Spatial and rainfall related patterns of bacterial contamination in Sydney Harbour estuary

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ABSTRACT

Water quality in recreational areas in Sydney Harbour, Australia, was analysed first to identify spatial patterns in faecal coliform and enterococci densities, and then to determine the relationship between bacterial densities and catchment rainfall. Non-metric multidimensional scaling separated sites closest to the mouth of the harbour from those further up the harbour's west and north-west arms. Sites closest to the harbour mouth generally had lower frequencies of high bacterial densities that exceeded median water quality guideline values. We attribute this to greater tidal flushing at sites closer to the harbour mouth. Eight site groups were identified within the harbour. Within each group, multiple regression analyses indicated rainfall accounted for between 15 and 66% of the variability in the bacterial densities. Variation in bacterial densities explained by rainfall was lower for sites closer to the harbour mouth where tidal flushing is greatest. Thus, our findings indicate that simple rainfall-based regression models are appropriate for predicting bacterial concentrations when flushing at a site is limited. More complex models incorporating a suite of environmental variables may improve the ability to predict bacterial concentrations at well-flushed sites, but even then, their predictive ability may be low.

Key words | enterococci, faecal coliforms, rainfall, recreational water quality, Sydney Harbour, tidal flushing

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INTRODUCTION

Water quality in recreational areas can be influenced by a range of toxicants and biological pathogens. Pathogens, such as bacteria, viruses and protozoans pose a health risk to swimmers (Henrickson *et al.* 2001). Following contact or ingestion, pathogens may cause a variety of diseases such as gastro, respiratory, dermatological, and ear, nose and throat infections (Henrickson *et al.* 2001). Numerous studies have linked recreational water quality with health effects in swimmers (e.g. Cabelli *et al.* 1979; Cartwright 1993; Corbett *et al.* 1993; Haile *et al.* 2001).

Most pathogens are not easily detected in water and instead, indicator bacteria are widely used. Faecal (thermo-tolerant) coliforms and enterococci bacteria are commonly used as indicators of faecal contamination in water bodies,

and recommended for monitoring recreational water quality in Australia (National Health and Medical Research Council 1990; ANZECC & ARMCANZ 2000). Faecal contamination is likely to result from sewage discharges, sewage overflows and stormwater as well as contamination from animals and swimmers using the water. The level of contamination is often greatest after rain as sewage may enter stormwater systems and be discharged into recreational swimming areas. Rainfall has frequently been identified as a significant determinant of faecal bacteria densities in recreational waters (Wyer *et al.* 1994, 1996; Armstrong *et al.* 1997; Krogh & Robinson 1997).

To minimize exposure of the public to pathogen contamination, water quality managers need quick and

reliable tools to indicate water quality conditions. Frequently, predictive models are used to determine the extent of pathogen contamination at a site (US EPA 1999). There are a number of models available, the simplest of which uses a regression approach to relate rainfall in a region to pathogen concentration. This approach has the advantages of being simple and relatively easy to construct and use, and provides a quick turn-around of predictions (US EPA 1999). However, development of such models requires a large amount of rainfall and water quality data.

Since 1994, the New South Wales Environment Protection Authority has been monitoring recreational water quality at popular swimming areas in Sydney Harbour, Australia, as part of the Beachwatch Programs. The programme routinely collects and analyses water samples for faecal coliforms and enterococci as indicators of faecal contamination. An extensive database of water quality information has been collated over the duration of the programme. Here, we analyse these data with the aims of (1) identifying spatial patterns in water quality and (2) investigating relationships between rainfall and bacterial contamination at swimming areas in Sydney Harbour. In the discussion, we consider the suitability of rainfall-based predictive models.

METHODS

Study region

Sydney Harbour (Port Jackson) is located on the south-eastern coast of Australia. The harbour is the centrepiece of the city of Sydney and serves an international shipping port, an important commercial fishery, a popular tourist destination and a conservation area. The harbour is popular for recreational boat users and fishers and has a number of popular beaches and ocean pools for swimming.

Sydney Harbour is a coastal plain estuary formed from a drowned river valley; as a result, the bathymetry of the harbour is complex (Das *et al.* 2000). The estuary has an area of 49.7 km^2 (Middleton *et al.* 1997) and is tidal over its entire area. Tides are semi-diurnal with a mean tidal range of 0.996 m (Middleton *et al.* 1997). Freshwater input is generally low with occasional high flows during rainfall events, and no large rivers enter the system (Das *et al.* 2000). The estuary is generally well mixed (Hatje *et al.* 2001) as a result of low freshwater inputs and tidal turbulence (Revelante & Gilmartin 1978). Under dry conditions, the estuary is saline throughout (Hatje *et al.* 2003). Flushing rates vary considerably along the estuary and a maximum flushing time of 225 days has been estimated for the estuary (Das *et al.* 2000).

Approximately 90% of the harbour catchment is urbanized and/or industrialized (Hatje *et al.* 2003) which poses a significant threat to water quality. There is no direct discharge of sewage effluent into Sydney Harbour but sewer blockages and overflows can divert sewage into the stormwater system. As a result, stormwater systems in Sydney have persistent faecal contamination even during dry weather (Sydney Water 1995). There are over 50 stormwater drains discharging to popular swimming areas of Sydney Harbour (Beachwatch 2003), and even more draining to other harbour areas. Thus, stormwater poses a significant threat to recreational water quality. This threat is greatest during rain events when incidence of sewer overflows and stormwater contamination is increased.

Sample collection

The NSW EPA has routinely monitored faecal contamination in Sydney Harbour since 1994. A single water sample is collected from each site by boat every six days. Samples are collected in sterile 250 ml plastic bottles at a depth of 30 cm. Samples are placed on ice immediately after collection and transported to a commercial laboratory for analysis. Samples are analysed for faecal coliforms and enterococci using methods 9222D and 9230C, respectively (*Standard Methods* 1998). Bacterial densities are reported as colony forming units (cfu) per 100 ml. Details of quality assurance for sample collection and analysis can be found in Beachwatch (2003).

Samples have been collected from over 50 sites in Sydney Harbour since the beginning of the Beachwatch programmes. Of these, 27 sites have been continually monitored since November 1996. These sites have been numbered in a clockwise fashion starting from the southern headland of the harbour mouth (Figure 1). With the exception of Darling Harbour (Site 6) all sites are popular swimming areas. Data from the 27 sites were analysed to investigate spatial patterns.

Data analysis

Faecal coliform and enterococci data were examined separately in all analyses. To explore spatial patterns in water quality, data were analysed using non-metric multi-dimensional scaling (MDS) with the Bray-Curtis similarity coefficient and a random starting configuration. The Bray-Curtis similarity coefficient does not consider joint absences and was chosen in order to weight the analyses towards those bacterial counts greater than zero, thus increasing the importance of elevated bacterial densities in shaping spatial patterns.

Multidimensional scaling (MDS) was used to identify groups of sites that had similar patterns of bacterial contamination. Sampling times were treated as variables; thus, the analysis reflects the similarity of bacterial levels among sites on each sampling occasion (i.e. temporal patterns). Bacterial densities were square root transformed prior to analysis. This transformation was selected to down-weight the importance of extremely high bacterial densities, and still allow intermediate abundances to contribute to the similarities (Clarke & Green 1988). Similarity matrices for the faecal coliform and enterococci datasets were compared using the RELATE module of PRIMER (version 5.2.4, Plymouth Marine Laboratories, UK). In our study, the RELATE module tested the null hypothesis that there was no similarity in the spatial structure of faecal coliform and enterococci densities in Sydney Harbour. The module performs a rank correlation of the similarities from the two datasets and compares this with the similarities from randomly permuted data (Clarke *et al.* 1993).

ANZECC and ARMCANZ (2000) recreational water quality guidelines are based on the median and 80th percentile of five values collected over a 1 month period. Median values should not exceed 150 cfu 100 ml^{-1} for faecal coliforms and 35 cfu 100 ml^{-1} for enterococci (ANZECC & ARMCANZ 2000). It is not the purpose of this paper to assess the compliance of sites with water quality guidelines (for this see Beachwatch 2003) but the median guideline values are used here as a yardstick for comparing water quality at each site. The proportion (%) of individual values from each site that exceeds median guideline values was superimposed on the MDS ordinations as bubble plots. The greater the size of the bubble surrounding the data points for each site, the greater the frequency of bacterial densities exceeding the guideline values.

From the multivariate analyses, groups of sites with similar bacterial densities and temporal patterns were identified. Each group was further analysed using all data available from November 1994 to April 2002. As replicate samples are not collected at each site (on each sampling event), sites within a group were used as replicates and the geometric mean of bacterial concentrations for each sampling event was determined (using log(x + 1) to allow for zero values). Rainfall data was collated from a network of 39 gauges spread across the harbour catchment. Rainfall on a particular day was determined as the average of rainfall
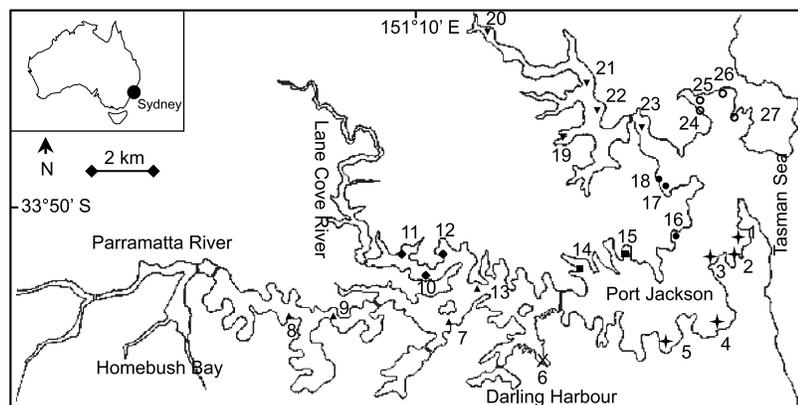

Figure 1 | Location of sampling sites (numbered 1 to 27) in Sydney Harbour, Australia, used for analyses of spatial pattern in recreational water quality. Symbols indicate sampling location and site groupings. ◆ = Lane Cove River ● = Middle Harbour; ■ = Port Jackson west; + = Port Jackson East; × = Darling Harbour; ▲ = Parramatta River; ○ = North Harbour; ▼ = Middle Harbour North. Map adapted from Hatje *et al.* (2003).

gauges nearest to the site/group. Gauges used were chosen to represent the rainfall in the particular sub-catchments, even though particular gauges may be several kilometres from the sampling site.

A series of general linear models (GLIM version 3.77, Royal Statistical Society, London) was fitted to the dataset to examine relationships between density of bacteria and rainfall. Bacterial density (the response variable in all analyses) was $\log(x + 1)$ transformed to approach normality and to ensure homogeneity of variances. Faecal coliforms and enterococci are relatively short-lived in seawater (Gabutti *et al.* 2000). Consequently, density estimates of live bacteria made every 6 days were considered independent of each other. Rainfall estimates were obtained for time intervals in the previous 24, 48, 72, 96, 120 and 144 hours prior to bacterial sampling. Rainfall estimates at each of these six time intervals were entered into models as explanatory variables. The contribution of rainfall at each time interval to variation in bacterial density was examined through the use of partial F tests (Norman & Streiner 2000). These tests determine how much variation in density is uniquely attributable to rainfall at each time interval. Here, we considered the unique contribution of rainfall at a particular time as rainfall that was independent of measurements at shorter time intervals. For example, the unique contribution of rainfall at 72 hours was determined by entry into models after rainfall at 24 and 48 hours were already in the model. Faecal coliforms and enterococci were considered in separate analyses. The full model regressions were determined using multiple linear regressions (Minitab Release 13.1, Minitab Inc., USA).

Patterns of bacterial concentrations and rainfall in each sub-catchment were explored by plotting bacterial concentrations against cumulative rainfall. Because the antecedent rainfall events do not contribute equally to the bacterial densities observed on any day, rainfall at each antecedent 24 h period was weighted based on multiple regression coefficients for each period (expressed as a proportion of the coefficient for 24 h) and with the y intercept omitted. The weightings for each sub-catchment were determined from the respective regression model. Model equations are available from the authors on request.

RESULTS

Spatial patterns

The MDS analyses of bacterial data from 1996 to 2002 indicated spatial patterns that reflected the geography of Sydney Harbour. The spatial structure of faecal coliform and enterococci densities was similar throughout the harbour (RELATE analysis, $\rho = 0.777$; $P = 0.0001$), illustrated in the patterns of the two ordination plots (Figures 2 and 3). The faecal coliform ordination showed a sharp division in which those sites closest to the mouth of the harbour ('downstream' sites, 1–5, 16–18 and 24–27) were separated from those further up the harbour's west and north-west arms ('upstream' sites) (Figure 2). A similar pattern was evident in the ordination of enterococci data although the distinction between upstream and downstream was represented more as a gradient without such a strong division in the ordination (Figure 3). In each ordination, Darling Harbour (site 6) stood alone, remote from other nearby sites.

Within the upstream/downstream division, there were further groupings in which sites close together geographically were located close to each other in ordination space. It therefore seemed logical to base site groupings primarily on the geography of the harbour (Figure 1), using the ordination plots to define boundaries between groups. With this in mind, site three was grouped with nearby sites (1 to 5) based on geography and catchment affinities, rather than with sites 24–27 if based on the ordination alone. Eight site groups were identified (Table 1; Figure 1). Site groups are hereafter referred to as sub-catchments.

In Figures 2 and 3, the axes on the ordinations have been rotated such that the x axis corresponds approximately to increasing distance from the harbour mouth from right to left (cf. Figure 1). The overlay of the bacterial data in the bubble plots suggests that those sites further up the estuary have greater frequency of high faecal coliform densities (Figure 2). This pattern is less marked for enterococci densities (Figure 3). There appeared to be less variability in the frequencies (more uniform bubble size) for the enterococci data compared with the faecal coliform data. Site 6, Darling Harbour, has the highest frequency of
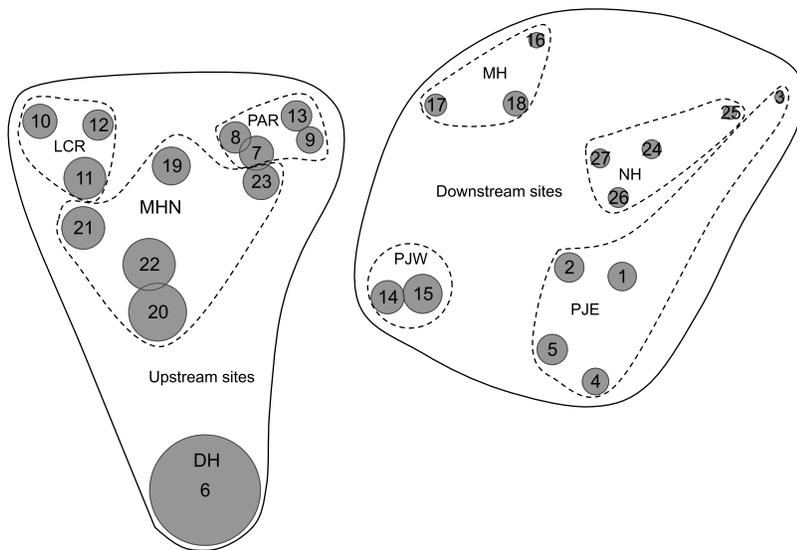
Figure 2 | Non-metric multidimensional scaling (MDS) ordination of faecal coliform densities at sites in Sydney Harbour from 1996 to 2002. Bubble size indicates the relative frequency of values exceeding the ANZECC & ARMCANZ (2000) water quality guidelines median limit. LCR = Lane Cove River; MH = Middle Harbour; PJW = Port Jackson West; PJE = Port Jackson East; DH = Darling Harbour; PAR = Parramatta River; NH = North Harbour; MHN = Middle Harbour North.

exceeding the water quality guideline values for both faecal coliforms and enterococci.

Response to rainfall

Multiple linear regression models based on antecedent rainfall accounted for between 16 and 66% of the variability in the faecal coliform data and between 15 and 58% of the enterococci data (Table 2). In general, those sub-catchments further away from the mouth of Sydney Harbour, i.e., Lane Cove River, Parramatta River and Middle Harbour North, had higher full-model r^2 values than those sites closer to the harbour mouth for both faecal coliforms and enterococci (Table 2). The exception was Darling Harbour,
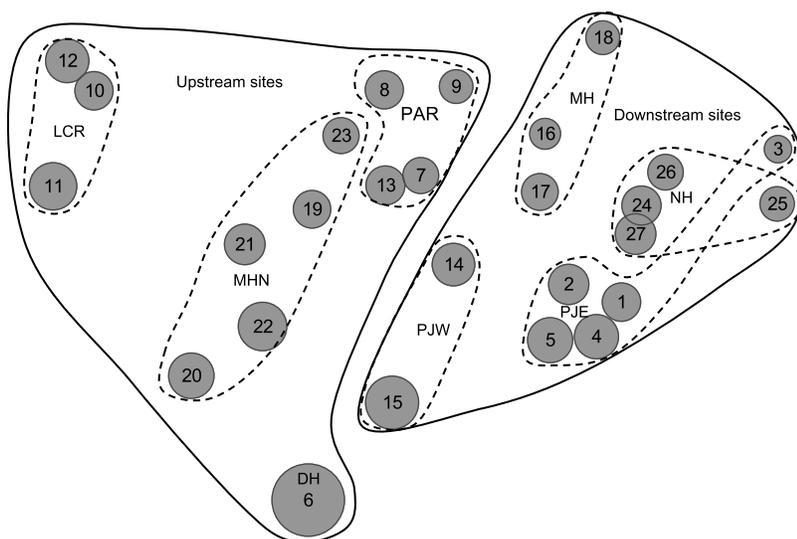

Figure 3 | Non-metric multidimensional scaling (MDS) ordination of enterococci densities at sites in Sydney Harbour from 1996 to 2002. Bubble size indicates the relative frequency of values exceeding the ANZECC & ARMCANZ (2000) water quality guidelines median limit. LCR = Lane Cove River; MH = Middle Harbour; PJW = Port Jackson West; PJE = Port Jackson East; DH = Darling Harbour; PAR = Parramatta River; NH = North Harbour; MHN = Middle Harbour North.

Table 1 | Site groups derived from multivariate analyses of bacterial densities in Sydney Harbour

Sub-catchment	Sites
Port Jackson East	1–5
Darling Harbour	6
Lower Parramatta River	7–9,13
Lane Cove River	10–12
Port Jackson West	14–15
Middle Harbour	16–18
Middle Harbour North	19–23
North Harbour	24–27

which had low full-model r^2 values for both faecal coliforms and enterococci (Table 2), despite being some distance from the harbour mouth.

In each sub-catchment, rainfall in the 24 h prior to sample collection was the greatest predictor of bacterial concentrations and accounted for 5 to 10 times more variability in the data than did subsequent time periods (Table 2). Partial r^2 values decreased for each consecutive period added to the regression model (Table 2). For both faecal coliform and enterococci, the Lane Cove, Parramatta River and Middle Harbour North sub-catchments had consistently higher partial r^2 values for each time period compared with the other sub-catchments (Table 2). The sub-catchments with the highest full-model r^2 values also had a greater number of significant variables in the regression equations (Table 2). In some sub-catchments, there was a slight increase in the partial r^2 value at 72 h. The reason for this is unknown, but the overall contribution of this slight increase to the total variation explained by the regression model is negligible.

At Darling Harbour, rainfall at 24 and 72 h contributed significantly to explaining faecal coliform densities; however, the rainfall at 48 h did not (Table 2). Non-significant intermediate time periods were also evident in the enterococci data for Middle Harbour, North Harbour, Port Jackson East and Darling Harbour sub-catchments (Table 2). However, given the low partial r^2 values for all time periods beyond 24 h, particularly for those

Table 2 | r^2 values for full multiple regression models, and the unique contribution (partial r^2) of rainfall at each of the six time intervals (24, 48, 72, 96, 120 and 144 hours) to variation in (a) faecal coliform and (b) enterococci densities at each of the eight sub-catchments (abbreviations below table). Significant r^2 values ($P < 0.05$) are in bold

Sub-catchment	Full model r^2	Partial r^2					
		24 h	48 h	72 h	96 h	120 h	144 h
Faecal coliforms							
PJE	**0.30**	**0.24**	**0.01**	**0.03**	**0.01**	**0.01**	0
DH	**0.16**	**0.14**	0	**0.01**	0.01	0	0
PAR	**0.60**	**0.32**	**0.09**	**0.11**	**0.05**	**0.02**	**0.01**
LCR	**0.60**	**0.30**	**0.08**	**0.13**	**0.06**	**0.02**	**0.02**
PJW	**0.22**	**0.19**	**0.01**	**0.02**	0	0	0
MH	**0.22**	**0.15**	**0.01**	**0.04**	**0.02**	0	0
MHN	**0.66**	**0.40**	**0.09**	**0.09**	**0.05**	**0.01**	**0.02**
NH	**0.20**	**0.16**	**0.01**	**0.02**	**0.01**	0	0
Enterococci							
PJE	**0.24**	**0.22**	**0.01**	0.01	0	**0.01**	0
DH	**0.27**	**0.25**	0	0	0	**0.01**	0
PAR	**0.42**	**0.30**	**0.05**	**0.04**	**0.01**	**0.01**	0
LCR	**0.50**	**0.35**	**0.05**	**0.06**	**0.02**	**0.01**	**0.01**
PJW	**0.23**	**0.21**	**0.01**	**0.01**	0	0	0
MH	**0.16**	**0.14**	0.01	**0.01**	0	0	0
MHN	**0.58**	**0.39**	**0.09**	**0.05**	**0.03**	**0.01**	**0.01**
NH	**0.18**	**0.15**	0.01	**0.01**	0	0	0

LCR = Lane Cove River; MH = Middle Harbour; PJW = Port Jackson West; PJE = Port Jackson East; DH = Darling Harbour; PAR = Parramatta River; NH = North Harbour; MHN = Middle Harbour North.

sub-catchments listed above, this apparent anomaly is likely to be inconsequential.

For all sub-catchments, bacterial concentrations generally increased with increasing rainfall, evidenced by mostly positive coefficients in the multiple regression models. High bacterial concentrations were often recorded after little or no

rainfall and fewer low concentrations were recorded after rain (Figure 4). The response of bacterial densities to rainfall varied among sub-catchments, but similar responses were evident among those sub-catchments close to and distant from the harbour mouth. The patterns for Middle Harbour North (Figure 4a,b) were indicative of the Parramatta River and Lane Cove River sub-catchments and were characterized by bacterial densities that increased almost linearly with rainfall. Log_{10} bacterial densities below 2 were rarely recorded above 20 mm of rain. The patterns for Port Jackson East (Figure 4c,d) were indicative of North Harbour, Middle Harbour and Port Jackson West sub-catchments. In those sub-catchments, log_{10} bacterial densities rarely exceeded 3 irrespective of rainfall. Darling Harbour had a response dissimilar to all other sub-catchments in which log_{10} bacterial densities frequently exceeded 3 even after little or no rainfall (Figure 4e,f). Log_{10} bacterial values below 2 were rare with greater than 10 mm of rain.

DISCUSSION

It is well established that stormwater runoff is a major source of faecal contamination in recreational waters (e.g. Weiskel *et al.* 1996; Krogh & Robinson 1997; Dwight *et al.* 2002; Ackerman & Weisberg 2003; Noble *et al.* 2003). The data presented here concur, showing that faecal coliform and enterococci densities in water at popular swimming areas increase with increasing rainfall.

Strong spatial patterns were evident in the harbour at broad and small scales. At a broad scale, sites closest to the mouth of the harbour were grouped together and distinguished from sites in the upper estuary. Within that division, nearby sites could be grouped together, indicating strong catchment influences on water quality. The groupings based on the MDS analysis indicate that sites grouped close together have similar temporal patterns in bacterial densities and respond similarly to particular rainfall events. Consistent
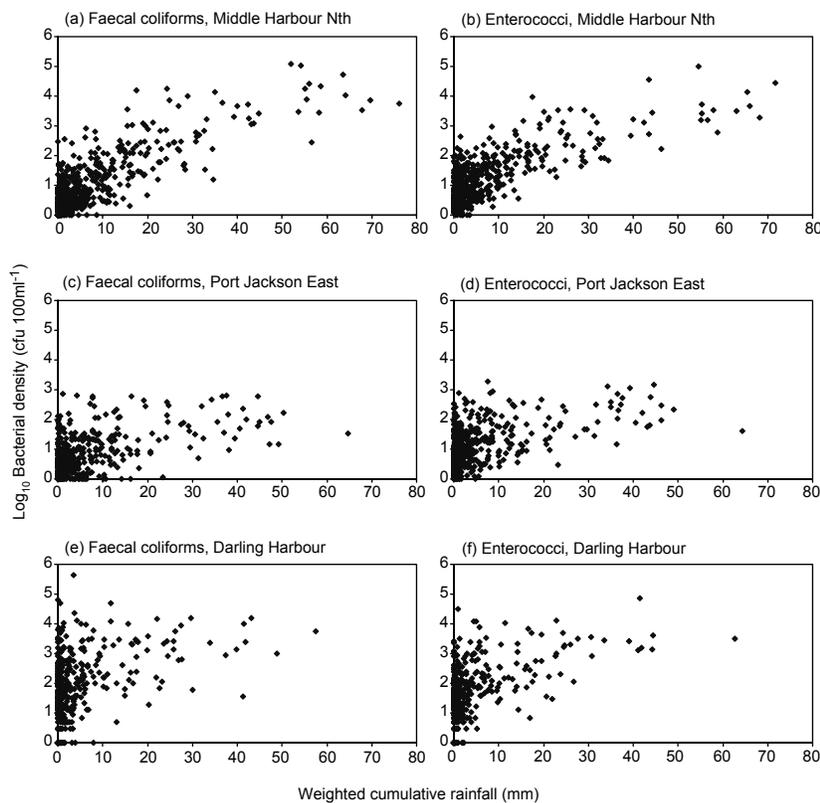

Figure 4 | Relationships between faecal coliform and enterococci density in sub-catchments and weighted cumulative rainfall over the previous 144 h (see text for explanation of weighting).

with this, sites grouped close together had similar frequencies of exceeding water quality guideline values.

Sites further up the main tributaries of the harbour had a greater frequency of exceeding water quality guideline values compared with sites close to the harbour mouth. This can be explained by patterns of tidal flushing which is greatest in the sites closest to the harbour mouth, decreasing with distance upstream (Das *et al.* 2000). Lower bacterial densities at sites towards the harbour mouth also correlate with trends of increasing salinity and decreasing concentrations of suspended particulate matter (Hatje *et al.* 2003). The increase in salinity downstream (range 21–35 ppt; Hatje *et al.* 2003) is of sufficient magnitude to reduce the T90 values (time required to inactivate 90% of organisms) for faecal coliforms from 72 to 48 h and faecal streptococci (of which enterococci are part) from 104 to 88 h (Gabutti *et al.* 2000). The increases in suspended particulate matter further upstream are likely to increase the longevity of bacteria that adhere to those particles (see Davies *et al.* 1995; Mallin *et al.* 2000). Turbidity itself reduces the bactericidal effects of light (Pommepuy *et al.* 1992). Both salinity and suspended sediments are likely to contribute to the greater densities of faecal bacteria at upstream sites.

Many other factors may influence broad-scale patterns in bacterial contamination including human population densities, and the relative proportions of industrial, residential and open-space land use areas within each sub-catchment. It is also unclear whether the similarity in bacterial densities among nearby sites is due to similar inputs (i.e. catchment traits), the result of factors (such as tidal flushing) that may affect survival or fate of the bacteria once in the water, or their interaction.

The faecal coliform and enterococci data showed similar spatial patterns. However, the bubble plots (Figures 2 and 3) indicate greater distinction among sites based on the frequency of exceeding the faecal coliform water quality guideline value compared with the enterococci value. All sites had a similar frequency of exceeding the enterococci value, but a range of frequencies of exceeding the faecal coliform value. In general, the water quality guideline value for enterococci was exceeded more frequently than was the guideline value for faecal coliforms. Faecal coliforms are indicative of very recent contamination whereas enterococci, which are more persistent in the marine environment

(Fujioka *et al.* 1981; Gabutti *et al.* 2000), are indicative of slightly 'older' contamination. The higher frequency with which the enterococci criterion was exceeded suggests that recreational water quality assessments were more affected by residual rather than very recent contamination. Enterococci densities were more strongly correlated with illness in swimmers than were faecal coliform densities (Cabelli *et al.* 1979; McBride *et al.* 1998) and are considered by many to be preferable indicators of faecal contamination.

Rainfall is widely used and recommended as a predictor of recreational water quality (US EPA 1999; NSW EPA 2002). Rainfall-based regression models are simple to use and provide rapid turn-around of predictions but vary in their ability to predict bacterial water quality from site to site. In this study, rainfall accounted for between 15 and 66% of variability in bacterial densities with the predictability greatest for the upstream sub-catchments that have relatively limited tidal flushing (Das *et al.* 2000). In contrast, those sub-catchments with a high degree of tidal flushing, i.e. North Harbour, Middle Harbour and Port Jackson East and West, have much lower r^2 values. Despite having limited flushing (Das *et al.* 2000), Darling Harbour had low rainfall-related r^2 values for both faecal coliforms and enterococci. Presumably this is due to the high levels of bacterial contamination at this site even during dry periods (Figure 4) and thus there was only a weak relationship with rainfall.

Rainfall in the previous 24 h accounted for the greatest proportion of the variability in the bacterial data (Table 2) with the importance of antecedent periods decreasing over time. At upstream sub-catchments where flushing is lower, bacteria are not diluted or removed quickly. Presumably, *in situ* mortality (rather than removal or dilution) is important in these areas. In upstream sub-catchments, rainfall remains more strongly and significantly related to bacterial densities for longer. This is illustrated by a greater number of significant variables and relatively larger coefficients for each variable in models for the upstream sub-catchments compared with those for downstream sub-catchments.

Patterns in r^2 values were similar for both faecal coliforms and enterococci. However, r^2 values for enterococci were generally lower than those for faecal coliforms (for both full models and the contribution of each period). The exceptions were for Port Jackson West and Darling Harbour. Crowther *et al.* (2001) showed that, over a range of

sites, there was no consistent pattern in the relative r^2 values for the predictability of faecal coliforms and faecal streptococci (of which enterococci are a subgroup) using rainfall and other environmental variables.

Krogh & Robinson (1997) and Crowther *et al.* (2001) constructed multiple regression models for faecal coliforms and faecal streptococci for ocean beaches near Sydney and Blackpool, UK, respectively. The suite of predictive variables included tide-height, sunlight and wind speed, yet the resulting models still only gave r^2 values between 0.08 and 0.50 in each study. For a simple rainfall-based model, Armstrong *et al.* (1997) derived r^2 values of 0.03 to 0.39 for ocean beaches around Sydney. These r^2 values derived for well-flushed beach sites are generally greater than those for the well-flushed harbour sites in our study. This suggests that complex models have a greater ability to predict bacterial densities in well-flushed sites than the simple rainfall-based models used here, but since r^2 values for those sites did not exceed 0.5, there may be an upper limit to which such models can be effective.

CONCLUSIONS

Spatial patterns in bacterial contamination appear to be influenced by a combination of catchment characteristics and flushing processes in the receiving waters. Distinct catchment related affinities among sites could be determined for Sydney Harbour. Rainfall alone varied in its ability to predict bacterial concentrations in different areas of Sydney Harbour. It appears that simple rainfall-based regression models are appropriate for predicting bacterial concentrations when flushing at a site is limited. More complex models incorporating a suite of environmental variables may improve the ability to predict bacterial concentrations at well-flushed sites, but even then, the literature suggests their predictive ability may be low.

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