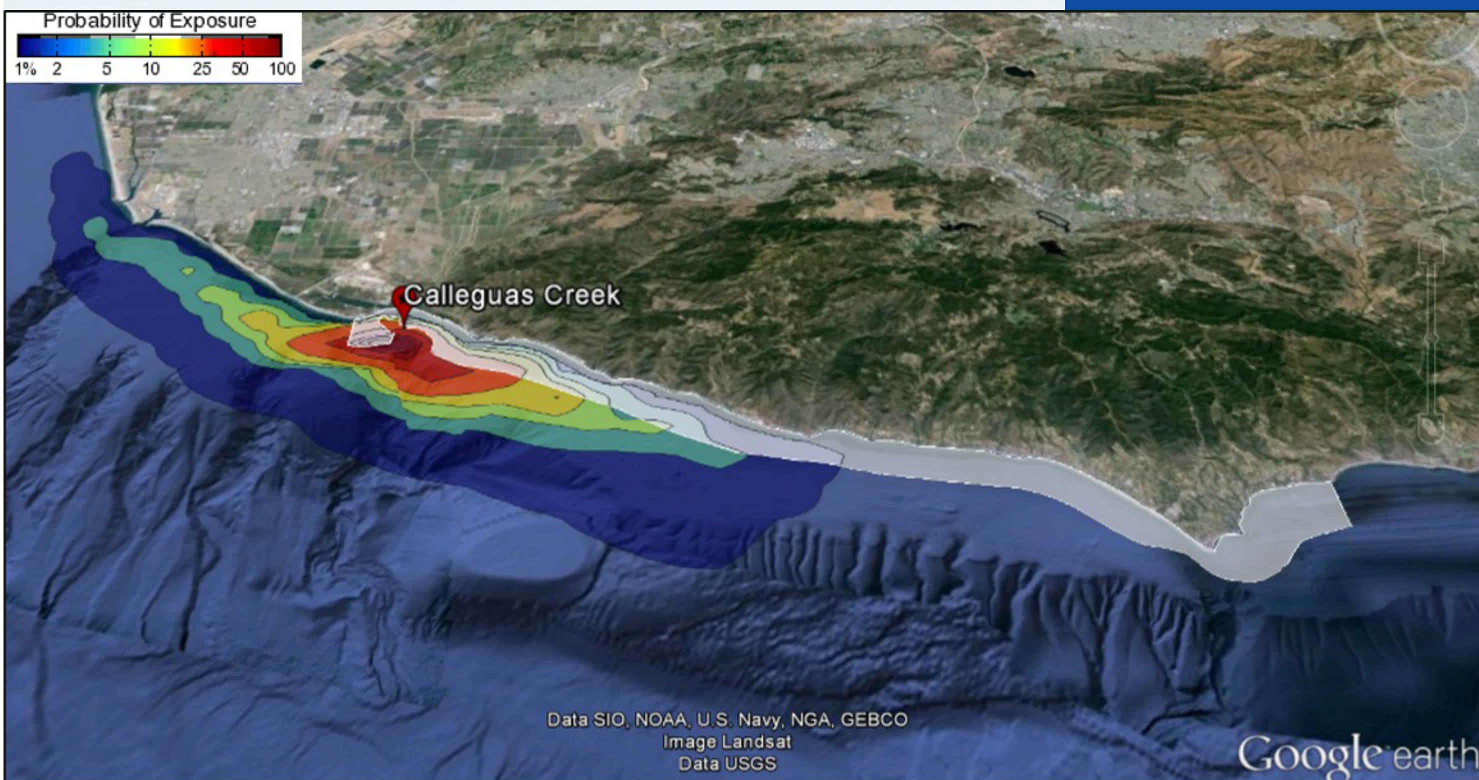
Assessing Areas of Special Biological Significance Exposure to Stormwater Plumes Using a Surface Transport Model



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Technical Report 817

Final Report

Assessing Areas of Special Biological Significance Exposure to Stormwater Plumes Using a Surface Transport Model

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March 18, 2014

Technical Report 817

EXECUTIVE SUMMARY

Introduction

Areas of Special Biological Significance (ASBS) are state water quality protected areas that, by legislative order, are not allowed to "receive discharges of waste" and must "maintain natural water quality." However, there are currently over 1,600 stormwater outfalls to ASBS statewide, the vast majority draining extremely small coastal catchments. The regulated parties have been rigorously working with the State Water Resources Control Board to ensure these outfalls do not contain waste. Meanwhile, much larger watersheds that discharge nearby ASBS, but not in them, are not subject to ASBS regulations. As a result, there is concern that plumes from these much larger watersheds may be transported into ASBS altering natural water quality. The goal of this study is to conduct preliminary modeling exercises to assess the potential of the plumes from large, neighboring watersheds to negatively impact ASBS water quality in southern California.

Methods

The conceptual approach for this study was to estimate the probability of plume exposure in ASBS based on a transport model that uses High Frequency (HF) radar derived surface current data as input. The model used two years (January 1 2008 - December 31, 2009) of surface current data for model runs and was applied to 20 rivers that discharge proximal to six ASBS from Malibu to San Diego. The plume probability exposure map was created by tracking 50 virtual water parcels released hourly, 1 km offshore of each river system. The cumulative number of tracers for a moving 3-day window (3600 tracers) were tracked for a given modeled time period. The probability of exposure was calculated for each ASBS by dividing the total number of virtual water parcel tracers advected into the ASBS by the total number of parcels introduced into the study region. A detailed description of the model assumptions, limitations and validation results is included in the full report.

Plume Exposure Probability

The ASBS with the greatest extent and largest magnitude of exposure probability is the Mugu Lagoon to Latigo Point ASBS (Table 1, Figure 1). Nearly half of this ASBS has a probability of plume exposure between 10-20% from the discharge of Calleguas Creek. The Robert Badham and Irvine Coast ASBS had the second greatest extent and magnitude of exposure probability; 100% of these ASBS had a probability of exposure between 1-10% from the discharge through Newport Bay. The ASBS with the least extent and smallest magnitude of exposure probability is Heisler Park where there was virtually no (<1%) probability of plume exposure. However, the probability of exposure from the Laguna Canyon Channel could not be determined.

The next steps for the Mugu Lagoon to Latigo Point or Robert Badham ASBS is to conduct more detailed studies focused on empirically measured plume tracers and associated water quality. Examples of appropriate follow-up studies might include ship-based salinity and turbidity measurements, in conjunction with real-time HFR surface currents. These measurements can then be placed in context with similar measurements from the smaller, but more localized, regulated ASBS discharges.

Table 1. Relative extent (as % of ASBS) of increasing plume exposure probabilities from neighboring river discharges. Modeled estimates of exposure are on an annual basis from 2008–2009.

ASBS Name	River	Extent of ASBS Potentially Impacted			
		Probability 0%	Probability <1%	Probability 1-10%	Probability 10-20%
Mugu Lagoon to Latigo Point	Calleguas Creek	53%			47%
	Malibu Creek	84%		16%	
Robert Badham	Newport Bay			100%	
Irvine Coast	Newport Bay			100%	
Heisler Park	Aliso Creek		100%		
	Laguna Canyon				
San Diego - Scripps	Los Penasquitos		100%		

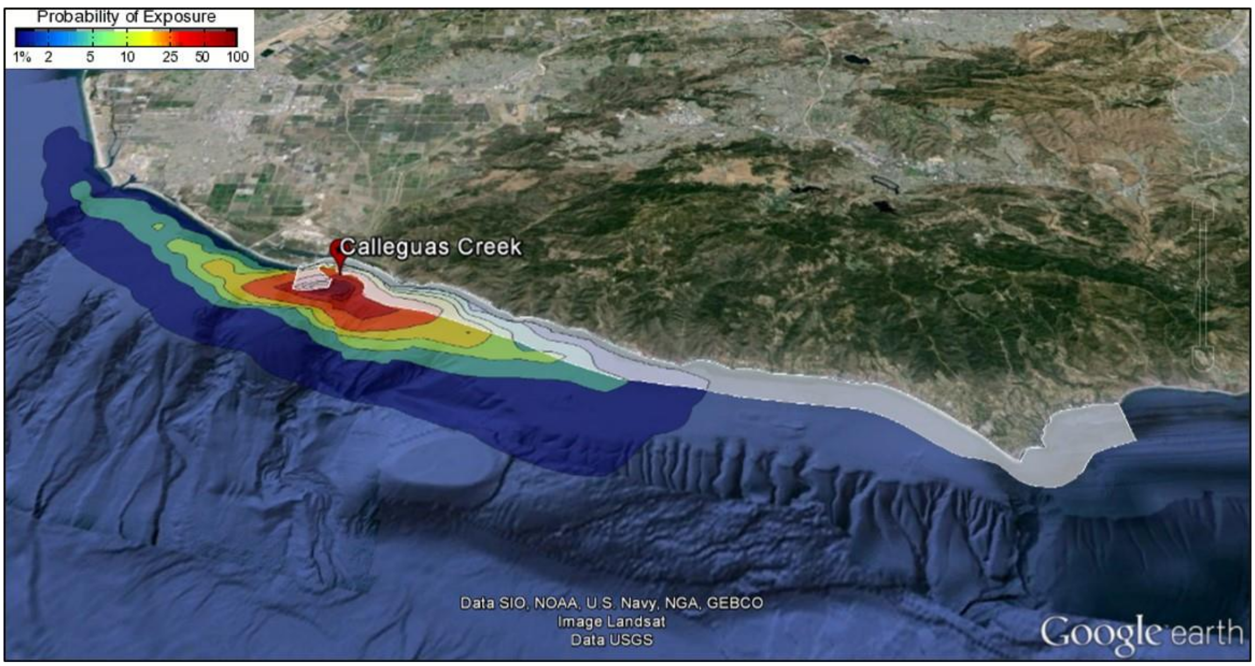

Figure 1. Plume probability contours for the Calleguas Creek watershed adjacent to the Mugu Lagoon to Latigo Point ASBS (in translucent white).

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INTRODUCTION

The urbanization of Southern California has resulted in one of the most densely populated coastal regions in the country. The coastal waters of the Southern California Bight (SCB) is typically the final destination for pollutants originating from the coastal counties of San Diego, Orange, Los Angeles, Ventura, and Santa Barbara which account for approximately 25% of the total US coastal population (Culliton et al. 2010). These pollutants, including pesticides, fertilizers, trace metals, synthetic organic compounds, petroleum, and pathogens, generally enter the coastal waters through two main pathways: seasonally variable stormwater runoff from urbanized watersheds and wastewater discharge from publicly owned treatment works (POTWs) and shoreline industries (DiGiacomo et al. 2004). However, various studies have concluded that stormwater runoff is the primary source of contamination that adversely affects the coastal ecosystem and human health (Ackerman and Weisberg 2003, Bay et al 2003, Noble et al. 2003, Schiff and Bay 2003, Reeves et al. 2004, Nezlin and Stein 2005). Seasonally variable storm events during the wet season (October through April) contribute to more than 95% of the annual runoff volume and pollutant load in the SCB (Schiff et al. 2001). The issue of runoff contamination is exacerbated by continual development (i.e., more impervious surfaces), increases in the number of sources, and concentrations of pollutants that accompany regional population increases. Additionally, sanitary and stormwater systems in Southern California are separate, thus the runoff receives minimal treatment prior to discharge into the ocean (Lyon and Stein 2009).

The California State Water Resources Control Board (SWRCB) has designated 34 Areas of Special Biological Significance (ASBS) to protect and preserve biological communities that are diverse and abundant with marine life with mandates of “no discharge of waste” and maintenance of “natural water quality” (SWRCB 2005) (Figure S1, Supporting Information). While the SWRCB restricts the flow of discharge into these protected areas, the transport of urban runoff by hypopycnal (surface) plumes advected into ASBS has the potential to negatively affect water quality within these protected zones. Schiff et al. (2011) analyzed water quality from urban storm drain outfalls discharging into ASBS, but did not determine the potential effects of urban runoff from rivers. To our knowledge, few studies have focused on the potential exposure of ASBS to stormwater river plumes.

A plume exposure hindcast model, driven by surface current data observed by a network of high-frequency (HF) radars, was used to generate probability exposure maps for 21 coastal discharges (Figure 2) located throughout Southern California. The resulting exposure maps for each region estimated the spatial extent of the surface plume as a function of release days. The maps were used to determine the probabilities of exposure of Southern California ASBS to coastal discharges for annual and seasonal circulation patterns, and for targeted storm events.

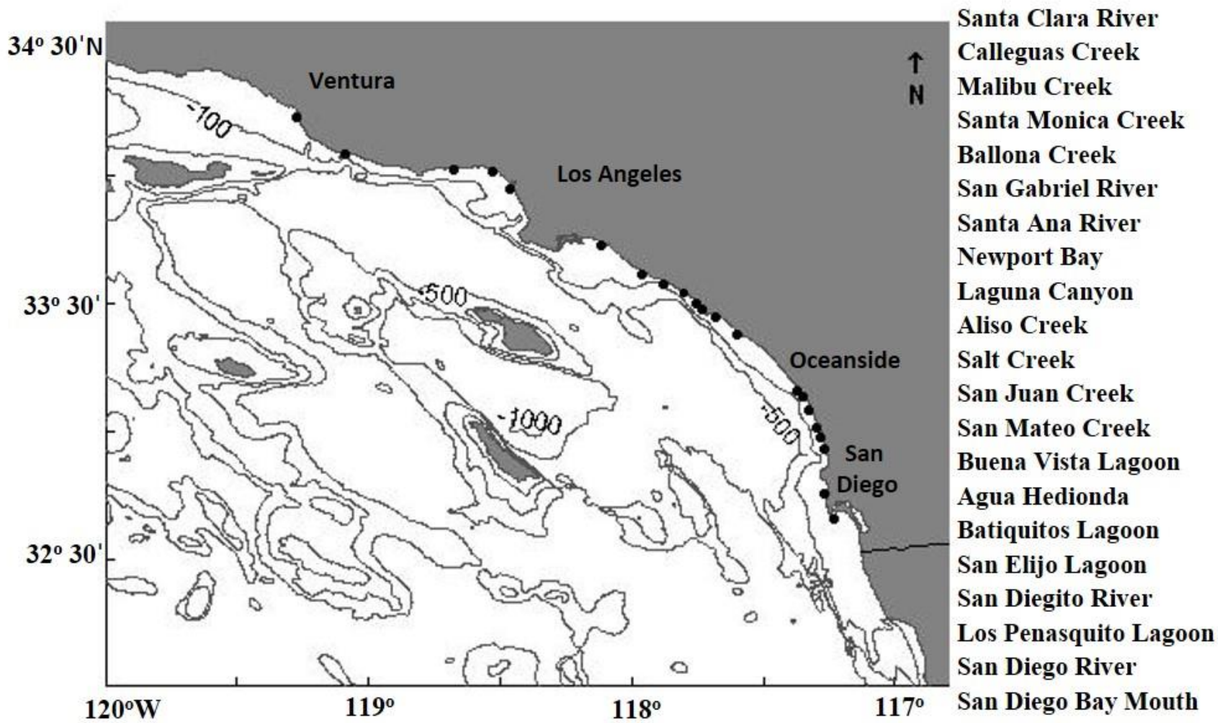

Figure 2. Southern California study domain showing the locations of the 21 modeled discharges. The adjacent labels define each coastal discharge location sequentially from North (Santa Clara River) to South (San Diego Bay Mouth).

MATERIAL AND METHODS

Surface Currents

An array of HF radars provides hourly surface coastal current maps with 6 km spatial resolution. Prior to their usage for Lagrangian trajectory computations, the currents are objectively mapped using a sample covariance matrix computed from two-year hourly data (2008–2009) to fill in missing data (Kim et al. 2007). The uncertainty of the estimated coastal current field is about 8.6 cm/s, which is roughly consistent with reported root-mean-square (rms) errors: 1–7 cm/s (Ohlmann et al. 2007, Kim et al. 2008).

A Plume Exposure Hindcast Model

The forward particle trajectory in the finite time domain is calculated as:

$$x(t) = \int_{t_0}^{t} (u(t') + \varepsilon^u) dt' + x(t_0) = \sum_k (u(t_k) + \varepsilon_k^u) \Delta t + x(t_0) \qquad (1)$$

$$y(t) = \int_{t_0}^{t} (v(t') + \varepsilon^v) dt' + y(t_0) = \sum_k \big(y(t_k) + \varepsilon_k^y\big) \Delta t + y(t_0) \qquad (2)$$

where $x(t) = [x(t)y(t)]^\dagger$ and $u(t)) = [u(t)v(t)]^\dagger$ denote the location of the particle and the surface currents at the particle location at a given time (t), respectively (t_0 is the initial time of the simulation and † denotes the matrix transpose). ε^u and ε^v are the random variables with zero mean and root mean square (rms) of ε.

In Lagrangian stochastic models, the random walk model inherits the similarity of the Lagrangian statistics of the passive tracer in the coastal region compared to the random flight model (Griffa et al. 1995, Griffa 1996). However, the random flight model has been used in studies of marine larvae spreading (Siegel et al. 2003, Isaji et al. 2005, Ullman et al. 2006, Spaulding et al. 2006) for the active tracer simulation. The random walk model is used in this study to preserve the shape of the power spectrum of the original current field and to simulate the coastal discharge as the passive tracer. The diffusion parameter (ε^u and ε^v) represents unresolved velocities as the uncertainty in the HF radar measurements (ε = 5 cm/s). A large number of particles are released and tracked with each time step so that their statistical distribution can be used to infer an exposure probability for a given discharge.

For this study, all discharges are assumed to be passive with no dynamical impact on the flow, allowing the mapped surface currents to be the initial current field into which the discharge occurs. Fifty water tracers are released hourly at each source location (Figure 2) and independently tracked for three days, which is consistent with the estimated lifetime of the Fecal Indicator Bacteria (FIB) (Noble et al. 2000, Ackerman and Weisberg 2003, Noble et al. 2004), regardless of the time-dependent nature of the discharge flow rate. When a particle crosses over the coastline boundary in a given current field, the trajectory is recalculated by applying the alongshore currents, which are simply the along-coast projection of currents measured 1 km offshore, to constrain the particle to follow the coastline. No time-dependent decay of the FIB is used for the analysis since the goal is to examine the plume water exposure probability as opposed to concentration prediction and because the decay rate of FIBs in marine waters are not well documented.

The coastal exposure kernel (CEK, P) indicates the relative probability to the number of particles at source location (or maximum number) resulting from surface transports:

$$P(x,y) = \frac{F(x,y)}{\max[F(x,y)]} \times 100 \qquad (3)$$

where *F(x,y)* denotes the number of particles in space (Kim et al. 2009).

The surface transport model discussed above was used to assess the fate and transport of the Tijuana River plume during storm events from April 2003 to March 2007. The skill of the model to assess low water quality in the surf zone was evaluated using receiver operating characteristic (ROC) analysis. For four years of water quality samples and model output comparisons during rain events, the average accuracy of the model was 70% (Kim et al. 2009).

Probability Exposure Maps

Probability exposure maps use many realizations of hourly water tracer trajectory estimates (Figure 3) to determine statistical convergence over various temporal periods. A total of nine probability exposure maps were generated for each of the twenty discharge locations including annual, seasonal, and targeted rain events. The water tracers for the annual exposure maps were driven by continual hourly forcing from surface currents from January 1, 2008 to December 31, 2009 while the seasonal maps used current data observed during Southern California's wet and dry seasons which occur from October through April and May through September respectively. In addition to the seasonal maps, targeted storm event maps for four 2008 rainfall events (January 24, February 23, November 28, December 20) and two 2009 rainfall events (February 8, December 9) were generated as examples of discharge variability (Figures S3–S23, Supporting Information).

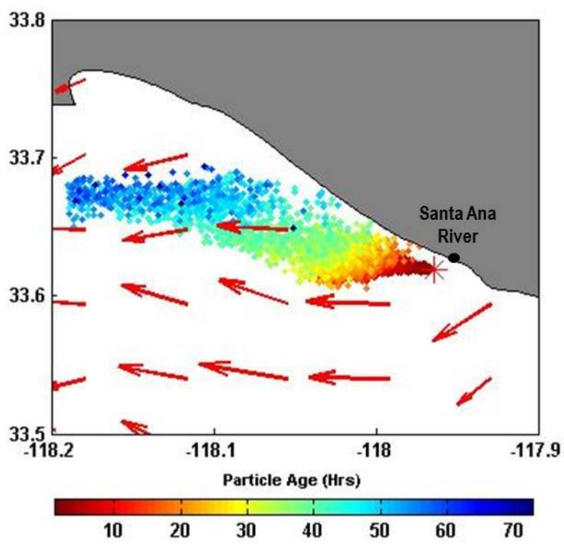

Figure 3. Santa Ana River particle trajectory estimate based on hourly water tracer seeding. The color of the hourly released tracers represent the particle age and are tracked for three days. The red arrows illustrate the average observed surface current during the 3-day time period.

RESULTS

Time-averaged syntheses of hourly particle trajectory maps were used to determine the probabilistic extent of each coastal discharge (Figure 2) at the various temporal periods discussed in the previous section. Probability exposure maps for Calleguas Creek, Newport Bay, and Santa Ana River (rows A, B, and C in Figure 4, respectively) for an annual period (2-year) and targeted rainfall events on February 22, 2008 and December 15, 2008 (columns a, b and c in Figure 4, respectively) are presented as a representative sample of all the probability exposure maps generated for the twenty coastal discharge sites. The annual exposure maps detail the potential exposure from coastal plumes that result from typical flow patterns found in each region while the targeted storm event maps provided examples of the variability of the plumes spatial extents during smaller temporal scales. The December 15 event was defined by a sustained rainfall from approximately December 15 to December 25 which led to a model run time of 13 days (10 days of measureable rain plus 3 days of residual runoff) while the February 22 event was a shorter duration event (six-day model run).

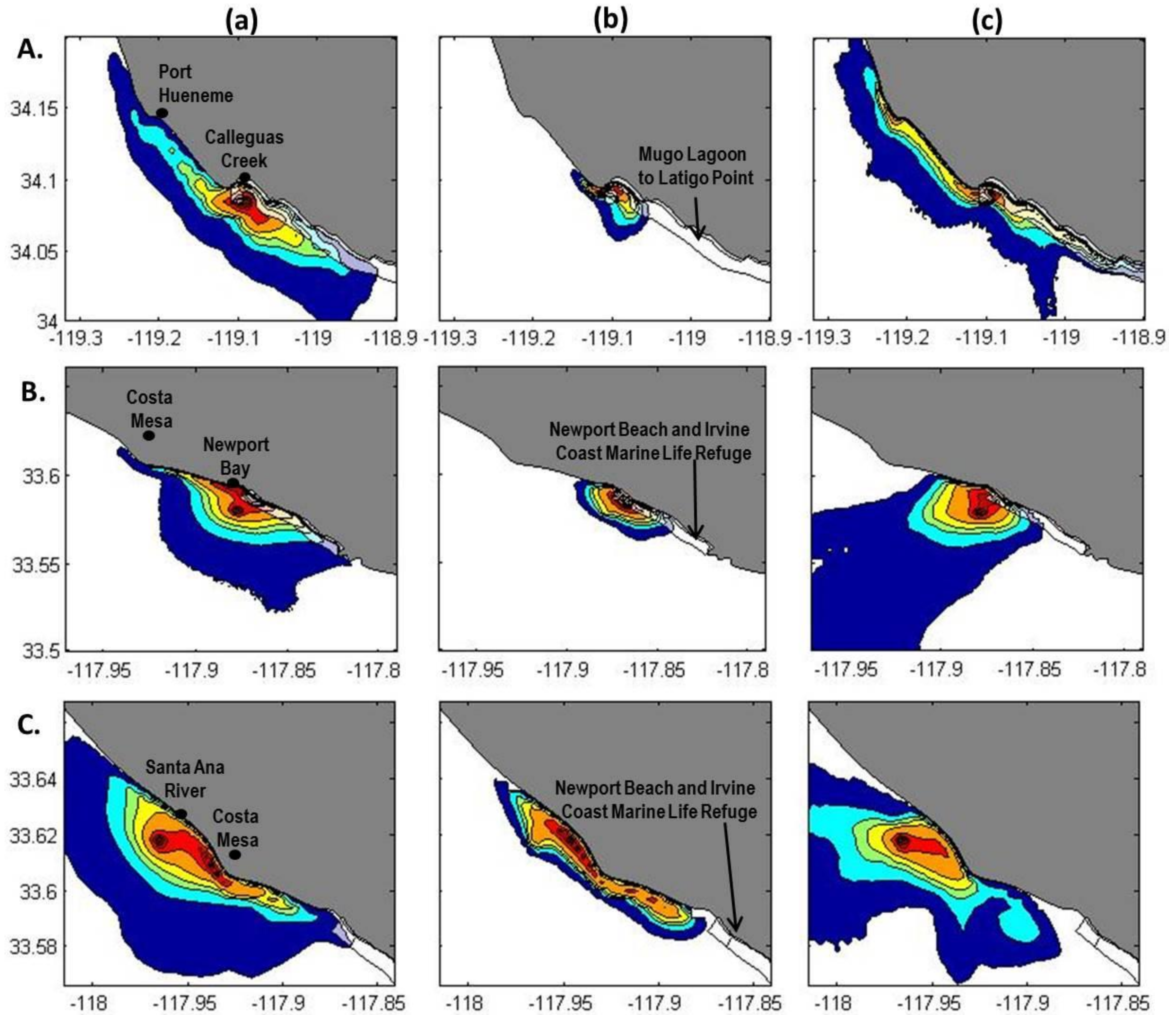

Figure 4. Probability exposure maps organized by rows for (A) Calleguas Creek, (B) Newport Bay, and (C) Santa Ana River. Additionally, each column represents a different temporal model run including (a) annual, (b) the February 22, 2008 storm event, and (c) the December 15, 2008 storm event. Local ASBS are also displayed in all figures and defined in column (b).

In addition to determination of the probabilistic spatial extent of each coastal discharge, the probability exposure maps were used to examine the potential exposure of ASBS to coastal discharges. For example, Calleguas Creek and Newport Bay had significant exposure to the adjacent protected areas of Mugo Lagoon to Latigo Point and Newport Beach/Irvine Coast Marine Life Refuge respectively (Figure 4A and 4B). A probability of exposure was computed for each ASBS by dividing the total number of water tracers advected into the ASBS by the total number of released tracers during a given temporal period. Probabilities of exposure of Calleguas Creek into the Mugo Lagoon to Latigo Point ASBS were 19.3%, 33.6%, and the 29% for the annual, February 22, and December 15 events respectively (Figure 4A). The Newport Bay discharge also had a significant potential of exposure to the Newport Beach Marine Life Refuge ASBS with probabilities of 7%, 13.8%, and 3% for the annual, February 22, and December 15 events respectively (Figure 4B). Additionally, probabilities of exposure to the Irvine Coast Marine Life Refuge were 9.3%, 18.6%, and 1.5% for each event. Minimal to no exposure was computed for the remainder of the modeled discharge sites. The ASBS probabilities of exposure for all protected areas exposed to plume discharge for all events are summarized in Table 3. Additionally, results were further summarized by the amount of area within an ASBS exposed to stormwater discharge for a given temporal period and presented in Table 4. Similarly to the ASBS probabilities of exposure, the Mugo Lagoon to Latigo Point, Newport Beach Marine Life Refuge, and Irvine Coast Marine Life Refuge have the highest spatial percentage of exposure from the Calleguas Creek, Newport Bay, and Newport Bay discharges respectively. We note that an additional discharge from Laguna Canyon was included into Table 3 but not Table 2. Probabilities of exposure within the Heisler Park Ecological Reserve (Table 2) could not be computed because the modeled grid did not have a high enough resolution within this ASBS. The ASBS probabilities of exposure to the Newport Bay and Irvine Coast Marine Life Refuge were less and 1%. We additionally note that the percentages computed in the last column of Table 3 (Heisler Park) were visually estimated based on the final probability maps since there was not full coverage of the model grid within this area. Table 4 combines the ASBS probabilities and spatial exposure percentages presented in Table 2 and Table 3 respectively. Additionally the table sorts the modeled events (color coded) by the percentage of area for no plume, and for probabilities of exposure less than 1%, between 1–10%, between 10–25%, and between 25–50%.

Table 2. Summary of the ASBS probabilites of exposure to coastal discharges for annual, wet/dry season, and storm events on January 23, 2008; February 22, 2008; November 26, 2008; December 15, 2008; February 5, 2009; and December 7, 2009.

	Mugo Lagoon to Latigo Point		*Newport Beach Marine Life Refuge*		*Irvine Coast Marine Life Refuge*		*Heisler Park Ecological Reserve*	*San Diego Marine Life Refuge*	*San Diego La Jolla Ecological Reserve*	
	River Discharge									
	Calleguas Creek	**Malibu River**	**Newport Bay**	**Santa Ana River**	**Newport Bay**	**Santa Ana River**	**Aliso Creek**	**Los Penasquitos Lagoon**	**Los Penasquitos Lagoon**	**San Diego River**
Model Period										
Annual	19.3%	1.4%	7%	<1%	9.3%	<1%	< 1 %	< 1 %	< 1%	NA
Wet Season	18%	1.5%	6.9%	NA	8.8%	NA	< 1 %	< 1 %	< 1%	NA
Dry Season	23.3%	1.1%	7.4%	<1%	10.8%	<1%	< 1 %	< 1 %	< 1%	NA
01/23/08	9.5%	NA	< 1%	NA	< 1%	NA	NA	NA	NA	NA
02/22/08	33.6%	NA	13.8%	NA	18.6%	NA	< 1 %	NA	NA	NA
11/26/08	26%	NA	2.10%	NA	8.0%	NA	NA	NA	NA	<1%
12/15/08	29%	6.2%	3%	NA	1.5%	NA	NA	< 1 %	NA	<1%
02/05/09	22%	<1%	1.5%	NA	2.9%	NA	NA	NA	NA	<1%
12/07/09	10.6%	NA	< 1%	NA	12.2%	NA	NA	NA	NA	NA

Table 3. Summary of the ASBS spatial exposure percentages computed from the ratio of area of exposed ASBS to the total area of the ASBS for annual, wet/dry season, and storm events on January 23, 2008; February 22, 2008; November 26, 2008; December 15, 2008; February 5, 2009; and December 7, 2009. The asterisk in the last column denotes a visual estimation of the spatial exposure since the resolution of the model grid nearshore was to low to encompass the Heisler Park ASBS.

	Areas Of Special Biological Significance					
	Mugo Lagoon to Latigo Point	*Newport Beach Marine Life Refuge*	*Irvine Coast Marine Life Refuge*	*Newport Beach Marine Life Refuge*	*Irvine Coast Marine Life Refuge*	*Heisler Park Ecological Reserve*
	River Discharge					
	Calleguas Creek / Malibu River	**Newport Bay /Santa Ana River**	**Newport Bay / Santa Ana River**	**Laguna Canyon**	**Laguna Canyon**	**Laguna Canyon***
Model Period						
Annual	47% / 16%	100% / < 1%	100% / < 1%	100%	100%	100%
Wet Season	43% / 16%	100% / NA	100% / NA	100%	100%	100%
Dry Season	50% / 16%	100% / < 1%	100% / < 1%	100%	100%	100%
01/23/08	5% / NA	40% / NA	54% / NA	NA	NA	40%
02/22/08	14% / NA	100% / NA	63% / NA	100%	100%	100%
11/26/08	8% / 2%	100% / NA	96% / NA	NA	NA	100%
12/15/08	63% / 26%	100% / NA	50% / NA	100%	100%	100%
02/05/09	41% / 1%	100% / NA	96% / NA	NA	3%	100%
12/07/09	8% / 4%	100% / NA	100% / NA	NA	NA	40%

Table 4. Summary of ASBS probabilities of exposure and spatial exposure percentages (i.e., combination of Table 2 and Table 3).

ASBS	*River Discharge*	*% area no plume*	*% area plume prob < 1%*	*% area plume prob 1-10%*	*% area plume prob 10-25%*	*% area plume prob 25-50%*
Mugu Lagoon to Latigo Point	*Calleguas Creek*	53% 57% 50% 95% 86% 92% 17% 59% 92%		5%	47% 43% 50% 41% 8%	14% 8% [illegible]
	Malibu River	84% 84% 84% [illegible] 99%	1%	16% 16% 16% [illegible]		
Newport Beach Marine Life Refuge	*Newport Bay*	60%	40% 100%	100% 100% 100% 100% 100% 100%	100%	
Irvine Coast Marine Life Refuge	*Newport Bay*	46% 37% 4% 50% 4%	54%	100% 100% 96% 50% 96%	100% 63% 100%	
Heisler Park* Ecological Reserve	*Aliso Creek*	75%	100% 100% 25%			
	Laguna Canyon	CND	CND	CND	CND	CND
San Diego Marine Life Refuge	*Los Penasquitos Lagoon*	[illegible]	100% 100% 100% [illegible]			
San Diego La Jolla Ecological Reserve	*Los Penasquitos Lagoon*	[illegible]	100% 100% 100% [illegible]			
	San Diego River	33% 15%	67% 85%			

Legend

Annual
Wet
Dry
1/23/2008
2/22/2008
11/26/2008
12/15/2008
2/5/2009
12/7/2009

CND – Could Not Determine

DISCUSSION

The discharge velocities after storm events and channel slopes of Southern California rivers result in jet-like hypopycnal plume structures that are dispersed by momentum, local wind stresses, and current forcing (Warrick et al. 2004). As momentum of the initial discharge is dissipated by turbulent mixing, buoyancy and rotational forcing become increasing important (Fischer et al. 1979). Previous work has shown that surface plumes are dramatically altered by local wind stresses and coastal currents (Kourafalou et al. 1996, Pullen and Allen 2000, Geyer et al. 2000). In Southern California, wind-generated surface currents are generally poleward (downwelling favorable) prior to and during peak river discharge, then equatorward (upwelling favorable) following a storm event (Harms and Winant 1998, Kim et al. 2009). To understand the effect the magnitude and direction of coastal currents had on the spatial evolution of the modeled plumes (Figures 3 columns a, b, and c), daily outputs of the particle trajectory exposure maps were analyzed.

The Santa Ana River mouth is approximately nine kilometers upcoast of the Newport Bay mouth yet localized current fields can advect each plume independently. An example of this mesoscale circulation and its impact on discharge plumes is evident in the daily probability exposure maps for December 15, December 17, and December 18, 2008 presented in Figure 5A, 5B, and 5C respectively. Probability exposure maps averaged over 24 hours are illustrated for the Santa Ana River discharge (upcoast plume) and the Newport Bay plume (downcoast plume) and are overlaid on HF radar derived surface current datasets averaged for the same period. On December 15 a predominantly onshore current direction “compressed” the plumes into a narrow overlapping alongshore distribution that advected downcoast. As the storm strengthens from December 16–17, the currents shift to a more poleward alongshore direction, which is the expected direction during peak discharge. To the north of the Santa Ana River discharge, the San Pedro Bay coastline (Figure 3) influences the currents resulting in a more westward direction. South of the Santa Ana River outlet, a localized offshore current field develops around the Newport Bay mouth from December 17–18 (Figures 5B and 5C). The spatial variability of the currents causes the Santa Ana River plume to extend in a northwestward direction, while the localized current field advects the Newport Bay plume approximately perpendicular to shore (southwest direction). This mesoscale current variability results in two spatially unique probability exposure maps illustrated in Figure 4B and 4C column c. Comparatively, the December 15 Calleguas Creek event probability map (Figure 4A column c) was driven by similar current fields to those illustrated in Figure 5. However, the mean current direction was more alongshore (upcoast and downcoast) than those experienced by the Santa Ana and Newport Bay discharges resulting in a significantly greater alongshore spatial extent (~ 44 km) when compared to ~ 17 km and ~ 6.7 km for the Santa Ana River and Newport Bay respectively.

The approximate cross-shore spatial extent for Calleguas Creek, Santa Ana River, and Newport Bay for the February 22 storm event was 5.1 km, 2.2 km, and 1.9 km (Figure 4, column b) respectively, exhibiting a narrow distribution in comparison to the 5.7 km, 16.7 km, and 8.4 km respective cross-shore extents for the December 15 storm event (Figure 3, column c). In general, the February 22 storm events coastal currents were less variable in magnitude and direction resulting in a more localized plume exposure. A summary of the spatial extents from all modeled discharges are presented in the Supporting Information, Table S1.

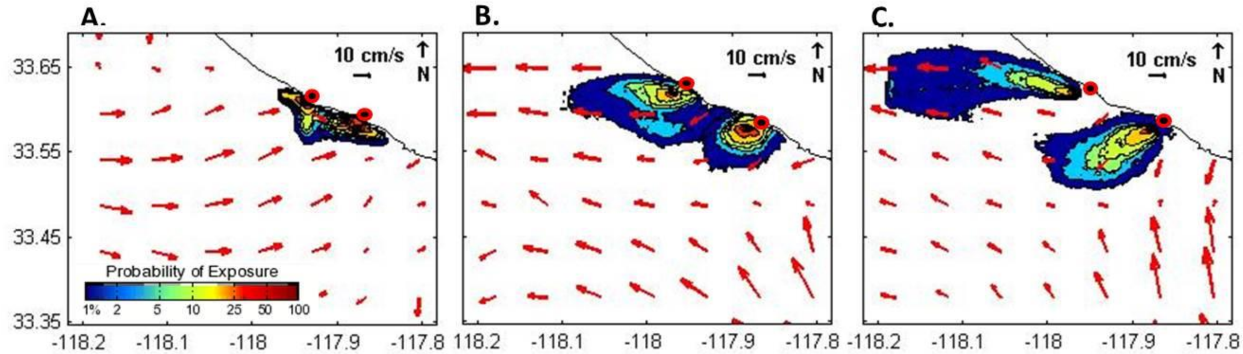

Figure 5. Daily averaged plume expsoure maps and currents (red arrows) illustrating the evolution of the Santa Ana River plume (north) and the Newport Bay plume (south) on (A) December 15, (B) December 17, and (C) December 18, 2008). The red circles denote the approximate outlet of each discharge.

Coastal and Surf Zone Applications

Coastal Discharge Concentration Estimates

The probability exposure maps as presented above are a probabilistic description of plume transport and not a measure of concentration. They are a measure of connectivity from a single discharge and should not be compared to probability exposure maps from other river discharges. However, a translation of results to assess mass transport of Calleguas Creek and the Santa Ana River was performed to allow comparisons between the sites. Estimates of discharge concentration at grid point (x,y) for each discharge were generated using the following equation:

$$C(x,y) = \frac{F(x,y)}{\max[F(x,y)]} \times \mathrm{C}_o \qquad (4)$$

where *F(x,y)* denotes the number of particles in space. Calleguas Creek and Santa Ana River flow data was used to estimate an initial concentration (C_o) of discharge given the area of the model grid (*dx*, *dy*) and an assumed vertical mixing extent (*dz*) which was "diluted" by the model results as described by Equation 4 (Figure S2, Supporting Information). Normalized concentration maps for the December 15 Santa Ana River and Calleguas Creek storm event are presented in Figure 6. The cumulative discharge for the Santa Ana River was approximately three times the amount discharged by Calleguas Creek during the 10-day storm event. This difference is illustrated by significantly lower concentrations of discharge for the Calleguas Creek when compared to Santa Ana River. The methodology used to determine river discharge concentrations can similarly be applied to estimate the dispersion of pollutants and nutrients from a coastal discharge following a storm event given an initial concentration (C_o).

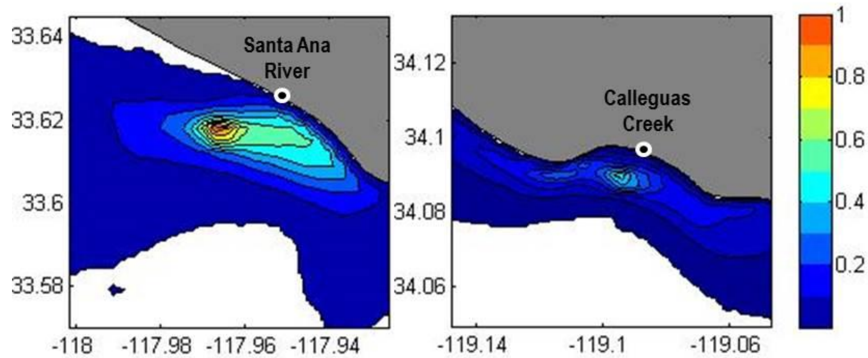

Figure 6. Santa Ana River and Calleguas Creek normalized concentration maps for the December 15 storm event, derived from model outputs. The cumulative flow during the storm event was used to estimate an initial concentration.

Surf Zone Water Quality Assessment

The inertial discharge of the Santa Ana River increases as a result of a storm event and is advected cross-shore in a jet-like hypopycnal plume where it interacts with coastal currents (Warrick et al. 2004). However, a fraction of the discharge is entrained in the surf zone and transported parallel to shore by wave-driven currents that are directionally forced by the approaching wave field. The beaches adjacent to the Santa Ana River outlet are approximately straight and face 214o southwest with alongshore currents driven by swells from the west or south while shore-normal southwesterly swells are blocked by the San Clemente and Catalina Islands (Figure 2) (Ahn et al. 2005, Clark et al. 2010). In the Santa Ana discharge region, coastal currents are often uncoupled from the wave-driven currents in the surf zone (Kim et al. 2004, Grant et al. 2005). Thus, to use storm event probability exposure maps (driven by coastal currents) to assess surf zone water quality, the incident wave direction during the storm event must be considered.

For example, on January 5, 2008 a storm with westerly winds moved through the study region causing a significant sea height of 2–3 m. The resulting west swell hit the shoreline at an oblique angle causing a wave-driven alongshore current in the downcoast direction. Evidence of this surf zone current can be seen in the water quality data south of the river outlet as measured by personnel at the Orange County Sanitation District (OCSD). The stations are designed by OCSD based on the respective distance (in thousands of feet) north or south of the Santa Ana River outlet (e.g., station 0 is located at the river origin while station 3S is approximately 3000 ft south of origin). Fecal coliform bacteria were used to assess water quality observed by stations adjacent to the Santa Ana River. The California State AB411 bathing water quality standard is 400 fecal coliform bacteria/100 ml (often reported as most probable number of coliform (MPN) per 100 mL). Degraded water quality due to the January 5 storm event is observed from station 3S to 15S on January 8 with exceedances observed at station 3S (Figure 7a). Station 0 is located on the north side of the Santa Ana River outlet and measured a fecal coliform count of ~200 MPN/100 mL with minimal signatures north of this station. The probability exposure map for the same time period (Figure 8a) show the highest probabilities of exposure are up-coast of the Santa Ana River suggesting the coastal currents are predominately in a northwestward direction, opposite of the surf zone currents.

Conversely, water quality data from the storm event on January 27, 2008 suggest the presence of an up-coast alongshore current due to water quality exceedances from Station 0 to 15N on January 28 (Figure

7b). A peak in concentration (~1600 MPN/ 100 mL) occurs at station 6N which is likely a result of the patchy nature of the discharge as it advects up-coast (Clark et al. 2010). The most significant areas of exposure are similarly in an up-coast direction (Figure 8b) indicating that the surf zone and coastal currents are coupled.

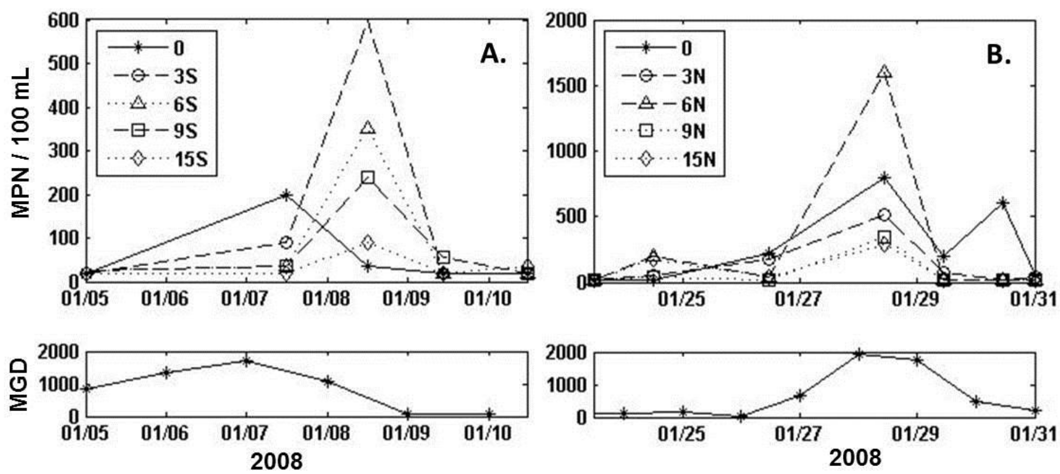

Figure 7. Water quality observations near the Santa Ana River discharge for storm events on (A) January 5, 2008 and (B) January 25, 2008. The stations names are organized according to their respective distances from the Santa Ana River outlet (e.g., 3N is 3000 ft north of the outlet). The bottom figures show the measured flow rate in Millions of Gallons per Day (MGD) within the river for each event.

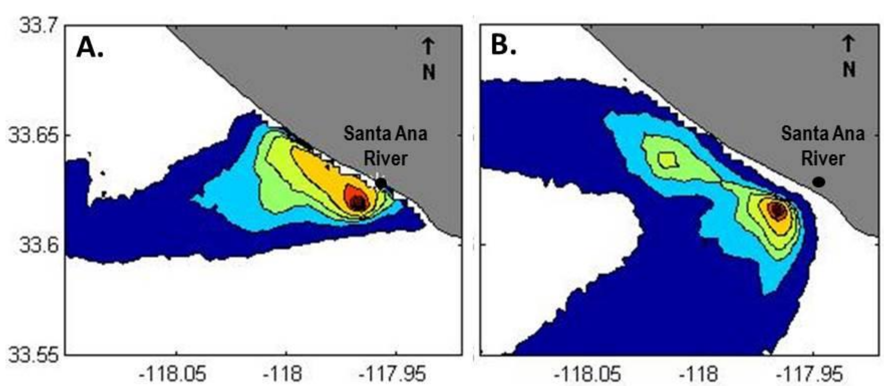

Figure 8. Santa Ana River probability exposure maps for storm events on (A) January 5, 2008 and (B) January 25, 2008.

The fate of pollutants discharged from rivers discussed in this paper are governed by a complex set of environmental conditions including the tidal phasing of pollutant input into the surf zone, prevailing wave direction, and the tidal phasing and magnitude of coastal currents (Kim et al. 2004). In its current form, the surface transport model used to generate the probability exposure maps ignores the effects of (1) cross-shore circulation across the breaking surf and (2) wave-driven surf zone currents which can be opposite in direction to adjacent coastal currents. Simple models balancing breaking-wave induced forcing with bottom stress can often predict mean alongshore current in the surf zone (e.g., Thornton and Guza 1986, Ruessink et al. 2001, Fedderson and Trowbridge 2005). A future objective is to improve the near-shore performance of the surface transport model by coupling it with a surf zone model to better estimate alongshore currents and cross-shore transport. Additionally, analysis of remote sensing data (e.g., satellite, plane based) during similar temporal periods of probability exposure maps would be beneficial in determining the feasibility of such comparisons.

Despite the near-shore limitation of the model, it has proven to be an effective tool for management of resources to mitigate potential environmental problems. A version of the surface transport model (the near real-time Tijuana River plume tracking model) is used by the San Diego Department of Environment Health for decision making and guidance in postings of beach advisories (Clifton et al. 2007).

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SUPPORTING INFORMATION

Southern California Areas of Biological Significance (ASBS)

The State Water Resources Control Board (SWRCB) has designated 34 Areas of Special Biological Significance (ASBS) to protect and preserve biological communities that are diverse and abundant with marine life. The network of ASBS runs from Redwood National Park in Northern California to La Jolla in Southern California. The Southern California ASBS boundaries and respective names are illustrated in Figure S1.

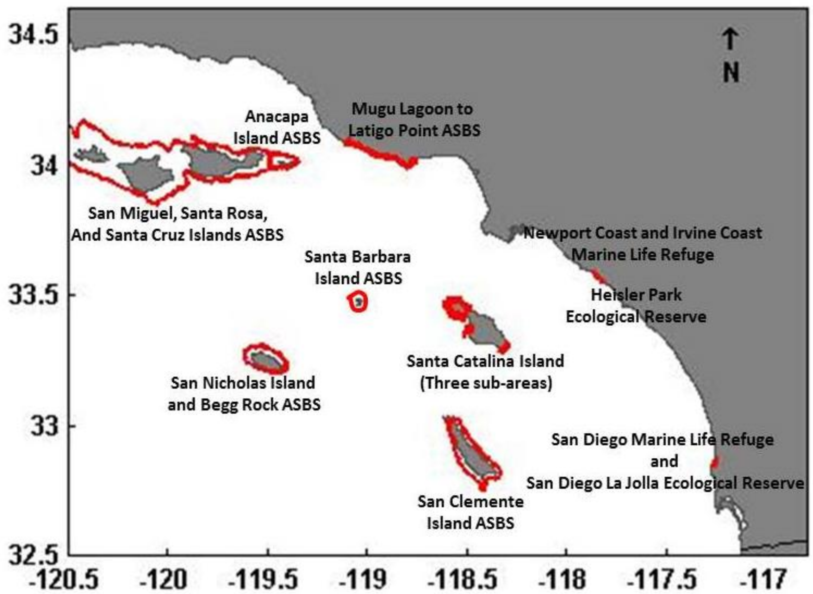

Figure S1. Map of Areas of Special Biological Significance (ASBS) in Southern California.

Modeled Discharge Concentration Analysis

The probability exposure maps were computed to understand the probabilistic spatial extents of each coastal discharge modeled. Due to differences in resolution, temporal scales, and flow rates, intercomparisons between discharges should not be made. However, a methodology to assess mass transport was presented which allows comparisons between sites assuming well mixed grid boxes and a 1 m vertical mixing extent of the hypoycnal plume. The assumed vertical mixing extent was chosen as an example; however in-situ observations could be used for a more accurate representation of the mixing extent. Next, the observed flow rate during a storm event was used to compute a cumulative volume of discharge released into the ocean and divided by the volume of the initial model water parcel (Figure S2). This initial concentration is “diluted” by the model results (ratio of the number of water tracers per grid box divided by the total number of water tracers) as shown by Equation 4.

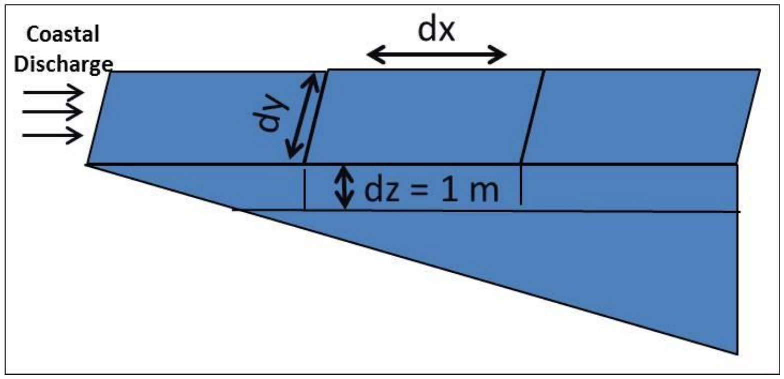

Figure S2. Idealized coastal discharge region showing the modeled grid boxes (dx, dy) and the assumed depth (dz) used to compute an initial flow concentration.

Summary of Probability Exposure Maps

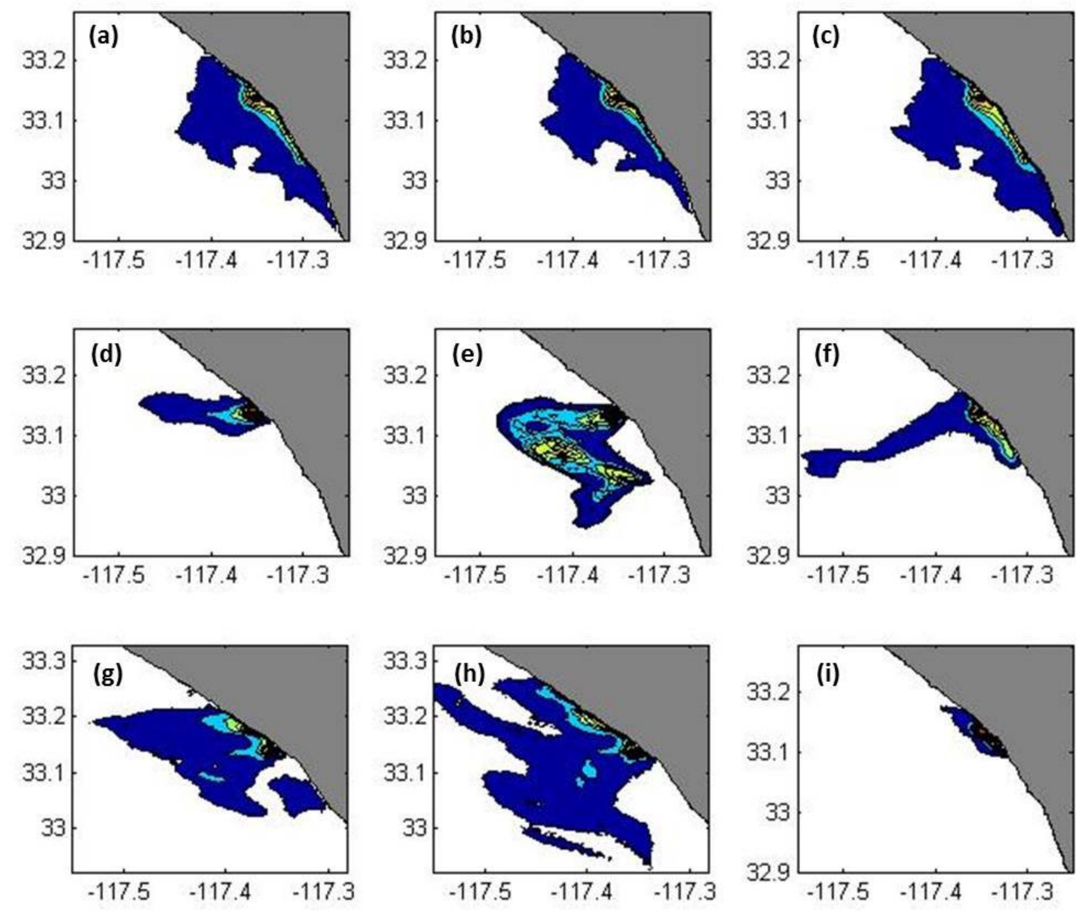

Figure S3. Agua Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

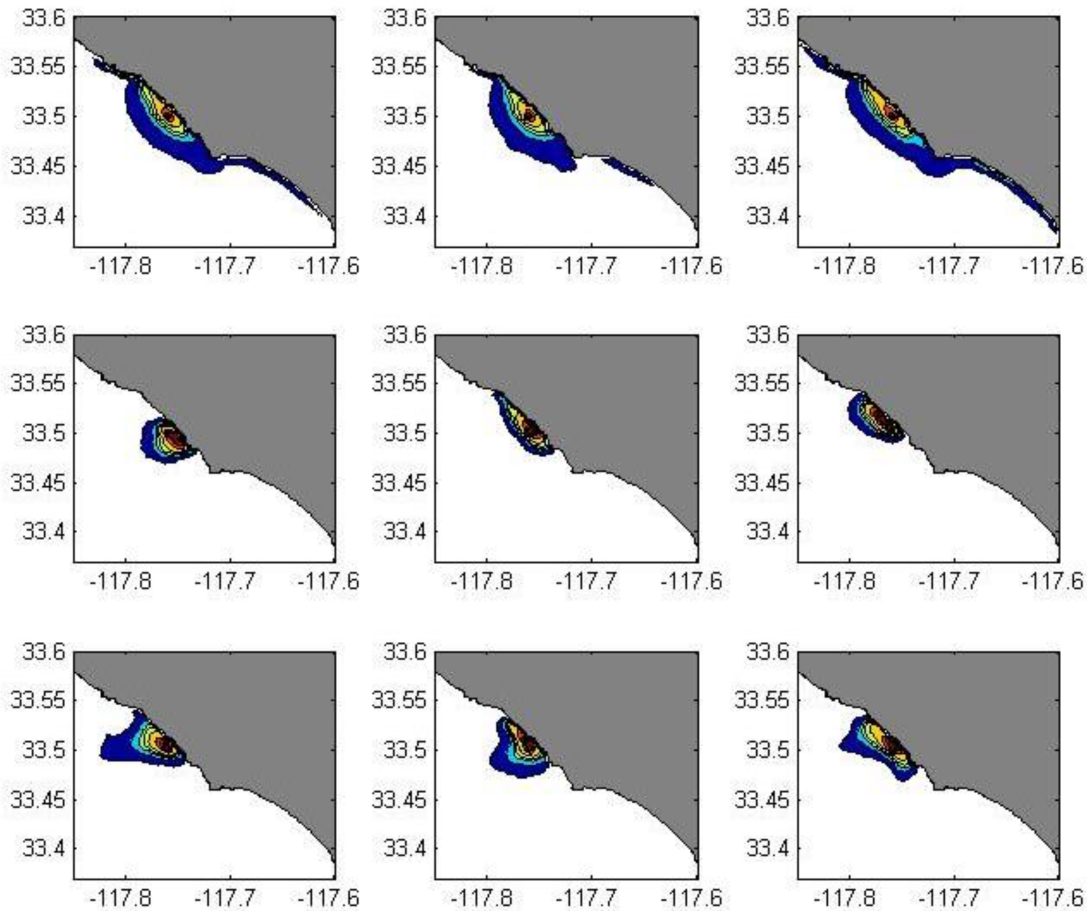

Figure S4. Aliso Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

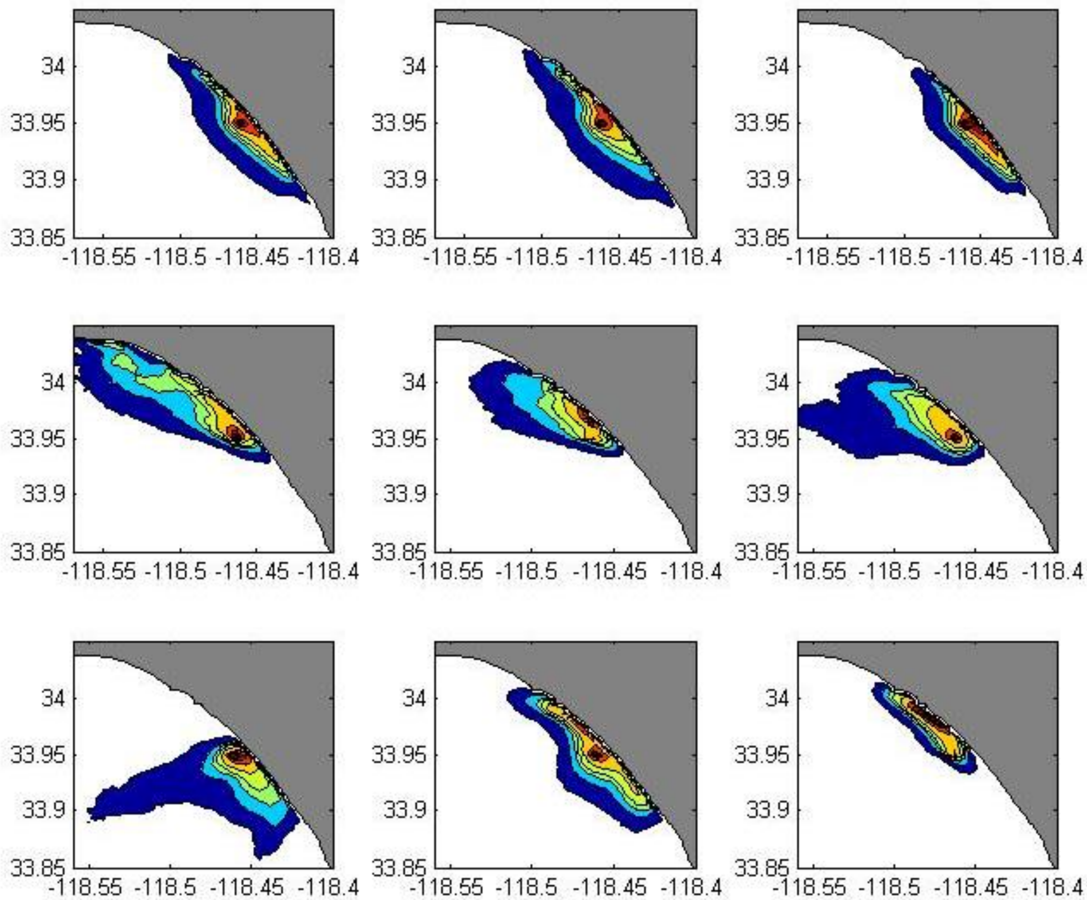

Figure S5. Ballona Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

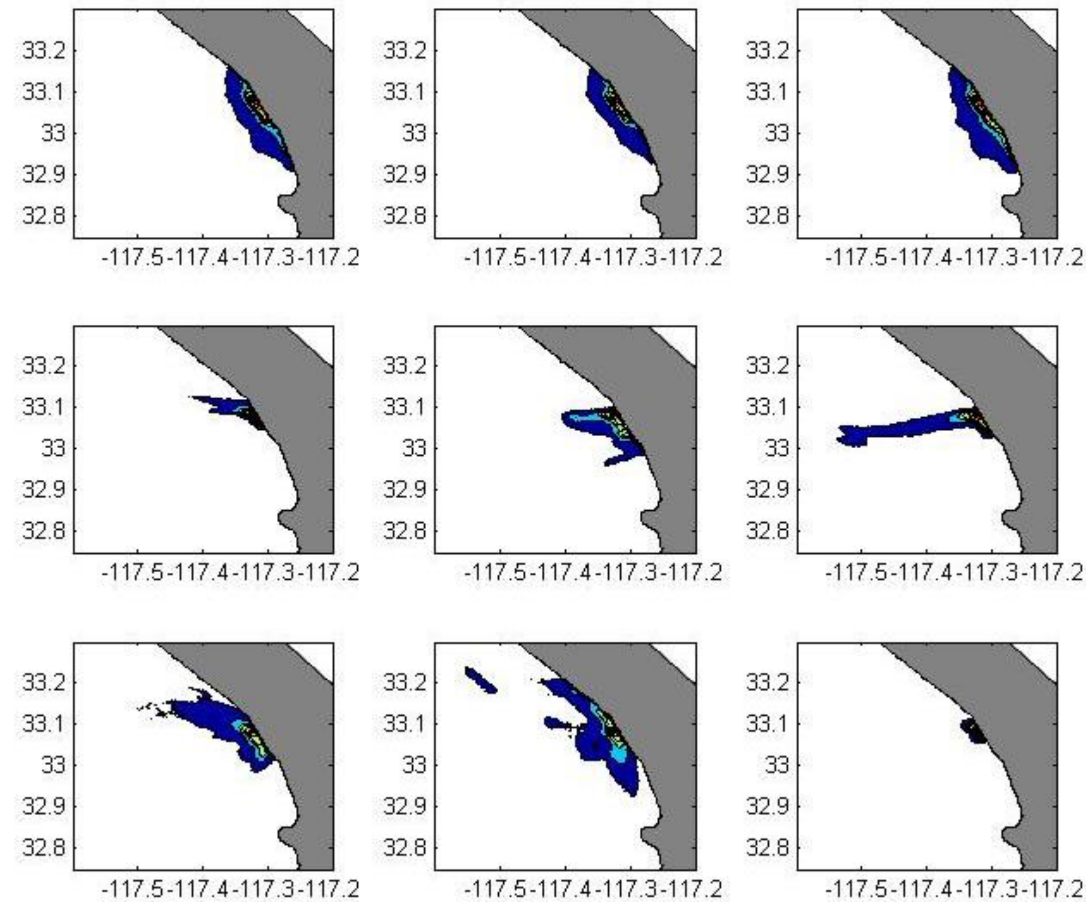

Figure S6. Batiquitos Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

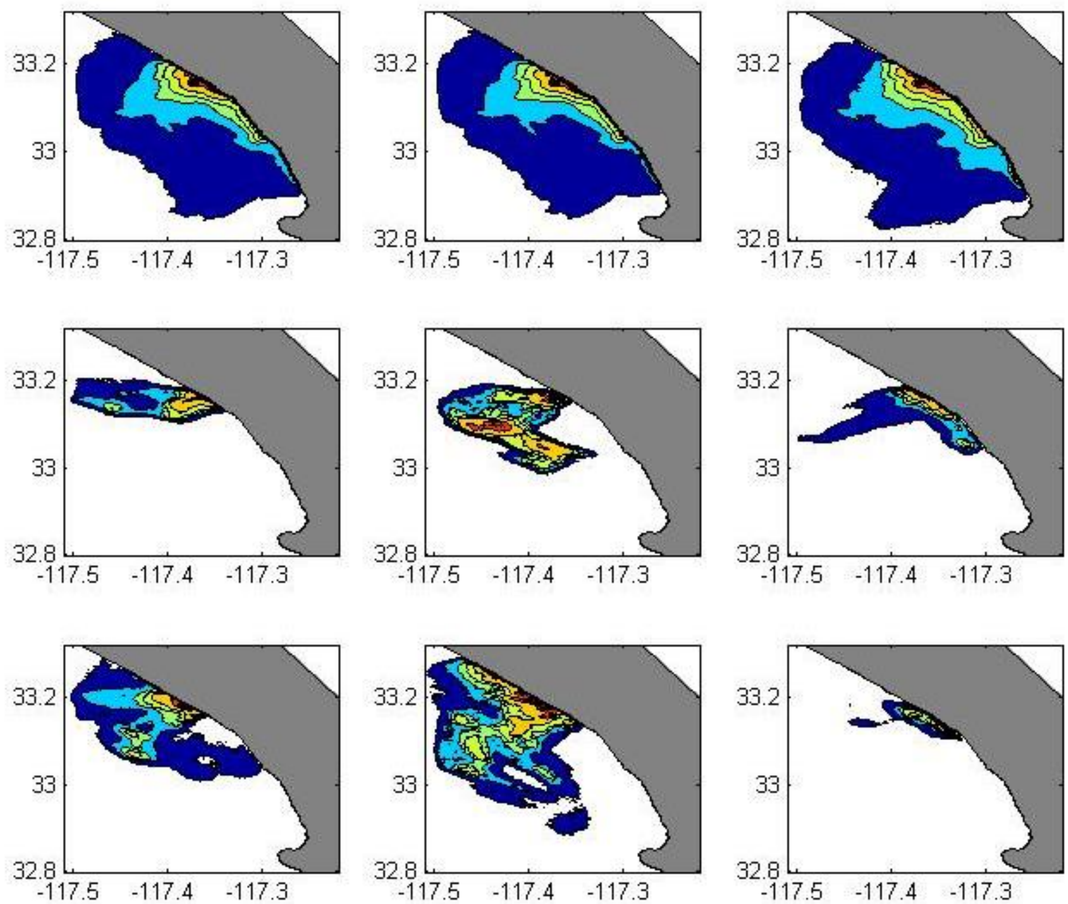

Figure S7. Buena Vista Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

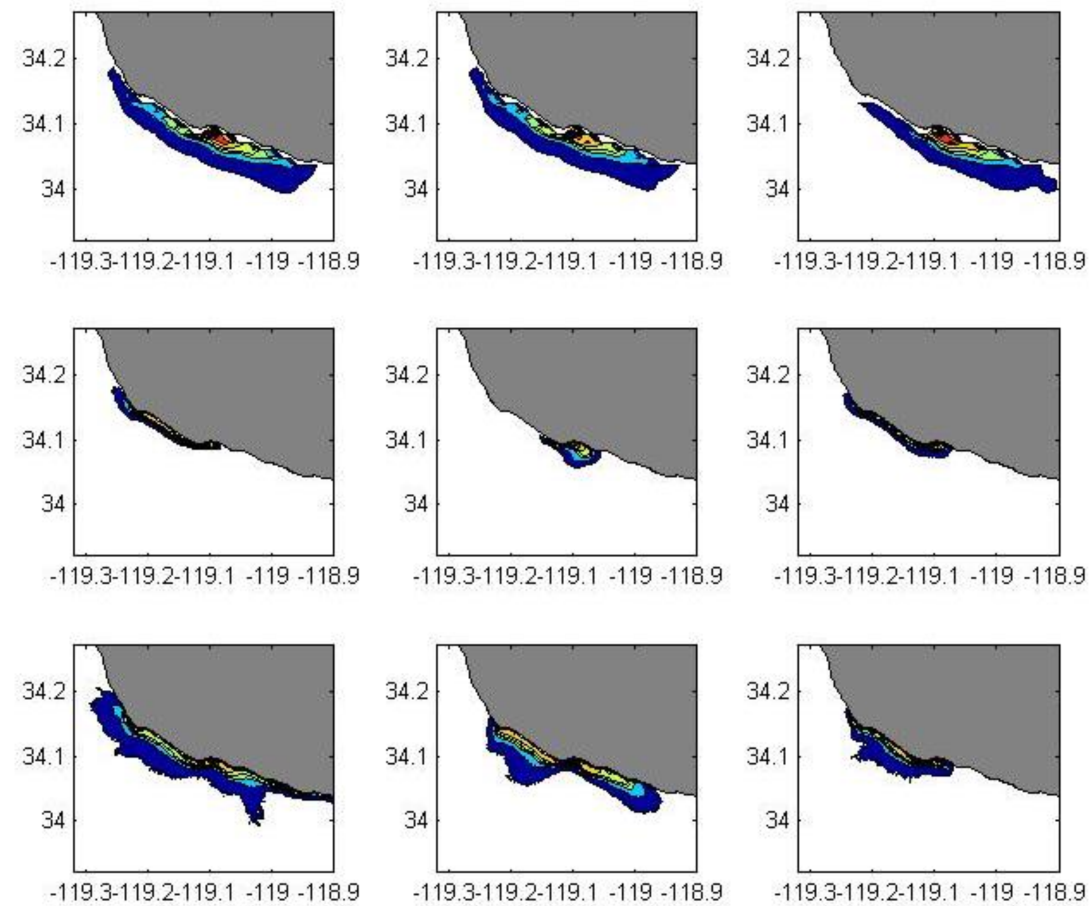

Figure S8. Calleguas Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

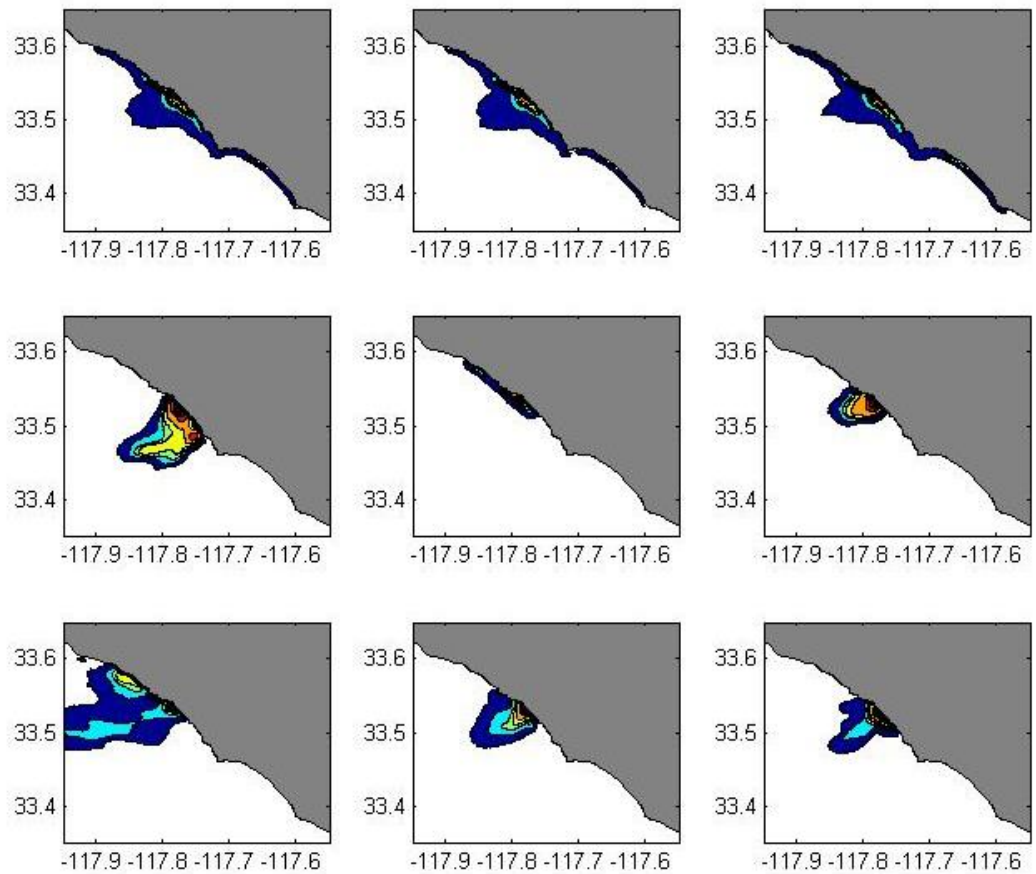

Figure S9. Calleguas Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

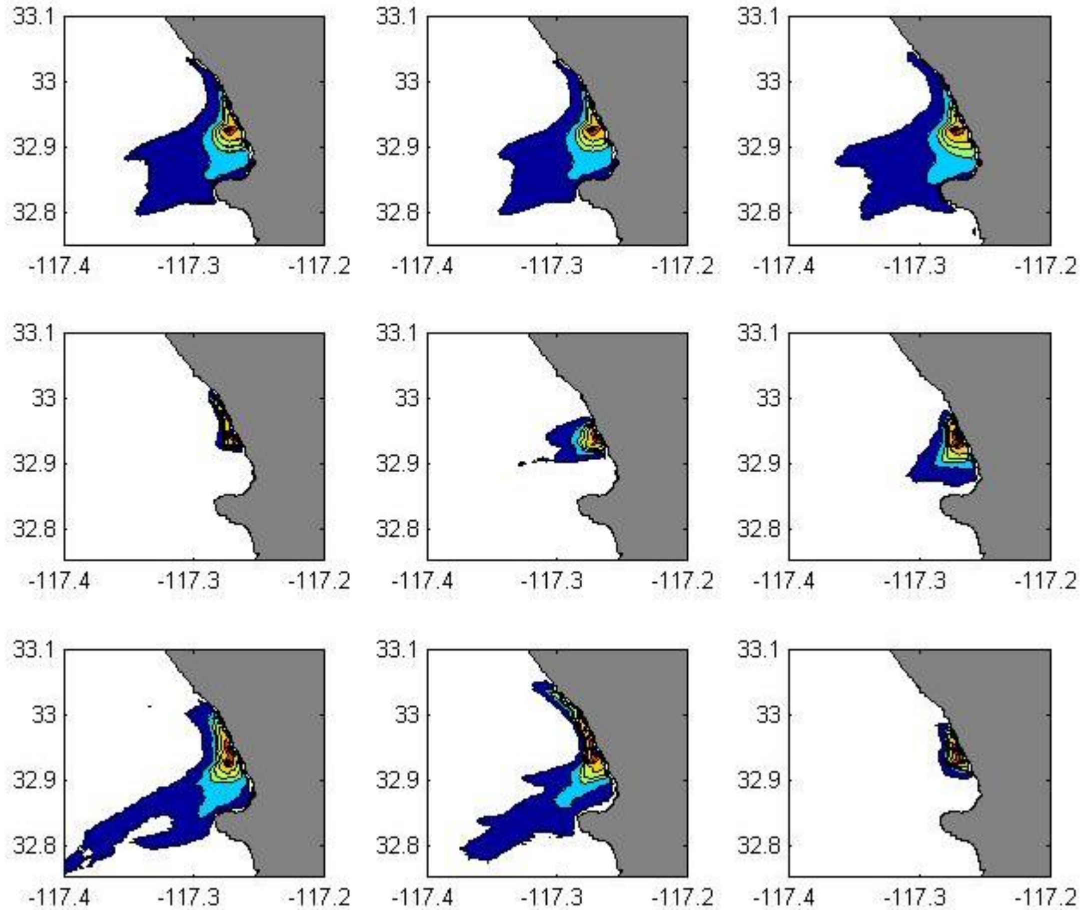

Figure S10. Los Penasquitos Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

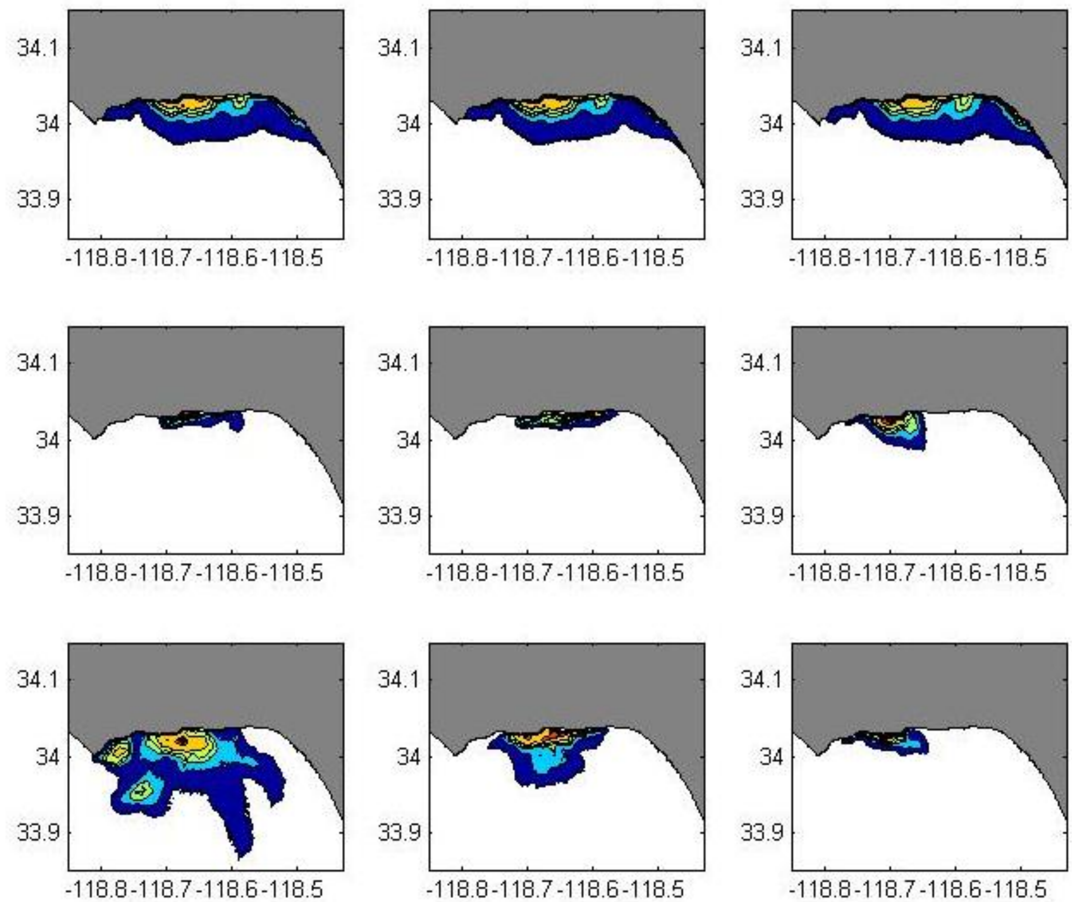

Figure S11. Malibu Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

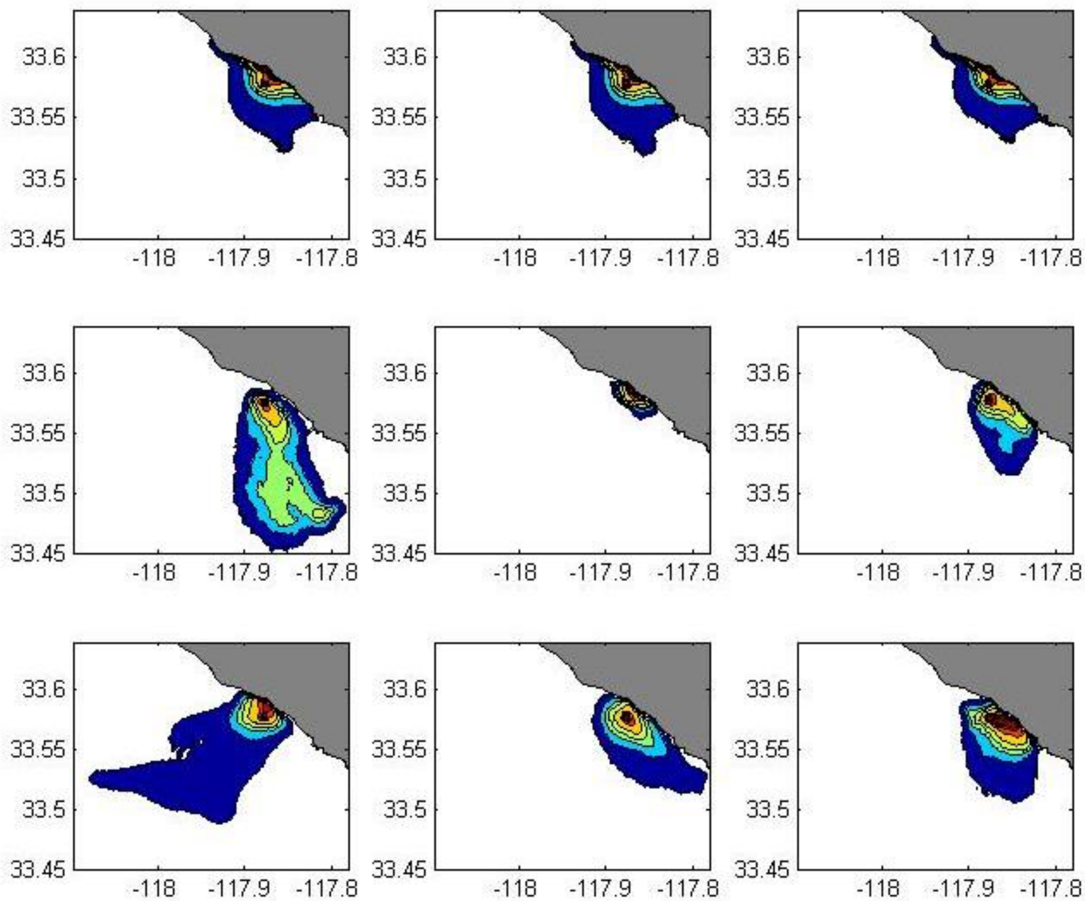

Figure S12. Newport Bay summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

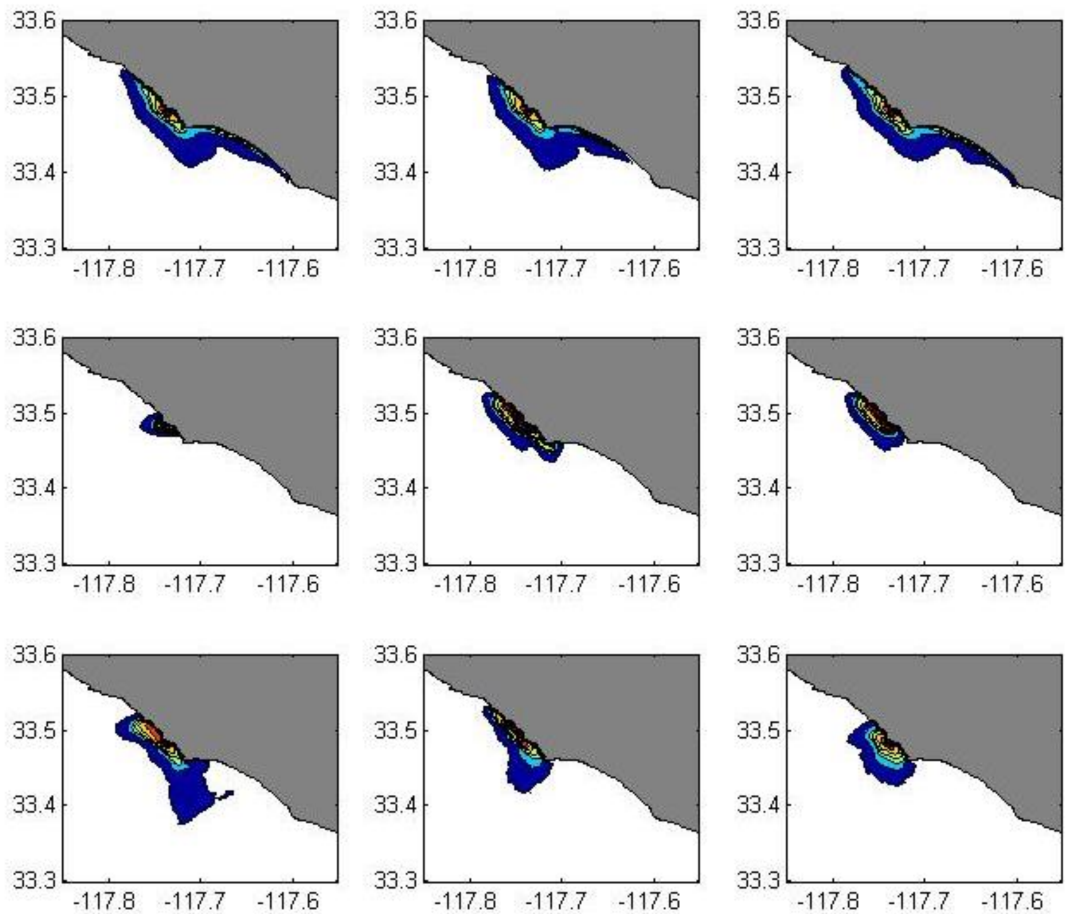

Figure S13. Salt Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

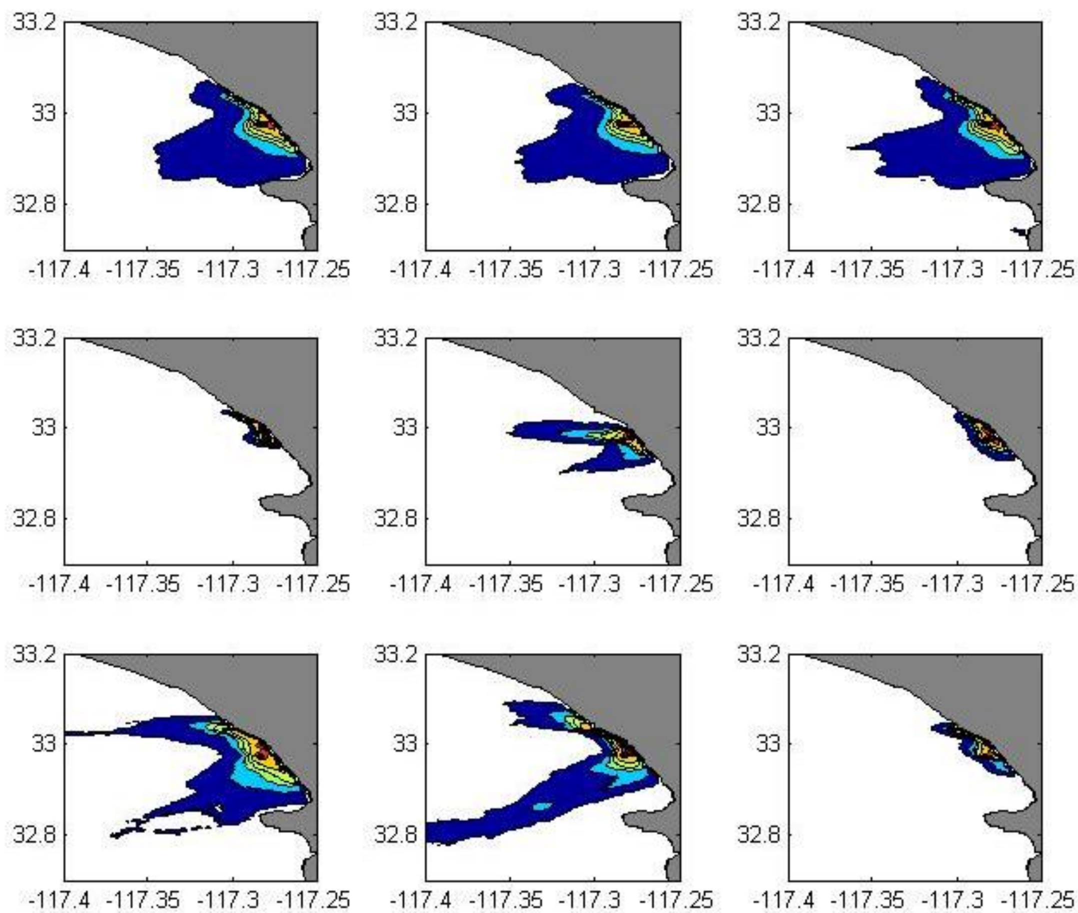

Figure S14. San Diegito Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

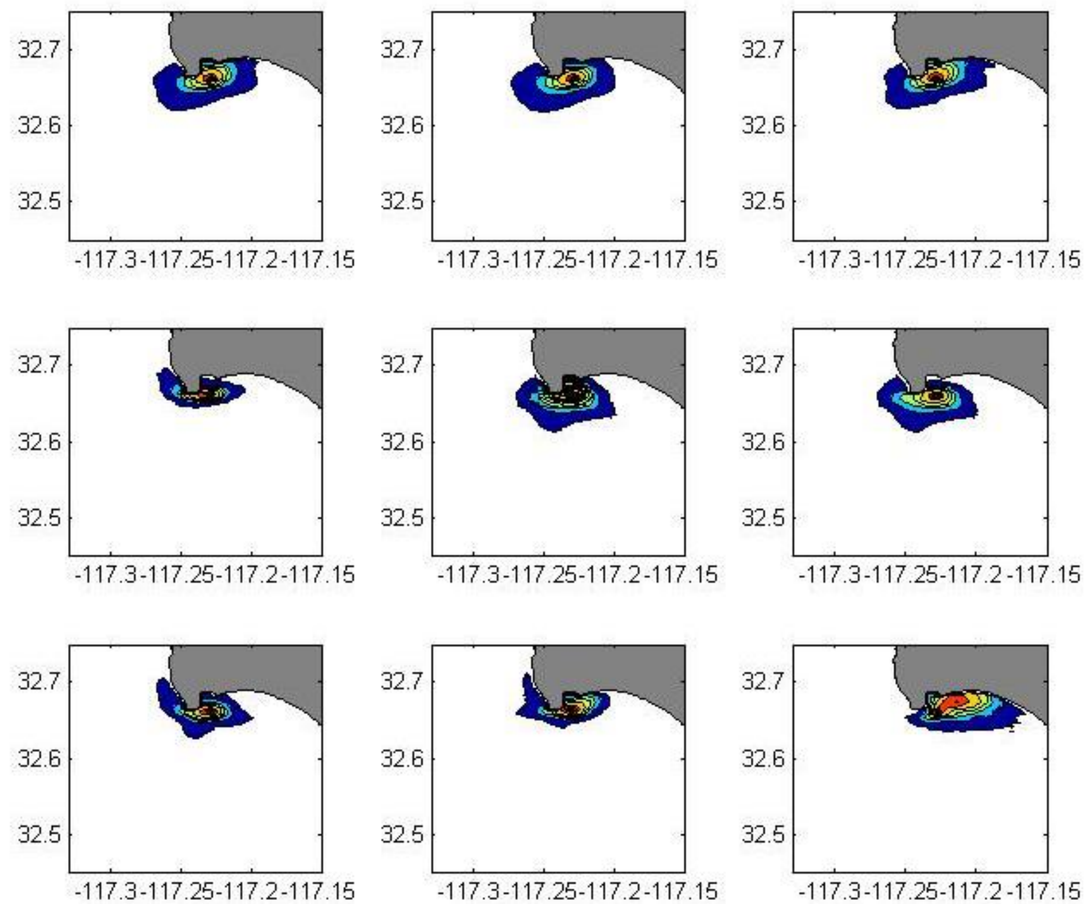

Figure S15. San Diego Bay summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

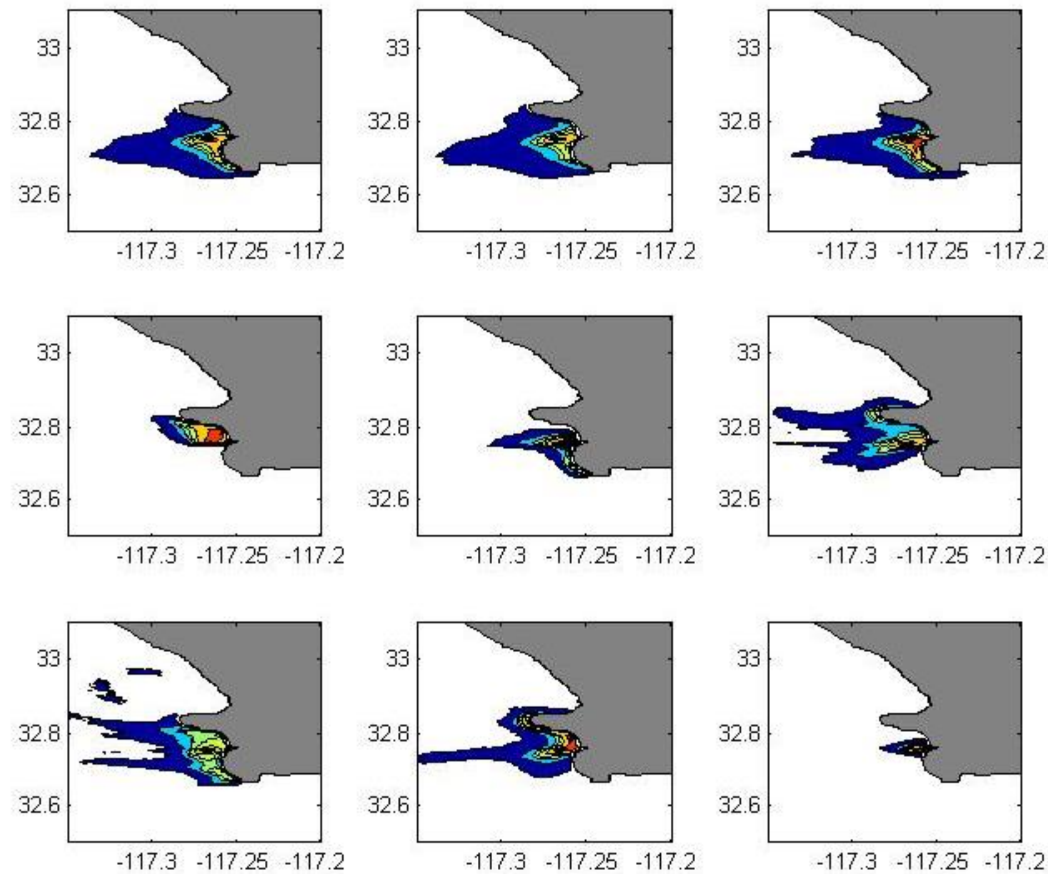

Figure S16. San Diego River summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

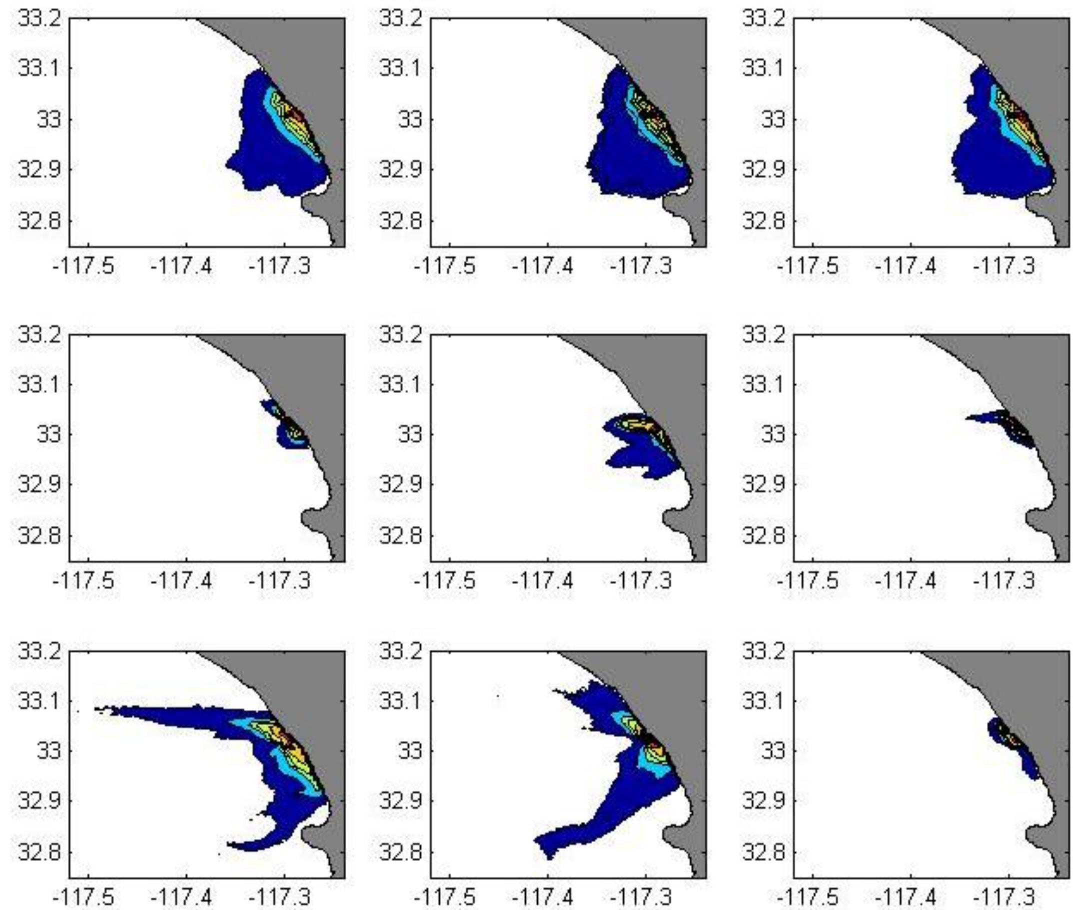

Figure S17. San Elijo Lagoon summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

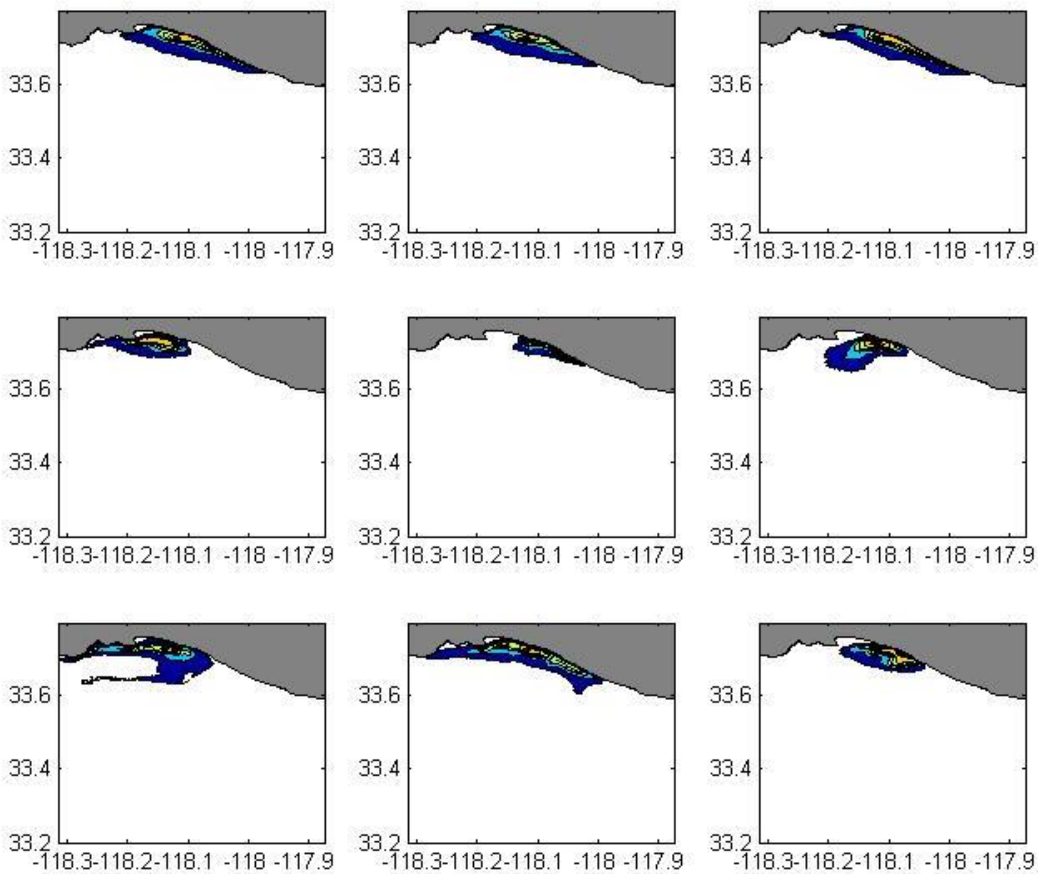

Figure S18. San Gabriel River summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

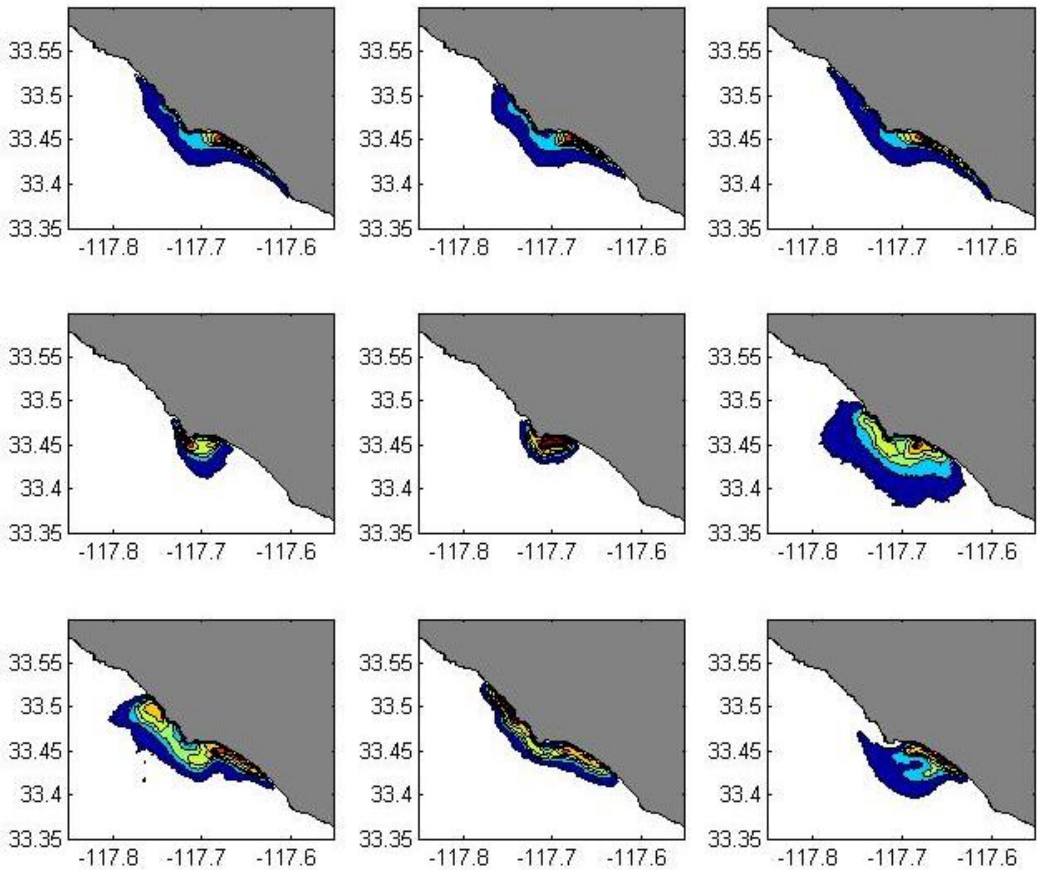

Figure S19. San Juan Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

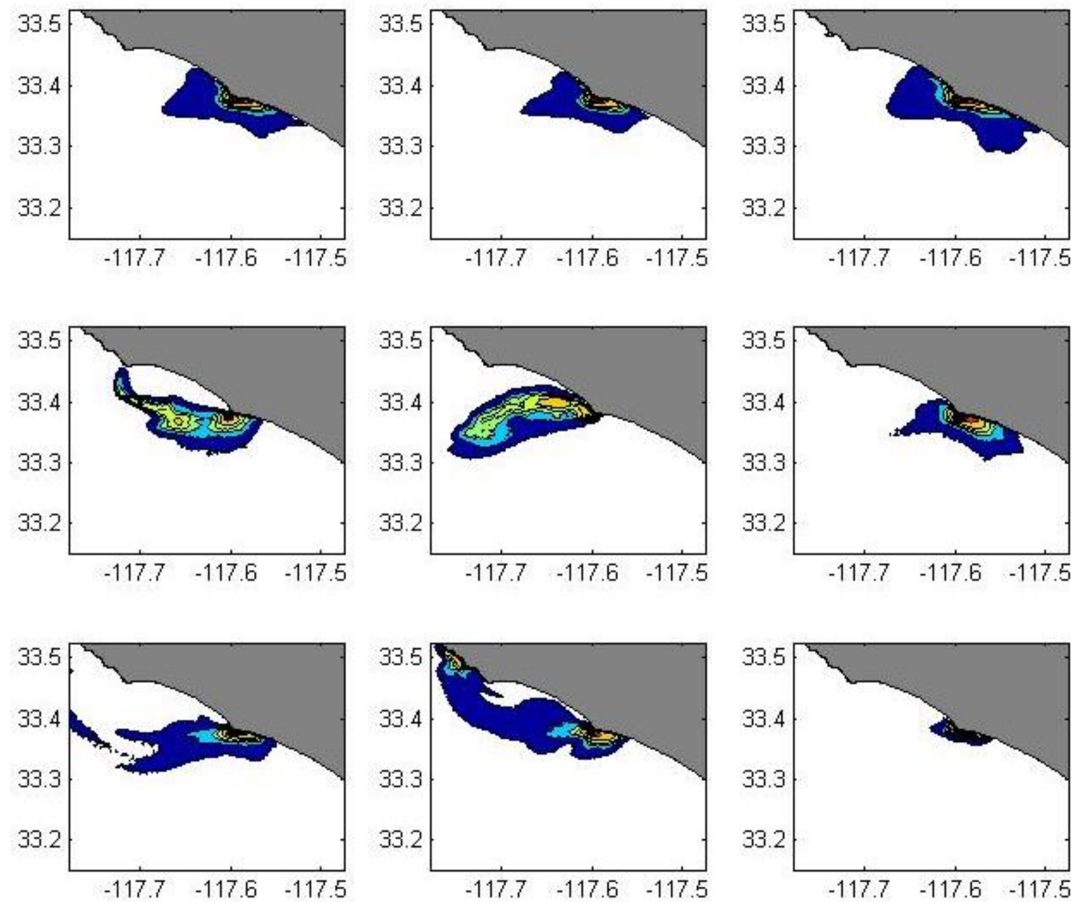

Figure S20. San Mateo Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

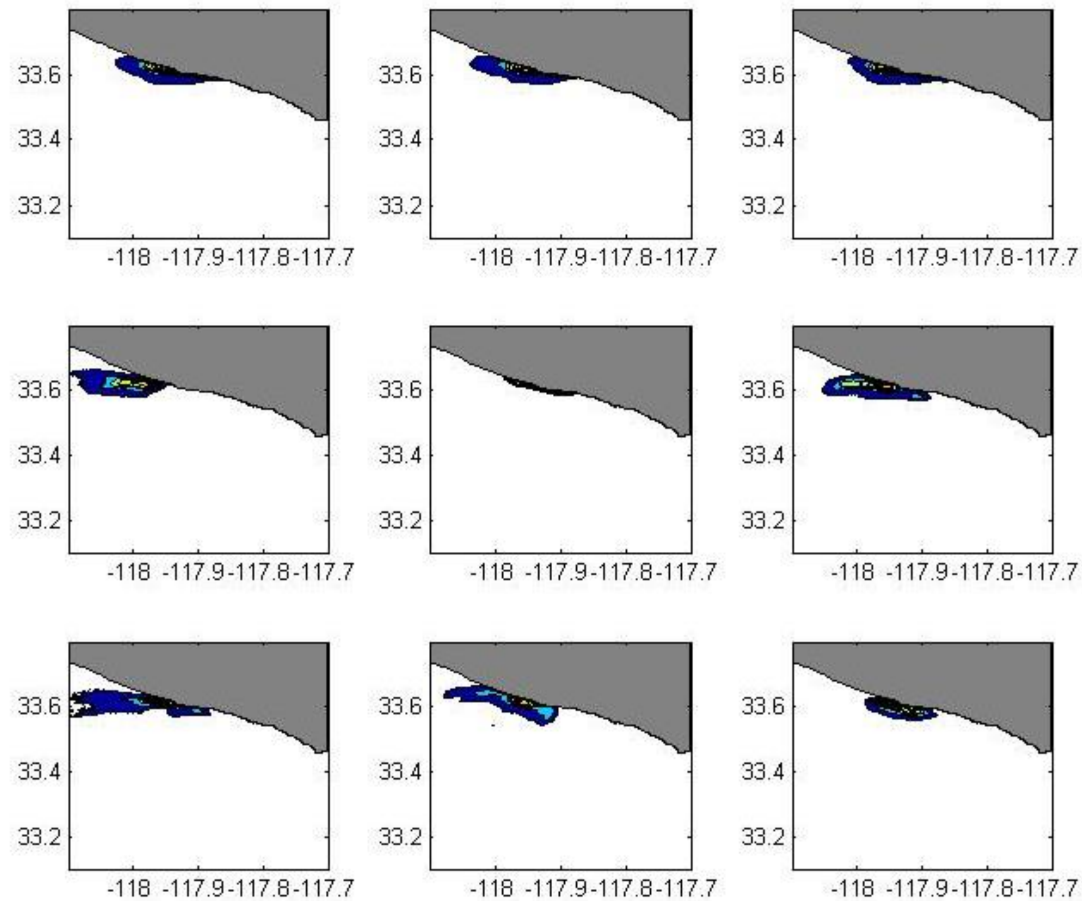

Figure S21. Santa Ana River summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

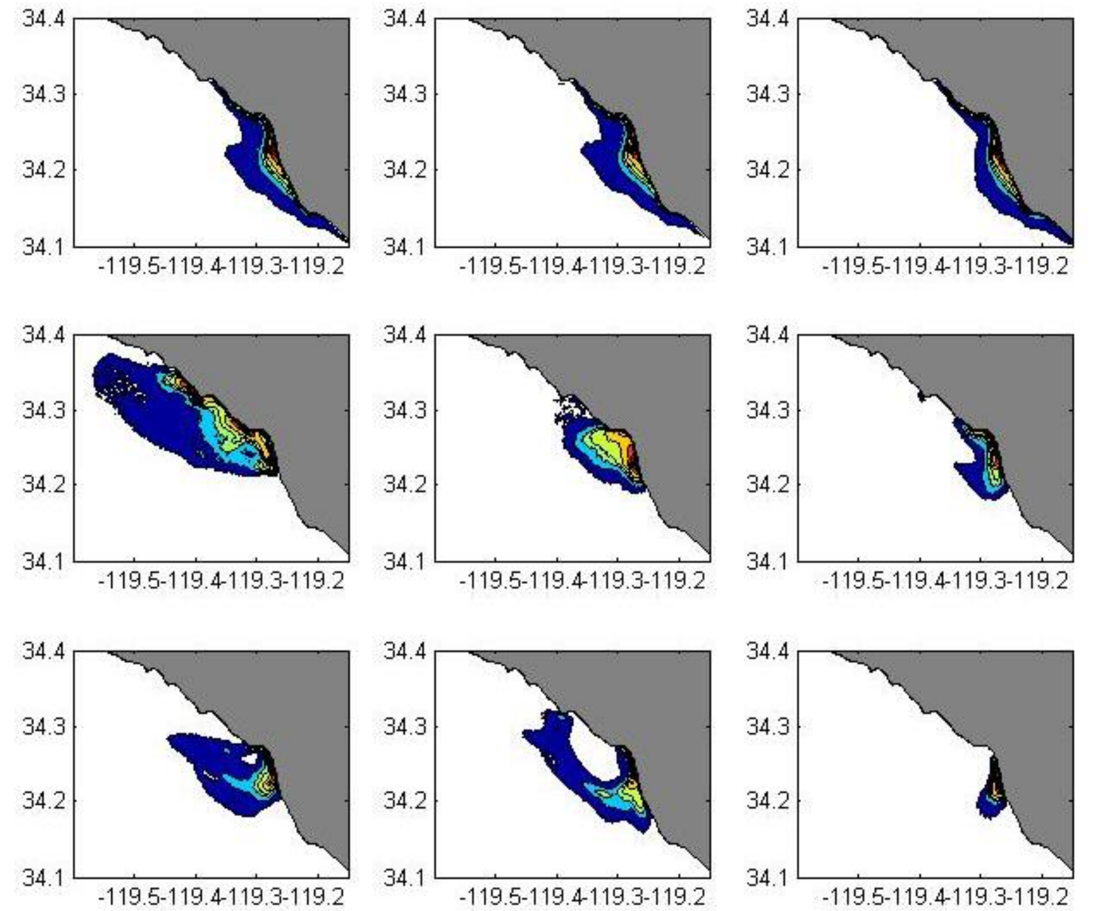

Figure S22. Santa Clara River summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

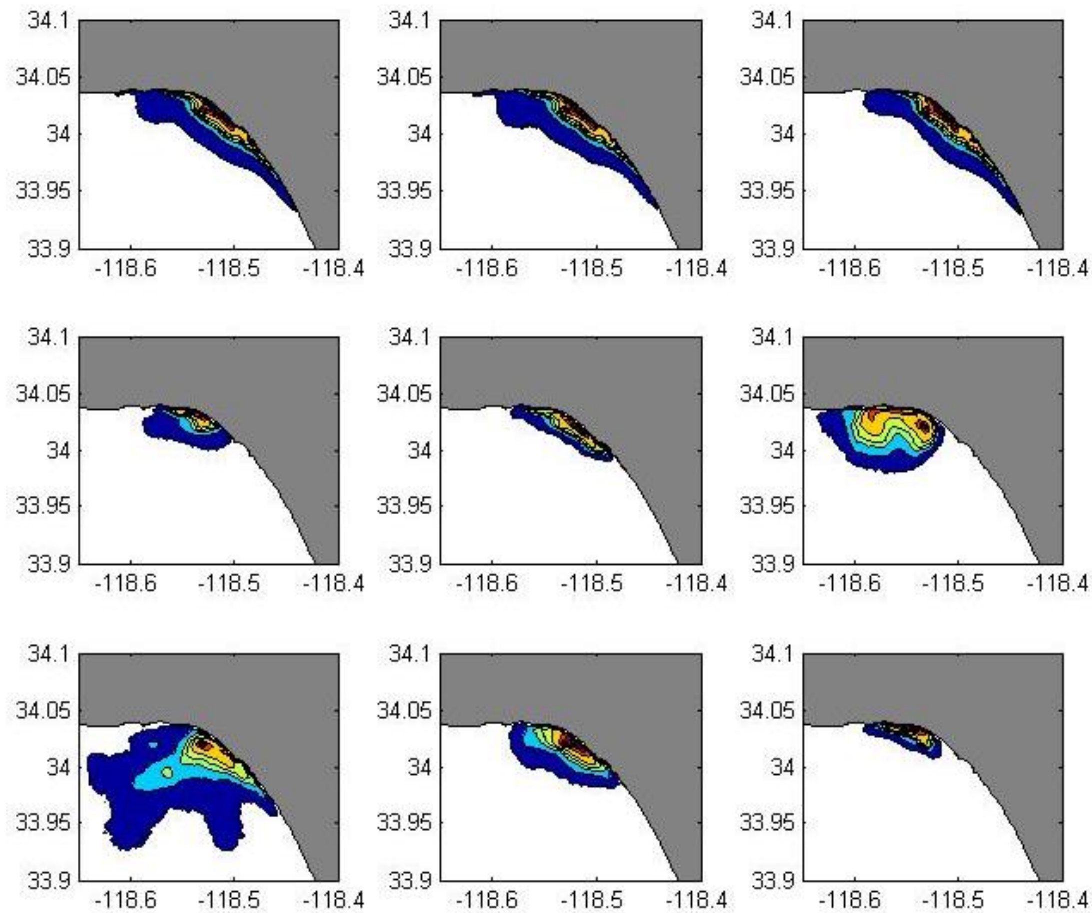

Figure S23. Santa Monica Creek summary of probability exposure maps for (a) annual, (b) wet, and (c) dry seasons and for target storm events on (d) January 26, 2008, (e) February 22, 2008, (f) November 26, 2008, (g) December 15, 2008, (h) February 5, 2009, and (i) December 7, 2009.

Summary of Spatial Extents

Table S1. Summary table of approximate alongshore and cross-shore spatial extents for all modeled regions.

	Date	Approximate Alongshore Scale (km)	Approximate Cross Shore Scale (km)
Agua Hedionda	12/15/2008	13.3	27.4
	2/22/2008	13.4	3.5
	1/23/2008	12.5	5.2
	11/26/2006	21.5	15.7
	2/5/2009	17.4	20.6
	12/7/2009	2.8	10.6
	Annual	11.5	35.1
	Dry	11.6	35.3
	Wet	10.2	32.0
Aliso Creek	12/15/2008	4.3	27.4
	2/22/2008	7.0	7.1
	1/23/2008	2.5	8.4
	11/26/2006	4.1	5.1
	2/5/2009	3.1	6.3
	12/7/2009	4.9	6.3
	Annual	4.8	7.9
	Dry	4.0	33.1
	Wet	5.3	21.4
Ballona Creek	12/15/2008	11.1	9.0
	2/22/2008	5.1	11.2
	1/23/2008	5.7	17.7
	11/26/2006	8.4	10.3
	2/5/2009	4.0	15.0
	12/7/2009	2.3	8.9
	Annual	3.2	17.0
	Dry	3.2	13.9
	Wet	3.8	18.0
Batiquitos Lagoon	12/15/2008	12.6	23.7
	2/22/2008	10.0	13.2
	1/23/2008	7.4	8.2
	11/26/2006	18.0	8.1
	2/5/2009	8.0	34.2
	12/7/2009	2.5	6.5
	Annual	4.8	29.1
	Dry	5.7	30.5
	Wet	4.3	27.0
Buena Vista Lagoon	12/15/2008	13.8	32.5
	2/22/2008	14.5	4.0
	1/23/2008	12.4	7.4

	11/26/2006	17.1	18.0
	2/5/2009	18.6	21.6
	12/7/2009	8.3	11.6
	Annual	16.1	44.6
	Dry	17.0	44.0
	Wet	16.0	44.8
Calleguas Creek	12/15/2008	9.2	43.0
	2/22/2008	4.9	9.3
	1/23/2008	2.4	18.9
	11/26/2006	3.7	18.8
	2/5/2009	8.2	29.9
	12/7/2009	7.1	19.8
	Annual	7.0	36.7
	Dry	6.9	32.3
	Wet	7.3	36.5
Laguna Canyon	12/15/2008	10.5	24.1
	2/22/2008	5.0	7.1
	1/23/2008	1.8	10.6
	11/26/2006	5.5	12.3
	2/5/2009	11.2	27.7
	12/7/2009	2.1	9.6
	Annual	38.0	6.8
	Dry	40.0	8.0
	Wet	37.0	7.7
Los Penasquitos	12/15/2008	15.0	24.0
	2/22/2008	13.2	2.0
	1/23/2008	8.7	11.3
	11/26/2006	6.1	5.8
	2/5/2009	8.5	9.0
	12/7/2009	9.4	9.0
	Annual	9.5	27.3
	Dry	10.4	29.7
	Wet	8.5	26.1
Malibu Lagoon	12/15/2008	19.7	22.4
	2/22/2008	2.6	13.8
	1/23/2008	3.1	11.7
	11/26/2006	6.2	11.0
	2/5/2009	8.9	15.4
	12/7/2009	4.8	10.7
	Annual	7.3	36.1
	Dry	7.6	37.1
	Wet	7.2	36.8
Newport Bay	12/15/2008	14.1	6.7
	2/22/2008	2.1	5.6
	1/23/2008	12.3	7.9

	11/26/2006	6.5	8.0
	2/5/2009	6.1	13.7
	12/7/2009	8.1	7.7
	Annual	5.7	14.1
	Dry	5.0	16.2
	Wet	6.1	14.1
Salt Creek	12/15/2008	5.5	10.8
	2/22/2008	3.0	7.8
	1/23/2008	3.2	4.1
	11/26/2006	3.3	9.2
	2/5/2009	5.2	11.1
	12/7/2009	5.0	8.1
	Annual	6.7	25.2
	Dry	5.8	26.3
	Wet	7.4	20.5
San Dieguito	12/15/2008	10.0	28.3
	2/22/2008	7.3	9.6
	1/23/2008	2.0	10.6
	11/26/2006	2.0	12.1
	2/5/2009	7.7	20.9
	12/7/2009	2.2	13.7
	Annual	8.5	28.0
	Dry	9.9	29.0
	Wet	8.8	26.7
San Diego Bay	12/15/2008	4.5	9.6
	2/22/2008	2.3	7.1
	1/23/2008	2.3	8.0
	11/26/2006	5.8	6.5
	2/5/2009	2.9	11.8
	12/7/2009	5.9	9.2
	Annual	5.1	9.4
	Dry	7.4	10.2
	Wet	5.4	8.3
San Diego River	12/15/2008	8.1	21.9
	2/22/2008	5.6	14.2
	1/23/2008	4.1	9.5
	11/26/2006	9.0	18.6
	2/5/2009	9.6	20.0
	12/7/2009	3.6	6.4
	Annual	7.5	20.9
	Dry	7.5	19.5
	Wet	7.3	21.3
San Elijo	12/15/2008	18.0	30.1
	2/22/2008	7.0	12.7
	1/23/2008	3.0	11.4

	11/26/2006	4.7	9.0
	2/5/2009	7.2	24.6
	12/7/2009	2.0	14.0
	Annual	9.2	29.5
	Dry	9.0	29.9
	Wet	10.0	27.6
San Gabriel	12/15/2008	14.6	30.4
	2/22/2008	4.5	13.8
	1/23/2008	7.8	18.3
	11/26/2006	12.0	7.9
	2/5/2009	7.0	33.9
	12/7/2009	8.5	13.6
	Annual	6.4	22.7
	Dry	5.3	23.9
	Wet	7.9	22.3
San Juan	12/15/2008	5.7	19.2
	2/22/2008	3.7	7.6
	1/23/2008	5.7	8.4
	11/26/2006	9.1	24.8
	2/5/2009	3.9	20.2
	12/7/2009	6.6	14.3
	Annual	5.6	23.5
	Dry	5.1	25.9
	Wet	5.4	19.6
San Mateo	12/15/2008	13.4	9.4
	2/22/2008	17.2	8.1
	1/23/2008	8.9	19.6
	11/26/2006	7.3	14.1
	2/5/2009	10.1	26.8
	12/7/2009	2.9	6.2
	Annual	8.3	16.0
	Dry	8.1	17.7
	Wet	8.7	12.6
Santa Ana	12/15/2008	11.9	17.6
	2/22/2008	11.9	19.3
	1/23/2008	30.8	33.8
	11/26/2006	7.4	14.5
	2/5/2009	10.7	17.2
	12/7/2009	5.5	7.4
	Annual	8.1	33.7
	Dry	5.6	36.0
	Wet	8.6	32.1
Santa Clara	12/15/2008	24.8	10.4
	2/22/2008	14.8	9.6
	1/23/2008	35.0	11.4

	11/26/2006	14.0	6.6
	2/5/2009	24.6	9.4
	12/7/2009	7.5	5.1
	Annual	33.4	7.5
	Dry	35.0	5.4
	Wet	31.7	8.2
Santa Monica	12/15/2008	13.8	16.3
	2/22/2008	2.3	10.8
	1/23/2008	3.7	8.2
	11/26/2006	8.6	12.4
	2/5/2009	5.5	11.6
	12/7/2009	2.4	7.5
	Annual	3.7	21.8
	Dry	3.6	20.0
	Wet	3.9	21.9