# Evaluation of Recreational Health Risk in Coastal Waters Based on Enterococcus Densities and Bathing Patterns

***David J. Turbow, Nathaniel D. Osgood, and Sunny C. Jiang***

Department of Environmental Analysis and Design, University of California Irvine, Irvine, California, USA

**We constructed a simulation model to compute the incidences of highly credible gastrointestinal illness (HCGI) in recreational bathers at two intermittently contaminated beaches of Orange County, California. Assumptions regarding spatial and temporal bathing patterns were used to determine exposure levels over a 31-month study period. Illness rates were calculated by applying previously reported relationships between enterococcus density and HCGI risk to the exposure data. Peak enterococcus concentrations occurred in late winter and early spring, but model results showed that most HCGI cases occurred during summer, attributable to elevated number of exposures. Approximately 99% of the 95,010 illness cases occurred when beaches were open. Model runs were insensitive to 0–10% swimming activity assumed during beach closure days. Comparable illness rates resulted under clustered and uniform bather distribution scenarios. HCGI attack rates were within federal guidelines of tolerable risk when averaged over the study period. However, tolerable risk thresholds were exceeded for 27 total days and periods of at least 6 consecutive days. Illness estimates were sensitive to the functional form and magnitude of the enterococcus density–HCGI relationships. The results of this study contribute to an understanding of recreational health risk in coastal waters. *Key words:* contact recreation, enterococcus, gastroenteritis, health risk, water. *Environ Health Perspect* 111:598–603 (2003). doi:10.1289/ehp.5563 available via *http://dx.doi.org/* [Online 28 October 2002]**

Southern California's beaches attract 100 million visitors annually. To protect swimmers from exposure to fecal contamination, the microbiological quality of coastal waters is extensively monitored by state and local agencies (*1*). Rapid population growth and urban development have resulted in regional domestic sewage and urban runoff problems, and beach contamination has become the focus of public safety concern. Elevated fecal bacterial indicator levels forced the Orange County Health Care Agency to close Huntington Beach, California, for much of the summer of 1999 (*2*). Large-scale investigations have been conducted to identify the source of contamination (*3*), but not to quantify an incidence rate of illness attributable to bathing there.

Exposure to marine recreational water of poor microbiologic quality has been linked to multiple adverse health outcomes including infections of the eyes, ears, skin, and gastroenteritis (*4*). The results of prospective studies (*5*), however, suggest that, of these outcomes, only gastrointestinal symptoms are both swimming associated and pollution related. Epidemiologic investigations of illness in marine recreational bathers have addressed gastroenteritis from exposure to sewage contamination (*5,6*) and, more recently, storm drain runoff (*7*).

Surf zone bacterial contamination at Huntington Beach may be due to sewage pollution, non–point source storm drain runoff, or a combination of these inputs. This region receives a mixture of primary and secondary sewage from the Orange County Sanitation District (OCSD) daily. The volume of sewage discharge fluctuates with seasonal water usage. Storm drain runoff reaches Southern California's coastal waters in high volumes following rainfall events during winter months and to a lesser extent during dry weather conditions in summer (*8,9*). The relative contribution of sewage effluent and non–point source runoff in driving surf zone bacterial fluctuations is currently under study by independent researchers (*10*).

Superimposed upon seasonal water quality trends are spatial and temporal variations in beach usage for marine water-contact recreation, which have important implications for microbial risk assessment. If recreational water contact occurs at times during which the water is safe, there may be a low degree of health risk to bathers. But if peak use of beaches occurs at locations and times during which unsafe levels of contaminants are present, then aggregate health risk will be elevated.

Of several bacterial indicators commonly used for microbial risk assessment (e.g., total coliform, fecal coliform, and enterococcus), the enterococcus density in seawater is believed to be the best single measure of its quality relative to the risk of swimming-associated, pollution-related infectious disease (*11–13*). For example, enterococci show higher correlation with swimming-associated gastroenteritis in wastewater-influenced water bodies than fecal coliform and total coliform (*13*). Changes made to California's monitoring standards (*14*) in 1998 required the adoption of enterococcus as an indicator of marine recreational water safety to supplement existing standards for fecal coliform and total coliform.

In the absence of large-scale prospective health risk studies, the objective of this study was to create a model to compute a historical incidence rate of gastroenteritis in swimmers based on enterococcus densities in Huntington Beach and neighboring Newport Beach. Three assumptions were tested in the model regarding *a*) the relationship between enterococcus density and gastrointestinal illness risk, *b*) bathing activity levels at sampling locations, and *c*) the fraction of beachgoers who bathed during beach closure days.

## Materials and Methods

***Study site.*** We studied a contiguous stretch of coastline (8.5 miles) in Huntington Beach and Newport Beach, California (Figure 1). Approximately 5.5 million instances of swimming and surfing occur there each year (*15*). The Santa Ana River (SAR), a major freshwater input draining a 2,850-square-mile watershed, bifurcates the beaches. Approximately 243 million gallons per day of treated sewage effluent are discharged into the ocean by the OCSD through an outfall pipe located 4 miles offshore from the mouth of the SAR (*2*).

***Data sources.*** Historical enterococcus density data were collected by the OCSD approximately three times per week at each of 13 surf zone monitoring stations located at 1,000-foot intervals along the beach (Figure 1). A total of 503 data points were available for the 31-month study period between 1 June 1998 and 31 December 2000. Missing values were treated in the model by linear interpolation of surrounding known values. In cases where sample counts were quantified as a range (i.e., above or below detection limits), the lower point of the range was used to provide conservative estimates of contamination.

Aggregate beach attendance was provided through local lifeguard agencies and fire departments and was available for > 99% of

Address correspondence to S.C. Jiang, 1367 Social Ecology II, University of California, Irvine, CA 92697 USA. Telephone: (949) 824-5527. Fax (949) 824-2056. E-mail: sjiang@uci.edu

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days studied. To estimate the fraction of beachgoers who bathe at different times of the year at local beaches, we used a report of the seasonal amount of marine water contact recreation activity as a fraction of beach attendance. During the months of October–March, approximately 18% of total beachgoers bathe, whereas the summertime fraction (April–September) is 27% (*15*).

The times and locations of beach closures were provided by the Orange County Health Care Agency. Of the sampling locations, beaches at stations 9N and 6N were closed the most frequently, with 55 total beach closure days each during the study period. Stations 3N, SAR, and 3S were each closed for 13 total days. Station 6S was closed for 10 total days. None of the beaches south of station 6S in the study area were closed during the study period.

***Enterococcus–HCGI relationships.*** We applied two relationships between enterococcus density and highly credible gastrointestinal illness (HCGI) to determine risk to the individual bather from exposure to sewage (*5*) and storm drain runoff (*7*), respectively. For consistency with the definition of exposure used in the original epidemiologic investigations, individuals engaged in water contact activities leading to likely immersion of the head, regardless of duration, were counted as bathers in the model. HCGI was defined as symptoms of vomiting, diarrhea, nausea, or stomachache, accompanied by a fever (*5*).

The primary enterococcus density–HCGI relationship used in the model was drawn from prospective health risk studies of sewage exposure conducted by Cabelli et al. (*5*), on which current federal bacterial water quality guidelines are based (*13*). A relatively strong ($r^2$ = 0.74) statistical association between enterococcus density and gastrointestinal illness risk was found across several years and at several sites. The dose–response relationship was expressed as follows:

$$Y = a + b\,(\log_{10})X,$$

where $X$ is the mean enterococcus density, and $Y$ is the rate difference of gastrointestinal illness in swimmers versus nonswimmers.

Application of this equation yielded a 1.9% attack rate of HCGI at an enterococcus density of 35 colony forming units (CFU) per 100 mL sewage-polluted seawater; the detectable increase in the attack rate for swimmers versus nonswimmers was 12 CFU/100 mL (*5*).

In the model created for this study, upper and lower confidence intervals (CIs) for the dose–response curve of Cabelli et al. (*5*) were reproduced at the 95% level by fitting the original reported data to a piecewise linear curve, which diverged from the mean response curve line at both low and high enterococcus densities.

The second relationship used in the model was drawn from a study of exposure to storm drain runoff conducted by Haile et al. (*7*). Haile et al. used the definition by Cabelli et al. (*5*) of HCGI as "HCGI1" and reported an elevated gastrointestinal illness risk in bathers near storm drain outlets only at enterococcus concentrations exceeding 104 CFU/100 mL. Because of the lack of a clear dose–response curve, the enterococcus–HCGI risk relationship of Haile et al. was represented in the model as a step, or threshold, function with a relative risk of 1.0 for exposure to enterococcus densities ≤ 104 CFU/100 mL, and a relative risk of 1.31 for bathing in waters above that count.

***Model architecture.*** The model was constructed using Vensim 4.0 software (Ventana Systems, Harvard, MA). The model made use of daily historical estimates of aggregate beach attendance for two beaches: Huntington Beach, California, (comprising Huntington City Beach and Huntington State Beach), and Newport Beach, California.

Figure 2 shows the flow of information within the model. For each day in the study period, an HCGI risk curve was applied to historical enterococcus counts at each sampling location to estimate elevated risk associated with bathing at each location. To estimate the number of bathers at each beach, historical beach attendance data for each day were combined with the seasonal fraction of beachgoers who bathe. Beach-specific aggregate bather counts were then combined with spatial distribution of bathers by season (winter or summer) to yield the total number of bathers by sampling location. Estimated bather counts by location were then multiplied by elevated HCGI risk associated with swimming to generate cumulative HCGI cases over the study period.

***Sensitivity analyses.*** Three sensitivity analyses were performed to examine the degree to which results reflect assumptions made about model input parameters. In the first sensitivity analysis, the enterococcus density–HCGI risk relationship for storm drain runoff exposure reported by Haile et al. (*7*) was substituted for the relationship established for sewage exposure reported by Cabelli et al. (*5*) (hereafter referred to as "Cabelli's and Haile's relationship," respectively).

In the absence of detailed historical data on the spatial patterns of bathing along each beach, the second one-way sensitivity analysis examined the impact of changed assumptions regarding bather distribution on illness estimates over the study period. Illness rates resulting from a uniform bather distribution scenario were compared with those under a clustered bather distribution scenario described in Table 1. In the clustered scenario, water contact activity is concentrated at

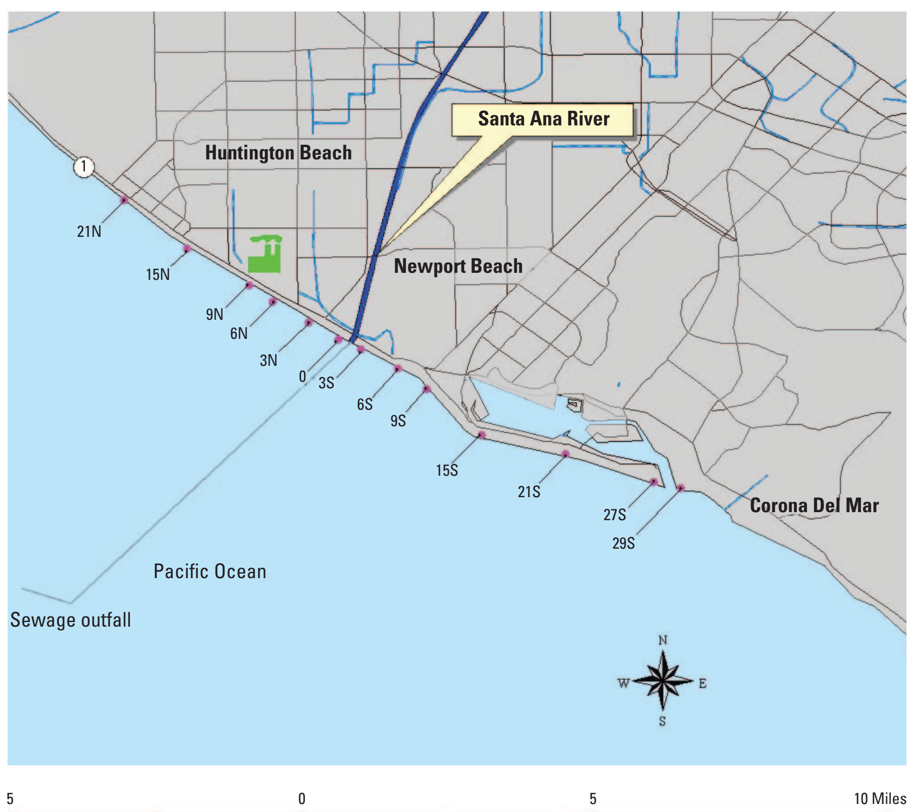


**Figure 1.** Map of study site.

beaches with coastal amenities such as parking lots, piers, jetties, and the mouth of the SAR. The clustered distribution of bathers, used as a default assumption in the model, is consistent with the assertion that beachgoers in this region prefer beaches with coastal amenities (*16*) and is substantiated by observations made for this study. Under a uniform distribution scenario, bathers were assumed to be equally spread between sampling locations along the 8.5-mile stretch of coastline over the study period.

For the third sensitivity analysis, no bathers were assumed to have been in the water during beach closure days, leading to a level of zero risk of contracting swimming-associated HCGI. The impact of varying this estimate to 10% of bathers in the water despite beach closures was examined in terms of total expected HCGI cases over the study period. This assumption was based on communication with a local public health official who revealed that beach closures may not completely prevent swimming on beach closure days (*17*).

## Results

***Beach usage and water quality.*** Combined beach attendance is shown in Figure 3. Approximately 42,520,000 people attended the beaches over the 31-month study period. Seasonal variations in beach attendance were pronounced, as well as increases in beach attendance during weekends and holidays. Many summer days had more than 180,000 beach visits, compared with several winter days with less than 3,000 total beachgoers.

Figure 4A shows the mean enterococcus levels for each sampling location over the study period. Highest enterococcus concentrations were found near the mouth of the SAR, where the average enterococcus density exceeded 100 CFU/100 mL. However, the SAR station was not included in the risk analysis because few or no bathers were observed at this location. Enterococcus levels were generally higher at sampling locations north of the SAR in Huntington Beach than at stations south of the SAR in Newport Beach.

A time series of enterococcus levels for all stations over the study period is shown in Figure 4B. A 31-day centered moving average for the data was superimposed on the time series. Peak enterococcus concentrations were frequently detected during late winter and early spring. For example, the highest daily average sample counts between February 2000 and April 2000 exceeded 350 CFU/100 mL. Abnormally high enterococcus concentrations were found during summer 1999, causing beach closures for most of the summer (*2*). A pronounced variation between years in mean enterococcus density for all stations combined was noted, with an average of 19 CFU/100 mL in 1999 and 30 CFU/100 mL in 2000.

***Risk analysis.*** Application of Cabelli's relationship to total number of exposures yielded 95,010 cumulative HCGI cases over the study period (Figure 5A). The total number of HCGI cases ranged from 47,012 to 129,853 when Cabelli's lower and upper 95% CIs were used, respectively. Figure 5A also shows that the use of Cabelli's relationship leads to gradual, low-frequency illness trends over time. Substitution of Haile's relationship for Cabelli's relationship yielded far fewer illness cases. A total of 2,056 HCGI cases occurred during the study period, approximately 98% fewer than total illness cases using Cabelli's relationship (Figure 5A).

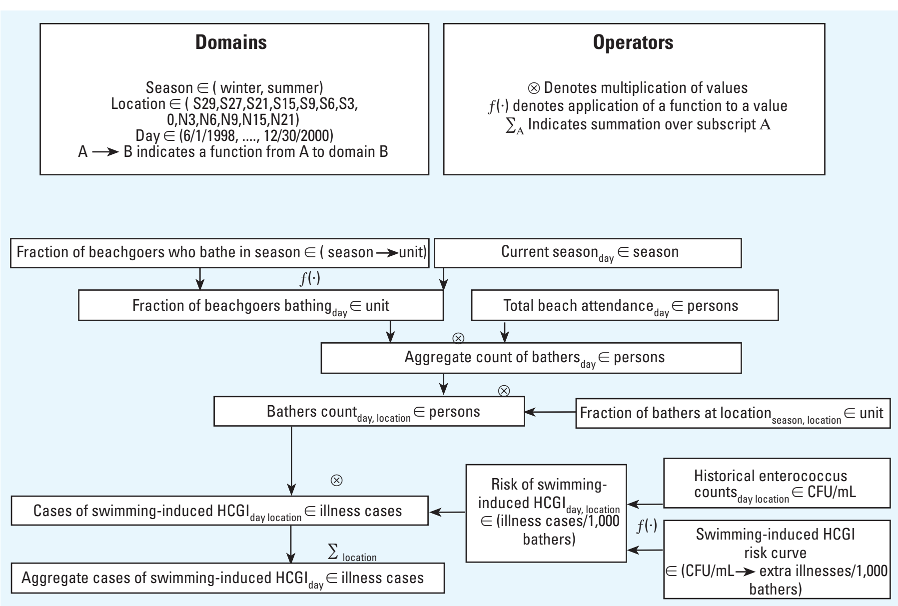


**Figure 2.** Flow of information within the health risk model.

Figure 5B compares the number of illness cases per day using two different relationships. Application of Cabelli's relationship resulted in peak attack rates of approximately 600 cases per day in summer months, with the maximum number of HCGI cases at 665. Roughly 75% of total days during the months of May through August have more than 100 individuals contracting HCGI. In contrast, < 0.3% of days in the months of November through February have 100 individuals contracting HCGI. Use of Haile's relationship led to an average of only two HCGI cases per day over the study period.

Figure 6 illustrates that HCGI attack rates are highly influenced by the enterococcus–HCGI risk relationships applied to the exposure data. The average risk for contracting HCGI over the study period was 0.89% when Cabelli's relationship was applied to enterococcus densities at each sampling location. Use of Cabelli's upper and lower 95% CIs yielded a 1.2 and 0.4% illness rate, respectively. The HCGI attack rate resulting from application of Haile's relationship was 0.2%.

***Effect of spatial distribution on illness estimates.*** Figure 7 shows a comparison of HCGI rates under the clustered and uniform bather distribution scenarios. Approximately 95,010 HCGI cases resulted under the clustered scenario, compared with 90,000 illness cases in the uniform distribution scenario. The two scenarios yielded broadly comparable results, suggesting that spatial location of bathers did not make a substantial difference in terms of the estimated aggregate illness rates. However, clustered patterns of bathing may heighten exposure to elevated enterococcus levels by up to 15% when particular beaches are examined in isolation (e.g., Stations 3S–29S in Newport Beach, data not shown).

***Bathing activity during beach closures.*** Adjustment of bathing activity during beach closures from 0 to 10% accounted for only a 0.1% increase in the total number of HCGI cases over the study period. Approximately

**Table 1.** Seasonal percentage of bathers distributed by sampling location under clustered scenario.

| Bacteria sampling location | Winter[a] (%) | Summer[b] (%) |
|---|---|---|
| N21 | 18 | 17 |
| N15 | 18 | 17 |
| N9 | 6 | 7 |
| N6 | 6 | 6 |
| N3 | 7 | 7 |
| Location 0 | 13 | 9 |
| S3 | 9 | 5 |
| S6 | 6 | 4 |
| S9 | 6 | 5 |
| S15 | 10 | 9 |
| S21 | 0.333 | 2 |
| S27 | 0.333 | 2 |
| S29 | 0.333 | 10 |

[a]October–March. [b]April–September.

95,010 HCGI cases resulted with no bathing activity assumed during beach closures, whereas 95,117 illness cases resulted when 10% of beachgoers bathed during beach closure days.

## Discussion

The results suggest that the majority of HCGI cases occur in the summer months and, to a lesser degree, in the late spring, regardless of bather distribution. This temporal illness pattern reflects a large number of exposed individuals in the water during summer months and holds despite the fact that late winter and early spring typically exhibit the poorest water quality.

Based on empirical analysis, aggregate beach usage patterns predispose individuals to only a 5.6% increase in risk over exposure levels had spatial considerations been ignored. Nonetheless, illness rates are substantially elevated at particular beaches when bathing activity is concentrated at contaminated locations.

The vast majority of illness cases (99%) occur when these beaches are open. A lack of sensitivity of model illness rate estimates to bathing activity during beach closures is attributable to the low number of beach closure days at most sampling stations. For example, there were no beach closures at 8 of 13 locations. Thus, reduced bathing activity during beach closure periods only minimally lessens the number of potential illness cases.

Although the computed HCGI attack rate is within the 1.9% level of acceptable risk under the U.S. Environmental Protection Agency's marine water contact guidelines (*13*) for the entire study period, illness rates exceed the threshold levels of acceptable risk for 2.9% of total days (Figure 8). The single sample beach closure standard is currently set at 104 CFU/100 mL, whereas the 1.9% acceptable risk threshold is reached at an enterococcus density of 35 CFU/100 mL.

The acceptable risk threshold can also be crossed when monthly standards are enforced, mandating no more than 20% of samples to exceed a 30-day log geometric mean enterococcus density of 35 CFU/100 mL. The average enterococcus density at all stations was 30 CFU for the year 2000. Application of Cabelli's relationship suggests 27 total days and periods of up to 6 consecutive days during which the tolerable risk threshold was crossed (Figure 8). Application of Cabelli's upper CI yielded periods of up to 20 consecutive days with risk levels considered unacceptable under federal guidelines (data not shown).

Relocation of amenities away from beaches with persistent water quality problems has been suggested as a means to dissuade potential bathers from swimming in contaminated waters (*16*). However, the lack of sensitivity of illness risk to bather distribution in this study indicated that bather relocation to less contaminated beaches may not substantially reduce public health risk in the long term. Addition of storm drain filters or implementation of other pollution abatement measures at contaminated beaches may reduce pathogen levels.

The implementation of more stringent marine water contact standards without water quality improvement would result in more frequent beach closures. Beach closures prevent illness, but also deprive public use and enjoyment of the beach, which is contradictory to the goals of the Clean Water Act (*18*).

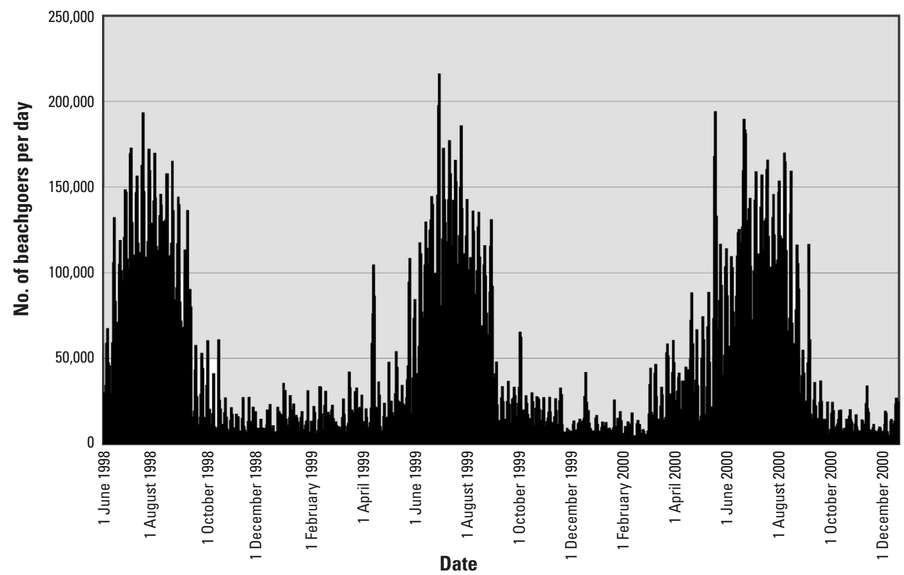


**Figure 3.** Total beach attendance for the study site. Pronounced seasonal variations, as well as quasi-periodic "impulses," correspond to weekend and holiday beach use.

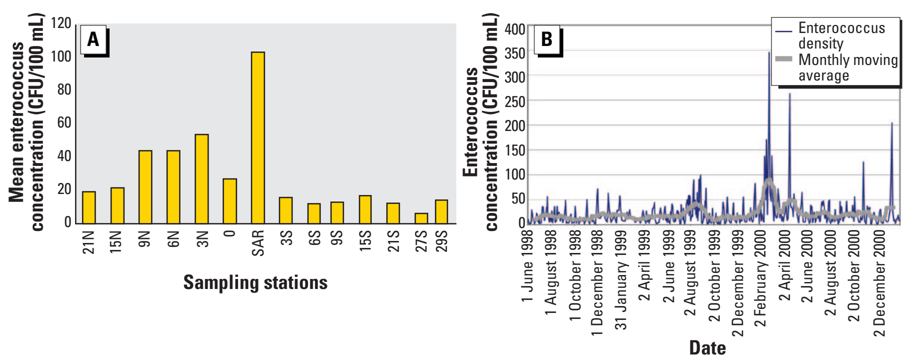


**Figure 4.** Spatial and temporal patterns of enterococcus density over the study period 1 June 1998–1 December 2000. (*A*) Mean value for each sampling station (CFU/100 mL). (*B*) Thirty-one-day moving average of time series.

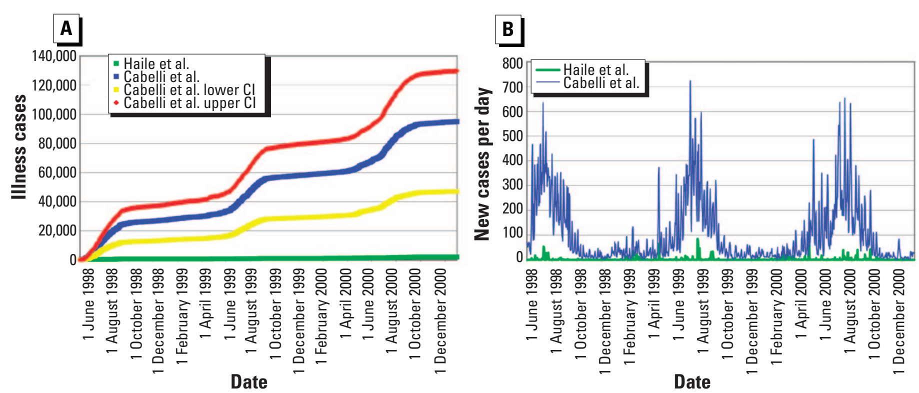


**Figure 5.** Comparison of HCGI cases using different enterococcus density–HCGI risk relationships. (*A*) Cumulative cases over the study period. (*B*) Cases per day. Data from Haile et al. (*7*) and Cabelli et al. (*5*).

An increase in the frequency of beach closures might also contribute to the fraction of bathers who enter the water despite beach closure warnings.

A number of caveats apply to the interpretation of our model results. First, the environmental conditions under which the original health risk studies were conducted may be of limited applicability. Cabelli et al. (*5*) measured illness rates in East Coast bathers exposed to sewage-based contamination in dry weather. Haile et al. (*7*) assessed exposure to storm drain runoff under exclusively dry weather conditions. Neither offers an exact match to the study period and region.

The defined susceptible population upon which illness rates were generated for this model might be more inclusive than the defined susceptible populations in the original health risk studies. Cabelli et al. (*5*) and Haile et al. (*7*) both excluded as potential subjects bathers who swam in the ocean in the weeks leading up to their trials in order to target single-exposure, water-related illness risk. This model drew bather numbers as a fraction of total beach attendance, including frequent beach users who would have been excluded as subjects from those studies. Consequently, the illness rate computations may overestimate or underestimate the true number of HCGI cases, depending upon the influence of repeat exposures and other susceptibility factors in frequent beachgoers.

Flat rates of water contact recreation for summer and winter months used in this model are based on limited published estimates of seasonal water use rather than upon objective measurements. The amount of marine contact recreation activity has first-order impacts on illness rate calculations. Further elucidation of the functional form and magnitude of the relationship between exposure to enterococcus and HCGI risk also has first-order impacts on illness rate estimates and the sensitivity of those estimates to other factors. A more detailed approximation of both point estimates and the functional form of the response relationship can be used to determine whether aggregate illness rates are likely to increase in punctuated or gradual manners. For example, the discontinuous functional form of Haile's relationship is represented as a threshold, making it highly sensitive to noise and changes in other parameter values. The assumption of a relative HCGI risk of 1 at enterococcus concentrations ≤ 104 CFU/100 mL is an issue raised in the original study (*7*). Non–water-related risk factors for HCGI, including food consumption, household illness, and medical history of stomach problems, may not have been adequately controlled for when the original concentration–response relationships were generated (*19*).

Conservative estimates of contamination are presented in this study (based on the use of lower limits of a range where enterococcus counts were provided as such) to reduce the probability of illness rate overestimation. Each enterococcus count is applied to a uniform risk level for an entire day in the model. Illness rate estimates may be affected by fluctuations of indicator level throughout the day (*20–22*). Furthermore, a reanalysis of the results of Cabelli et al. (*5*) by other researchers suggested the possibility of underestimating true HCGI risk by 14–57% (*21*). Despite asserted weaknesses in the methodology and data analysis of Cabelli et al. (*23*), federal marine water contact recreation guidelines remain based on the results of their studies because of the strength and power of statistical association found between indicator density and health outcome over many years at multiple sites.

The presumed etiologic agent of HCGI is frequently a suspected Norwalk-like virus or human rotavirus (*5,24,25*). A one-dimensional functional relationship between enterococcus density and HCGI risk only indirectly accounts for nonbacterial contributions to water-related illness. Indicator bacteria concentrations may exhibit low correlation to levels of viruses and protozoa in coastal waters (*7,26*). Using protozoa and viruses, dynamic population-level models of infectious disease transmission have been developed for drinking water as well as selected recreational waters (*27–32*). However, a lack of sufficient time-series data on specific pathogens in our study site precludes the use of these organisms for water-based risk assessment at present. Therefore, in the absence of adequate virus and protozoa data for coastal waters, enterococci are believed to be the best available predictors of adverse health outcomes with a viral-based etiology (*1,25*).

During model construction, immune response variability and secondary transmission of illness were ignored because of lack of information on infection status. Illness transmission was treated as a stationary process

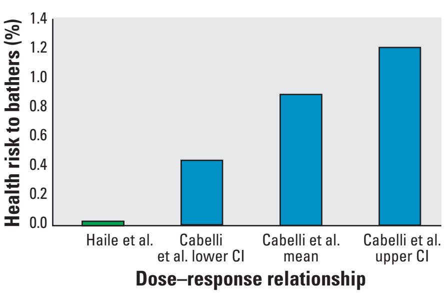


**Figure 6.** Comparison of average risk using different relationships between enterococcus density and HCGI risk over the study period.

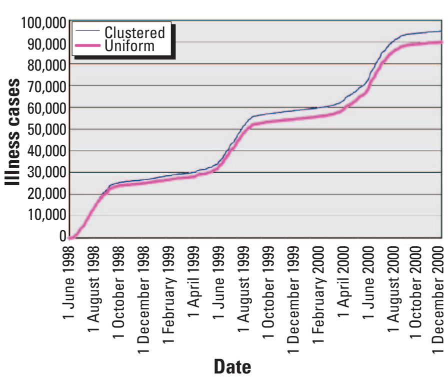


**Figure 7.** Aggregate illness cases for study period under clustered versus uniform bather distribution scenarios using the enterococcus density–HCGI risk relationship of Cabelli et al. (*5*).

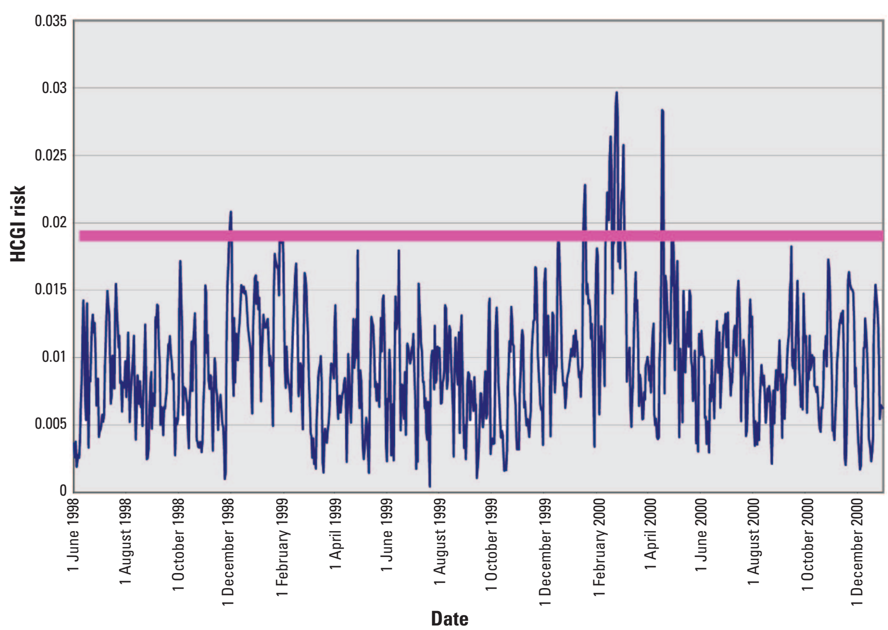


**Figure 8.** Average daily HCGI risk over the study period using Cabelli et al.'s relationship (*5*). The horizontal line corresponds to a 1.9% threshold of acceptable risk.

where the probability of individual infection was multiplied by the number of exposed individuals to predict disease incidence. The model does not take bather shedding of pathogens into account. The exposure of an individual to microbial hazards is assumed to be independent of the infection status of other individuals in the population, and the overall magnitude of exposure is assumed to be independent of the total number of infected individuals. Therefore, the results of this study present the most conservative estimates of recreational illness at the study site.

## Conclusion

This study combined spatial and temporal patterns of marine recreational water usage with historical microbial indicator levels to illustrate the public health implications of recreational exposure to contaminated waters. Results indicated that illness rates were highest during the summer months, despite peak concentrations of fecal enterococcus frequently detected during late winter and early spring. Spatial distribution of bathers along the beach had minimal effect on aggregate illness rates, but may account for up to a 15% increase at selected beaches. Illness rates were highly sensitive to the relationship between enterococcus density and HCGI risk. The daily risk level fluctuated throughout the study period, with 2.9% of total days in excess of federal recreational risk guidelines. Further characterization of the enterococcus density–HCGI risk relationship will provide a better understanding of these recreational health risks.

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