Detection of Coastal Urban Stormwater and Sewage Runoff with Synthetic Aperture Radar Satellite Imagery

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Jan Svejkovsky[1*] and Burton Jones[2]

* To whom correspondence should be addressed.

1 Ocean Imaging Corp., 201 Lomas Santa Fe Dr., Suite 370, Solana Beach CA 92075
Phone: (858) 792-8529 Fax: (858) 792-8761 e-mail: jan@oceani.com

[2] Dept. of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, Los Angeles, CA 90089-0371

Storm and dry-weather runoff from coastal metropolitan areas has been increasingly recognized as a major source of marine pollution. Runoff escaping into the ocean through storm drains and creek beds includes bacteria and anthropogenic components from sewage, as well as fuel, oil, brake, tire and asphalt-related compounds from roadways, and industrial and agricultural substances. Unlike offshore-reaching sewage outfalls, effluent escaping through storm drains and natural outlets is released directly at the ocean shore. The resultant health hazards cause temporary beach closures and possible long-term effects through the accumulation of pollutants in near-shore sediments.

The accumulation of pollutants on roadways, urban surfaces and storm drains between rain events can cause a “First Flush Effect” (FFE) sometimes detected as an increased load of particulate and dissolved compounds in the initial runoff volume from a storm. A seasonal FFE has also been found in coastal Southern California where rain between May and October is extremely rare, resulting in pollutant accumulation periods of several months (Tiefenthaler et al., 2001). A controversial measure to reduce runoff pollution through control of the FFE has been recently adopted in Los Angeles and is being considered in other California cities. It mandates all new commercial development to include mechanisms to divert the initial 2 cm of rainfall during each storm event from directly reaching the ocean.

Studies of urban runoff commonly rely on samples taken from collectors on land or at the mouth of storm drains and creeks. Sampling the runoff plume in the ocean is considerably more difficult, since the work must be done during or immediately after the stormy conditions. The sampling difficulties thus also impede accurate determination of the spatial extent and time-dependent dispersion of runoff constituents along the coast. Satellite remote sensing presents a potential technique by which to synoptically image runoff plumes and track their transport. However, cloudy conditions during storms usually render timely detection of the plumes impossible with optical sensors. Such imagery is also unavailable at night. Synthetic Aperture Radar (SAR) is the only high-resolution instrument capable of imaging the Earth surface through cloudy conditions and at any time of day. SAR imaging of the ocean surface records the resonant or Bragg scattering from small (<10 cm) ocean waves (Valenzuela, 1978). At winds speeds between roughly 2 and 7 m/s, areas containing biogenic or anthropogenic surfactant films that dampen the small waves are discernible with SAR as patterns of low backscatter return (Gade et al., 1998). For this reason, SAR data have been widely used to detect offshore oil spills, and slicks usually attributed to the accumulation of biogenic substances by waves, winds or currents are also often seen in SAR imagery. A number of field studies in different world regions have documented that the ocean surface microlayer near urban or industrial areas contains highly elevated concentrations of pollutants, some with surfactant properties (Duce et al., 1972, Garabetian et al., 1993). We thus tested SAR's utility to discern polluted urban runoff plumes.

We examined two sample areas: 1) Santa Monica Bay, California which receives stormwater runoff from Los Angeles as well as several undeveloped drainages; 2) the coastal waters near the U.S. / Mexico border which contain urban stormwater outlets from San Diego and Tijuana, Mexico, and at least one major source of minimally treated sewage being discharged directly into the surf zone.

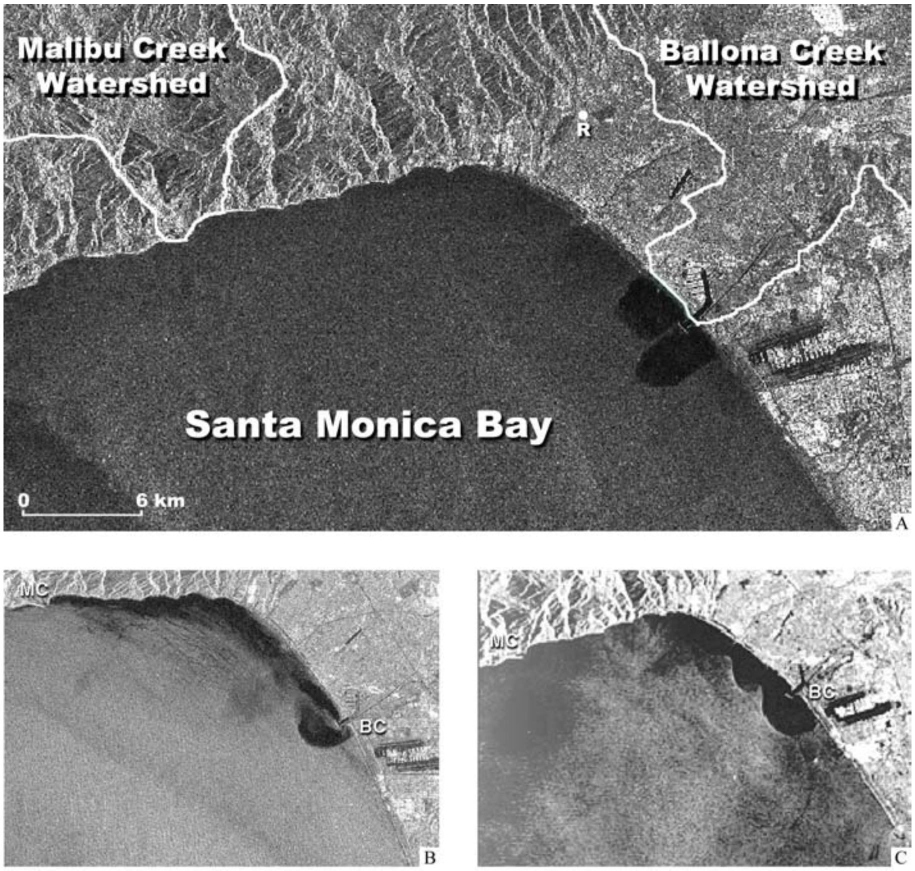


Fig. 1. Satellite SAR images of Santa Monica Bay, California showing surfactant-laden storm water runoff plumes emanating from the Ballona Creek Watershed which contains highly urbanized areas of Los Angeles. In contrast, no runoff surfactant signature is apparent from the mostly undeveloped Malibu Creek Watershed. (A) 11/8/98, and (B) 11/21/96 represent conditions during the first storm of the season, and (C) 2/14/95 corresponds to the third seasonal storm. (D) Aerial photo of the Ballona Creek outlet area and surrounding jetties which often split the runoff into two lobes. (MC) and (BC) indicate outlet locations of Malibu and Ballona Creeks. (R) indicates the location of the Santa Monica weather station and rain gauge.

Urban Stormwater Runoff Seen in SAR Imagery

The two largest watersheds emptying into Santa Monica Bay are Ballona and Malibu Creeks, approximately equal in size. Over 80% of the Ballona Creek watershed encompasses metropolitan Los Angeles. Its main channel is almost completely concrete-lined. This contrasts with the Malibu Creek watershed to the north, 88% of which is undeveloped. The two large watersheds are separated by three smaller ones that primarily drain heavily vegetated and relatively sparsely populated canyons. Field studies have shown that the Ballona Creek runoff plume and underlying bottom sediments consistently contain numerous anthropogenic contaminants at much higher concentrations than the nearby Malibu Creek region (Bay and Schiff, 1998).

Since all SAR satellites must be pre-tasked to acquire data over a chosen area, the use of historical data thus relies on archived incidental acquisitions. The European Space Agency (http://odisseo.esrin.esa.it/) and Canadian Center for Remote Sensing (http://ceocat.ccrs.nrcan.gc.ca/) provide internet-based archive catalogs listing previously acquired ERS-I/II and Radarsat data. In many cases a reduced resolution preview of the processed image is also provided. The two catalogs were utilized to search for any available data from the two study regions. A search targeting Santa Monica Bay revealed that in 1996 and 1998 SAR data were coincidentally acquired during the first seasonal storm. In 1995 data from the third seasonal storm are available. Table 1 lists the rainfall amounts and dry period lengths preceding each image.

Table 1. *Rain statistics for SAR images in Fig. 1 and 2 as measured at the Santa Monica Weather station. The station's position is shown as (R) in Fig. 1 (A). A significant storm was defined by rainfall totaling more than 1.3 cm.*

Image Date	Figure No.	No. of Previous Storms in Season	No. of Days Since Last Storm	Precipitation in Prior 3 Days (cm)	Wind Speed (m/s)	Wind Direction
11/08/98	1A	0	209	5.8	5	SW
11/21/96	1B	0	215	5.3	3	S
02/14/95	1C	2	13	4.4	4	SW
03/26/98	2A	9	28	3.7	4	SW

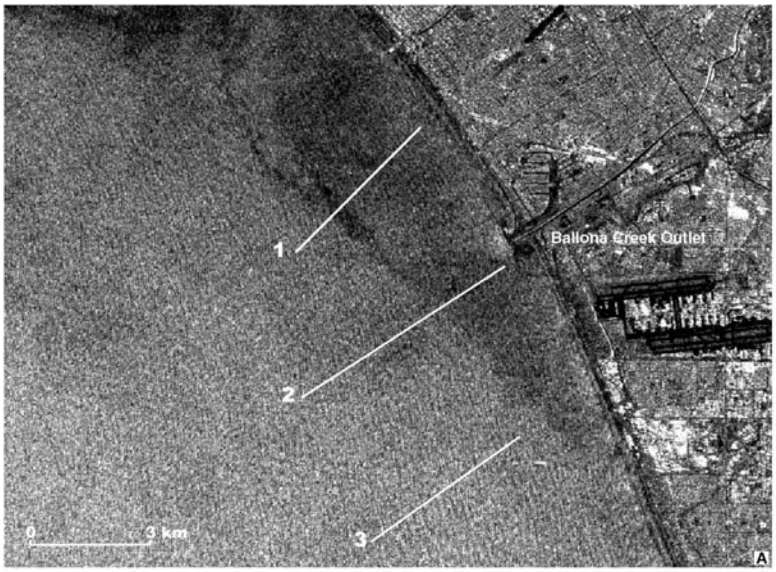
In all three cases, the SAR data (Fig. 1A-C) clearly reveal strong reduced backscatter signatures emanating from the urbanized Ballona Creek watershed. The plume signatures represent an average signal decrease (from surrounding ocean surface) of 21dB, 16dB and 23dB for 1995, 1996 and 1998, respectively. This is in sharp contrast to the mostly undeveloped Malibu Creek and adjoining watersheds which, while they were subject to similar rainfall volume during the storms, do not show any distinct reduced backscatter characteristics in their runoff plumes. We believe the large backscatter decrease in the Ballona Creek plume is due to surfactant effects of compounds contained in the Los Angeles metropolitan runoff at uniquely high concentrations.

In addition to surfactant compounds, areas of low backscatter in SAR imagery can be due to topographical wind-sheltering effects (e.g. calm areas in the lee of islands or hills) or marine atmospheric layer variability. The Ballona Creek terminus region is very flat and has no topographical feature that could cause a wind-sheltering effect of such spatial magnitude. Additionally, the observed SAR patterns differ from such effects by their unique shape and by being very obviously attached to the creek mouth. The splitting of the runoff plume into north and south lobes is due to the effects of two jetties and a breakwater of the Marina del Rey anchorage channel adjoining Ballona Creek to the north. Typically, a larger volume of runoff escapes directly seaward on the breakwater's southern side, while a lesser volume is channeled northward closer to shore between the jetties and the breakwater (Fig. 1D).

The detected patterns emanating from Ballona Creek were never observed during dry periods. Although large reduced backscatter areas were sometimes visible offshore or within Santa Monica Bay during dry weather, they were not attached to the creek mouths and lacked the characteristic runoff plume shape. Such features are more commonly present in coastal SAR imagery, representing low wind effects and large-scale aggregations of biogenic surfactant materials.

Several archived SAR images acquired within 24 to 48 hours after a storm passed over Santa Monica Bay are also available. They tend to show a less prominent but more spatially extensive reduced backscatter region around the Ballona Creek terminus. An ERS-II image acquired on 3/26/98 followed a rain event by approximately 17 hours and coincided with a field sampling effort done to map the spatial extent and vertical characteristics of the Ballona Creek runoff plume. This allowed correlation of the SAR-sensed patterns with field data gathered from a small vessel.

Cross-shelf sections of physical and bio-optical variables were obtained with a towyo system equipped with a Sea-Bird 9/11 CTD, a Wetlabs C-Star transmissometer with 25 cm path length, a Wetlabs fluorometer, and a Biospherical Instruments PAR sensor. The towyo was towed behind the boat at approximately 4 knots and raised and lowered between the surface and 3 meters above the bottom. Horizontal spacing between cycles was approximately 250 meters. Position was recorded from a GPS receiver and merged with the in situ measurements for horizontal position. The CTD recorded at 24 Hz and the data were averaged to 1 second intervals for analysis and graphics. The data are shown in Figure 2 and the relevant rain statistics are listed in Table 1.



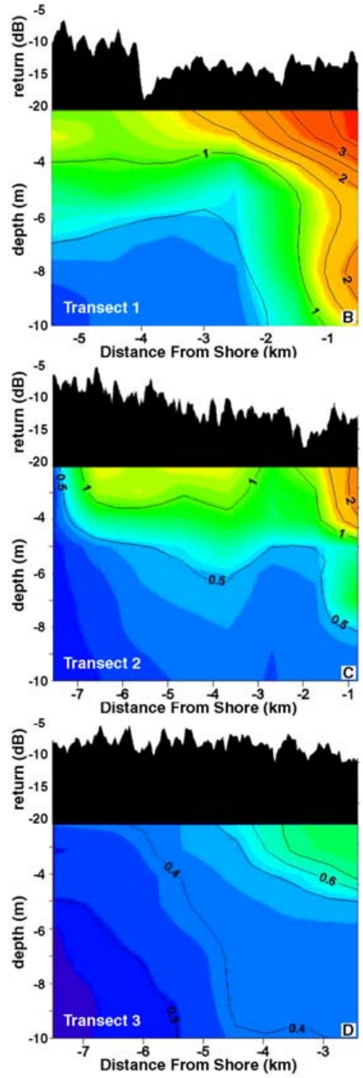


Fig. 2. (A) SAR image of Santa Monica Bay captured on 3/26/98, after the 10th major storm of the 1997-98 rainy season. Locations of three field sampling transects completed within 2 hours of the satellite overpass are also shown. (B, C, D) Vertical cross sections of the field-determined turbidity (shown as Beam-C/m) along transects 1, 2 and 3 and corresponding SAR backscatter profiles. The field data reveal the runoff plume as a relatively shallow surface layer of turbid (as well as low salinity and high temperature) water. Significant decreases in SAR backscatter are evident over waters with turbidities of Beam-C>1.5.

Two of the three field transects crossed through a reduced SAR backscatter feature lining the northeast coast of the Bay and were completed 1.8 hrs. before and 2.0 hrs. after the SAR data acquisition. The third southernmost transect did not reach the inshore dampened region and was completed 0.1 hrs. after the satellite overpass. The field data revealed a runoff plume characterized by high turbidity (e.g. high Beam-C values), and relatively low salinity and high temperature, confined to within 3-4 m of the surface, and extending 1 to 5km offshore. This concurs with previous studies of the Ballona Creek plume extent and toxicity patterns in both surface water and bottom sediments (Bay and Schiff, 1998, Bay et al., 1999).

SAR backscatter profiles along the three field transects show a marked correspondence with near-surface turbidity. Beam-C values greater than 1.5 correspond to a significant decrease in backscatter. This finding suggests that SAR-sensed surfactant signatures can reveal the spatial extent of the concentrated Los Angeles runoff for at least a day after the storm event. However, the magnitude of the signal decrease is smaller (6 to 12 dB) than was measured in images acquired during early season storms. With wind speeds being comparable, the difference is most likely due to the dispersion of the surfactant concentrations with time and decreased outflow volume. However, it is important to note that while the 3/26/98 post-storm example followed the 10th major storm of the 1997-98 rainy season, the mid-storm data sets all represent runoff from early season storms. The very high surfactant damping effects observed could thus be due, at least in part, to a significant seasonal FFE. Toxicity tests of Ballona Creek runoff using a sea urchin fertilization test during the SAR-recorded 11/21/96 storm showed toxicities 2 to 5 times greater than during subsequent storms, and a similar seasonal toxicity FFE was also noted during the 1997-98 rain season (Bay et al., 1999). Significantly higher concentrations of suspended solids and anthropogenic substances have also been recorded during the first four storms of 1997-98 in runoff from the Santa Ana River transecting Southern California's heavily urbanized Orange County (Tiefenthaler et al., 2001).

Detecting Sewage Runoff From Space

The San Diego/Tijuana coast receives significantly less rainfall than Santa Monica Bay, rarely experiencing more than 5 major (>1.3 cm total precipitation) storms annually. Although more than 120 high-resolution images are available from ERS and Radarsat since 1995, none were acquired during or immediately after a significant rain event. It was thus not possible to examine the SAR signatures of storm runoff. A prominent dry-weather runoff signature was consistently located, however, emanating from the Los Buenos Creek mouth located approximately 10 km south of the U.S./Mexico border (Fig. 3).

The Los Buenos Creek has no natural flow during the dry season but receives a daily input of 76 to 114 million liters of minimally treated sewage effluent from the San Antonio de Los Buenos Sewage Treatment Facility near Tijuana, Mexico. This volume can more than double during rain events. Treatment consists of passing part of the sewage influx through a series of sedimentation and aeration ponds and, at least on some days, the addition of chlorine to the effluent. Due to capacity limitations, however, some of the sewage is diverted around the ponds and is left untreated. The effluent is discharged into the creek channel 1km upstream from its mouth and flows into the surf zone over a rocky beach (Fig. 3D). It quite possibly represents the largest year-round runoff source in the region. A surfactant plume from this source was detected in 64% of SAR data sets previewed for this study. The plume's size and direction varied somewhat between data sets, most likely reflecting variations in volume output, surfactant concentration and longshore current direction.

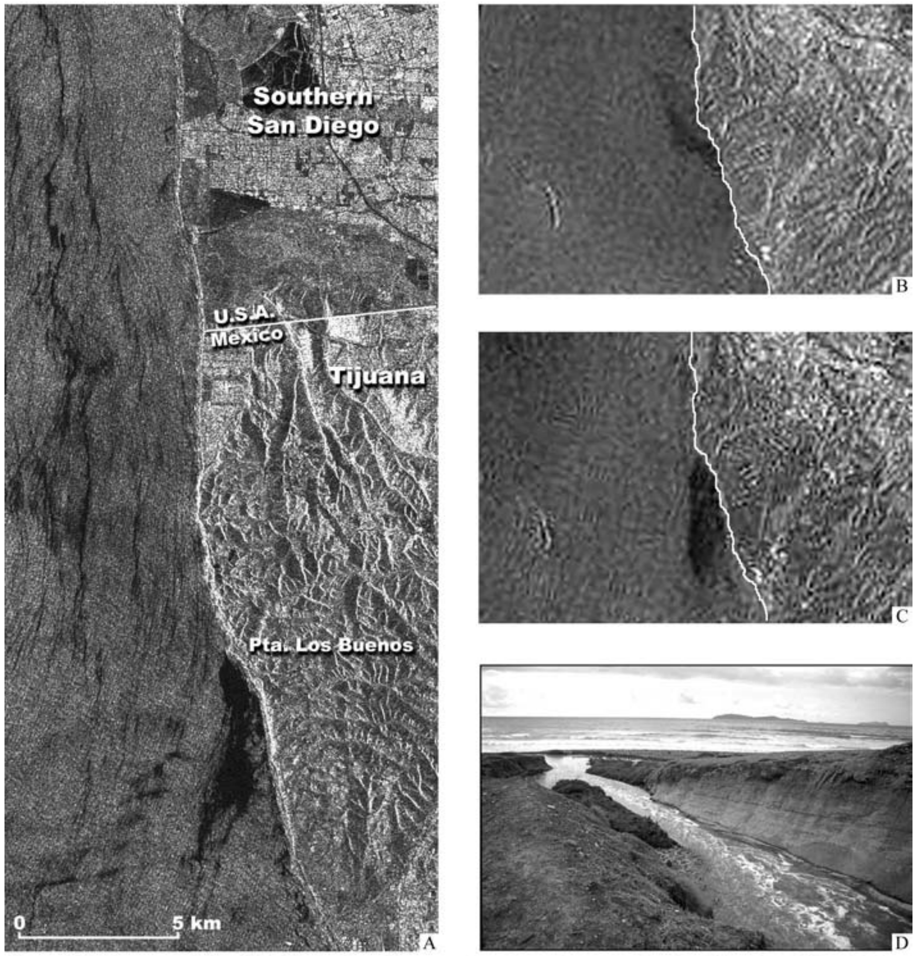


Fig. 3. SAR imagery of the U.S.-Mexico Pacific coast border region acquired on (A) 7/7/99, (B) 12/20/95 and (C) 3/19/97. The images show a large surface slick emanating from the outlet of Los Buenos Creek into which a local sewage treatment plant empties its effluent. The direction of the surfactant plume varies with local current conditions. (D) The outlet of Los Buenos Creek containing sewage effluent discharge. (B) and (C) are spatially resampled images from the ESA browse catalog (Ref. 15).

Probable Causes of Urban Runoff Slicks

Although no chemical assays were available coincidentally with the studied satellite data for either Santa Monica Bay or the San Diego/Tijuana regions, several previous studies provide information on the probable composition of the microlayer responsible for the observed SAR features. Biogenic surface films from non-urban regions off Southern Baja California, Mexico contain dissolved and particulate organic carbon, carbohydrates, lipids, inorganic nutrients, microplankton and bacteria with mean enrichment concentrations (relative to samples taken 10cm below the surface) of 1.1 to

3.7 (Williams et al., 1986). The major components of natural surface films tend to be proteins and carbohydrates, not lipids as was originally assumed (Espedal et al., 1996). Dry weather microlayer analysis of waters near Los Angeles revealed increased trace metals such as cadmium, copper, zinc and lead, and chlorinated hydrocarbon and polycyclic aromatic hydrocarbon concentrations several orders of magnitude higher than subsurface or offshore samples (Cross et al., 1987). Similar contaminant enrichment is also documented in microlayer studies of Puget Sound (Hardy et al., 1987) and in surface slicks near heavily urbanized regions of the Mediterranean with enrichment values for hydrocarbons and anionic detergents ranging from 6 to 15 (Garabetian et al, 1993). It can be assumed that the SAR-sensed urban stormwater runoff films are caused by these and additional constituents at very high concentrations, especially during the seasonal FFE. Films caused primarily by sewage will contain especially high concentrations of lipids from cooking grease, as well as high coliform, enterococus and other bacteria concentrations (Hlavka et al., 1973). Abnormally high counts of coliforms and enterococus were indeed recorded at a northern field sampling station when an ERS-II SAR image showed it enveloped in the slick on 8/30/99.

Our results indicate that SAR-based remote sensing can be effective in identifying major sources of polluted runoff and sewage near highly urbanized coastal areas, and help determine their spatial extent even under cloudy conditions. With more frequent data acquisitions, the technique could also help evaluate the magnitude of a seasonal FFE in arid coastal metropolitan regions.

Acknowledgments

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