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An assessment of the transport of southern California stormwater ocean discharges

Peter A. Rogowski [a,*], Eric Terrill [a], Kenneth Schiff [b], Sung Yong Kim [c]

[a] Coastal Observing R&D Center, Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, CA 92093-0214, USA
[b] Southern California Coastal Water Research Project, Costa Mesa, CA, USA
[c] Division of Ocean Systems Engineering, School of Mechanical, Aerospace and Systems Engineering, Korea Advanced Institute of Science and Technology, Yuseong-gu, Daejeon, Republic of Korea

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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 non-point 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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* Corresponding author.
E-mail address: progowski@ucsd.edu (P.A. Rogowski).

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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:

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

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

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_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 rms of ε. The diffusion parameter (ε^{u} and ε^{v}) represents unresolved velocities as the uncertainty in the HF radar measurements ($\varepsilon = 5$ 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).