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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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 stormwater 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 four 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. In 2014 BlackBridge Inc. took over the management and resale of RapidEye data and in 2016 Planet Labs, Inc. acquired BlackBridge and the RapidEye fleet of 5 satellites. Subsequently, OI renegotiated with Planet Labs to preserve the original structure and pricing for the continued purchase and use of RapidEye 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. In 2016 Ocean Imaging continued the development of imagery and data services so that the data are compatible with the City's new ESRI ArcGIS online map server. The original add-on products ranged from atmospherically corrected satellite images of sea surface temperature and chlorophyll to radar and model-derived surface current fields and since have been expanded to include ocean currents and mixed layer depth data products derived from the U.S. Navy's Hybrid Coordinate Ocean Model (HYCOM – www.hycom.org).

This report summarizes observations made during the period 1/1/2016 – 12/31/2016.

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-Near Infrared 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/ArcGIS Server-directed products are produced daily by OI and are automatically linked with the server when available.

2.4 Future Enhancements of the Remote Sensing Monitoring Project

In 2016, OI began to generate the ocean currents and other HYCOM-derived products in a Web Map Service (WMS) Representational State Transfer (REST) service format which is directly compatible with the ESRI WMS the City is working to implement. In 2017, it is planned that all of the OI-delivered data products, including all of the satellite imagery be delivered via this mechanism for easy ingestion into the City's ArcGIS online WMS. While the historical imagery, data and reports will remain accessible via the existing web portal, OI will migrate all 2017 data products to OI's ArcGIS Server by the fall of 2017 or whenever the City is ready to ingest the data feed from OI's server. Following the completion of the migration of the 2017 data to this system, OI will progressively work backwards in time to make all historical data available to the City's ArcGIS online WMS.

Beginning in 2017, OI is also processing and posting imagery from a new satellite, SENTINEL-2A. SENTINEL-2A is a satellite operated by the European Space Agency (ESA) and is the spaceborne platform for the Multispectral Instrument (MSI). The SENTINEL-2 Multispectral Instrument (MSI) samples 13 spectral bands: four bands at 10 meters, six bands at 20 meters and three bands at 60-meter spatial resolution. The green band focusing in the 560 nm wavelength is ideal for detecting turbidity plumes from the outfalls both at the surface and at depths down to 40 feet depending on ocean conditions. The revisit time of the SENTINEL-2A satellite is approximately five days. **Figure 1** shows MSI imagery from February 19, 2016. A wastewater plume is clearly observed over the South Bay Ocean Outfall (SBOO). Data from the Landsat and RapidEye satellites were not available on this day, so

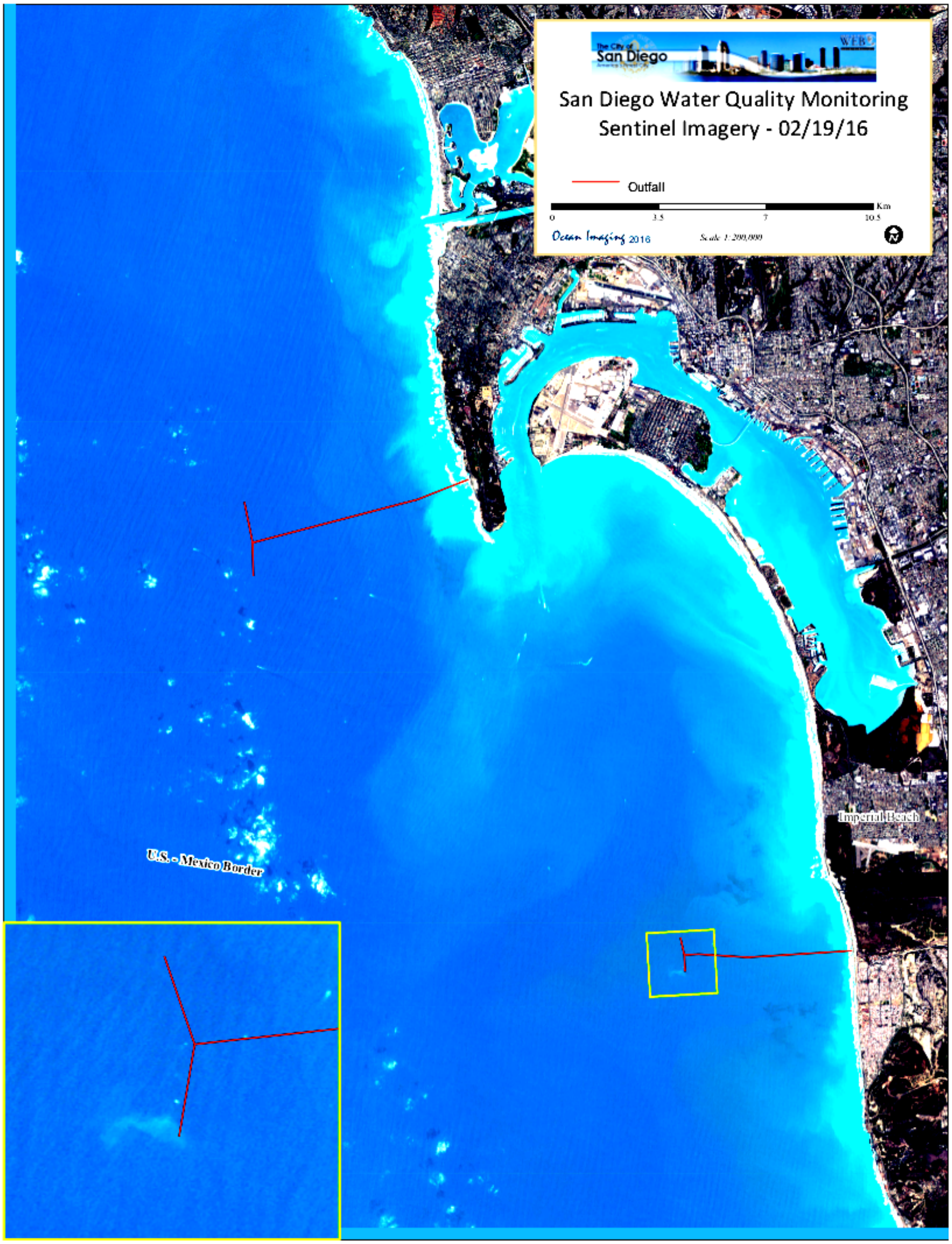


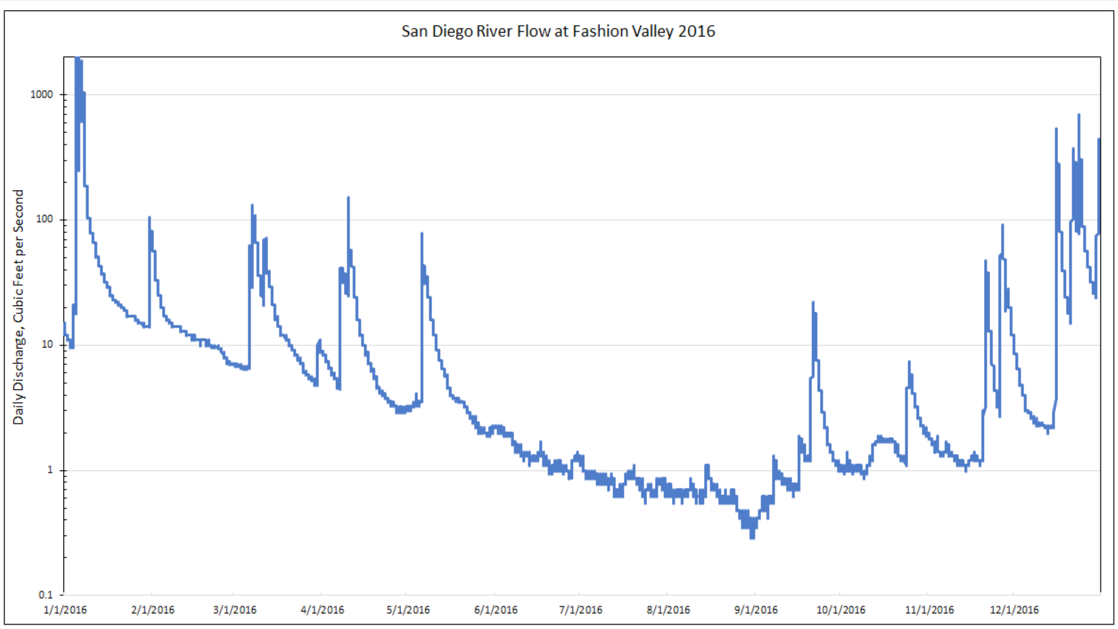
Figure 1. SENTINEL-2A MSI image from 02/19/16 showing overall project AOI as well as area around the SBOO. Note the obvious wastewater plume over the outfall.

this dataset provides a encouraging example of how the increased temporal satellite data coverage will enhance this monitoring and documentation effort. A second satellite carrying the MSI sensor, the SENTINEL-2B, has already been launched into orbit by the ESA and is in the commissioning phase at the time of this report. It is expected that OI will have access to the data from this new satellite/sensor by early summer of 2017. This will increase the temporal frequency of high resolution satellite imagery to roughly every 2-3 days – significantly improving our near-real-time monitoring capability.

3. HIGHLIGHTS OF 2014 MONITORING

3.1 Atmospheric and Ocean Conditions

As in 2015, 2016 conditions represented a contrast to the preceding years 2012, 2013, and 2014, not only in having significant precipitation during the traditional rainy months, but also because the cumulative annual rainfall in 2016 as determined from the monthly rainfall totals at Lindbergh Field **(Figure 2)** was 10.23 inches compared to 9.89 inches in 2015 and 7.78 inches in 2014. This represents a near 24% total increase from 2014 to 2016. In contrast to 2015, however, much of the 2016 precipitation occurred during the months of January and December as opposed to being spread relatively evenly over the entire year in 2015. The resulting point and non-point runoff affected coastal water quality in some areas, especially during the winter months. **Figure 3** shows daily precipitation in the Tijuana River Estuary. The table to the side of the plot shows the dates on which the effluent plume was visible in the available satellite imagery as shaded cells. 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 3, rain events totaling considerably higher daily totals occurred during the winter to spring “rainy months” as well as in May and late September – causing polluted Tijuana River effluent to be discharged into the ocean, however relatively infrequently being directly relatable to wastewater plumes over the SBOO being visible in the satellite imagery. Almost no rainfall occurred during the months of June through



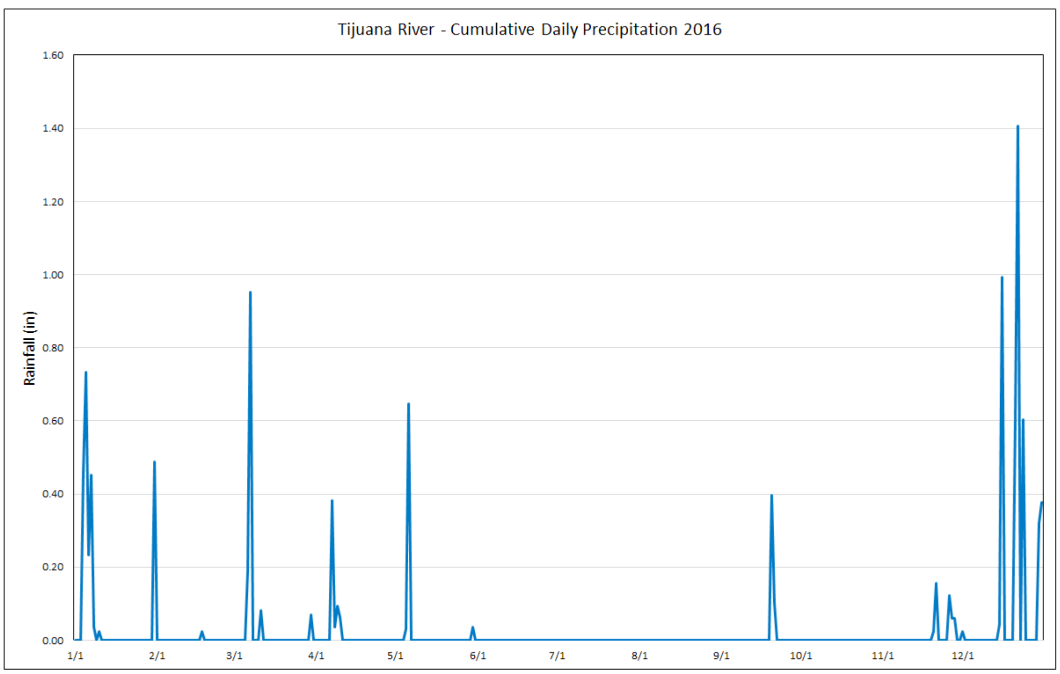
Lindbergh Field Rainfall 2016	
Jan	3.21
Feb	0.05
Mar	0.76
Apr	0.55
May	0.44
Jun	0
Jul	0
Aug	0
Sep	0.32
Oct	0.07
Nov	0.61
Dec	4.22

Figure 2. Mean daily flow of the San Diego River during 2016 (measured at Fashion Valley). Table on the right shows monthly rainfall totals in inches at Lindbergh Field.

mid-September in 2016 which is evident in the non-existence of a river plume visible in the satellite data during this time.

Similar patterns can be seen in Figure 3 which shows monthly precipitation totals at Lindbergh Field and San Diego River discharge rate at the Fashion Valley gaging station. The 2016 river flow rates were much like in 2014 when the River's flow was below 1 cubic foot per second from June through early September and unlike 2015 when we observed discharge rates above this level with a large spike in July resulting from a heavy rain event. The 2016 flow spikes correspond well with the rainfall data from both the Tijuana River and Lindbergh Field reporting stations.

The result of the 2016 winter-spring and fall-winter rain events was that the shoreline near the Tijuana River mouth experienced frequent closures due to contamination during the rainy season. Rainfall events during the months of January, March, April and May as well as September, November and December can be indirectly



Date	CumPrcp (in)
1/1	0.02
1/4	0.46
1/5	0.73
1/6	0.23
1/7	0.45
1/8	0.03
1/12	0.00
1/24	0.00
1/27	0.00
1/31	0.48
2/3	0.00
2/8	0.00
2/10	0.00
2/15	0.00
2/16	0.00
2/18	0.02
2/19	0.00
2/27	0.00
3/6	0.18
3/7	0.95
3/9	0.00
3/11	0.08
3/30	0.07
4/7	0.38
4/8	0.03
4/9	0.90
4/10	0.60
5/5	0.30
5/6	0.64
5/30	0.03
9/20	0.39
9/21	0.10
10/21	0.00
11/20	0.02
11/21	0.15
11/22	0.00
11/26	0.12
11/27	0.05
12/1	0.02
12/8	0.00
12/15	0.04
12/16	0.99
12/21	0.59
12/22	1.40
12/24	0.60
12/30	0.31
12/31	0.37

Figure 3. Daily cumulative rainfall in the Tijuana Estuary. The shaded dates in the accompanying table show those days on which the effluent plumes were visible in the available visible and/or thermal infrared satellite imagery.

correlated with shoreline closures and advisories from Border Field State Park up to Silver Strand State Beach as well as in Mission Bay and the bay side of Coronado Island. Over the 2015-2016 and 2016-2017 winter months, the Border Field State Park shoreline was closed as long as 54 and 40 days respectively. A few closure events in May, June and August cannot be directly associated to rainfall events, high river runoff nor any turbidity features seen in the available imagery.

Although discharge from the San Diego River does not cause the beach contamination issues of the Tijuana River discharge, the runoff from the two rivers, Mission Bay and coastal lagoons affected nearshore water clarity on many occasions in 2016, directly as a source of suspended sediment and indirectly as a source of nutrients feeding localized plankton blooms. While there were several phytoplankton blooms off the coast of San Diego throughout the year, only a few can possibly be attributed to rainfall and/or high river flow rate events. Noteworthy plankton blooms which were visible in the MODIS satellite imagery occurring between La Jolla and the U.S. Mexico border were many and are listed in **Table 1**. Seven out of the twelve notable plankton blooms could be attributed to rainfall event and hence nutrient influx from river discharge. The remaining phytoplankton bloom events are most likely the result of coastal upwelling in the region. **Figures 4a and 4b** show example plankton bloom events off San Diego County during the periods of 03/16/16 – 03/25/16 and 08/13/16 – 08/22/16 visible in the MODIS-derived Chlorophyll imagery.

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

Date Range of Plankton Bloom Visible in MODIS Imagery	Closest Significant Rainfall Event	Closest San Diego River Discharge Rate Above 10 cu. ft. /sec.
03/15/16 – 03/25/16	03/07/16, total = 0.95 inches	03/06/16 – 03/21/16
04/10/16 – 04/28/16	04/07/16 – 04/10/16, total = 1.91 inches	04/07/16 – 04/16/16
05/10/16	05/05/16 - 05/06/16, total = 0.94 inches	05/06/16 – 05/11/16
06/13/16 – 06/29/16	05/30/16, total=0.03 inches	none within same time period
07/04/16 – 07/09/16	none within same time period	none within same time period
07/31/16 – 08/23/16	none within same time period	none within same time period
09/03/16 – 09/08/16	none within same time period	none within same time period
09/14/16 – 10/03/16	09/20/16 – 09/21/16, total = 0.49 inches	09/21/16 – 09/22/16
10/06/16 – 10/26/16	none within same time period	none within same time period
11/01/16 – 11/25/16	11/20/16 – 11/27/16, total = 0.34 inches	11/21/16 – 11/23/16, 11/27/16 – 12/01/16
12/04/16 – 12/08/16	12/01/16, total = 0.02 inches	11/27/16 – 12/01/16
12/17/16 – 12/27/16	12/15/15 – 12/24/16, total = 3.62 inches	12/16/16 – 12/27/16

Table 1. Periods of plankton blooms off the coast of San Diego County as indicated by high Chlorophyll levels detected in MODIS satellite imagery along with the dates of the closest significant rainfall event as measured by the Tijuana Estuary gauge and the dates of closest San Diego river discharge above 10 cubic feet per second measured at the USGS Fashion Valley recording station.

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.

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.

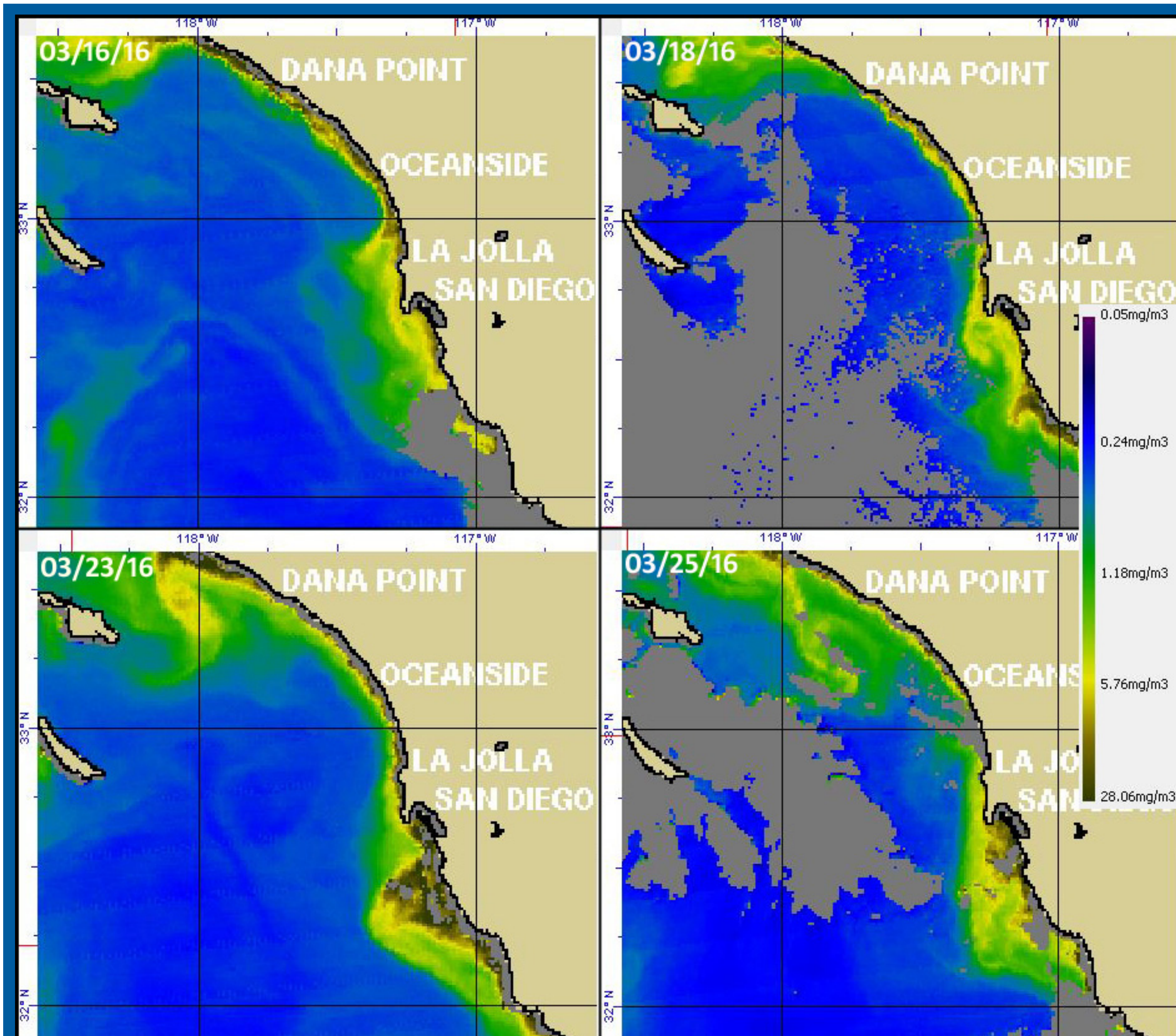


Figure 4a Chlorophyll imagery derived from the MODIS sensor on the NASA Aqua satellite showing strong phytoplankton blooms off the coast of San Diego during the periods of 03/16/16 – 03/25/16.

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. As opposed to previous years during which there were instances when the plume was detectable on the surface with the multi-spectral sensors, but became only detectable with thermal imaging a day or two later, there were four occurrences in 2016 when the plume was visible in the multispectral imagery at the same time as was seen a cool water signature over the outfall. The existence of a thermal

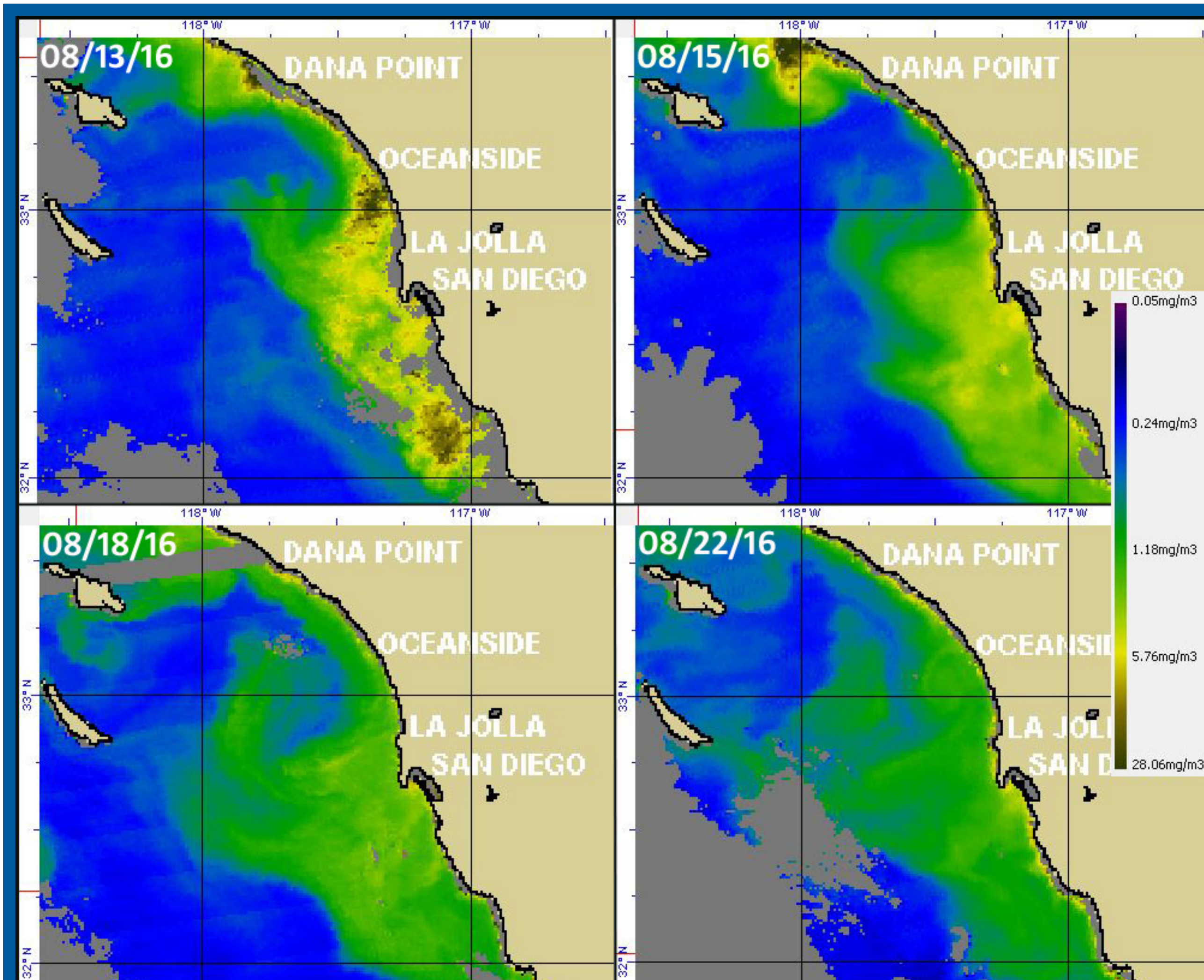


Figure 4b. Chlorophyll imagery derived from the MODIS sensor on the NASA Aqua satellite showing strong phyto-plankton blooms off the coast of San Diego during the period of 08/13/16 – 08/22/16.

plume signature simultaneously with a turbidity plume shows the effluent reached the ocean surface, however unlike previous years the water was not in a diluted state, but rather still concentrated. Most likely on these days the vertical stratification was completely broken down allowing the wastewater plume to quickly travel to the surface before becoming diluted. It should also be noted that in many cases when a plume signature was observed in the multispectral imagery, it was in the RapidEye data which does not have a Thermal Infrared (TIR) channel. Additionally, during much of 2016, the Landsat 8 sensor had its TIR sensor inactive due to system problems. So, there may have been more cases for which the TIR signal would have been seen simultaneously with the multispectral feature. **Figures 5a and 5b** show the Landsat imagery in which the outfall plume is apparent in both the multispectral visible and the TIR bands of the data.

In 2016's early months the SBOO plume was detectable in ten remote sensing datasets through the month of March as opposed to half that number by the same time in 2015. The plume signatures in the 2016 incidents were relatively large in size compared to previous years and also simultaneously visible in the TIR imagery in three cases – which

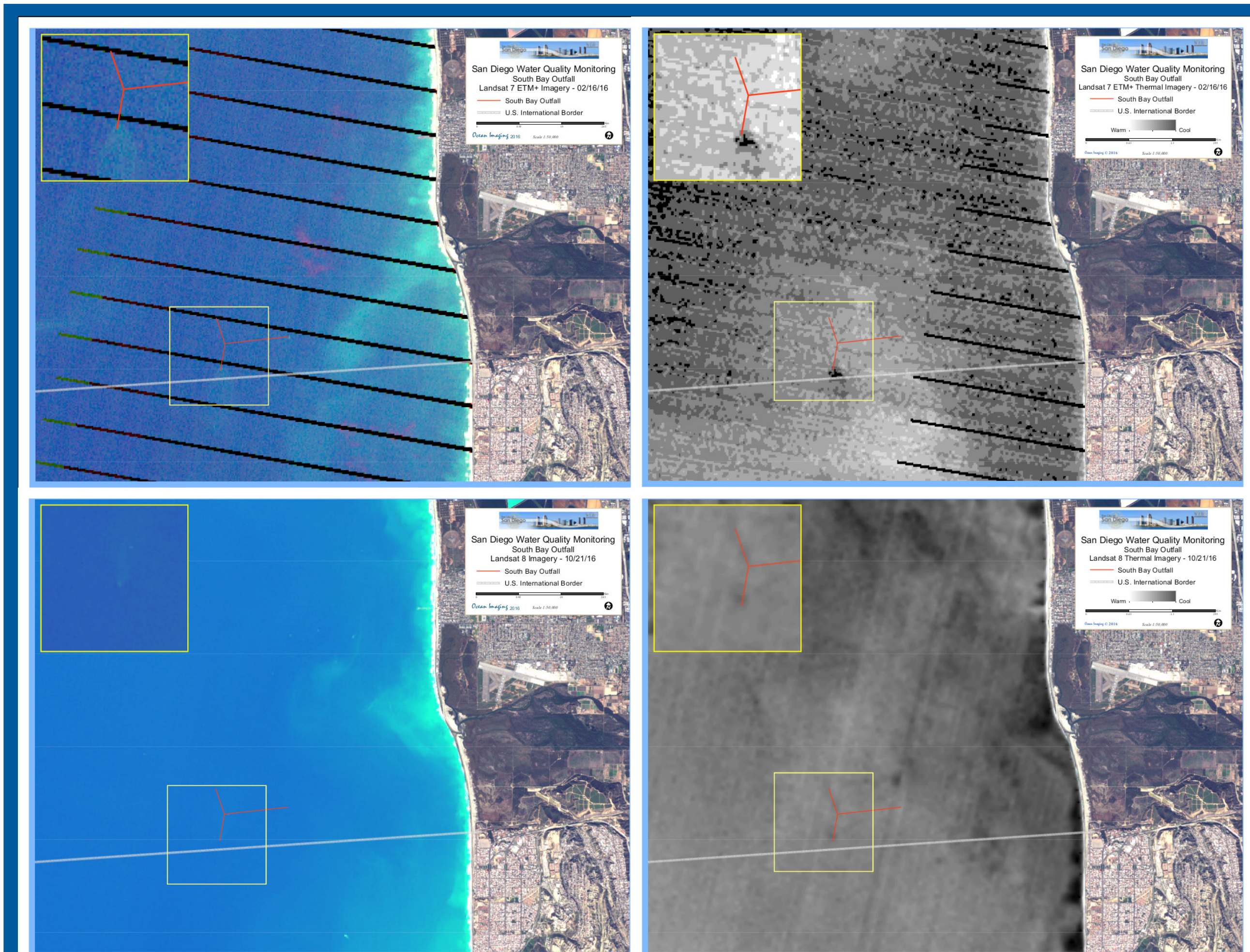


Figure 5a. Landsat 8 imagery showing turbidity plumes emanating from the SBOO. The plumes are visible both in the RGB composite version of the multispectral data as well as in the TIR imagery. Cooler water appears darker in the TIR scenes.

was not the case in previous years. These observations most likely point to a lack of strong vertical stratification during the winter to spring months of 2016 with the seasonal reformation of vertical stratification beginning around mid-March. This idea is reinforced by the relatively high rainfall amounts during the months of April and May, yet no wastewater plumes were visible in the available satellite imagery during those two months, indicating that any turbid outfall water was kept at depth by stratification. Beach closures north of Border State Park did occur during these months, however, except for a seven-day long closure at Imperial Beach from 05/06/16 – 05/13/16 caused by a coincidental rain event, the closures were only for short periods of time. **Figure 6** shows an example of one of the smaller plume signatures during early 2016 seen in RapidEye imagery on 02/10/16 with the bacteria sampling results from 02/10/16 overlaid. Northward flow of the effluent from the SBOO corresponds well with the lower bacteria values south of the outfall and higher levels measured north of the SBOO at sampling stations I25 and I39. Elevated values were also seen at stations along the coast around and to the north of the Tijuana River mouth. A few days later on 02/15/16 and 02/16/16, the surface plume from the SBOO was observed to switch to a south-

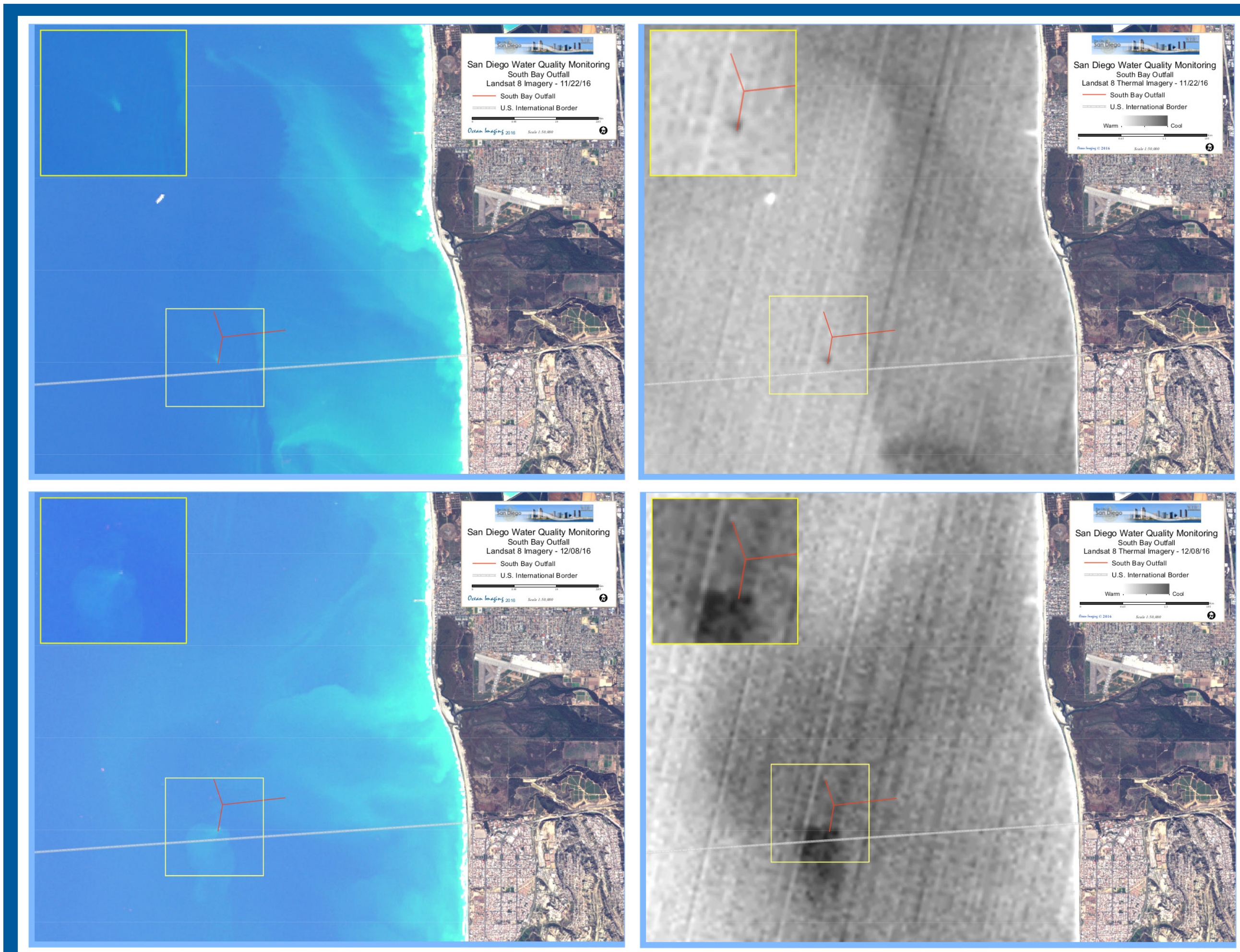


Figure 5b. Landsat 8 imagery showing turbidity plumes emanating from the SBOO. The plumes are visible both in the RGB composite version of the multispectral data as well as in the TIR imagery. Cooler water appears darker in the TIR scenes.

ward direction up until 02/27/16 when plume changed its orientation northward again. On 03/09/16 the plume was observed to have shifted back to a south-southeast moving direction. The plume signature observed in the 03/09/16 imagery was undoubtedly the result of heavy rains a few days prior on 03/06/16 and 03/07/16. **Figure 7** shows the inshore sampling stations from data acquired on 03/10/16 overlaid on the 03/09/16 RapidEye imagery. Only inshore data were available around this date. Note the southward direction of the turbidity plume over the southern wye and the fact that the southernmost sampling stations showed the highest bacteria levels. This shifting of the plume direction back and forth during the months of January through March highlight the dynamic nature of both the surface and subsurface currents during the early part of 2016.

The best water quality and clarity in the South Bay region in 2016 was observed from late June all the way through the summer up through mid-October. Only five instances of above normal bacteria levels were recorded at the shoreline stations and only five as well recorded at the offshore sampling stations during this almost five-month period. The only rain event of significance during

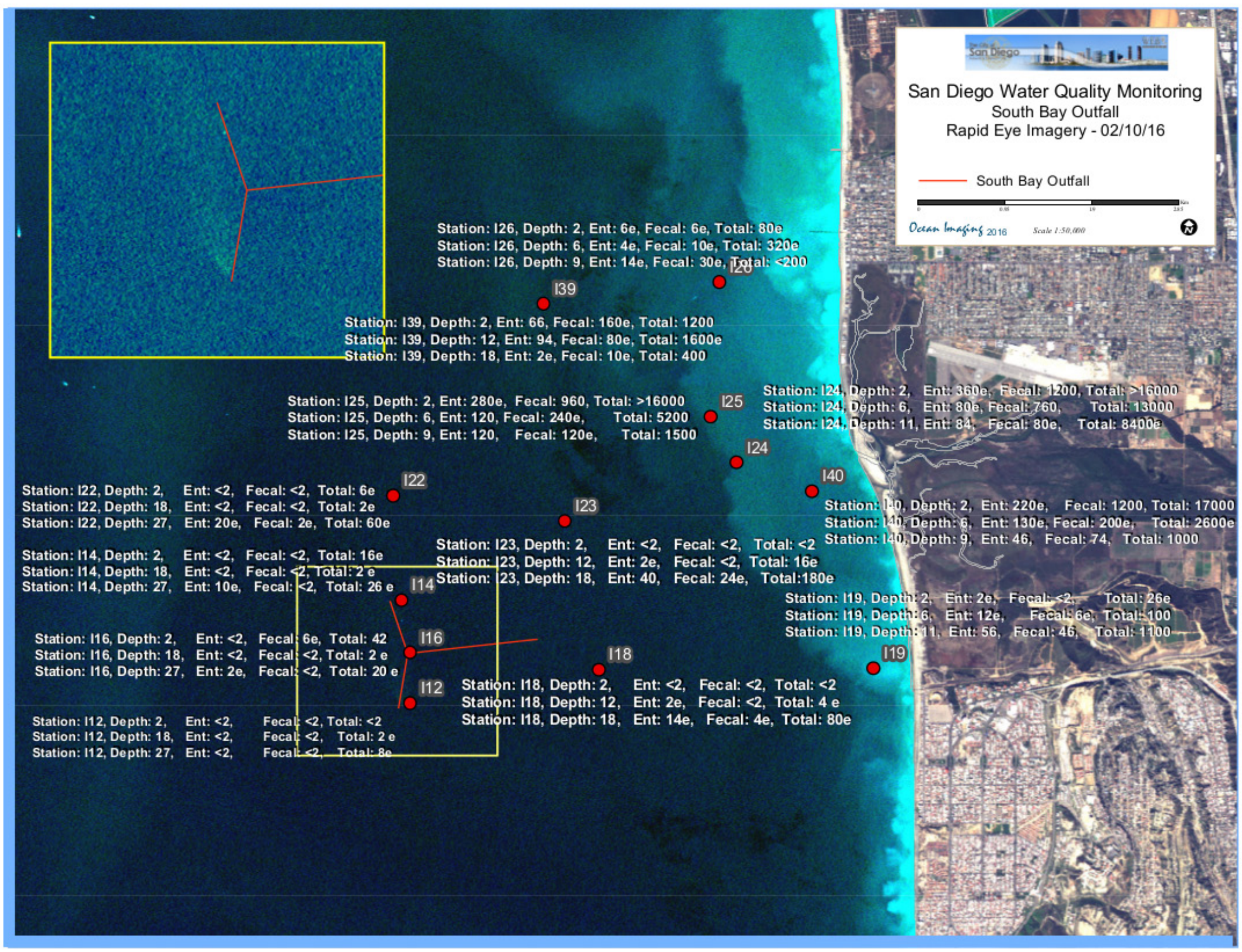


Figure 6. RapidEye image of the SBOO region acquired on 02/10/16 and near-surface bacterial sampling results collected on 02/10/16. Elevated values at the northern sampling stations I24, I25, I26 and I39 correspond with the direction of flow of the surfacing SBOO plume.

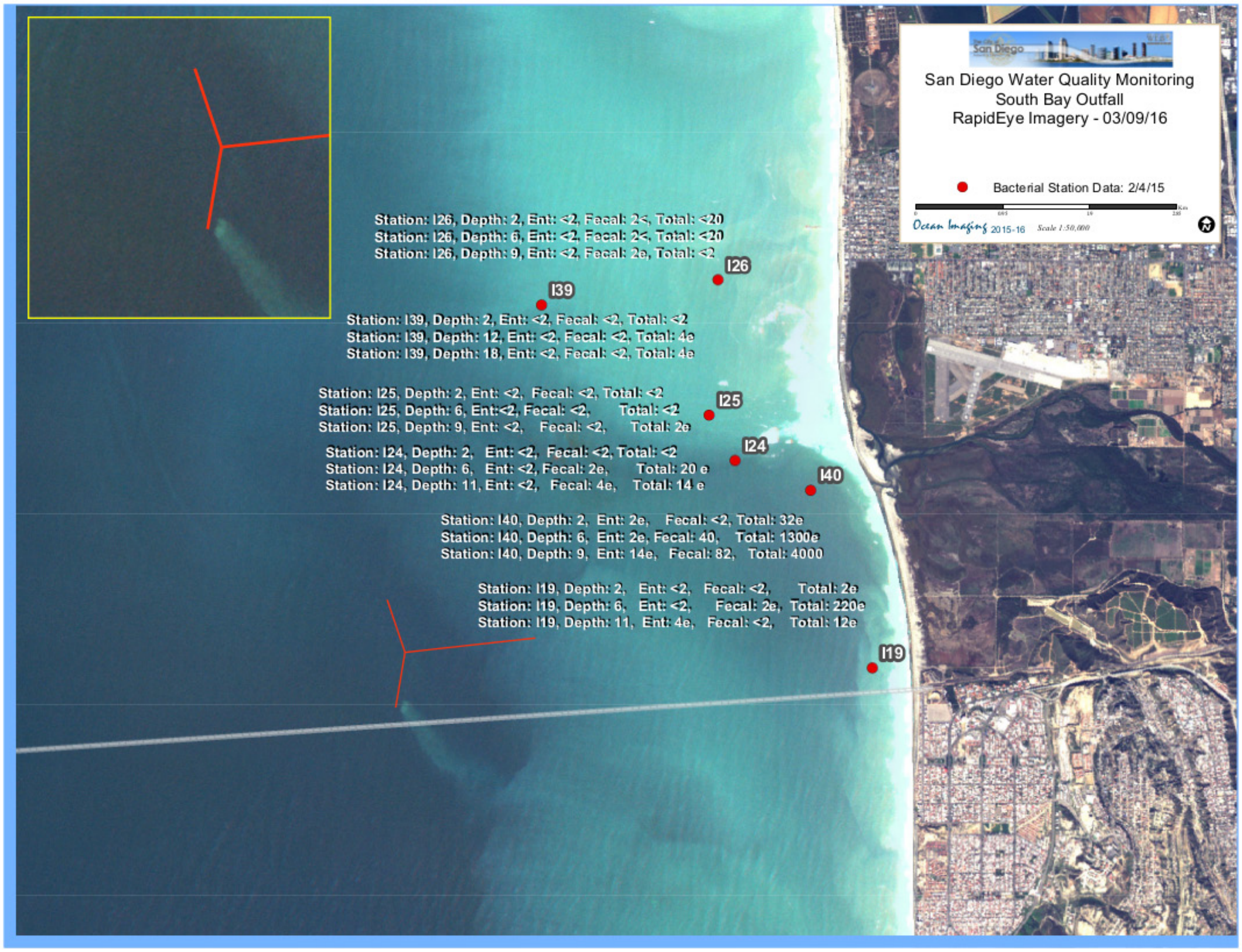


Figure 7. RapidEye image of the SBOO region acquired on 03/09/16 and near-surface coastal bacterial sampling results collected on 03/10/16. Elevated values at I19 and I40 south of the Tijuana River mouth correspond with the direction of flow of the surfacing SBOO plume.

this time occurred on 09/20/16 with 0.49" recorded at the Tijuana Estuary during which shoreline bacteria sampling did show elevated levels. No SBOO plume signatures were seen in the satellite imagery during this time. Historically, September is still considered a dry month. A Landsat 8 image acquired on 09/03/16 shows low turbidity along the shoreline with a pattern indicative very little surface flow. The bacteria sampling data from 09/01/16 overlaid on top of the September 3rd Landsat 8 image corroborates this low activity period (**Figure 8**).

The next, very small, barely detectable, northward-moving SBOO plume was noticeable in a 10/21/16 Landsat 8 scene – in both the multispectral channels as well as the TIR band, which is significantly earlier than has been the case in recent years. The next visible waste water turbidity plume was evident in the 11/22/16 Landsat 8 imagery showing northward movement of the plume extending from the southern wye as well as the turbidity patterns along the coast. The signature was observed in the TIR imagery as well as the multispectral data. This observation falls more in line with what would expected from a seasonal standpoint. Late November is the beginning of the time period when vertical stratification of the water column begins to degrade, but it is also when the Davidson Current (a northward moving subsurface countercurrent) starts to rise to the surface breaking down the density barriers in the water column and exhibiting a northward surface flow.

Heavy rainfall during the month of December, especially after 12/15/16 caused the expected heavy outflow from the Tijuana River, in turn causing beach warnings and closures around the river mouth up to Imperial Beach during the latter part of December. The SBOO plume was not, however, regularly observed to surface in December although a relatively large plume was visible in the Landsat 8 imagery from 12/08/16. This plume was visible in both the multispectral visible as well as the TIR imagery. Even close examination of the coarser-resolution MODIS multispectral visible imagery did not reveal any SBOO-related turbidity plume after 12/08/16, however heavy shoreline turbidity was apparent in all satellite data during the entire month of December. All of the high resolution RapidEye and Landsat imagery showing evidence of SBOO related turbidity plumes can be found in **Appendix A**.

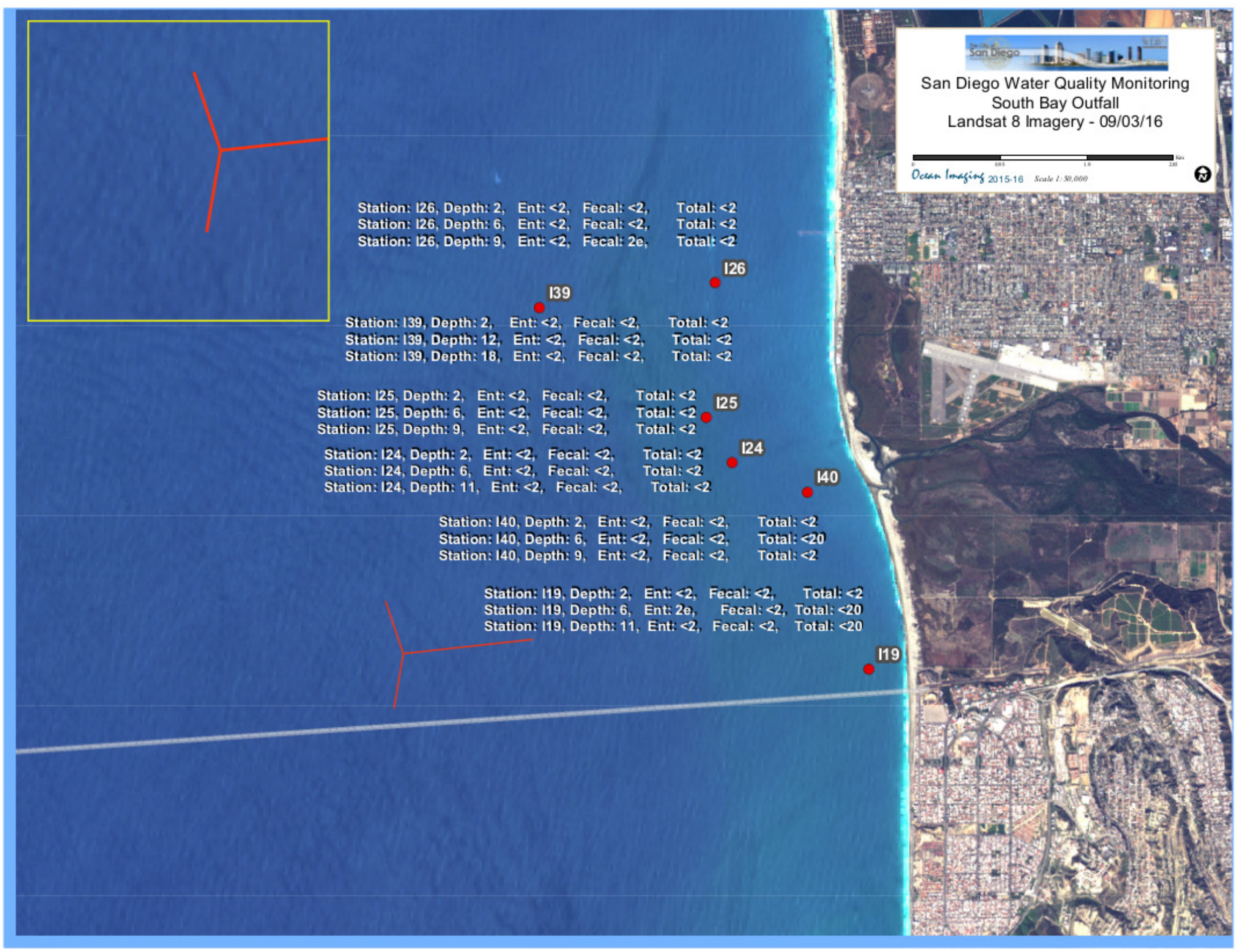


Figure 8. Landsat 8 image of the SBOO region acquired on 09/03/16 and near-surface coastal bacterial sampling results collected on 09/01/16. Note the clear water along with the low bacteria levels.

Throughout 2016 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 effluent from the Tijuana River, especially after seasonal rain events during the winter and spring 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 by the doming up of the discharged effluent and laterally displacing the near-surface waters above it.

Figure 9. RapidEye image of the Pont Loma region acquired on 03/09/16 and near-surface coastal bacterial sampling results collected on 03/10/16. Note the higher bacteria levels at the southern stations, however no obvious turbidity plume emanating from the outfall.

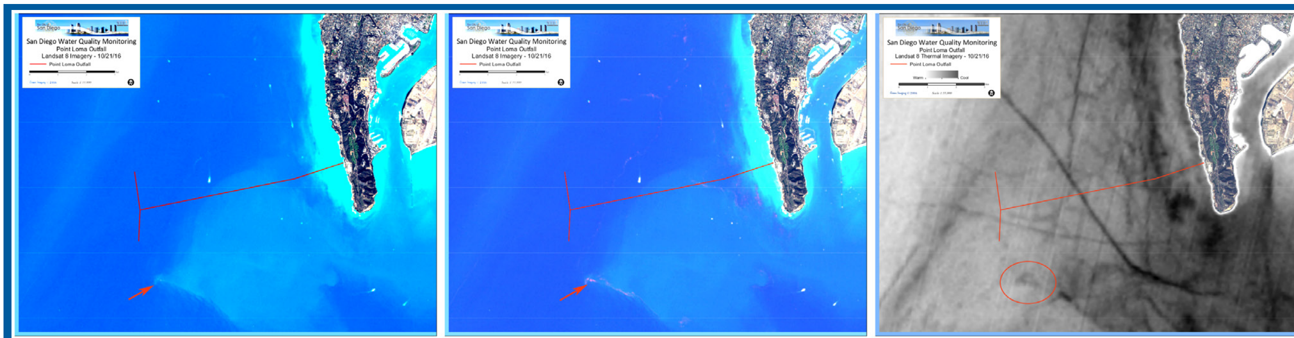


Figure 10. High resolution Landsat 8 images showing the Pt. Loma kelp bed on 10/21/16. The left image is a Red-Green-Blue rendering of the visible channels, the center image is a Near-Infrared-Green-Blue rendering and the right image is the TIR channel with cooler water represented as the darker shades. Note the orange-red kelp-like signature at the western-most tip of the plume in the center (NIR-Green-Blue) image.

In 2016 the Point Loma region was affected by conditions already described for the South Bay region: significant seasonal rainfall during the winter and spring months with zero rainfall during June July and August. 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 major seasonal rain events. Both shoreline and periodic kelp bed bacterial sampling generally showed only occasional and marginally increased concentrations. Field sampling showed elevated bacteria levels on 02/20/16, 03/09/16, 03/10/16, 03/14/16, 12/12/16 and 12/24/16. All the high bacteria measurements during March and December can be correlated with heavy rain events either prior to or during the site sampling. **Figure 9** shows the March 10th shoreline and offshore bacteria data plotted over the March 9th RapidEye image. While no plume associated with the outfall is visible, heavy coastal turbidity was apparent as well as turbidity plumes emanating from Mission Bay and San Diego Bay. 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 in 2016.

One anomalous event possibly associated with the lateral displacement of turbidity, thermal or chlorophyll features around the outfall wye is visible in the 10/21/16 Landsat 8 imagery. A distinct turbidity plume is evident in the multispectral visible imagery with the apparent point of origin located approximately 1, 500 meters south south-east of the southern wye (**Figure 10**). The presumed point of origin feature is also visible in the TIR data as an area slightly cooler than the surrounding water. Although this feature cannot be positively associated with the Point Loma outfall, as noted above, the plume could be explained by the doming up of the discharged effluent water laterally displaced in its surface manifestation. One observation to consider is the bright reflectance in the near-infrared channel of the sensor (orange spots in center image in Figure 10), which indicate the strong possibility of some sort of biological material (most probably floating kelp) at the apex of this turbidity plume. This still, however, does not explain the shape and size of the plume. It is also important to mention that no significant rainfall or river discharge events nor any high bacteria counts were recorded on or near this day, however there was a very strong phytoplankton plume extending from the San Diego County coast all the way out to San Clement Island during that time period.

One observation provided by the satellite image archive was the significant reduction in size of the Pt. Loma kelp bed during 2016 compared to previous years (**Figure 11**). The satellite data show it to begin to decrease in size during February of 2016, perhaps due to the storm events taking place during early to mid- January. The bed continued to appear sparse in the October imagery when normally the kelp biomass is at its peak. The lack of kelp was even apparent through December which is evident in the 12/18/16 RapidEye imagery (Figure 11). While it would be expected that the kelp bed would have returned to its normal size during the storm-free summer months, perhaps the seasonal winter and spring storms created constant stress in the area resulting in decreased canopy size.

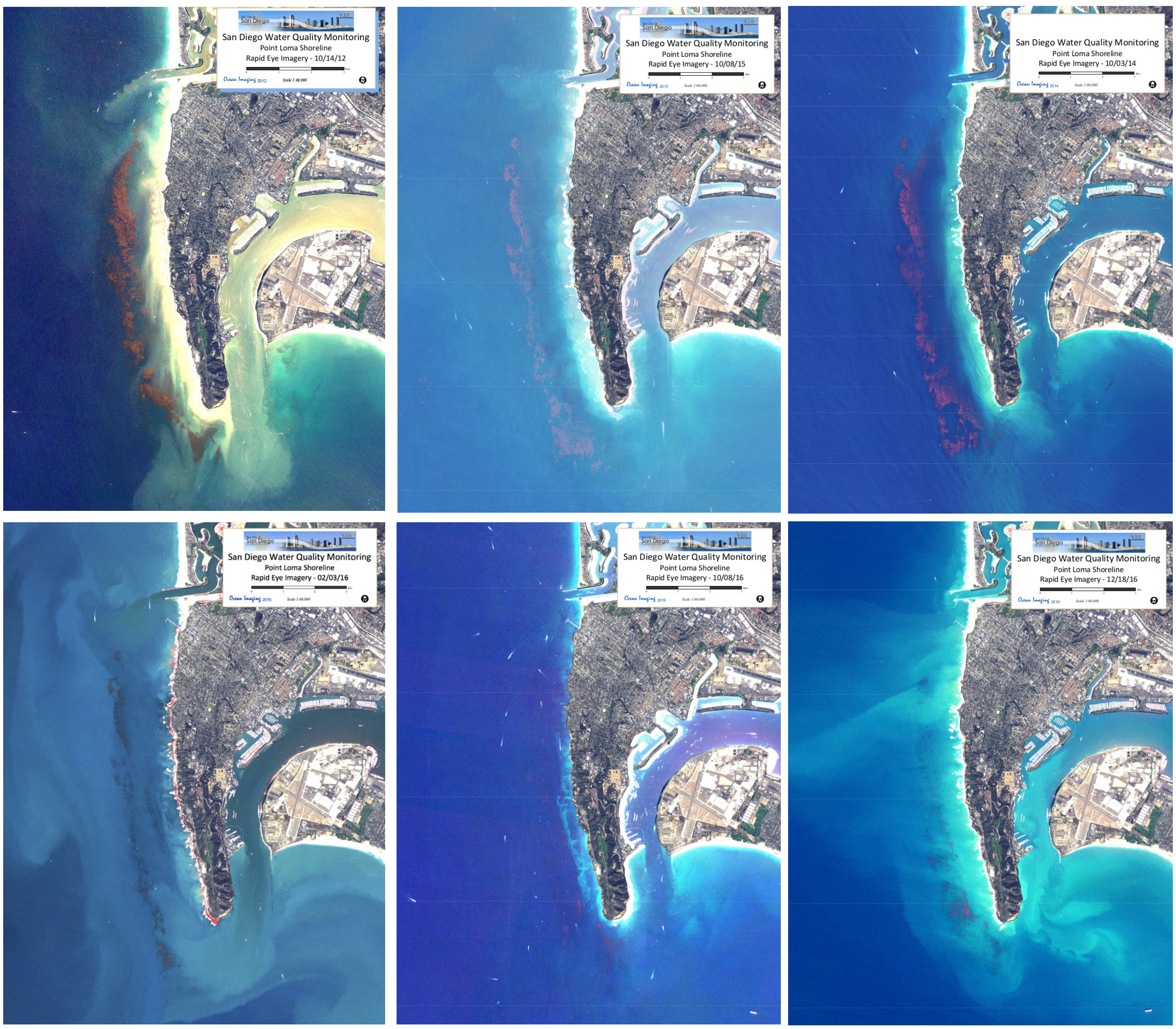
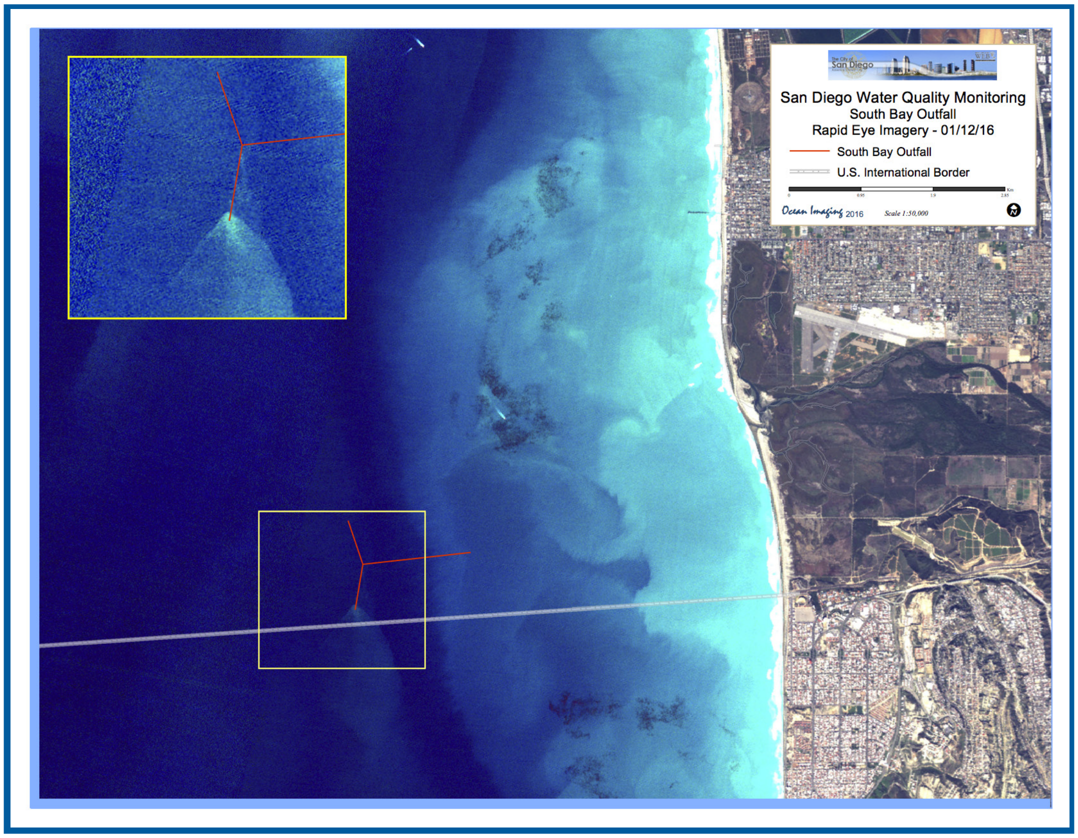
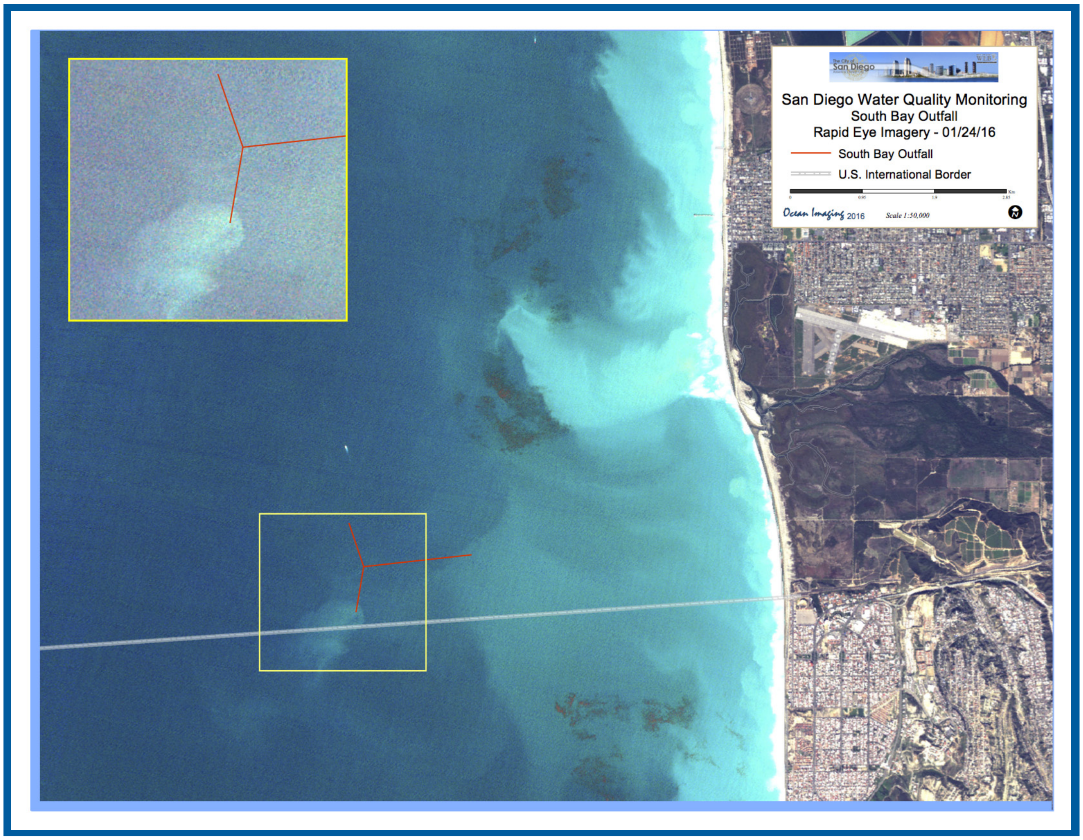
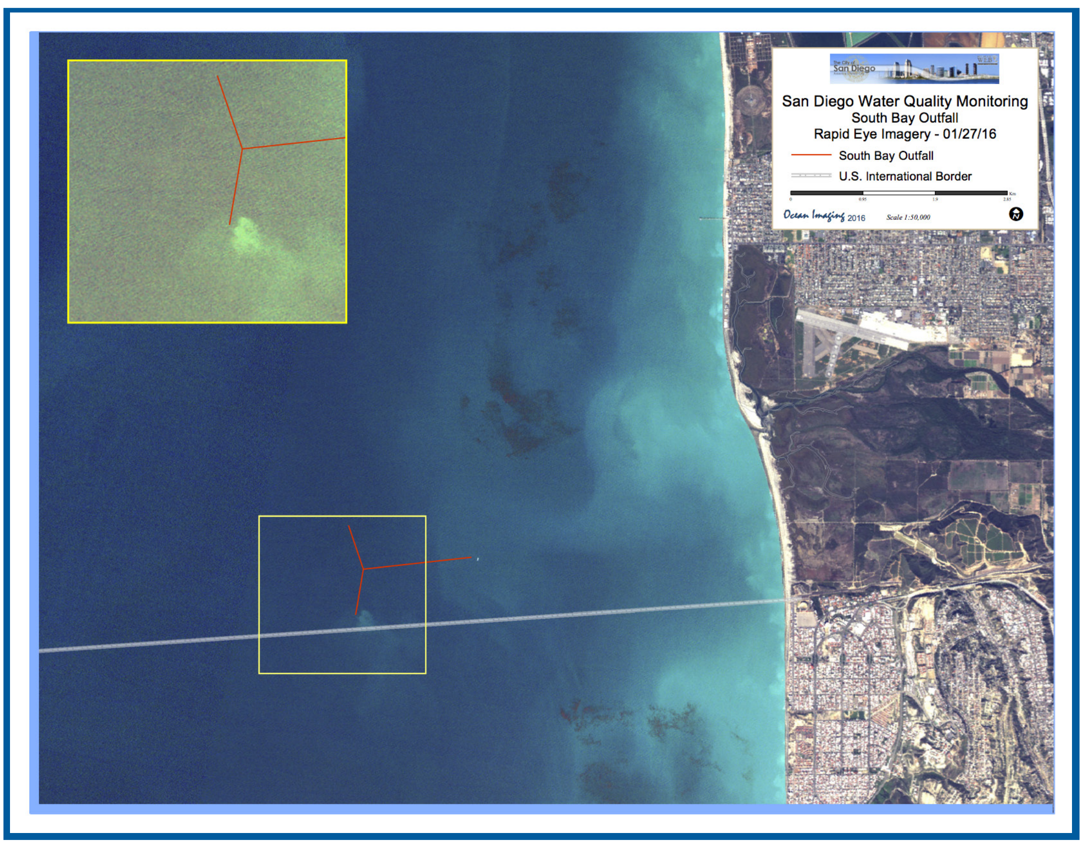


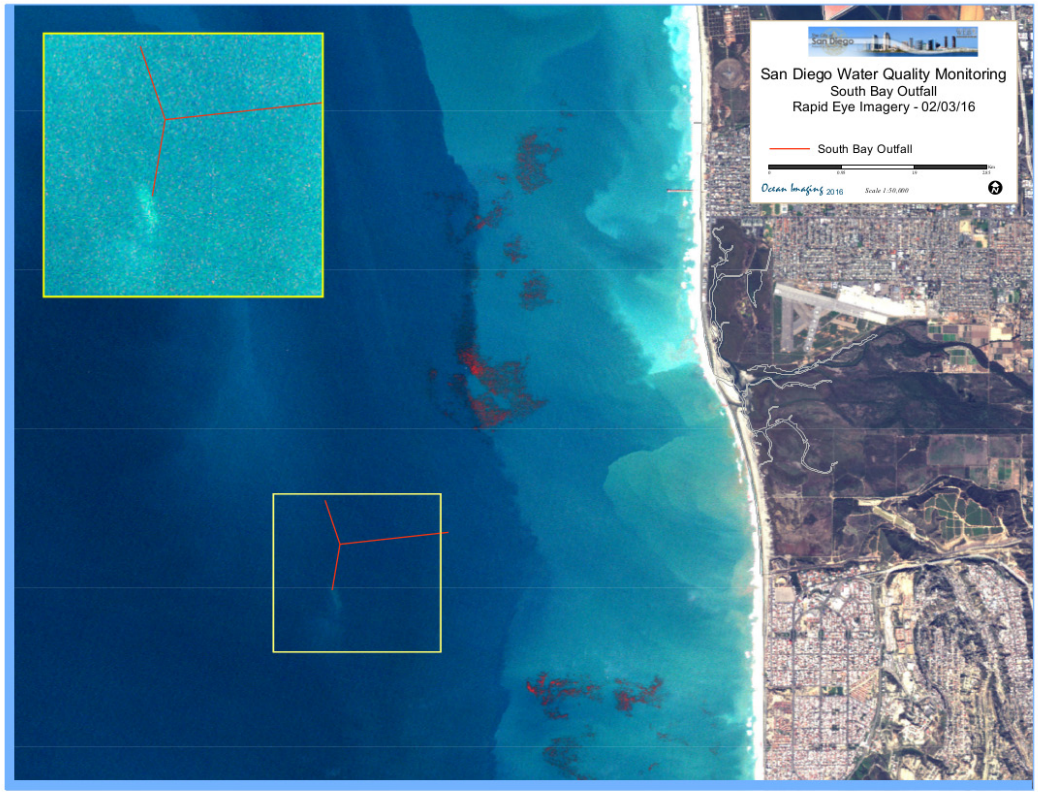
Figure 11. High resolution RapidEye images showing the Pt. Loma kelp bed on 10/14/12 (top left), 10/03/14 (top center), 10/08/16 (top right), 02/03/16 (bottom left), 10/08/16 (bottom center) and 12/18/16 (bottom right). Note the significant decrease in canopy area coverage in 2016 compared to the previous four years, even during potentially peak growth months.

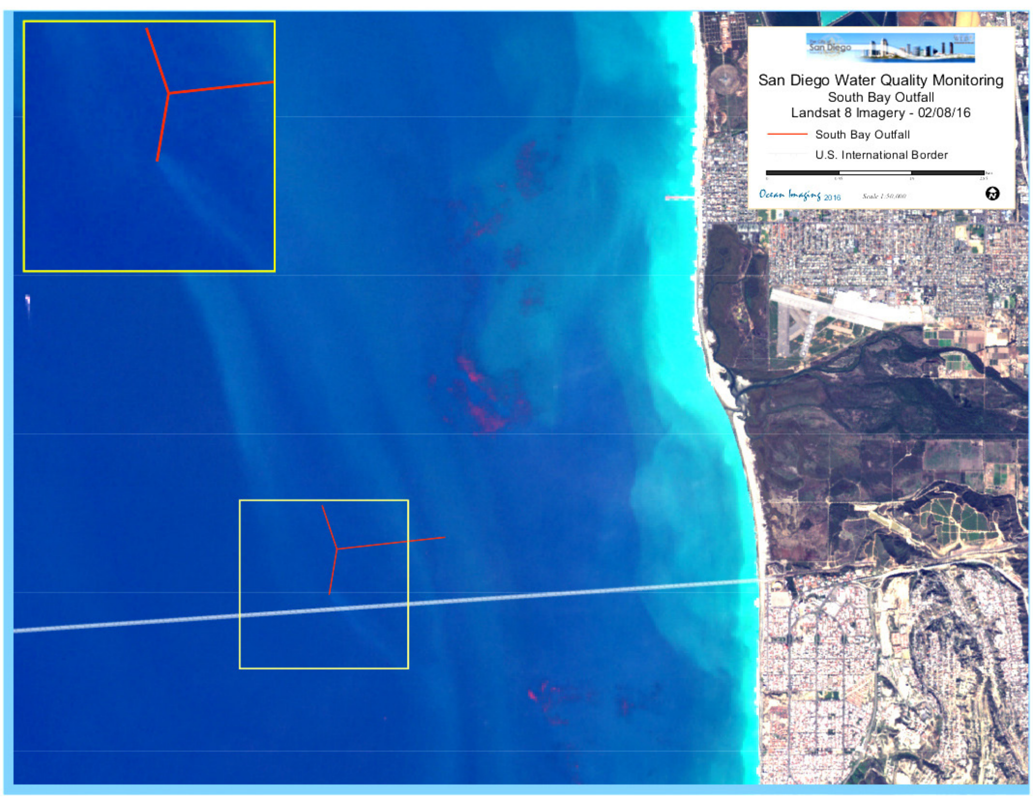
APPENDIX A – HIGH RESOLUTION SATELLITE IMAGERY SHOWING SBOO-RELATED WASTEWATER PLUME

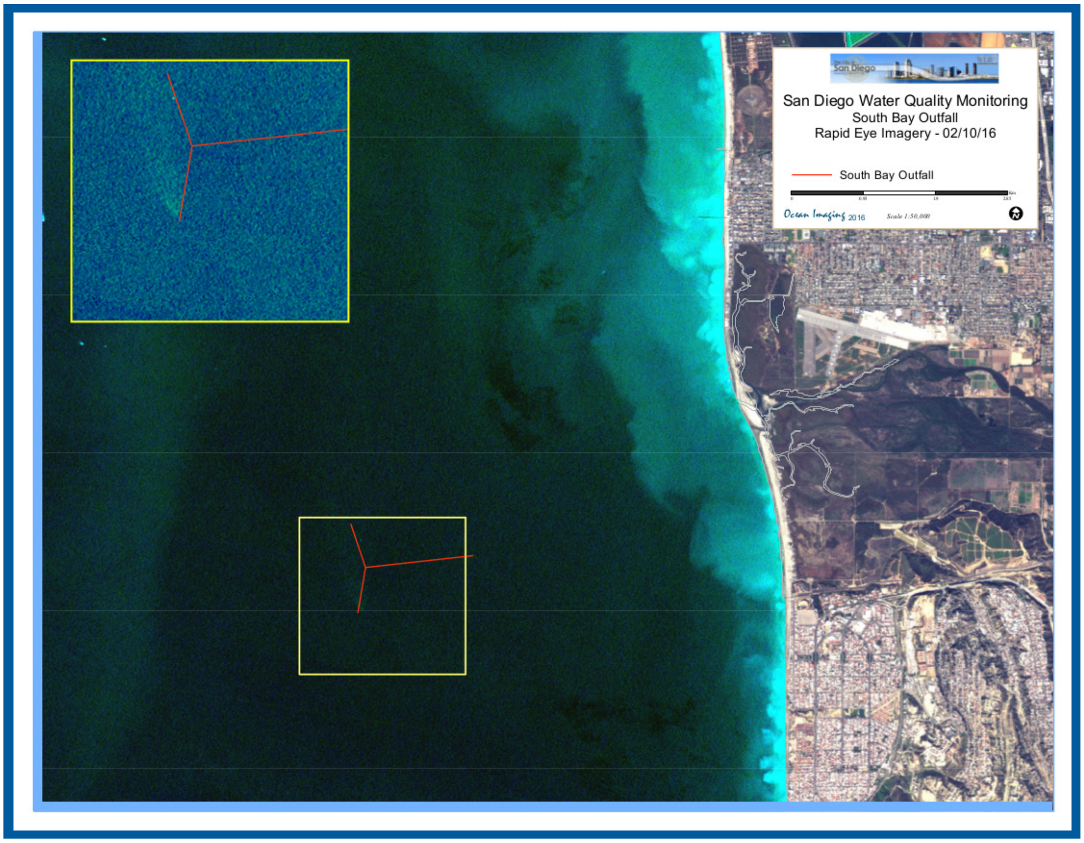



San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 01/24/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016
Scale 1:50,000


San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 01/27/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016
Scale 1:50,000


San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 02/03/16
South Bay Outfall
Ocean Imaging 2016
Scale 1:50,000


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery - 02/08/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016
Scale 1:50,000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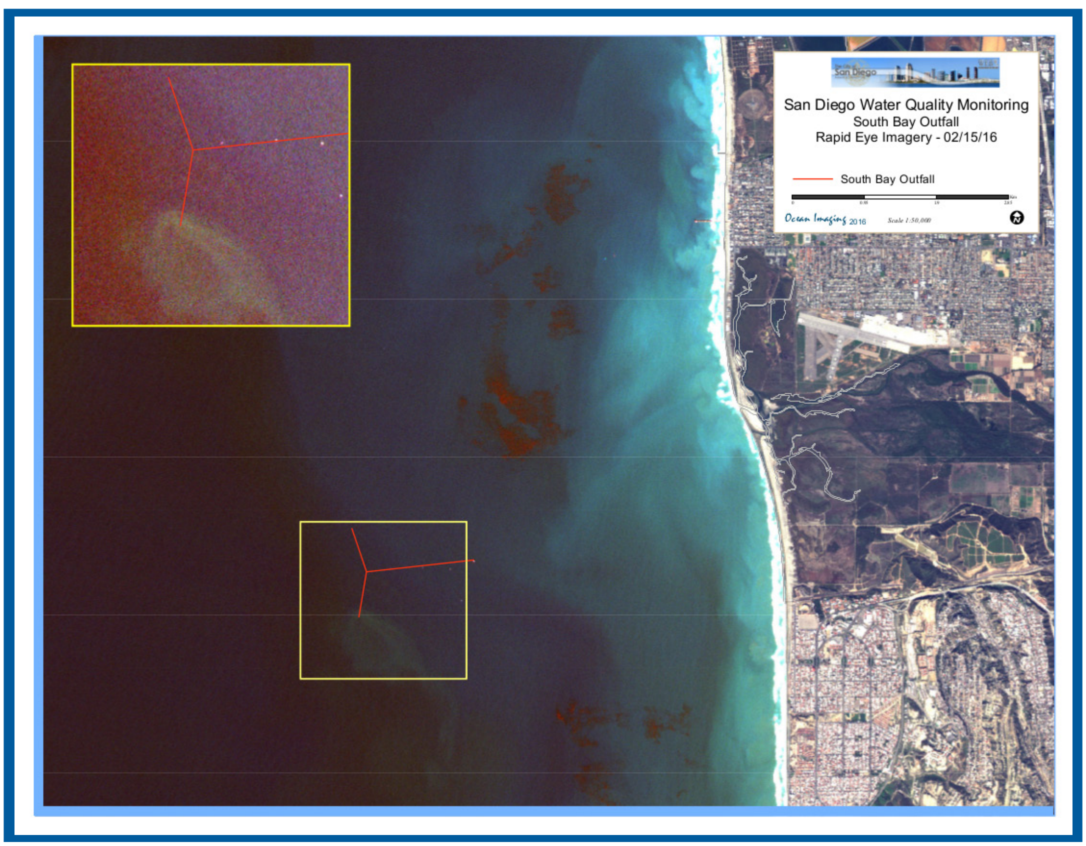
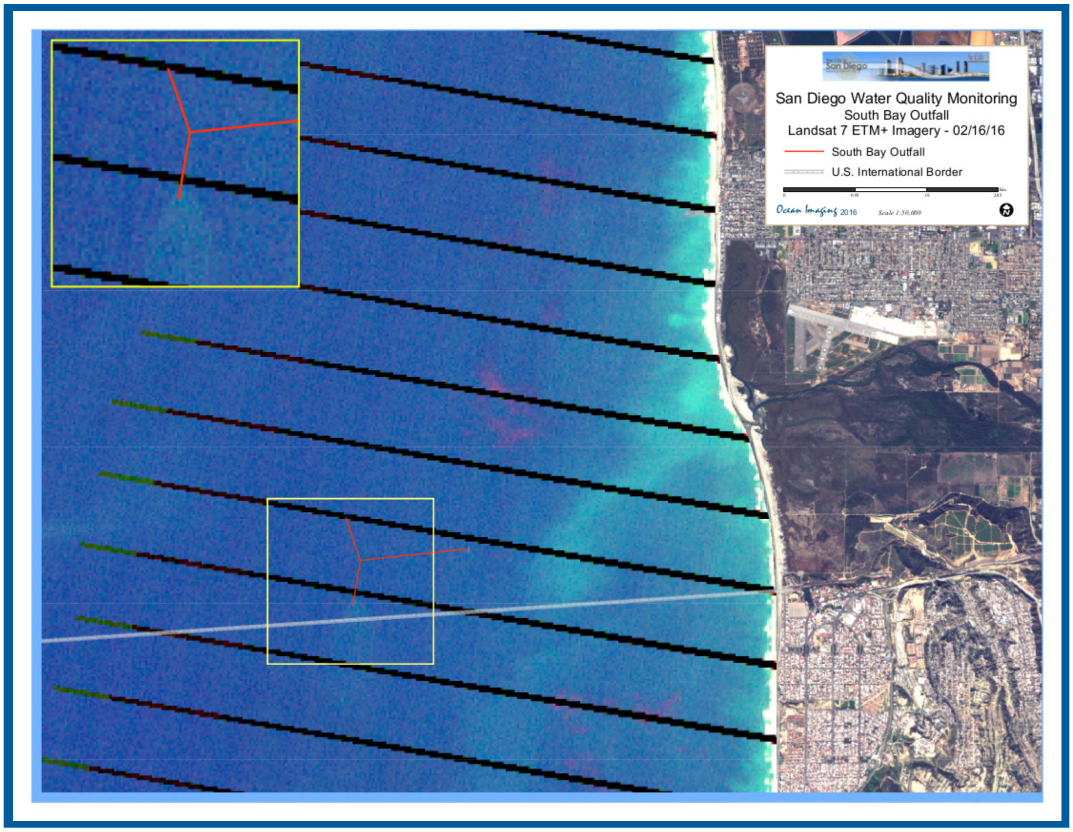
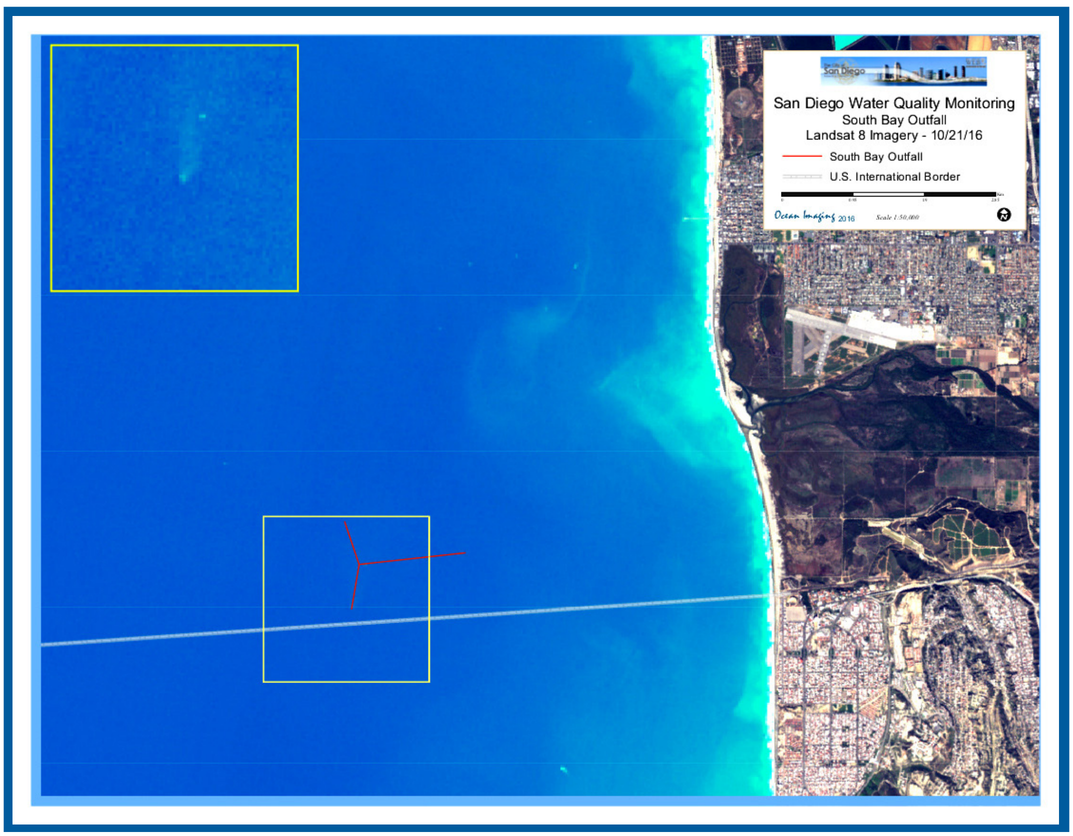
Rapid Eye Imagery - 02/10/16
South Bay Outfall
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 02/15/16
South Bay Outfall
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 7 ETM+ Imagery - 02/16/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016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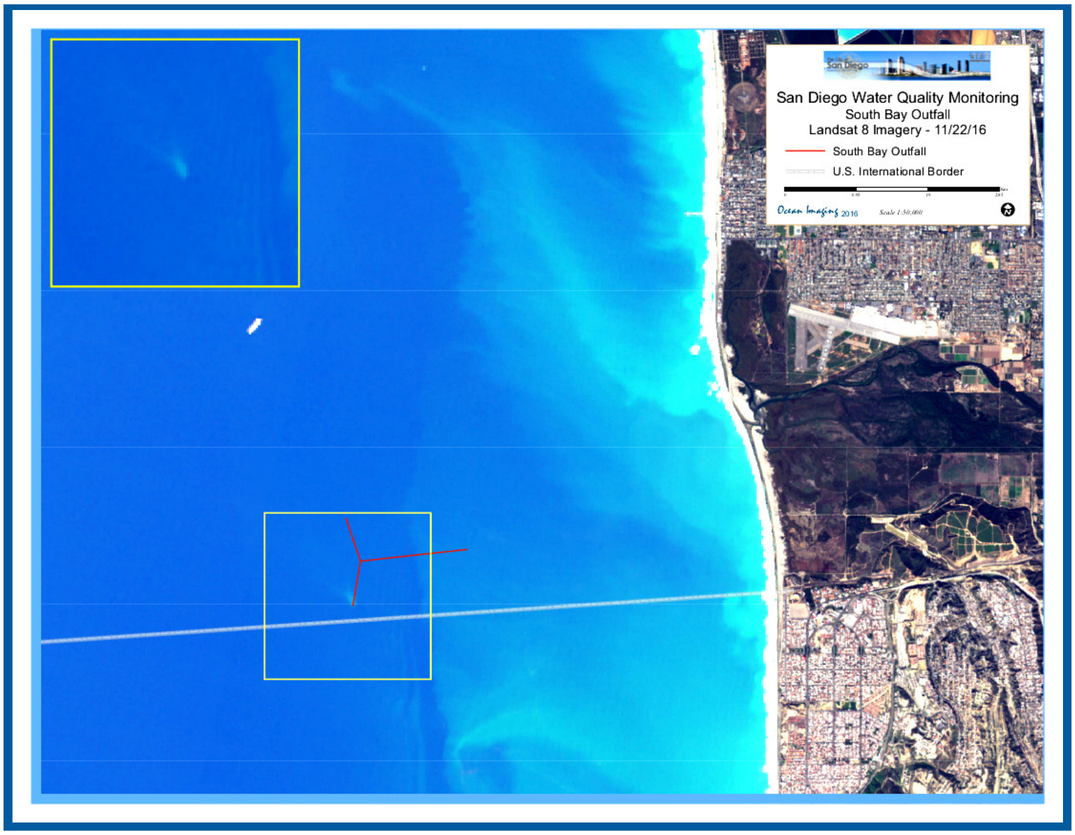
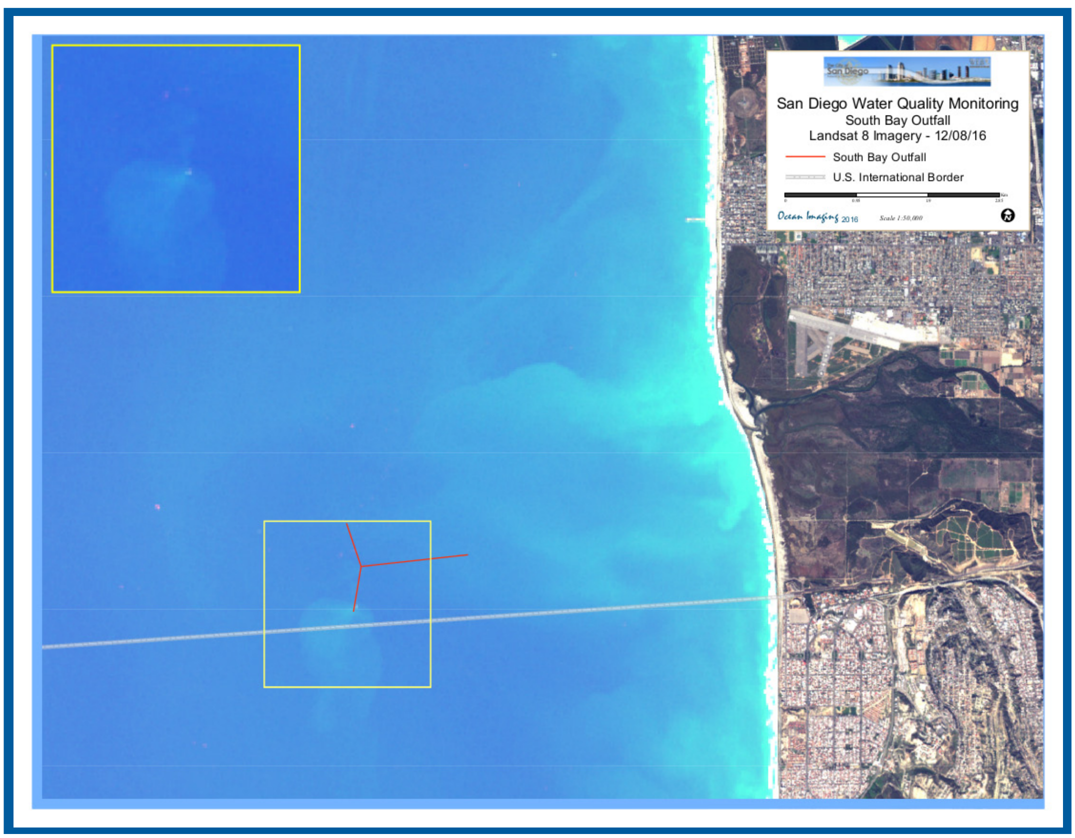
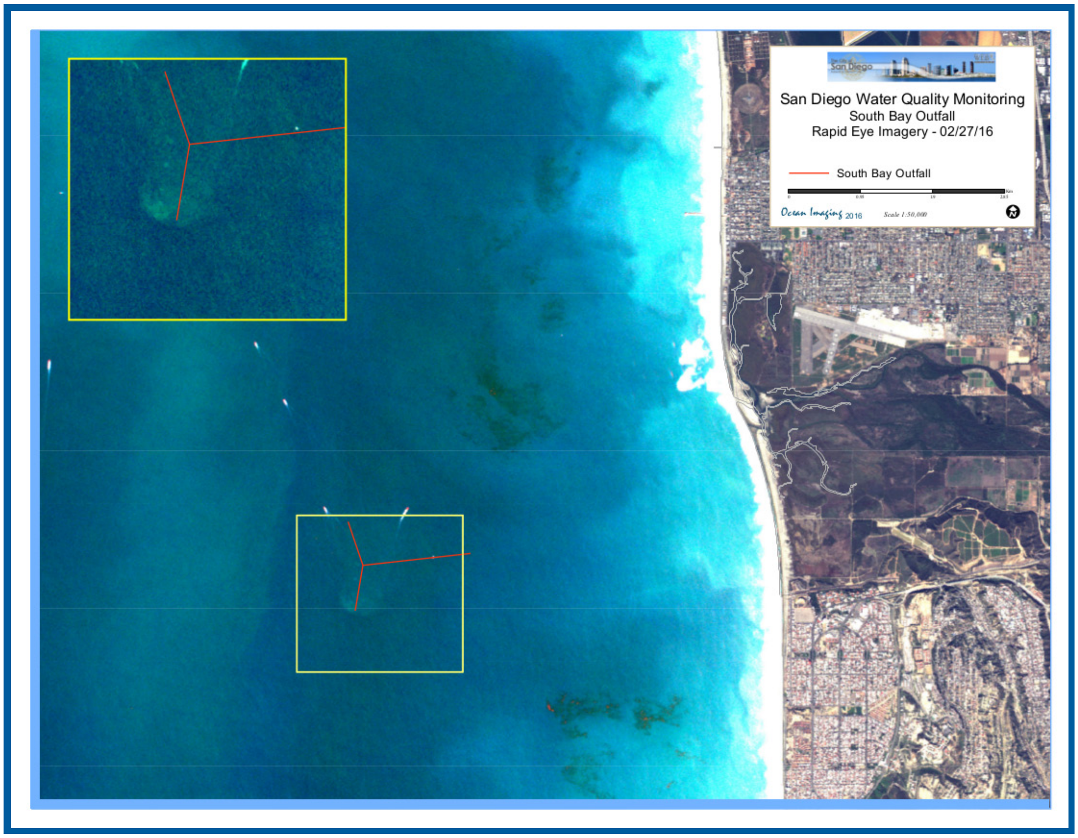
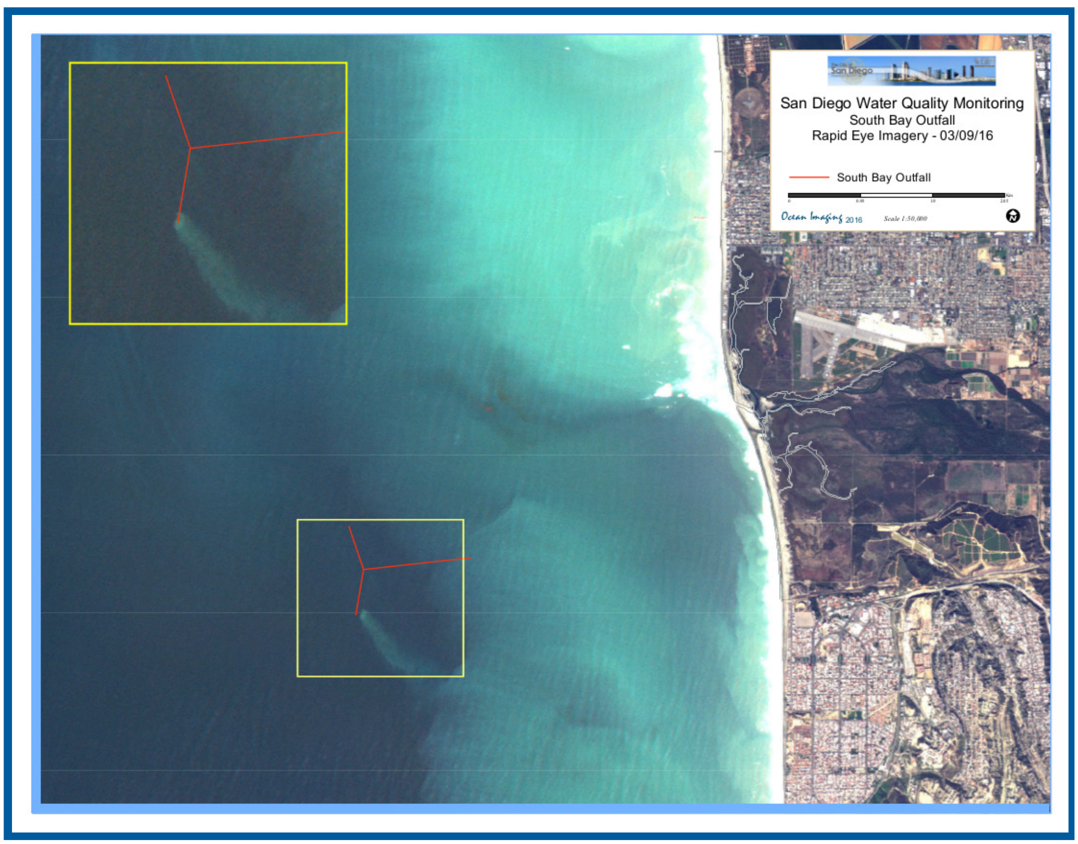
South Bay Outfall
Landsat 8 Imagery - 10/21/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery - 11/22/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery - 12/08/16
South Bay Outfall
U.S. International Border
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 02/27/16
South Bay Outfall
Ocean Imaging 2016


San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 03/09/16
South Bay Outfall
Ocean Imaging 2016