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

By Mark Hess

Annual Summary Report

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Ocean Imaging

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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 Landsat Thematic Mapper TM5, TM7 and Landsat 8 OLI/TIRS color and thermal imagery (each available approximately every 16 days). 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 intent was to delivery all of the remote-sensing and model-derived products to the City's end users by fall of 2017. This effort is discussed in more detail in latter sections of this report. The original add-on products ranged from atmospherically corrected satellite images of sea surface temperature (SST) 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). Also added as a full-time operational data set in 2017 was satellite imagery from the Sentinel satellites. These data are now included as regular image products in the high-resolution satellite data mix.

This report summarizes observations made during the period 1/1/2017–12/31/2017.

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.

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 are thus processed and posted within 1–2 days after acquisition and the aerial sensor imagery (which when used prior to 2010 required 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 ArcGIS Server Web Map Service (WMS)-directed products are produced daily by OI and are automatically linked with the server as soon as 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. It was planned that all of the OI-delivered data products, including all of the satellite imagery would be delivered via OI's ArcGIS Server for easy ingestion into the City's ArcGIS online WMS by fall of 2017. To date, the City's WMS is not fully functional and ready to ingest data from OI's server, however OI has put in place all of the delivery infrastructure to transition to this means of data and product delivery as soon as the City is ready. While the historical imagery, data and reports will remain accessible via the existing web portal, OI will migrate all 2016–2018 data products to OI's ArcGIS once the City is ready to ingest the data feed from OI's server. Following the completion of the migration of the 2016–2018 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 also began processing and posting imagery from the Sentinel-2A satellite. 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 ten days. In fact, the Sentinel data were the only higher resolution satellite images during the month of May which provided a view of the Point Loma Outfall (PLO) and South Bay Ocean Outfall (SBOO). A second satellite carrying the MSI sensor, the Sentinel-2B, was launched into orbit by the ESA and provided the first set of data from the MSI sensor as of March 17, 2017. Sentinel-2B data availability during 2017 was not as frequent as was expected, however as the year progressed and the United States Geological Survey (USGS) fully implemented operational delivery of these data, the frequency of 2B data increased. Twenty-one Sentinel images were posted to the OI-SDWQ web site during 2017 out of fifty-seven total high-resolution satellite images. In 2016 forty high resolution images were processed and posted as part of this project. In 2018, there have already been twenty Sentinel images covering the SDWQ AOI posted to the web portal. Appendix A includes the Sentinel imagery in which the SBOO plume was detected. In two cases on 12/17/17 and 12/27/17, Sentinel-2A data were acquired within only a few minutes of RapidEye and Landsat 8 data—both showing SBOO plume surface signatures (Figure 1). On close inspection of both the RapidEye and Sentinel imagery (Figure 1 and Appendix A) effluent can be seen emanating from both the northern-most and southern-most wye risers. These extra data sets provided validation of the RapidEye and Landsat data. The addition of the Sentinel imagery in 2017 increased the temporal frequency of high resolution satellite imagery to five to twelve images per month by the end of the year. Now with both of the satellites delivering data and the USGS data service fully operational, we expect the average number of high resolution satellite-derived datasets to increase to approximately six to ten images per month, depending on weather conditions and sun angle.

OI will also start processing and posting Chlorophyll and SST data from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor which is one of the key instruments onboard the Suomi National Polar-Orbiting Partnership (NPP) spacecraft. This sensor was launched in 2011, however VIIRS data have only become available on a daily basis over the past year or so. The value of the VIIRS Chlorophyll and SST data is in the more detailed 750-meter spatial resolution compared to the 1000-meter MODIS data. Figure 2 shows a MODIS-derived Chlorophyll image off of the Southern California coast side by side with a VIIRS-derived Chlorophyll image. These data will start posting to the OI_SDWQ web site beginning in the summer of 2018 and eventually be delivered via OI's ArcGIS server for the City's WMS.

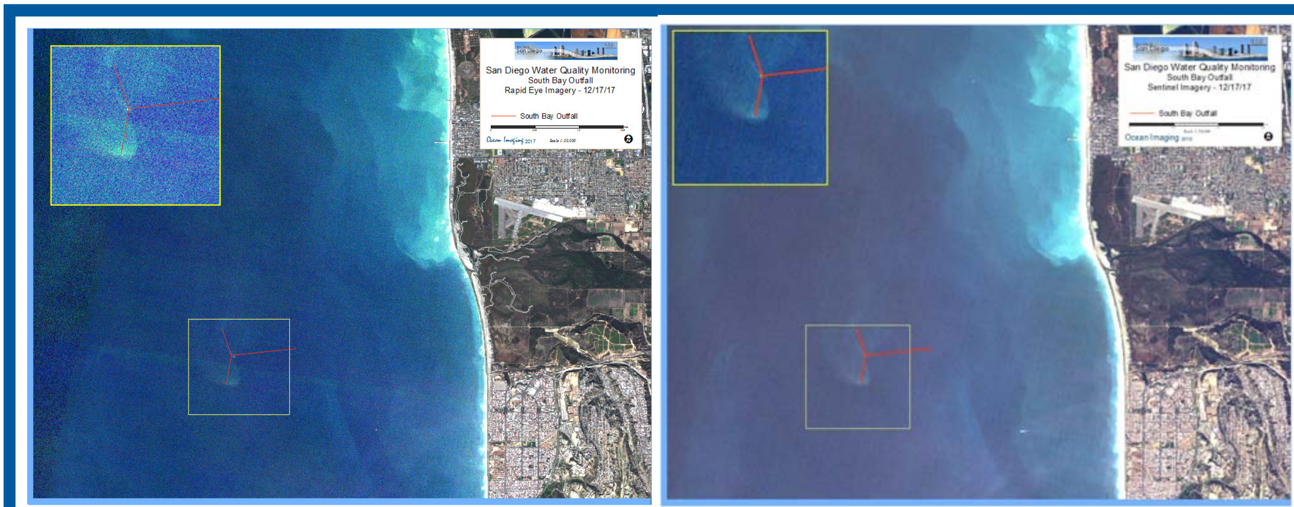


Figure 1: RapidEye imagery of the SBOO region acquired 12/17/17 at 18:39 GMT (10:39 AM PST) (right) and Sentinel-2A imagery acquired 12/17/17 at 18:33 GMT (10:33 AM GMT) (left). Note almost identical SBOO plume signatures in both datasets.

3. HIGHLIGHTS OF 2017 MONITORING

3.1 Atmospheric and Ocean Conditions

2017 showed a notable difference in precipitation, both in monthly and annual rainfall totals, but also in the seasonal pattern. According to the Lindberg stationin 2017, San Diego experienced a total of 5.63 inches of cumulative annual precipitation compared to 10.23 inches in 2016 and 9.89 inches in 2015 (Table 1). 2017 rainfall numbers were more comparable to 2012 and 2013. The Tijuana Estuary station reported a higher cumulative precipitation total in 2017 of 8.99 inches compared to 11.73 inches in 2016. As seen in Table 1, the monthly and annual precipitation amounts differ significantly at times between the two reporting stations with the Tijuana Estuary station recording lower precipitation totals than the Lindberg Field station for the years 2012–2015 and higher amounts for years 2016 and 2017. This equates to a 23% or 44% decrease in annual precipitation from 2016 to 2017 as recorded at Lindberg Field and the Tijuana Estuary respectively.

The most significant difference between 2017 and preceding years was the relatively heavy rainfall events in January and February, but then—except for an event on May 6th through 7th—virtually no precipitation in the region from March 1st through the end year. Typically, the rainy season begins in November and runs through March of the following year, however only 0.02 inches of rain were recorded at Lindberg Field during the Months of November and December 2017 (0.15 inches recorded at the Tijuana Estuary station). 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. The resulting point and non-point runoff

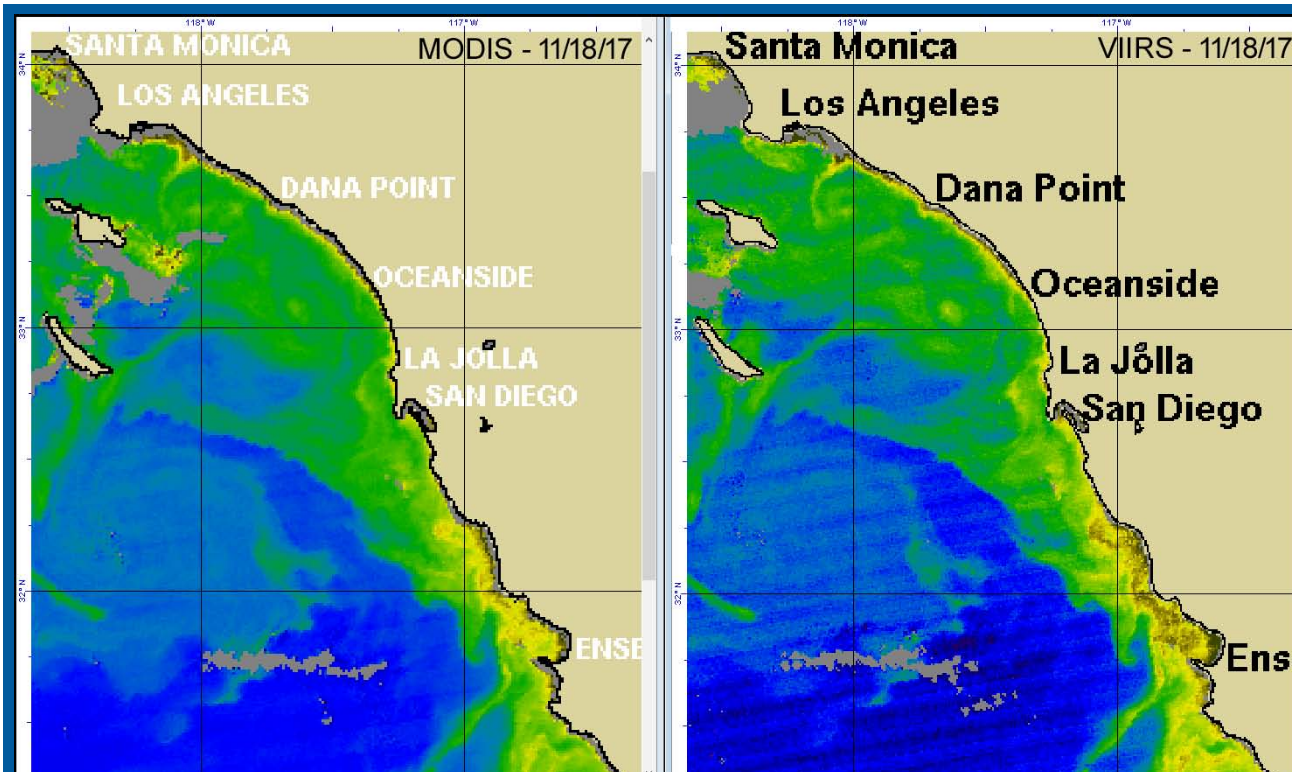


Figure 2. 1000-meter MODIS-derived Chlorophyll image showing a phytoplankton bloom off the Southern California coast region (left) compared to 750-meter VIIRS-derived Chlorophyll image of the same area (right).

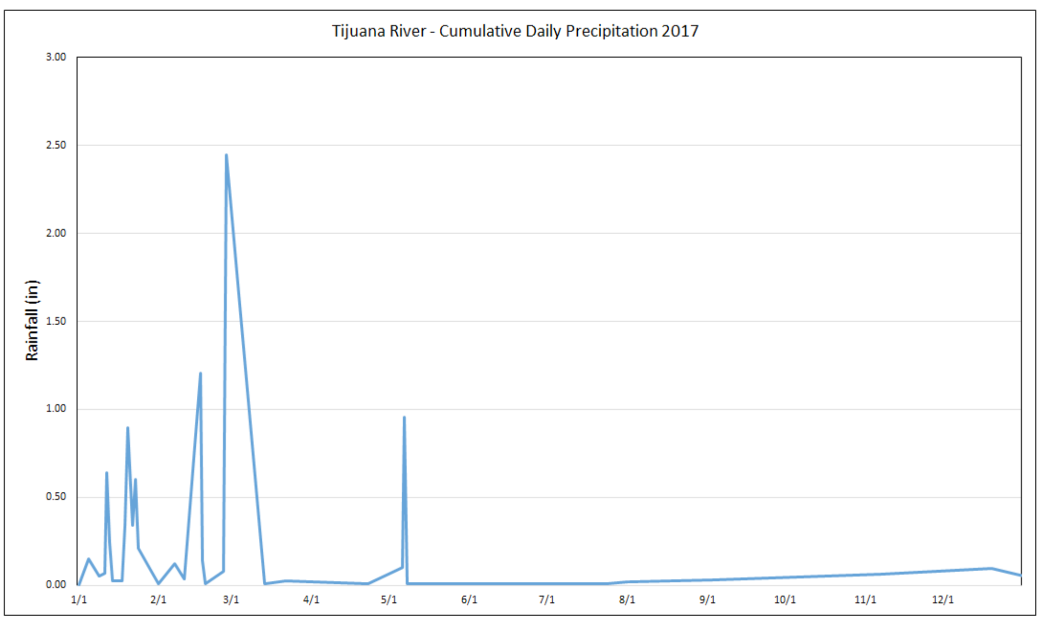
Lindberg Field Cumulative Monthly Precipitation in Inches						
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
January	0.40	0.70	0.01	0.42	3.21	2.99
February	1.19	0.63	1.00	0.28	0.05	1.58
March	0.97	1.22	1.28	0.93	0.76	0.08
April	0.88	0.01	0.54	0.02	0.55	0.01
May	0.02	0.26	0.00	2.39	0.44	0.87
June	0.00	0.00	0.00	0.04	0.00	0.02
July	0.00	0.05	0.00	1.71	0.00	0.00
August	0.00	0.00	0.08	0.01	0.00	0.00
September	0.00	0.00	0.00	1.24	0.32	0.06
October	0.70	0.25	0.00	0.43	0.07	0.00
November	0.28	1.48	0.37	1.54	0.61	0.02
December	2.19	0.46	4.50	0.88	4.22	0.00
Annual Total	**6.63**	**5.06**	**7.78**	**9.89**	**10.23**	**5.63**

Tijuana Estuary Cumulative Monthly Precipitation in Inches						
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
January	0.70	0.05	0.08	0.32	2.40	3.61
February	0.86	0.00	1.35	0.13	0.02	4.06
March	1.21	1.43	0.55	1.01	1.28	0.04
April	0.82	0.11	0.35	0.07	1.91	0.01
May	0.00	0.36	0.00	1.13	0.97	1.07
June	0.00	0.00	0.12	0.00	0.00	0.00
July	0.00	0.01	0.33	0.39	0.00	0.01
August	0.00	0.00	0.04	0.00	0.00	0.02
September	0.02	0.01	0.00	0.48	0.49	0.03
October	0.50	0.41	0.00	0.21	0.00	0.00
November	0.00	0.25	0.29	0.61	0.34	0.06
December	0.04	0.50	3.09	0.61	4.32	0.09
Annual Total	**4.15**	**3.13**	**6.20**	**4.94**	**11.73**	**8.99**

Table 1: 2017 Monthly and annual rainfall totals as recored by the Lindberg Field and Tijuana Estuary stations.

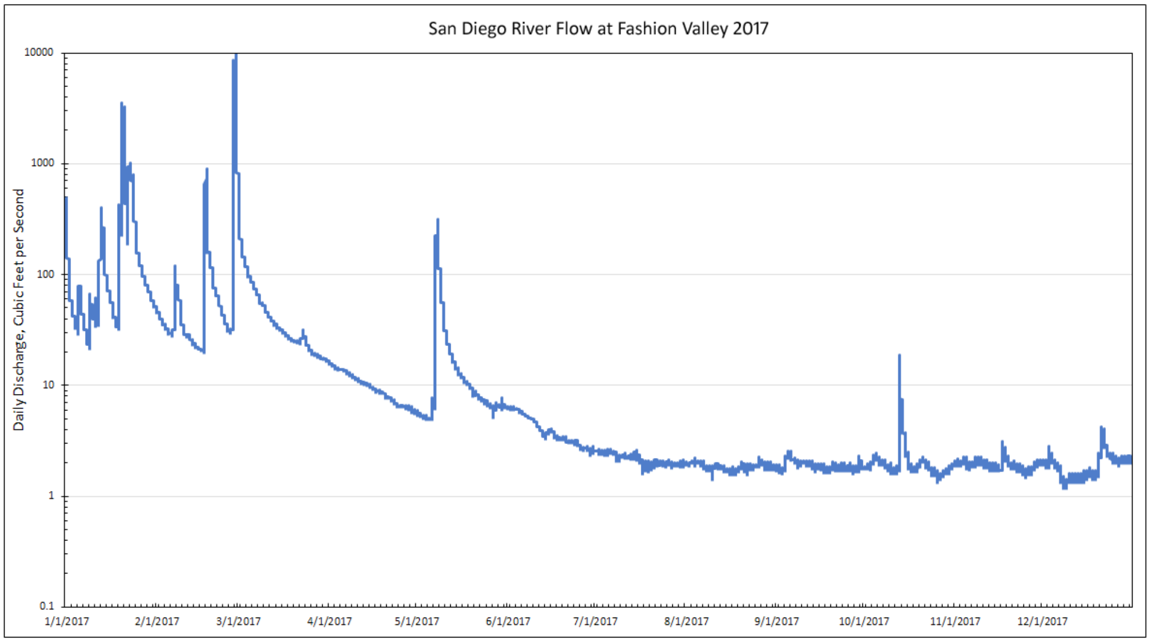
affected coastal water quality in some areas, especially during the months of January and February (Figures 11–13). As a general rule of thumb, precipitation resulting in 0.1" or less tends to be blocked by the SBOO-linked diverter above the estuary and does not cause significant runoff to reach the ocean. As can be seen from Figure 3, rain events totaling considerably higher daily totals occurred during of January and February as well as one event occurring between 05/06/17–05/07/17. Aside from the storm in early May, all of these events caused significant Tijuana River effluent to be discharged into the ocean. Only the rainfall between 01/11/17–01/13/17 and 01/19/2017–01/24/17 generated effluent which were directly relatable to wastewater plumes over the SBOO being visible in the satellite imagery. The SBOO plume was visible in Landsat TM7 imagery on 01/17/17, Landsat 8 imagery on 01/25/17 and RapidEye Imagery on 01/27/17 (See Appendix A). Plumes over the SBOO were not visible in the satellite imagery following the very large rain event which took place on 02/27/17 nor after the 05/07/17 rainfall. Additional discussion follows on these events and the corresponding plume detections in the satellite imagery.

Similar patterns can be seen in Figure 4 which shows monthly precipitation totals at Lindbergh Field and San Diego River discharge rate at the Fashion Valley gauging station. The 2017 river flow rates were quite dissimilar to previous years in that the river maintained a



Date	CumPrcp (in)
1/1	0.00
1/5	0.15
1/9	0.06
1/11	0.07
1/12	0.64
1/13	0.24
1/14	0.02
1/17	0.00
1/18	0.02
1/19	0.34
1/20	0.90
1/22	0.34
1/23	0.60
1/24	0.21
1/25	0.00
1/27	0.00
2/1	0.01
2/7	0.12
2/11	0.04
2/17	1.20
2/18	0.14
2/19	0.01
2/26	0.08
2/27	2.45
3/14	0.01
3/22	0.02
4/23	0.01
5/6	0.10
5/7	0.96
5/8	0.01
7/24	0.01
8/1	0.02
9/3	0.03
11/7	0.06
12/2	0.00
12/17	0.00
12/20	0.09
12/27	0.00

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



Lindbergh Field Rainfall 2017	
Jan	2.99"
Feb	1.58"
Mar	0.08"
Apr	0.01"
May	0.87"
Jun	0.02"
Jul	0.00"
Aug	0.00"
Sep	0.06"
Oct	0.00"
Nov	0.02"
Dec	0.00"

Figure 4. Mean daily flow of the San Diego River during 2017 (measured at Fashion Valley). Table on the right shows monthly rainfall totals at Lindbergh Field.

discharge rate above 10 cubic feet per second from the beginning of the year all the way through the middle of April. One day after the 02/27/17 heavy rain event, the discharge rate peaked at 9,810 cubic feet per second–a flow rate which has not been experienced in several years. However, after the spike in flow on 05/07/17, except for a small increase on 10/14/17, the river discharge dropped to just over one cubic foot per second for the remainder of the year. Due to lack of rainfall during what would normally be the fall–winter rain season, there was almost no increase in discharge during the months of October through December when we would expect to see seasonal spikes. The 2017 flow spikes correspond well with the rainfall data from both the Tijuana River and Lindbergh Field reporting stations.

The result of the 2017 January and February rain events was that the shoreline near the Tijuana River mouth experienced frequent closures due to contamination during the early part of the year. Border Field State Park was closed north of the border fence from 01/01/17 to 06/07/17. From the 2016–2017 winter months through June of 2017, the Border Field State Park shoreline was closed as long as 197 days. Farther up the coast, rainfall events during the months of January and February can be indirectly correlated with shoreline closures and advisories from Border Field State Park up to Silver Strand State Beach as well as Spanish Landing Park in San Diego Bay. The area of Seacoast drive along Imperial beach was closed on an off between late 2016 through March of 2017. RapidEye imagery from 01/04/17 shows significant TJR runoff extending up to the northwest most likely contributing to the conditions necessitating the closure. Beaches as far north as Coronado were also frequently closed between late January and early March likely due in part to the intense rain events, heavy TJR runoff and high coastal turbidity. Even satellite images between the 01/24/17, 02/17/17 and 02/26/17 rain events show persistent TJR runoff and coastal turbidity—an example being the Sentinel image from 02/13/17 (Figure 5). There were no beach closures between May and early November, however Border Field State Park did close between 11/08/17

Figure 5: Sentinel satellite imagery from 02/13/17 showing TJR runoff plume and shoreline turbidity extending up to Silver Strand State Beach.

to 11/17/17 and Imperial Beach closed from 11/10/17 to 11/12/17. There was a minor rain event (0.06 inches reported by the Tijuana Estuary station) on 11/07/17 and RapidEye Imagery from 11/11/17 does show increase TJR runoff and shoreline turbidity in that area (Figure 6).

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 several occasions from January to March in 2017, 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, as in 2016, only a few in January and February can possibly be attributed to rainfall and/or high river flow rate events. Twelve noteworthy plankton blooms which were visible in the MODIS satellite imagery occurring between La Jolla and the U.S. Mexico border and are listed in Table 2. Four 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. The blooms in January and February as well as the high Chlorophyll levels at the end of April encompassed the entire California Bight. Figures 7A and 7B show example plankton blooms covering the entire Bight region during the periods of 01/25/17–02/01/17 and 02/28/17–03/08/17 visible in the MODIS-derived Chlorophyll imagery—mostly fueled by region-wide rainfall occurring just prior to these occurrences. Figure 8 shows a times series in July of phytoplankton blooms developing into gyres and moving north from La Jolla and the Tijuana River coastal region. Figure 9 shows a likely plankton bloom streaming down from the La Jolla region seen in the MODIS visible imagery from 04/20/17 which is possibly related to the closure of the Vista de la Playa region between 04/20/17 to 04/23/17.

Date Range of Plankton Bloom Visible in MODIS Imagery	*Closest Significant Rainfall Event*	*Closest San Diego River Discharge Rate Above 10 cu. ft. /sec.*
01/14/17	*01/11/17–01/14/17, total = 0.97 inches*	*01/11/17–01/14/17*
01/25/17–02/01/17	*01/19/17–01/24/17, total = 2.39 inches*	*01/19/17–01/24/17*
02/12/17	*02/07/17–02/11/17, total = 0.16 inches*	*02/07/17–02/11/17*
02/28/17–03/08/17	*02/26/16–02/27/17, total = 2.53 inches*	*02/26/16–02/27/17*
04/02/17–04/08/17	*none within same time period*	*04/02/17–04/08/17*
04/11/17–04/21/17	*none within same time period*	*04/11/17–04/15/17*
04/26/17–05/01/17	*none within same time period*	*none within same time period*
05/20/17	*none within same time period*	*none within same time period*
05/27/17	*none within same time period*	*none within same time period*
07/02/17–07/18/17	*none within same time period*	*none within same time period*
11/14/17–11/18/17	*none within same time period*	*none within same time period*
12/12/17	*none within same time period*	*none within same time period*

Table 2. Periods of plankton blooms off of 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.

Figure 6: RapidEye image from 11/11/17 exhibiting a relatively strong TJR runoff plume extending up to Imperial Beach.

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. This held true in 2017 as there were no observations of the plume reaching the surface between February and November.

The SBOO treatment plant switched from advanced primary to secondary treatment in January, 2011. This

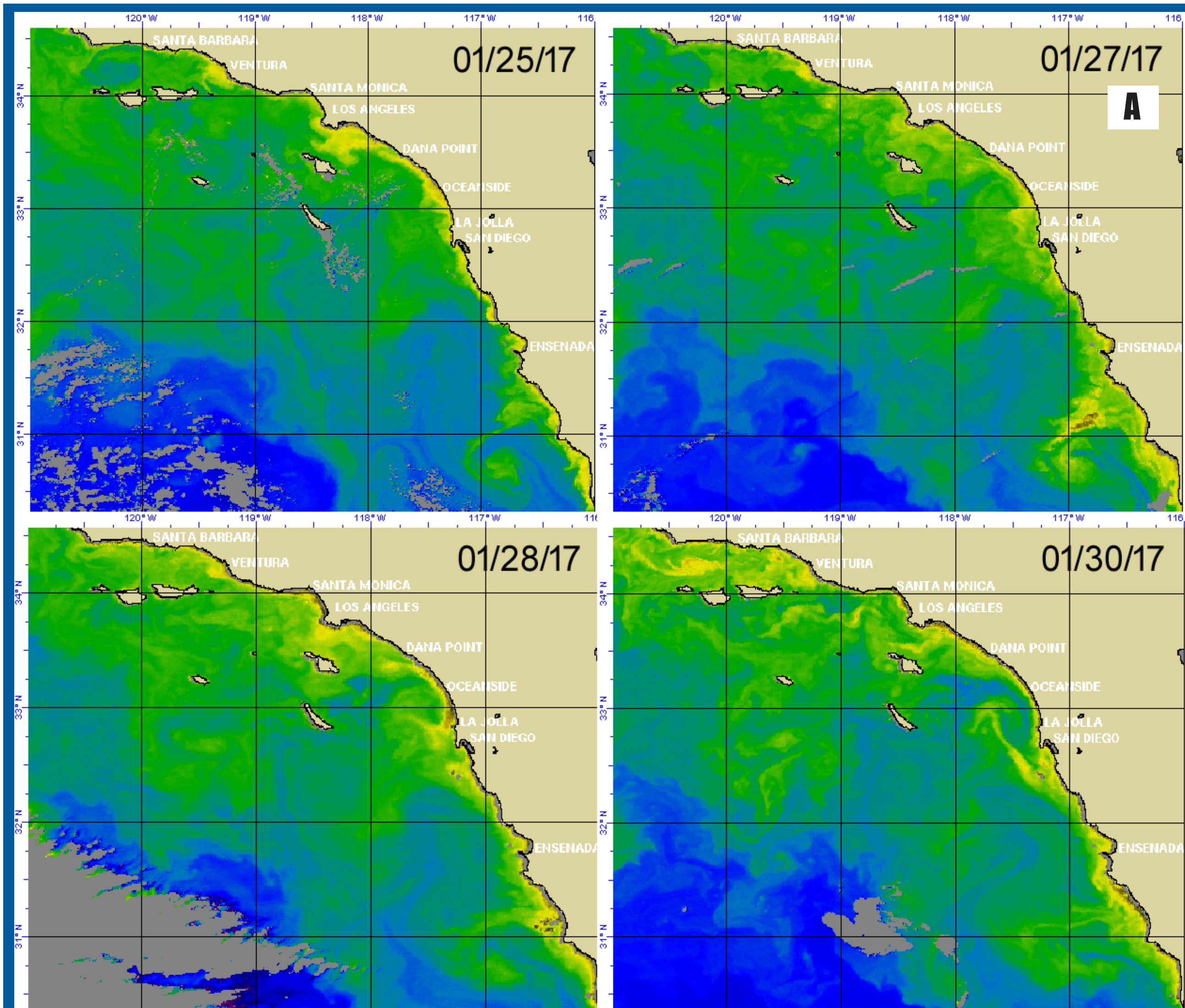
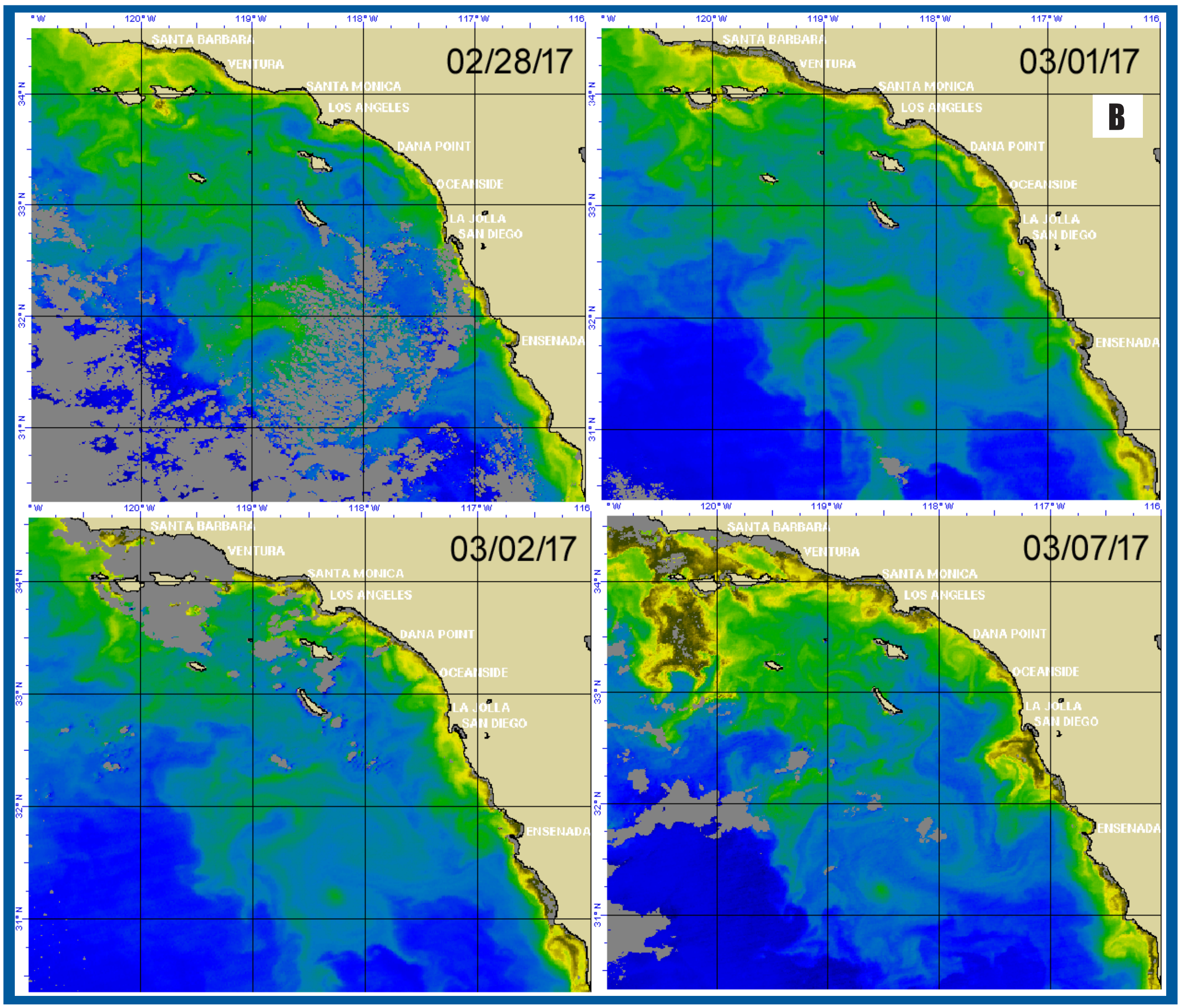


Figure 7A and 7B: Chlorophyll imagery derived from the MODIS sensor on the NASA Aqua satellite showing strong phytoplankton blooms off the coast of San Diego County as well as the entire Southern California Bight during the periods of 01/25/17–01/30/17 (A: above) and 02/28/17–03/07/17 (B: below).

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 multi-spectral 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.

As opposed to 2016 when the SBOO plume was observed a total thirteen times out of forty high resolution satellite scenes, there were only eight instances in 2017 during which the plume was observed in the fifty-seven acquired high resolution datasets. Of those eight observations, two were on the same dates (12/17/17 and 12/27/17), but from different satellites/sensors Sentinel, Landsat and RapidEye. In the case of the 01/25/17 Landsat 8 and the 01/27/17 RapidEye imagery the SBOO plume shows up as clearer than the surrounding water due to the condition of the sediment plume from the Tijuana River (TJR) extending unusually far offshore over the SBOO. The CTD readings taken on 01/25/17 by the City showed unusually low transmissivity, temperature and salinity. The clear effluent signal in the imagery was mostly like due to the extreme contrast between the high turbidity TJR plume surface waters and the 'normal' level of turbidity of the effluent water breaking the surface. It is also possible that the effluent water became somewhat diluted on its way to the surface if weak vertical stratification did exist, thus slowing down its rise in the water column. The observation of the SBOO plume on 01/25/17 was the only instance during which the plume was visible in both the visible and thermal infrared imagery. The low temperature of the TJR runoff water is also contrasted with the warmer temperature of the SBOO effluent plume as seen in Figure 10. It should be noted that in most of the other cases when a plume signature was observed in the multispectral imagery, it was in the RapidEye or Sentinel data which do not have Thermal Infrared (TIR) channels.

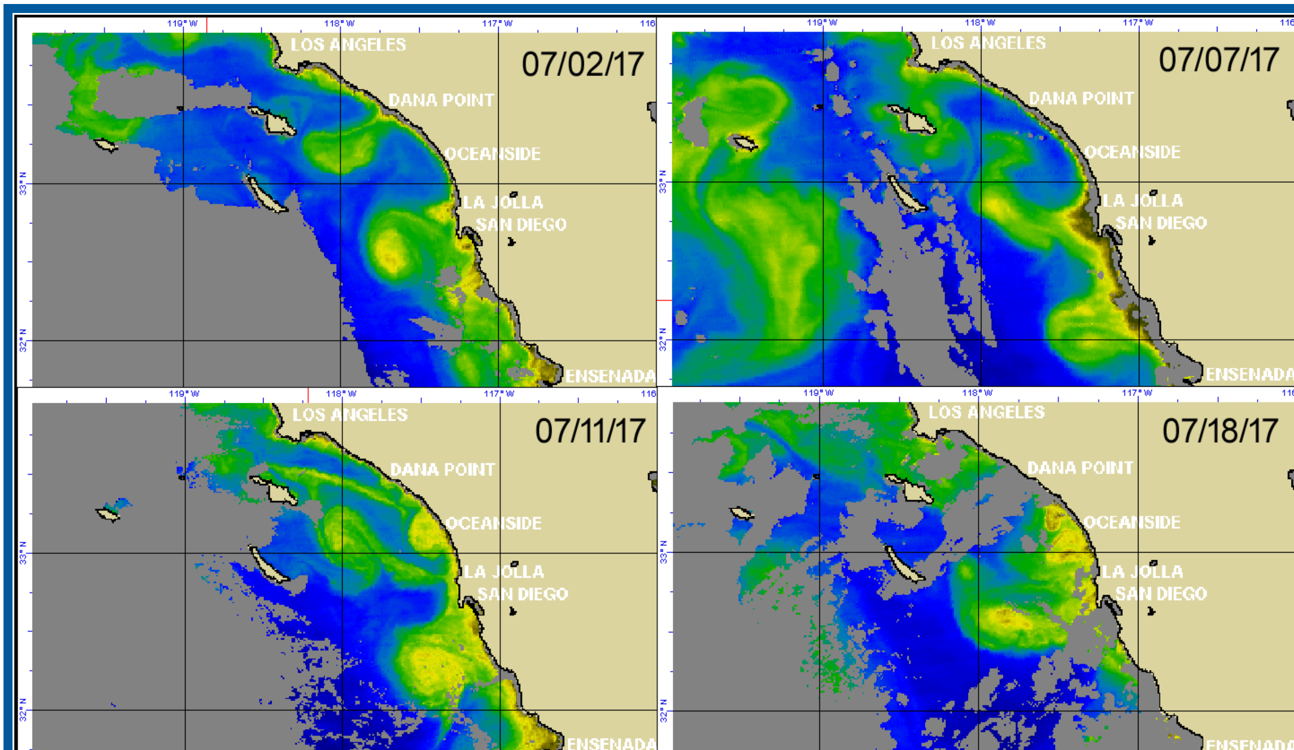


Figure 8: Chlorophyll imagery derived from the MODIS sensor on the NASA Aqua satellite showing strong phytoplankton blooms off the coast of San Diego during the period of 07/02/17 through 07/18/17.

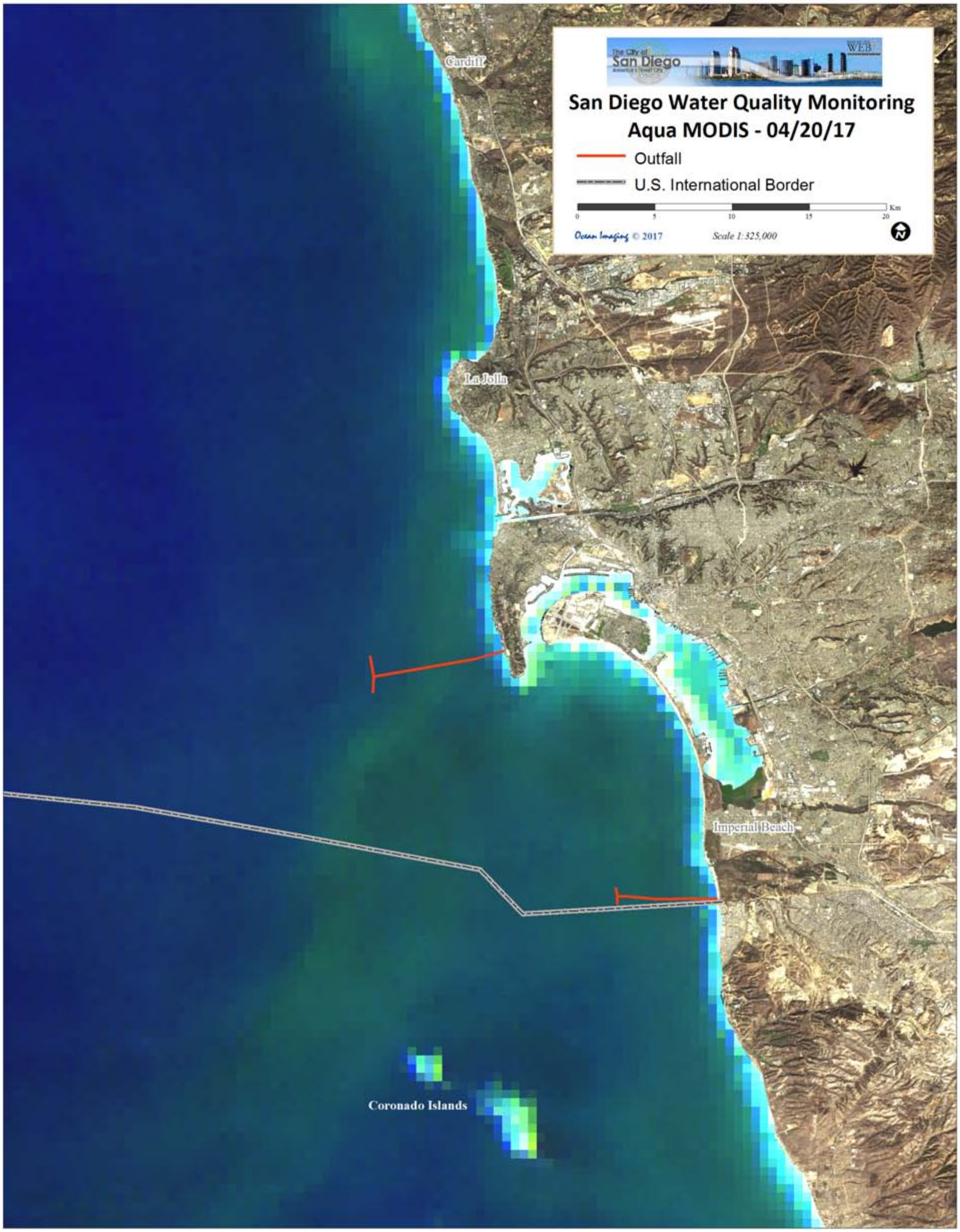


Figure 9: MODIS visible image from 04/20/17 showing a plankton bloom streaming down from the Ja Jolla-Mission Bay region.

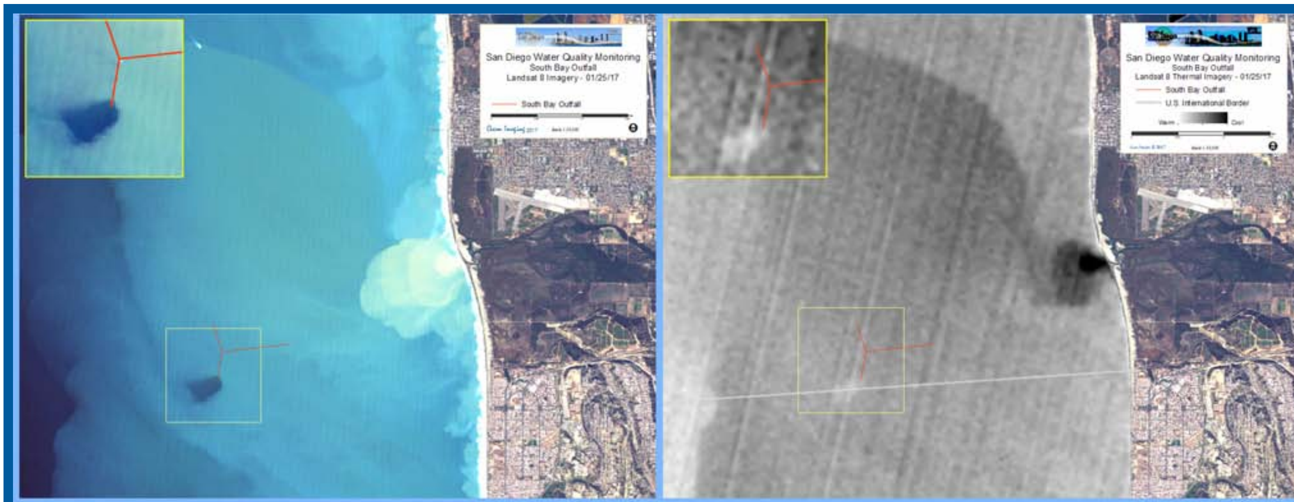


Figure 10: Landsat 8 imagery from 01/25/17 showing a plume emanating from the SBOO. The plume is visible both in the RGB composite version of the multispectral data as well as in the TIR imagery. Cooler water appears darker in the TIR scene.

The January and December plume observations most likely point to a lack of strong vertical stratification during the winter months of 2017 with the seasonal reformation of vertical stratification beginning around mid-February. This idea is reinforced seeing that the plume was not visible in the late February to early March satellite imagery even after the very heavy rainfall event of 02/27/17, indicating that any turbid outfall water was kept at depth by stratification. Relatively heavy discharge continued to flow from the TJR through the end of March with no SBOO plume visible in any of the satellite imagery.

The shoreline area of the Tijuana River outflow experienced sixty-four days on which the field sampling showed elevated bacteria levels (either enterococcus, fecal coliforms and/or total coliforms >= 500 CFU/100ml). The offshore SBOO region including the area encompassing the Imperial Beach kelp beds (or where the bed would normally be) and the area above the outfall experienced a total of twenty-three days for which the sampling showed elevated bacteria levels. Figure 11 shows an example of a large, SBOO plume observed on 01/25/17 in RapidEye imagery with the bacteria sampling results from the same day overlaid. Samples from the stations over the SBOO were not available within a reasonable timeframe from the satellite data. Very high bacteria counts are apparent within the TJR outflow plume which is a result of the heavy rainfall which took place from 01/19/17–01/24/17. The SBOO plume is shown to be flowing to the southwest which matches the direction of the TJR outflow. High bacteria levels correlate well with the inshore “Fresh Core” (FC) and “Old Core” (OC) components of the TJR runoff plume (as defined in the 2015 Five Year Summary Report) and appear to decrease as the plume moves offshore and transitions into what is defined as “Old Plume” (OP) water. This is further substantiated a few days later in the 01/27/17 RapidEye data and 01/29/17 field sampling data when the samples show higher bacteria levels closer to the FC and to the south, while lower levels are seen offshore and to the north (Figure 12). Note that the SBOO plume shows a strong southward movement. Sentinel and RapidEye imagery from 03/02/17 and 03/03/17 respectively also show positive correlations between the TJR runoff turbidity plume caused by the rains on 02/27/17 and the bacteria samples—with high bacteria levels existing even five days after the rain event. In this case there was no indication in the satellite imagery of a SBOO effluent plume at the ocean’s surface (Figure 13).

Following the plume observations in January of 2017, the next, very small, barely detectable, SBOO plume was noticeable in the 12/02/17 RapidEye scene. This occurrence was somewhat later than has been the case in recent years. The next visible waste water turbidity plume was evident in both the 12/17/17 RapidEye and Sentinel-2A imagery showing northward movement of the SBOO plume extending from the southern wye as well as the turbidity patterns along the coast. These plume signatures appeared as more turbid than the surrounding water in contrast to the plumes observed in the end of January when the TJR runoff water extended out past the extent of the SBOO. 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. The last plume detection of 2017 was on 12/27, again the plume being barely detectable in the imagery. None of these occurrences can be directly associated with a rainfall event.

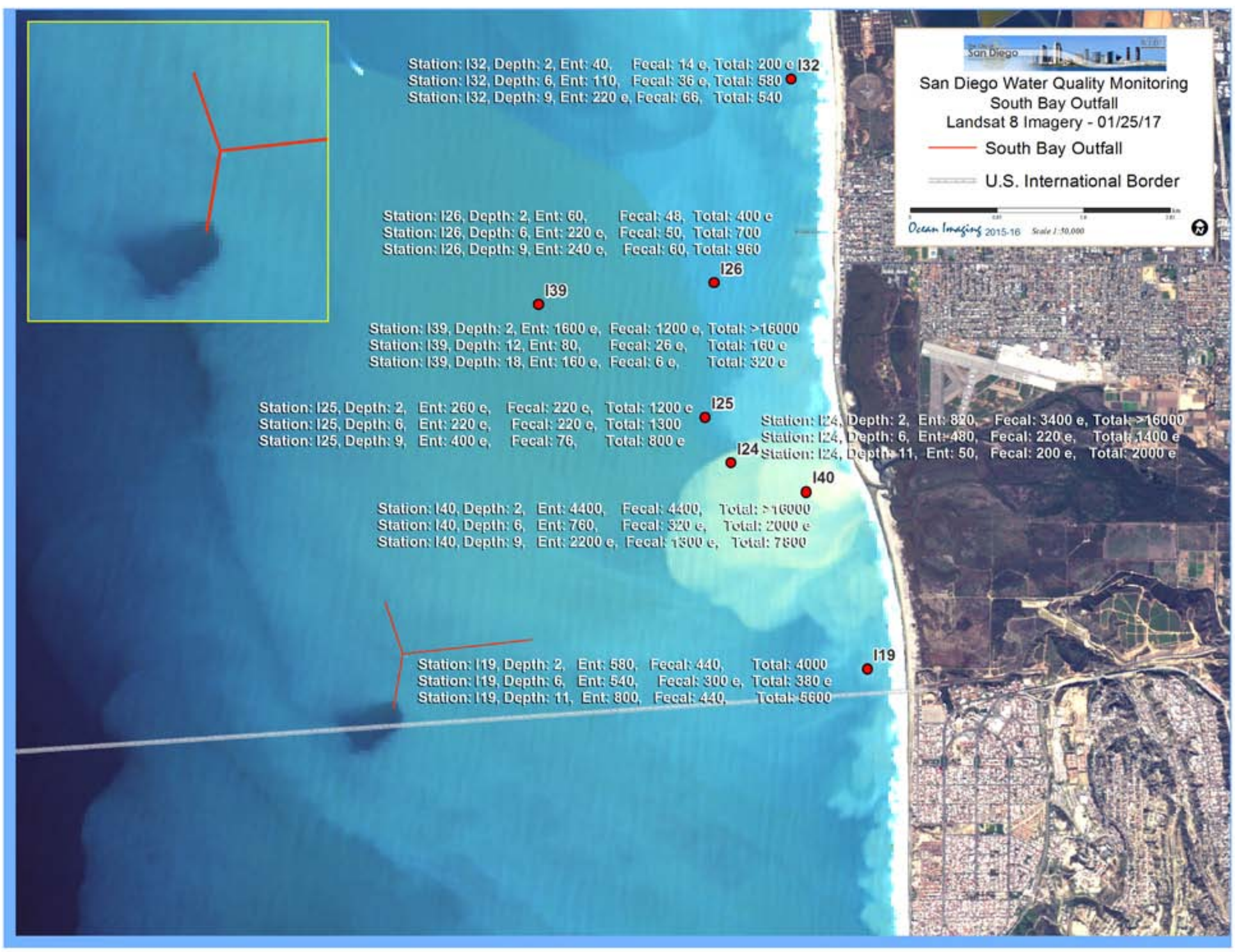


Figure 11. RapidEye image of the SBOO region acquired on 01/25/17 and near-surface bacterial sampling results collected on the same day. Elevated bacteria values are evident within the core of the TJR runoff plume.

Figure 12: RapidEye image of the SBOO region acquired on 01/27/17 and near-surface coastal bacterial sampling results collected on 01/29/17. Elevated values at stations I24, I25, I40, S5 and S10 are seen in the Fresh Core (FC) and Old Core (OC) of the TJR runoff.

The best water quality and clarity in the South Bay region in 2017 was observed from May through the summer up through late September. Thirteen instances of above normal bacteria levels were recorded at the shoreline stations while only one was recorded at the offshore sampling stations during this almost five-month period. The only rain event of significance during this time occurred on 05/07/17with 0.96" recorded at the Tijuana Estuary after 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 09/06/17 shows low turbidity along the shoreline with a pattern indicative very little surface flow. The bacteria sampling data from 09/05/17 overlaid on top of the 09/06/17 Landsat 8 image corroborates this low activity period (Figure 14).

Throughout 2017 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

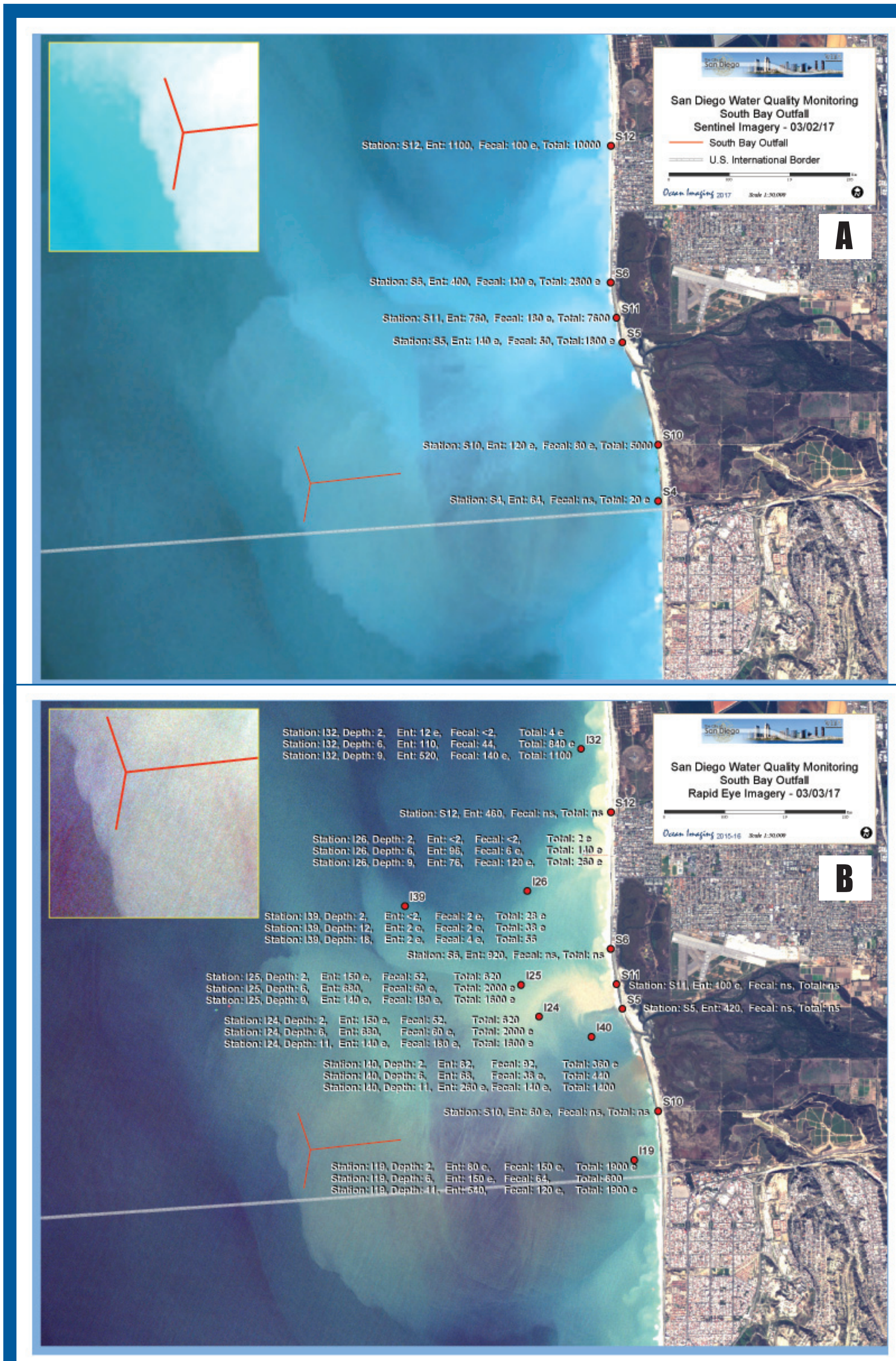


Figure 13. Sentinel image of the SBOO region acquired on 03/02/17 (A–top) and RapidEye image acquired on 03/03/17 (B–bottom) along with overlaid near-surface coastal bacterial sampling results collected on the same days. These data are from four–five days after a heavy rain event and high bacteria values still existed in the TJR runoff plume. However, no effluent plume is visible above the SBOO in either satellite image.

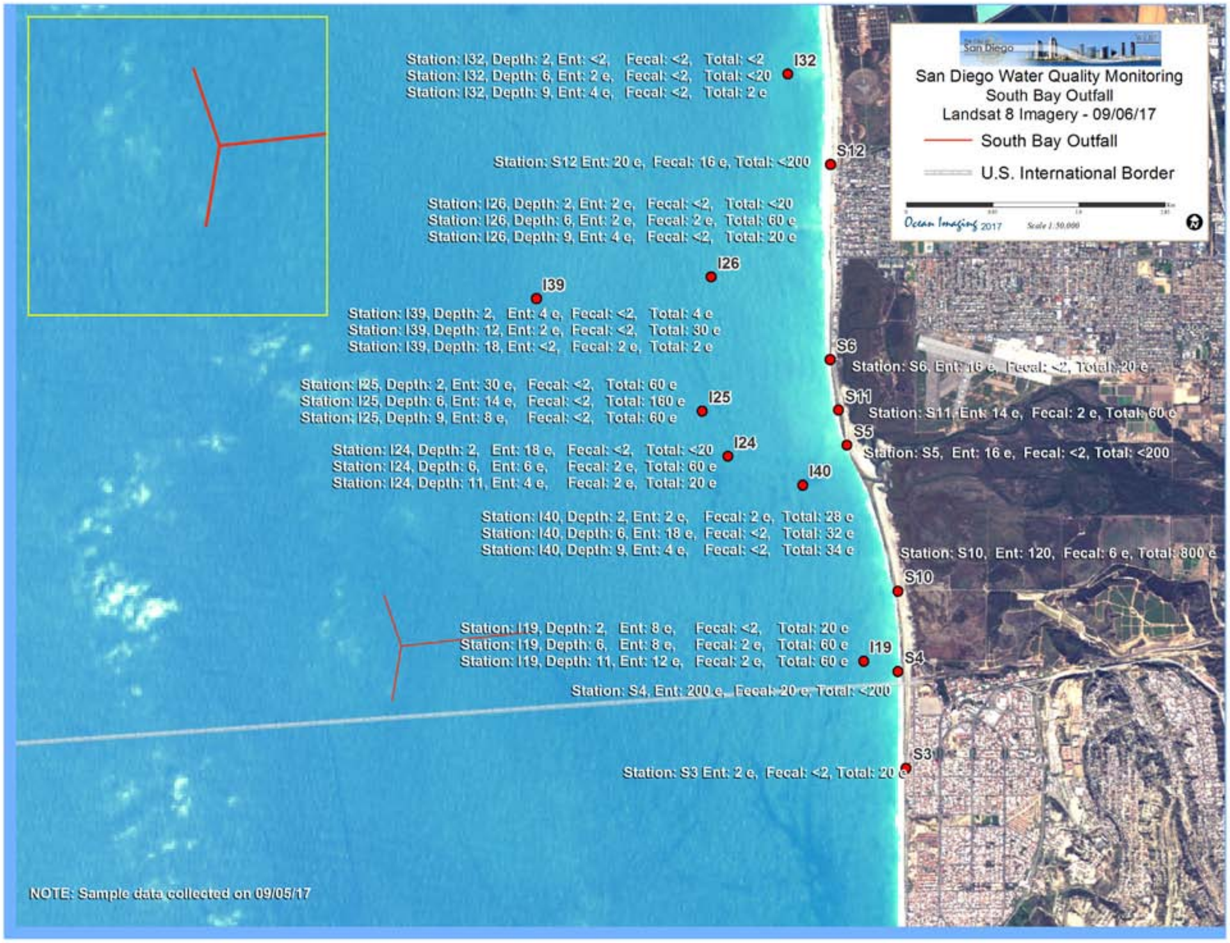


Figure 14. Landsat 8 image of the SBOO region acquired on 09/06/17 and near-surface coastal bacterial sampling results collected on 09/05/16. Note the clear water along with the low bacteria levels.

was 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 be- 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.

In 2017 the Point Loma region was affected by conditions already described for the South Bay region: significant seasonal rainfall during the months of January and February with near zero rainfall during June, July, August and September. This compromised water clarity in the nearshore areas in January and late February to early March 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 rain events described above. Both shoreline and periodic kelp bed bacterial sampling generally showed only occasional and marginally increased concentrations. Shoreline field sampling showed elevated bacteria levels on twelve days in 2017. Offshore sampling only showed elevated levels on one occasion during the year. The high bacteria measurements during January, February and March can be correlated with heavy rain events either prior to or during the site sampling. Figure 15 shows the 01/25/17 shoreline and offshore bacteria data plotted over RapidEye of the same day. While no plume associated with the outfall is visible, heavy coastal turbidity was apparent fueled by heavy sediment/turbidity plumes emanating from Mission Bay and San Diego Bay. Satellite data were also acquired on 03/02/17 and 03/03/17—shortly after the 02/27/17 rain storm. The RapidEye image of the Pont Loma region acquired on 03/03/17 and near-surface coastal bacterial sampling results also collected on 03/03/17 are shown in Figure 16. Despite high turbidity levels resulting from the rain five days earlier, elevated bacteria levels did not exist at the kelp bed stations. Data from the northern stations west of Mission Bay were not available for this date.

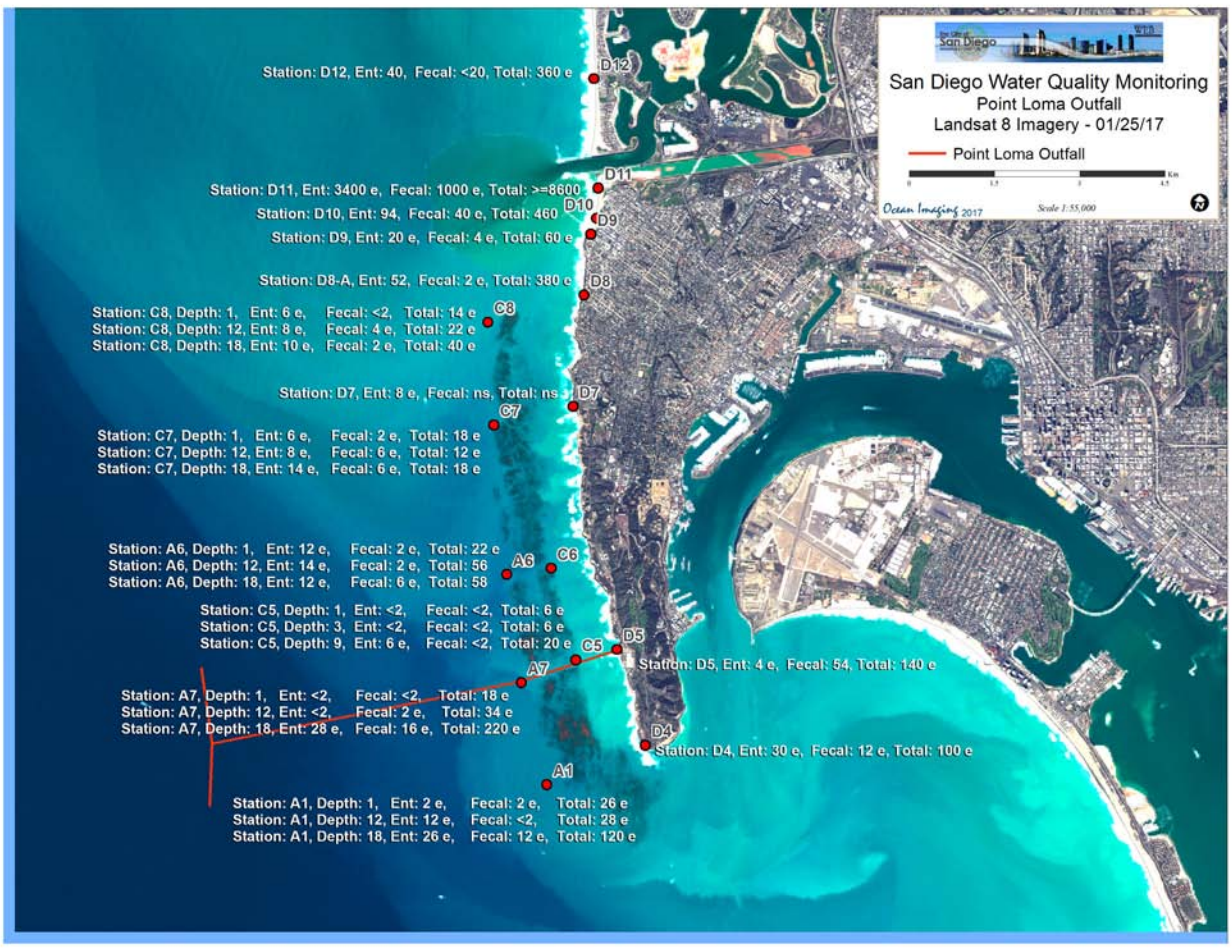


Figure 15: RapidEye image of the Pont Loma region acquired on 01/25/17 and near-surface coastal bacterial sampling results collected on the same day. Note the higher bacteria near the outflow of Mission Bay, however no obvious turbidity plume emanating from the outfall.

As has been 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 heavy rain events, this was not directly observed in 2017.

One observation provided by the satellite image archive was the continuing small size of the Point Loma kelp bed from 2016 into 2017 (Figure 17). As was reported last year, the satellite data show the bed to begin to decrease in size during February of 2016, perhaps due to the storm events taking place during early to mid-January. The kelp bed appeared to be coming back in January of 2017, but then decreased in size as the year progressed resulting in much smaller than average canopy coverage by the end of the year (Figure 18). Table 3 shows the area in km2 of three notable kelp beds in the San Diego region. The October dates chosen to represent the kelp bed canopy coverage are normally when the canopy size is near its peak. Evident in the table is, not only the dramatic reduction in size of the Point Loma bed after 2015 through the end

Figure 16. RapidEye image of the Pont Loma region acquired on 03/03/17 and near-surface coastal bacterial sampling results also collected on 03/03/17. Despite high turbidity levels resulting from rains five days earlier on 02/28/17, elevated bacteria levels did not exist at the kelp bed stations. Data from the northern stations west of Mission Bay were not available for this date.

of 2017, but also the total absence of the Imperial Beach and Tijuana beds. While it would be expected that these kelp beds would have returned to their normal size during the storm-free summer months, perhaps the January and late February storms created enough stress in the area resulting in the inability of the beds to grow back to their normal size or rejuvenate at all. As can be seen in Figures 7,8,15 and 16, the Point Loma kelp bed region was almost constantly covered by southward-swept turbidity plumes and/or plankton blooms from January through July. This may have also in inhibited the regrowth of the kelp.

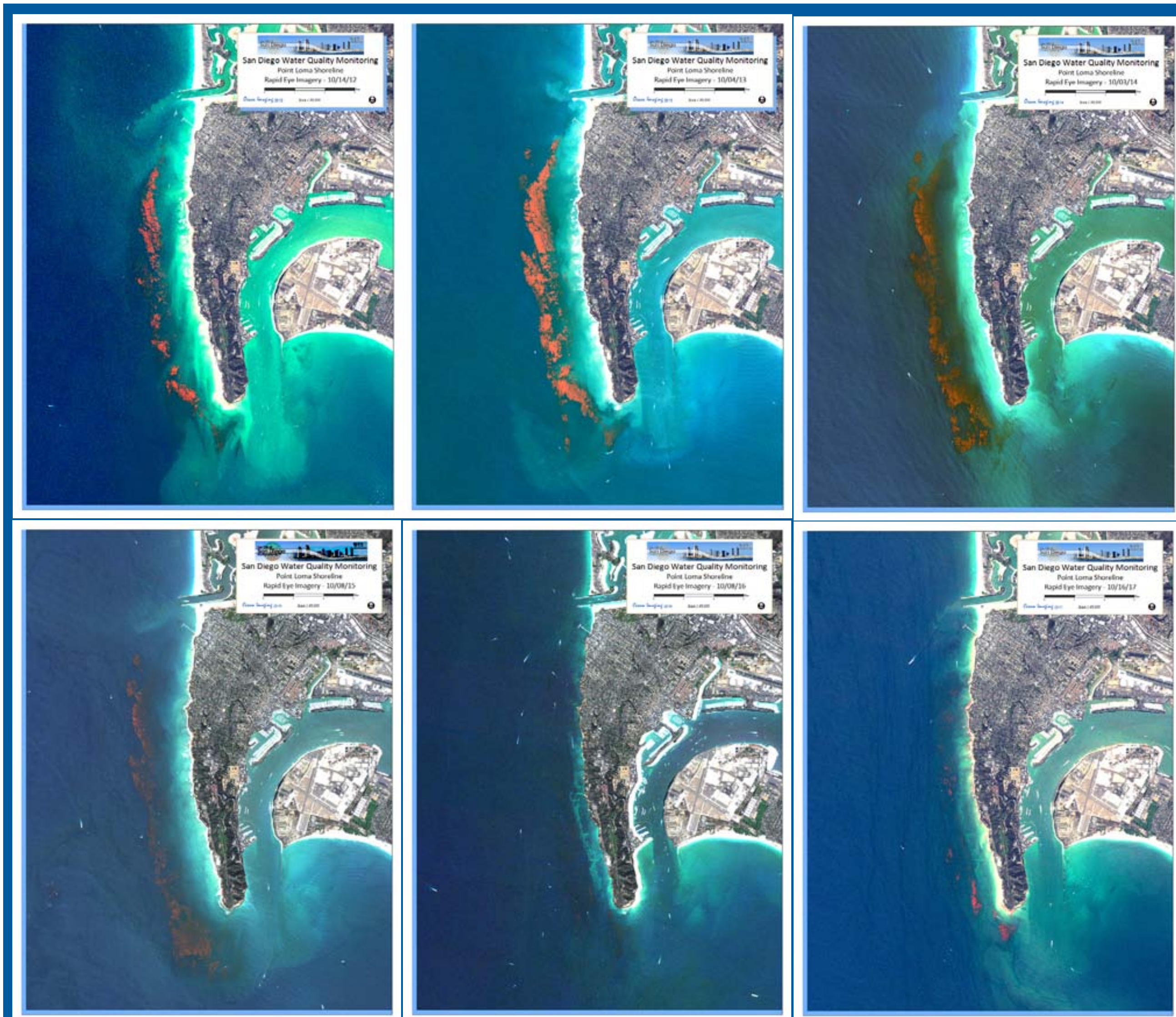


Figure 17. High resolution RapidEye images showing the Pt. Loma kelp bed on 10/14/12 (top left), 10/04/13 (top center), 10/03/14 (top right), 10/08/15 (bottom left), 10/08/16 (bottom center) and 10/16/17 (bottom right). Note the significant decrease in canopy area coverage in 2016 and 2017 compared to the previous four years, even during potentially peak growth months.

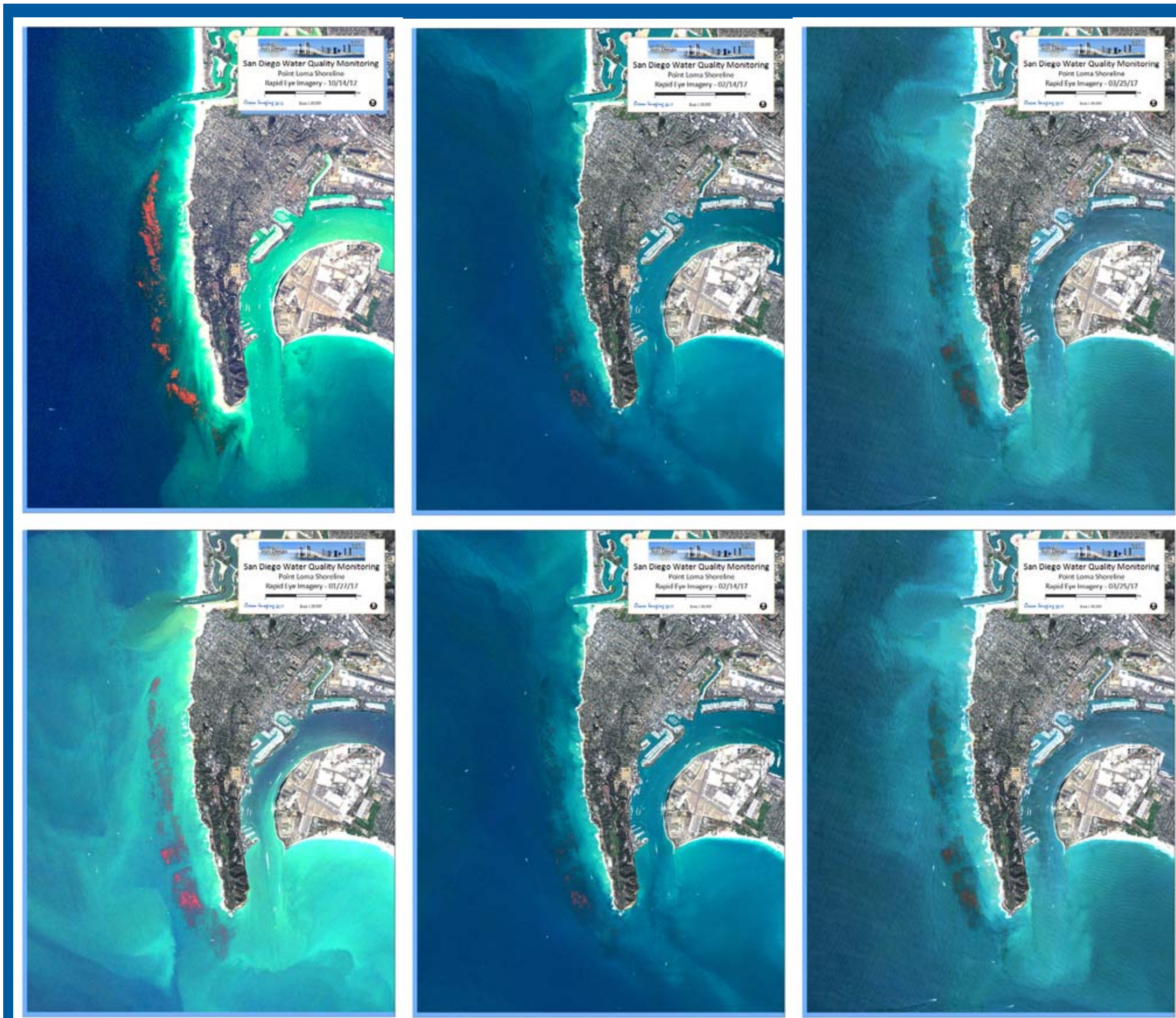


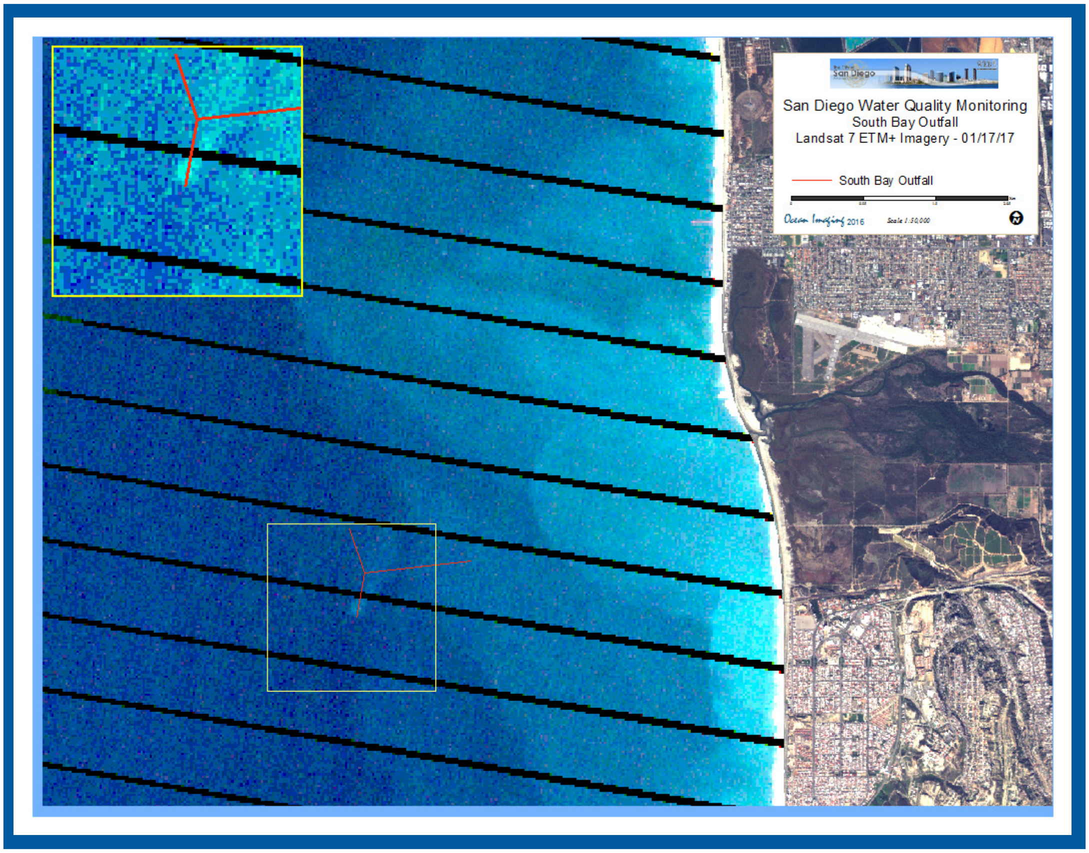
Figure 18. High resolution RapidEye images showing the Pt. Loma kelp bed on 01/27/17 (top left), 02/14/17 (top center), 03/25/17 (top right), 04/04/17 (bottom left), 11/03/17 (bottom center) and 12/13/17 (bottom right). Note an increase from late 2016 in canopy area coverage in the January image, but the bed never grew to the size observed in the years 2012–2015.

			Kelp (km²)		
Year	Date	Satellite	Point Loma	Imperial Beach	Tijuana
2017	10/04/2017	RapidEye	1.05	0.00	0.00
2016	09/08/2016	RapidEye	0.22	0.00	0.00
2015	09/17/2015	Landsat 7	4.11	0.39	0.29
2014	09/14/2014	Landsat 8	5.42	0.59	0.30
2013	09/23/2013	RapidEye	5.89	0.19	0.05
2012	09/15/2012	RapidEye	2.91	0.00	0.00
2011	09/01/2011	RapidEye	1.99	0.00	0.00
2010	09/27/2010	Landsat 7	6.01	0.00	0.00
2009	09/16/2009	Landsat 5	5.96	1.01	0.21
2008	09/05/2008	Landsat 7	8.66	0.82	0.01

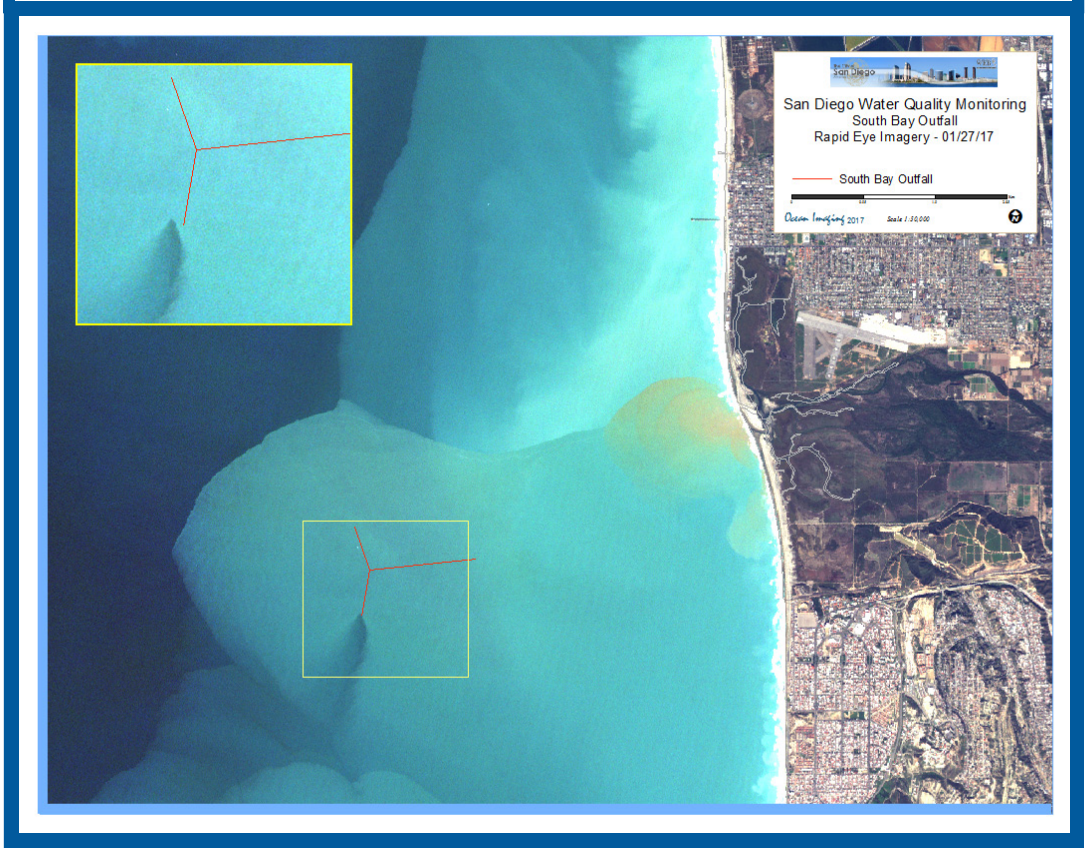
Table 3. Kelp canopy areas of three San Diego kelp beds measured from satellite imagery collected for this project.

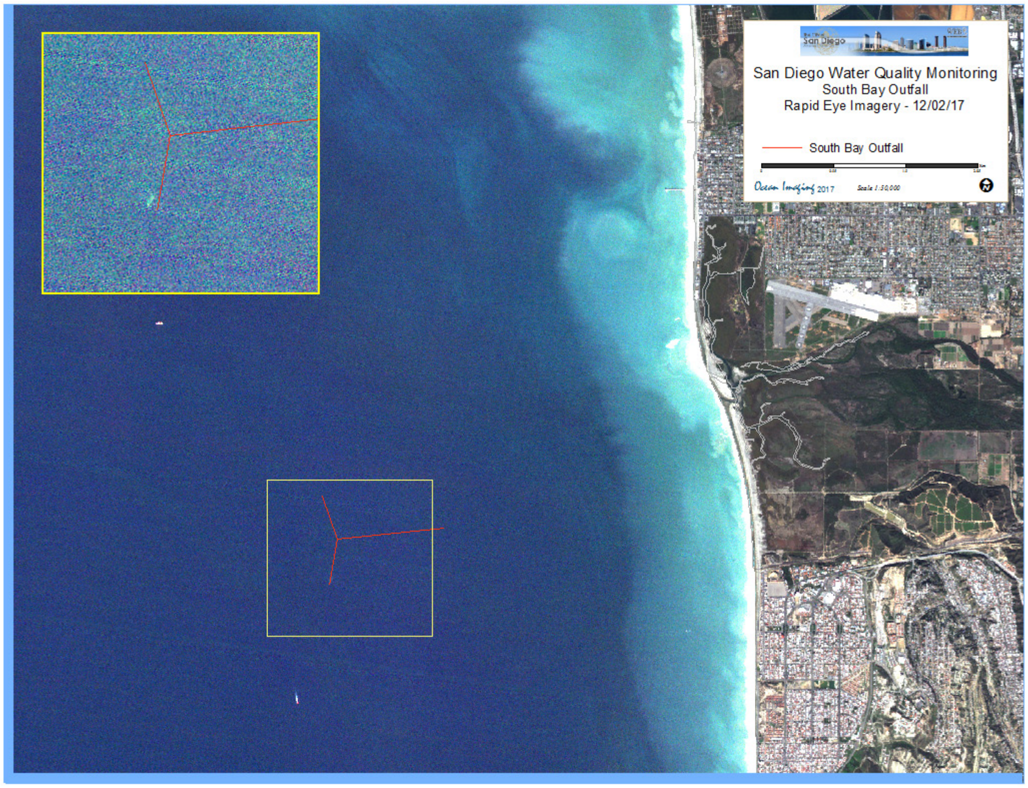
Appendix A–High Resolution Satellite Imagery Showing SBOO-related Wastewater Plume

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




San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery - 01/25/17
South Bay Outfall
Ocean Imaging 2017


San Diego Water Quality Monitoring
South Bay Outfall
Rapid Eye Imagery - 01/27/17
South Bay Outfall
Ocean Imaging 2017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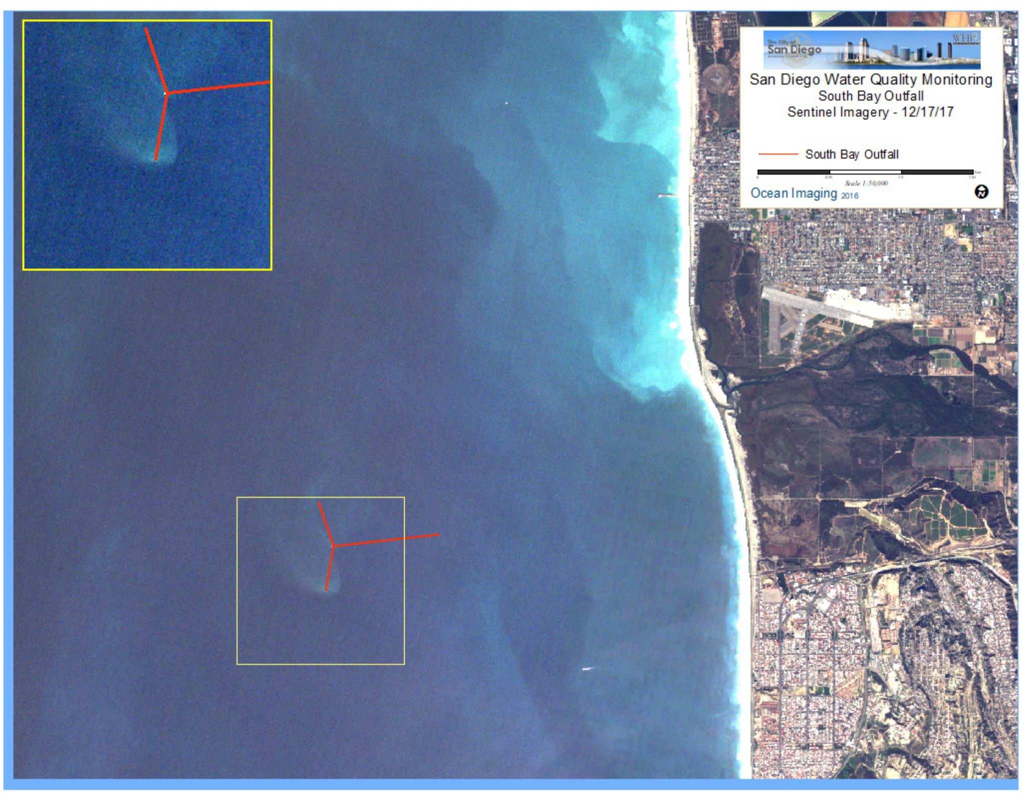
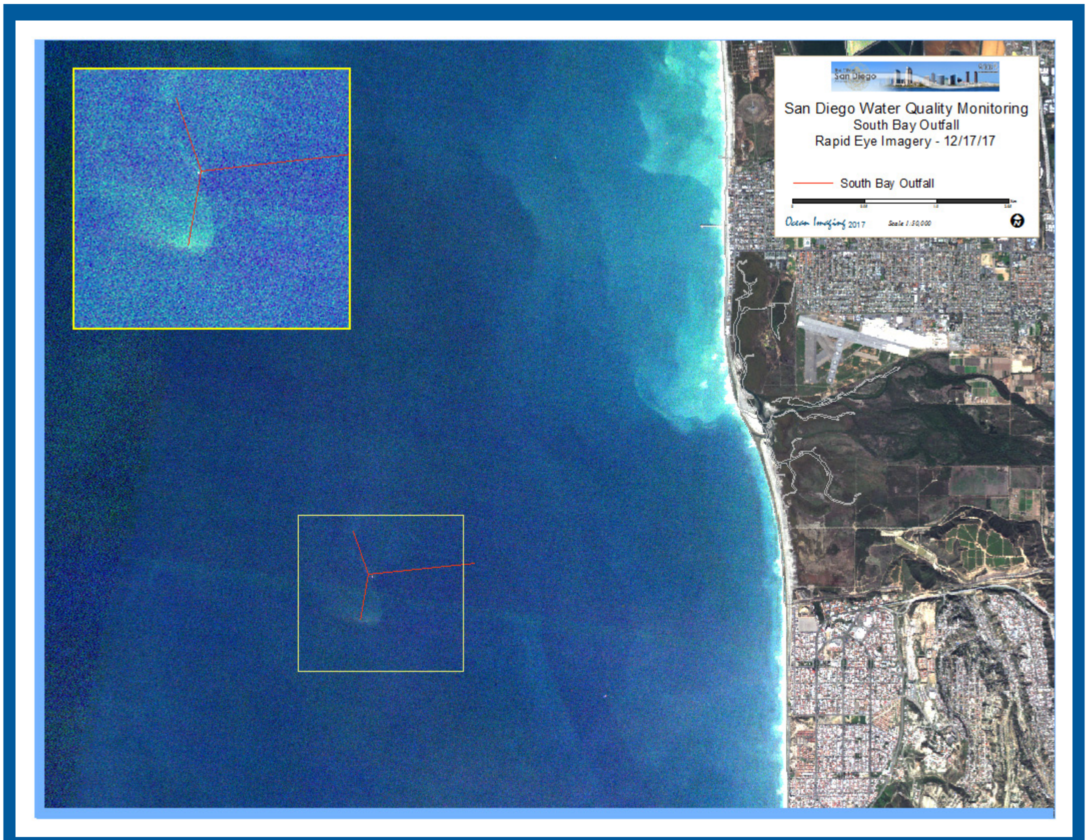
South Bay Outfall
Rapid Eye Imagery - 12/02/17
South Bay Outfall
Ocean Imaging 2017


San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel Imagery - 12/17/17
South Bay Outfall
Ocean Imaging 2016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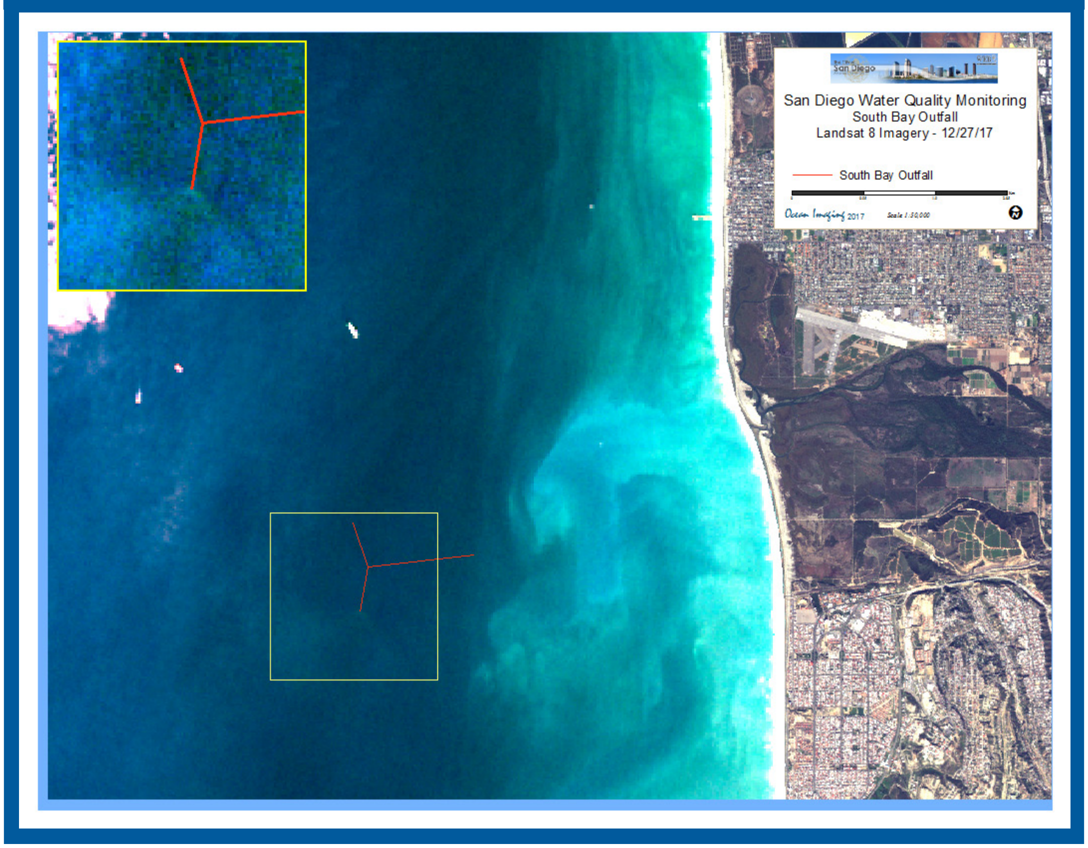
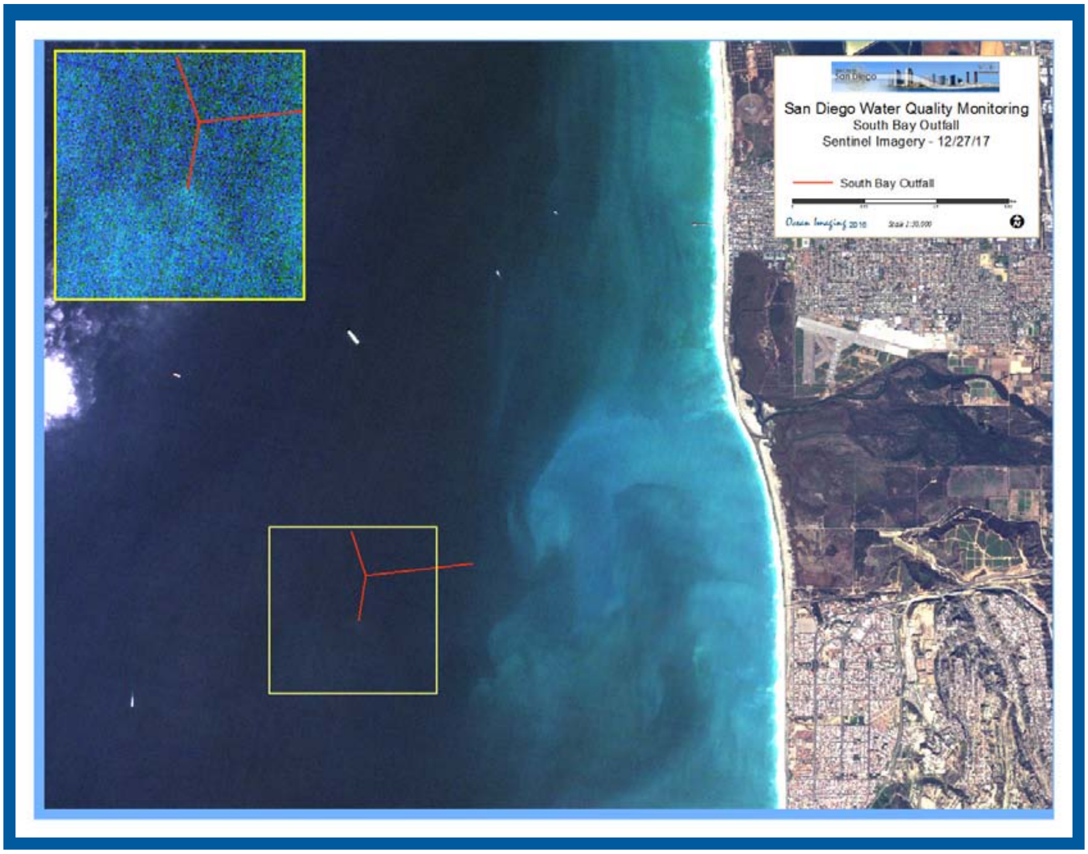
South Bay Outfall
Rapid Eye Imagery - 12/17/17
South Bay Outfall
Ocean Imaging 2017


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery - 12/27/17
South Bay Outfall
Ocean Imaging 2017


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel Imagery - 12/27/17
South Bay Outfall