Evaluation of the dry and wet weather recreational health risks in a semi-enclosed marine embayment in Southern California

Keah-Ying Lim¹, Stella Shao², Jian Peng², Stanley B. Grant¹, Sunny C. Jiang^{1*}

¹Department of Civil and Environmental Engineering, University of California, Irvine

²Orange County Environment Resources, The County of Orange, California

Revised 12/5/2016

*Corresponding Author: Sunny Jiang, University of California, Irvine, CA 92607. Email:

sjiang@uci.edu; Tel: 949-824-5527

Abstract:

For many coastal regions around the world, recreational beach water quality is assessed using fecal indicator bacteria (FIB). However, the utility of FIB as indicators of recreational waterborne illness (RWI) risk has been questioned, particularly in coastal settings with no obvious sources of human sewage. In this study we employed a source-apportionment quantitative microbial risk assessment (SA-QMRA) to assess RWI risk at a popular semi-enclosed recreational beach in southern California (Baby Beach, City of Dana Point) with no obvious point sources of human sewage. Our SA-QMRA results suggest that, during dry weather, the median RWI risk at this beach is below the U.S. EPA recreational water quality criteria (RWQC) of 36 illness cases per 1000 bathers. During wet weather, the median RWI risk predicted by SA-QMRA depends on the assumed level of human waste associated with storm water; the RWI risk is below the EPA RWQC illness risk benchmark 100% of the time provided that <2% of the FIB in stormwater are of human origin. However, these QMRA outcomes contrast strongly with the EPA RWQC for 30-day geometric mean of enterococci bacteria. Our results suggest that SA-QMRA is a useful framework for estimating robust RWI risk that takes into account local information about possible human and non-human sources of FIB.

Keywords: fecal indicator bacteria; beach water; recreational health risk; risk assessment; non-point source; stormwater

Abbreviations used:

BMPs: Best Management Practices

ENT: Enterococcus

FC: Fecal coliforms

FIB: Fecal indicator bacteria

GM: Geometric mean

MST: Microbial source tracking

QMRA: Quantitative microbial risk assessment

SA-QMRA: Source apportionment quantitative microbial risk assessment

STV: Statistical threshold value

RWI: Recreational water illnesses

RWQC: Recreational Water Quality Criteria

TC: Total coliforms

TMDL: Total Maximum Daily Load

U.S. EPA: United States Environmental Protection Agency

1. INTRODUCTION

Public beaches in the United States are often monitored for fecal contamination using fecal indicator bacteria (FIB), a broad group of enteric bacteria that are present at high concentrations in human and animal waste (U.S. EPA 2012). FIB are not a direct measure of the fecal-oral pathogens responsible for most recreational waterborne illness (RWI) (Boehm et al. 2009), but they have been universally adopted as an indicator of fecal pollution based on two considerations: (1) epidemiological studies have long demonstrated a significant correlation between RWI rates and swimming in sewage-contaminated recreational waters containing elevated concentrations of FIB, in particular enterococci bacteria (ENT) in marine waters (Prüss 1998) and; (2) they are relatively easy and inexpensive to measure using culture-based methods (Boehm and Soller 2013). However, many recent studies have shown that the correlation between ENT and RWI weakens when the bacteria originate from non-point sources (e.g., runoff, bird waste) and not human fecal pollution (Arnold et al. 2013, Colford et al. 2012, Colford Jr et al. 2007, Fleisher et al. 2010). As a result, the marine RWI health risks implied by ENT measurements are likely to be site-specific, as acknowledged in the most recent recreational water quality criteria (RWQC) published by the U.S. EPA in 2012 (U.S. EPA 2012). Indeed, the 2012 RWQC offers beach managers the flexibility to develop site-specific water quality criteria based on epidemiological studies, quantitative microbial risk assessment (QMRA), and/or sanitary surveys (U.S. EPA 2012). The new RWQC includes both FIB-based criteria, such as the 30-day geometric mean (GM) and statistical threshold value (STV), as well as the illness-based criteria derived from epidemiological studies.

The FIB-based criteria are generally used as the default approach for assessing RWI risk because of the high cost of epidemiological studies. However, this default approach does not distinguish between different sources of FIB, but rather compares FIB measurements to RWQC as an indirect risk management approach. At the mean time, recent epidemiological studies at beaches impacted by non-point source pollution (such as runoff) demonstrate: (1) a weak or non-existent correlation between FIB and RWI; and (2) increased illness risk for bathers compared to non-bathers, possibly indicating the presence of fecal-oral pathogens (Arnold et al. 2013, Colford et al. 2012, Colford Jr et al. 2007, Fleisher et al. 2010). These epidemiological results are consistent with many field studies conducted over the years that demonstrate a disconnection between FIB concentrations in recreational waters and the presence or absence of human viruses responsible for most RWI, such as norovirus and adenovirus. In some cases FIB concentrations are elevated when viral pathogens are absent, while in other cases FIB concentrations are low when viral pathogens are present (Jiang et al. 2007, Love et al. 2014, McQuaig et al. 2012). The underlying reasons for this disconnection are complex and site-specific, but include: (1) the existence of multiple environmental reservoirs for FIB, such as sediments (Piggot et al. 2012), algae (Whitman et al. 2003), and the water column itself (Surbeck et al. 2006); and (2) the different environmental fate and transport characteristics of FIB and viral pathogens (Byappanahalli et al. 2012). The net result is that strict enforcement of FIB criteria can lead to a misrepresentation of the true health risk, either by unnecessarily posting beaches as unfit for recreating (with attendant loss of the socio-economic benefits) or not warning the public when a true health risk exists (resulting in RWI and attendant economic losses) (Given et al. 2006, Kim and Grant 2004).

The problems outlined above beg for a more tailored and holistic approach to beach water quality monitoring and public notification that specifically considers the location,

hydrometeorologic conditions (Surbeck et al. 2006), historical water quality data (Boehm et al. 2002), and possible sources of both fecal and non-fecal FIB (Abdelzaher et al. 2011, McQuaig et al. 2012). Recently, a Source Apportionment Quantitative Microbial Risk Assessment (SA-QMRA) framework was proposed for evaluating RWI health risks in recreational waters not affected (or at least not primarily affected) by point sources of human sewage (Soller et al. 2015, Soller et al. 2010b, Soller et al. 2014). The SA-QMRA framework simulates RWI risks based on the variety of different FIB sources at a particular beach, for example from seagulls, humans, pigs, cows, or mixed sources. FIB-to-pathogen ratios for various beach-specific point and non-point sources are used to infer human pathogen concentrations (the causative agents for RWI) from shoreline measurements of FIB concentration. The FIB sources can be informed by sanitary surveys of the site, and microbial source tracking (MST) techniques (Fung et al. 2007, Sercu et al. 2008). In principle, the SA-QMRA framework can also account for how runoff from separate storm sewer systems is locally managed. For example, at many coastal sites in Southern California, dry weather runoff is diverted to wastewater treatment plants with documented benefits for coastal water quality (Dorsey 2010). In addition to providing a more tailored approach for assessing RWI risk and public water quality notifications, the SA-QMRA approach can enable scenario testing, for example to assess how health risks might change under different mixes of human and non-human fecal sources, different FIB-to-pathogen ratios, or a changing climate.

While SA-QMRA has been applied to hypothetical scenarios, it has not yet been applied to an actual test case due to the challenge of quantitative apportionment of fecal sources. However, as demonstrated in this study the source apportionment process can be achieved through meta-analysis of relevant literature and a survey of the available site-specific data in the form of local

reports and grey literature. In this paper we apply the SA-QMRA framework to Baby Beach in Dana Point, Orange County, California. This particular beach has suffered elevated FIB concentrations for a number of years, and is included on the State Water Quality Control Board Clean Water Act Section 303(d) List (State Water Resources Control Board 2004). A number of best management practices (BMPs) have been put in place to reduce FIB pollution at this site, including beach clean-up and dry weather runoff diversion. While these activities appear to have reduced the concentrations of total coliforms (TC) and fecal coliforms (FC), concentrations of ENT are still frequently in excess of the 2012 RWQC during both wet and dry periods. Accordingly, the main objective of this study was to quantify, using SA-QMRA, the dry weather and wet weather RWI risks associated with the ENT measurements at Baby Beach. Our results demonstrate the potential utility of this approach for providing robust RWI risk assessments, and more generally demonstrate the power of a risk assessment approach to beach water quality management.

2. MATERIALS AND METHODS

2.1. Site description

The study site is located at Baby Beach, a small man-made and semi-enclosed beach in Dana Point Harbor, California with approximately 183 meters long of recreational shoreline (Figure 1). Protected by two breakwaters from the Pacific Ocean, the shoreline of Baby Beach is characterized by warm and calm water, which makes the beach a popular family destination that receives an estimated 1 million visitors annually. The catchment basin of Baby Beach drains an area of 175,630 m², which covers undeveloped open spaces with some residential and

commercial land uses. The region receives annual rainfall averaged around 325 mm (Orange County Public Works).

In contrary to the seemingly child-friendly water it offers, Baby Beach has had historically high FIB level that are considered as “unsafe” for recreational uses. After an eleven months initial closure of the beach in 1996 and a two-month health risk advisory posting at the beach in 2002 due to elevated FIB levels, massive investigative measures have been taken to lower the FIB level of the beach (County of Orange & City of Dana Point 2011). The most notable actions were the construction of a dry weather runoff diversion near the main storm drain line in late 2005 that resulted in close-to-zero runoff to the beach during the summer/dry season (April 1st to October 31st each year), as well as the installation of media filter vaults for filtering the stormwater when the dry weather diversion is not in effect (November 1st to March 31st each year).

2.2. Data source

The ENT concentrations at four sampling points along the recreational shorelines of Baby Beach (BDP12, 13, 14, 15 in Figure 1) since 1999 were provided by the state certified laboratories from the County of Orange Health Care Agency. Because the temporal variation of ENT concentration was similar across the four sampling sites, the GM of ENT concentrations (calculated from all measurements on a single sampling day) were used to represent the ENT concentration at Baby Beach. These daily GM values were used in our QMRA to be consistent with the approach used for the development of U.S. EPA 2012 RWQC (U.S. EPA 2012). Data mining indicated a significant decline in the historical ENT level starting in late 2005 (see Supplementary Figure S1), which coincided with the implementation of the dry weather runoff diversion and the installation of media filtration system near the main storm drain. These water quality

improvements confirm the important impacts of dry weather runoff from the storm drain on the water quality of Baby Beach (Rippy et al. 2014). As the main objective of our study is to investigate the current RWI risk at Baby Beach, dry weather ENT concentration data (n=188) collected between August 31st, 2005 and October 27th, 2011 after the implementation of these BMPs were used for the dry weather SA-QMRA. On the other hand, the wet weather SA-QMRA were facilitated by wet weather ENT concentration data, which were defined by water samples collected on days that were preceded by > 5 mm (0.2 inch) of rainfall within 72 hours prior to the sampling events. All the wet weather samples collected between April 8th, 1999 and September 8th, 2011 (n=60) were used for the wet-weather QMRA because the wet weather runoff was not diverted.

2.3. ENT source during dry weather conditions

2.3.1 ENT levels during dry weather conditions

During dry weather condition, which is defined as no rain event occurring within the 72 hours prior to the sampling date, two scenarios were considered: Scenario 1) storm drain runoff is diverted to a sanitary sewer with close-to-zero discharge from storm drain to the beach water (April 1st to October 31st, n=117), and Scenario 2) storm drain runoff is not diverted, but filtered by media filter vault and discharged to the Baby Beach recreational shoreline (November 1st to March 31st, n=71).

Scenario 1 represents that of the dry season in California, defined as the period from April 1 to October 31 annually following the definition adopted by the California AB411 legislation (Dorsey 2010). During this season, rainfall events are rare; the beach water is warmer and

attracts the highest number of beachgoers. Due to the small size of the Baby Beach watershed, virtually all dry weather runoff ($\text{max}=1.14 \text{ m}^3/\text{day}$) generated in the watershed and received by the stormwater drains has been effectively diverted to the neighboring wastewater treatment plant since 2005 (Dorsey 2010). The dry weather runoff from storm drains to the beach is non-existent or insignificant.

In the absence of significant storm drain inputs and sewage discharge, the possible sources of ENT at the beach include birds' feces and bathers' shedding. The ENT level of the beach water was elevated on days with high numbers of seagull and non-speciated birds and no preceding rainfall events, suggesting the contribution of birds' feces to dry weather ENT level (Science Applications International Corporation 2003). This source-apportionment assumption during the dry season is also supported by a source tracking bacteriological study of Baby Beach conducted before the urban runoff diversion and installation of the stormwater filtration system (Orange County Public Health Laboratory et al. 2003). This trend is expected to be preserved even after the implementation of dry weather runoff diversion because of the presence of high bird feces counts as recorded by the County's janitors (Orange County Environmental Resources 2015a). Other factors that could contribute to the variability of the ENT level during dry weather condition include tidal waves and human activities that could disturb the beach sediments and reintroduce ENT into the water column (Graczyk et al. 2010). In spite of this possibility, the shedding of bathers recreating in the waters were propounded to be a more significant ENT source than that from beach sediments to influence recreational water quality based on studies for beaches similar to Baby Beach (Elmir et al. 2009, Elmir et al. 2007).

Scenario 2 represents that of the winter/wet season in California when precipitation is more likely (November 1st to March 31st). During this time period, the valve for diverting dry weather runoff from Baby Beach is closed to prevent excess stormwater from overwhelming the sanitary sewer during storm events that may cause the backflow of sewage-contaminated stormwater. Instead, the dry weather runoff collected is filtered by a set of media filter vaults before discharging to Baby Beach. We postulated that the contribution of ENT from dry weather runoff collected in the storm drain during this time period is negligible due to the barrier provided by the media filters and the low dry weather runoff flow. This postulation was verified by comparing the dry weather ENT concentration data collected during wet season and dry season. As a consequence, the dry weather ENT sources for Scenario 2 are assumed to be the same as that of Scenario 1. However, the period during Scenario 2 usually coincides with declining beach usages by the public due to the colder water and air temperature and a general increase in bird densities due to birds migrating to the region, which changes the contribution of ENT from each ENT source (Science Applications International Corporation 2003).

2.3.2 ENT source-apportionment for dry weather conditions

In apportioning the ENT source, human shedding during water recreation is assumed to be characteristics of primary sewage, an assumption that is not far-fetched considering the analogy between dilution of bathers' sheddings by beach waters and dilution of human fecal waste by sewer water. Additional evidence of bathers' shedding is supported by natural recreational water outbreaks reports in the U.S., where feces in water, ill bathers, and bathers overcrowding in recreational waters were identified as the main contributing factors to waterborne outbreaks (Craun et al. 2005). According to studies that simulate bather's exposure to marine water, the

average ENT loading from bather's shedding ranged from 1.8×10^4 to 2.8×10^6 CFU per bather (Elmir et al. 2007 and 2009). This range brackets the average ENT loading from seabird feces of 4.7×10^5 CFU per fecal event (Wright et al. 2009). Therefore, for the purpose of our study we assumed that ENT loading from bather shedding is approximately equivalent to one bird fecal event (Wright et al. 2009). Based on this premise (i.e. 1 bather = 1 bird fecal event), the bird counts and human visitor counts data logged by janitors working at the beach were used to apportion the ENT contributed by these two sources. This approach assumes that each human beachgoer enters the water and every bird on the beach (assumed to be a gull) defecates in the water.

Using the aggregated average of birds and bathers count in each month during the dry season from year 2007 to 2011, it is estimated that 10% of the total ENT level is attributed to gull feces and the remaining 90% to human bathers' shedding under Scenario 1 (dry season runoff diversion in effect). As for Scenario 2 (runoff is not diverted, but filtered), 35% of the total ENT is attributed to gull feces and the remaining 65% to human bathers' shedding.

The ENT concentration during the dry weather condition can then be decomposed to:

$$\begin{aligned} ENT_{dry} &= F_{dry}^{Gull} \times ENT_{dry} + F_{dry}^{PSew} \times ENT_{dry} \\ &= ENT_{dry}^{Gull} + ENT_{dry}^{PSew} \end{aligned} \quad (1),$$

where ENT_{dry} is the ENT concentration during dry weather condition (CFU/100mL), F_{dry}^{Gull} and

F_{dry}^{PSew} are the fractions of ENT concentrations attributed to gulls' feces and primary sewage

(surrogate for bathers' sheddings) during dry weather condition (%), and ENT_{dry}^{Gull} and ENT_{dry}^{PSew}

are the ENT concentrations attributed to gulls' feces and primary sewage (bather sheddings) during dry weather condition (CFU/100mL).

2.4. ENT source during wet weather conditions

2.4.1. ENT levels during wet weather conditions

In comparison with the dry weather ENT concentration data, the wet weather ENT concentration data were scarce due the low incidence of rainfalls in the region. In addition, the trends of wet weather ENT levels were highly variable — changing significantly with the rainfall intensity, the duration, and the timing of antecedent precipitation. In order to account for this dynamic, over 10 years (1999 to 2011) of observational wet weather ENT concentration data (n=60) were included to address its variability. These data were collected both before and after the installation of BMPs, which were mainly for improving dry weather water quality — the wet weather ENT levels were not improved significantly even after the BMPs implementations (see Supplementary Figure S1).

2.4.2. ENT source-apportionment for wet weather conditions

Increasing evidences have shown that urban stormwater systems that are separated from sewage lines can still act as a conduit for sewage due to unforeseen breeches in sanitary sewer infrastructures and/or misconnections of stormwater and sewage pipelines, in which the magnitude of sewage contamination is exacerbated by wet weather flows (Marsalek and Rochfort 2004, Sauer et al. 2011). For context, the average misconnection rates of stormwater lines to sewage line in the U.S. and Europe were estimated to be 3–4% across the national, regional, and local levels (Ellis and Butler 2015). In assessing the human sewage contamination

in stormwater, human *Bacteriodes* has been used as one of the most successful MST markers to identify human waste among mixed source of human and non-human fecal matters in water samples (Harwood et al. 2014). Sauer et al. quantified the proportion of the human *Bacteriodes* to the total *Bacteriodes spp.* in several stormwater outfalls in metropolitan Milwaukee during storm events and found that untreated sewage marker can make up 10 to 16% of the total stormwater *Bacteriodes* markers at the end of the stormwater pipelines that were separated from the sanitary pipelines (Sauer et al. 2011).

In the context of Baby Beach, the land uses of its watershed explicitly excluded any potential ENT contribution from agricultural animals such as pigs, chickens, and cows that are known to harbor human pathogens. A preliminary tracer study also did not find any obvious cross-connection of storm drains and sanitary sewage line during dry weather condition (Orange County Environmental Resources 2015b). However, the same result is not guaranteed during storm events as the volume of wet weather flow is several times higher than dry weather flow and has much higher potential to be cross-contaminated with human sewage.

Based on the above information, it was postulated from 0% to 20% ENT in the stormwater could be from primary sewage due to the cross contamination of stormwater and sewage. The remaining portion of the ENT was considered as from non-pathogenic sources (i.e. from plants, lawns, soil and other indigenous sources) that do not contain human pathogens. Although wild and domestic animal feces are also likely ENT sources in storm runoffs, they impose much lower risk than human sewage sources (Soller et al. 2014). To evaluate this assumption, we conducted an assessment of the RWI risk associated with dog feces contaminated water. The results indicated that the RWI risk from dog feces (inferred from ENT measurements) is at least two

orders-of-magnitude lower than the RWI risk from human sewage at the same ENT level (See Supplementary Figure S2). In other words, the dog-derived ENT concentrations would have to be >3500 CFU/100mL to pose the same RWI risk as a human-derived ENT concentration of 35 CFU/100mL. Since wet weather ENT concentrations never exceeded 1800 CFU/100ml at Baby Beach, the inclusion of dog fecal ENT would not change the overall risk significantly. As a result, the contribution of wild and domestic animal feces to ENT in storm runoff was not currently included in this study. The ENT concentration contributed by stormwater discharge to Baby Beach can then be decomposed to:

$$\begin{aligned} ENT_{storm} &= F_{storm}^{PSew} \times ENT_{storm} + F_{storm}^{non-path.} \times ENT_{storm} \\ &= ENT_{storm}^{PSew} + ENT_{storm}^{non-path.} \end{aligned} \quad (3),$$

where ENT_{storm} is the portion of wet weather ENT concentration (CFU/100mL) brought in by the stormwater, F_{storm}^{PSew} and $F_{storm}^{non-path.}$ are the fractions of ENT concentrations attributed to primary sewage and non-pathogenic ENT source during wet weather condition (%), and where ENT_{storm}^{PSew} and $ENT_{storm}^{non-path.}$ are the ENT concentrations (CFU/100mL) attributed to primary sewage and non-pathogenic ENT source from the storm drains during wet weather condition.

Therefore, the overall mathematical expression for ENT concentration during wet weather condition is the sum of two terms: the baseline contamination term (ENT_{dry}) from the local source as represented by the geometric mean of the dry weather ENT during wet season (Nov 1st to March 31st) and the additional ENT contribution (ENT_{storm}) from the storm drain, which can be expressed as

$$ENT_{wet} = ENT_{dry} + ENT_{storm} \quad (4),$$

where ENT_{wet} is the observed wet weather ENT (CFU/100mL) at Baby Beach. Any observed wet weather ENT level that is lower than the baseline term is effectively apportioned using the dry weather ENT apportionment during wet season.

2.5. SA-QMRA

The core QMRA methodology, assumptions, and justifications as used in this study are based on the work of Soller et al. (Soller et al. 2010b, Soller et al. 2014). The illness end-point is characterized as gastroenteritis in bathers, which is also defined as RWI in this study. Figure 2 shows a flowchart of modeling procedures that summarize the flow of information in the risk analysis. Briefly, the source-specific RWI risks as contributed by each ENT source were calculated by the following steps: 1) estimate the dose of each reference pathogen ingested by bathers that are commonly found in a specific ENT source based on its ENT level, 2) estimate the RWI risk attributed to each reference pathogen in the ENT source based on the dose-response models for each reference pathogen, and 3) sum up the RWI risk attributed to all of the reference pathogens in each ENT source.

The dose of each reference pathogen in a specific ENT source, D_{rp}^S (Step 1) is calculated as:

$$D_{rp}^S = \frac{ENT_{weather}^S}{R_{ENT}^S \times 100} \times R_{rp}^S \times P_{rp}^S \times I_{rp}^S \times V \quad (5),$$

where $ENT_{weather}^S$ is the ENT concentration (CFU/100mL) in the recreational water contributed by a specific source, S , during a certain weather scenario, R_{ENT}^S is the density of ENT (CFU/g or L) in the source samples (i.e. wet mass of feces or sewage), R_{rp}^S is the reference pathogen

concentration (# pathogen/g or L) in the specific source, P_{rp}^S is the fraction of human-infectious pathogenic strains among the reference pathogen of a specific source, I_{rp}^S is the prevalence of infection from a non-human source, and V is the volume of water ingested (mL).

The parameter values for Equation (5) presented in Table 1 were based on the study by Soller et al. (Soller et al. 2010b). Uniform distribution was assumed for random sampling within the range of each parameter to derive the dose of each pathogen. Values for P_{rp}^{PSew} and I_{rp}^{PSew} are set to 1.0 for reference pathogens found in human sewage (maximum infectivity for human). The volume of water ingested by bathers, V , can vary among different sex and age groups (Dufour et al. 2006, Schets et al. 2011), but was a relatively insensitive parameter to the overall risk estimate as supported by a sensitivity analysis done by Soller et al. (Soller et al. 2010a) and also validated by a separate sub-study on our part (results not shown). For this reason, a point-estimate of 33mL for V — which corresponds to the highest average water volume ingested by swimmers — is used (Soller et al. 2010a, Soller et al. 2015, Soller et al. 2010b, Soller et al. 2014).

The RWI risk due to each reference pathogen (Step 2) is calculated based on the published infection dose-response models and morbidity data for inferring the portion of illness cases among infection cases (Table 2). The illness risk of each reference pathogen, Ill_{rp} , is computed as the product of infection risk (as a function of pathogen dose) and the portion of illness among each infection case.

In summing up the illness risk due to all of the reference pathogen in a single ENT source (Step 3), the theorem of independence from probability (i.e. the illness risk due to a reference pathogen is independent of that due to another reference pathogen) was used (Haas et al. 1999):

$P_{ill}^S = 1 - \prod_{rp} (1 - Ill_{rp}^S)$, where P_{ill}^S is the illness risk that is attributed to a single ENT source and

Ill_{rp}^S is the individual illness risk due to a reference pathogen in the ENT source.

As the overall ENT level during any weather condition is attributed to different ENT source (e.g. seagulls and primary sewage), the illness risk from each ENT source is summed up again using the theorem of independence from probability to compute the overall illness risk due to multiple

ENT sources: $P_{ill} = 1 - \prod_S (1 - P_{ill}^S)$, where P_{ill} is the overall illness risk that is attributed to

multiple ENT sources during a weather scenario and P_{ill}^S is the illness risk that is attributed to a single ENT source.

2.6. Risk characterization

The RWI risks at Baby Beach during dry weather conditions and wet weather (post-storm) conditions were assessed separately to account for the seasonal variation of ENT sources. For dry weather conditions, the observed ENT concentrations from either of the two dry weather scenarios (with stormwater diversion or with stormwater filter vault in effect) were also used separately. For wet weather conditions, different presumptive levels of ENT of sewage origin in stormwater runoff were included in the risk computation.

For both dry and wet weather RWI risk computation, the observed cumulative distribution of ENT GM values was binned into 2.5 percentile increments (from 2.5th to 97.5th percentile) for each scenario. Each increment was used to predict the range of each RWI risk using 1,000 iterations. For all of the risk calculation procedures, uniform random samplings from the range of

QMRA parameters as described in section 2.5 were also implemented. Each scenario of RWI risk distribution that comprised of 39,000 calculations was produced using predicted values from each percentile increment. This incremental computational approach reduced the power needed for continuous calculation. All computational procedures were performed using the software package, MATLAB 2014b (Natick, MA).

For risk characterization, it is important to highlight the difference between FIB-based and the illness-based risk benchmarks proposed by U.S. EPA. The RWQC illness benchmark of 36 illness cases per 1000 bathers (which is derived from epidemiological studies) does not equate to the QMRA RWI risk estimated from the maximum allowed ENT GM threshold of 35 CFU/100mL assuming sewage as the sole source of ENT (Schoen et al. 2011). In other words, using 35 CFU/100mL sewage ENT for QMRA would result in a median risk of 11 illness cases per 1000 bathers, which is significantly lower than the RWQC illness benchmark derived from epidemiological studies. This outcome is not surprising because: 1) not all human pathogens present in sewage are accounted for in the QMRA analysis; and 2) it is unlikely that all of the ENT measured in the epidemiological study (from which the threshold of 35 CFU/100 mL were based) were of raw sewage origin (see Supplementary Figure S3). To compare the illness risk associated with ENT from non-human sources with that of ENT from human sewage, the median QMRA risk value (11 cases per 1000 bathers) deduced from 35 CFU/100mL human sewage ENT is used as a benchmark, and termed as the “QMRA-equivalent risk of the EPA RWQC illness benchmark”.

3. RESULTS

3.1. RWI risks during dry weather conditions

Measurements of ENT at Baby Beach are expressed as cumulative distributions in the top panel of Figure 3. Approximately 12.5% of the ENT GM values exceeded the maximum allowed 30-day ENT GM threshold during the dry season, but none exceeded the STV. During the wet season the GM values exceeded the 30-day ENT GM threshold 25% of sample days, but still none of the GM values exceeded the STV (Table 3). It should be noted that although the exceedance of the GM threshold in any single day is not equivalent to a violation of the RWQC, it indicates a potential water quality issue.

An analysis of bather and bird count data suggest that ENT are primarily from human sources (bather shedding) during dry weather (Figure 3, Top panels). RWI risk based on the apportioned ENT sources and concentrations are shown in the bottom three panels of Figure 3. The RWI risk due to bird feces ($<10^{-4}$) is significantly lower (by two orders-of-magnitude) than the RWI risk attributed to bather shedding. The overall dry weather median RWI risk (red solid lines), attributable almost entirely from bather human shedding, was below 22 illness cases per 1000 bathers (Figure 3 bottom two panels). These results indicate that overall dry weather median RWI risk is below the RWQC illness risk benchmark 100% of the time. However, when compared to the QMRA-equivalent risk, approximately 5% and 15% of the median risks exceeded the benchmark during dry and wet season, respectively (Table 3).

3.2. RWI risks during wet weather conditions

The cumulative distribution of ENT concentrations at Baby Beach during wet weather is shown in Figure 4. Approximately 69% of the wet weather ENT concentrations at Baby Beach exceed

the ENT GM threshold of 35 CFU/100 mL, and 56% exceeded the STV. Our estimates of the RWI risk corresponding to these wet weather ENT concentrations are shown in Figure 5, for various levels of presumed sewage contamination. Remarkably, the wet weather median RWI risk at Baby Beach does not exceed any of the risk benchmarks provided the stormwater is not contaminated by primary sewage, even though the ENT concentrations exceed the EPA RWQC thresholds (Figure 5 and Table 3). However, the median RWI risk (red solid line) increases sharply if only 1% of the ENT in stormwater originates from sewage; approximately 27.5% of the median risks exceeded the QMRA-equivalent risk. On the other hand, our estimate of RWI risk is below the EPA RWQC illness threshold provided that <2% of ENT in stormwater are from human sewage (Table 3). Interestingly, the median RWI risk increases non-linearly with the percentage of ENT attributable to sewage.

Overall, the results showed that the wet weather RWI risks at Baby Beach were significantly affected by the sources of ENT input into the beach. Yet, these risks were deemed to be a constant risk when interpreted solely based on the ENT concentration and the ENT thresholds recommended by the EPA.

4. DISCUSSION

The case study presented here demonstrated the successful application of SA-QMRA in understanding of RWI risk at a non-point source pollution-impacted recreational beach. This approach is useful for developing site-specific recreational water quality criteria for polluted beaches. However, site-specific data including geographic setting, land-use, sanitary survey, historical FIB record, beach usage pattern, domestic animal and wildlife feces survey as well as contamination source tracking results are necessary to feed into the SA-QMRA model.

The experience from this SA-QMRA practice also highlights some important future improvements towards a more accurate and relevant risk assessment. For example, the number of visitors and bird counts at the beach as recorded by the County's janitors were used to estimate the ratio of bather sheddings and gull fecal events in apportioning the dry weather ENT source. However, the portion of visitors who actually recreate in the water and contribute to the ENT level is not known, which led to our conservative assumption of treating all visitors as bathers. The observational biases that are present in the data collected by different personnel (e.g. County's janitors) can also lead to inconsistent results, which were presumably mitigated by using an aggregated average of the data in this study. A more systematic method of data collection following a set of protocols, such as the classification of bathers among beach visitors and the sampling timeframe can therefore ensure consistency of the data and reduce observational bias. Nonetheless, as the total ENT at Baby Beach during the dry season is mostly below the EPA FIB threshold, the RWI risks mostly fall within the acceptable RWQC illness risk benchmark regardless of the source of the ENT. The precise contribution of bathers shedding would be more important at other sites when the higher percentage of total ENT exceed the EPA benchmark.

Furthermore, the wet weather risk result as presented in this study is very site-specific to the Baby Beach since only the level of sewage contamination in the stormwater is considered. Dog feces and bird feces although are likely contributors to the ENT level in storm runoff, the human health risk posted by these sources are two orders of magnitude lower than human source. It is justifiable to apportion the ENT to the high-risk source in this residential and commercial dominated watershed as a conservative estimation for the worst-case scenario. However, large watersheds are likely to have more complicated sources of ENT, including agriculture and other

human sources, which makes the source apportionment challenging. As shown by Soller et al. (Soller et al. 2010b), agriculture sources present much greater human health risks than bird feces and are approximately equivalent to secondary sewage. The precise apportionment to agricultural sources in such cases would be critical for accurate risk assessment and management, especially considering the similar risk potency of agricultural sources to that of human sources (see Supplementary Figure S3).

Despite the large range of presumptive sewage contamination in stormwater presented in this study, the RWI risk at Baby Beach is likely meeting the RWQC illness risk benchmark >95% of the times because the percentage of sewage ENT as part of the storm runoff collected by stormwater drains of Baby Beach is probably less than 5%. This assumption is supported by the dye studies that indicate no obvious connections with sewage system during the dry weather (Orange County Environmental Resources 2015b). The assumption for possible sewage contamination can be viewed as a conservative estimate or the worst-case scenario based on previous stormwater source tracking studies (Ellis and Butler 2015, Sauer et al. 2011). However, in comparison with the metropolitan watersheds of Milwaukee, Michigan — where up to 16% of sewage signal was detected among total bacteriodes in the stormwater collected —, the Baby Beach watershed is much smaller in size with far less complicated storm and sewer lines networks.

In a practical context, while the post-storm RWI risks are visibly elevated, fewer visitors would actually swim following storm events. The number of visitors to the beach also decline dramatically due to the lower water and air temperature during such weather conditions. This is especially the case at Baby Beach, which is popular for family-friendly activities. Overall, the

low numbers of RWI cases during the winter rainy months have been documented in a retrospective study of the number of RWI cases along Southern California coasts (Turbow et al. 2008). The decline in the number of bathers in the water also reduces the bather sheddings, which further reduces the level of risk. In rare occasions though, summer rain could occur, especially with the uncertainties associated with the changing climate. Beach managers should be prepared for these unexpected circumstances since post-storm illness risks in summer can have much greater health impacts due to the large number of beach visitors to the beach. The popular surfing beaches may, however, present a slightly different scenario with the avid surfers in search of big waves and less crowded water during the storm and post-storm conditions (SCCRWP 2016).

Increasing efforts have been placed on rain and stormwater capture and treatment through low impact developments (Grant et al. 2013, Grant et al. 2012, Hatt et al. 2007, Hatt et al. 2006). However, reducing FIB in storm runoff to meet water quality criteria would be a challenging task due to large water volume generated by storm events and also the many different FIB sources that would cause a shock loading of FIB into the receiving waters (Surbeck et al. 2006). Understanding how the RWI risks vary with the weather conditions and different sources of FIB, therefore, have important risk management implications for non-point source-influenced beaches to comply with the wet weather TMDL (Total Maximum Daily Load), especially when the true RWI risk is only depending on the portion of FIB in the storm runoff that are associated with human pathogens.

Risk management based on quantified risks has strong merits than that solely based on an indirect risk measure (i.e. FIB criteria). By using a regulatory FIB threshold, the RWI risk is only

categorized as a dichotomous measure: acceptable or unacceptable; the magnitude of the risk is not understood for facilitating a more layered decision-making process that optimizes the trade-off between risk and reward (higher human illnesses for higher swimmability and vice versa) (Nevers et al. 2013). This dichotomous decision also ignores the probabilistic nature of RWI risk, wherein the true risk is conditional on many confounding factors that simply cannot be generalized by any number of epidemiological studies. Moreover, epidemiological studies are very costly to conduct and are not always a suitable option for all types of beaches, especially for a smaller beach with many visitors (i.e. $\geq 50,000$ visitors annually) that requires the implementation of a robust health risk management plan, but do not receive enough visitors to warrant a reliable epidemiological study.

Under such circumstances, QMRA provides a useful alternative for health risk assessment that allows for scenario explorations through leveraging the findings of epidemiological studies. For instance, the epidemiological study at Doheny State Beach conducted by Colford et al. (Colford et al. 2012) had supported the importance of identifying ENT source for indicating the RWI risk of recreational waters. In their study, Colford et al. suggested a significant association between FIB and RWI when the berm that block the discharge of urban runoff to the beach is opened, but such association is not significant when the berm is closed. The berm status is likened to the presence/absence of anthropogenic influence (e.g. diversion of/input from wastewater effluent) on the water quality of recreational water, which can be used to improve our conceptual understanding of FIB as conditional risk indicators. It is also important to note that QMRA only provides us with a conceptual estimate of the risk, whose validity should be supported by hard data that may be provided by epidemiological study whenever feasible or possible.

The practical value of the RWI risk estimates derived from QMRA is made more credible when the estimates align with comparable empirical illness cases reported by epidemiological studies, in which a good agreement is usually defined by the same order-of-magnitude difference between the RWI risk estimate and the empirical RWI cases. The difference between the two can only be reduced to a certain extent because QMRA risk estimates are based on the availability of dose-response models for a few known pathogens. These estimates likely do not cover the complete suite of pathogens that are present in the water and cause RWI among bathers. Moreover, the definition of illness adopted by the RWQC may encompass more illness symptoms (e.g. various combination of vomiting, diarrhea, stomachache, and/or nausea) than the gastroenteritis as represented by QMRA. These differences further explain for the lower RWI risk estimate based on QMRA than the empirical RWI cases reported. Although both risk benchmarks are within the same order of magnitude, the QMRA-equivalent risks are slightly lower than RWQC illness risk as defined by previous epidemiological studies (i.e. NEEAR studies). Presumably, this gap can be further narrowed by refinement of dose-response models and a better understanding of the indicator and pathogen relationships associated with different sources of ENT. Until such refinements are undertaken, SA-QMRA results should be compared to the QMRA-equivalent risk to avoid underestimating the true RWI risk.

For practical application, the use of QMRA result for RWI management should be facilitated through benchmarking against a uniform risk standard. Since important decision-making and risk management strategies are often made through the comparison of the QMRA risk result with a specific risk benchmark, it is imperative to select an appropriate risk benchmark that serves the best interests of the stakeholders. As was demonstrated in the present study, only about 5% of the median RWI risks in wet weather would exceed the RWQC illness risk benchmark even when 5%

of ENT in the storm runoff was of sewage origin. Yet, using QMRA-equivalent risks as benchmarks, the exceedance rate will be between 20-45% at the same level of sewage contamination. Presently, the use of QMRA-equivalent risk as risk benchmark has not been embraced for recreational beach management since RWI has been built around epidemiological studies. Based on these sets of considerations, the SA-QMRA methodology can be further refined and standardized. Through the standardization of the method, it is desirable that an illness risk ruler/standard can be established, which can be used as a RWI risk benchmark for ensuring the adequate recreational safety of non-point sources beaches.

5. CONCLUSION

A new SA-QMRA approach for risk management based on the site-specific condition of a small semi-enclosed Southern California Beach is carried out to understand the recreational health safety that is currently regulated only by the water quality criteria developed for point-source impacted beaches through epidemiological studies. The following conclusions can be made from the results of the study:

- Exceeding the EPA ENT numerical concentration standard is not always indicating the violation of the EPA RWQC illness risk standard derived from epidemiological studies because the magnitudes of illness risks are most sensitive to the presence of ENT of human waste origin.
- The inclusion of gull feces as a source of ENT contamination at the beach did not have a significant impact on the level of the overall illness risk.

- During wet weather conditions, the median RWI risks varied significantly depending on the hypothetical degree of sewage contamination of the stormwater. The magnitude of the risk is proportional to the level of contamination but in a non-linear function.
- SA-QMRA outcomes facilitate a more layered decision-making process that captures the probabilistic nature of RWI risk, which is in contrast with ENT numerical benchmarks that only categorize the water quality into dichotomous measure.
- Finally, the results of the study highlight the importance of risk benchmark that serves the best interests of the stakeholders. To facilitate the practical application of SA-QMRA, a QMRA-based risk benchmark is needed to establish an acceptable level of RWI risk at non-point source impacted beaches.

ACKNOWLEDGEMENTS

Funding for this research is partially provided by U.S. National Science Foundation Partnerships for International Research and Education (OISE-1243543).

Figure Legends

Figure 1. Study site at Baby Beach, Dana Point, California and its surrounding land uses.

Figure 2. Flow diagram indicates modeling procedures and information flow in risk analysis.

Figure 3. Top panel: cumulative distribution of dry weather ENT GM concentrations and source apportionments under two dry weather conditions. Two vertical lines indicate the EPA ENT GM threshold and STV benchmark, respectively. The horizontal lines indicate the exceedance rates for each benchmark. Bottom three panels: The RWI risks that are associated with each percentile value of ENT concentration for ENT assigned to gull feces (panel 2), human sheddings (panel 3), and overall ENT (panel 4). The median risk value is shown as the red curve and is bounded by the interquartile range (yellow area) and the 10th-90th percentile range of the risk (pink area). The EPA RWQC illness risk benchmark and the median QMRA-equivalent risks based on the ENT GM threshold were also plotted as vertical lines on the bottom three panels.

Figure 4. Empirical cumulative distribution of the wet weather ENT GM concentrations used for assessing the wet weather RWI risks. EPA ENT thresholds and the dry weather GM for Baby Beach during wet season were also plotted to benchmark the exceedance rates of the wet weather ENT level at Baby Beach.

Figure 5. Wet weather RWI risks at Baby Beach as a function of the percentile values of wet weather ENT concentrations and the hypothetical percentage of sewage ENT in stormwater. The median risk value is shown as the red curve and is bounded by the interquartile range (yellow area) and the 10th-90th percentile range of the risk (pink area). The EPA RWQC illness risk benchmark and the median QMRA-equivalent risks based on the ENT GM threshold are also plotted as vertical lines.

REFERENCES

- Abdelzaher, A.M., Wright, M.E., Ortega, C., Hasan, A.R., Shibata, T., Solo-Gabriele, H.M., Kish, J., Withum, K., He, G. and Elmir, S.M. (2011) Daily measures of microbes and human health at a non-point source marine beach. *Journal of Water and Health* 9(3), 443-457.
- Arnold, B.F., Schiff, K.C., Griffith, J.F., Gruber, J.S., Yau, V., Wright, C.C., Wade, T.J., Burns, S., Hayes, J.M. and McGee, C. (2013) Swimmer illness associated with marine water exposure and water quality indicators: impact of widely used assumptions. *Epidemiology* 24(6), 845-853.
- Boehm, A., Ashbolt, N., Colford, J., Dunbar, L., Fleming, L., Gold, M., Hansel, J., Hunter, P., Ichida, A. and McGee, C. (2009) A sea change ahead for recreational water quality criteria. *Journal of Water and Health* 7(1), 9-20.
- Boehm, A.B., Grant, S.B., Kim, J.H., Mowbray, S.L., McGee, C.D., Clark, C.D., Foley, D.M. and Wellman, D.E. (2002) Decadal and shorter period variability of surf zone water quality at Huntington Beach, California. *Environmental science & technology* 36(18), 3885-3892.
- Boehm, A.B. and Soller, J.A. (2013) Environmental Toxicology: Selected Entries from the Encyclopedia of Sustainability Science and Technology. Laws, E.A. (ed), pp. 441-459, Springer New York, New York, NY.
- Byappanahalli, M.N., Nevers, M.B., Korajkic, A., Staley, Z.R. and Harwood, V.J. (2012) Enterococci in the environment. *Microbiology and Molecular Biology Reviews* 76(4), 685-706.
- Colford, J.M., Schiff, K.C., Griffith, J.F., Yau, V., Arnold, B.F., Wright, C.C., Gruber, J.S., Wade, T.J., Burns, S. and Hayes, J. (2012) Using rapid indicators for Enterococcus to assess the risk of illness after exposure to urban runoff contaminated marine water. *Water research* 46(7), 2176-2186.
- Colford Jr, J.M., Wade, T.J., Schiff, K.C., Wright, C.C., Griffith, J.F., Sandhu, S.K., Burns, S., Sobsey, M., Lovelace, G. and Weisberg, S.B. (2007) Water quality indicators and the risk of illness at beaches with nonpoint sources of fecal contamination. *Epidemiology* 18(1), 27-35.
- County of Orange & City of Dana Point (2011) Baby Beach Dana Point Harbor Bacterial Indicator Total Maximum Daily Load, Annual progress report FY 2009-2010. Available at: <http://cms.ocgov.com/gov/pw/watersheds/programs/ourws/dpcoastalstreams/dphbabybeach/csbabybeach.asp> (accessed November 15, 2016)
- Craun, G.F., Calderon, R.L. and Craun, M.F. (2005) Outbreaks associated with recreational water in the United States. *International journal of environmental health research* 15(4), 243-262.
- Dorsey, J.H. (2010) Improving water quality through California's Clean Beach Initiative: an assessment of 17 projects. *Environmental monitoring and assessment* 166(1-4), 95-111.
- Dufour, A., Evans, O., Behymer, T. and Cantu, R. (2006) Water ingestion during swimming activities in a pool: a pilot study. *Journal of Water and Health* 4(4), 425-430.
- Ellis, J.B. and Butler, D. (2015) Surface water sewer misconnections in England and Wales: Pollution sources and impacts. *Science of The Total Environment* 526, 98-109.
- Elmir, S.M., Shibata, T., Solo-Gabriele, H.M., Sinigalliano, C.D., Gidley, M.L., Miller, G., Plano, L.R., Kish, J., Withum, K. and Fleming, L.E. (2009) Quantitative evaluation of enterococci and Bacteroidales released by adults and toddlers in marine water. *Water research* 43(18), 4610-4616.

- Elmir, S.M., Wright, M.E., Abdelzaher, A., Solo-Gabriele, H.M., Fleming, L.E., Miller, G., Rybolowik, M., Shih, M.-T.P., Pillai, S.P. and Cooper, J.A. (2007) Quantitative evaluation of bacteria released by bathers in a marine water. *Water research* 41(1), 3-10.
- Fleisher, J.M., Fleming, L.E., Solo-Gabriele, H.M., Kish, J.K., Sinigalliano, C.D., Plano, L., Elmir, S.M., Wang, J.D., Withum, K. and Shibata, T. (2010) The BEACHES Study: health effects and exposures from non-point source microbial contaminants in subtropical recreational marine waters. *International journal of epidemiology* 39(5), 1291-1298.
- Fung, D.Y., Fujioka, R., Vijayavel, K., Sato, D. and Bishop, D. (2007) Evaluation of Fung double tube test for *Clostridium Perfringens* and easyphage test for F-specific RNA coliphages as rapid screening tests for fecal contamination in recreational waters of Hawaii. *Journal of Rapid Methods & Automation in Microbiology* 15(3), 217-229.
- Given, S., Pendleton, L.H. and Boehm, A.B. (2006) Regional public health cost estimates of contaminated coastal waters: A case study of gastroenteritis at southern california beaches. *Environmental science & technology* 40(16), 4851-4858.
- Graczyk, T.K., Sunderland, D., Awantang, G.N., Mashinski, Y., Lucy, F.E., Graczyk, Z., Chomicz, L. and Breyse, P.N. (2010) Relationships among bather density, levels of human waterborne pathogens, and fecal coliform counts in marine recreational beach water. *Parasitology research* 106(5), 1103-1108.
- Grant, S.B., Fletcher, T.D., Feldman, D., Saphores, J.D., Cook, P.L.M., Stewardson, M., Low, K., Burry, K. and Hamilton, A.J. (2013) Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia. *Environmental science & technology* 47(19), 10727-10734.
- Grant, S.B., Saphores, J.D., Feldman, D.L., Hamilton, A.J., Fletcher, T.D., Cook, P.L.M., Stewardson, M., Sanders, B.F., Levin, L.A., Ambrose, R.F., Deletic, A., Brown, R., Jiang, S.C., Rosso, D., Cooper, W.J. and Marusic, I. (2012) Taking the "Waste" Out of "Wastewater" for Human Water Security and Ecosystem Sustainability. *Science* 337(6095), 681-686.
- Haas, C.N., Rose, J.B. and Gerba, C.P. (1999) *Quantitative microbial risk assessment*, John Wiley & Sons.
- Harwood, V.J., Staley, C., Badgley, B.D., Borges, K. and Korajkic, A. (2014) Microbial source tracking markers for detection of fecal contamination in environmental waters: relationships between pathogens and human health outcomes. *FEMS microbiology reviews* 38(1), 1-40.
- Hatt, B., Deletic, A. and Fletcher, T. (2007) Stormwater reuse: designing biofiltration systems for reliable treatment. *Water Science & Technology* 55(4), 201-209.
- Hatt, B.E., Deletic, A. and Fletcher, T.D. (2006) Integrated treatment and recycling of stormwater: a review of Australian practice. *Journal of Environmental Management* 79(1), 102-113.
- Jiang, S.C., Chu, W. and He, J.-W. (2007) Seasonal detection of human viruses and coliphage in Newport Bay, California. *Applied and environmental microbiology* 73(20), 6468-6474.
- Kim, J.H. and Grant, S.B. (2004) Public mis-notification of coastal water quality: A probabilistic evaluation of posting errors at Huntington Beach, California. *Environmental science & technology* 38(9), 2497-2504.
- Love, D.C., Rodriguez, R.A., Gibbons, C.D., Griffith, J.F., Yu, Q., Stewart, J.R. and Sobsey, M.D. (2014) Human viruses and viral indicators in marine water at two recreational beaches in Southern California, USA. *Journal of Water and Health* 12(1), 136-150.
- Marsalek, J. and Rochfort, Q. (2004) Urban wet-weather flows: sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. *Journal of Toxicology and Environmental Health, Part A* 67(20-22), 1765-1777.

McQuaig, S., Griffith, J. and Harwood, V.J. (2012) Association of fecal indicator bacteria with human viruses and microbial source tracking markers at coastal beaches impacted by nonpoint source pollution. *Applied and environmental microbiology* 78(18), 6423-6432.

Nevers, M.B., Byappanahalli, M.N. and Whitman, R.L. (2013) Choices in recreational water quality monitoring: new opportunities and health risk trade-offs. *Environmental science & technology* 47(7), 3073-3081.

Orange County Environmental Resources (2015a) Beach sweeping report by OC Dana point harbor through contract with Dana West Marina: Logging of human visitors, birds, and bird feces counts 2007 to 2009.

Orange County Environmental Resources (2015b) Sanitary survey, BMP investigation, & Sewer investigation/repairs (Internal report).

Orange County Public Health Laboratory, Science Applications International Corporation and Department, C.o.O.P.F.R. (2003) Baby Beach Bacteriological Special Studies Report Dana Point Harbor, California. Available at: <http://ocwaterlab.com/civicax/filebank/blobdload.aspx?BlobID=10343> (accessed November 16, 2015).

Orange County Public Works Historic Rainfall Data, San Clemente (Palisades Reservoir). Available at: <http://prg.ocpublicworks.com/DocmgmtInternet/Download.aspx?id=947> (accessed November 16, 2015).

Piggot, A.M., Klaus, J.S., Johnson, S., Phillips, M.C. and Solo-Gabriele, H.M. (2012) Relationship between enterococcal levels and sediment biofilms at recreational beaches in South Florida. *Applied and environmental microbiology* 78(17), 5973-5982.

Prüss, A. (1998) Review of epidemiological studies on health effects from exposure to recreational water. *International journal of epidemiology* 27(1), 1-9.

Rippy, M.A., Stein, R., Sanders, B.F., Davis, K., McLaughlin, K., Skinner, J.F., Kappeler, J. and Grant, S.B. (2014) Small Drains, Big Problems: The Impact of Dry Weather Runoff on Shoreline Water Quality at Enclosed Beaches. *Environmental science & technology* 48(24), 14168-14177.

Sauer, E.P., VandeWalle, J.L., Bootsma, M.J. and McLellan, S.L. (2011) Detection of the human specific *Bacteroides* genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment. *Water research* 45(14), 4081-4091.

SCCRWP (2016) The Surfer Health Study, A three-year study examining illness rates associated with surfing during wet weather. Available at: http://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/943_SurferHealthStudy.pdf (accessed November 16, 2016).

Schets, F.M., Schijven, J.F. and de Roda Husman, A.M. (2011) Exposure assessment for swimmers in bathing waters and swimming pools. *Water research* 45(7), 2392-2400.

Science Applications International Corporation (2003) Data mining task for state of the beach report: Evaluation of bacteriological data and associated parameters for Baby Beach, Dana Point Harbor, CA. Available at: <http://cms.ocgov.com/civicax/filebank/blobdload.aspx?BlobID=10353> (accessed November 17, 2016).

Sercu, B., Werfhorst, L.C.V.D., Murray, J. and Holden, P.A. (2008) Storm drains are sources of human fecal pollution during dry weather in three urban southern California watersheds. *Environmental science & technology* 43(2), 293-298.

- Soller, J.A., Bartrand, T., Ashbolt, N.J., Ravenscroft, J. and Wade, T.J. (2010a) Estimating the primary etiologic agents in recreational freshwaters impacted by human sources of faecal contamination. *Water research* 44(16), 4736-4747.
- Soller, J.A., Eftim, S., Wade, T.J., Ichida, A.M., Clancy, J.L., Johnson, T., Schwab, K., Ramirez-Toro, G., Nappier, S. and Ravenscroft, J.E. (2015) Use of quantitative microbial risk assessment to improve interpretation of a recreational water epidemiological study. *Microbial Risk Analysis* 1, 2-11.
- Soller, J.A., Schoen, M.E., Bartrand, T., Ravenscroft, J.E. and Ashbolt, N.J. (2010b) Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water research* 44(16), 4674-4691.
- Soller, J.A., Schoen, M.E., Varghese, A., Ichida, A.M., Boehm, A.B., Eftim, S., Ashbolt, N.J. and Ravenscroft, J.E. (2014) Human health risk implications of multiple sources of faecal indicator bacteria in a recreational waterbody. *Water research* 66, 254-264.
- State Water Resources Control Board (2004) Water Quality Control Policy for Developing California's Clean Water Act Section 303(d) List. Available at: http://www.waterboards.ca.gov/water_issues/programs/tmdl/docs/ffed_303d_listingpolicy093004.pdf (accessed November 17, 2016).
- Surbeck, C.Q., Jiang, S.C., Ahn, J.H. and Grant, S.B. (2006) Flow fingerprinting fecal pollution and suspended solids in stormwater runoff from an urban coastal watershed. *Environmental science & technology* 40(14), 4435-4441.
- Turbow, D.J., Kent, E.E. and Jiang, S.C. (2008) Web-based investigation of water associated illness in marine bathers. *Environmental research* 106(1), 101-109.
- U.S. EPA (2012) Recreational Water Quality Criteria, EPA 820-F-12-058. Office of Water, Washington, DC, United States Environmental Protection Agency.
- Whitman, R.L., Shively, D.A., Pawlik, H., Nevers, M.B. and Byappanahalli, M.N. (2003) Occurrence of *Escherichia coli* and enterococci in *Cladophora* (Chlorophyta) in nearshore water and beach sand of Lake Michigan. *Applied and environmental microbiology* 69(8), 4714-4719.
- Wright, M.E., Solo-Gabriele, H.M., Elmir, S. and Fleming, L.E. (2009) Microbial load from animal feces at a recreational beach. *Marine Pollution Bulletin* 58(11), 1649-1656.

Table 1. Summary of parameters used in Equation 5.

Source	Primary sewage		Gulls			
	Density of ENT or reference pathogen in sewage (log ₁₀ range) ^a	References	Density of ENT or reference pathogen in fecal waste (log ₁₀ range) ^b	Fraction of human-infectious strain	Prevalence of human infection potential	References
<i>Enterococcus</i>	5.8—8	1, 2	6.0—8.0	-	-	
<i>Cryptosporidium spp.</i>	-0.3—2.6	3	5.5—8.4	None reported	None reported	
<i>Giardia lamblia</i>	0.8—4	3	None reported	None reported	None reported	
<i>Campylobacter jejuni</i>	Non-detected—2.3 ^c	2, 4	3.3—6.0	1.0	0—0.33	5, 6
<i>E. coli</i> O157:H7	Non-detected—3.3 ^c	7	None reported	None reported	None reported	
<i>Salmonella enterica</i>	0.5—3	2	2.3—9.0	1.0	0—0.33	5, 6
Norovirus	3—6	8, 9	Not applicable	Not applicable	Not applicable	

^aThe units in log₁₀ scale for *Enterococcus*, *Campylobacter jejuni*, *E. coli* O157:H7, and *Salmonella enterica* are in CFU/L; for *Cryptosporidium spp.* and *Giardia lamblia* is in oocysts/L and cysts/L, respectively; and for norovirus is gc/L.

^bThe units in log₁₀ scale for *Enterococcus*, *Campylobacter jejuni*, and *Salmonella enterica* are in CFU/g; for *Cryptosporidium spp.* is in oocysts/g.

^cNon-detect is imputed as log₁₀(1), which correspond to “0” on normal scale., for QMRA calculation.

Table 2: Dose-response models and parameters used in this study.

Reference pathogen	Form of model	Model parameters	% of infections resulting in illness	Reference
<i>Cryptosporidium spp.</i>	Exponential	$r=0.09$	50%	10
<i>Giardia lamblia</i>	Exponential	$r=0.0199$	45%	11
<i>Campylobacter jejuni</i>	Beta-Poisson	$\alpha=0.145$ $\beta=7.59$	28%	12, 13
<i>E. coli</i> O157:H7	Beta-Poisson	$\alpha=0.4$ $\beta=45.9$	28%	14
<i>Salmonella enterica</i>	Beta-Poisson	$\alpha=0.3126$ $\beta=2884$	20%	11
Norovirus	Hypergeometric	$\alpha=0.04$ $\beta=0.055$	60%	15

Table 3. Exceedance rate of ENT concentrations and RWI risks (median values) at Baby Beach based on different ENT and risk benchmarks.

		Percentage of ENT concentration exceeding each ENT threshold		Percentage of RWI risk exceeding each risk benchmark	
<i>Types of weather</i>		<i>RWQC ENT GM threshold (35CFU/ 100Ll)</i>	<i>RWQC ENT STV (130CFU/ 100mL)</i>	<i>Median QMRA risk at GM threshold (QMRA-equivalent)</i>	<i>RWQC illness risk</i>
Dry weather	Dry season (urban runoff diverted)	12.5	0.0	5.0	0.0
	Wet season (urban runoff filtered, but not diverted)	25.0	0.0	15.0	0.0
Wet weather	% of ENT of sewage origin				
	0%	69.1	44.1	0.0	0.0
	1%	69.1	44.1	27.5	0.0
	2%	69.1	44.1	40.0	0.0
	3%	69.1	44.1	42.5	2.5
	4%	69.1	44.1	45.0	5.0
	5%	69.1	44.1	45.0	5.0
	10%	69.1	44.1	57.5	20.0
	15%	69.1	44.1	57.5	27.5
	20%	69.1	44.1	62.5	27.5
	100%	69.1	44.1	80.0	57.5

References

1. George, T.; Franklin, L.; Stensel, H. D., Wastewater engineering: treatment and reuse. *Metcalf & Eddy, Inc., New York* **2003**.
2. Lemarchand, K.; Lebaron, P., Occurrence of *Salmonella* spp. and *Cryptosporidium* spp. in a French coastal watershed: relationship with fecal indicators. *FEMS Microbiology Letters* **2003**, *218*, (1), 203-209.
3. Rose, J. B.; Farrah, S. R.; Harwood, V. J.; Levine, A.; Lukasik, J.; Menendez, P.; Scott, T. M., *Reduction of pathogens, indicator bacteria, and alternative indicators by wastewater treatment and reclamation processes*. Water Environment Research Foundation: 2004.
4. Stampi, S.; Varoli, O.; Zanetti, F.; De Luca, G., *Arcobacter cryaerophilus* and thermophilic campylobacters in a sewage treatment plant in Italy: two secondary treatments compared. *Epidemiology and infection* **1993**, *110*, (03), 633-639.
5. Lévesque, B. t.; Brousseau, P.; Bernier, F.; Dewailly, É.; Joly, J., Study of the bacterial content of ring-billed gull droppings in relation to recreational water quality. *Water Research* **2000**, *34*, (4), 1089-1096.
6. Soller, J. A.; Schoen, M. E.; Bartrand, T.; Ravenscroft, J. E.; Ashbolt, N. J., Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water Research* **2010**, *44*, (16), 4674-4691.
7. García-Aljaro, C.; Bonjoch, X.; Blanch, A., Combined use of an immunomagnetic separation method and immunoblotting for the enumeration and isolation of *Escherichia coli* O157 in wastewaters. *Journal of applied microbiology* **2005**, *98*, (3), 589-597.
8. Haramoto, E.; Katayama, H.; Oguma, K.; Yamashita, H.; Tajima, A.; Nakajima, H.; Ohgaki, S., Seasonal profiles of human noroviruses and indicator bacteria in a wastewater treatment plant in Tokyo, Japan. *Water Science & Technology* **2006**, *54*, (11-12), 301-308.
9. Katayama, H.; Haramoto, E.; Oguma, K.; Yamashita, H.; Tajima, A.; Nakajima, H.; Ohgaki, S., One-year monthly quantitative survey of noroviruses, enteroviruses, and adenoviruses in wastewater collected from six plants in Japan. *Water research* **2008**, *42*, (6), 1441-1448.
10. U.S. EPA, National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR): Final Rule. In Federal Register: 2006; Vol. 71, pp 654-702.
11. Haas, C. N.; Rose, J. B.; Gerba, C. P., *Quantitative microbial risk assessment*. John Wiley & Sons: 1999.
12. Medema, G.; Teunis, P.; Havelaar, A.; Haas, C., Assessment of the dose-response relationship of *Campylobacter jejuni*. *International Journal of Food Microbiology* **1996**, *30*, (1), 101-111.
13. Teunis, P. F. M.; Havelaar, A., The dose-response relation in human volunteers for gastro-intestinal pathogens. **1996**.

14. Teunis, P.; Ogden, I.; Strachan, N., Hierarchical dose response of E. coli O157: H7 from human outbreaks incorporating heterogeneity in exposure. *Epidemiology and Infection* **2008**, *136*, (06), 761-770.
15. Teunis, P. F.; Moe, C. L.; Liu, P.; E Miller, S.; Lindesmith, L.; Baric, R. S.; Le Pendu, J.; Calderon, R. L., Norwalk virus: how infectious is it? *Journal of medical virology* **2008**, *80*, (8), 1468-1476.

Figure1

Figure2

Figure3

Figure4

Figure5

Recreational water illness risks during dry and wet weather