Satellite & Aerial Coastal Water Quality Monitoring in the San Diego / Tijuana Region

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Annual Summary Report

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Ocean Imaging

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Table of Contents

1. Introduction and Project History

Ocean Imaging Corp. (OI) specializes in marine and coastal remote sensing for research and operational applications. In the 1990s, OI received multiple research grants from NASA's Commercial Remote Sensing Program for the development and commercialization of novel remote sensing applications in the coastal zone. As part of these projects, OI developed methods to utilize various types of remotely sensed data for the detection and monitoring of storm water runoff and wastewater discharges from offshore outfalls. The methodology was initially demonstrated with collaboration of the Orange County Sanitation District. The NASA-supported research and demonstration led to a proof-of-concept demo project in the San Diego region co-funded by the EPA in 2000. Those results led, in turn, to adding an operational remote imaging-based monitoring component to the San Diego region's established water quality monitoring program, as stipulated in discharge permits for the International Wastewater Treatment Plant and Pt. Loma outfalls. The project was spearheaded by the State Water Resources Control Board (SWRCB), EPA Region 9, and continues to be jointly funded by the International Boundary Waters Commission and the City of San Diego.

The first phase of the project was a historical study utilizing various types of satellite data acquired between the early 1980s and 2002. The study established, among other findings, the prevailing near-surface current patterns in the region under various oceanic and atmospheric conditions. The current directions were deduced from patterns of turbidity, ocean temperature and surfactant slicks. In some cases, near-surface current velocity could be computed by tracking recognizable color or thermal features in time-sequential images. The historical study thus established a baseline data base for the region's current patterns, their persistence and occurrence frequency, and the historical locations, size and dispersion trajectories of various land and offshore discharge sources (e.g. the offshore outfalls, Tijuana River, Punta Bandera Treatment Plant discharge in Mexico, etc.).

In October, 2002 the operational monitoring phase of the project was initiated. This work utilizes 500m resolution Moderate Resolution Imaging Spectroradiometer (MODIS) color imagery (available near-daily), and 27m & 60m Thematic Mapper TM5 & TM7 color and thermal imagery (available 4 times per month). In addition, the project relied heavily on acquisition of multispectral color imagery with OI's DMSC-MKII aerial sensor and thermal infrared (IR) imagery from a Jenoptik thermal imager integrated into the system (see details in the "Technology Overview" section). These aerial image sets were most often collected at 2m resolution. The flights were done on a semi-regular schedule ranging from 1-2 times per month during the summer to once or more per week during the rainy season. The flights were also coordinated with the City of San Diego's regular offshore field sampling schedule so that the imagery was collected on the same day (usually within 2-3 hours) of the field data collection. Additional flights were done on an on-call basis immediately after major storms or other events such as sewage spills. In late 2010 OI negotiated a special data collection arrangement with Germany's RapidEye Corporation and this project began utilizing their multispectral imagery in lieu of most of the aerial DMSC image acquisitions. RapidEye maintains a unique constellation of 5 satellites which deliver 6.5 m resolution multispectral imagery. Unlike other single high resolution satellites, the multi-satellite constellation enables revisits of the San Diego region on a near-daily basis. Another advantage of using this imagery is the much larger spatial coverage available with each data set that was not possible using the aerial sensor. This enables a more regionally contiguous monitoring of events affecting the target areas. In 2012 OI also began operationally providing the City with a suite of additional oceanographic products on a daily basis through the City's EMTS web-based GIS "BioMap" Server, and continued expanding the product selection and delivery through 2014 and into 2015. These products range from atmospherically corrected satellite images of sea surface temperature and chlorophyll to radar and model-derived surface current fields.

This report summarizes observations made during the period 1/1/2015 – 12/31/2015.

2. TECHNOLOGY OVERVIEW

OI uses several remote sensing technologies to monitor San Diego's offshore outfalls and shoreline water quality. Their main principle is to reveal light, heat or microwave signal patterns that are characteristic of the different discharges. Most often this is due to specific substances contained in the effluent but absent in the surrounding water.

2.1 Imaging in the UV-Visible-NearInfraRed Spectrum

This is the most common technique used with satellite images and the DMSC aerial sensor. Wavelengths (colors) within the range of the human eye are most often used but Ultraviolet (UV) wavelengths are useful for detecting fluorescence from petroleum compounds (oil, diesel, etc.) and near-IR wavelengths can be useful for correcting atmospheric interference from aerosols (e.g. smog and smoke).

The best detection capabilities are attained when several images in different wavelengths are acquired simultaneously. These "multispectral" data can be digitally processed to enhance features not readily visible in simple color photographs. For example, two such images can be ratioed, thus emphasizing the water features' differences in reflection of the two wavelengths. A multi-wavelength image set can also be analyzed with "multispectral classification algorithms" which separate different features or effluents based on the correlation relationships between the different color signals.

The depth to which the color sensors can penetrate depends on which wavelengths they see, their sensitivity and the general water clarity. In the San Diego region, green wavelengths tend to reach the deepest and, as elsewhere, UV and near-IR wavelengths penetrate the least. Generally, OI's satellite and aerial sensor data reveal patterns in the upper 15-40 feet.

The color channels on satellite sensors cannot be changed, so they tend to be relatively broad, separating red, green, blue and near-IR, and sometimes blue parts of the spectrum. OI's DMSC aerial 4-channel sensor has the added advantage of allowing each channel wavelength to be precisely customized. Through experimentation, OI has determined the exact wavelength relationships that maximize the detection of the offshore sewage outfall plumes and nearshore discharges such as the Tijuana River. With this channel configuration it is possible to monitor the plumes even when they are not visible to the naked eye.

2.2 Imaging in the Infrared Spectrum

Some satellite and aerial sensors image heat emanating from the ground and the ocean. They thus reveal patterns and features due to their differences in temperature. Since infrared wavelengths are strongly absorbed by water, the images reveal temperature patterns only on the water's surface. Such images can help detect runoff plumes when their temperatures differ from the surrounding ocean water. Runoff from shoreline sources tends to be warmer than the ocean water, although the reverse can be true during the winter. Plumes from offshore outfalls can sometime also be detected with thermal imaging. Since the effluent contains mostly fresh water, it is less dense than the surrounding salt water and tends to rise to the surface. If it makes it all the way, it is usually cooler than the surrounding sun-warmed surface water. If it is constrained by a strong thermocline and/or pycnocline ("vertical stratification"), it sometimes tends to displace some of the water above it in a doming effect. This displacement pattern is revealed in the thermal surface imagery.

2.3 Data Dissemination and Analysis

The satellite and aerial imaging data are made available to the funding agencies, the San Diego County Dept. of Health and the EPA through a dedicated, password-protected web site. Although it is possible to process most of the used data in near-real-time, earlier in the project the funding agencies decided that the emphasis of this project is not on providing real-time monitoring support and the extra costs associated with the rapid data turn-around are not warranted. Most satellite data is thus processed and posted within 1-2 days after acquisition and the aerial sensor imagery (which requires the most labor-intensive processing), within 2-5 days. OI has, however, in a number of cases, made some imagery available to the CDH and others in near-real time when observations were made that appeared to be highly significant for the management of beach closures or other sudden events. The BioMap Server-directed products are produced daily by OI and are automatically linked with the server when available.

3. HIGHLIGHTS OF 2015 MONITORING

3.1 Atmospheric and Ocean Conditions

2015 conditions represented a stark contrast to the preceding 3 draught years, not only in having significant precipitation during the traditional rainy months, but also because major rains occurred during the usually dry months of May, July and September. Although the rain events helped erase San Diego's rain deficit through the year, the resulting point and non-point runoff affected coastal water quality in some areas, especially during the summer months. **Figure 1** shows daily precipitation in the Tijuana River Estuary. As a general rule of thumb, precipitation resulting in 0.1" or less tends to be blocked by the SBOO-linked diverter above the estuary and does not cause significant runoff to reach the ocean. As can be seen from Figure 1, rain events totaling considerably higher daily totals occurred during the "rainy months" as well as in May, July and September – causing polluted Tijuana River effluent to be discharged into the ocean. Since the summer events included considerable thunderstorm activity east of the San Diego/Tijuana coastline, the Tijuana Estuary gauge totals shown likely considerably underestimate the volume of precipitation that actually filled the Tijuana River watershed. The result of the 2015 rain events was that shoreline near the Tijuana River mouth experienced frequent closures due to contamination during the rain season as well as during the summer months. Imperial Beach shoreline was also closed more frequently than in preceding years, as was Coronado's Silver Strand beach. Indicator bacteria sampling results taken after the mid-July rain event actually made the County Department of Health close all of Coronado's shoreline for several days.

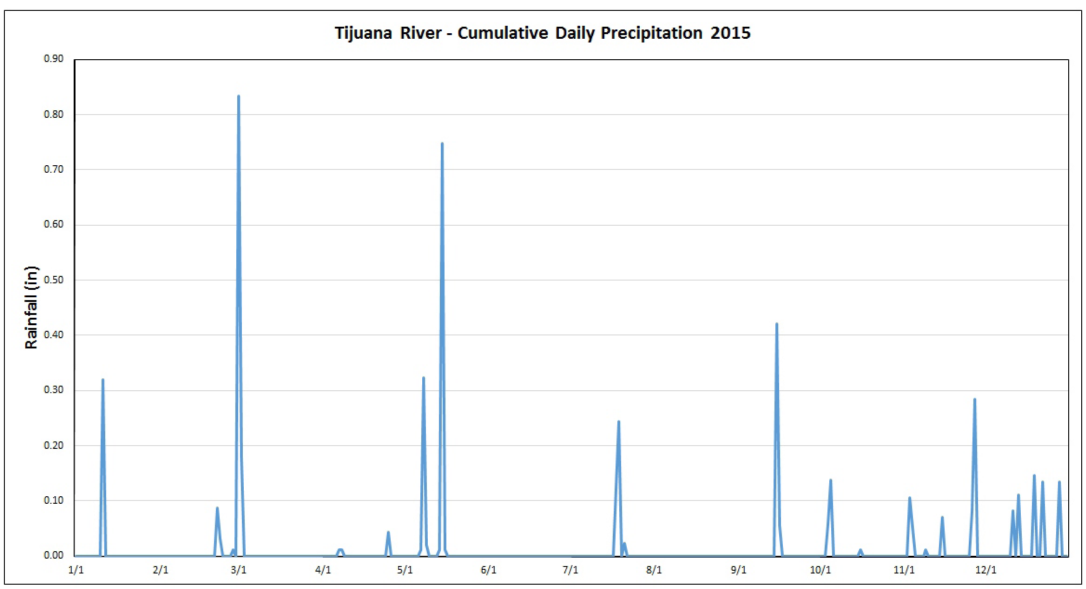
The same patterns can be seen in **Figure 2** which shows monthly precipitation totals at Lindbergh Field and San Diego River discharge rate at the Fashion Valley gaging station. Unlike in 2014 when the

River's flow was below 1 cubic foot per second from June through early September, the 2015 flow remained well above that through the summer. The flow spikes corresponding to the May, July and September rain events actually surpassed most of the events occurring during the "rainy months".

Although discharge from the San Diego River does not cause the beach contamination issues of the Tijuana River discharge, the persistent runoff from the two rivers, Mission Bay and coastal lagoons affected nearshore water clarity through much of 2015, directly as a source of suspended sediment and indirectly as a source of nutrients feeding localized plankton blooms.

3.2 The South Bay Ocean Outfall Region

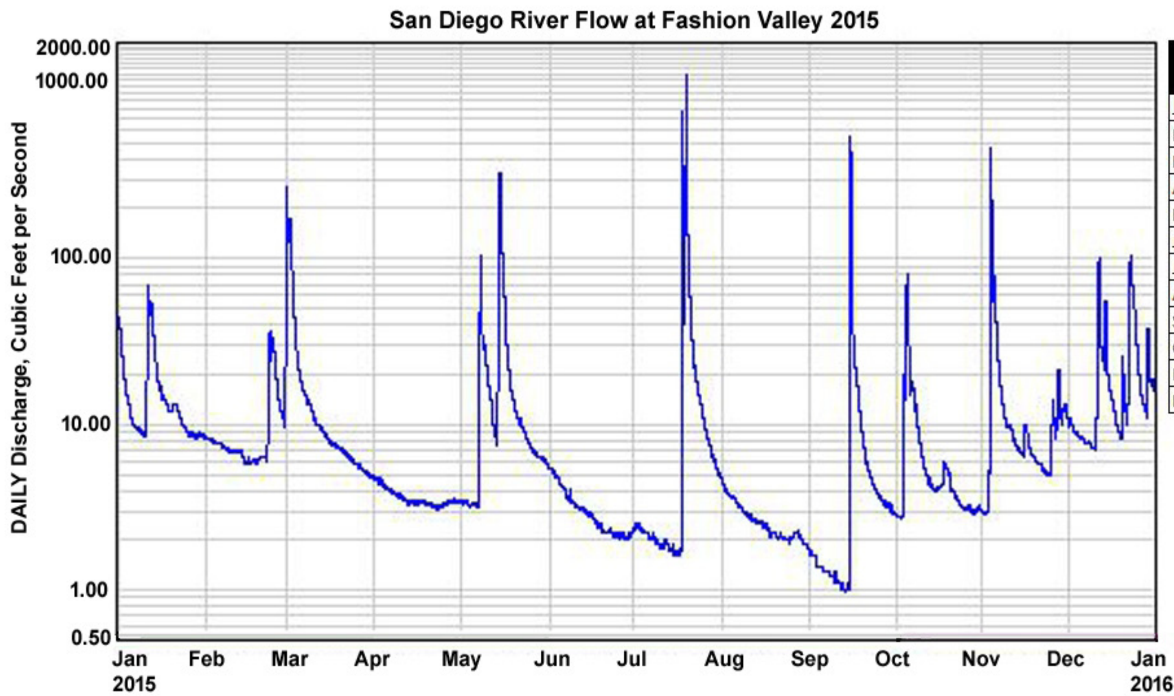
The South Bay Ocean Outfall (SBOO) wastewater plume generally remains well below the surface between approximately late March and November due to vertical stratification of the water column. During that period, it usually cannot be detected with multispectral aerial and satellite imagery which penetrate the upper 7 to 15 meters (depending on water clarity). The plume also cannot be detected with thermal IR imaging which does not penetrate below the surface. Seasonal breakdown of the vertical stratification results in the plume's rise closer to the surface or to actually reach the surface between approximately late November and late March, when it can often be detected with aerial and satellite imaging.



Date	CumPrcp (in)
1/11	0.32
2/22	0.09
2/23	0.03
2/28	0.01
3/1	0.83
3/2	0.18
4/7	0.01
4/8	0.01
4/25	0.04
5/7	0.01
5/8	0.32
5/9	0.02
5/14	0.01
5/15	0.75
5/16	0.01
7/18	0.12
7/19	0.24
7/21	0.02
9/15	0.42
9/16	0.06
10/4	0.06
10/5	0.14
10/16	0.01
11/3	0.11
11/4	0.05
11/9	0.01
11/15	0.07
11/26	0.08
11/27	0.28
12/11	0.08
12/13	0.11
12/19	0.15
12/22	0.13
12/28	0.13

Figure 1.

Daily cumulative rainfall in the Tijuana Estuary.



Lindbergh Field Rainfall 2015	
Jan	0.42"
Feb	0.28"
Mar	0.93"
Apr	0.02"
May	2.39"
Jun	0.04"
Jul	1.71"
Aug	0.01"
Sep	1.24"
Oct	0.43"
Nov	1.54"
Dec	0.88"

Figure 2.

Mean daily flow of the San Diego River during 2015 (measured at Fashion Valley). Table on the right shows monthly rainfall totals at Lindbergh Field.

The SBOO treatment plant switched from advanced primary to secondary treatment in January, 2011. This change resulted, among other factors, in the reduction of total suspended solids (TSS) concentrations from an average of 60 mg/l for several years prior to the change, to 15 mg/l. Prior to 2011, a distinct plume signature was regularly detected in multispectral imagery as per the seasonal fluctuation described above. Since then, the plume signature continues to be observed with multispectral color and thermal imagery during months with weak vertical stratification, however, more intermittently. On occasion the plume signature is distinctly discernable in thermal images (indicating it has fully reached the ocean surface) but undetectable in the color imagery. We believe this is due to the reduction in TSS concentrations.

The plume's reflectance signature in the multispectral visible and near-IR imagery is dominated by reflectance spectrum characteristics of its suspended sediment. Hence a reduction in the sediment concentration can be expected to affect the detectability of the plume. However, analysis of the size and intensity of the plume patterns relative to the TSS reductions does not show a direct correlation. In fact, some of the largest plume signatures have been imaged after the secondary treatment switch, such as on 4 January, 2012, when the TSS load was approximately 50% of concentrations in the early years. In that instance the plume signature was identifiable up to more than 4km away from SBOO wye. Other plume signatures imaged during 2013 and 2014 when TSS loads were approximately 16 mg/L show that these are sufficient for adequate separation of the effluent from surrounding waters if the plume remains concentrated. However, in the past 3 years, numerous instances occurred when the plume was detectable on the surface with the multispectral sensors but became only detectable with thermal imaging a day or two later, only to reappear again in the next acquired color image data set. The existence of a thermal plume signature shows the effluent reached the ocean surface, but its simultaneous lack of a color signature implies it reached the surface in a significantly diluted state.

We posit that on days with significant subsurface currents and/or vertical mixing the SBOO effluent plume with its present approximately 16 mg/L TSS load becomes sufficiently diluted as it travels up through the water column to not sufficiently alter the turbidity reflectance of the surface layer.

In 2015's early months the SBOO plume was detectable in remote sensing imagery only intermittently and as a relatively small signature until early March. This corresponds to observations in previous years

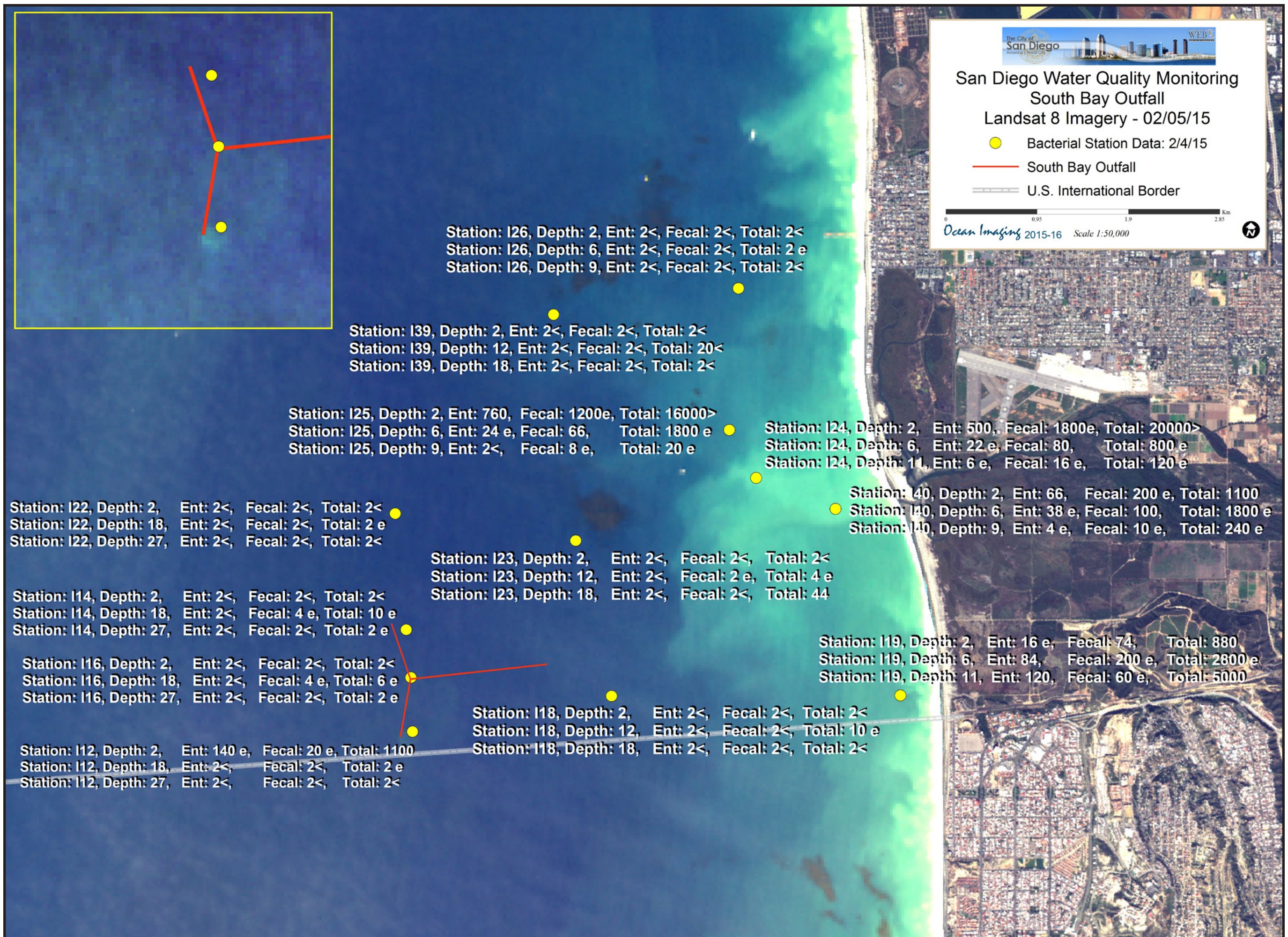


Figure 3.

Landsat eTM image of the SBOO region acquired on 2/5/2015 and near-surface offshore bacterial sampling results collected on 2/4/2015. Elevated values at I12 correspond to the surfacing SBOO plume and elevated values at I19, I24 and I40 correspond to turbid waters containing runoff from the Tijuana River.

and also corresponds to the seasonal rebuilding of vertical stratification. **Figure 3** shows an example of the relatively small plume signature on 2/5/2015 and corresponding offshore bacterial sampling data from the previous day. The elevated numbers near the surface at I12 correspond to the imaged plume signature. The elevated values at I19, I24 and I40 correspond very closely with the nearshore high turbidity features that include runoff effluent from the Tijuana River.

The best water quality and clarity in the South Bay region in 2015 was achieved during April amidst a lull in rain events and minimal outflow from the Tijuana River. **Figure 4** shows these conditions in Landsat TM imagery on 4/2/2015 and 4/18/2015.

A multiday rain event in mid-May caused significant runoff from the Tijuana River into South Bay's coastal waters outside of the usual seasonal range. Coupled with a northward current flow regime existing at the time, elevated bacteria samples north of the River mouth triggered beach closures up to Coronado. The next seasonally anomalous rain event, larger than the May rains in terms of runoff volume, occurred in mid-July. On 7/18/2015 Lindbergh Field recorded 1.04" of precipitation, with further rains lingering through 7/19/2015 for a

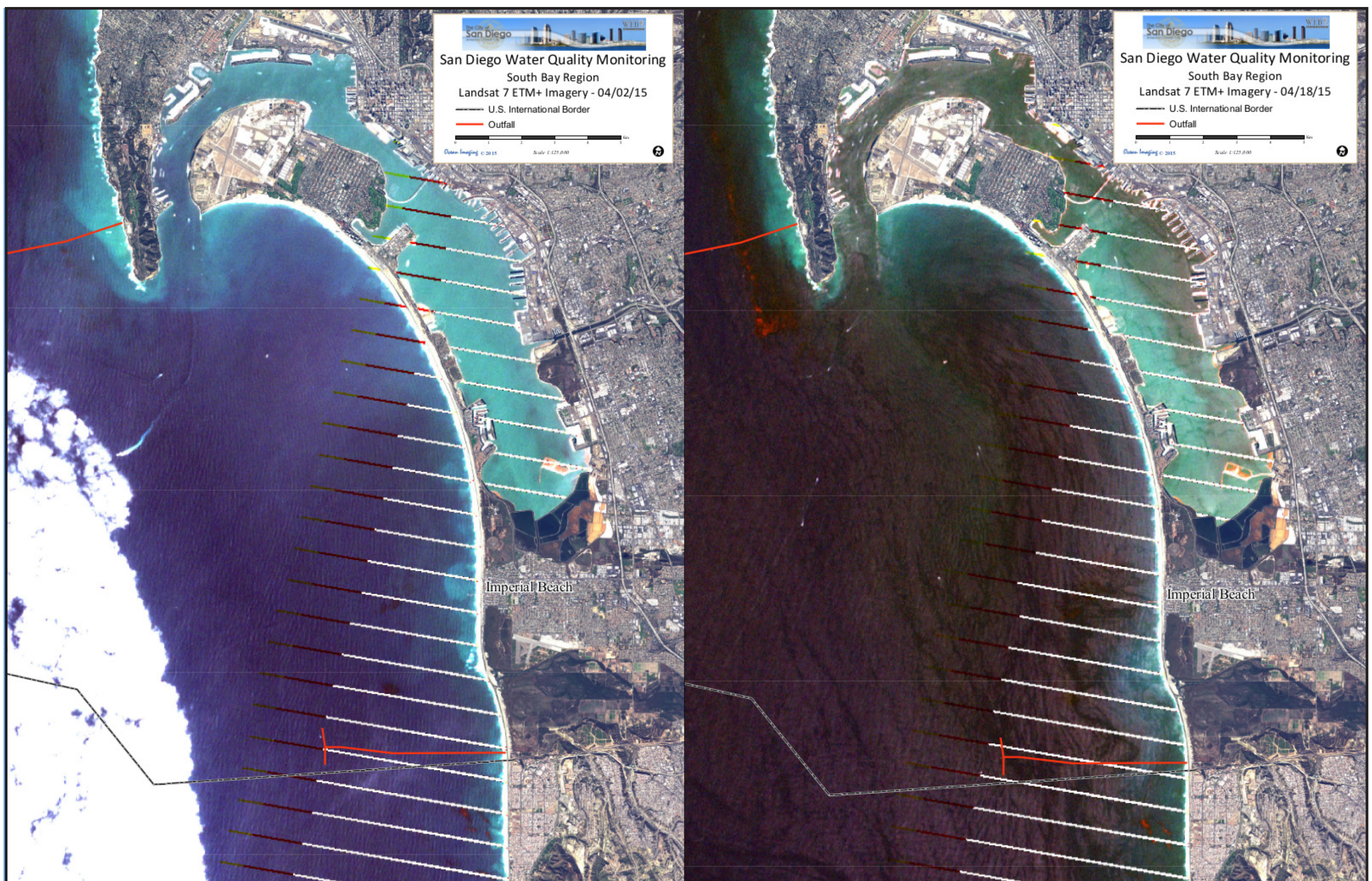


Figure 4.

Landsat TM imagery of the SBOO region acquired on 4/2/2015 (left) and 4/18/2015 (right) showing relatively high water clarity.

Lindbergh total of 1.7”. Curiously, the various satellite data sources available from days immediately following that rain event do not show a high degree of turbidity nearshore, despite the high runoff volumes from the Tijuana and San Diego Rivers, as well as the North County lagoons. A Landsat image acquired on 7/23/2015 shows signs of somewhat turbid runoff reaching around and past the Imperial Beach kelp beds (**Figure 5**), indicating the Tijuana River outflow had spread northward prior to that date. This corresponds to results of shoreline bacterial sampling which showed highly elevated concentrations all the way past Coronado’s Silver Strand. This, in turn, prompted the County Department of Health to extend the initial post rain beach closure to include the entire Coronado shoreline for several days – a rare event and unprecedented during the summer months in recent years. It should be noted that historical HF Radar current data as well as Acoustic Doppler Current Profile data have shown us

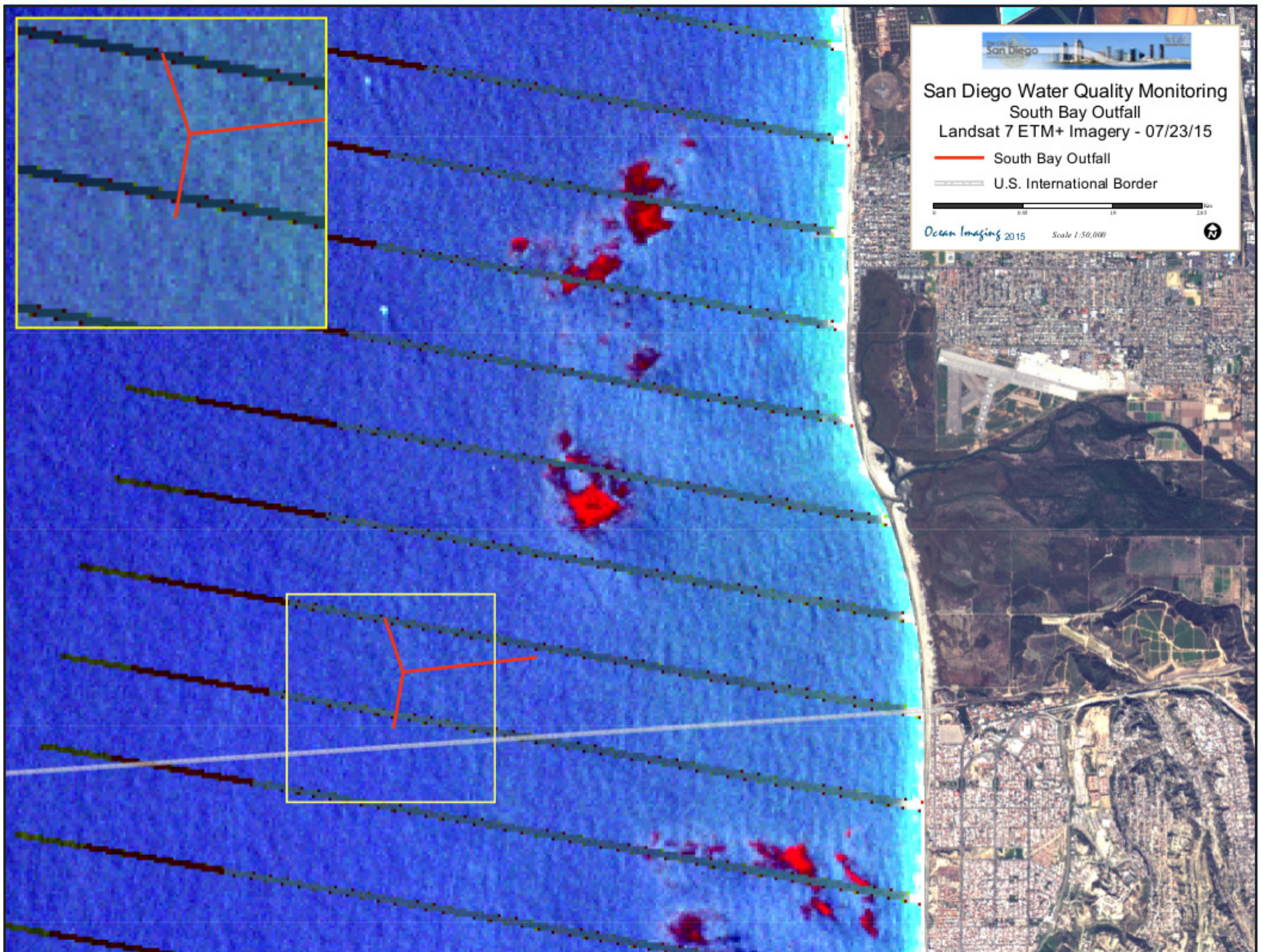


Figure 5.

Landsat TM image of the SBOO region acquired on 7/23/2015 after heavy rains on 7/18-19/2015. Some residual runoff turbidity is evident around and northward of the Imperial Beach kelp beds, indicating northward flow in days prior.

that current direction and strength can change significantly in a matter of hours given certain oceanographic and weather conditions.

The next rain event occurred on 15 September, 2015 with 1.21″ recorded at Lindbergh Field and 0.75″ at the Tijuana Estuary. Historically, September is still considered a dry month. A Landsat eTM image acquired on 9/17/2015 shows relatively low turbidity along the shoreline with a pattern indicative of southward flow (**Figure 6**). Contamination warnings were posted northward through the Silver Strand area.

The SBOO plume was again seasonally detected in a 4 November, 2015 Landsat eTM image (**Figure 7**), which is somewhat earlier than has been the case in recent previous years. As was noted above, direct near-surface observations of the plume in multispectral color imagery has been more intermittent since its TSS concentrations were lowered to around 16

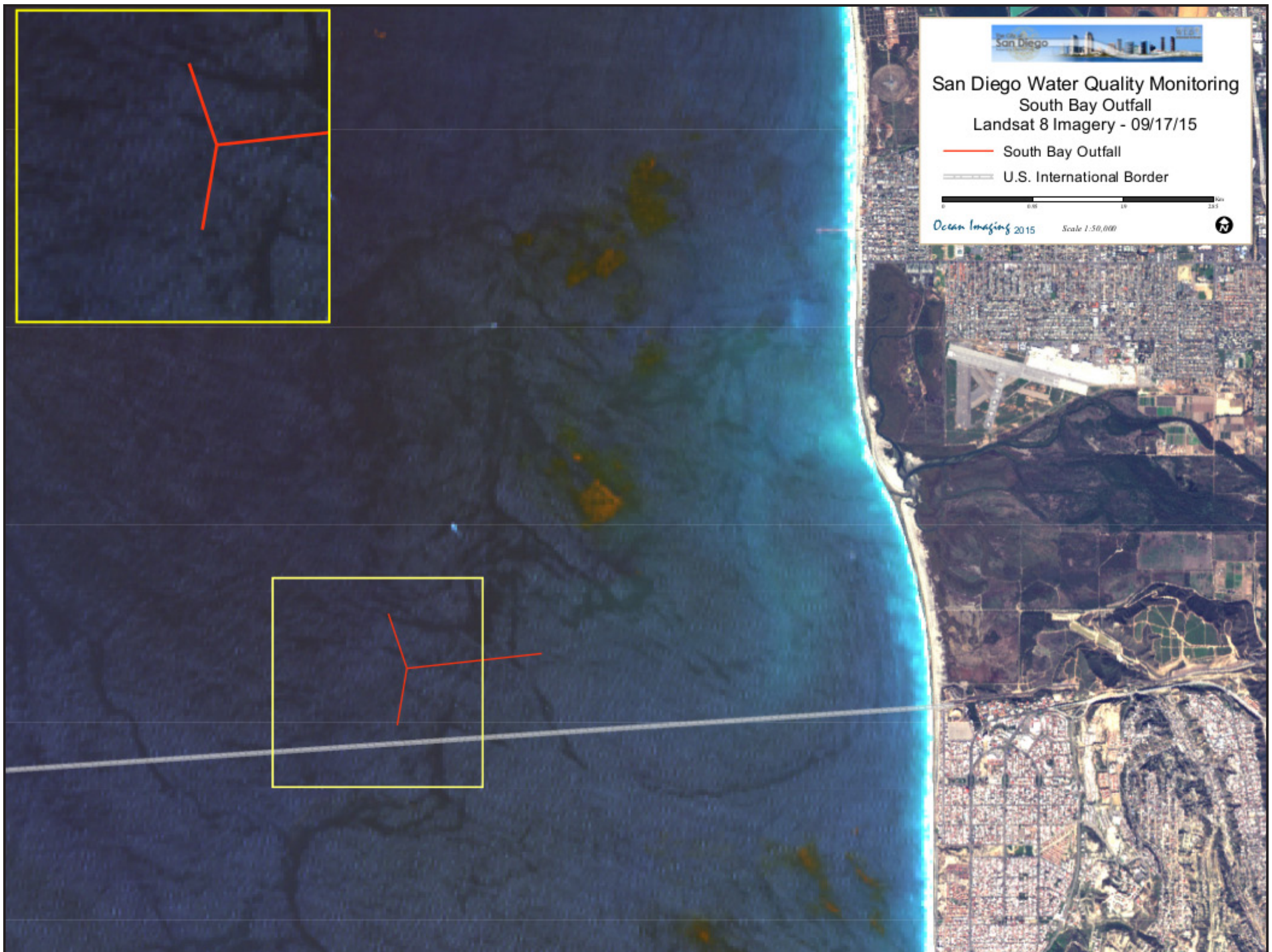


Figure 6.

Landsat eTM image acquired on 9/17/2015 shows relatively low turbidity along the shoreline with a pattern indicative of southward flow.

mg/L and is likely related to near-surface current strength. An example of this can be observed in RapidEye imagery acquired the following day – 5 November, 2015 in which the plume is no longer discernible, despite RapidEye's higher spatial resolution (**Figure 8**). The 11/4 eTM and 11/5 RapidEye data show that a regional current flow reversal occurred overnight, with a relatively strong northward flow regime pushing coastal turbidity features along the South Bay shoreline and at Pt. Loma northward. In the past, the SBOO plume has been observed to curve northwestward numerous times under such a flow field, but was likely dispersed below detection limits by the strong currents on 11/5/2015. In contrast, a Landsat eTM image acquired on 11/20/2015 during a weak current regime shows a relatively strong SBOO plume signature directed southward (**Figure 9**). The strength of the currents can be assessed with available CODAR data, as well as by noting that the plume's base is positioned directly above the main southern wye riser group – indicating a vertical rise

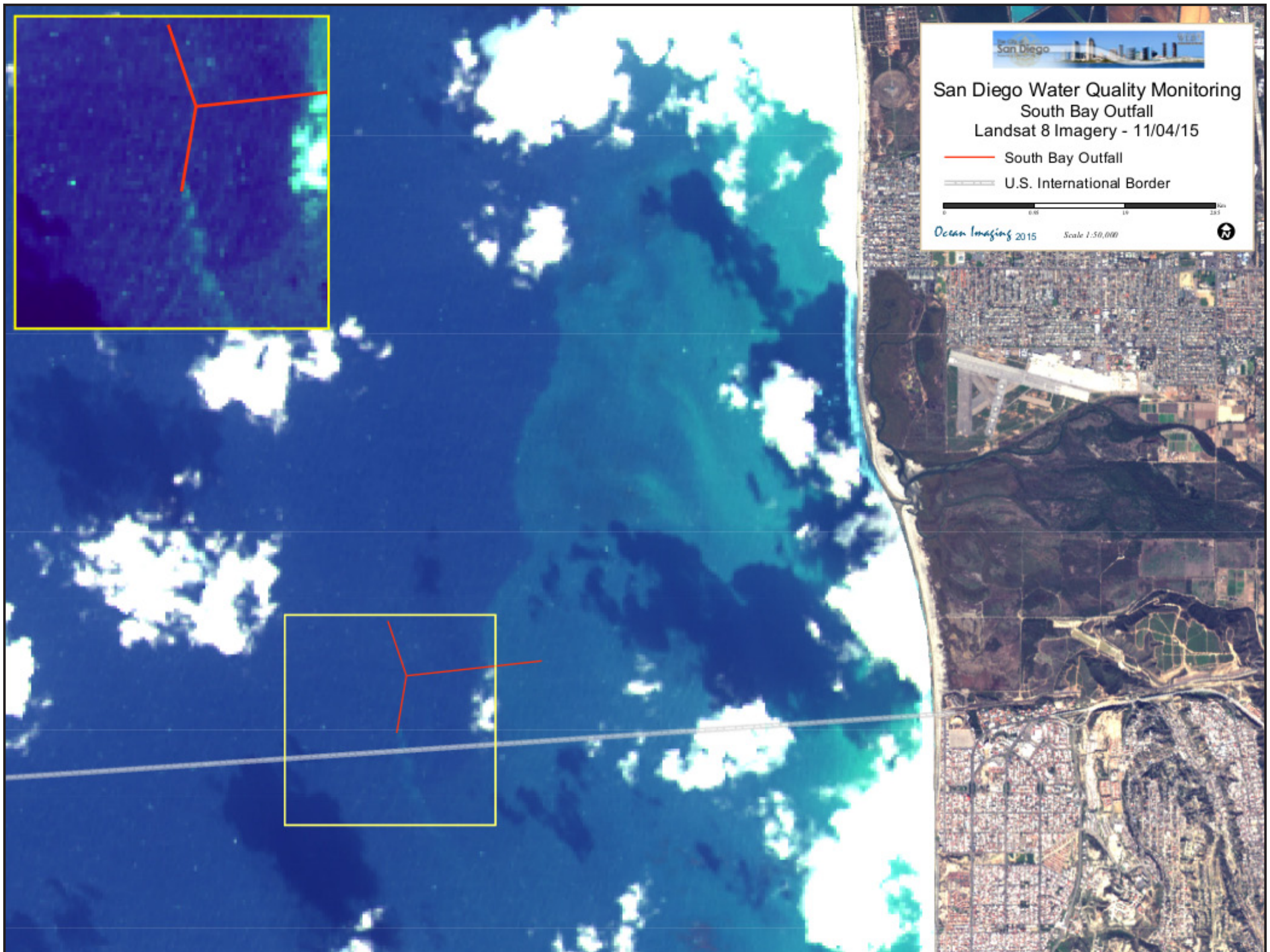


Figure 7.

Landsat eTM image acquired on 11/4/2015 showing a distinct SBOO plume signature.

of the effluent (vs. a down-current spatial displacement observed during stronger currents).

Several interspersed rain events from early November through December caused a seasonally expected outflow from the Tijuana River, in turn causing beach warnings and closures around the river mouth and in late November northward to the Silver Strand. The SBOO plume was regularly observed to surface in December although, as is discussed above, purported dilution of its sediment load during stronger current conditions made it detectable solely with thermal imaging. An example from 12/30/2015 is shown in **Figure 10**.

Throughout 2015 there were no major sewage spills reported in the South Bay region and our data did not detect any obvious transport of waters from the los Buenos Creek nearshore northward past the US/Mexico border. Based on our data, the main source of beach contamination in the SBOO region was thus effluent from the Tijuana River, especially after several anomalous rain events during the summer months.

3.3. The Point Loma Outfall Region

After its seaward extension in 1993, the Point Loma Outfall (PLO) is one of the deepest and longest wastewater outfalls in the world, discharging at the depth of 320 feet, 4.5 miles offshore. The outfall's plume is generally not observed directly with multispectral color or thermal imagery. It appears to not reach the surface waters, even during the winter months when the water column's vertical stratifications is weakened. We believe, however, that on some occasions we have observed the plume's extents indirectly through an anomalous lateral displacement of thermal or chlorophyll features around the outfall wye. This effect can be explained

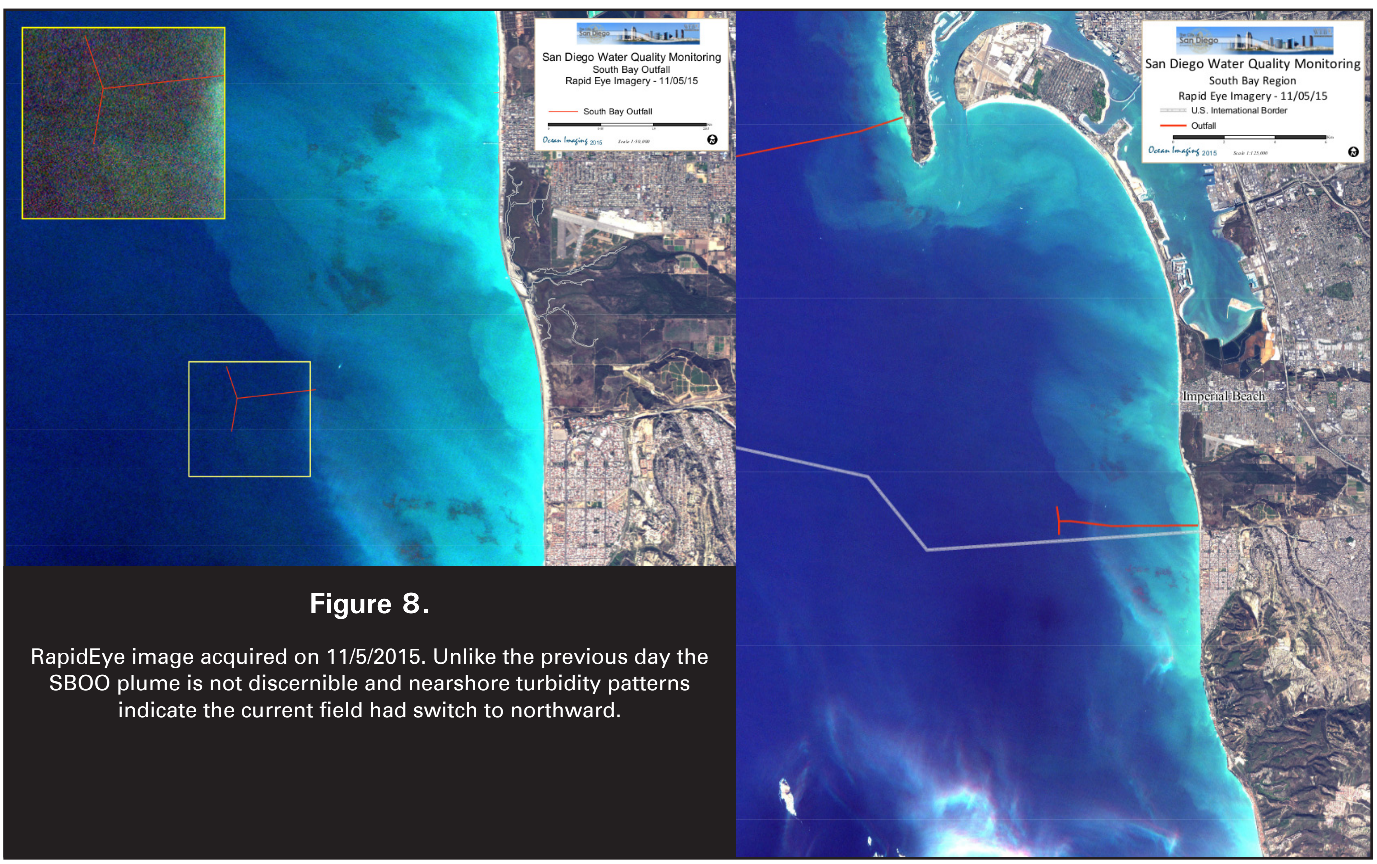


Figure 8.

RapidEye image acquired on 11/5/2015. Unlike the previous day the SBOO plume is not discernible and nearshore turbidity patterns indicate the current field had switch to northward.

by the doming up of the discharged effluent and laterally displacing the near-surface waters above it.

In 2015 the Point Loma region was affected by conditions already described for the South Bay region: much increased rainfall than in the previous three years that occurred even during the summer months. This compromised water clarity in the nearshore areas as runoff from the San Diego River and Mission Bay brought sediment-laden water inside and outside the Point Loma kelp bed after the rain events. Both, shoreline and periodic kelp bed bacterial sampling generally showed only marginally increased concentrations. As was reported in previous years, strong, multi-day northward current episodes after rains can bring contaminated waters from sources in Mexico (e.g. los Buenos Creek) and the Tijuana River northwestward and occasionally affect the southern Pt. Loma area. Despite the multiple rain events, this was not directly observed

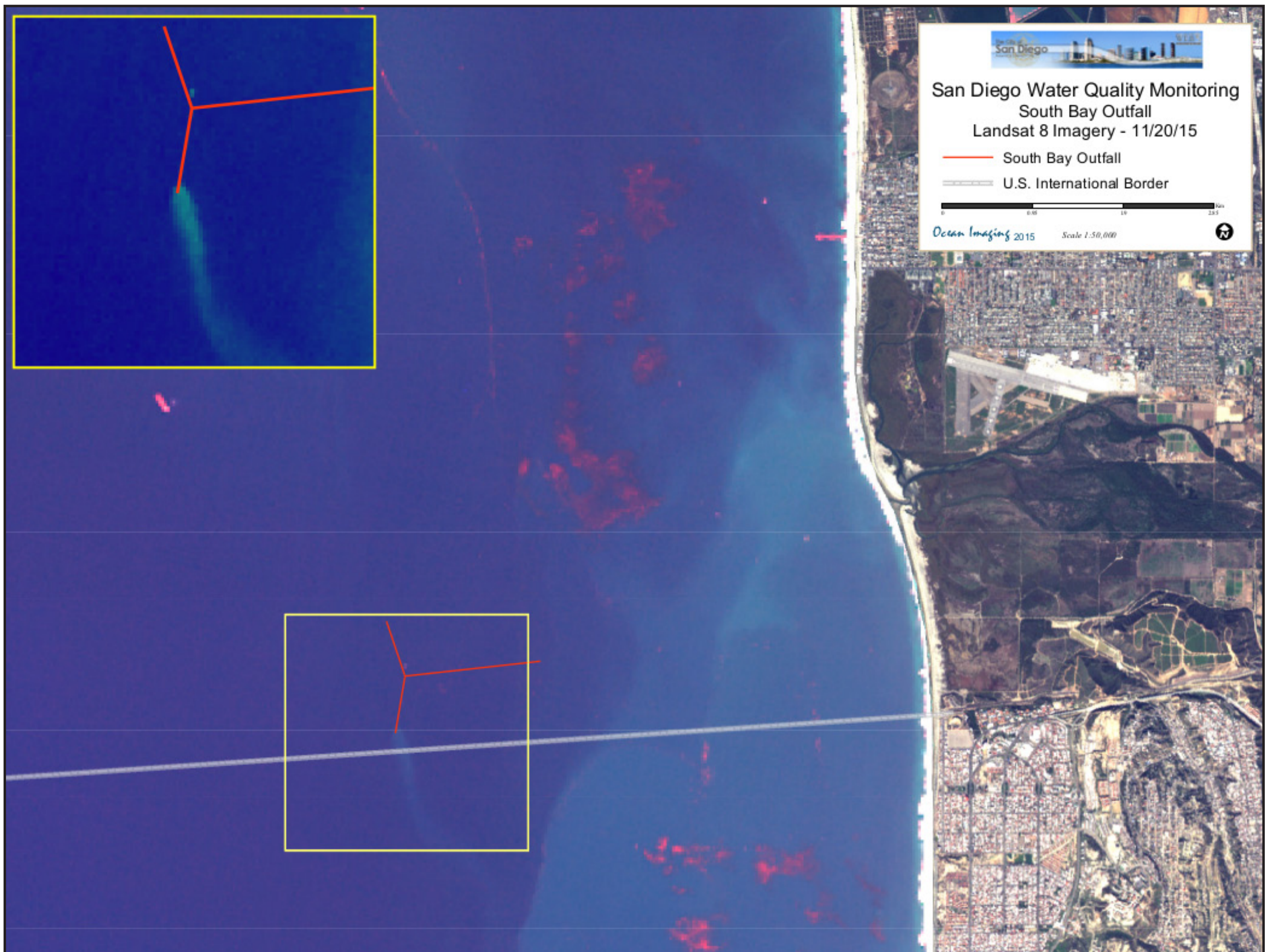


Figure 9.

Landsat eTM image acquired on 11/20/2015 showing a relatively large SBOO plume.

in 2015. **Figure 11** shows a RapidEye image after a March rain event that documents waters from los Buenos Creek and Tijuana River crossing the US/Mexico border offshore on a Pt. Loma trajectory, however, subsequent satellite imagery did not show it reaching further north.

One observation provided by the satellite image archive was the rapid expansion of the southern portion of the Pt. Loma kelp bed during 2015. The satellite data show it to begin rapidly in May and persist throughout the rest of 2015. **Figure 12** shows a 2014 vs. 2015 comparison in October.

The offshore near-surface waters surrounding the PLO wye remained clear through most of the year, as the rain runoff-related turbidity was generally contained to area inside and just outside the kelp bed. Although no major red tide episodes were observed during 2015, the summer months between May through August included multiple phytoplankton blooms from approximately La Jolla southward past Pt. Loma covering both inshore and offshore waters past the PLO wye. It is possible they were accentuated by runoff nutrient inputs from the anomalous summer rains. Examples are shown in **Figure 13.**

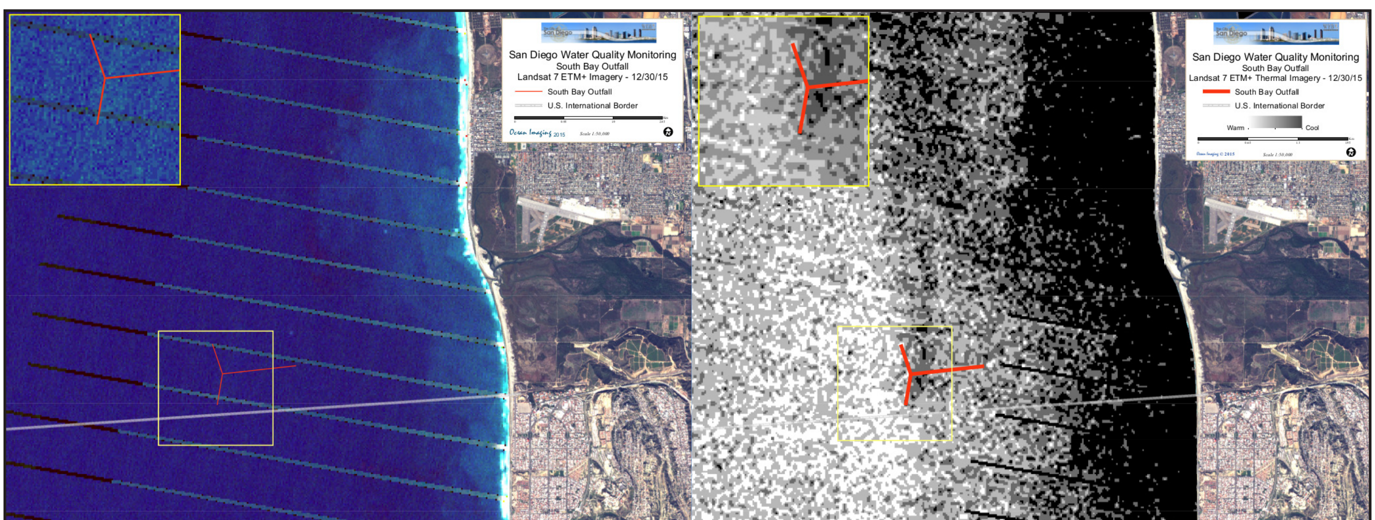


Figure 10.

Landsat eTM image of the SBOO region acquired on 12/30/2015 rendered in multispectral color (left) and thermal IR (right). The SBOO plume is not discernible in the color image but is detected in the IR as a cool, northward-directed linear feature.

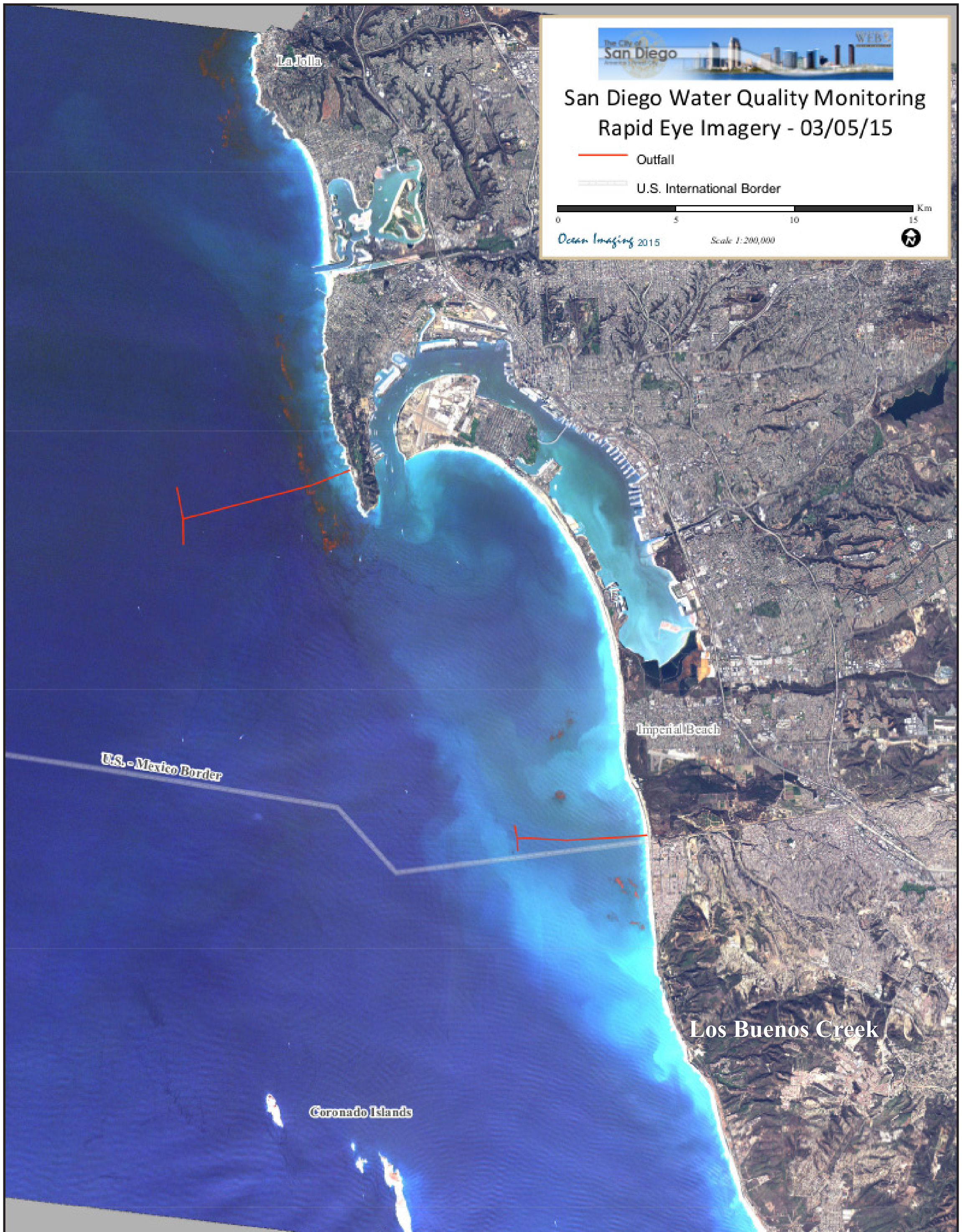


Figure 11.

RapidEye image acquired on 3/5/2015 after a spring rain event showing an extensive turbidity plume containing runoff from the los Buenos Creek in Mexico crossing the US/Mexico border toward the northwest. It was not observed to reach Pt. Loma, however.

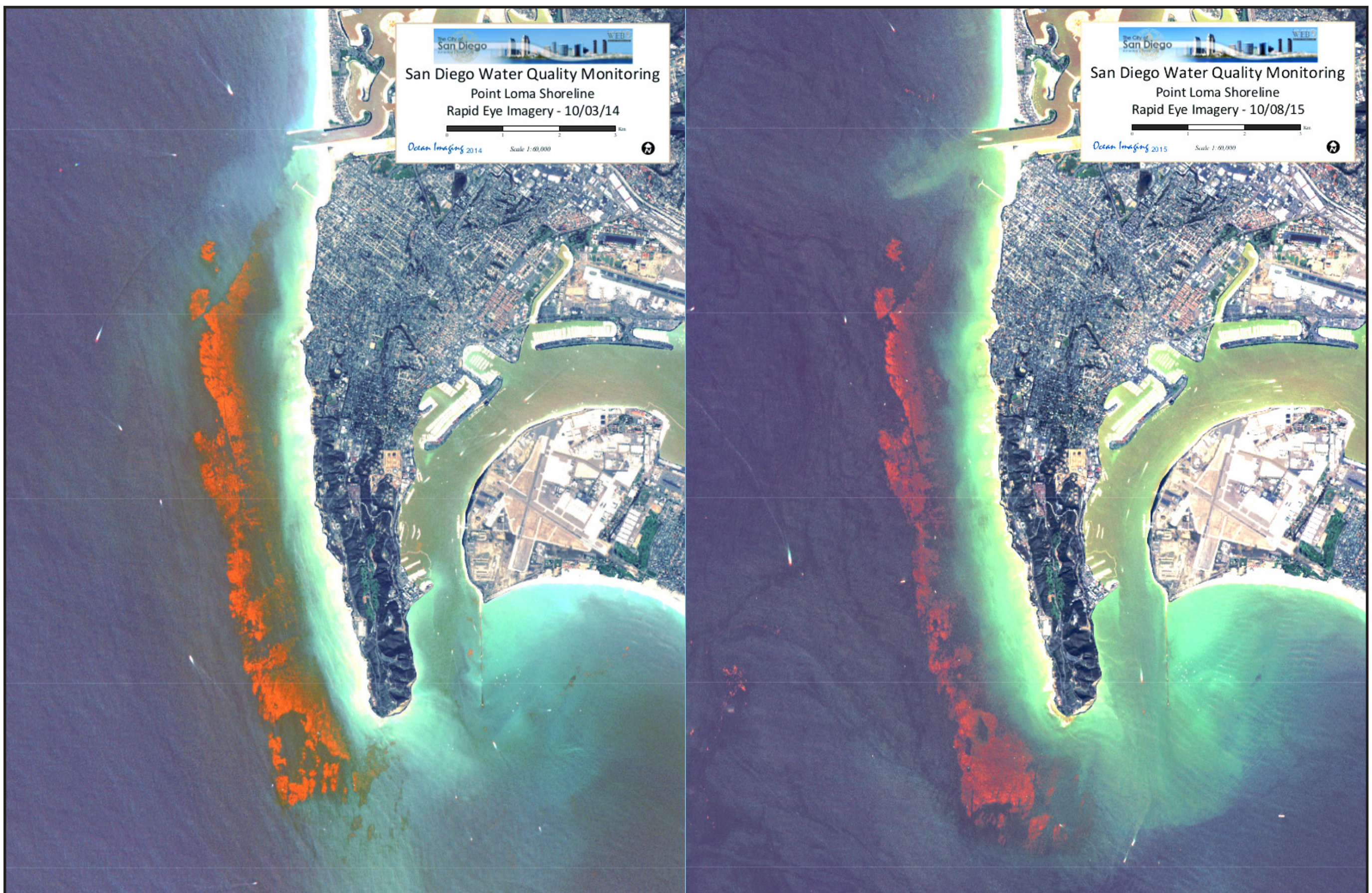


Figure 12.

High resolution images showing the Pt. Loma kelp bed on 10/3/2014 (left) and 10/8/2015 (right). Note the large expansion of the southern portion of the bed in 2015.

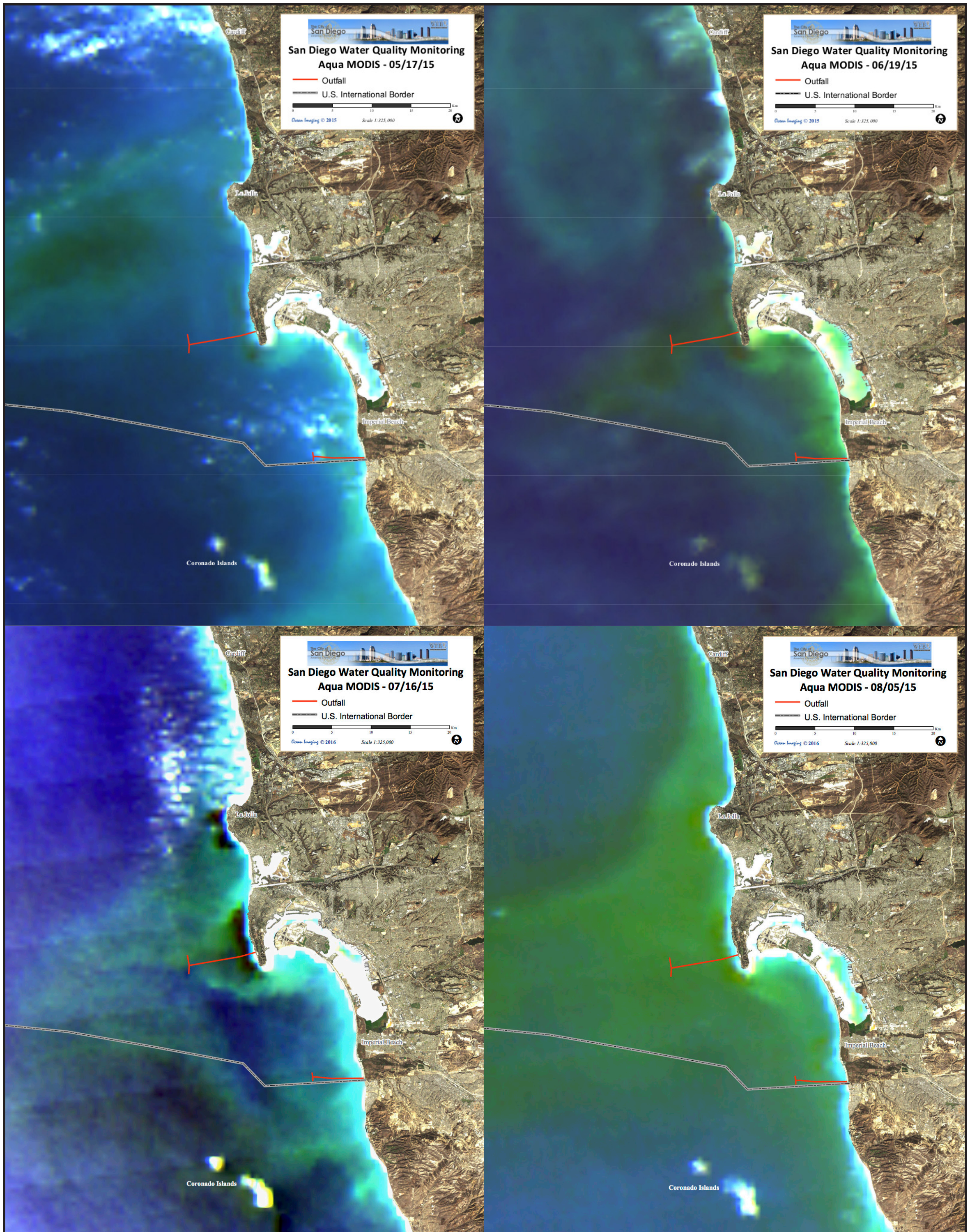


Figure 13.

MODIS imagery of the San Diego region showing periodic plankton blooms covering the PLO region on 5/17/2015, 6/19/2015, 7/16/2015 and 8/5/2015.