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An assessment of the transport of southern California stormwater ocean discharges

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ABSTRACT

The dominant source of coastal pollution adversely affecting the regional coastal water quality is the seasonally variable urban runoff discharged via southern California's rivers. Here, we use a surface transport model of coastal circulation driven by current maps from high frequency radar to compute two-year hindcasts to assess the temporal and spatial statistics of 20 southern California stormwater discharges. These models provide a quantitative, statistical measure of the spatial extent of the discharge plumes in the coastal receiving waters, defined here as a discharge's "exposure". We use these exposure maps from this synthesis effort to (1) assess the probability of stormwater connectivity to nearby Marine Protected Areas, and (2) develop a methodology to estimate the mass transport of stormwater discharges. The results of the spatial and temporal analysis are found to be relevant to the hindcast assessment of coastal discharges and for use in forecasting transport of southern California discharges.

1. Introduction

The urbanization of southern California has resulted in one of the most densely populated coastal regions in the country (Crossett et al., 2004). Coastal waters of the Southern California Bight (SCB) are typically the final destination for pollutants originating from coastal counties of San Diego, Orange, Los Angeles, Ventura, and Santa Barbara that account for approximately 25% of the total US coastal population (Culliton et al., 1990). 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 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), which are discharged offshore via jet-like hypopycnal plume structures that are dispersed by momentum, local wind stresses, and current forcing (Warrick et al., 2004). The issue of runoff contamination is exacerbated by continual development (i.e., more impervious surfaces), increases in the number of nonpoint sources, and higher 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).

Surface plumes are dramatically altered by local wind stresses and coastal currents (Kourafalou et al., 1996b) making the acquisition of relevant spatial and temporal scaled data essential to evaluating and managing pollution hazards posed by stormwater runoff. Acquiring this data in-situ is a challenge for fixed, boat-based, and mobile sensors because of the episodic nature and spatial extents of stormwater flows. The spatial and temporal variability of stormwater discharges limits the effectiveness of an array of fixed current meters to consistently observe plume transport direction due to the complexities of circulation within the SCB (DiGiacomo and Holt, 2001; DiGiacomo et al., 2004). Offering an improvement over fixed-sensors, the use of boat-based sampling and mobile sensors (e.g., Autonomous Underwater Vehicles, gliders) can increase the spatial resolution of the output results, but currently the cost of this type of data collection is prohibitive,

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which often limits a surveys spatial extent (Terrill, 2009; Smith et al., 2010; Rogowski et al. 2012). Additionally, near-synoptic observations are difficult to acquire due to the temporal variability of the discharge and receiving waters (i.e., changes in current magnitude and direction). These challenges are reflected in the fact that the majority of in-situ stormwater studies have focused on small-scale discharges and their transport to adjacent beaches and nearshore waters (e.g., Ackerman and Weisberg, 2003; Bay et al., 2003; Reeves et al., 2004; Ahn et al., 2005).

For synoptic observations of stormwater plumes, one valuable research tool is satellite based remote sensing of coastal regions using visible, near-, and thermal-infrared portions of the electromagnetic spectrum. However, these types of images are adversely effected by cloud cover and low light conditions and typically have a ground resolution between 0.3 and 1 km, which limits their ability to capture the small scale plume features. Additionally, the intermittency of cloud free days makes collection of the continual time evolution of the discharge challenging, and the co-mingling of neighboring plumes increases the difficulty of distinguishing the optical signatures of each plume (Warrick et al., 2007). Using active microwave remote sensing approaches often overcome these types of limitations (DiGiacomo et al., 2004). For example, satellite-borne synthetic aperture radar (SAR) is a remote sensing approach that is not limited by cloud cover or light availability, and offers a ground resolution of approximately 100 m or less allowing for visualization of small-scale, oceanographic processes, such as coastal eddies on a synoptic time scale (e.g., Munk et al., 2000; DiGiacomo and Holt, 2001). While SAR imaging can be limited by environmental conditions (e.g., wind and waves), the temporal sampling remains the most significant constraint (similar to other satellite based remote sensing methods). For SAR monitoring the observational sampling frequency is variable and can range from twice-per-day to only several observations per week (DiGiacomo et al., 2004). Because of these often relatively large time gaps between measurements the SAR monitoring method is limited in its ability to consistently observe both periodic and episodic stormwater plumes.

The limitations of in-situ and remote based sampling, makes it elusive to create a consistent methodology to assess multiple stormwater discharges across an entire region. In light of the challenges of in-situ and satellite based studies of stormwater, model-based assessments of stormwater discharges represents one of the few strategies to provide a consistent and cost-effective framework for examining the regional variability of stormwater transport and their impacts. This strategy has been demonstrated by Ackerman and Schiff, (2003) who developed a stormwater runoff model to estimate mass emissions into the entire SCB and Kim et al. (2009) who developed a surface transport model to assess discharges in the San Diego/Tijuana border region. A novel aspect of the latter study was the use of coastal current time series provided by High Frequency (HF) radar, which drove the transport model of the plume.

The work presented in this paper extends the surface transport hindcast approach developed by Kim et al. (2009) to assess the potential transport of 20 stormwater coastal discharges (Fig. 1) located throughout southern California. Exposure maps of each discharge are computed to define the spatial extent of the plume for each day the discharge was active. We term these active days "release days". The hindcast approach allows for the identification of annual and seasonal circulation patterns as well as targeted storm events. These exposure maps provide a tool to assess how Areas of Special Biological Significance (ASBS) in Southern California will be exposed to stormwater. ASBS have been designated by the California State Water Resources Control Board (SWRCB) to protect and preserve biological communities that are diverse and abundant with marine life. The SWRCB mandates that ASBS receive "no discharge of waste" and maintain "natural water quality" (State Water Resources Control Board, 2005) (Fig. S1, Supporting Information). While the computed exposure is a statistical measure of the plume's connectivity with neighboring waters, with initial concentration and plume mixing assumptions, the model results can be extended to estimate the mass transport of coastal discharges.

2. Material and methods

2.1. Surface currents

Ocean surface currents used to drive the transport model are provided by HF radar (Paduan and Graber, 1997). To reduce the number of spatial and temporal gaps we objectively map the currents to a 6 km grid using a sample covariance matrix computed from two years (2008–2009) of hourly data (Kim et al., 2007). The uncertainty of the estimated coastal current field is approximately 8.6 cm s^{-1}, which is consistent with reported root-mean-square (rms) errors between surface current measurements derived from HF radars and drifter velocity observations (Ohlmann et al., 2007; Kim et al., 2008, 2009).

2.2. A plume exposure hindcast model

A Lagrangian forward particle trajectory, representing parcels of water, is computed in the time domain:

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

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

where $x(t) = [x(t)y(t)]^\dagger$ and $u(t) = [u(t)v(t)]^\dagger$ denote the location of the particle (i.e., water tracer) and the surface currents at the tracer location at a given time (t), respectively. Here, t_o 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 rms of ε. The diffusion parameter (ε^u and ε^v) represents unresolved velocities as the uncertainty in the HF radar measurements (ε = 5 cm s^{-1}).

In Lagrangian stochastic models, the random walk model inherits the similarity of the Lagrangian statistics of the passive tracer in the coastal region (Griffa et al., 1995; Griffa, 1996). Random flight models are another common stochastic approach that are better suited for active tracers and have been used in studies of marine larvae spreading (Siegel et al., 2003; Isaji et al., 2005; Spaulding et al., 2006; Ullman et al., 2006). The random walk model was chosen for this study to preserve the shape of the power spectrum of the original current field, and to better represent the coastal discharge as a passive tracer.

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. The Monte Carlo simulations using the formulation in Eqs. (1) and (2) were computed using 50 trajectories constantly being released each hour at each source location (Fig. 1). Trajectories were computed for the two-year hindcast period and each tracked for three days, consistent with estimates for the efficacy of Fecal Indicator Bacteria (FIB) (Noble et al., 2000, 2004; Ackerman and Weisberg, 2003).

To transport the numerical parcels of water near the coastal boundary we use an along-coast projection of currents inshore of the 1 km boundary, which is the nearshore extent of the HF radar's observations. No time-dependence of the FIB decay in the 0–3 day time window was assumed since the study objective was to assess the probabilistic transport of the plume as opposed to concentration prediction. The results presented should be considered conservative as the decay rate of FIBs in marine waters are poorly understood (Davies-Colley et al., 1994).

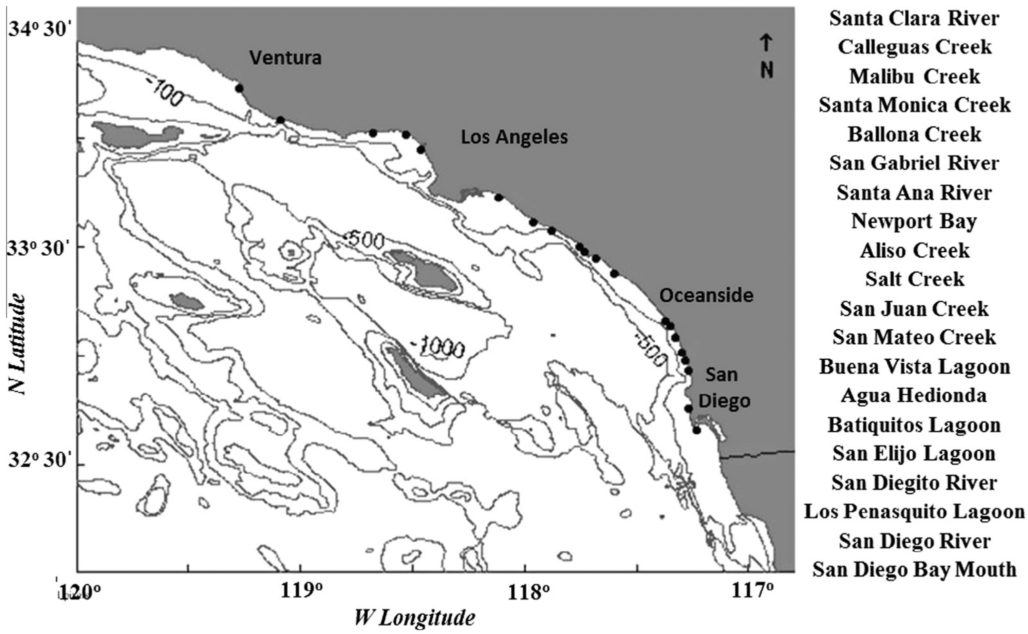

Fig. 1. Map of southern California showing the 20 discharges sites locations. Names of the discharge sites are listed sequential from north to south in the right hand pannel. Off shore bathymetry contours are also shown in units of meters below sea-level.

The coastal exposure kernel (CEK, P) defined as the relative probability of plume exposure computed from the ratio of the number of water tracers at a given location $F(x,y)$ to the total number released at the source location, expressed in percent is (Kim et al., 2009):

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

This surface transport model was used to assess the fate and transport of several discharges in the San Diego/Tijuana border region during high FIB events from April 2003 to March 2007. The model's skill in assessing water quality in the surf zone was evaluated using receiver operating characteristic (ROC) analysis, which showed 70% accuracy over a four-year period (Kim et al., 2009).

2.3. Probability exposure maps

Probability exposure maps at the 20 discharge sites (Fig. 1) are computed using the hourly hindcasts over a two-year period (Fig. 2) to provide a statistical convergent depiction of the modes of plume transport. The statistics from the hindcasts analysis are computed for annual and seasonal patterns and 6 different rain events. The annual exposure maps are based upon hourly computations from January 1, 2008 to December 31, 2009 while the seasonal maps used surface current data observed during southern California's wet and dry seasons defined as October through April and May through September, respectively. In addition, 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 (Figs. S2–S21, Supporting Information).

3. Results and discussion

3.1. Probability exposure maps

Probability exposure maps for Calleguas Creek, Santa Ana River, and Newport Bay (rows A, B, and C in Fig. 3, respectively) for the

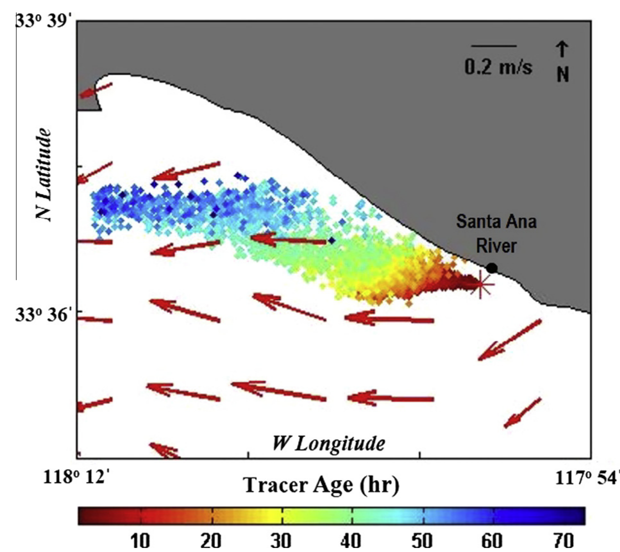

Fig. 2. Example of the Santa Ana River particle trajectory estimate using the hourly hindcast approach during the December 15, 2008 storm event. The color of the numerical water tracers represent the age of the discharge. The plume is tracked for three days. The red arrows illustrate the hourly observed surface currents (from HF radar) that drive the trajectory estimates.

two-year hindcast period (2008–2009) and targeted rainfall events on February 22, 2008 and December 15, 2008 (columns) are selected as a representative sample of the probability exposure maps generated for the 20 coastal discharge sites. The annual exposure maps emphasize the average circulation in the region neighboring each discharge while the targeted storm event maps provide examples of the variability of the plumes during each discharge event that occurs over a short finite time. The storm events range in duration, the December 15 was particularly long, sustained by rainfall from approximately December 15 to December 25 (10 days) whereas the February 22 storm event had a much shorter duration of 3 days. The event window for each storm considered the number of days of active rain plus 3 additional days to

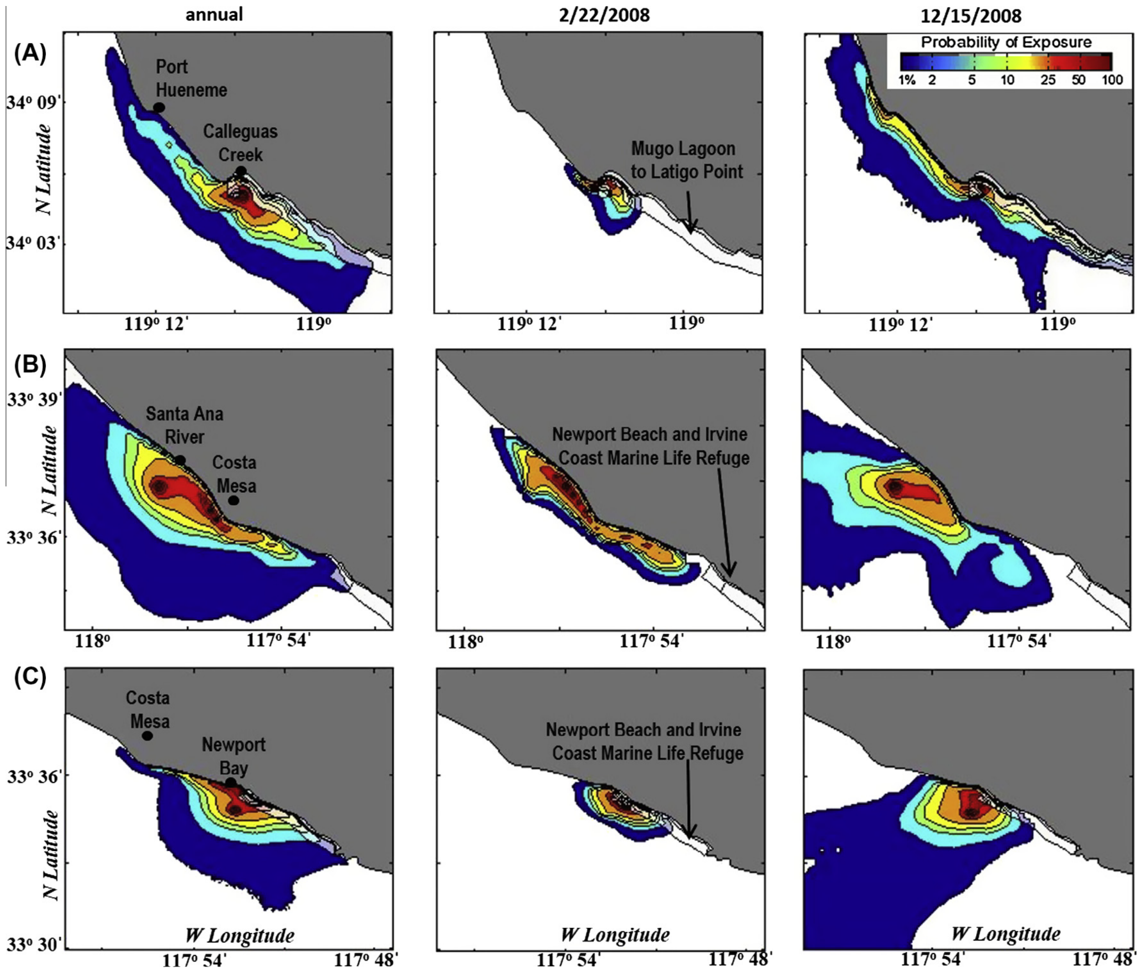

Fig. 3. Probability exposure maps organized by rows for (A.) Calleguas Creek, (B.) Santa Ana River, and (C.) Newport Bay. Additionally, each column represents a different temporal model run including annual, the February 22, 2008 storm event, and the December 15, 2008 storm event. Local ASBS boundaries are also displayed in all figures and defined in February 22, 2008 column. Warm colors indicate areas of significant probabilities that transition to cooler colors that represent an expontial decrease in probabilities.

account for elevated levels of bacterial concentrations that persist following a storm event (Ackerman and Weisberg, 2003).

Coastal circulation differences cause variations in the plume transport (Fig. 3). Substantial differences between the February 22nd and December 15th along-shore and cross-shore plume extents illustrate how the exposure maps are affected by the variability in surface currents. As expected the final spatial extent of the plume is also a function of the time duration of discharge, where broader spatial extents are realized during periods of longer discharge. The seasonal and annual exposure maps exhibit larger extents due to the tracking of high number statistics in the model (e.g., annual model run time is 730 days and 876,000 Lagrangian trajectories) compared to targeted storm events that have typical run times between 6 and 10 days (7200 and 12,000 trajectories, respectively). In addition, longer discharges improve the ability to compute low probability (<1%) statistics for the annual and seasonal periods resulting in larger spatial extents. Summaries of the spatial extents from all modeled discharges are presented in Supporting Information, Table S1.

3.2. Spatial evolution of probability exposure maps

The urban nature of the southern California coastal landscape creates numerous stormwater discharges, many of which are often in close proximity to one other. The spatial and temporal resolution of the hindcast model allows the assessment of neighboring plumes to provide insight on which discharge may be impactful to a particular stretch of coast. To discriminate multiple plumes we conduct a case-study of the Newport Bay discharge, which is located north of the Santa Ana River. We created daily probability exposure maps averaged over 24 h for the Santa Ana River discharge (upcoast plume) and the Newport Bay plume (downcoast plume), which we overlaid with a surface current field averaged for the same period (Fig. 4). On December 15, a predominantly onshore current direction restricted the cross-shore extent of both plumes as observed in the probability exposure map's narrow overlapping alongshore distribution (Fig. 4A). A poleward coastal current flow is observed as the storm strengthened from December 16 to 17 resulting in a northwestward alongshore shift in direction of the Santa Ana plume, which persists through peak discharge observed on December 18 (Fig. 4B and C). As the plume advects upcoast, it shifts to a westward direction as a result of the strong curvature of the San Pedro Bay coastline (Fig. 2). During the same period, a localized current field with mean offshore transport developed within the receiving waters of the Newport Bay discharge which resulted in a probability exposure map that was independent of the observed regional flow field (Fig. 4B and C). The sub-mesoscale current variability resulted in two spatially unique probability exposure maps for the close proximity discharges (Fig. 3B and C, December 15, 2008 column).

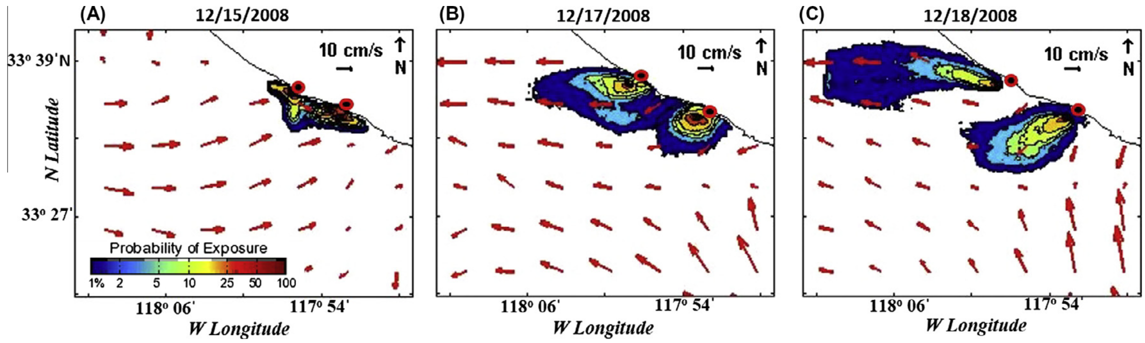

Fig. 4. Daily averaged plume exposure maps and current field (red arrows) illustrating the evolution of the Santa Ana River plume (north) and the Newport Bay plume (south) on (A) December 15, (B) December 17, and (C) December 18, 2008. The red circles denote the approximate outlet of each discharge.

3.3. Stormwater exposure to Marine Protected Areas (MPAs)

We use our resulting stormwater exposure maps for the 20 coastal discharges to assess the probability of exposure to MPAs located in the SCB. The ASBS stormwater probability of exposure was calculated from the ratio of the total number of Lagrangian trajectories that cross the ASBS boundary to the total number of trajectories modeled during a given temporal period. We summarize the ASBS probabilities of exposure that are greater than 1% in Table 1. The results indicate ASBS probabilities of exposure over the modeled temporal periods are primarily a function of the proximity of an ASBS to a discharge source. Of the 20 modeled discharges, the most significant annual exposure probability is ~19% to the receiving waters of Calleguas Creek, which is within the boundaries of the Mugu Lagoon to Latigo Point ASBS. Similarly, the minimal alongshore distance of the Newport Beach and Irvine Coast Marine Life Refuge to the Newport Bay outlet (0.5 km and 1.5 km, respectively) also resulted in consistent exposures to its discharge (Fig. 3A and C) with annual exposures of 7% and 9.3%, respectively. In addition to the Newport Bay and Calleguas Creeks discharges, the Malibu River discharge, located ~7.5 km from the downcoast boundary of the Mugu Lagoon to Latigo Point ASBS, was the only other discharge of the 20 studied to have probabilities of exposure greater than 1% with an annual exposure of 1.4%. Importantly, these model results suggest that there is potential exposure of stormwater discharges to MPAs that are separated by several kilometers of coastline. For example, the December 15, 2008 sustained storm events longer modeling period (10 days) and current variability increased the Malibu River discharges alongshore spatial extent that resulted in a probability of exposure of 6.2% to the Mugu Lagoon to Latigo Point ASBS.

3.4. Coastal discharge concentration estimates

Probability exposure maps are a statistical measure of the stormwater plume's spatial connectivity with neighboring waters, it is not a measure of concentration. To allow for inter-comparisons between discharges, model results were extended to estimate the mass transport of a discharge assuming (1) water tracers are confined to the surface depth layer where HF radar surface currents are measured, (2) near-coast tracers follow the along-coast projection estimated from surface observations 1 km offshore, and (3) the initial concentration was constant throughout the modeling period. Mass transport estimates (C) were computed by multiplying an initial concentration (C_o) by the ratio of the number of water tracers at a given location $F(x,y)$ to the total number of water tracers released at the source location:

$$C(x,y) = \frac{F(x,y)}{\max[F(x,y)]} \times C_o \tag{4}$$

We next conduct a case-study to assess the mass transport between the Santa Ana River and Calleguas Creek discharges. The Santa Ana River annual mean discharge from 2000 to 2013 was ~3.2 cubic meters per second (cumec), compared to ~1.4 cumec for Calleguas Creek as measured by the United States Geological Society (USGS) water gauge data (site numbers 11,106,550 and 11,078,000, respectively). The cumulative discharge volume for the 10 day December 15, 2008 storm event was $\sim 9.65 * 10^9$ l and $3.7 * 10^9$ l for the Santa Ana River discharge and the Calleguas Creek discharge, respectively. The discharge volumes were used to estimate an initial concentration of discharge given the area of the model grid (dx, dy) and an assumed vertical mixing extent (dz = 1 m). The initial discharge concentrations (C_o) were dispersed

Table 1
Summary of the ASBS probabilities 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.

	Areas of Special Biological Significance			
	Mugu Lagoon to Latigo Point		Newport Beach Marine Life Refuge	Irvine Coast Marine Life Refuge
	River discharge			
	Calleguas Creek (%)	Malibu River	Newport Bay (%)	Newport Bay (%)
Model period				
Annual	19.3	14%	7.0	9.3
Wet season	18.0	1.5%	6.9	8.8
Dry season	23.3	1.1%	7.4	10.8
01/23/08	9.5	NA	<1	<1
02/22/08	33.6	NA	13.8	18.6
11/26/08	26.0	NA	2.1	8.0
12/15/08	29.0	6.2%	3.0	1.5
02/05/09	22.0	<1%	1.5	2.9
12/07/09	10.6	NA	<1	12.2

according to the model results to assess mass transport differences between the Santa Ana River and Calleguas Creek discharge. While the spatial extent of each discharge remains unchanged (from earlier maps), normalized concentration maps illustrate the differences of the spatial extent of high discharge concentration areas resulting from varying mass loadings (Fig. 5). We find that the higher mean flow rate of the Santa Ana River during the December 15, 2008 storm resulted in a substantial area of the receiving waters being exposed to high discharge concentration levels while the Calleguas Creek receiving waters were exposed to comparatively low discharge concentrations.

3.5. Surf zone water quality assessment

Storm events cause an increase in the inertial discharge of the Santa Ana River, which advects cross-shore in a high momentum hypopycnal plume that interacts with offshore currents. 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. Offshore of the surf zone, coastal currents are primarily driven by tides, winds, and remote forcing which can result in different flow directions compared to wave-driven surf zone currents (Ahn et al., 2005; Kim et al., 2004; Grant et al., 2005). The HF radar surface current observations cannot capture near-shore dynamics at the resolution needed to resolve surf zone currents. Given this nearshore data limitation, we decided to assess the feasibility of using probability exposure maps in the Santa Ana River receiving waters as a predictive tool of near-shore water quality under varying wave fields. To accomplish this we assessed two high intensity storm events on January 5, 2008 and January 27, 2008. Each storm had a peak significant wave height of ~2.5 m and peak flow rates of ~1700 and ~1900 cubic feet per second (CFS), respectively.

The beaches adjacent to the Santa Ana River outlet are approximately straight and face southwest at an approximate angle of 214°. The surf zone currents are primarily driven by swells from the west or south. Southwesterly swells (shore-normal) are blocked by the San Clemente and Catalina Islands preventing them from reaching the Santa Ana River receiving waters (Clark et al., 2010). Since 1958, the Orange County Sanitation District (OCSD) has routinely measured surf zone water quality in the region, and a detailed description of the sampling method and history can be found in Boehm et al., 2002. The locations of sample stations, placed at 3000 ft intervals, are based on their respective distances (in thousands of feet) north or south of the Santa Ana River outlet (e.g., station 0 is located at the discharge origin while the next closest stations 3S and 3N are approximately 3000 ft south and north of origin respectively). Fecal coliform (FC) observations were used to assess water quality at stations adjacent to the Santa Ana River during the two storm events. The California State AB411 bathing water quality standard is 400 FC/100 ml (often reported as most probable number (MPN) of coliform per 100 mL).

The January 5, 2008 storm produced westerly winds throughout the study region causing significant wave heights of 2–3 m. The resulting west swell interacted with the shoreline at an oblique angle causing a wave-driven alongshore current in the downcoast direction. Evidence of the resulting surf zone current can be seen in the water quality data south of the Santa Ana River outlet. Degraded water quality was observed from station 3S to 15S on January 8, 2008 with exceedances observed at station 3S (Fig. 6a). Station 0 is located on the north side of the Santa Ana River outlet and measured FC at ~200 MPN/100 mL with minimal stormwater signatures north of the station. The probability exposure map for the time period preceding and during the exceedances (January 7–9, 2008) show the highest offshore probabilities of exposure upcoast of the Santa Ana River driven by coastal currents that are predominately in a northwestward direction, opposite of the surf zone currents (Fig. 7a). Conversely, water quality data from the storm event on January 27, 2008 that produced a southerly swell suggest the presence of an upcoast alongshore current resulting in water quality exceedances from Station 0 to 15N on January 28, 2008 (Fig. 6b). A peak in concentration (~1600 MPN/100 mL) occurs at station 6N that is likely a result of the patchy nature of the discharge as it advects upcoast (Clark et al., 2010). The most significant areas of exposure (from January 27 to 29, 2008) are similarly in an upcoast direction (Fig. 7b) indicating that the surf zone and coastal currents are orientated similarly.

We also found that surf zone water quality is dependent on the regions swell direction for other high discharge storm events. Increased flow from the Santa Ana River from February 9, 2009 to February 11, 2009 was impacted by a westerly swell with peak significant wave height of ~3 m resulting in a downcoast surf zone current. Same direction coastal currents suggested potential water quality impairment south of the Santa Ana River. OCSD surf zone measurements on February 10, 2008 confirm FC exceedances of 1000 MPN/100 mL, 800 MPN/100 mL, and 800 MPN/100 mL at stations 3S, 9S, and 12S, respectively. An additional example of a storm event which resulted in uncoupled surf zone and coastal currents was observed during the December 17, 2008 storm event which produced a southerly swell that generated an upcoast surf zone current, opposite of offshore currents, resulting in FC exceedances from station 0 to 9N on December 17, 2008.

The fate of pollutants discharged from rivers are governed by a complex set of environmental conditions including the tidal phasing of pollutant input into the surf zone, bathymetry, the nature of the prevailing wave field, and the tidal phasing and magnitude of coastal currents (Kim et al., 2004). Using our model results as a

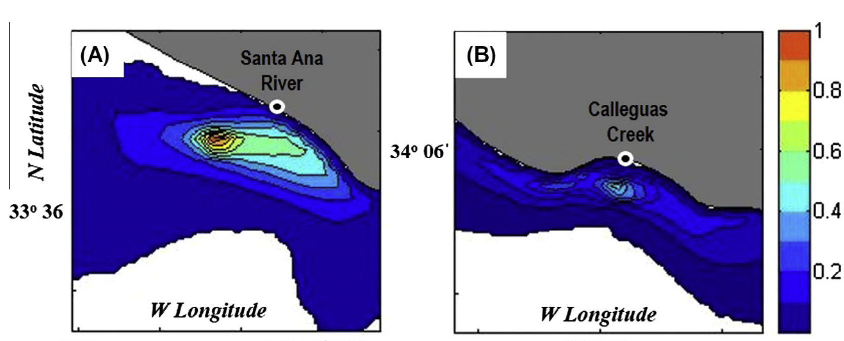

Fig. 5. (A) Santa Ana River and (B) Calleguas Creek normalized concentration maps for the December 15 storm event, derived from model outputs. The cumulative flow during the storm event was used to estimate an initial concentration.

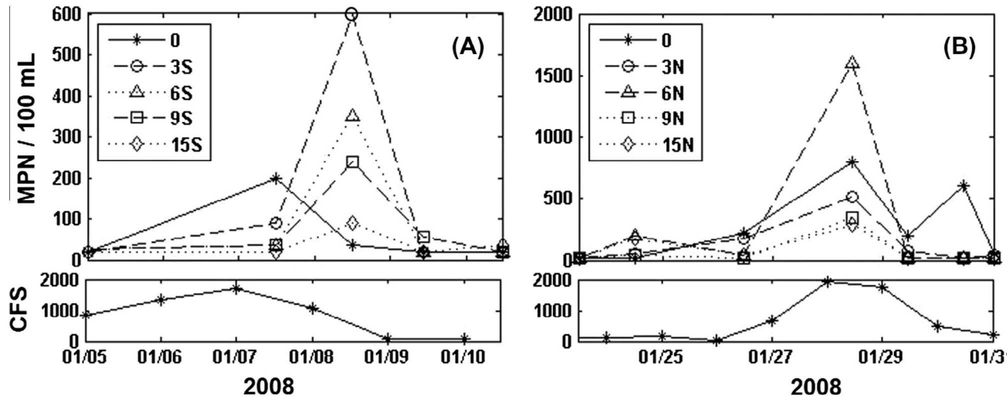

Fig. 6. Water quality observations near the Santa Ana River discharge for storm events on (A) January 5, 2008 and (B) January 25, 2008. The stations names are organized according to their respective distances from the Santa Ana River outlet (e.g. 3N is 3000 ft north of the outlet). The bottom figures show the measured flow rate in cubic feet per second (CFS) within the river for each event.

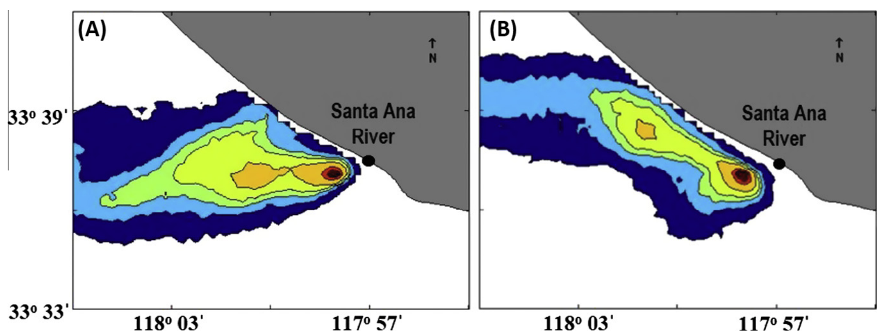

Fig. 7. Santa Ana River probability exposure maps generated from the statistical distribution for the temporal ranges (A) January 7–9, 2008 and (B) January 27–29, 2008.

predictive tool for nearshore water quality in the Santa Ana River region is limited because of the highly dynamic surf zone currents that determine longshore transport and offshore exchange. In its current form, the surface transport model does not include the effects of cross-shore circulation across the wave-driven surf zone. 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; Feddersen and Trowbridge, 2005; Grant et al., 2005). Near-shore performance of the surface transport model can be improved by coupling the model output results with surf zone model outputs. Making use of both model results will provide a better estimate of the alongshore currents and cross-shore transport, which will improve our capabilities to use these results as a predictive tool.

4. Conclusions

This paper discusses the utility of a Lagrangian particle trajectory (random walk) model, driven by hourly HF radar surface current maps, to estimate the probabilities of exposure of coastal receiving waters to stormwater discharges in the southern California region. The approach is cost effective relative to ship-based monitoring and overcomes the limitations of SAR imagery that is not always able to capture short-term variability in plume dispersal because of temporal gaps between observations. The dense HF radar coverage enables modeling of all major discharges in the SCB to determine general circulation patterns for annual, seasonal (wet and dry) temporal scales, and smaller scale targeted storm events. Results indicate that major river systems (e.g., Calleguas Creek, Newport Bay, and Malibu River) in southern California have the potential to expose MPAs to urban stormwater runoff. This study is unique in its scale, modeling 20 coastal discharges from the Santa Clara River to the San Diego Bay (~300 km alongshore distance) and the development of a technique to extend model results to estimate mass transport of a discharge. A case study was performed using the cumulative volume of discharge during a storm event to determine the initial concentration (C_o) of stormwater runoff to be dispersed by model results. This type of assessment technique can similarly be applied to estimate the dispersion of pollutants and nutrients from a coastal discharge, which will be beneficial to future fate and transport studies.

Environmental managers have recognized the utility of the trajectory model we present in this work. For example, managers tasked with maintaining natural water quality in ASBS have used our model results to understand out-of-range pollutant and nutrient values. When proximal sources appear to be remediated, they have discovered that stormwater discharge from watersheds kilometers away could be advected into their MPA. In addition, 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 despite the nearshore limitations of the model (Clifton et al., 2007). Continued investment into shore-based HF radar systems domestically and globally is resulting in an expanding footprint in which stochastic particle trajectory models operated in a hindcast or near real-time mode are an economically feasible method for large-scale stormwater fate and transport assessment studies.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2014.11.004.

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