers on the microbial water quality of bathing beaches was first evaluated by assessing the correlation between bather numbers and microbial indicator densities at the nine beaches under study.

Secondly, experiments were carried out at two popular bathing beaches, namely Repulse Bay and Clear Water Bay Beaches, where the microbial indicator levels measured in a crowded weekend day were compared with those obtained in another day with small number of bathers. This study was undertaken only during neap tides, when the influence of tide on the microbial quality at a beach is minimal. To further minimize the tidal effect, only microbial densities obtained over the same narrow range of tidal height in the 2 days were compared.

Studies on sources of microbial indicators

The levels of the nine microbial indicators in various external sources of pollution of bathing beaches were obtained. Monthly samples were taken for microbiological analysis at the landward end of a submarine sewage outfall at Rambler Channel, discharging to the east of Lido Beach; and from Tuen Mun Nullah and Pai Min Kok Stream, which are heavily polluted by livestock wastes. Tuen Mun Nullah is a source of pollution of Butterfly, and New and Old Cafeteria Beaches. Pai Min Kok Stream heavily contaminates a beach which has been declared unacceptable for swimming. The densities of these microorganisms in 10 samples of pooled pig excreta, freshly collected from different livestock farms, were also analysed.

The densities of the microbial indicators in urine samples from 20 volunteers (16 male and 4 female, age between 22 and 36) were tested by the membrane filtration methods, immediately after sample collection. This was to elucidate the type and quantity of microorganisms possibly introduced by bathers urinating in beach-waters.

RESULTS

Daily and hourly variations in microbial indicator densities

The range of microbial indicator densities over different sampling days for two beaches, Repulse Bay and Old Cafeteria, is presented in Table 1. Significant difference in the levels of *E. coli*, faecal coliforms, *Klebsiella* spp., staphylococci and total fungi between days were observed for Repulse Bay Beach ($P \leqslant 0.05$, t test). For Old Cafeteria Beach (which is more polluted than the others), there were significant daily variations in the densities of all the nine indicators ($P \leqslant 0.05$).

The hourly counts for some microorganisms also varied greatly within a single sampling date. The *E. coli* densities varied from 94 to 1300 per 100 ml, and the

Fig. 2. Relationships between tidal height and densities of *E. coli* or staphylococci at Repulse Bay and Old Cafeteria Beaches, 1987. ——, Expected bacterial densities, derived from equation using tidal height data. □, ○, Bacterial densities measured in beach water samples. † Recorded by Urban Services Department or Regional Services Department of the Hong Kong Government. r, Correlation coefficient for expected bacterial counts against actual densities in beach water. * $P < 0.1$ (t test).

staphylococci counts from 540 to 4600 per 100 ml, at Repulse Bay Beach on a weekend day under study. At Old Cafeteria Beach, the *E. coli* levels changed from 290 to 5300 per 100 ml; and for staphylococci, from 530 to 4700 per 100 ml on a single day.

Distributions of microbial indicator densities

The frequency distributions of *E. coli* and staphylococci counts in 667 samples collected from the nine beaches under study are shown in Fig. 1. The curves indicate approximately log-normal distributions of the two bacterial indicators, as they do not depart greatly from straight lines.

Effect of tide on microbial indicator levels

The relationships between tidal height and the densities of *E. coli* and staphylococci at Repulse Bay and Old Cafeteria Beaches are presented in Fig. 2. By looking at the correlation coefficients between the expected microbial indicator levels (calculated from tidal height and overall geometric mean densities in a sampling period) and the actual counts measured in beach-water, it was found that tide was important in causing the hourly fluctuation of *E. coli* densities in beach-water during spring tides, where there is a major source of pollution (namely a sewage outfall or river) nearby. High bacterial counts were generally observed during spring floods, and low counts during ebb tides. This was most apparent for Repulse Bay and Old Cafeteria Beaches – which are affected by major pollution sources (a submarine outfall at Repulse Bay and Tuen Mun Nullah, respectively) close to the beaches.

The influence of tide, although less prominent, could also be observed for Lido, Deep Water Bay, Butterfly and New Cafeteria Beaches, which are further away from major pollution sources. Significant relationships between tidal height and *E. coli* densities were not found for beaches affected by relatively small pollution sources – namely Shek O, Stanley Main and Clear Water Bay Beaches, which are contaminated by stormwater drains running into the beaches.

Correlation between staphylococci densities and tidal height was only observed at Old and New Cafeteria Beaches during spring tides; but not at the rest of the seven beaches under study. This relationship was particularly prominent for Old Cafeteria Beach during spring tides (see Fig. 2).

Effect of bathers on microbial beach-water quality

Figure 3 shows the relationships between the estimated number of bathers in beach-water and the observed levels of *E. coli* and staphylococci at two selected beaches, Shek O and Repulse Bay. Correlation between bather numbers (which are independent of tidal conditions but fluctuate with different times of the day) and staphylococci densities was found at Shek O, Repulse Bay and Deep Water Bay Beaches. This was particularly apparent during neap tides. Correlation between bather numbers and staphylococci levels was not apparent at Old and New Cafeteria Beaches, where the bather numbers were small. Significant relationships between bather numbers and *E. coli* counts were only observed at Repulse Bay Beach on one sampling date; and none at all at the other eight beaches under study.

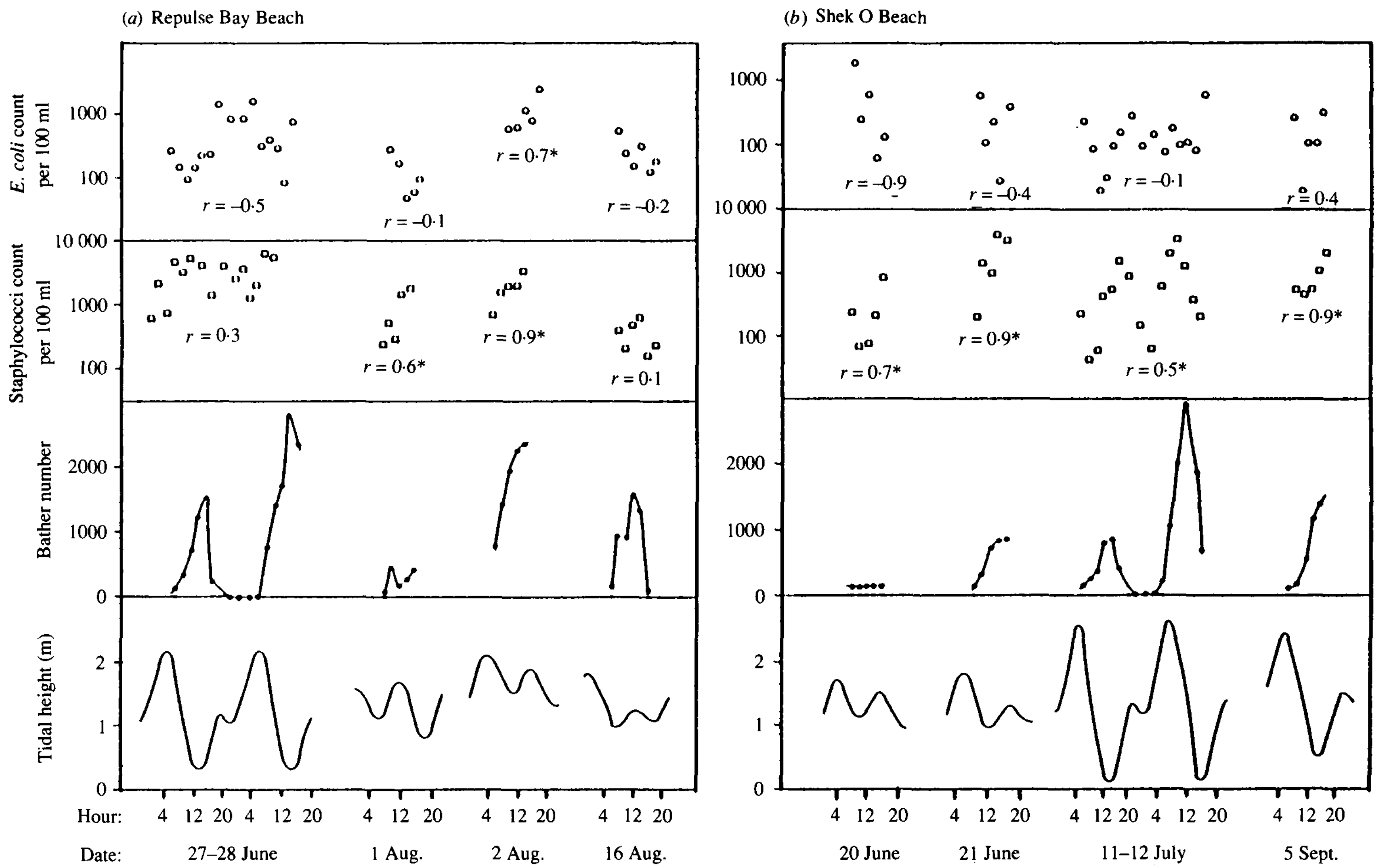

Fig. 3. Effects of bather numbers on *E. coli* or staphylococci densities at Repulse Bay and Shek O Beaches, 1987. □, ○, Bacterial densities measured in beach water samples. ●, Numbers of bathers in beach water estimated at the time when water samples were taken. *r*, Correlation coefficient between bacterial counts and bather numbers. * $P < 0·1$ (*t* test).

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Table 2. *Effect of bathers on the microbial water quality (geometric mean counts/100 ml) of Repulse Bay and Clear Water Bay Beaches during neap tides, 1987*

	Repulse Bay Beach					
	14 Aug. Fri.	2 Aug. Sun.	1 Aug. Sat.	2 Aug. Sun.	14 Aug. Fri.	1 Aug. Sat.
Bather number†	(50)	(1380)	(240)	(1680)	(190) (Control)	(220)
Tidal range (m)‡	1·18–1·48	1·18–1·45	1·33–1·50	1·32–1·45	1·32–1·66	1·33–1·66
Faecal coliforms	122	1452**	318	1791*	90	237
E. coli	83	948**	279	1048	60	130
Klebsiella spp.	36	459*	75	736	28	45
Faecal streptococci	74	54	89	54	53	44
Enterococci	60	59	111	79	31	73
Staphylococci	159	1040**	263	1394*	327	240
Pseudomonas aeruginosa	4	4	10	5	2	5
Total fungi	55	295	84	328	29	62
Candida albicans	7	3	4	3	13	3
	Clear Water Bay Beach					
	17 July Fri.	19 July Sun.	18 July Sat.	19 July Sun.	17 July Fri.	18 July Sat.
Bather number†	(260)	(1530)	(210)	(1530)	(300) (Control)	(240)
Tidal range (m)‡	1·18–1·48	1·18–1·45	1·33–1·50	1·32–1·45	1·32–1·66	1·33–1·66
Faecal coliforms	191	746*	458	746	222	312
E. coli	105	444**	225	444	112	129
Klebsiella sp.	84	291	225	291	101	167
Faecal streptococci	76	129	121	129	80	87
Enterococci	126	217	128	217	112	83
Staphylococci	464	5248*	137	5248**	501	278
Pseudomonas aeruginosa	2	4	6	4	5	8
Total fungi	35	1303**	72	1303**	57	202
Candida albicans	8	25	6	25	5	6

** Significantly higher than the mean microbial densities on a less crowded day at $P \leqslant 0{\cdot}01$; * $P \leqslant 0{\cdot}05$ (*t* test).

† Average number of bathers immersed in beach-water observed at different sampling time on the day under study.

‡ Microbial indicator densities obtained over the same range of tidal height on the 2 days were compared.

The data obtained in a separate study on the effects of bathers on the densities of the nine microbial indicators at Repulse Bay and Clear Water Bay beaches during neap tides are given in Table 2. For both beaches, the mean densities of staphylococci were consistently higher ($P \leqslant 0{\cdot}05$) on a crowded weekend day than on a day with relatively small number of bathers. There was no appreciable difference in microbial indicator densities on the 2 days when bather numbers at both beaches were low (the control).

Table 3. *Geometric mean densities of nine microbial indicators at various faecal pollution sources**

Pollution source	Geometric mean densities†								
	Faecal coliforms	*E. coli*	*Klebsiella* spp.	Faecal streptococci	Enterococci	Staphylococci	*Pseudomonas aeruginosa*	Total fungi	*Candida albicans*
Rambler Channel sewage outfall (2210 m^3/day)‡	$2{\cdot}7 \times 10^6$	$3{\cdot}4 \times 10^6$	$9{\cdot}3 \times 10^4$	$8{\cdot}4 \times 10^5$	$4{\cdot}9 \times 10^5$	$7{\cdot}2 \times 10^5$	1200	$1{\cdot}5 \times 10^5$	840
Tuen Mun Nullah (64800 m^3/day)‡	$7{\cdot}0 \times 10^5$	$5{\cdot}5 \times 10^5$	$1{\cdot}0 \times 10^5$	$5{\cdot}2 \times 10^4$	$3{\cdot}5 \times 10^4$	$1{\cdot}2 \times 10^5$	320	$2{\cdot}3 \times 10^4$	120
Pai Min Kok Stream	$9{\cdot}8 \times 10^6$	$8{\cdot}8 \times 10^6$	$1{\cdot}3 \times 10^5$	$9{\cdot}6 \times 10^5$	$4{\cdot}1 \times 10^5$	$1{\cdot}1 \times 10^7$	$1{\cdot}5 \times 10^4$	$4{\cdot}9 \times 10^5$	3100
Livestock waste	$5{\cdot}8 \times 10^7$	$5{\cdot}7 \times 10^7$	190	$4{\cdot}4 \times 10^5$	$1{\cdot}0 \times 10^5$	$3{\cdot}9 \times 10^5$	< 10	$1{\cdot}5 \times 10^4$	489

* Monthly sewage and river water samples were collected from November 1987 to February 1989 (15 samples in total for each pollution source). For livestock waste, 10 samples of pig excreta were taken from different farms.

† Expressed in number per 100 ml for all water and sewage samples, and number per g for livestock waste.

‡ Mean daily flow rate, only obtained for Rambler Channel sewage outfall and Tuen Mun Nullah.

Table 4. *Average ratios of staphylococci to* E. coli *densities in individual samples from nine Kong Kong beaches and faecal pollution sources*

	No. of samples	Average ratio of staphylococci to *E. coli*	Daily beach visitor no.* (× 1000)
Beach			
Deep Water	74	67	22
Shek O	75	78	37
Stanley Main	74	30	14
New Cafeteria	70	3	2
Clear Water Bay	45	15	15
Lido	75	17	34
Repulse Bay	75	42	45
Butterfly	74	18	36
Old Cafeteria	105	2	7
Pollution source			
Rambler Channel sewage outfall	15	0·8	
Tuen Mun Nullah	15	0·6	
Pai Min Kok	15	3	
Livestock waste	10	0·04	

* Average of visitors numbers recorded by Urban Services Department or Regional Services Department of the Hong Kong Government on those weekend days when beach-water samples were taken.

Sources of microbial indicators

Table 3 shows high densities of faecal coliforms, *E. coli*, *Klebsiella* spp., faecal streptococci, enterococci, staphylococci, and total fungi were also found in domestic sewage, pig excreta, and river-water heavily polluted by faecal wastes. The daily quantities of *E. coli* and staphylococci, discharged from Tuen Mun Nullah were estimated to be $3{\cdot}6 \times 10^{15}$ and 7.8×10^{14}, respectively. For the sewage outfall at Rambler Channel which serves a population of 641 600, the total daily *E. coli* and staphylococci loads were $1{\cdot}3 \times 10^{14}$ and $2{\cdot}8 \times 10^{13}$, respectively.

The mean ratios of staphylococci to *E. coli* densities in individual samples from the nine beaches and various sources of faecal pollution are given in Table 4. It can be seen the ratios were 0·04–3 for human sewage, pig waste, and faecally polluted river-waters. High ratios ranging from 30 to 78 were observed for those beaches which were very popular, and where staphylococci densities were strongly correlated with bather numbers. For Old and New Cafeteria Beaches where swimmer numbers were relatively small and relationships between staphylococci densities and bather numbers were not observable, the ratios were 2 and 3, respectively. There was no apparent relationship between such ratios and the distance of the bathing beaches from their respective major faecal pollution sources.

The levels of the microbial indicators in urine samples from 20 individuals are shown in Table 5. *E. coli* and faecal coliforms were only detected in 3 out of the 20 samples. Faecal streptococci and enterococci were more common in urine; they were found in varying numbers in 15 out of 20 samples. Staphylococci were present in the urine of all the volunteers, with a geometric mean density of 10^4 per

Table 5. *Densities of nine microbial indicators in urine samples from 20 individuals**

Volunteers		Geometric mean densities per 100 ml								
Sex	Age	Faecal coliforms	*E. coli*	*Klebsiella* spp.	Faecal streptococci	Enterococci	Straphylococci	*Pseudomonas aeruginosa*	Total fungi	*Candida albicans*
M	22	0	0	0	6×10^4	$6{\cdot}4 \times 10^4$	$2{\cdot}5 \times 10^4$	< 10	< 10	< 10
M	22	0	0	0	< 10	< 10	2200	< 10	< 10	< 10
M	23	0	0	0	< 10	< 10	7800	< 10	< 10	< 10
M	26	0	0	0	< 10	< 10	1900	< 10	< 10	10
M	27	0	0	0	7×10^4	$4{\cdot}5 \times 10^4$	$3{\cdot}5 \times 10^4$	< 10	< 10	< 10
M	27	560	560	0	5200	6000	2300	< 10	< 10	< 10
M	28	0	0	0	1200	750	4900	< 10	< 10	< 10
M	28	0	0	0	$1{\cdot}8 \times 10^5$	$1{\cdot}3 \times 10^5$	$7{\cdot}2 \times 10^4$	< 10	180	200
M	30	0	0	0	< 10	< 10	480	< 10	< 10	40
M	31	0	0	0	7300	7500	1×10^4	< 10	< 10	< 10
M	31	0	0	0	50	40	660	< 10	< 10	< 10
M	32	0	0	0	5000	10	1700	< 10	< 10	< 10
M	32	0	0	0	< 10	10	2000	< 10	< 10	< 10
M	32	0	0	0	10	20	6500	< 10	< 10	< 10
M	32	0	0	0	5800	4500	1900	< 10	< 10	< 10
M	35	$2{\cdot}4 \times 10^4$	$2{\cdot}4 \times 10^4$	0	$3{\cdot}5 \times 10^4$	$1{\cdot}8 \times 10^4$	$1{\cdot}1 \times 10^4$	< 10	< 10	< 10
F	25	0	0	0	$1{\cdot}7 \times 10^4$	$1{\cdot}8 \times 10^4$	$> 2 \times 10^5$	< 10	6×10^4	$> 2 \times 10^5$
F	25	0	0	0	< 10	< 10	6600	< 10	< 10	< 10
F	26	0	0	0	$3{\cdot}1 \times 10^4$	$2{\cdot}5 \times 10^4$	$1{\cdot}6 \times 10^4$	< 10	80	60
F	27	$4{\cdot}3 \times 10^4$	$4{\cdot}3 \times 10^4$	0	$> 2 \times 10^5$	$> 2 \times 10^5$	$> 2 \times 10^5$	< 10	60	< 10

* Around 200 ml of urine was collected for each individual. Volumes of 0·1, 1, 10 and 100 ml were filtered for analysing *E. coli*, faecal coliforms and *Klebsiella* spp.; and for faecal streptococci, enterococci, staphylococci, *Pseudomonas aeruginosa*, total fungi and *Candida albicans*, 0·1, 1 and 10 ml were filtered.

100 ml. Total fungi and *Candida albicans* were detected in high numbers in one single sample from a female. *Pseudomonas aeruginosa* and *Klebsiella* spp. were not detected in any urine sample.

DISCUSSION

The present study has demonstrated the temporal variation in the densities of *E. coli* and staphylococci – the two bacterial indicators found to good indexes of different health effects due to swimming [4] – in the coastal beaches of Hong Kong. This helps to explain the fluctuating *E. coli* levels obtained in the routine beach-water quality monitoring programme for individual beaches (see Fig. 4). It points out such variations between different dates are not primarily due to sampling or analytical errors. Figure 4 also shows the long-term water quality trends of these beaches can be revealed by plotting running log-mean trend lines [10].

Tide has been found to be a major factor in causing the time-related changes in *E. coli* levels at those beaches with major pollution sources (sewage outfalls or polluted rivers) nearby. The tidal effect is most obvious during spring tides; and high bacterial counts are usually observed at spring floods at these beaches. The movement of microorganisms to a beach during flood tides and away from it at the subsequent ebbs has been confirmed by microbial tracer studies undertaken in Hong Kong [11]. The effect of tide on the densities in this indicator at those beaches with minor localized pollution sources (such as stormwater drains contaminated by septic tank overflows) is less apparent. Bather densities do not seem to be an important factor in causing variations in *E. coli* levels at bathing beaches.

Significant correlation between bather numbers and staphylococci densities in beach-waters have been observed for those beaches with high bather numbers. These relationships are particularly prominent during neap tides, when there is least dilution by tidal currents and faecal contaminants are less likely to be brought in from external pollution sources. It has also been found that the densities of staphylococci are consistently higher on a crowded day than on a day with small number of bathers at a beach in such tidal conditions.

Robinton and Mood [12] have shown that staphylococci are shed by bathers while swimming. It has been suggested they are derived from the mouth, nose, skin and throat of bathers, and are a good indicator of illness due to cross-infection among swimmers, such as respiratory or ear disease [13]. The present study indicates urine from bathers is another source of staphylococci contamination in swimming pools or natural bathing beaches. Their consistent presence in all urine samples tested adds support to the view that staphylococci are the best indicator of bather density or body contaminants from bathers. Also commonly occurring in urine are enterococci or faecal streptococci. They are probably less specific indicators of faecal contamination than *E. coli*, particularly for those beaches with high bather densities.

One would however need to be careful in interpreting the staphylococci data obtained for natural beach-waters. The present study shows that staphylococci are present in high numbers in external sources of faecal pollution, such as sewage

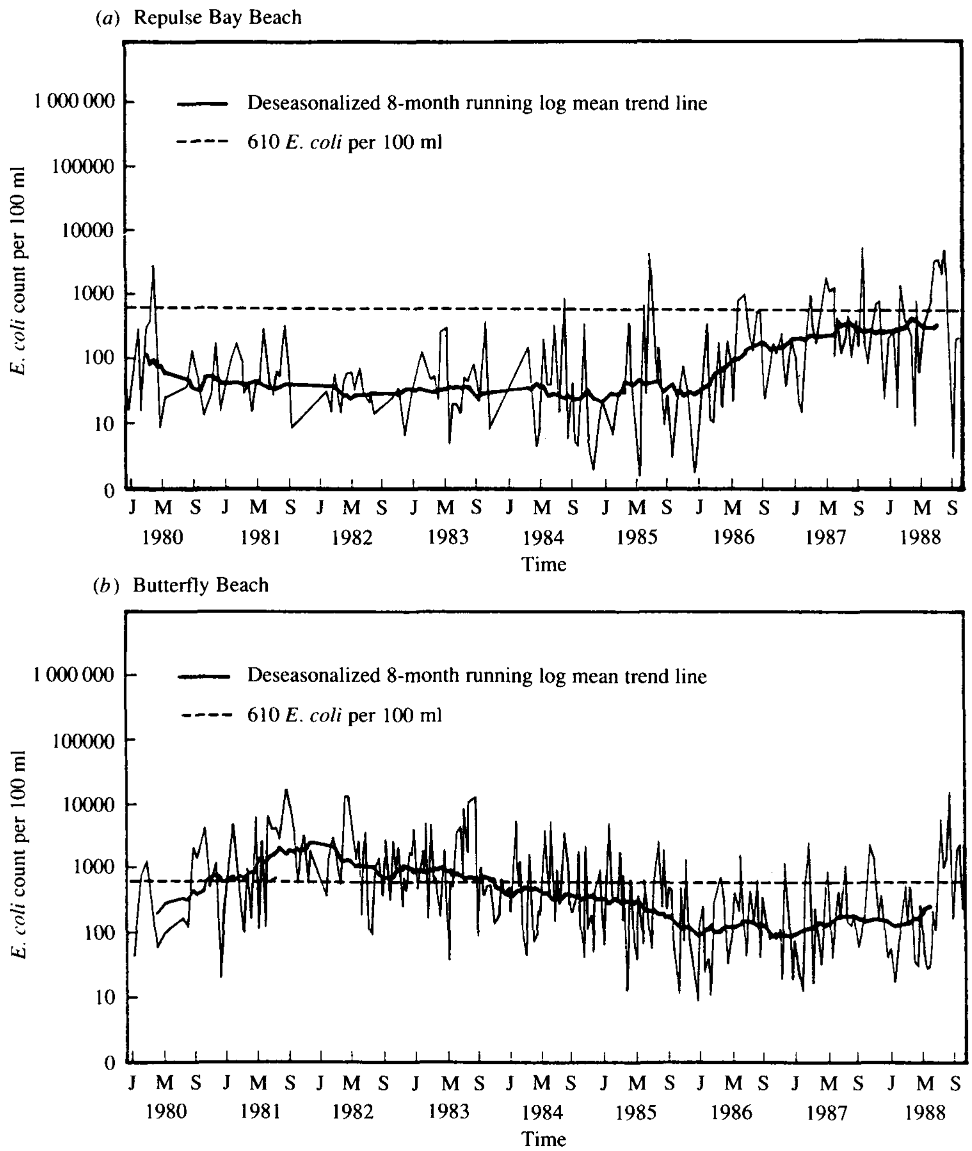

Fig. 4. The fluctuating *E. coli* counts obtained for Repulse Bay and Butterfly Beaches. The 8-month running log mean trend lines have also been plotted. The water quality of Repulse Bay Beach has deteriorated since 1986. Butterfly Beach was 'closed' in 1982; the subsequent implementation of remedial measures has resulted in the beach reopened in 1987.

outfalls and river-waters heavily contaminated by livestock wastes, in similar order of magnitude as *E. coli*. At some beaches, staphylococci are apparently acting as an indicator of faecal pollution, rather than of contaminants from bathers. This was obviously the case for Old and New Cafeteria Beaches – where the number of swimmers were low during the study, and the densities of staphylococci in beach-waters were predominately influenced by tide.

For the rest of the bathing beaches under study, there was little correlation between tide and staphylococci densities. This may be due to staphylococci being shed by bathers in considerable quantities in beach-waters, blurring any potential relationships between tide and this group of bacteria.

The correlation coefficient between staphylococci and swimming-associated respiratory or total perceived illness rates at the nine beaches was found to be 0·36 ($P > 0{\cdot}1$) in a previous epidemiological study of beach-water pollution [4]. It may be possible that because staphylococci are derived both from bathers themselves and from external faecal pollution sources for some beaches, a linear relationship between the densities of this indicator and disease due to cross-infection amongst bathers could not be established for Hong Kong beaches.

The present study reveals that the mean staphylococci to *E. coli* ratio for individual beach-water samples is useful for determining whether the staphylococci densities at a beach are reflecting contamination from bathers themselves and the risk of cross-infection among them. These ratios were very high (greater than 40) for those beaches with staphylococcal densities strongly correlated with bather numbers. They ranged from 15–30 for beaches where the relationships between staphylococci levels and bather densities are less strong, but nevertheless exist. For those beaches where the bather effect is minimal, the ratios were low (3 or below). This is logical because the staphylococci to *E. coli* ratios for the sources of faecal pollution of bathing beaches are 0·04–3; and if bathers are shedding significant quantities of staphylococci into the beach-water, the ratio for the beach should be higher than 3. It is not known whether such observations in Hong Kong are applicable to other places of the world. Further research in this area is obviously needed, in view of the recent proposals on the use of staphylococci for measuring the pollution due to bathers in beach-waters and swimming-associated health risks [3, 4, 13, 14].

Given the marked variations in microbial indicator densities in beach-water within a day or on different sampling dates, it is imperative that health-related microbiological monitoring of bathing waters should be carried out on weekend days rather than week-days, when the greatest number of bathers are exposed to the water, as previously suggested by Brenniman, Rosenberg and Northrop [6]. This has been the practice in Hong Kong since early 1989.

Such sampling at weekends should be spread throughout the bathing season – so that long-term water quality trend can be revealed (see Fig. 4); and a general level of microbial quality over the season be obtained for estimating swimming-associated health risks [4]. Taking into account the variability of microbial indicator densities, it is not advisable to judge the acceptability of beach-water quality based on the microbial indicator density obtained on one sampling occasion, or on the mean density of a number of samples obtained in a day (which covers only part of a tidal cycle), no matter how precisely these densities were measured. Fleisher [7] has suggested emphasis should shift from maximizing the number of sampling date to maximizing the number of replicate determinations made per sampling date, in order to improve the precision in estimating coliform counts. This objective would better be achieved by adopting the membrane filtration method, which gives more precise microbial counts than the MPN method [8].

Microbiological beach-water standards have been set in terms of percentage compliance [15–17] or geometric mean [18]. It has been shown in the present study that *E. coli* and staphylococci counts for the beach-waters of Hong Kong tend to follow log-normal distributions. The geometric mean is the best method for measuring the central tendency of the varying densities of these two bacterial indicators. While the percentage compliance considers only the frequency of occurrence of high values (for instance, greater than 1000 per 100 ml), the geometric mean gives full weight to the magnitude of all values in the distribution. Most importantly, geometric mean indicator densities correlate with disease risk data from the epidemiology studies of beach-water pollution [1–4]. The health-related beach-water quality standards newly developed and used in Hong Kong are expressed in geometric mean rather than percentage compliance [10].

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