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Comparison of recreational health risks associated with surfing and swimming in dry weather and post-storm conditions at Southern California beaches using quantitative microbial risk assessment (QMRA)

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ABSTRACT

Southern California is an increasingly urbanized hotspot for surfing, thus it is of great interest to assess the human illness risks associated with this popular ocean recreational water sport from exposure to fecal bacteria contaminated coastal waters. Quantitative microbial risk assessments were applied to eight popular Southern California beaches using readily available enterococcus and fecal coliform data and dose-response models to compare health risks associated with surfing during dry weather and storm conditions. The results showed that the level of gastrointestinal illness risks from surfing post-storm events was elevated, with the probability of exceeding the US EPA health risk guideline up to 28% of the time. The surfing risk was also elevated in comparison with swimming at the same beach due to ingestion of greater volume of water. The study suggests that refinement of dose-response model, improving monitoring practice and better surfer behavior surveillance will improve the risk estimation.

1. Introduction

Stormwater runoff transports a large number of urban pollutants to the coastal ocean (Ahn et al., 2005; Bay et al., 2003; Field et al., 1993; Handler et al., 2006; Jones and Obiri-Danso, 1998; Lipp et al., 2001; Raco-Rands and Andrea, 2001; Reeves et al., 2004; Weiskel et al., 1996; Wyer et al., 1995). These pollutants can originate from municipal wastewater (Raco-Rands and Andrea, 2001), industrial facilities effluent (Steinberger and Schiff, 2001), atmospheric deposition (Offenberg and Baker, 1997; Stolzenbach et al., 2001), and urban litter (Abu-Hilal and Al-Najjar, 2004; Moore et al., 2002; Sheavly and Register, 2007). Urban coastal ocean has been shown to have a significantly higher level of bacteria loading following a rainfall event (Ahn et al., 2005; Dwight et al., 2002; Field et al., 1993; Reeves et al., 2004). Human specific fecal waste markers have recently been detected in urban stormwater in cities of US (Sauer et al., 2011) likely due to aging sanitary infrastructure underneath streets of some cities. In particular, fecal pathogens of anthropogenic sources receive much attention because humans generally are more susceptible to pathogens from anthropogenic sources (Glassmeyer et al., 2005; Griffith et al., 2003).

To protect human health, EPA recommended fecal indicator bacteria (FIB) as surrogates to fecal pathogens for water quality assessment and monitoring due to their correlation to the presence of fecal pathogens (US EPA, 1986). Epidemiological studies that used FIB as an indication for fecal contamination (Griffin et al., 2001) have shown positive correlations between elevated health risks for bathers and swimmers and concentration of FIB in contaminated marine and freshwater environments (Cabelli et al., 1983; Haile et al., 1999; Kay et al., 1994). These studies also formulated quantitative relationship between gastrointestinal illnesses (GI), the most frequent adverse health outcome associated with exposure to contaminated waters, and FIB concentration in the recreational waters (Prüss, 1998; WHO, 2003).

Southern California is an increasingly urbanized hotspot for surfing, thus it is of great interest to assess the human illness risk associated with this popular ocean recreational water sport from exposure to fecal bacteria contaminated coastal waters (Given et al., 2006; Turbow et al., 2003). There are two distinct seasons in Southern California: dry season, between May and September, is characterized with less than 2 inches of total rainfall, while wet season, between October and April, has 90% of annual rainfall. Surfers are a particularly interesting group for health risk investigation because they frequent the beach during both the dry season and the storm season. Surfers often prefer large waves that usually accompany a storm event (Bradley and Hancock, 2003), and stay in the water for a prolonged period of time (Turbow et al., 2008). The illness risks of surfing may vary during dry and post-storm weather conditions.

Based on epidemiology survey at two California Beaches, Dwight et al. (2004) concluded that storm and urban runoff increase the risks of GI in surfers. However, assessing human illness

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risk associated with surfing via large-scale epidemiological surveys is cost prohibitive (Haas et al., 1999). Quantitative microbial risk assessment (QMRA) using readily available bacteriological water quality data and dose-response relationship offers an effective alternative to epidemiological study for estimating health risks (Ashbolt et al., 2010; Schoen et al., 2011). Comparative risk analysis at dry weather and post-storm conditions also provides insights to policy decision of coastal and human health management.

This study reports QMRA of the health risks of surfing during dry weather and post-storm conditions at eight selected Southern California beaches. In this study, we also estimated the elevated health risks of surfers compared to that of swimmers.

2. Materials and methods

2.1. Data sources

We selected three coastal counties in Southern California, USA and acquired bacteriological monitoring data from the responsible agency in each county. Beach locations were chosen based on their popularity among surfers, proximity to nearby weather stations, and availability of bacteriological monitoring data. Four beach monitoring locations were selected from Los Angeles, two from Orange County, and two from San Diego County (Fig. 1). The FIB data were retrieved from online public database through Los Angeles County Department of Public Health (excluding Long Beach) (http://www.lapublichealth.org/eh/ehftp/), Orange County Health Care Agency (http://www.ocbeachinfo.com/data), and San Diego County Department of Environmental Health (http://www.sccoos.org/data/waterquality/?r=3). In addition, San Diego County Department of Environmental Health also supplemented us via e-mail with the most recent monitoring data. This study used FIB data from January 2008 through May 2010. The geographic location of the study sites and weather stations are mapped in Fig. 1.

Land-based daily precipitation data were obtained from the National Climate Data Center (NCDC) of National Environmental Satellite, Data, and Information Service (NESDIS) (http://www7.ncdc.noaa.gov/CDO/cdo). The weather station recording rainfall for a selected beach was chosen according to its vicinity to the bacteriological monitoring location.

2.2. Data treatment

In this study we defined "post-storm" as the period between 24 h and 72 h after a recorded precipitation event of greater than 0.2 inches of rain. The "dry weather" was defined as the dates with either no recorded precipitation, or a time period of at least 72 h following a recorded precipitation. FIB data were excluded from analysis on the dates that missing precipitation information. FIB data were also excluded on the day of recorded precipitation because the exact time of the FIB sample collection on the day of rain was not reported (which can either be before or after the rain). Table 1 shows the number of qualified data in each category and at each study site.

Under each of the weather categories, ENT and FC data were extracted for each monitoring location selected for analysis. Where FIB concentrations were reported as less than the detection limit, they were treated as equaling to the detection limit concentration, and where data were higher than the quantification capability, they were treated as equaling to the highest quantification concentration.

2.3. Data analyses

All the distribution fittings, calculations, and random sampling for this study were conducted using MATLAB®.

2.3.1. Ingestion dose

The base-10 logarithm of ENT and FC bacterial concentrations were plotted and fitted to a kernel distribution for each monitoring location and randomly sampled from its inverse cumulative density function of the distributions. The randomly sampled concentrations were then combined with randomly sampled ingestion

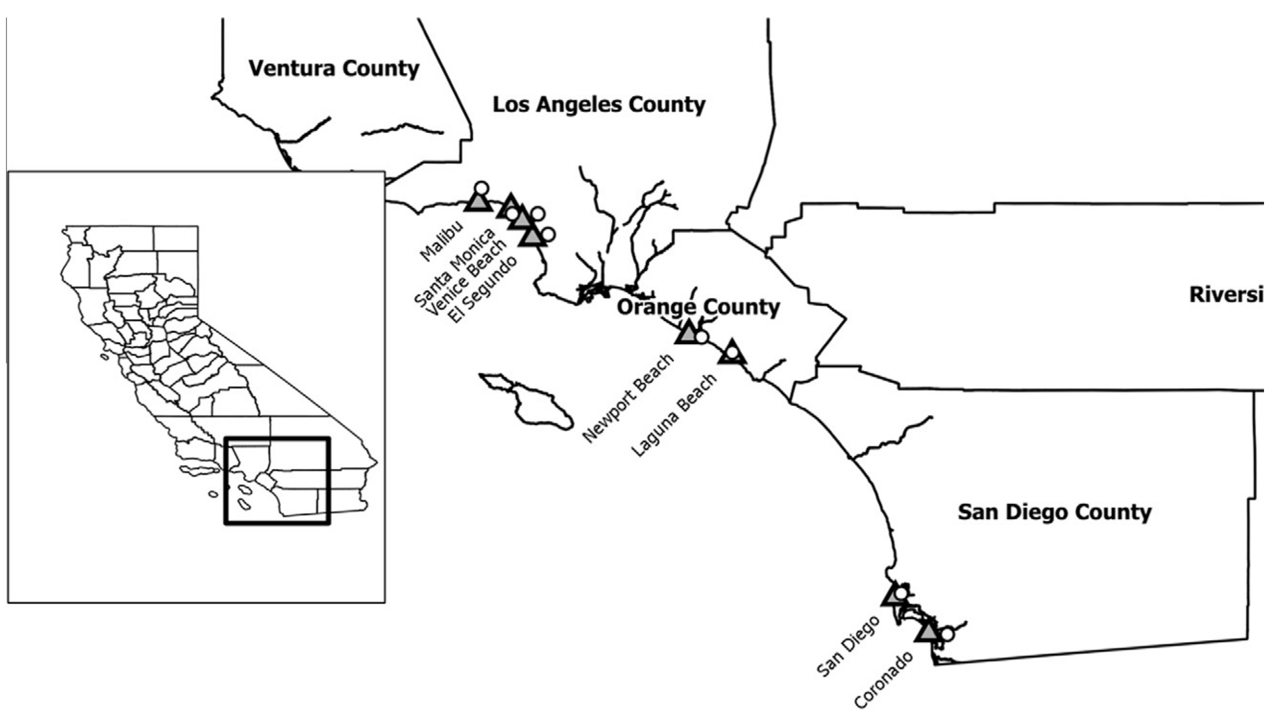

Fig. 1. Map of selected bacteriological monitoring locations (dots) and weather stations (triangles) in Southern California, USA.

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Table 1
Summary of bacteriological monitoring data used in this study.

County	Beach site	Number of qualified data	
		Post-storm	Dry
Los Angeles	Malibu	17	80
	Santa Monica	16	74
	Venice	14	95
	El Segundo	20	96
Orange	Newport	120	358
	Laguna	16	107
San Diego	San Diego	29	93
	Coronado	19	84

volume or ingestion rate and exposure time to calculate for the ingested FIB dose.

The equation, $D_{oral} = I_{oral} \times C$, gives the ingested dose of ENT or FC by surfers, where D_{oral} is the ENT or FC dose ingested in MPN or CFU, I_{oral} is the ingested seawater volume by surfers in ml, and C is the seawater concentration of ENT or FC in MPN·ml^{-1} or CFU·ml^{-1}. We chose to use the surfer ingested seawater volume distribution model from Stone et al. (2008). The ingestion distribution that was based on the survey is lognormal and has a mean and a standard deviation of 3.54 and 1.80 ml d^{-1}, respectively. The ingested volume in our study was randomly sampled from the seawater ingested volume distribution curve. Since the ingestion volume during surfing includes time factor, the ingestion dose represents dose per surfing event.

2.3.2. Dose-response models

The daily surfer risk of GI from ENT was estimated by applying the exponential dose-response model (Haas et al., 1999; Stone et al., 2008),

$$p(ill)_{ENT,\ day} = [1 - exp(-D_{ENT,\ oral}/k)] \times \Psi,$$

where $p(ill)_{ENT,\ day}$ is the daily probability of GI associated with ENT, $D_{ENT,\ oral}$ is the number of ENT organisms ingested, k is an organism-specific infectivity parameter, and Ψ is the ratio of illness to infection. The infectivity parameter, k, is the inverse of the probability that the organism survives to initiate an infection (Haas et al., 1999). This could be interpreted as 1 in k organisms survives to initiate an infection. Using the same distribution and values as Stone et al., k was randomly drawn from a triangular distribution with a minimum, a mode, and a maximum of 177, 1442, and 14427, respectively. The ratio of illness to infection, Ψ, again using the values from Stone et al., was drawn from a triangular distribution with a minimum, a mode, and a maximum of 0.1, 0.2, and 0.3, respectively.

The daily surfer risk of GI from FC was estimated by applying the Beta-Poisson model from Haas et al. (Haas et al., 1999),

$$p(ill)_{FC,\ day} = 1 - [1 + (D_{FC,\ oral}/N_{50}) \times (2^{1/\alpha} - 1)]^{-\alpha},$$

where $p(ill)_{FC,\ day}$ is the daily GI probability associated with FC, $D_{FC,\ oral}$ is the number of FC organisms ingested, N_{50} is the median infective dose that causes half of the population to be infected, and α is the slope parameter. N_{50} and α were derived from (Pai et al., 1986) and have the value of 5.96×10^5 and 0.49 (Haas et al., 2000).

2.3.3. Comparison of surfers vs. swimmers' risks

Similar to the approach by Donovan et al. (2008), we also estimated the elevated GI risks of surfing to those of swimming using FC. For this comparison, the ingested seawater volume in ml by swimmers is given by the equation,

$$I_{oral,\ swim} = T_{exposure} \times R_{ingestion},$$

where $I_{oral,\ swim}$ is the ingested seawater volume by swimmers, $T_{exposure}$ is the time of swimming in minutes, and $R_{ingestion}$ is the water volume rate of ingestion in ml min^{-1}. For swimmer exposure time, we referred to EPA's Exposure Factors Handbook (US EPA, 1997) and the study of Tsang and Klepeis (1996). Then we fit the exposure time data to a Rayleigh distribution with a mean of 0.97 h. We also compiled swimmer water ingestion rates from available literature (see Supplementary Table S1). An extensive literature search revealed a range of swimmer water ingestion rates, and for many studies, an ingestion rate was often treated as a constant value within a population. Based on these studies (Craig et al., 2003; Donovan et al., 2008; Dufour et al., 2006; Schijven and de Roda Husman, 2006; Steyn et al., 2004), we decided to address the variable rates within a population by drawing the ingestion rates from a triangular distribution with a minimum, mode, and maximum of 20, 35, and 50 ml h^{-1}, respectively. The elevated risks of GI for surfers were estimated by the modified regression from Cabelli et al. (1983),

$$p(ill)_{FC,\ elevated} = \{5.88 + 6.3. \times \log_{10}[C_{FC} \times (I_{oral,\ surf}/I_{oral,\ swim})]\}/1000,$$

where $p(ill)_{FC,\ elevated}$ is the elevated daily illness probability of surfers to swimmers associated with FC, C_{FC} is the seawater concentration of FC in MPN·ml^{-1} or CFU·ml^{-1}, and $I_{oral,\ surf}$ and $I_{oral,\ swim}$ are the ingested seawater volumes in ml by surfers and swimmers, respectively. Again, $I_{oral,\ surf}$ is randomly sampled from the surfer ingested seawater volume distribution model from Stone et al. (2008).

We assumed in this study that the predicted GI risks only apply to healthy adults.

3. Results

3.1. GI risk of surfing during dry weather and post-storm conditions

The Monte Carlo simulation outputs from ENT dose-response model for surfing during dry weather and post-storm conditions are shown in Fig. 2. The y-axis indicates illness cases per 1000 surfers while the x-axis shows the dose of ENT ingested. The 10,000 data points in each individual chart give the probability of illness from 10,000 iterations. In comparison with the acceptable recreational water health risk of 19 GI cases per 1000 people set by US EPA (Cabelli et al., 1983), a number of predicated points were above the guideline at both dry weather and post-storm conditions (Fig. 2). The maximum probability of illness was near 300 cases per 1000 bathers at some beach locations, while the averages were generally below 15 cases (Table 2). The average illness estimations based on FC model were near zero per 1000 bathers with a wide range of distribution. The maximum probability of illness based on FC model was between 11 and 994 per 1000 bathers (Table 2).

Fig. 3 shows the frequency of illness exceeding EPA guideline of 19 cases per 1000 exposures based on ENT (Fig. 3 top) and FC (Fig. 3 bottom) models. The comparison revealed that surfing post-storm may exceed EPA risk guideline up to 28% of time, while the chance of exceeding the risk guideline during dry weather conditions was mostly below 15% based on the ENT model (Fig. 3, top panel). At Santa Monica, El Segundo, San Diego and Coronado beaches, health risk associated with surfing at post-storm conditions was significantly elevated ($p < 0.01$) in comparison with dry weather conditions (Fig. 3, Table 2). Only Laguna Beach did not show any statistically significant difference ($p > 0.1$) when comparing surfing risk at dry weather and post-storm conditions. The elevated risk at post-storm conditions was less pronounced based on the Monte Carlo outputs from FC Beta-Poisson dose-response model (Fig. 3, bottom panel). The elevated risk at post-storm conditions was observed at three of eight beaches evaluated (Table 2). The rest of the locations either had no significant difference between the

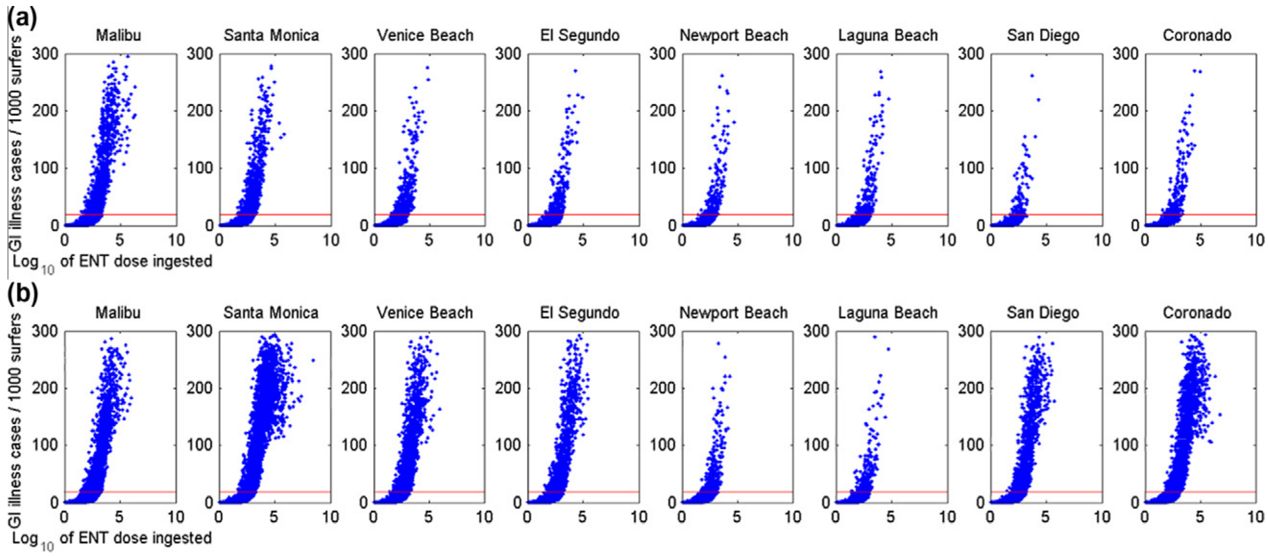

Fig. 2. Comparison of Monte Carlo simulation of GI cases per 1000 surfers based on the exponential dose-response model for enterococcus (ENT) during dry (a) and post-storm (b) conditions. The *x*-axis is the base-10 logarithm of ingested dose of FIB and the *y*-axis is the GI cases per 1000 surfers. The line indicates the acceptable recreational water health risk of 19 GI cases per 1000 people set by US EPA. The Monte Carlo simulation was run for 10,000 iterations.

Table 2
Average and maximum gastrointestinal illness cases per 1000 surfers based on enterococcus (ENT) or fecal coliform (FC) during dry and post-storm conditions.

Beach site	ENT				FC			
	Dry		Post-storm		Dry		Post-storm	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max
Malibu	11 ± 35.9	295	15 ± 39.7	288	0 ± 2.6	112	0 ± 1.0	33
Santa Monica	7 ± 24.0	279	34 ± 63.7	294	0 ± 2.8	221	4 ± 20.1	834
Venice	3 ± 14.4	245	17 ± 39.6	290	1 ± 17.9	664	0 ± 1.2	36
El Segundo	3 ± 12.6	270	11 ± 34.1	293	2 ± 21.2	768	0 ± 3.0	163
Newport Beach	2 ± 11.4	261	3 ± 12.6	279	0 ± 1.7	70	0 ± 1.7	72
Laguna Beach	2 ± 12.5	268	2 ± 10.6	289	0 ± 0.3	11	0 ± 0.7	46
San Diego	1 ± 7.4	261	12 ± 37.5	289	0 ± 2.7	173	2 ± 18.1	653
Coronado	2 ± 11.5	270	22 ± 51.5	293	0 ± 2.2	188	30 ± 127.1	994

dry weather and post-storm conditions or had a slightly higher risk during dry weather. The estimated risks based on FC model were significantly lower than those based on the ENT model, exceeding EPA health guideline at 1–12% of the time.

3.2. Surfing GI risk compared to swimming

We compared the predicated GI risks of surfing to those of swimming during both dry weather and post-storm conditions using FC with modified regression from Cabelli et al. (1983). Table 3 shows the frequency of observing an elevated risk from surfing in comparison to swimming during wet and dry weather conditions. Surfing presented higher level of risks in comparison to swimming in the same beach water 81–99.9% of the time (Table 3). The elevated risk was exacerbated during post-storm conditions at seven of the eight beaches studied with Coronado beach as the only exception.

4. Discussion

This study used modeling to assess the GI risks of surfing during dry weather and post-storm conditions using readily available ENT and FC data and dose-response models. The results showed that it was more likely to exceed the EPA risk guideline surfing 24–72 h post-storm than during dry weather conditions. Although this study found higher surfing risks of GI post-storm, the frequency of the risks exceeding the U.S. EPA guideline at seven out of eight selected beaches was less than 25% of the time predicted by ENT and was less than 15% predicted by FC. These results also demonstrated that there were significant differences in estimated surfing GI risks at the same beach using different FIB and QMRA models. Higher risks were found using the ENT exponential model than using the FC Beta-Poisson model. Several factors may have contributed to this discrepancy: (1) the models have different assumptions, such that model developed for specific beach locations may have different illness thresholds; (2) risk models were not developed specifically for surfing; (3) the two FIB used in this study differ in their survival ability in the seawater; (4) the FIB in urban runoff-impacted beaches might not be indicative of human pathogen and health risks due to their non-human sources such as animal feces.

This study indicated that the risk of GI per bathing event was higher for surfing than for swimming, which was attributable to the increased volume of contaminated water ingested. However the actual cases of GI are dependent on the number of surfers and swimmers at each beach. If the majority of the beach-goers are swimmers during dry weather, then the larger number of GI cases is likely found during the dry weather among swimmers. The higher risk among surfers will only affect a small fraction of beach-goers during post-storm conditions. Incorporating the beach

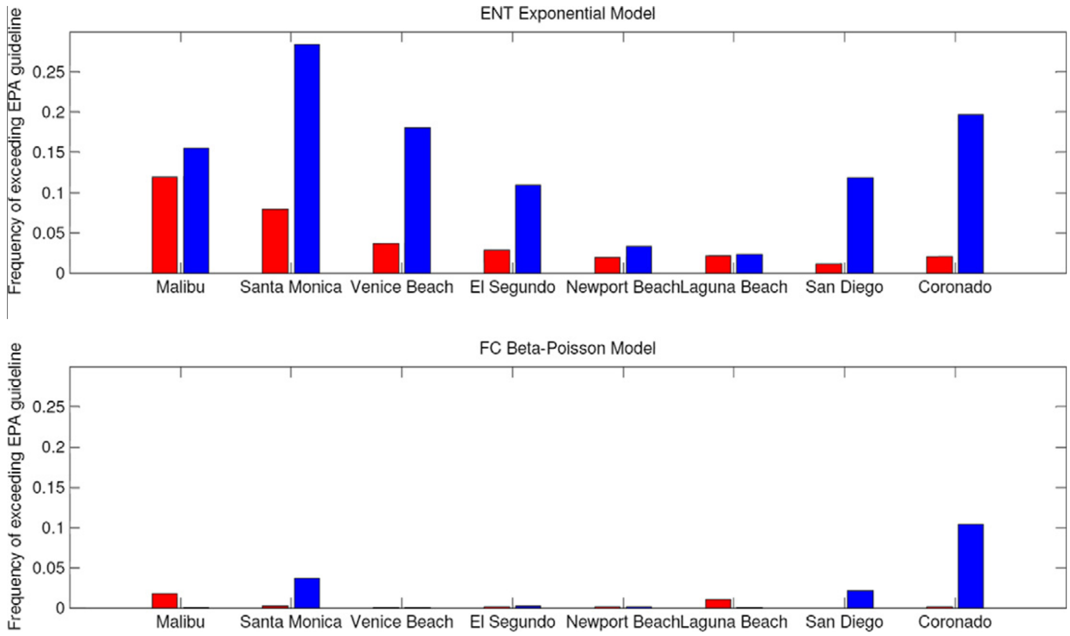

Fig. 3. Frequency of GI risk exceeding the US EPA guideline (19 GI cases per 1000 people) at selected Southern California beaches during dry (red bar) and post-storm conditions (blue bar). The top graph is Monte Carlo outputs estimated based on the enterococcus (ENT) exponential dose-response model, and the bottom graph is Monte Carlo outputs estimated based on the fecal coliform (FC) Beta-Poisson dose-response model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
The frequency of observing an elevated risk from surfing in comparison to swimming during wet and dry weather conditions at each beach.

Beach site	Dry	Post-storm
	% of elevated observation	
Malibu	95.0	99.4
Santa Monica	99.3	99.9
Venice	98.1	99.8
El Segundo	96.8	99.2
Newport Beach	98.6	99.2
Laguna Beach	83.3	95.6
San Diego	95.7	96.5
Coronado	83.7	81.0

attendance data, Turbow et al. (2003) estimated that most of the GI cases occurred during summer dry weather conditions in Southern California.

This study applied an existing modified regression using FC to evaluate the relative risk of GI for surfing comparing to swimming since FC concentrations are one of the most commonly reported water quality parameters. While the model showed a difference in GI risk between two recreational water activities typical of Southern California, as our goal was not to evaluate whether FC was a better FIB to use in predicting the relative risk of GI of surfing to swimming, the prediction may vary with different models and different FIB. A comparison model based on ENT has not yet developed.

This study predicted human health risk with only the available bacteriological monitoring data. We did not take into account of the speed and direction of ocean currents and tide levels due to the lack of sampling time at some beaches, thus the GI risks predicted would be most applicable to near-shore surfing in the proximity of the bacteriological monitoring locations. One of the biggest challenges in this study was that the number of qualified FIB data was limited by the frequency of monitoring (Leecaster and Weisberg, 2001), thus some beaches have more data than others, which may have resulted poor data fitting. In addition, although the monitoring of FIB is required by the State of California, many monitoring locations have different detection limits due to different sample analysis and reporting methods by different laboratories. The different sampling depths such as ankle or waist depth at the monitoring locations, however, should not produce significant differences (Boehm et al., 2003; Grant and Sanders, 2010; Ki et al., 2007). The water ingestion rates during surfing were adapted from survey data collected in Oregon (Stone et al., 2008). Although surfing behavior can be generalized, surfers in Southern California may have longer duration of exposure since the water is warmer. Refined estimates of ingestion rates would be useful for improving QMRA.

Although QMRA enables the assessment of human health risk based on the best available information of potential effects from microbial exposure (Haas et al., 1999), it has some drawbacks. There may be incomplete or a dearth of available information, for example the survival rate of the pathogen in relationship to indicator bacteria, thus assumptions are usually applied to QMRA and one must determine the potential errors involved (Haas et al., 1999). Another challenge of QMRA with regards to available data is that the presence of a short-term fluctuation in a data set may have a major effect of the overall health risks (WHO, 2003). Thus such results of QMRA have to be used carefully, particularly during policy decision-making.

The results of this study suggest the dose-response model and FIB selection can affect the risk prediction outcome significantly. The GI risk assessment from the ENT exponential model seemed to be consistent with previous studies that showed higher GI risks for recreational water activities during wet season and El Niño season in Southern California beaches (Dwight et al., 2002), but the assessment from FC Beta-Poisson model did not have such a clear trend. The forthcoming US EPA Ambient Water Quality Criteria actually support the use of ENT for human health protection among marine recreational bathers. Nonetheless, the QMRA model outcome in this study offers surfing beach-goers and Southern California coastal communities a cost-effective and rapid measure for predicting the likelihood of illness. These models still require fur-

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ther refinements and model parameter validations with more epidemiological studies at Southern California surfing locations to improve the illness risk prediction. A better system of recreational disease surveillance should be established to validate the predictions about illness rates (Turbow, 2009; Turbow et al., 2008). The large discrepancies found in QMRA models also show the need for a better understanding in FIB choice for human health protection.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2012.03.009.

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