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Health Risk of Bathing in Southern California Coastal Waters

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ABSTRACT. Urbanized areas often discharge large volumes of contaminated waste into coastal waters, which may pose a health risk to bathers at nearby beach areas. In this investigation the authors estimated the number of gastrointestinal and respiratory illness episodes associated with the microbial contamination of coastal waters among bathers at Southern California beaches from 2000 through 2004. Bathers at the 67 beaches along the 350-km coastline of Southern California were the study population in this investigation. The authors' estimates were derived from a simulation model, which utilized water quality, beach attendance, and bathing-rate data, along with the three concentration-response relationships that underlie US Environmental Protection Agency, World Health Organization, and European Union marine water-quality guidelines. Given the absence of a general surveillance program to monitor these illnesses in Southern California, simulation modeling provides an established method to derive health risk estimates, despite additional analytic uncertainty that may accompany modeling-based analyses. An estimated 689,000 to 4,003,000 gastrointestinal illness episodes and 693,000 respiratory illness episodes occurred each year. The majority of illnesses (57% to 80%) occurred during the summer season as a result of large seasonal increases in beach attendance and bathing rates. As 71% of gastroenteritis episodes were estimated to occur when the water quality was considered safe for bathing, California's marine water-contact standards may be inadequate to protect the health of bathers.

KEYWORDS: enterococcus, gastroenteritis, health risk, recreational water quality criteria

Coastal water contamination in Southern California may be responsible for a considerable disease burden. The 350-km coastline from Los Angeles to San Diego is a popular recreational destination for the region's 16 million residents as well as national and international tourists. Each year, over 100 million visitors arrive at these beaches and participate in recreational activities such as swimming, surfing, and diving.[1,2] Contamination in Southern California coastal waters may threaten the health of these bathers. Fecal contamination levels at these beaches frequently exceed regulatory standards and force public health officials to issue hundreds of advisories against bathing every year.[3] Even when regulatory standards are not exceeded, chronic low-level water contamination is common throughout the region. The significant health risk that may result from these coastal water-contamination problems deserves further investigation, especially in light of the large populations at risk in Southern California.

The two primary sources of coastal water contamination in Southern California are urban runoff and treated domestic sewage. The dense pattern of roadways, parking lots, and buildings associated with Southern California's heavy urbanization accelerates the transit of large volumes of surface runoff to coastal discharge sites.[4-6] This urban runoff can

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carry a wide variety of microbial contaminants, and bathers near runoff-discharge sites experience increased rates of gastrointestinal, respiratory, eye, ear, and skin illnesses.[7–9] The large populations in these urbanized areas also generate an enormous volume of domestic sewage (over 1 billion gallons/day), which is discharged along this coastline. Although sanitation agencies treat much of this waste to remove pathogens, significant levels of pathogenic bacteria, viruses, and protozoa survive treatment and are released into the coastal environment.[10,11]

To protect bathers from the health risk posed by water contamination, California adopted new water-quality standards in 1998 based on guidelines provided by the US Environmental Protection Agency (EPA).[12,13] The EPA guidelines were derived from prospective cohort studies conducted in the United States from 1973 to 1977 by Cabelli et al in which bathers and nonbathers at beaches with varying water quality were monitored for illness following their beach visit.[14] Cabelli et al reported a significant relationship between enterococcus levels in coastal waters and the risk of gastroenteritis for bathers, which estimates that California's maximum acceptable risk of gastroenteritis (1.9%) will be reached at an enterococcus level of 35 colony-forming units (cfu)/100 ml.[13]

Another landmark study on the health risk of bathing was conducted in the United Kingdom from 1989 to 1992 by Kay et al.[15] The Kay et al investigators reported significant relationships between fecal streptococcus levels and the risk of both gastroenteritis and acute febrile respiratory illness (AFRI).[16] These relationships now provide the foundation for water-quality guidelines from the World Health Organization (WHO) and the European Union.[17,18]

The findings of Cabelli et al, Kay et al, and many other epidemiological investigators[19–22] demonstrate that coastal water contamination can result in a significant health risk to bathers. The magnitude of this health risk in Southern California is suggested by investigations conducted by Turbow et al, who estimated that over 37,000 annual episodes of gastroenteritis occurred at two of the region's beaches, and by Given et al, who estimated that 630,000 to 1.48 million annual episodes of gastroenteritis occurred at 29 of the region's beaches in 2000.[23,24] In the current study we expand beyond previous investigations to estimate the disease burden for the entire Southern California region over 5 years of varying weather and water-quality conditions. We also include estimates for one of the nongastrointestinal illnesses associated with water contamination and utilize direct observations of bathing populations to estimate exposure rates.

METHODS

In this study we examined the health risk of bathing at the 67 beaches along the 350-km coastline of Southern California from January 2000 through December 2004. More than 16 million people live within the 9,082 square miles of the three counties (Los Angeles, Orange, and San Diego) that form the study region.

Study Population

We collected beach attendance data from January 2000 through December 2004 from records at lifeguard agencies (76%), parks departments (16%), and environmental health departments (8%). We utilized 122,409 daily beach attendance values in the analysis. We excluded attendance at coastal piers, parks, and boardwalks from this analysis because visitors to these areas may be unlikely to enter the water. The use of daily observations to determine beach attendance captures the effects of rainfall, temperature, and other important influences on this model input.

We derived monthly average bathing rates from long-term data sets recorded independently at Del Mar and Oceanside beaches in San Diego County (lifeguards at these beaches estimated beach attendance and the number of people entering the water, ie, bathers, daily). We utilized these bathing rates when we estimated the number of bathing events at all of the study beaches. The application of these bathing rates at the other beaches in the study is supported by the many shared characteristics of the beaches, including their similar seasonal patterns of attendance, their open sandy geography, their close proximity to vehicular and pedestrian access sites, and the similar climatic patterns and coastal water temperatures across these 3 contiguous coastal counties.

We estimated the number of daily bathing events at each beach by multiplying each daily beach attendance value by the corresponding monthly bathing rate. The number of bathing events does not necessarily represent the total number of individuals who bathe, as visitors may make multiple trips to the beach (and bathe) each year. Therefore, in this analysis we assumed that the probability of illness associated with any single bathing event was independent of other bathing events. Detailed descriptions of the methods used to determine beach attendance, bathing rate, and bathing event data are available elsewhere.[25]

Water Quality

Water-quality data (enterococcus levels) were compiled by the various monitoring agencies in the region. In this study we made use of 56,215 reported enterococcus level measurements from 185 monitoring stations. Enterococcus monitoring was conducted weekly for 70% of the monitoring values used in the analysis and more frequently (variably from 3 to 7 times per week) for the remainder of monitoring values. When water-quality data were reported as being above or below a detection limit, we used the detection limit value for analysis. When water-quality data were unavailable, we estimated values for missing data of less than 7 sequential days by using cubic spline interpolation (77% of values). Cubic spline interpolation tends to be unbiased and the curvilinear changes in enterococcus concentrations observed in our data were better represented with this form of imputation.[26,27] We estimated the values for missing data of 7 or more sequential days by means of regression using data from the nearest monitoring station, where the data available at the station with known data and the station with missing data had a coefficient of determination (R^2) greater than 0.6 (7% of values).

We assumed that the enterococcus value measured at each monitoring site represented the mean enterococcus exposure level for bathers at the beach area adjacent to that site. When multiple monitoring sites were located at a beach, we assumed that the bathers at that beach were evenly distributed among the monitoring sites. This per-monitoring-station unit of analysis permits a high-resolution analysis of exposure.

Health Risk

We integrated multiyear data sets of water quality, beach attendance, and bathing rates into a simulation model along with published concentration-response relationships between enterococcus levels and gastroenteritis and AFRI rates. For each day of the study, we applied each concentration-response relationship to the enterococcus level at each of the 185 water-quality monitoring stations to estimate the risk of illness at the beach area adjacent to that station. We then multiplied the number of bathers at each beach area by the risk of illness to yield the estimated number of illnesses at each beach area for each day of the study.

We evaluated the seasonal distribution of illnesses by using summer (May through October) and winter (November through April) seasonal divisions, which were based on historical precipitation patterns. We evaluated the geographic distribution of illnesses using beach areas designated by current jurisdictional boundaries. In accordance with WHO practices, we substituted the term *enterococcus* for the term *fecal streptococcus* for the purposes of this study.[17] The terms *enterococcus* and *fecal streptococcus* have often been used interchangeably in the past, partially as a result of the limited ability of water-quality monitoring programs to distinguish between them. The substitution just described may result in an underestimation of the health risk found by using the Kay et al relationship, because there may be an underestimation of fecal streptococcus levels when reported levels of the enterococcus subgroup are used.

The use of the general term *gastroenteritis* is supported by the similar definitions for this term used in the Cabelli et al relationship (defined as any episode of vomiting, any episode of diarrhea that was either disabling or accompanied by a fever, or any episode of either a stomachache or nausea accompanied by fever) and in the Kay et al relationship (defined as any episode of vomiting or diarrhea, defined as three or more bowel movements per day, or any episode of either indigestion or nausea accompanied by a fever).[14,15] Fleisher et al defined AFRI as a febrile illness accompanied by a headache, body aches, unusual fatigue, or anorexia and either a sore throat, runny nose, or cough.[16]

We based the estimates of excess gastroenteritis risk on the epidemiologic relationships from Cabelli et al and Kay et al.[14,15] Fleisher et al estimated the excess risk of gastroenteritis by using the formula from Cabelli et al: episodes of gastroenteritis per 1000 bathers = 12.2 log (m) + 0.2, where m is the mean enterococcus density/100 ml of seawater (Figure 1).[14] The Kay et al relationship describes the long odds of acquiring gastroenteritis (b) as $b = 0.20102\,(c - 32)^{1/2} - 2.3561$, where c is the fecal streptococcus density/100 ml of seawater to which an individual is exposed.[15,27] We then calculate the excess probability of gastroenteritis (p) for that individual by means of the formula $p = \{1/[1 + \exp(-b)]\} - 0.0866$ (Figure 1). Following Kay et al, we capped the relationship between risk of gastroenteritis and the individual level of exposure at the risk level that was obtained at the highest level of exposure observed in the original investigation (158 cfu/100 ml).[15] In accordance with WHO guidelines and Kay et al, the corresponding relationship specified risk of gastroenteritis, taking into account a log normal probability density function for (highly variable) levels of individual bather exposure around a given measured enterococcus value.[17,28] This risk adjustment yields nonzero risks of gastroenteritis given a fecal streptococcus level below the 32 cfu/100ml (the lowest level at which the original Kay et al study reported an increased risk of gastroenteritis). For the standard deviations of the log (base 10) of enterococcus level, we adopted the value (0.813) used in WHO water-quality guidelines. We estimated the AFRI relationship, which describes the risk of AFRI based on enterococcus levels, on the basis of 97 concentration-response pairs from Figure 1 in Fleisher et al (Figure 1).[16] The use of single daily monitoring values to estimate risk is a limitation imposed by the available data and introduces a sampling error that may add uncertainty to these health risk estimates. This data limitation is shared by many other published studies investigating

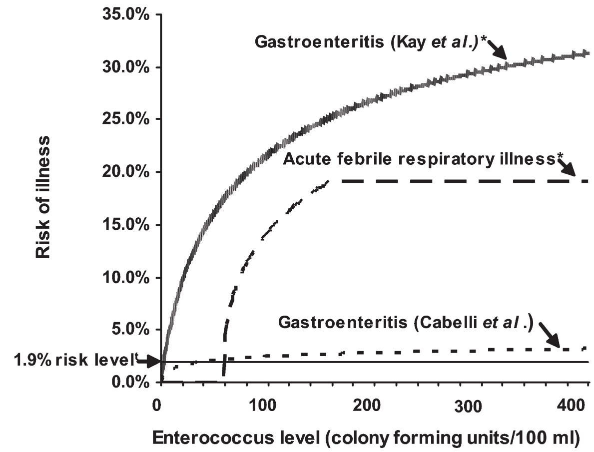


Fig. 1. Risk of illness among bathers as a function of coastal water enterococcus levels, from three concentration-response relationships. Exposure levels for the Kay et al[15] gastroenteritis risk curve and the acute febrile respiratory illness risk curve were capped at 158 enterococcus colony-forming units/100 ml. Also, California's marine water-contact standards designate 1.9%, shown by the solid line, as the maximum acceptable risk of gastroenteritis among bathers.

the health risk of bathing in recreational waters. Uncertainty bounds on these health risk estimates are not estimated, as the Kay et al and AFRI relationships, as well as model inputs, are not accompanied by defined uncertainty levels.

We considered beach closure and advisory data when estimating the number of exposures at each beach and for each day. To capture the expected reduction in bathing events in response to these measures, we assumed that no bathers entered the water during beach closures and water-contamination advisories. When only a section of a beach was affected by a closure or advisory, we reduced the bathing populations in a manner proportionate to the length of beach affected. Beach closure and advisory data were compiled by health agencies in each county.

RESULTS

Study Population

Southern California beaches attracted an average of 129 million visits during each year of the study. Most of these visits (76%) occurred during the summer. Nearly half of all visits (48%) occurred on weekends, and large peaks in attendance were frequently observed during holidays. More than half (51%) of the total beach attendance occurred at just 15 of the 67 study beaches. The mean percentage of beach visitors who entered the water ranged from a low of 26% in January to a high of 54% in August, with gradual transitional periods in the spring and fall.

An average of 56 million annual bathing events (when beach visitors were exposed to coastal water) occurred during each year of the study. Approximately 84% of all bathing events occurred during the summer, and 45% of all bathing events occurred at 15 highly attended beaches.

Water Quality

Enterococcus levels often peaked across large groups of beaches after rainfall events. During the study, 21% of coastal water enterococcus monitoring levels exceeded California's 35 cfu/100 ml marine water-contact standard (Table 1), and 11% of monitoring values exceeded the 104 cfu/100 ml single sample standard (which is a 75% confidence interval around the 35 cfu/100 ml standard). The California water-quality standard (35 cfu/100 ml) was exceeded during an average of 30% of monitoring values on winter days and 12% of monitoring values on summer days. On average, enterococcus levels during the winter (M = 170 cfu/100 ml) were more than threefold higher than they were during the summer (M = 47 cfu/100 ml).

Health Risk

Application of the Cabelli et al relationship (C relation) and Kay et al relationship (K relation) yielded estimates of 689,000 (C relation) and 4,003,000 (K relation) mean annual episodes of gastroenteritis (Table 2). Figure 2 graphically depicts how the seasonal variation in contamination levels and daily illness counts demonstrated opposing cyclical patterns, with contamination levels peaking during the winter and daily illness rates peaking during the summer. Summer accounted for over three fourths (80% of the C relation and 76% of the K relation) of the gastroenteritis episodes; this occurred as a result of the large seasonal increases in bathing populations. The summer season's dominant contribution to disease burden totals was evident through all the years of the study and at all of the study beaches. The (untransformed Pearson) correlation coefficient between the daily regional attendance total and the daily regional number of gastroenteritis episodes was r = .97 for the C relation and r = .94 for the K relation, respectively.

In spite of fluctuations in mean annual contamination levels, the annual number of gastroenteritis episodes varied little from year to year (C relation, M = 689,000, range = 652,000–719,000, SD = 26,000; K relation, M = 4,003,000, range = 3,736,000–4,274,000, SD = 232,000). The stability in the total annual number of illnesses was due to the large proportion of illnesses that occur in the summer, when consistently dry weather and low levels of coastal water contamination are found in the region. Most of the estimated number of gastroenteritis episodes (71% for the C relation and 61% for the K relation) occurred when the water quality met California's enterococcus standard of 35 cfu/100 ml (Table 2).

The estimated mean annual risk of gastroenteritis was 1.26% (C relation) and 7.30% (K relation; see Table 2). The

Table 1.—Number and Percentage of Coastal Water-Quality Monitoring Values in Southern California, 2000–2004, Associated with a Risk of Illness Greater Than 1.9%

	Concentration-response relationships					
	C relation[14]		K relation[15]		AFRI[16]	
Period	*n*	%	*n*	%	*n*	%
Annual	14,204	21	51,912	76	10,003	15
Summer	4,047	12	25,273	74	2,430	7
Winter	10,157	30	26,638	78	7,573	22

Note. AFRI = acute febrile respiratory illness. California water quality standards define 1.9% as the maximum acceptable risk of gastroenteritis for bathers.

Table 2.—Number of Illness Episodes and Disease Incidence Among Bathers Exposed to Coastal Water Contamination in Southern California, 2000–2004

	Concentration-response relationships					
	C relation[14]		K relation[15]		AFRI[16]	
Period	*n*	%	*n*	%	*n*	%
Illness						
Annual	689,000	—	4,003,000	—	693,000	—
Summer	551,000	80	3,060,000	76	398,000	57
Winter	138,000	20	943,000	24	295,000	43
Annual total*	491,000	71	2,434,000	61	—	—
Disease incidence						
Annual	1.26		7.30		1.26	
Summer	1.19		6.65		0.86	
Winter	1.55		10.62		3.32	

Note. AFRI = acute febrile respiratory illness. California marine water-contact standards define a coastal water enterococcus level < 35 colony forming units (cfu)/100 ml as associated with an acceptable risk of gastroenteritis for bathers. Annual disease incidence refers to this value. Disease incidence is expressed as the estimated percentage of bathers who become ill.
*When water quality met California standards.

risk of gastroenteritis was higher during the winter (1.55% for the C relation and 10.62% for the K relation) than it was during the summer (1.19% for the C relation and 6.65% for the K relation). Gastroenteritis risk levels at individual beaches ranged from 0.53% to 2.34% for the C relation (Figure 3) and from 2.32% to 19.39% for the K relation. The 1.9% maximum acceptable risk guideline for gastroenteritis in California was exceeded by 21% (C relation) and 76% (K relation) of water-quality values.

Approximately one half of the estimated gastroenteritis disease burden (52% of the C relation and 50% of the K relation) occurred at the 12 most highly attended beaches. Many highly attended beaches are located in heavily populated Los Angeles County, and this county and 3 neighboring beaches in northern Orange County (Huntington city and state beaches and Newport city beach) contributed approximately 60% of all gastroenteritis episodes (61% of the C relation and 60% of the K relation, respectively; see Figure 3). The estimated annual number of gastroenteritis episodes at individual beaches ranged from 140 episodes to 46,200 episodes for the C relation and from 634 episodes to 265,800 episodes for the K relation. The geographic distribution of health risk among beaches is detailed in Tables 3, 4, and 5, which uniquely enumerate the disease burden and disease incidence estimates of each study beach. The large number of scientists and health officials engaged in the study and management of this important coastal region are familiar with specific study beaches. The detailed data in Tables 3–5 may provide valuable information for decision makers who must prioritize research and management projects at these beaches. The (untransformed Pearson) correlation coefficient between the mean annual attendance and the mean annual number of gastroenteritis episodes among individual beaches was $r = .95$ and $r = .90$ for the C relation and K relation, respectively.

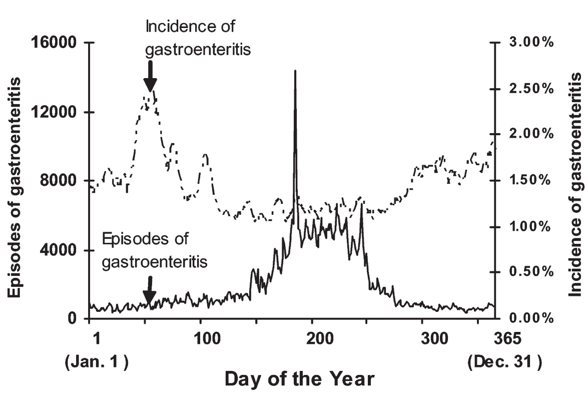
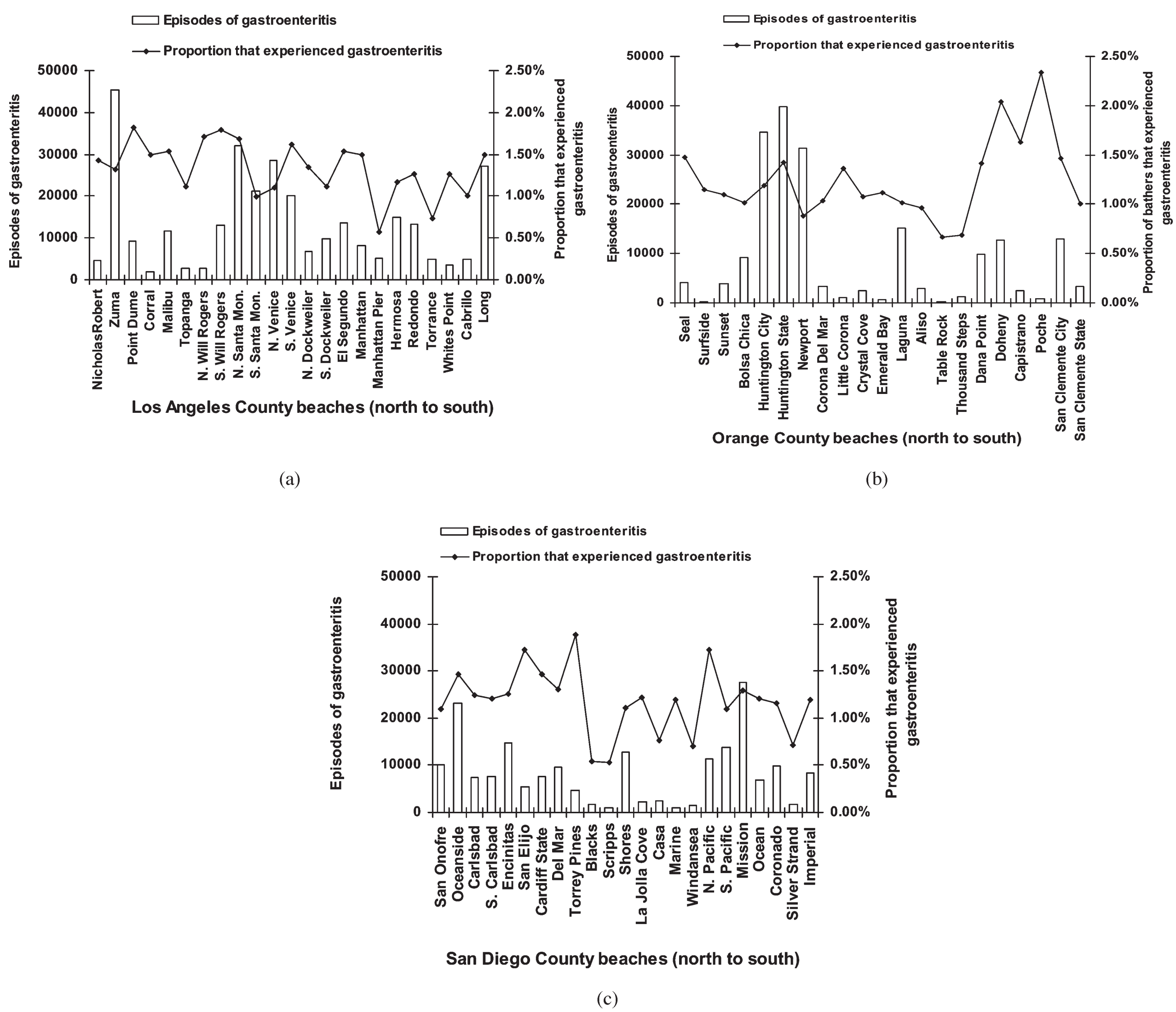


Fig. 2. Estimated mean daily number of episodes (solid curve) and mean daily incidence (dotted curve) of gastroenteritis among bathers exposed to coastal water contamination in southern California, 2000–2004. Disease incidence is expressed as the estimated percentage of bathers who become ill. The values in this figure were determined by using the relationship between enterococcus levels and the risk of gastroenteritis from the 1982 Cabelli et al study.[14] The peak in incidence of gastroenteritis around day number 180 was due to high beach attendance and bathing rates during the Fourth of July weekend.

Application of the AFRI relationship yielded an estimate of 693,000 mean annual episodes of AFRI (range = 631,000–776,000; *SD* = 55,000; see Table 2). The summer peaks in the number of AFRI episodes (57% of AFRI episodes) were attenuated relative to the summer peaks in the number of gastroenteritis episodes. The attenuation of AFRI peaks was due to the higher minimum threshold for increased risk in the AFRI relationship (60 cfu/100 ml), which was exceeded less frequently by lower summer contamination levels. The estimated mean annual AFRI risk level was 1.26% (0.86% in the summer and 3.32% in the winter). Twelve highly attended beaches, again predominantly in Los Angeles County, accounted for 50% of AFRI episodes. The estimated



Figs. 3a–3c. Estimated mean annual number of episodes of gastroenteritis and mean annual incidence of gastroenteritis at (Figure 3a) Los Angeles County beaches, (Figure 3b) Orange County beaches, and (Figure 3c) San Diego County beaches, 2000–2004. The expression of disease incidence and the determination of values procedure are the same as in Figure 2.

annual number of AFRI episodes at individual beaches ranged from 34 to 82,200 episodes. The (untransformed Pearson) correlation coefficient between the daily regional attendance total and the daily regional number of AFRI episodes was $r = .50$. The (untransformed Pearson) correlation coefficient between the mean annual attendance and the mean annual number of AFRI episodes among the individual beaches was $r = .61$.

Discussion

Coastal water contamination in Southern California represents a considerable public health risk. The 5 years of water-quality data that we analyzed demonstrate both persistent low-level contamination and recurring peaks in contamination levels, each of which pose a significant health risk to bathers. The magnitude and distribution of these health risks are driven primarily by the size of the bathing populations at these beaches, where 56 million visitors recreate in coastal waters every year. The predominant influence of the size of bathing populations on the seasonal distribution of these health risks is demonstrated by the large peaks in daily illness rates during the summer, when large numbers of visitors arrive at these beaches to swim, dive, and surf in coastal waters. The summer peaks in daily illness rates occur in spite of the much higher contamination levels (and associated risk) that occur during the winter, when increased rainfall flushes contaminated urban runoff into these coastal waters.[5,6] The strong influence of beach attendance on illness rates is also evident from the strong correlation between these two variables when they are analyzed both over the study period and among the study beaches. Furthermore, the disease burden

Table 3.—Estimated Annual Number of Illness Episodes and Disease Incidence Using 3 Concentration-Response Relationships, For Bathers Exposed to Coastal Water Contamination at Los Angeles County Beaches, 2000–2004

	Mean annual number of illness episodes			Mean annual disease incidence (%)		
Los Angeles County beaches	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]
Nicholas/Robert Meyer	4,627	25,532	2,971	1.42	7.84	0.91
Zuma	45,336	229,400	7,486	1.32	6.72	0.21
Point Dume	9,193	64,745	17,826	1.82	12.88	3.54
Corral	1,963	11,400	1,345	1.49	8.65	1.02
Malibu	11,648	77,766	20,139	1.54	10.31	2.67
Topanga	2,742	16,872	3,648	1.11	6.87	1.48
North Will Rogers	2,677	17,734	3,489	1.71	11.38	2.24
South Will Rogers	13,154	96,746	30,761	1.79	13.21	4.20
North Santa Monica	32,138	210,800	41,188	1.69	11.15	2.17
South Santa Monica	21,128	117,121	15,369	0.99	5.52	0.72
North Venice	28,584	151,067	13,667	1.10	5.86	0.53
South Venice	20,235	127,936	24,240	1.62	10.27	1.94
North Dockweiler	6,788	39,870	6,369	1.35	7.96	1.27
South Dockweiler	9,874	54,930	7,905	1.12	6.24	0.89
El Segundo	13,516	79,591	13,499	1.53	9.02	1.53
Manhattan County	8,025	48,234	10,966	1.50	9.07	2.06
Manhattan Pier	5,119	28,049	4,535	0.57	3.13	0.50
Hermosa	14,816	80,875	8,958	1.17	6.42	0.71
Redondo	13,369	79,989	11,081	1.27	7.64	1.05
Torrance	4,826	22,623	947	0.74	3.49	0.14
Whites Point	3,437	21,494	4,279	1.27	7.98	1.58
Cabrillo	4,825	25,768	2,492	1.00	5.34	0.51
Long	27,293	159,065	18,457	1.50	8.77	1.01
Los Angeles County total	305,314	1,787,606	271,618	1.31	7.67	1.16
Southern California total	688,980	4,002,765	692,622	1.26	7.30	1.26

Note. Disease incidence is expressed as the estimated percentage of bathers who become ill.

Table 4.—Estimated Annual Number of Illness Episodes and Disease Incidence Using 3 Concentration-Response Relationships, For Bathers Exposed to Coastal Water Contamination at Orange County Beaches, 2000–2004

	Mean annual number of illness episodes			Mean annual disease incidence (%)		
Orange County beaches	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]
Seal	4,064	24,830	4,523	1.48	9.09	1.65
Surfside	131	634	34	1.15	5.55	0.30
Sunset	3,905	18,022	177	1.10	5.07	0.05
Bolsa Chica	9,254	49,023	6,658	1.01	5.36	0.72
Huntington City	34,537	201,200	30,467	1.19	6.98	1.05
Huntington State	39,693	265,800	82,209	1.42	9.54	2.95
Newport	31,306	150,740	15,953	0.88	4.25	0.45
Corona Del Mar	3,264	17,112	2,098	1.03	5.43	0.66
Little Corona	1,074	6,063	760	1.36	7.69	0.96
Crystal Cove	2,497	12,330	1,012	1.08	5.36	0.44
Emerald Bay	613	2,965	137	1.12	5.44	0.25
Laguna	15,159	80,813	13,758	1.01	5.39	0.91
Aliso	2,877	14,637	1,943	0.96	4.89	0.65
Table Rock	186	775	70	0.67	2.82	0.25
Thousand Steps	1,153	5,076	515	0.69	3.08	0.31
Dana Point	9,904	63,581	15,793	1.41	9.05	2.25
Doheny	12,680	95,189	33,666	2.04	15.37	5.43
Capistrano	2,432	15,613	3,158	1.63	10.49	2.12
Poche	796	6,613	3,113	2.34	19.49	9.17
San Clemente City	12,930	77,984	14,988	1.47	8.91	1.71
San Clemente State	3,193	15,102	1,337	1.00	4.77	0.42
Orange County total	191,649	1,124,102	232,371	1.18	6.97	1.44
Southern California total	688,980	4,002,765	692,622	1.26	7.30	1.26

Note. Disease incidence is expressed as the estimated percentage of bathers who become ill.

Table 5.—Estimated Annual Number of Illness Episodes and Disease Incidence Using 3 Concentration-Response Relationships, For Bathers Exposed to Coastal Water Contamination at San Diego County Beaches, 2000–2004

	Mean annual number of illness episodes			Mean annual disease incidence (%)		
San Diego County beaches	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]	C relation[14]	K relation[15]	Acute febrile respiratory illness[16]
San Onofre	10,047	57,211	9,501	1.10	6.31	1.04
Oceanside	23,030	135,406	19,857	1.46	8.58	1.25
Carlsbad	7,421	46,312	11,763	1.25	7.84	1.99
South Carlsbad	7,676	42,037	6,710	1.21	6.67	1.06
Encinitas	14,674	88,189	23,339	1.26	7.61	2.01
San Elijo	5,411	36,807	7,689	1.72	11.71	2.44
Cardiff State	7,650	47,679	10,511	1.46	9.12	2.01
Del Mar	9,718	55,838	8,734	1.31	7.57	1.18
Torrey Pines	4,675	32,696	7,711	1.89	13.22	3.11
Blacks	1,840	9,846	1,869	0.54	2.91	0.55
Scripps	892	3,882	194	0.53	2.32	0.11
La Jolla Shores	12,875	61,983	7,595	1.11	5.35	0.65
La Jolla Cove	2,283	12,040	2,202	1.22	6.45	1.18
Casa/Children's	2,379	13,404	3,399	0.76	4.33	1.09
Marine	916	4,882	245	1.19	6.36	0.31
Windansea	1,380	6,299	361	0.70	3.23	0.18
North Pacific	11,254	73,483	12,808	1.72	11.26	1.96
South Pacific	13,694	76,592	14,278	1.09	6.14	1.14
Mission	27,559	147,643	22,593	1.29	6.92	1.05
Ocean	6,774	35,988	5,884	1.21	6.44	1.05
Coronado	9,739	50,136	5,074	1.16	5.98	0.60
Silver Strand	1,722	7,406	761	0.71	3.08	0.31
Imperial	8,408	45,297	5,554	1.20	6.47	0.79
San Diego County total	192,017	1,091,057	188,633	1.24	7.04	1.21
Southern California total	688,980	4,002,765	692,622	1.26	7.30	1.26

Note. Disease incidence is expressed as the estimated percentage of bathers who become ill.

associated with water contamination accumulates rapidly at beaches with large bathing populations, even when these beaches are characterized by relatively low levels of contamination. This effect is further illustrated by the observation that just 12 beaches account for half of the total region disease burden from coastal water contamination.

The large gastroenteritis and AFRI disease burdens estimated in this analysis raise questions about the effectiveness of California public health policy regarding recreational coastal waters. Of concern is the high acceptable risk level for gastroenteritis (1.9%, or 35 cfu/100ml enterococcus) in current guidelines. A meta-analysis by Wade et al concluded that support for the current guideline could be derived from their finding that health risk studies with indicator densities below the current guideline were associated with a lower risk of gastrointestinal illness than were studies with indicator densities above this guideline.[22] However, the meta-analysis by Wade et al also reported an elevated risk of gastrointestinal illness in the studies with indicator densities below the current guideline (mean relative risk = 1.36). This is consistent with the conclusion of this analysis, which is that in settings of very high numbers of exposed bathers, even low levels of risk accumulate into a large disease burden.

The 1.9% gastroenteritis risk level was provided by the EPA with the expectation that local health officials would lower this level to further reduce the health risk at their beaches.[13,29] This risk level has been reduced elsewhere (eg, in the state of Hawaii, where the maximum acceptable risk level is 1.05%, or 7 cfu/100 ml enterococcus). California has not enacted policies to lower this risk level. From our analysis we estimate that, as a result of this inaction, between 500,000 and 2.4 million bathers (C and K relations, respectively) experience gastroenteritis each year from exposure to coastal waters that are defined as safe by current standards (Table 2).

More stringent acceptable risk guidelines would have little impact on health risk without an accompanying reduction in coastal water-contamination levels. The high rate of water-quality violations in Southern California (14,200/year) did not decrease during the 5 years of the study, which suggests that current efforts to reduce these contamination levels have not been successful. California's efforts to mitigate water pollution have often been focused on chronically contaminated beaches that pose the highest risk to individual bathers (eg, Doheny: mean annual risk = 3%, C relation; gastroenteritis episodes = 13,000 annually, C relation). However, it is important to recognize that the majority of this region's water-contamination-related illnesses originate from highly attended beaches that generally have low levels of contamination (eg, Zuma: risk = 1.3%, gastroenteritis episodes = 45,000 annually, C relation). Thus, reducing contamination to very low levels at highly attended beaches will have the greatest impact on the regional disease burden.

The accuracy and validity of the data for beach attendance, bathing rate, and water quality are critical to the reliability of these health risk estimates. In this analysis we utilized the most comprehensive compilation of beach-attendance data for this region to date. The methods used to determine beach attendance in this region yield estimates that have been found to be within 10% of true attendance values.[30] To our knowledge, the bathing-rate data that we used in this analysis were the first to be derived from direct observation of the bathing activity of beach visitors in this region. The validity of these bathing rates is supported by the strong correlation ($p < .01$) between the two sources for these data as well as their agreement with the bathing rate in California that was determined by the National Oceanic and Atmospheric Administration (annual mean of the current study = 43%; the administration's annual mean = 47%).[2] Water-quality data were based on standardized techniques and were analyzed over an unprecedented 5 years of data. However, water-quality monitoring at the beaches in this region is frequently conducted at less than daily intervals. This limited schedule of water-quality monitoring may mask significant health risks, given the large bathing populations at risk and the demonstrated inability of low-frequency monitoring to identify hazardous peaks of water-contamination levels.[31] In spite of these limitations, the conclusions we reach from our analysis are similar to the conclusions of other investigations into the health risk of bathing in Southern California.[23,24]

A direct corroboration of this study's health risk estimates is limited because of the lack of formalized surveillance programs for these illnesses. However, the conclusions of our analysis are supported by the significant risks of gastroenteritis associated with bathing that were reported in three major epidemiologic investigations conducted on California coastal waters (and respiratory illness in two of these three studies).[8,9,32] In an analysis of data from an internet-based self-reporting program in California, researchers also found seasonal distribution patterns of illnesses that were very similar to those found in this analysis, with peaks in illness counts occurring during the summer months, especially at high-attendance beach areas.[33]

The differing relationships reported by Cabelli et al and by Kay et al (and consequently the differing estimates for health risk in this analysis) are generally attributed to differences in their study design. The randomization of the Kay et al study and this study's precise monitoring of exposure levels for individual bathers have been described in scientific reviews of these investigations as key influences leading to these differences.[20,34,35] The established epidemiologic strengths of randomized study design lend support to the relationship reported from the Kay et al investigation. Many scientists and regulatory bodies (including the WHO, the European Union, and many other national health agencies) have noted these strengths and have concluded that the Kay et al relationship represents the strongest foundation upon which to base water-quality guidelines.[17,18,36,37] However, the Cabelli et al study underlies current water-quality guidelines in California and throughout much of the United States, and thus it remains an important measure of health risk in this setting.

Several conservative aspects of the model used for this analysis may have led to an underestimation of the true disease burden. For example, in this study's application of the Kay et al relationship, the enterococcus exposure level was "capped" at 158 cfu/100 ml (the highest enterococcus level observed in the original investigation).[15] Therefore, no additional risk was assumed beyond the risk at the 158 cfu/100 ml level from the 28,390 water-quality samples that exceeded this level during the study (linear extrapolation of the Kay et al relationship beyond this level would have increased the estimated annual number of gastroenteritis episodes by 47%). In addition, the restrictive definitions of gastroenteritis and AFRI used in these concentration-response relationships exclude many other illnesses associated with water contamination, including other forms of gastrointestinal and respiratory illness; diseases of the eyes, ears, and skin; and sometimes fatal central nervous system and systemic infections.[16,38] Moreover, the current study did not consider the elevated risk of gastroenteritis for children (odds ratio of 1.85 relative to adult bathers), who compose approximately half of the visitors to Southern California beaches.[29,38] The estimates reported here also exclude the health risk at the numerous bathing beaches inside coastal bays and harbors in the region, which may be considerable given that limited summer data at a subset of these beaches yielded annual estimates of 7,800 to 43,100 episodes of gastroenteritis (C and K relations, respectively) and 6,000 episodes of AFRI.

The primary limitation to the interpretation of these results stems from the fact that the three concentration-response relationships that we used in this analysis were derived from studies conducted in sewage-contaminated waters,[14–16] whereas urban runoff is the primary source of water contamination in Southern California.[5,6] The applicability of these relationships in this setting is supported by two points. First, the coastal waters of Southern California are impacted by sewage in offshore discharges, river discharges, and urban runoff. Urban runoff in this region often carries significant volumes of untreated sewage from leaking pipeline infrastructure, illegal discharges, and other sources of waste. The result is that many beaches in Southern California regularly experience water-contamination levels that are much higher than those measured in the original Cabelli et al and Kay et al studies. Second, two meta-analyses and two systematic reviews of the epidemiologic evidence from recreational marine water studies conducted under a wide range of contamination sources concur that enterococcus levels consistently demonstrate a significant relationship with the risk of gastroenteritis for bathers.[19–22]

In summary, coastal water contamination in Southern California is associated with a considerable health risk regardless of the concentration-response relationship used for analysis. The large numbers of illnesses that occur when bathers recreate in coastal waters with "acceptable" contamination levels raise significant concerns about current water-quality standards. Highly attended beaches deserve a greater emphasis in future pollution-remediation efforts, as these beaches account for the majority of contamination-related illnesses. By quantifying the scale and distribution of health risk in this important coastal region, this study may provide a greater understanding of the important pubic health issue of recreational water quality, both nationally and internationally.

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APPENDIX

Functional Forms of the Two Health-Risk Models Used in This Analysis Estimation of the Excess Likelihood of Gastroenteritis From Cabelli et al[14]

We estimated the excess risk of gastroenteritis by using the formula from Cabelli et al[14]:
Estimated cases per 1,000:

$$12.2\log[m_i(t)] + .2,$$

where $m_i(t)$ are enterococcus samples for each sample location i and day t.

Estimation of the Excess Likelihood of Gastroenteritis from Kay et al[15]

We follow the 2004 study by Kay et al[15] to derive the relationship between enterococcus sample values and risk. Within this section, we discuss the functional form and parameters for several components that jointly define this relationship.

Dose-Response Relationship Given Exposure Level

Following Kay et al[15], we assumed that, given exposure of an individual to a specific enterococcus concentration c, the excess likelihood $p(c)$ of gastroenteritis is given by

$$p(c) = \begin{cases} \dfrac{1}{1+e^{-b(c)}} - 0.0866 & c \geq 32, \\ 0 & \end{cases}$$

otherwise where $b(c)$ is the natural log of the odds of gastroenteritis at concentration c, defined as

$$b(c) = 0.20102\sqrt{c-32} - 2.3561.$$

Thus, for $c \geq 32$,

$$p(c) = \frac{1}{1+e^{-\left(0.20102\sqrt{c-32}-2.3561\right)}} - 0.0866.$$

Probability Distribution in Exposure Concentration Distribution

We assumed that individuals at a given sampling location and day are exposed to a wide range of enterococcus levels, where the likelihood density of exposure to enterococcus level c is lognormally distributed, with the log of c having mean m and standard deviation s:

$$y(c) = \frac{1}{s\sqrt{2\pi}} e^{-(\log_{10} c - m)^2/2s^2}$$

.

Distribution Parameters

For our distribution parameters, and in accordance with the 2004 study by Kay et al,[15] we assumed a constant value for s that was equal to that used by the World Health Organization guidelines on recreational bathing ($s = 0.8103$).

By contrast to the fixed value of s, we assumed a mean m of log10 c that varies daily for each sample location. Specifically, we made use of historical data that specified sample $m_i(t)$ for each sample location and day t. As we described in the text of the article, some of these values were imputed. For a given day t, we assumed a value for m that was the log (base 10) of the measured sample $m_i(t)$; thus, $m = \log10\ m_i(t)$. As a limitation of our approach, we note that although the log of a single sample is an unbiased minimum-variance estimate for the mean of the log-transformed values, the use of a single-sample estimate of m does lead to high variance in this estimate as a result of sampling error. The high variance associated with the use of a single sample can significantly bias risk estimates in the direction of higher risk. Although it would be preferable to use the geometric mean of many samples to estimate m, the data set only had recorded at most a single sample point for each sample location and day.

Excess Likelihood of Gastroenteritis at Sampling Location

Given a mean m and standard deviation s of the $\log_{10}$-transformed concentration c, we express the excess likelihood of contracting gastroenteritis through exposure at any exposure c within a range $[c_a,c_b]$ of concentration values c as $\phi(m, s)$ where

$$\phi(m,s) = \int_{\max(c_a,32)}^{c_b} p(c)y(c)d\log_{10} c = \int_{\max(c_a,32)}^{c_b} \left(\frac{1}{1+e^{-\left(0.20102\sqrt{c-32}-2.3561\right)}} - 0.0866 \right)\left(\frac{1}{s\sqrt{2\pi}} e^{-(\log_{10} c-m)^2/2s^2} \right) d\log_{10} c.$$

Transforming from a $\log_{10} c$ measure to a c measure, we obtain

$$\phi(m,s) = \int_{\max(c_a,32)}^{c_b} \left(\frac{1}{1+e^{-\left(0.20102\sqrt{c-32}-2.3561\right)}} - 0.0866 \right)\left(\frac{1}{\ln(10)cs\sqrt{2\pi}} e^{-(\log_{10} c-m)^2/2s^2} \right) dc.$$

To estimate the entirety of the excess likelihood of gastroenteritis, we integrate this value over the range from $c_a = 0$ to $c_b = +\infty$. Thus,

$$\phi(m,s) = \int_{32}^{\infty} \left(\frac{1}{1+e^{-\left(0.20102\sqrt{c-32}-2.3561\right)}} - 0.0866 \right)\left(\frac{1}{\ln(10)cs\sqrt{2\pi}} e^{-(\log_{10} c-m)^2/2s^2} \right) dc.$$

We carried out the integration of $\phi(m, s)$ numerically for the fixed value of s specified herein and for each integer value of $0 \leq m \leq 200$, for those m where m MOD $5 = 0$ for $200 \leq m \leq 1000$, and for those integers m where m MOD $1000 = 0$ for $1000 \leq m \leq 200{,}000$. For $m > 200{,}000$, we assumed the value of $\phi(m, s)$ to be the same as that obtaining at $m = 200{,}000$. In between the risk estimates computed through numerical integration, we linearly interpolated the values of $\phi(m, s)$.

Estimation of Number of Excess Cases of Illness

Given the definition for $\phi(m, s)$, we estimated the number of excess cases of illness from exposure on a given day t at a given sampling location i as the following:

$$g_i(t) = d_i(t)\phi[m_i(t),s]$$

where $d_i(t)$ is the number of bathers estimated to be bathing at sample location i on day t (subsequently derived), $m_i(t)$ is sample value for sample location i on day t, and s is an empirically estimated standard deviation of the $\log_{10}$ sample values. As noted in the article, as we were lacking direct data to estimate this, we used the value of 0.8103 adopted for the WHO guidelines for recreational waters.

Estimation of Number of Bathers per Sampling Location

We define $d_i(t)$ as a product of the number of beachgoers for the beach in which sampling location i is found, and a coefficient giving the fraction of those beachgoers who are present at this sample location. Specifically,

$$d_i(t) = D_{B(i)}(t)\alpha_{B(i)}(i),$$

where $\alpha_b(i)$ is the fraction of beachgoers on beach b who are present at sampling location i. For the present article, we assume all sample locations within a given beach to include an equal fraction of the beach's population; that is,

$$\alpha_b(i) = \frac{1}{\left|\left\{ l \in SampleLocations \mid B(l) = b \right\}\right|}$$

In addition, $D_b(t)$ is the number of bathers for beach b on day t, and $B(i)$ is a function that maps sample locations to beaches.

Estimation of Number of Bathers per Beach

We further estimate $D_b(t)$, the daily number of bathers on beach b on day t, as the product of the historically recorded number of beachgoers for the beach on that day and coefficients expressing the fraction of beachgoers entering the water and the effect of beach closures.

$$D_b(t) = n_b(t)\gamma[M(t)]\lambda_b(t)$$

where $n_b(t)$ is the number of beachgoers at beach b on day t, which is drawn from historical records; $M(t)$ is a function mapping days to months; and $\gamma(m)$ is a function giving the estimated fraction of beachgoers who bathe during month m.

The function is as follows: January, 0.2559; February, 0.2797; March, 0.3287; April, 0.3077; May, 0.4144; June, 0.4976; July, 0.5218; August, 0.5438; September, 0.4996; October, 0.3562; November, 0.2928; December, 0.2657. Note that $\lambda_b(t)$ is a coefficient giving the fraction of normal bathers who bathe on day t on beach b that is due to any closures or advisories in effect for that beach on that day. We estimated this coefficient from historical data on the spatial extent of closures and advisories.