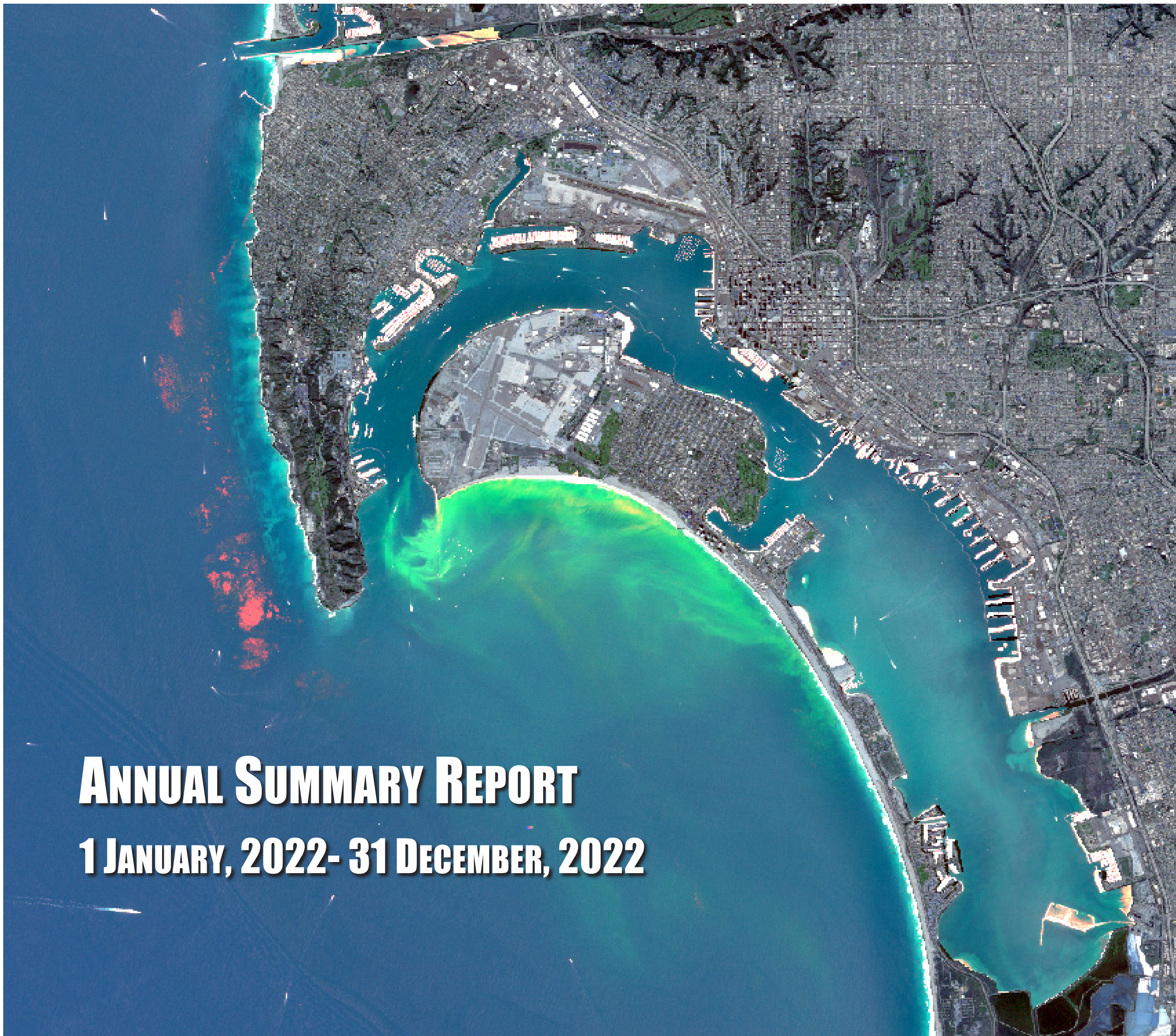
Satellite & Aerial Coastal Water Quality Monitoring in the San Diego / Tijuana Region

By Mark Hess



Annual Summary Report

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Ocean Imaging

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1. INTRODUCTION AND PROJECT HISTORY

In the 1990s, Ocean Imaging Corporation (OI) received multiple research grants from NASA's Commercial Remote Sensing Program for the development and commercialization of 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 in California (Svejkovsky and Haydock, 1998). The NASA-supported research led to a proof-of-concept demonstration project in the San Diego, California region co-funded by the EPA in 2000. Those results led, in 2002, to adding an operational remote sensing-based monitoring component to the San Diego region's established water quality monitoring program. The project continues as a joint effort between the Ocean Monitoring Program of the City of San Diego's Public Utilities Department (SDPUD) and the International Boundary and Water Commission (IBWC).

The first phase of the project was a historical study utilizing several types of satellite data acquired between the early 1980s and 2002. The study established 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 baseline data for the region's current patterns, their persistence, their frequency, and the historical locations, size and dispersion trajectories of various land and offshore discharge sources from Publicly Owned Treatment Works (POTW) (e.g., the offshore outfalls, Tijuana River, Punta Bandera Treatment Plant discharge in Mexico, etc.).

The prime objectives of the project have expanded somewhat since its inception. Initially, emphasis was on utilizing the image data to discern and monitor surface and near-surface signatures from the South Bay Ocean Outfall (SBOO) and Point Loma Ocean Outfall (PLOO), separate them from other nearshore point and non-point runoff features, and monitor their locations, extents, and potential impact on the shoreline. Prior to this project, the spatial extents of the plumes could only be estimated from a relatively sparse spatial grid of field samples, which made it difficult to separate, for example, the SBOO near surface plume from the Tijuana River runoff plume. This ambiguity made it difficult, in turn, to objectively evaluate the potential contribution, if any, of the SBOO plume to beach contamination along the nearby shoreline. The satellite and aerial imagery helped directly establish the dispersal trajectories of the SBOO effluent during months when it reaches the near-surface layer and support the claim that it likely never reaches the surf zone.

In October 2002, the operational monitoring phase of the project was initiated using the variety of satellite- and model-derived datasets discussed below. Over the past five to ten years, the project's objectives have broadened from focusing primarily on the outfalls to also provide larger-scale, regional observations of the physical and biological patterns and processes affecting the San Diego County and Tijuana River discharge regions. It is this broader-view perspective that led to the creation of the additional image products from additional sensors for the City.

This report summarizes observations made during the period 1/1/2022 – 12/31/2022.

2. METHODS AND 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 reflectance and heat emission patterns that are characteristic of the different discharges, water masses, plankton blooms and suspended sediment loads. 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 and aerial images. 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). Near-IR wavelengths are also highly reflected from kelp seaweeds, so such data are particularly useful for delineating the region's kelp beds and monitor their extents through time.

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 specific wavelengths. A multi-wavelength image set can also be analyzed with multispectral classification algorithms which separate distinctive 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 1-15 meters.

2.2 Imaging in the Thermal 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 thermal infrared (TIR) 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 sometimes 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 towards the surface. How far it rises depends on outfall depth, ocean currents, and stratification conditions. If it makes it all the way to the surface, it is usually cooler than the surrounding sun-warmed surface water. A plume signature detectable in multispectral color imagery but not detectable in simultaneously collected TIR imagery indicates the rising plume has not reached the actual ocean surface and remains submerged.

2.3 Satellites and Sensors Utilized

Until 2010, the project relied heavily on acquisition of multispectral color imagery with OI's DMSC-MKII aerial sensor and TIR imagery from a Jenoptik thermal imager integrated into the system. 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 Digital Multispectral Camera (DMSC) image acquisitions. The use of satellite as opposed to aerial data also enables a more regionally contiguous monitoring of events affecting the target areas. In late 2019 the RapidEye satellite constellation was decommissioned by the current operator Planet Labs. Subsequently, OI secured the regular acquisition of SPOT 6 and SPOT 7 satellite imagery covering the same geographical area beginning in 2020. Table 1 lists the properties of the remote sensing image sources routinely used during the project.

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-2A and 2B MSIs sample 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. 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. Beginning in 2018, data from Sentinel 2B became a regular addition to the satellite imagery products posted to the OI web portal. On average the Sentinel 2A and 2B imagery processed to highlight anomalous turbidity signals emanating from the PLOO, SBOO, as well as the discharge from the Tijuana River (TJR) are posted to the OI web portal within 24-36 hours of satellite data acquisition. In some cases, if the data are available to OI earlier, the image products are delivered as quickly as 12 hours post acquisition. During 2022 the Sentinel 2A and 2B satellites provided the most temporally comprehensive set of high-resolution satellite imagery. In total, 117 high resolution satellite images showing the offshore San Diego County region were acquired, processed, and delivered in 2022. This equates to a 13% decrease in satellite data used to document the area when compared to 2021 – most probably due to more instances of total cloud cover over the San Diego region in 2022. Of the 117 total image sets, 81 were from Sentinel 2A or 2B data making up 69% of the high-resolution satellite data processed and posted as part of the project and an increase of 4% over 2021.

In October 2018, OI began using imagery from Sentinel-3A. Shortly thereafter, in December 2018 imagery from Sentinel-3B was incorporated into the mix of observation platforms. Just like Sentinel 2, Sentinel-3A and Sentinel-3B are earth observation satellites developed by the ESA for the Copernicus Program. Sentinel-3A was launched on February 16, 2016, and Sentinel-3B followed on April 25, 2018. The 3A and 3B satellites are identical and deliver products in near-real time. The satellites include four different remote sensing instruments. The Ocean and Land Colour Instrument (OLCI) covers 21 spectral bands (400–1020 nm) with a swath width of 1270 km and a spatial resolution of 300 m. SLSTR covers 9 spectral bands (550–12 000 nm), using a dual-view scan with swath widths of 1420 km (nadir) and 750 km (backwards), at a spatial resolution of 500 m for visible and near-infrared, and 1 km for thermal infrared channels. The Sentinel 3 mission's main objectives are to measure sea surface topography along with the measurement of ocean/land surface temperature and ocean/land surface color. One of the satellites' main secondary missions is to monitor sea-water quality and marine pollution. The instrument on these satellites designed for these purposes is the OLCI. Ocean Imaging creates

Table 1. Satellite sensors utilized in the project and their characteristics.

Sensor	Utilization Period	Resolution (m)	Utilized Wavelength Range
AVHRR	2003 - Present	1100	Channel 4: 10.30 – 11.39 um Channel 5: 11.50 – 12.50 um
MODIS	2003 - Present	250/500/1000	Band 1 (250 m): .620 – .670 um Band 2 (250 m): .841 – .876 um Band 3 (500 m): .459 – .479 um Band 4 (500 m): .545 – .565 um
Landsat TM/ETM+ 4-7	2003 - Present	30 (visible - Near-IR) 60 (Thermal-IR)	Band 1: .450 - .520 um Band 2: .520 - .600 um Band 3: .630 - .690 um Band 4: .760 - .900 um Band 6: 10.40 - 12.50 um (TM5 Thermal not used due to noise)
Landsat 8 OLI, TIRS	2013 - Present	30 (visible - Near-IR) 100 (Thermal-IR)	Band 2: .452 - .512 um Band 3: .533 - .590 um Band 4: .636 - .673 um Band 5: .851 - .879 um Band 10: 10.60 - 11.19 um Band 11: 11.50 - 12.51 um
Sentinel 2A/2B	2017 - Present	10 (visible - Near-IR) 60 (Vegetation Red Edge) 60 (UV, SWIR)	Band 1: .443 um Band 2: .490 um Band 3: .560 um Band 4: .665 um Band 5: .705 um Band 6: .740 um Band 7: .783 um Band 8: .842 um Band 8A: .865 um
Sentinel 3A/3B	2018 - Present	300 (all utilized bands)	Band Oa2: .412.5 um Band Oa3: .442.5 um Band Oa4: .490 um Band Oa5: .510 um Band Oa6: .560 um Band Oa7: .620 um Band Oa8: .665 um Band Oa10: .68125 um Band Oa11: .07875 um Band Oa17: .865 um
VIIRS	2019 - Present	750 (all utilized bands)	Band M1: 0.402 - 0.422 um Band M2: 0.436 - 0.454 um Band M3: 0.478 - 0.488 um Band M4: 0.545 - 0.565 um Band M5: 0.662 - 0.682 um Band M6: 0.739 - 0.754 um Band M7: 0.846 - 0.885 um Band M8: 1.23 - 1.25 um Band M9: 1.371 - 1.386 um Band M10: 1.58 - 1.64 um Band M11: 2.23 - 2.28 um Band M12: 3.61 - 3.79 um Band M13: 3.97 - 4.13 um Band M14: 8.4 - 8.7 um Band M15: 10.26 - 11.26 um Band M16: 11.54 - 12.49 um
SPOT 6/7	2019 - Present	6	Band 1: .450 - .745 um Band 2: .450 - .525 um Band 3: .530 - .590 um Band 4: .625 - .695 um Band 5: .760 - .890 um
Sentinel 1A/1B SAR	2021 - Present	5 x 20	C-band operating at a center frequency of 5.405 GHz
Landsat 9 OLI-2, TIRS-2	Late 2021 - Present	30 (visible - Near-IR) 100 (Thermal-IR)	Band 2: .452 - .512 um Band 3: .533 - .590 um Band 4: .636 - .673 um Band 5: .851 - .879 um Band 10: 10.60 - 11.19 um Band 11: 11.50 - 12.51 um

daily products dependent on cloud cover for the entire San Diego/Tijuana region using the OLCI instrument. Between the 3A and 3B satellites this results in better than daily coverage with 3A and 3B data occasionally both being available on the same day. True color, near infrared, products are posted bi-monthly along with the similar resolution MODIS products. Potential future products derived from the Sentinel 3 sensors include total suspended matter, chlorophyll, and sea surface temperature as well as cyanobacteria monitoring. Sentinel 3 carries the only satellite sensor package with the necessary spectral bands, spatial resolution, and coverage for near real-time detection of cyanobacteria. The results of these products may also be compared to the field sampling data in order to assess accuracy.

As stated above, the RapidEye satellite data were discontinued as of late 2019 and replaced by data from the SPOT 6 and SPOT 7 satellites in January of 2020. The two SPOT satellites/sensors are identical in design and function. They both image in spectral bands similar to the RapidEye satellites at a ground sampling distance of 8.8 meters for the multispectral data (see Table 1). The dynamic range of these sensors is 12-bits per pixel. OI uses the blue, green, red, and near-infrared bands from these sensors. Empirically we have found that the SPOT data have a high signal to noise ratio and therefore produce a high-quality product for detecting wastewater surface manifestations and delineating the river run-off plumes. Because of the ability of these sensors to image from off-nadir viewing angles it is also possible to obtain more frequent data. Figure 1 shows a set of images from 11/23/22, 11/24/22, 11/26/22 and 11/29/22 from Landsat 8, SPOT and Sentinel 2 highlighting the ability to obtain high-resolution imagery from multiple satellites on successive days. Note the visible SBOO surface plume on all four days and the TJR discharge moving offshore to the northwest on the 23rd and 24th and then shifting direction and beginning to dissipate by the 29th. 25-hour averaged High Frequency Radar-derived (HF Radar) ocean currents from these days computed from the period one to two hours of the satellite data acquisition are overlaid on the imagery to help illustrate the shift in surface flow direction.

As detailed in Table 1, to date, this work utilizes 1100 m resolution Advanced Very High Resolution Radiometer (AVHRR)-derived imagery (available multiple times per day), 1000 m resolution chlorophyll and sea surface temperature (SST) Moderate Resolution Imaging Spectroradiometer (MODIS)-derived imagery (available multiple times per day), 500 m resolution MODIS true color imagery (available near-daily), 750 m resolution Visible Infrared Imaging Radiometer Suite (VIIRS) chlorophyll and SST imagery (available multiple times per day), 300 m resolution Sentinel 3 color and thermal imagery (available daily), 30 m & 60 m Landsat 7 ETM+ and Landsat 8 OLI/TIRS and Landsat 9 OLI-2/TIRS-2 color and thermal imagery (each available approximately every 16 days), 10 m resolution Sentinel 2 multispectral imagery (available 2-4 times per week), and 6m resolution Satellite Pour l'Observation de la Terre (SPOT) 6 and SPOT 7 (available approximately every 4-5 days).

Synthetic Aperture Radar (SAR) from the Sentinel 1A and 1B satellites (available every 3-6 days at a spatial resolution of 5m x 20 m) were added to the suite of remote sensing data products in late 2021. SAR can detect surfactant films associated with natural processes (Svejkovsky and Shandley 2001) and plumes containing anthropogenic substances (Svejkovsky and Jones 2001, Gierach et al. 2017, Holt et al. 2017) when optical sensors might be limited by cloud cover or heavy atmospheric haze. The primary purpose of these satellites for this project is to provide another look at the TJR discharge plume to assess its extent and direction of flow. The runoff often contains the natural and anthropogenic surfactants that dampen the SAR signal and therefore make it detectable in the data. In 2022 89 SAR images were acquired and processed for the San Diego region providing an additional source of information even during cloudy conditions. Figure 2

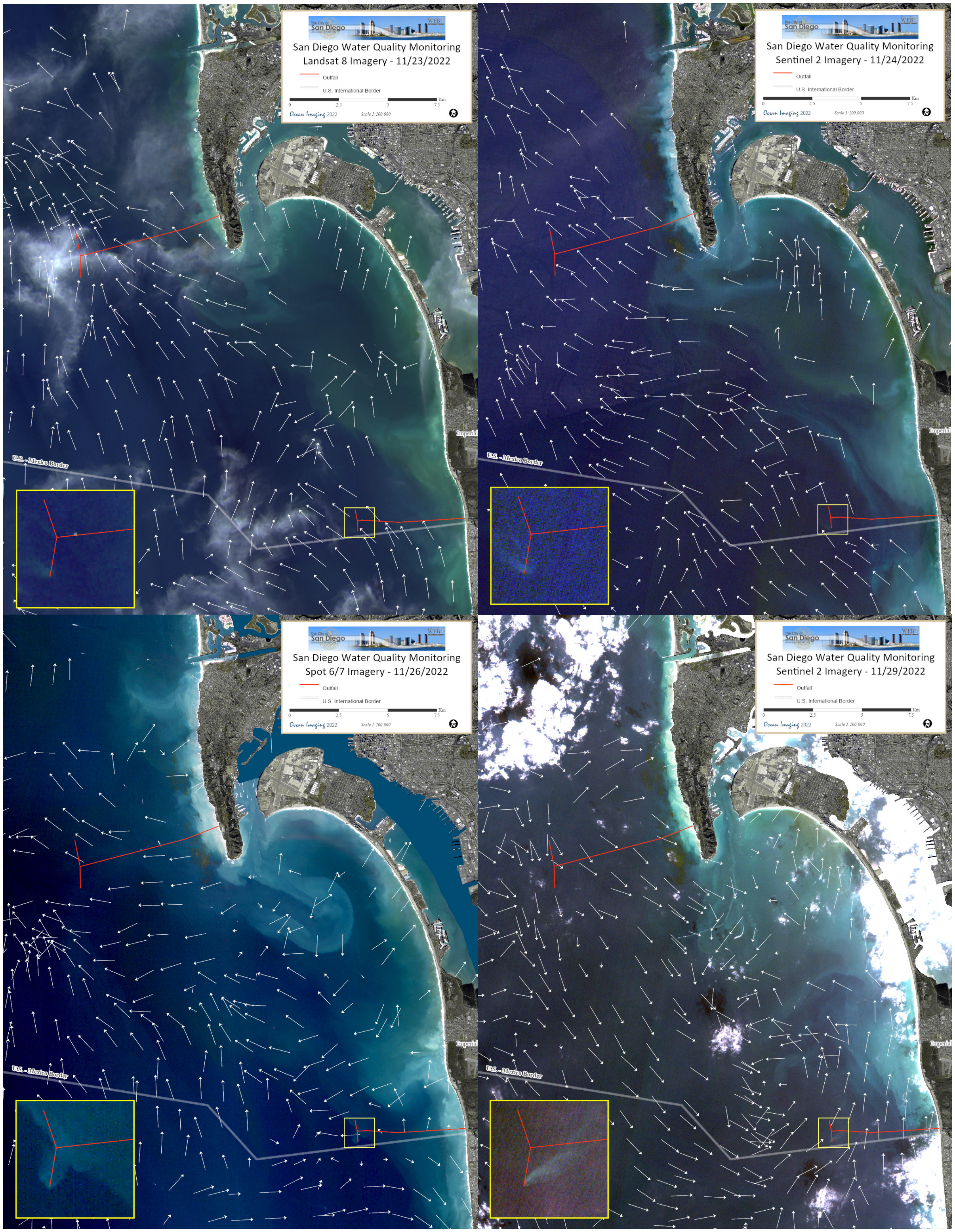


Figure 1. A time series of images from 11/23/22, 11/24/22, 11/26/22 and 11/29/22 from Landsat 8, SPOT and Sentinel 2 monitoring the movement of the TJR discharge plume over the seven-day period as it is pushed to the northwest, shifts direction, and then begins to dissipate. Note the presence of the SBOO outflow surface manifestation through the time series and the relatively fast development and disappearance of a turbidity plume streaming down from the Point Loma area.

shows a sample SAR image from 03/09/22 alongside a Sentinel 2B image highlighting a potential surfactant signature from the TJR discharge.

In 2012, OI added additional broad-scale products to the datasets available to the City and project partners. These include two types of ocean current data: High Frequency Radar-derived surface currents (HF Radar) and Hybrid Coordinate Ocean Model (HYCOM) model-derived surface currents (http://hycom.org). The raw data for the HF Radar currents are retrieved from National HF Radar Network via the Scripps Coastal Observing Research and Development Center (CORDC) on an hourly basis and reformatted into ESRI-compatible shapefiles. The hourly products are averages of the previous 25 hours and generated at 1 km and 6 km spatial resolutions. Additional HYCOM model-based products include daily ocean salinity, mixed layer depth, and subsurface temperature at 50, 100, 150 and 200 meters. In 2016 these products were delivered in a Web Map Service (WMS) Representational State Transfer (REST) service format compatible with the City's now retired BioMap server. They are presently being generated and archived in preparation for delivery via a next generation WMS dashboard planned for the future. The existing high resolution (6-30 m) observation region extends from approximately La Jolla southward to Rosarita Beach, Mexico and out approximately 50 miles. The coarser-scale products (250-1000 m) such as chlorophyll, SST, ocean currents and HYCOM-derived products encompass the entire Southern California Bight (SCB).

2.4 Data Dissemination and Analysis

The satellite data are made available to the SDPUD and other project constituents through a dedicated, password-protected web site. Although it is possible to process most of the data in near-real-time, earlier in the project it was decided that the emphasis of this program 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. As noted above however, OI has in a number of cases made imagery available to the SDPUD in near-real time (within 12-24 hours) via email when observations appeared to be highly significant to the management of beach closures or other sudden/anomalous events. The website was updated in 2022 to improve its ease of use and presentation of available imagery. Details on the site enhancements follow in section 4 below.

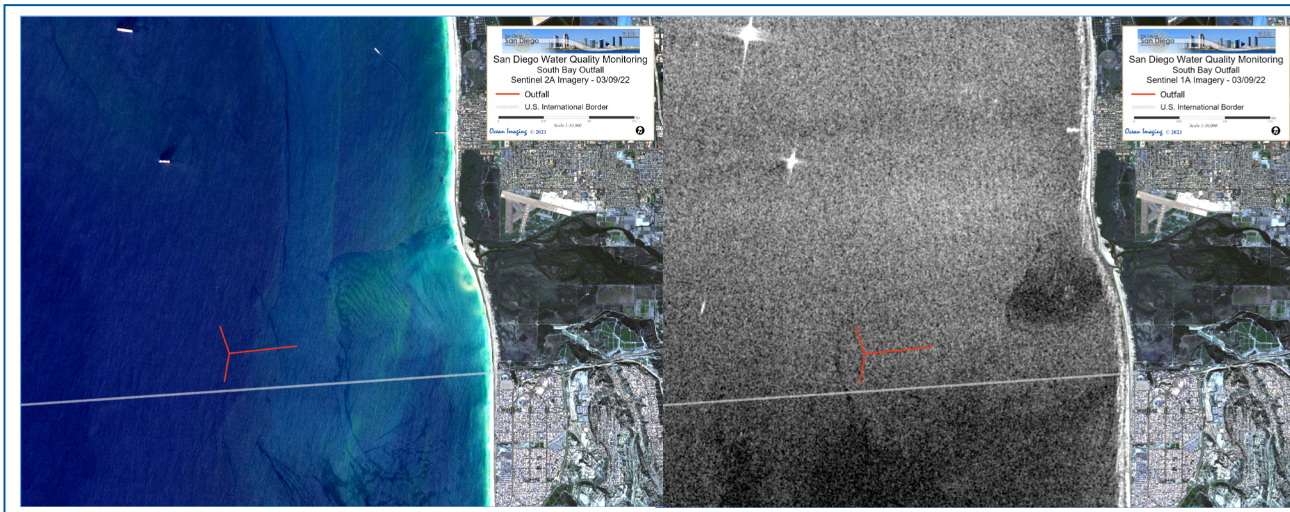


Figure 2. Sentinel 2A imagery acquired on 03/09/22 (left) enhanced to show the TJR discharge plume alongside a Sentinel 1 SAR image acquired that same morning five hours prior to the Sentinel 2 data collection.

3. HIGHLIGHTS OF 2022 MONITORING

3.1 Atmospheric and Ocean Conditions

Coastal and oceanic water quality can often be correlated to rainfall events. Annual recorded precipitation for 2022 was below the previous 10-year average for the region. The San Diego International Airport station (SDIA) measured 5.87 inches of total annual rainfall and the TJR Estuary 5.38 inches, both lower than 2012-2021 averages of 8.13 and 7.61 inches respectively (see Table 2). The monthly rainfall followed normal patterns seasonally, with the winter and spring months matching the expected rainy season and the summer months being dry. Only 0.02 inches of precipitation were recorded between both sites from May through August.

Figure 3 shows cumulative daily precipitation in the Tijuana Estuary. The table to the side of the plot gives the dates for which there was measurable precipitation at that station. As has been noted in the previous reports, the monthly and annual precipitation amounts can differ at times between the two reporting stations. The primary periods of consistent and/or heavy precipitation occurred during the months of February, March, November, and December. All (36 out of 36) significant TJR discharge events observed in the remotely sensed data occurred during the months of January through April and October through December, which is considered to be the Southern California rainy season. Most can be associated with a rainfall event occurring within a few days of the observation (Figure 3).

The coastal turbidity and TJR discharge levels mostly followed the rainfall patterns with water quality levels decreasing one-to-two days following the more significant rain events and water clarity increasing only after a few days of low to zero rainfall. Figure 4 provides an example of heavy coastal turbidity and a large TJR plume observed in the satellite imagery resulting from almost an inch of precipitation between 11/07/22 – 11/09/22 followed by a period of dry and calm conditions and then subsequent improvement of water quality conditions.

As noted above, there was almost no precipitation in the San Diego region during the months of May through the first week of September. River flow rates in cubic feet per second (cfs) measured by the United States Geological Survey (USGS) Fashion Valley gauge correspond well with the rainfall data. In Figure 5 daily SDIA precipitation totals are plotted with river flow data and monthly precipitation totals are displayed to the right of the plot. The 2022 the river flow rates matched what would be expected given seasonal rainfall patterns.

Despite the dry summer conditions with little coastal runoff measured by the USGS gauge or observed in the satellite data, there were several days during this time period that exhibited strong coastal phytoplankton blooms (Figure 6). This is an indication that the nutrients fueling the blooms likely entered the San Diego region from offshore and/or via upwelling events. Figure 7 shows a summer satellite image with reflectance signatures indicative of a strong red tide event. Also seemingly unrelated to the rainfall and river flow data, November experienced several days late in the month during which the TJR discharge extended far offshore and was documented pushing up past the southern tip of Point Loma - well after the heavy rain event on 11/08/22 (Figure 1 above).

In 2022 the county of San Diego issued 202 posted shoreline and/or rain advisories and 61 beach/shoreline closures. This is a 78.8% and 38.6% increase over the number of advisories and closures as in 2021 (113 and 44 respectively). The longest contiguous 2022 closure lasting the full year and into 2023 was at Border Field State Park along the south end of the Tijuana Slough Shoreline. As is typical for the region, the majority of the closures were in the area between the Tijuana River mouth and Avenida Del Sol at the south end of North Island and the result of contamination from

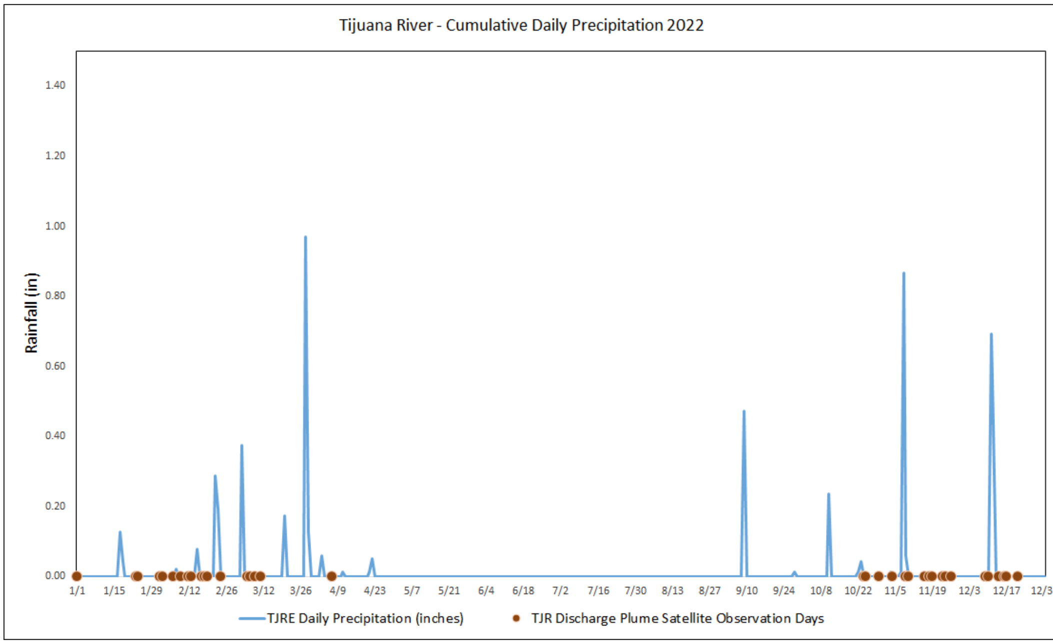
Table 2. San Diego and Tijuana Estuary precipitation totals 2012-2022

San Diego International Airport Cumulative Monthly Precipitation in Inches

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
January	0.40	0.70	0.01	0.42	3.21	2.99	1.77	2.42	0.48	1.80	0.16
February	1.19	0.63	1.00	0.28	0.05	1.58	0.35	4.04	0.38	0.10	0.70
March	0.97	1.22	1.28	0.93	0.76	0.08	0.65	1.23	2.15	1.48	1.61
April	0.88	0.01	0.54	0.02	0.55	0.01	0.02	0.10	3.68	0.07	0.02
May	0.02	0.26	--	2.39	0.44	0.87	0.09	0.86	0.02	0.07	0.02
June	--	--	--	0.04	--	0.02	--	0.01	0.14	0.01	--
July	--	0.05	--	1.71	--	--	--	--	--	--	--
August	--	--	0.08	0.01	--	--	0.02	--	--	0.23	--
September	--	--	--	1.24	0.32	0.06	--	0.11	--	0.50	0.65
October	0.70	0.25	--	0.43	0.07	--	0.57	--	0.12	1.01	0.09
November	0.28	1.48	0.37	1.54	0.61	0.02	0.69	2.72	0.14	--	1.07
December	2.19	0.46	4.50	0.88	4.22	--	0.83	4.03	0.60	2.58	1.55
Annual Total	**6.63**	**5.06**	**7.78**	**9.89**	**10.23**	**5.63**	**4.99**	**15.52**	**7.71**	**7.85**	**5.87**

Tijuana Estuary Cumulative Monthly Precipitation in Inches

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
January	0.70	0.05	0.08	0.32	2.40	3.61	0.82	1.80	0.61	2.21	0.17
February	0.86	--	1.35	0.13	0.02	4.06	0.47	3.62	0.51	0.06	0.58
March	1.21	1.43	0.55	1.01	1.28	0.04	1.17	1.33	2.59	1.12	1.64
April	0.82	0.11	0.35	0.07	1.91	0.01	0.10	0.33	5.52	0.04	0.13
May	--	0.36	--	1.13	0.97	1.07	0.08	0.50	0.02	0.01	--
June	--	--	0.12	--	--	--	--	0.02	0.21	0.06	--
July	--	0.01	0.33	0.39	--	0.01	0.01	--	--	--	--
August	--	--	0.04	--	--	0.02	--	--	--	0.02	--
September	0.02	0.01	--	0.48	0.49	0.03	--	--	--	--	0.48
October	0.50	0.41	--	0.21	--	--	0.13	--	0.04	0.91	0.29
November	--	0.25	0.29	0.61	0.34	0.06	0.82	2.99	0.08	0.02	0.95
December	0.04	0.50	3.09	0.61	4.32	0.09	3.16	3.82	0.60	1.18	1.13
Annual Total	**4.15**	**3.13**	**6.20**	**4.94**	**11.73**	**8.99**	**6.76**	**14.41**	**10.18**	**5.63**	**5.38**



Date	CumPrcp (in)
01/17/22	0.13
01/18/22	0.04
02/07/22	0.02
02/15/22	0.08
02/22/22	0.29
02/23/22	0.19
03/04/22	0.37
03/20/22	0.17
03/28/22	0.97
03/29/22	0.13
04/03/22	0.06
04/11/22	0.01
04/21/22	0.01
04/22/22	0.05
09/09/22	0.47
09/28/22	0.01
10/11/22	0.24
10/22/22	0.01
10/23/22	0.04
11/03/22	0.01
11/07/22	0.01
11/08/22	0.87
11/09/22	0.06
12/11/22	0.69
12/12/22	0.43

Figure 3. Daily accumulated rainfall in the Tijuana Estuary and days on which significant TJR discharge was observed in the high-resolution satellite imagery, including the Sentinel 1 SAR data.

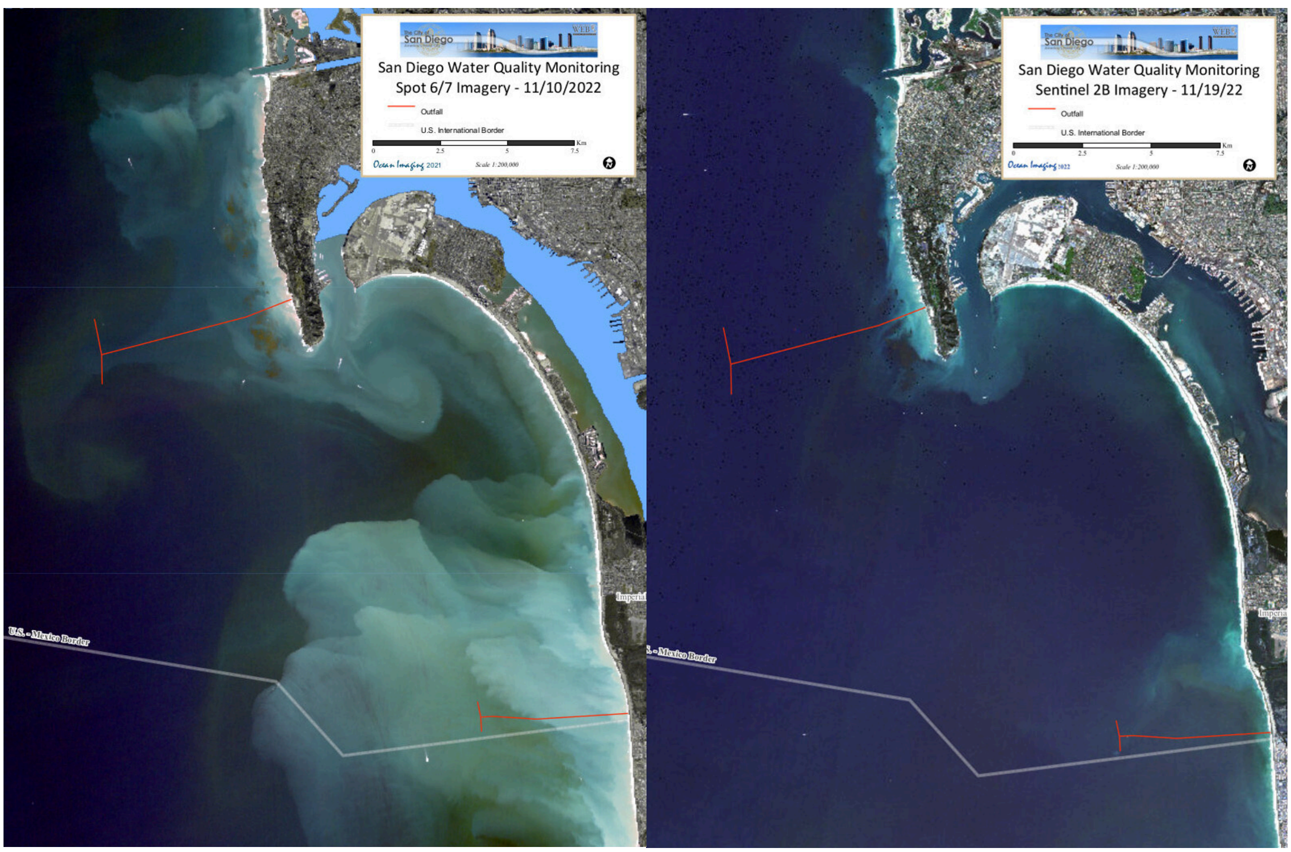
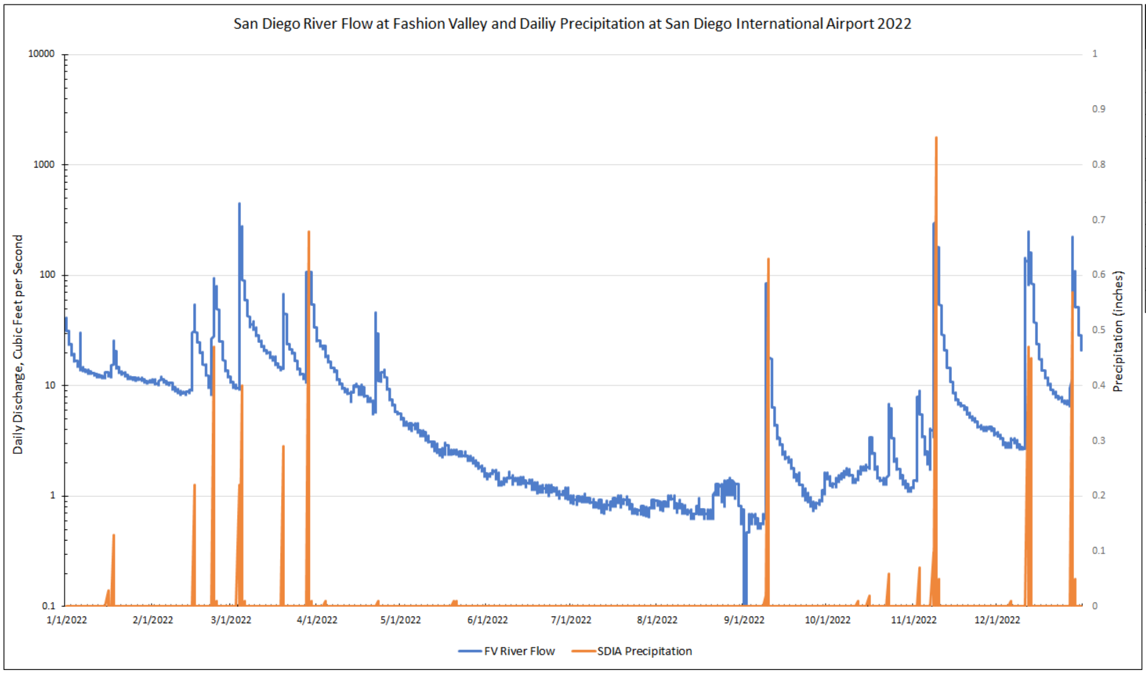


Figure 4. SPOT imagery acquired on 11/10/22 showing heavy coastal turbidity, San Diego River and TJR discharge following 0.94 inches of rainfall measured at the TJR estuary station occurring during the three days prior. A Sentinel 2B image acquired on 11/19/22 shows how the water cleared up during a period of dry and calm conditions after the rain event.



San Diego Intl. Airport Rainfall 2022	
Jan	0.16
Feb	0.70
Mar	1.61
Apr	0.02
May	0.02
Jun	--
Jul	--
Aug	--
Sep	0.65
Oct	0.09
Nov	1.07
Dec	1.55

Figure 5. Daily San Diego River flow rates in cubic feet per second measured by the USGS Fashion Valley gauge plotted with daily precipitation amounts as recorded at the San Diego International Airport. Monthly precipitation totals at the SDIA station are displayed to the right of the plot.

the TJR runoff. There were nine exceptions when measurements taken from the Avenida Del Sol station warranted the closure of all Coronado City beaches and four sewage spills caused closures in San Diego Bay, at Ocean Beach and the Encina Creek outlet in Carlsbad (Table 3). In some cases, the closures could be attributed to a rain event prior to and/or during the closure period. However, 25 of the 61 closures during 2022 happened between 04/23/22 and 09/08/22 when no rainfall was recorded at the Tijuana Estuary station. As noted above there were strong phytoplankton and red tide blooms during this time which may account for closures, if any, related to harmful algal blooms. Diatoms (primarily *Pseudo-nitzschia* spp) and dinoflagellates are largely responsible for the local harmful algal blooms and red tides when they occur (Southern California Coastal Water Research Project 2019). Figure 8 shows a strong plankton bloom on 06/14/22 close to the shoreline which was likely a red tide event. Table 3 also shows the date of the high-resolution satellite data in the project's archive acquired closest in time to the start date of the closure and/or rain advisory. The high-resolution satellite data during the beach closure time periods show high turbidity and suspended solid and/or high plankton levels along the coastline near the closed regions as well as greater than normal TJR runoff, sometimes being carried north by the ocean currents. Figure 4 (above) and Figure 9 provide examples of the Tijuana River plume extending north corresponding with shoreline closures beginning the day prior or on the same day.

Although discharge from the San Diego River and Mission Bay do not cause the same level of beach contamination issues as the Tijuana River, the runoff from the bay, river, and coastal lagoons did affect nearshore water clarity and quality on several days throughout the year in 2022, directly as a source of suspended sediment and indirectly as a source of high nutrient input, encouraging large scale phytoplankton blooms. While not at the scale or as dramatic as observed in 2020 and 2021, turbidity plumes emanating from the Mission Bay entrance and/or phytoplankton blooms either along the coast or offshore of the area were documented on 57 days in the medium- (MODIS and Sentinel 3) and high-resolution satellite imagery

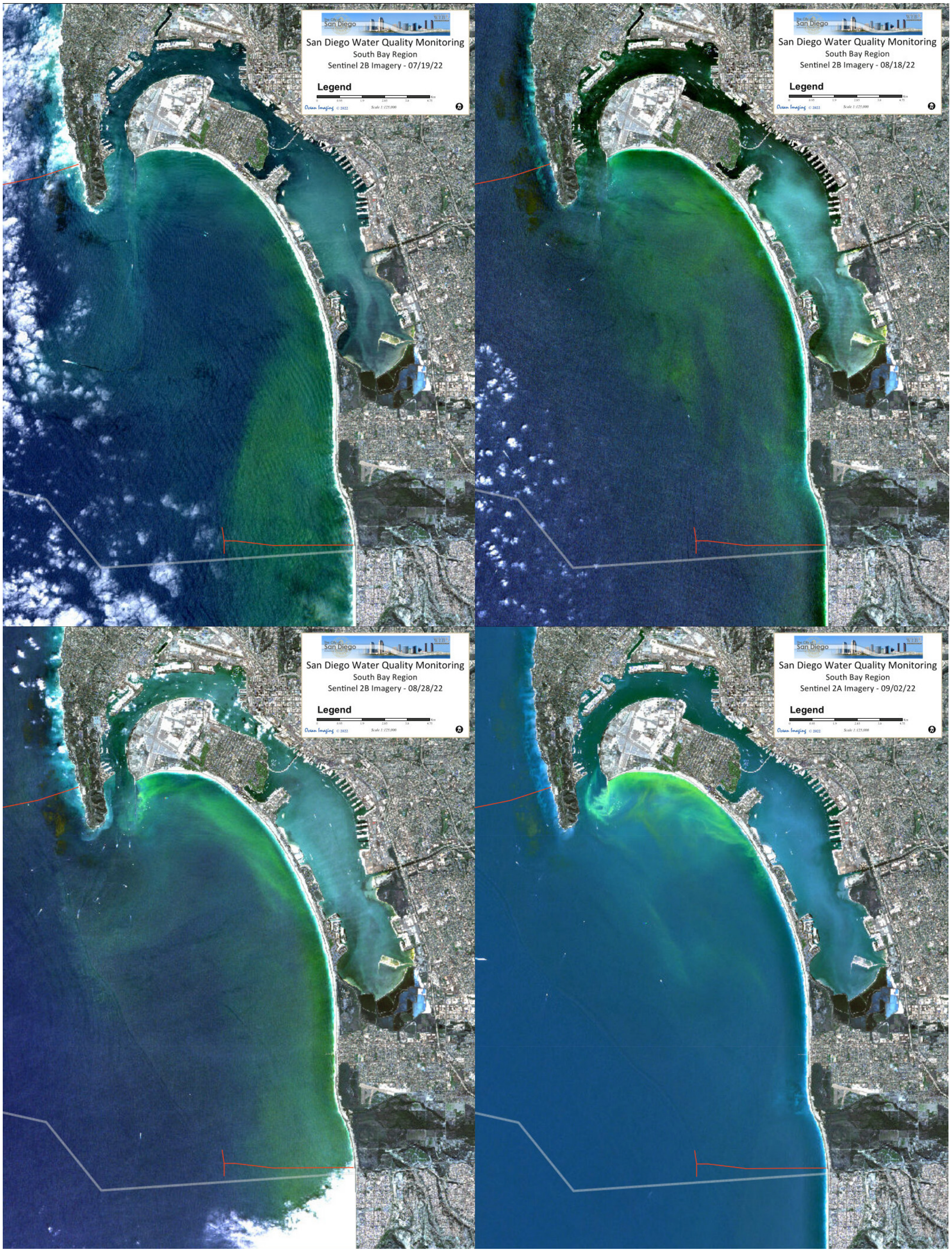


Figure 6. Sentinel 2A and 2B data from 07/19/22, 08/18/22, 08/28/22 and 09/02/22 highlighting the strong phytoplankton blooms which occurred in the San Diego South Bay region during July, August, and September.

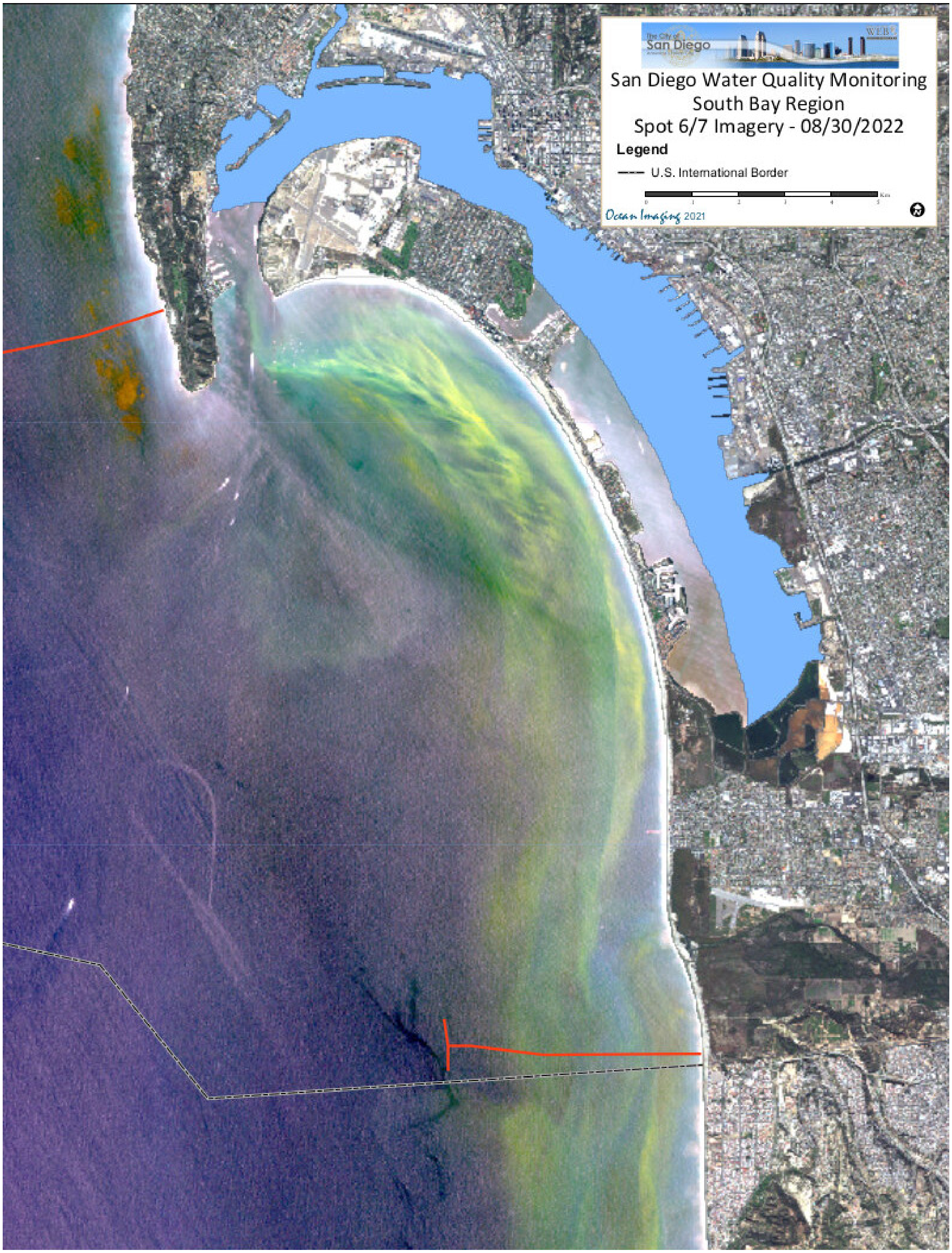


Figure 7. SPOT image acquired on 08/30/22 showing indications of a probable strong red tide event.

Table 3. 2022 County of San Diego shoreline closures and advisories and associated project satellite data (courtesy of the County of San Diego Department of Environmental Health).

StationDescription	Beach Name	Station Name	Type	Cause	Source	Start Date	End Date	Duration (days)	Nearest Rain Date	Time From Rain Event	Satellite Image Data
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			1/1/2022	1/1/2022	1	1/16/2022	15	1/1/22, 1/3/2022
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	1/1/2022	1/3/2022	3	1/16/2022	15	1/1/22, 1/3/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/1/2022	1/7/2022	7	1/16/2022	15	1/1/22, 1/3/22, 1/5/22
Border Fence N side	Border Field State Park	IB-010	Closure	Tijuana River Associated	Sewage/Grease	1/1/2022	12/31/2022	365	1/16/2022	15	All
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/9/2022	1/13/2022	5	1/16/2022	7	1/5/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/17/2022	1/22/2022	6	1/17/2022	0	1/19/2022, 1/20/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			1/18/2022	1/21/2022	4	1/18/2022	0	1/19/2022, 1/20/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/23/2022	1/25/2022	3	1/18/2022	5	1/23/22, 1/24/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/27/2022	1/29/2022	3	1/18/2022	9	1/30/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	1/31/2022	2/7/2022	8	2/15/2022	15	1/30/22, 2/2/22, 2/4/22, 2/7/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	2/18/2022	2/20/2022	3	2/16/2022	2	2/17/22, 2/29/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			2/23/2022	2/26/2022	4	2/23/2022	0	2/24/2022
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			3/4/2022	3/7/2022	4	3/4/2022	0	3/4/22, 3/6/22, 3/7/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Bacterial Standards Violation	Sewage/Grease	3/4/2022	3/8/2022	5	3/4/2022	0	3/4/22, 3/6/22, 3/7/22, 3/9/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Bacterial Standards Violation	Sewage/Grease	3/4/2022	3/8/2022	5	3/4/2022	0	3/4/22, 3/6/22, 3/7/22, 3/9/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	3/11/2022	3/15/2022	5	3/6/2022	5	3/11/22, 3/14/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	3/11/2022	3/15/2022	5	3/6/2022	5	3/11/22, 3/14/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			3/20/2022	3/23/2022	4	3/20/2022	0	3/21/22, 3/22/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			3/29/2022	4/1/2022	4	3/29/2022	0	3/30/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	3/29/2022	4/5/2022	8	3/29/2022	0	3/30/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	4/28/2022	4/30/2022	3	4/23/2022	5	4/28/22, 4/29/22, 4/30/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	5/5/2022	5/16/2022	12	4/23/2022	12	5/5/22, 5/10/22, 5/13/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	5/10/2022	5/13/2022	4	5/20/2022	10	5/10/22, 5/13/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	5/10/2022	5/14/2022	5	5/20/2022	10	5/10/22, 5/13/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	5/17/2022	5/28/2022	12	5/20/2022	3	5/18/22, 5/30/22, 6/14/22, 6/24/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	5/17/2022	6/20/2022	35	5/20/2022	3	5/18/22, 5/30/22, 6/14/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	5/18/2022	5/26/2022	9	5/20/2022	2	5/18/22, 5/30/22, 6/14/22, 6/24/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	5/30/2022	6/1/2022	3	5/21/2022	9	5/30/2022
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	6/2/2022	6/8/2022	7	5/21/2022	12	5/30/2022
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	6/4/2022	6/6/2022	3	5/21/2022	14	5/30/22, 6/14/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	6/10/2022	6/14/2022	5	5/21/2022	20	6/14/2022
Avd. del Sol	Coronado City beaches	IB-080	Closure	Bacterial Standards Violation	Sewage/Grease	6/11/2022	6/14/2022	4	5/21/2022	21	6/14/2022
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	6/15/2022	6/17/2022	3	5/21/2022	25	6/14/2022
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	6/18/2022	6/20/2022	3	5/21/2022	28	6/14/22, 6/24/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	6/24/2022	7/1/2022	8	5/21/2022	34	6/24/22, 6/29/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	6/29/2022	7/1/2022	3	5/21/2022	39	6/29/22, 7/2/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	6/29/2022	7/1/2022	3	5/21/2022	39	6/29/22, 7/2/22
Silver Strand (bayside)	San Diego Bay	EH-090	Closure	Sewage Spill	Sewage/Grease	7/14/2022	7/15/2022	2	5/21/2022	54	7/18/22, 7/19/22
Bayside Park (J Street)	San Diego Bay	EH-120	Closure	Sewage Spill	Sewage/Grease	7/15/2022	7/16/2022	2	5/21/2022	55	7/18/22, 7/19/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	7/18/2022	7/23/2022	6	5/21/2022	58	7/18/22, 7/19/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	7/20/2022	8/8/2022	20	5/21/2022	60	7/19/22, 8/1/22, 8/3/22, 8/8/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	8/2/2022	8/7/2022	6	5/21/2022	73	8/1/22, 8/3/22, 8/8/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	8/3/2022	8/6/2022	4	5/21/2022	74	8/3/22, 8/8/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	8/3/2022	8/6/2022	4	5/21/2022	74	8/3/22, 8/8/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	8/8/2022	8/9/2022	2	5/21/2022	79	8/8/22, 8/11/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	8/10/2022	8/15/2022	6	5/21/2022	81	8/11/22, 8/18/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	8/10/2022	8/18/2022	9	5/21/2022	81	8/11/22, 8/18/22
San Diego River outlet	Dog Beach, O.B.	FM-010	Closure	Sewage Spill	Sewage/Grease	9/1/2022	9/4/2022	4	5/21/2022	103	8/30/22, 9/2/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			9/9/2022	9/12/2022	4	9/9/2022	0	9/15/2022
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	9/10/2022	9/17/2022	8	9/10/2022	0	9/15/22, 9/16/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	9/10/2022	9/26/2022	17	9/10/2022	0	9/15/22, 9/16/22, 9/20/22, 9/21/22, 9/22/22, 9/25/22, 9/27/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	9/12/2022	9/16/2022	5	9/10/2022	2	9/15/22, 9/16/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	9/24/2022	9/26/2022	3	9/10/2022	14	9/25/22, 9/27/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	10/13/2022	10/16/2022	4	10/11/2022	2	10/17/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	10/13/2022	10/16/2022	4	10/11/2022	2	10/17/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	10/23/2022	10/25/2022	3	10/23/2022	0	10/24/22, 10/25/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	10/24/2022	10/25/2022	2	10/23/2022	1	10/24/22, 10/25/22
San Diego River outlet	Dog Beach, O.B.	FM-010	Closure	Sewage Spill	Sewage/Grease	10/24/2022	10/25/2022	2	10/23/2022	1	10/24/22, 10/25/22
Newport Ave	Ocean Beach	PL-100	Closure	Bacterial Standards Violation	Unknown	10/27/2022	10/28/2022	2	10/23/2022	4	10/27/22, 10/30/22
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			11/8/2022	11/12/2022	5	11/8/2022	0	11/9/22, 11/10/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	11/9/2022	11/12/2022	4	11/9/2022	0	11/9/22, 11/10/22
Avd. del Sol	Coronado City beaches	IB-080	Closure	Tijuana River Associated	Sewage/Grease	11/9/2022	11/12/2022	4	11/9/2022	0	11/9/22, 11/10/22
Encina Creek outlet	South Carlsbad State Beach	EN-030	Closure	Sewage Spill	Sewage/Grease	11/9/2022	11/12/2022	4	11/9/2022	0	11/9/22, 11/10/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	11/9/2022	11/18/2022	10	11/9/2022	0	11/9/22, 11/10/22, 11/16/22, 11/18/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	11/13/2022	11/14/2022	2	11/10/2022	3	11/10/2022
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			12/12/2022	12/15/2022	4	12/12/2022	0	12/11/22, 12/15/22, 12/16/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	12/12/2022	12/25/2022	14	12/12/2022	0	12/11/22, 12/15/22, 12/16/22, 12/19/22, 12/24/22
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	12/12/2022	12/26/2022	15	12/12/2022	0	12/11/22, 12/15/22, 12/16/22, 12/19/22, 12/24/22
Silver Strand N end (ocean)	Silver Strand State Beach	IB-070	Closure	Tijuana River Associated	Sewage/Grease	12/28/2022	12/31/2022	4	12/28/2022	0	12/24/2022
End of Seacoast Dr	Imperial Beach municipal beach, other	IB-050	Closure	Tijuana River Associated	Sewage/Grease	12/28/2022	12/31/2022	4	12/28/2022	0	12/24/2022
All_SanDiego_County_Beaches	All_SanDiego_County	All_SanDiego_County_Beaches	Rain			12/28/2022	12/31/2022	4	12/28/2022	0	12/24/2022

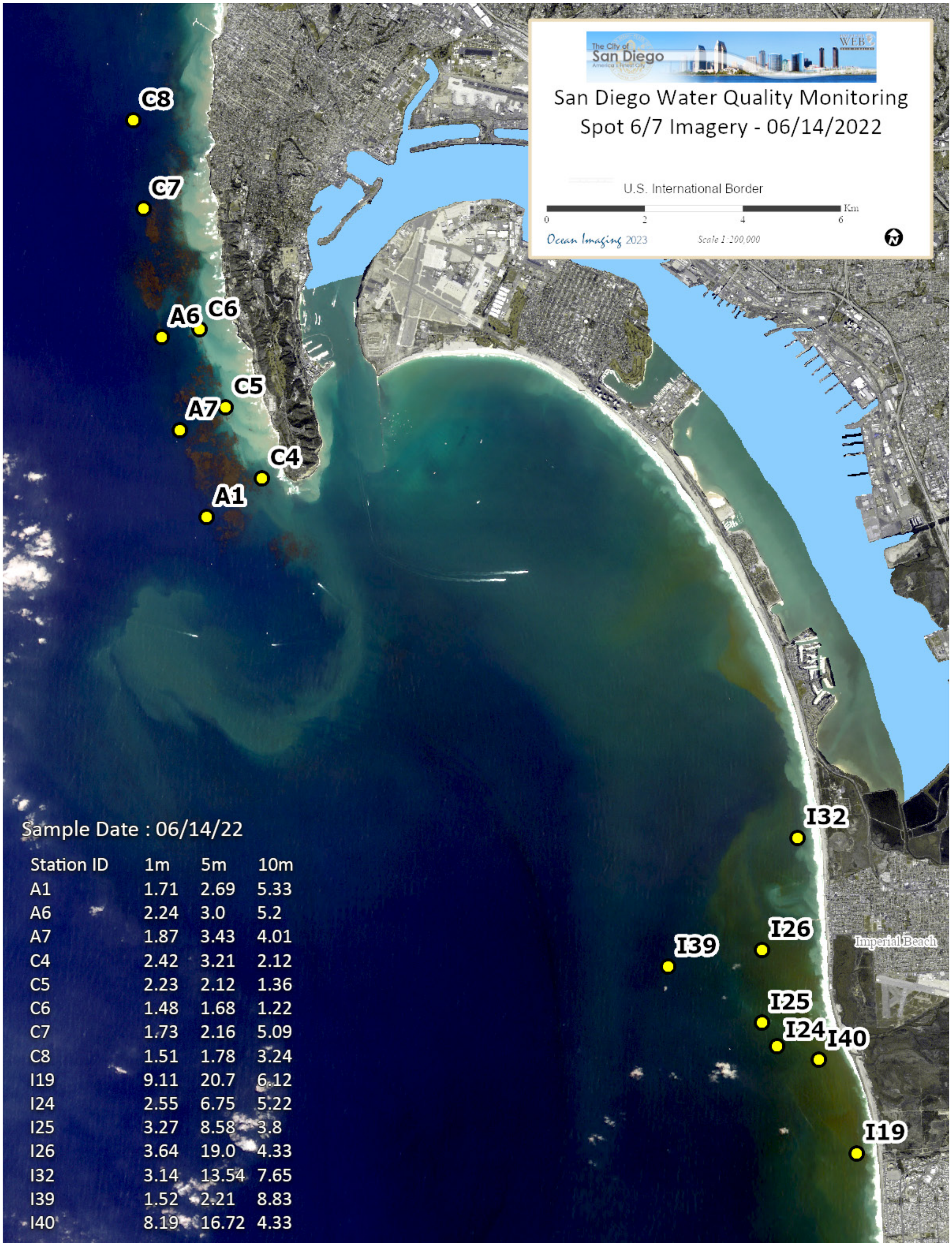


Figure 8. SPOT image acquired on 06/14/22 showing a strong coastal plankton bloom with the City's fluorometry data overlaid from the same day. The bloom was likely a red tide event. Imperial Beach, Silver Strand State Beach and Coronado City beaches were closed during the period between 06/10/22 – 06/20/22.

throughout the year. The area surrounding the Point Loma kelp bed tended to be more often affected by direct shore runoff and discharges from the San Diego River and Mission Bay during the prevalent southward current regime. Figure 10 provides examples of a few days on which the data revealed heavy discharge, runoff, and plankton blooms in this northern section of the project's area of interest.

The SCB experienced lower overall chlorophyll and plankton in 2022 than in the previous year. The California Current did bring chlorophyll-rich waters deeper into the Southern California region during the early part of the year, especially March through June, however a significant decrease in the SCB-wide levels occurred during the summer months. Figure 11 provides representative MODIS- and VIIRS-derived chlorophyll images for each month of 2022. As is seen in the image data, during the months of July through August, the California Current's southeastward push relaxed. However, the coastal San Diego region did experience pulses of phytoplankton blooms throughout the summer and into the fall and winter, but not to the extent of what was observed in 2021. As highlighted in the figures above and in the images with the fluorometry data overlays in Figure 12, there were periods in the spring and summer months that showed periodic heavy plankton blooms, especially in the areas directly west of Point Loma and along the southern shoreline.

The City of San Diego CTD sampling results correlated well with what was observed in the satellite data. Some of the highest chlorophyll levels recorded via CTD (as high as 68.16 µg/L at station I32, 3-meter depth on 06/28/22) occurred between April and June which is later in the season than prior years. Figures 8 (above) and 12 offer examples of the CTD fluorometry data in correlation with the high-resolution satellite imagery on or near the same day as the field samples. While the high-resolution remotely sensed data do not depict quantitative chlorophyll levels, the plankton blooms are self-evident in the imagery and correlate well with the CTD data.

3.2 The South Bay Ocean Outfall Region

The South Bay International Wastewater Treatment Plant (SBIWTP) switched from advanced primary to secondary treatment in January 2011. This change resulted in the reduction of total suspended solids (TSS) concentrations from an average of 60 mg/l for several years prior to the change to the TSS loads reading consistently below 20 mg/L since 2012. Prior to 2011, a distinct effluent signature was regularly detected in multispectral imagery as per the seasonal fluctuation described above. Since then, the effluent signature continues to be observed with multispectral color and thermal imagery during months with weak vertical stratification, however, more intermittently. On occasion the signature is distinctly discernable in thermal images (indicating it has fully reached the ocean surface), but undetectable in the color imagery. We theorize this is due to the reduction in TSS concentrations.

The 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), nor can it 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 April when it can often be detected with aerial and satellite imaging. This concept held true in 2022, as the last observation of a SBOO surface plume during the beginning of the year was on 04/23/22 and then was not seen in the image data again until 11/09/22. In total, there were 23 instances during which the SBOO effluent plume was observed

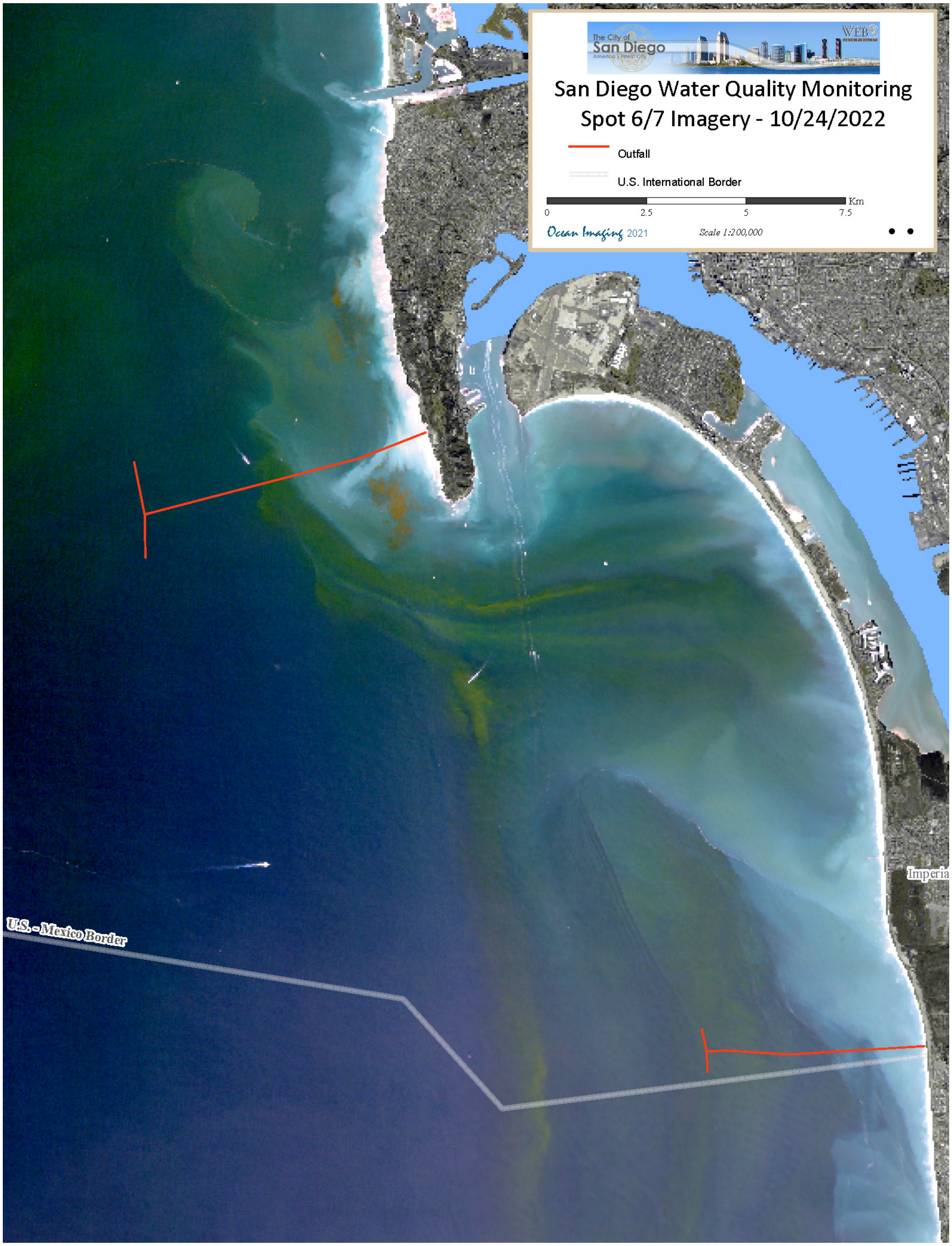


Figure 9. SPOT image acquired on 10/24/22 showing the TJR discharge mixed with coastal and offshore plankton blooms being pushed to the north and northwest. Imperial Beach and Silver Strand State Beach were closed between 10/23/22 and 10/25/22.

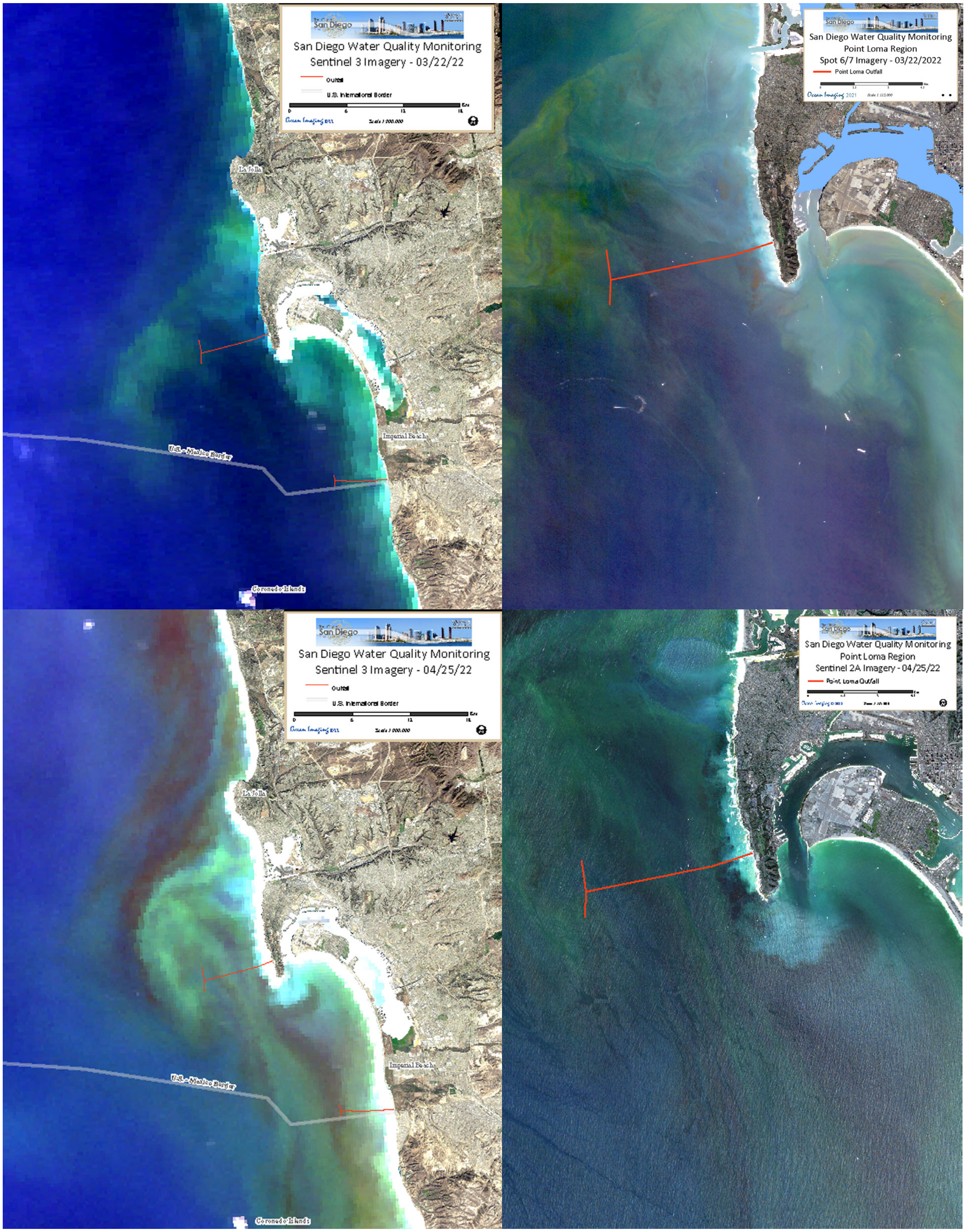


Figure 10. Sentinel 3 images (left side) and the higher resolution SPOT and Sentinel 2A images (right side) showing the turbid water flowing out of the Mission Bay entrance and associated plankton blooms on 03/22/22 (top) and 04/25/22 (bottom).

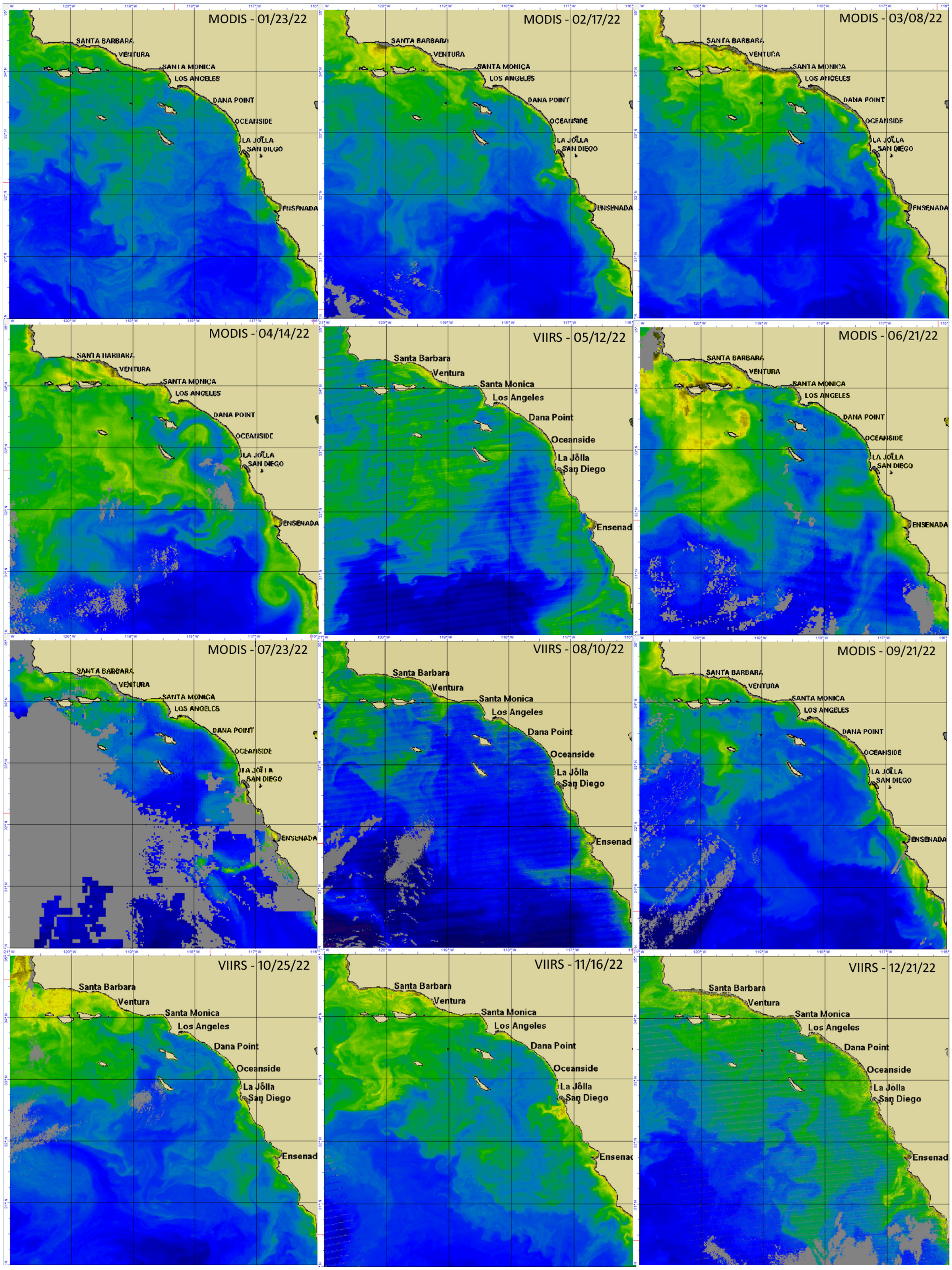


Figure 11. Representative MODS- and VIIRS-derived chlorophyll images for each month of 2022 in the SCB showing a strong push of chlorophyll-rich California Current water pushing into the bight during the spring months, a relaxation in July, August, and September and then a resurgence of chlorophyll levels beginning in October.

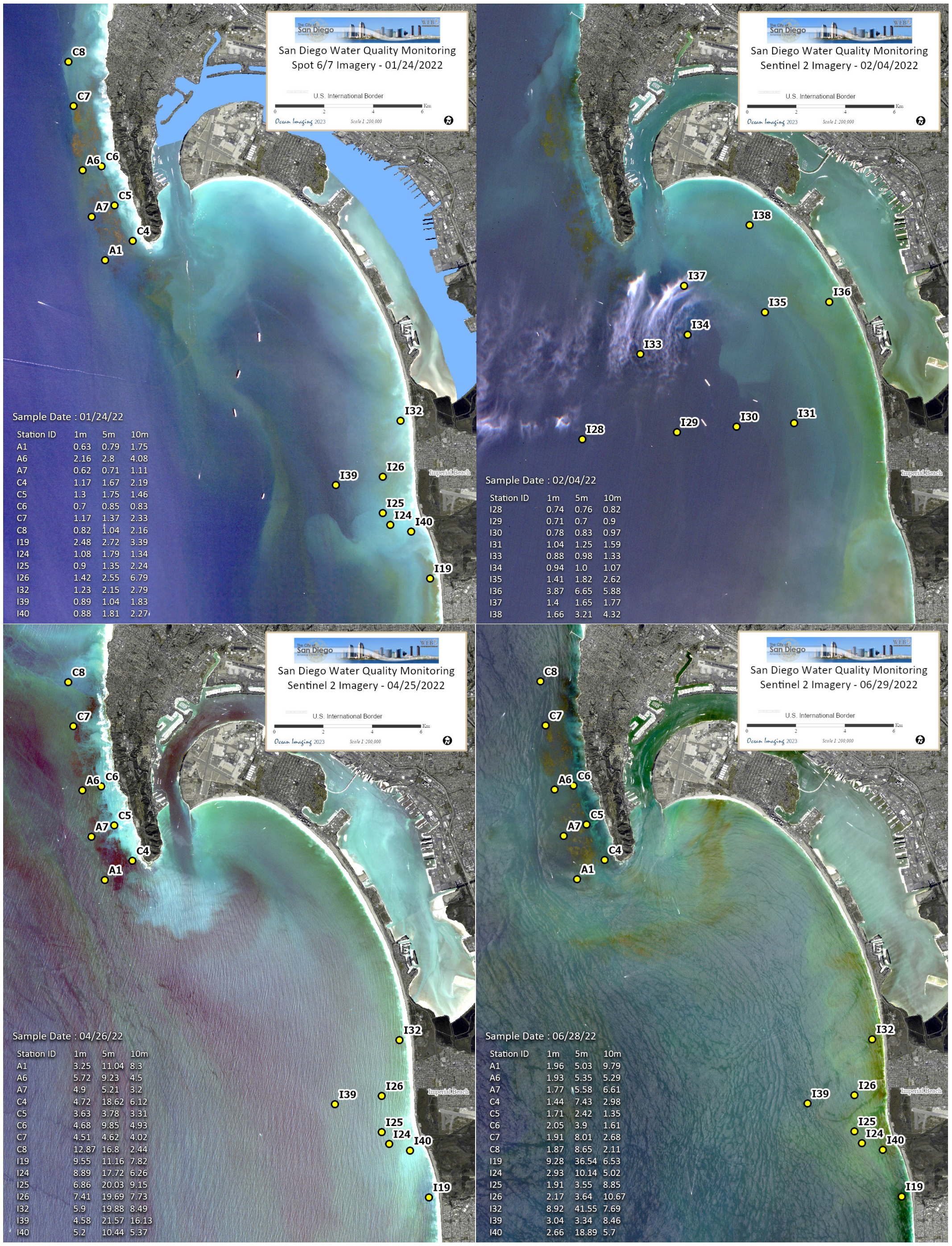


Figure 12. SPOT and Sentinel 2 imagery with CTD sampling data overlaid. SPOT image from 01/24/22 (top left) shows a day exhibiting high turbidity levels mixed with patchy plankton blooms. The Sentinel 2 image data from 02/04/22 (top right) is a day when samples were taken at the sites farther offshore and illustrates a time period when the offshore waters were relatively clear and low in chlorophyll, yet there were relatively strong plankton blooms right along the shoreline. The water column reflectance seen in the imagery from 04/25/22 (bottom left) was obscured somewhat by sun glint, but the green tint of the region-wide high chlorophyll levels is readily apparent and corresponds with the high sample measurements. The Sentinel 2 imagery from 06/29/22 (bottom right) with CTD data from 06/28/22 overlaid provides the most dramatic example of remarkably high chlorophyll measurements matching the green water in the South Bay region – especially along the shoreline.

in 2022 out of the 117 high resolution satellite scenes acquired and processed. Of the 23, two were instances of the plume observed by different satellites on the same day. This equates to 21 days when the plume was visible in the high-resolution imagery - five more than observed in 2021, but below the average percentage of SBOO plume surface observations per days imaged when compared to the previous 10 years (17.9% vs. 19.4% respectively). Appendix A includes the 2022 SPOT, Sentinel and Landsat imagery on days which the SBOO plume was detected. There were two occurrences when either Sentinel 2A or 2B data were acquired within only a few minutes of SPOT 6/7 data providing a near time-coincident validation of features observed in the imagery.

As has been the case in previous years, there was an occurrence when the SBOO effluent plume appeared in the imagery as a patch of clearer water breaking the more turbid water on the surface. As discussed in prior reports, the clear effluent signal in the imagery is most likely due to the contrast between the higher turbidity coastal surface waters and the 'normal' level of turbidity of the effluent water breaking the surface. It is also possible that the effluent plume became somewhat diluted on its way to the surface if weak vertical stratification did exist, thus slowing down its rise in the water column. Figure 13 provides an example of this situation as well as the satellite's view of a large, discolored discharge plume moving south from the TJR.

The period between 11/19/22 and 12/16/22 exhibited the highest frequency of 2022 SBOO effluent plume observations in the satellite data. As has been documented in previous reports, it is typical to see the highest number of SBOO surface plumes during the November to January timeframe. According to the 2022 IBWC Transboundary Flow Report the documented instances of sewage, solid waste and sediment moving across the U.S.-Mexico border and into the Tijuana Estuary and U.S. coastal waters occurred mainly between 01/07/22 and 03/11/22 and not in the latter part of the year (San Diego Regional Water Quality Control Board 2022). As is typically the case, the relatively frequent effluent surface manifestations that occurred during this time period were most probably the result of two primary factors: the lack of strong vertical stratification during the winter months and relatively weak subsurface currents over the SBOO which allowed the undispersed effluent to reach the surface.

There were several instances during this time period when the SBIWTP took on excess sewage from Tijuana exceeding the maximum capacity (25 MGD) of the SBIWTP. On 07/30/22 Mexico lost pumping capability at their main pumping station and additional flow was diverted to the SBIWTP. This can be seen in Figure 14, which shows the SBIWTP Effluent Flow rate (EFF Flow) and the Effluent Total Suspended Solids (EFF TSS) over the 2022 time period plotted with the dates on which SBOO effluent was observed on the surface of the ocean in the high-resolution satellite imagery. As is also apparent, there were a few spikes in EFF Flow and EFF TSS in the end of February and end of March, both due to rainfall events. Beginning in August the EFF flow averaged higher than the maximum capacity (25 MGD) of the treatment plant through the end of the year due to the loss of pumping capability mentioned above (IBWC monthly NPDES reports). However, no SBOO effluent was observed in the satellite data during the early season flow/TSS spikes or prior to November. There were 12 days on which the SBOO surface plume was evident in the satellite imagery between November 1st and the end of 2022 and 2, 15 and 8 documented days during the same periods of 2021, 2020 and 2019 respectively. This indicates that, while there were a relatively high number of effluent surface observations late in 2022, it cannot be concluded that the additional flow diverted through SBIWTP resulted in the effluent reaching the ocean's surface more often. It should also be noted that the higher flow rate did not result in the effluent breaking through the pycnocline during the months of August through October. This corroborates the belief that the instances of effluent reaching the surface almost always occur because of seasonal changes in ocean conditions when the water column stratification breaks down and is not directly related to a higher flow rate through the system.

A total of 19 shoreline stations, ranging from Mission Beach to northern Baja (across the US/Mexico border) are sampled weekly by City of San Diego staff to monitor the levels of three types of fecal indicator bacteria (i.e., total coliform, fecal coliform, Enterococcus bacteria) in recreational waters. An additional 15 nearshore (kelp) stations are also sampled weekly to monitor Fecal Indicator Bacteria (FIB) and a range of water quality parameters (i.e., temperature, salinity, dissolved oxygen, pH, transmissivity, Chlorophyl-a, CDOM). Furthermore, 69 offshore stations are sampled quarterly to monitor both water quality conditions and one or more types of FIB. PLOO stations are located along, or adjacent to, the 18, 60, 80, and 98-m depth contours, and SBOO stations are located along the 9, 19, 28, 38, and 55-m depth contours.

The City Marine Microbiology Laboratory (CMML) follows guidelines issued by the U.S. Environmental Protection Agency (USEPA) Water Quality Office, State Water Resources Control Board (SWRCB) including the 2019 Ocean Plan, the California Department of Public Health (CDPH), and Environmental Laboratory Accreditation Program (ELAP) with respect to sampling and

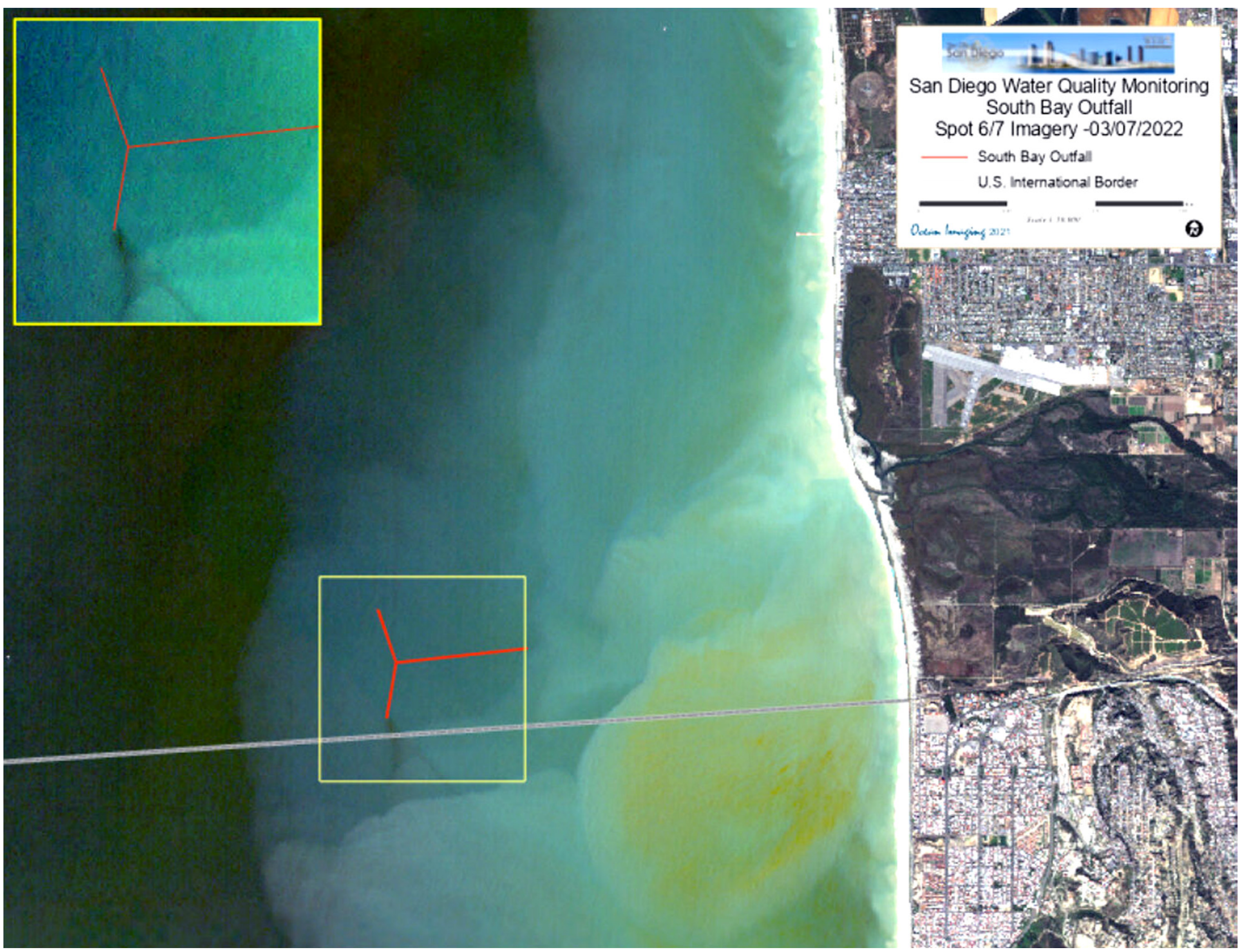


Figure 13. SPOT image showing a SBOO surface signature being clearer than the surrounding turbid water. Also note the heavy TJR discharge moving south from the river mouth.

analytical procedures (Bordner, et. al. 1978, American Public Health Association (APHA) 2012, CDPH 2019, USEPA 2014). All bacterial analyses were initiated within eight hours of sample collection and conformed to standard membrane filtration techniques, for which the laboratory is certified (ELAP Field of Testing 126). FIB densities were determined and validated in accordance with USEPA and APHA guidelines as follows in APHA (2012).

In 2022, the sampling area of the SBOO/Tijuana River outflow region experienced 56 days on which the field sampling showed FIB measurements exceeding the single sample maximum for fecal coliform density for one or more sampling stations as defined by the 2019 California Ocean Plan (the single sample maximum fecal coliform density at a site will not exceed 400 per 100 mL) (SWRCB, 2019). The offshore SBOO region, which includes the stations over the SBOO wye experienced only two days of elevated bacteria levels at depths of six meters or shallower and the nearshore region (referred to as the "kelp" region in previous reports) experienced 21 days on which the bacteria levels were deemed elevated. There were 47 sampling days when at least one shore station showed elevated levels. The total number of sampling days for all three SBOO areas totaled 96 in 2022 and 122 in 2021. Therefore, in 2022 for the three sampling regions combined, 58.3% of the sampling days resulted in elevated bacteria levels at one station or more, which is less than the 64.7% recorded in 2021 (using the same 2019 California Ocean Plan standards). As has been typical in recent years, the majority of the samples showing elevated levels were recorded at the shore stations. Elevated levels offshore near the SBOO wye are rare. Of the two days when elevated bacteria levels were recorded at an offshore station, both (station I5 and I11) are over five kilometers from the SBOO wye.

The satellite imagery showing substantial discharge from the TJR region often correlate with times when the shoreline and kelp area sampling showed elevated bacteria levels. Heavy and/or persistent rainfall is the

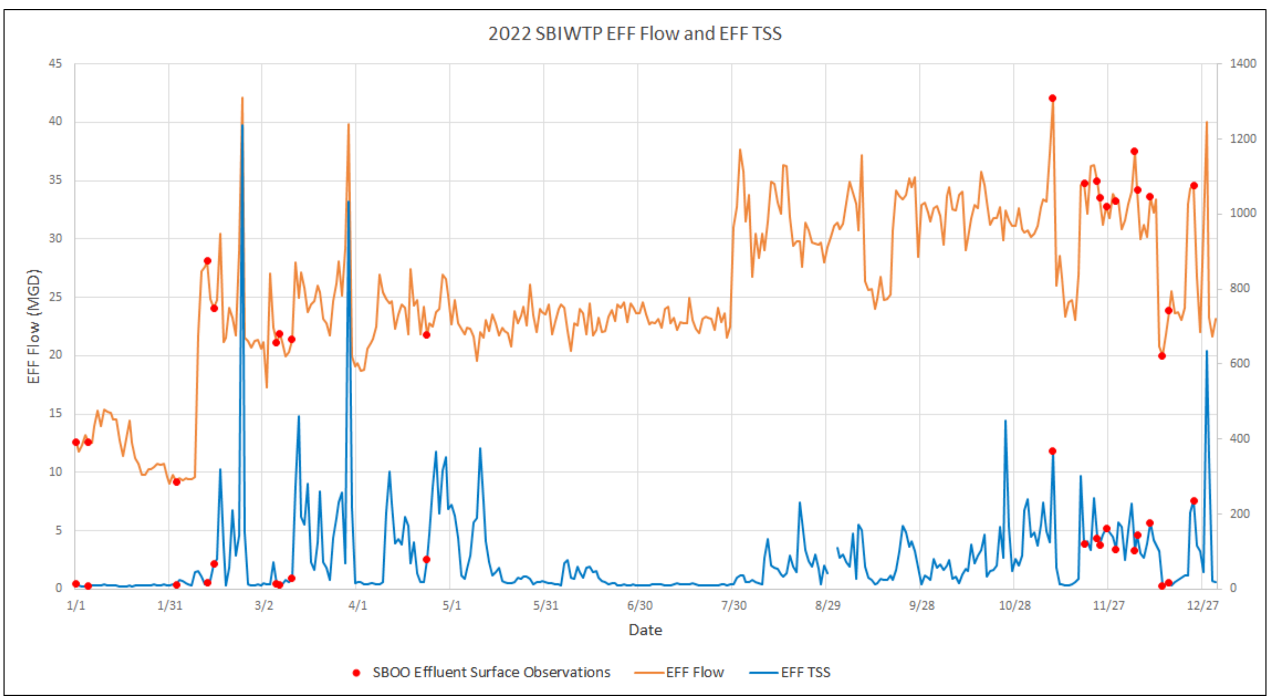


Figure 14: SBIWTP EFF flow rate and EFF TSS over the 2022 time period plotted with the dates on which SBOO effluent was observed on the surface of the ocean in the high-resolution satellite imagery (red dots = dates for the same date are plotted with the corresponding EFF flow and EFF TSS data). Data courtesy of the IBWC.

most plausible cause for the majority of the elevated bacteria samples and turbid waters seen in the remote sensing data. Figure 15 shows a few examples of the bacteria sample data overlaid on top of imagery from either the same day or on day after the sampling date. Note the very turbid water emanating from the TJR river and nearby coastline moving to the north on 12/14/22. The southern San Diego beaches were closed from 12/01/22 through the end of the year.

Typically, the best water quality and clarity in the South Bay region is observed from May through August. This was generally true in 2022. Water clarity in the South Bay region was, however, variable during May though August as phytoplankton blooms in the area were prevalent during the summer months.

3.3 The Point Loma Outfall Region

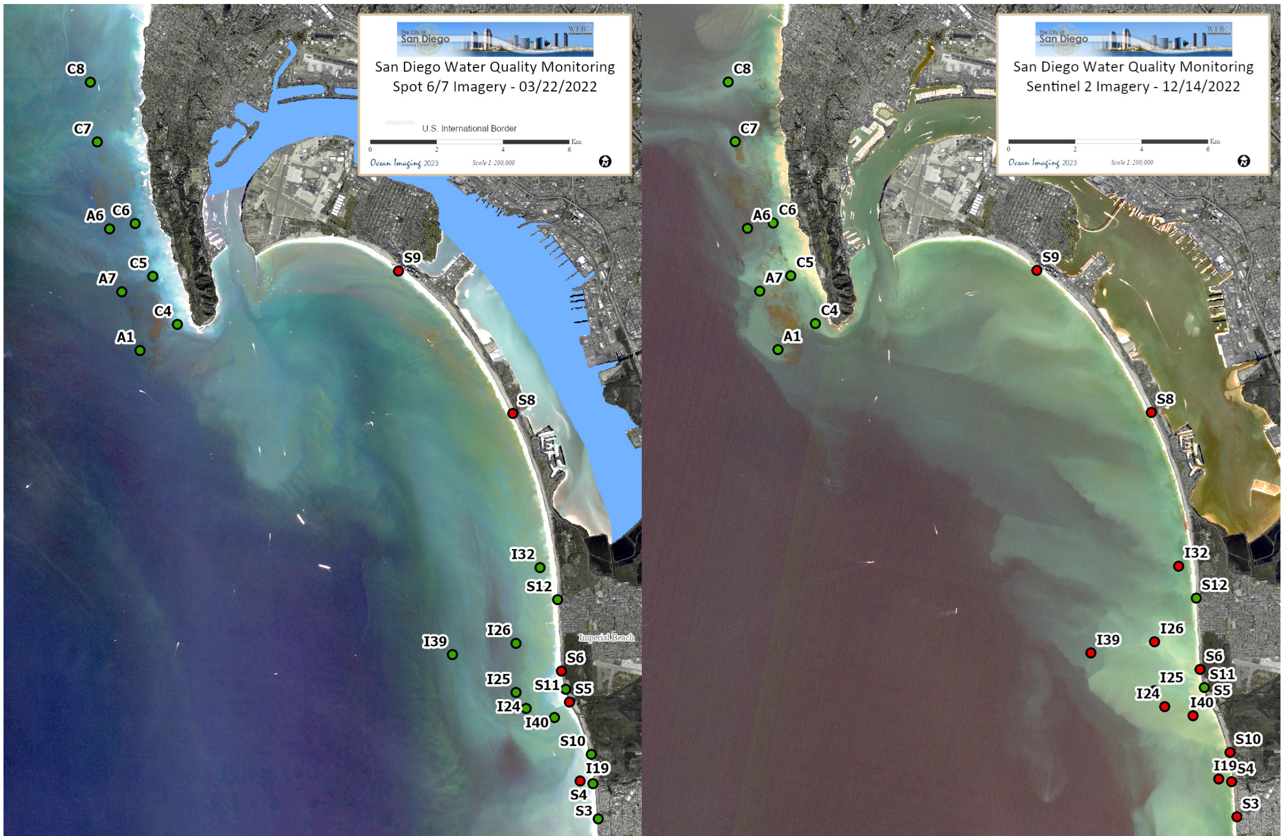
After its seaward extension in 1993, the Point Loma Ocean Outfall (PLOO) is one of the deepest and longest wastewater outfalls in the world, discharging at the depth of 320 feet, 4.5 miles offshore. The outfall's plume is generally not observed directly with multispectral color or thermal imagery. It appears to not reach the surface waters, even during the winter months when the water column's vertical stratifications are weakened. We believe 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.

In 2022 the Point Loma region was affected by conditions already described for general San Diego County: significant seasonal rainfall during the months of January through March and then again in September through December and almost no rainfall during the months of April through August. Similar to past years, this compromised water clarity is likely a result of runoff from the San Diego River and Mission Bay bringing sediment-laden water inside and outside the Point Loma kelp bed after the rain events described above.

The shoreline, kelp and offshore bacterial sampling resulted in a slightly higher number of elevated bacteria measurements than in 2021 as defined by the 2015 California Ocean Plan (Total coliform density will not exceed 10,000 per 100 mL; or Fecal coliform density will not exceed 400 per 100 mL; or Total coliform density will not exceed 1,000 per 100 mL when the ratio of fecal/total coliform exceeds 0.1; or enterococcus density will not exceed 104 per 100 mL) (SWRCB, 2015). Shoreline field sampling yielded 10 days on which one or more stations experienced high bacteria counts. Offshore and kelp station sampling resulted in 8 days and 0 days respectively when stations recorded excessive FIBs. Figure 16 presents an example when three stations in the Point Loma sampling area showed high FIB numbers on 11/15/22. These data are plotted on top of the Sentinel 2 image from 11/16/22. While the imagery from the 16th does not show evidence of any direct correlation to the bacteria samples taken the day before, the image from 11/10/22 does offer an explanation as it documents the substantial discharge from the Mission Bay entrance along with the heavy coastal runoff from there to the south. The Tijuana Estuary station measured 0.94 inches of precipitation between 11/07/22 – 11/09/22 and the SDIA station reported 0.91 inches between 11/08/22 and 11/10/12. An alternate explanation would be that the measurements (all in close proximity to the PLOO wye risers) show high FIB originating from the outfall trapped by a pycnocline barrier at depth so any surface presence would not be visible in the satellite imagery.

3.4 Kelp Variability

One observation provided by the satellite image archive is the continuing variability in the size of the Point Loma kelp bed over time (Figure 17). Table 4 shows the area in km^2 of three notable kelp beds in the San Diego region over the past 15 years.

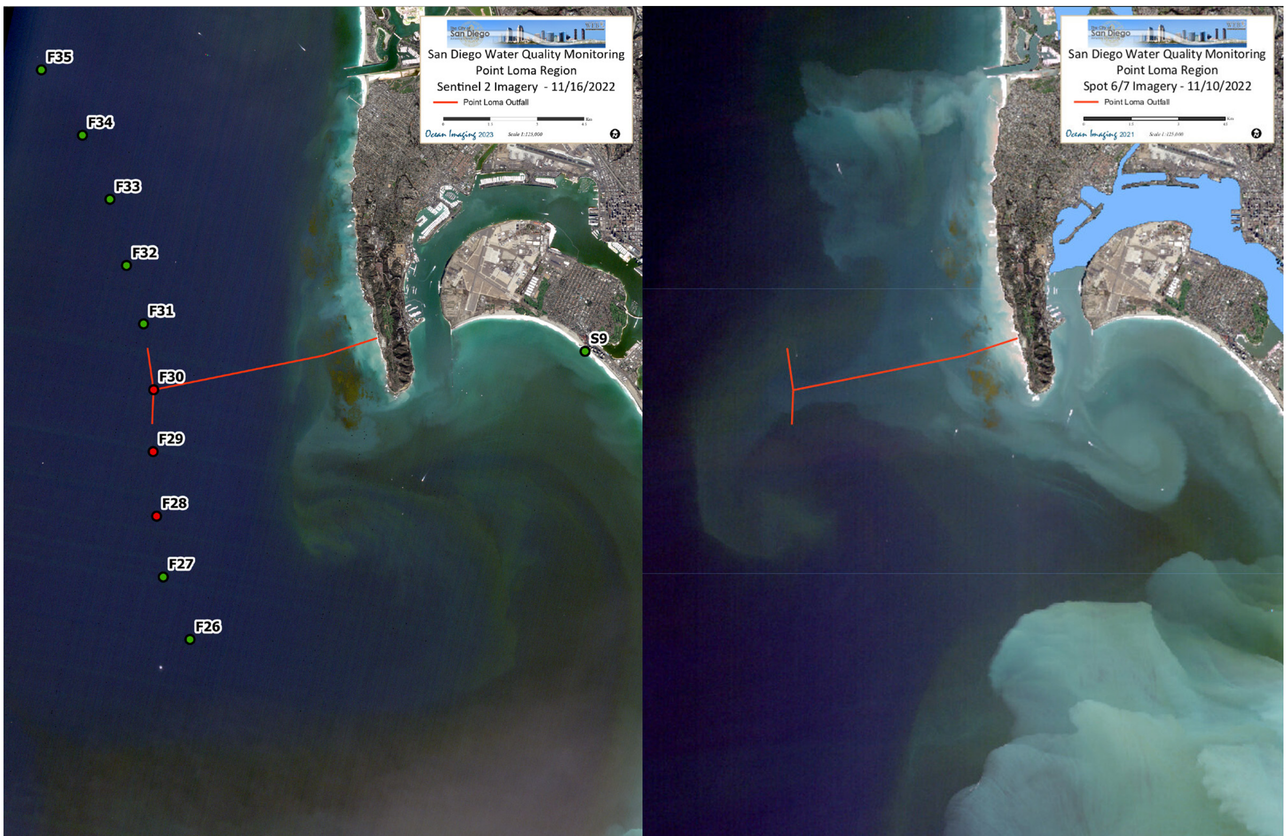


Station	Depth (M)	Entero	Fecal	Total
I19	2	680	12000	16000
	6	66	900	9600
	11	300	2200	16000
S0	NA	12000	6200	16000
S2	NA	12000	12000	16000
S5	NA	120	3400	16000
S6	NA	1400	12000	16000
S8	NA	12000	12000	16000
S9	NA	12000	12000	16000

Station	Depth (M)	Entero	Fecal	Total
I19	2	320	300	1400
	6	280	480	3400
	11	280	140	1600
I24	2	580	740	4400
	6	100	80	840
	11	6800	6400	16000
I25	2	420	680	4400
	6	980	980	5400
	9	880	700	9600
I26	2	200	80	1800
	6	3400	5400	16000
	9	5800	4000	16000
I32	2	240	320	3200
	6	280	300	3200
	9	400	460	3400
I39	2	680	1000	20
	12	160	100	2
	18	200	160	20
I40	2	1000	840	15000
	6	980	800	3000
	9	4800	2800	16000
S0	NA	1400	1400	5800
S2	NA	2600	2200	16000
S3	NA	1400	880	15000
S4	NA	460	940	10000
S5	NA	1600	800	11000
S6	NA	2400	1800	14000
S8	NA	2600	3600	16000
S9	NA	11000	12000	16000
S10	NA	860	760	6600

Figure 15. Sentinel 2 and SPOT data with near-surface bacterial sampling data overlaid from the same day of image acquisition. Stations showing FIB measurements exceeding the single sample maximum as defined by the 2019 California Ocean Plan are shown as red dots. Green dots identify stations at which the FIB levels were in compliance. The tables below each image show the measurement values by depth for each station with elevated bacteria levels. Stations S0 and S2 listed in the table are not shown in the imagery.

The September and October dates were chosen to represent the kelp bed canopy coverage for each year since spring and fall are considered to be the time periods when the canopy size is thought to be at or near its peak. The estimated size of the Point Loma bed canopy in the fall of 2022 (4.48 km^2) was larger than the average canopy coverage for the 15-year period (4.07 km^2). As has been reported in previous years, the satellite data show the bed begin to decrease in size during February of 2016, perhaps due to the storm events taking place during early to mid-January, effects from the 2014-2016 strong El Niño event and/or the Northeast Pacific marine heat wave (Di Lorenzo 2016). Noted in the 2017 and 2018 annual reports, 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 that year. Using the fall imagery as an indicator for annual health, the bed size appears to be stabilizing since the 2016 and 2017 lows. Contrary to 2018, 2020 and 2021 when the canopy area exhibited significant intra-annual variability, in 2022 the bed size remained somewhat consistent throughout the year. While there were short periods of time in 2022 when the bed's canopy showed a significant decrease in size, overall, the monthly variability in canopy area as judged by visual assessment was relatively stable



Station	Depth (M)	Entero	Fecal	Total
F28	80	320	NA	NA
F29	60	1100	NA	NA
	80	180	NA	NA
F30	60	200	NA	NA
	80	120	NA	NA

Figure 16. Sentinel 2 image acquired on 11/16/22 with bacterial sampling data overlaid from the day prior (top left). Stations showing FIB measurements exceeding the maximum allowed as defined by the 2015 California Ocean Plan are shown as red dots. Green dots identify stations at which the FIB levels were in compliance. The table below the 11/16/22 image shows the measurement values by depth for each station with elevated bacteria levels. SPOT image from 11/10/22 (top right) reveals the heavy river and bay discharge as well as coastal runoff a few days prior to the station sampling.

(Figure 18). On average, the month of September exhibited the largest decrease in canopy coverage – even though September is typically considered to be a peak growth month. While there were significant differences in tidal heights at the time of each satellite image acquisition, tides cannot be flagged as the primary reason for the difference in canopy coverage observed in the satellite data. There were days when the areal coverage was high, but the tide level was also high and vice versa when the imagery revealed smaller bed size, but the tides were relatively low.

Canopy coverage for each year in Table 4 was computed by first running a Normalized Difference Vegetation Index (NDVI) classification followed by an unsupervised iso cluster unsupervised classification to generate a single exposed kelp class. It is important to point out that the canopy

Figure 17. The Point Loma kelp bed as observed in high-resolution satellite imagery for the years 2013-2022 (top to bottom). September and October dates were chosen to represent the kelp bed canopy coverage for each year since that period is when the canopy size is thought to be at or near its peak.

Table 4. Kelp canopy areas of three San Diego kelp beds measured from satellite imagery collected for this project.

			Kelp (km^2)		
Year	Date	Satellite	Point Loma	Imperial Beach	Tijuana
2022	10/20/2022	Sentinel-2B	4.48	0.00	0.00
2021	09/30/2021	Sentinel-2B	3.82	0.00	0.00
2020	09/22/2020	Sentinel-2A	2.93	0.00	0.00
2019	09/18/2019	Sentinel-2A	5.17	0.00	0.00
2018	10/16/2018	Sentinel-2A	2.44	0.00	0.00
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

* Average surface canopy coverage 2008-2022 = 4.07 km^2

coverages shown in Table 4 may differ slightly from those provided in the Southern California Bight Regional Aerial Kelp Survey reports. This is because the canopy areas for the Point Loma bed computed for those reports are averages of four surveys performed throughout the year; while the coverage estimates shown in this report are taken from single satellite images acquired during the fall time period chosen to represent the maximum coverage experienced during that time of year. Tide levels were not a factor in the inter-year comparison as there was little variability in tide level between the years (often approximately two feet or less). However, due to the overflight times of these satellites, the canopy areas could be underrepresented compared to the kelp survey reports because the tide levels at the time of satellite data acquisition could vary significantly from the tides during the aerial surveys. The Imperial Beach and Tijuana beds have not been visible in the satellite data since 2015. It documented that kelp forests along the West Coast have been experiencing noteworthy variability in canopy size for the past several years, and thus warrants keeping a close watch on the health of the kelp beds in the San Diego region (Bell, et al. 2020, Schroeder 2019).

4. PRESENT AND FUTURE ENHANCEMENTS OF THE 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 was working to implement. It was intended that all the OI-delivered data products, including all the satellite imagery would be delivered via OI's ArcGIS Server for easy ingestion into the City's WMS by fall of 2017. While this system has not yet been implemented, OI is in discussion with the City about further developing the project's web server into dashboard style site that incorporates an interactive WMS to better facilitate the delivery of all the existing data products, the HYCOM oceanographic products and any other data sets that the City choose to visualize via the platform. Not only will the server give the user the capability to overlay different data types on top

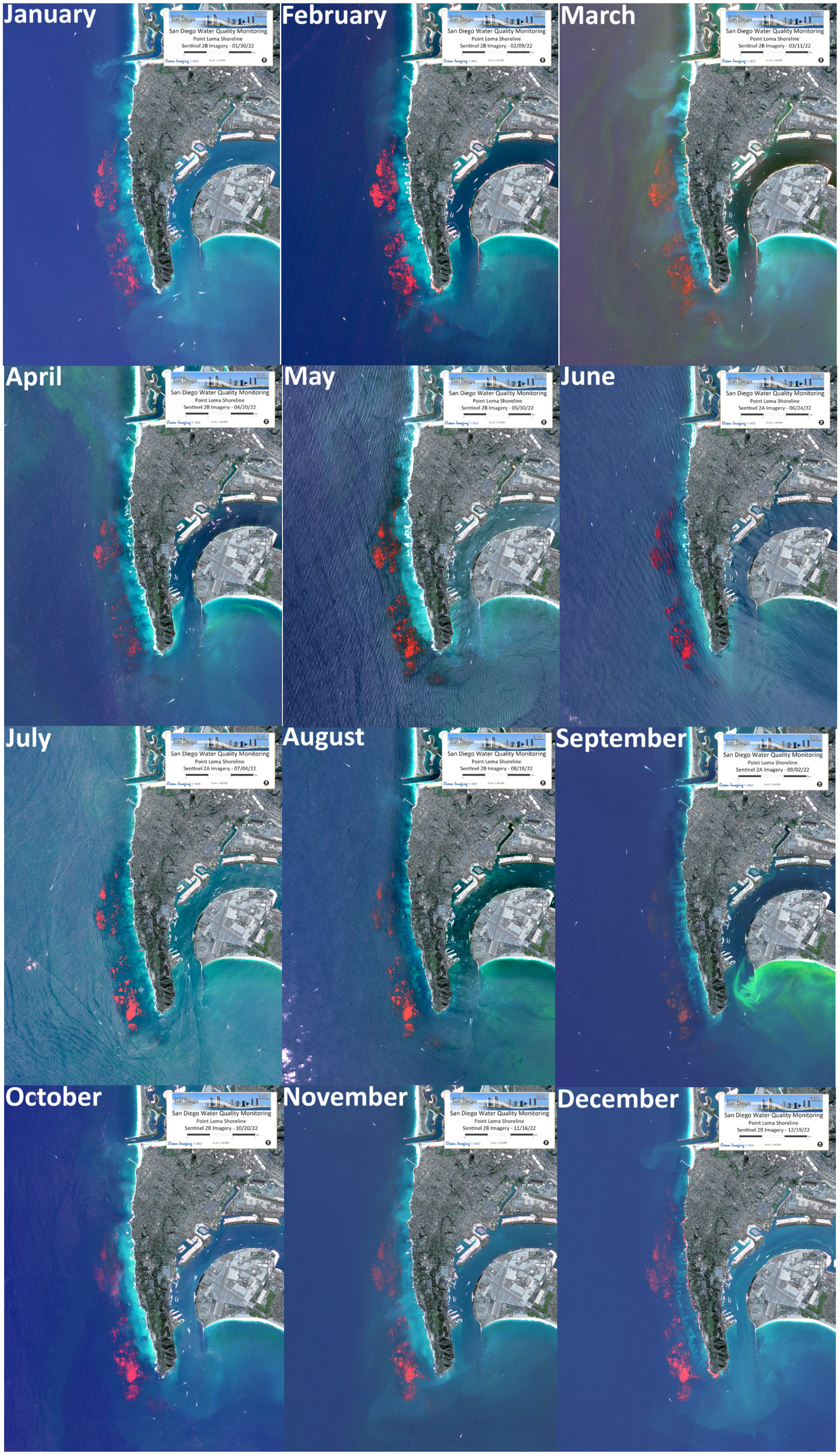


Figure 18. Sentinel 2 satellite imagery documenting the month-to-month variability in the Point Loma kelp bed canopy coverage. The dates were chosen to best represent the maximum-observed canopy coverage for each month.

of each other (i.e., ocean currents on top of satellite imagery) it will significantly enhance the information experience providing easy, near real-time access to the many data products delivered as part of this project. As part of this process, the historical imagery, data, and reports will remain accessible via the existing web portal. If a more capable web server comes online, OI will progressively work backwards in time to make all historical data available via the City's online WMS, including the archived HYCOM data products.

In the interim this past year, OI updated the project's existing web site to better present the various data products and increase end user interaction. Figures 19a and 19b provide examples of the new look. The upgrades to the site are intended to give the visitor quick, "at a glance" access to thumbnail images for a particular monitoring region from the most recent 10 days in an interactive carousel-style gallery. Clicking on a thumbnail image will open a page with access to the matching month and imaging region. The new site also reduces excessive text links for the older data sets and provides one-click access to the data archive pages. If implemented, the new, dashboard style site will include some of the aspects of this design but add different data types to the front page 'dashboard' and include the interactive WMS component allowing the overlay and comparative analysis of different oceanographic and biological data types.

Figure 19a. (left) Home page of OI's updated water quality monitoring website showing the image slider display of the most recent imagery.

Figure 19b. (right) Data access page for the South Bay high-resolution satellite imagery on the updated web server.

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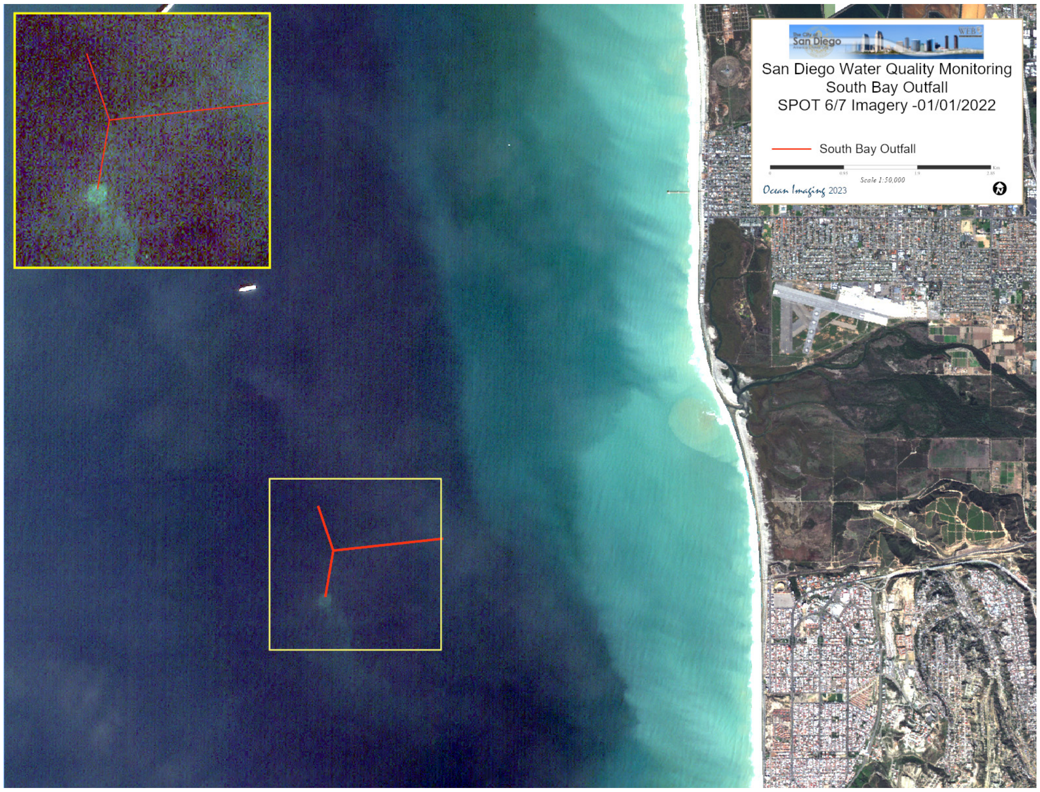
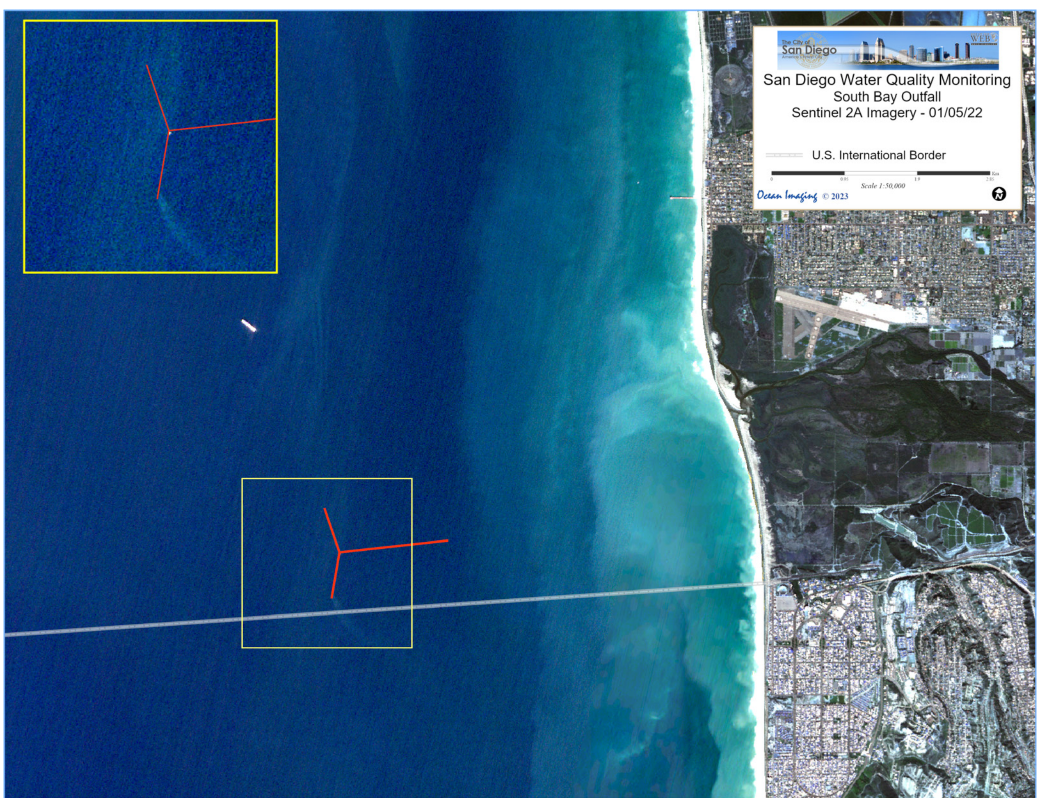
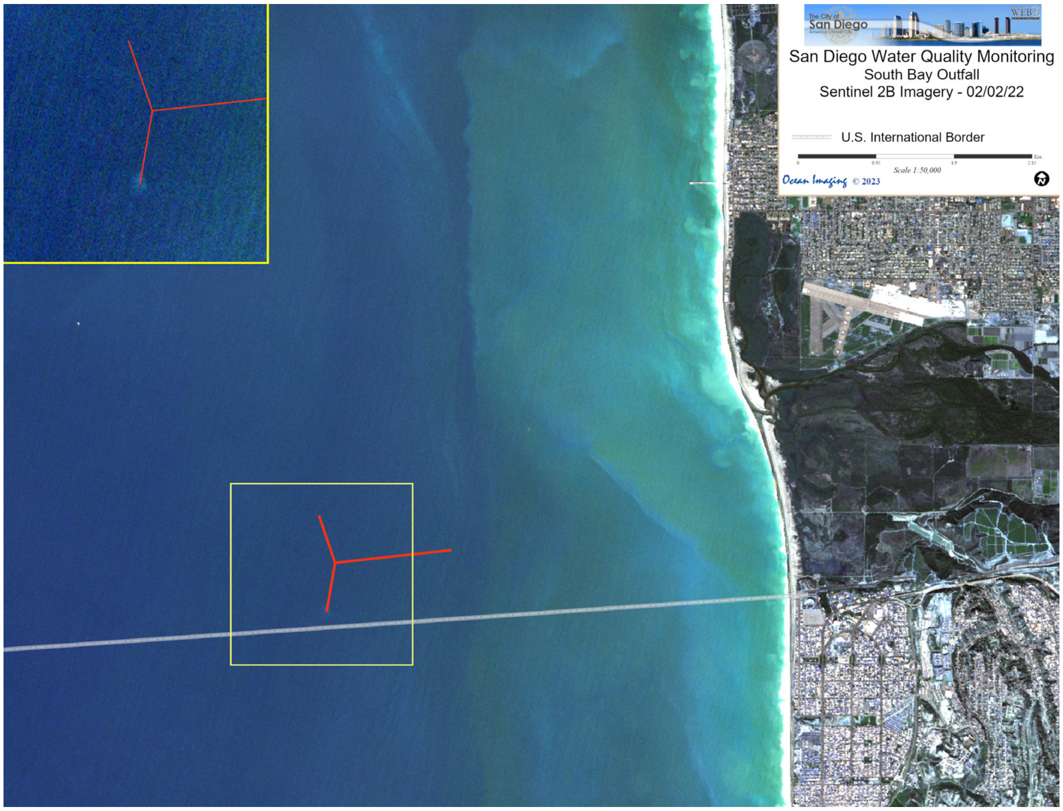
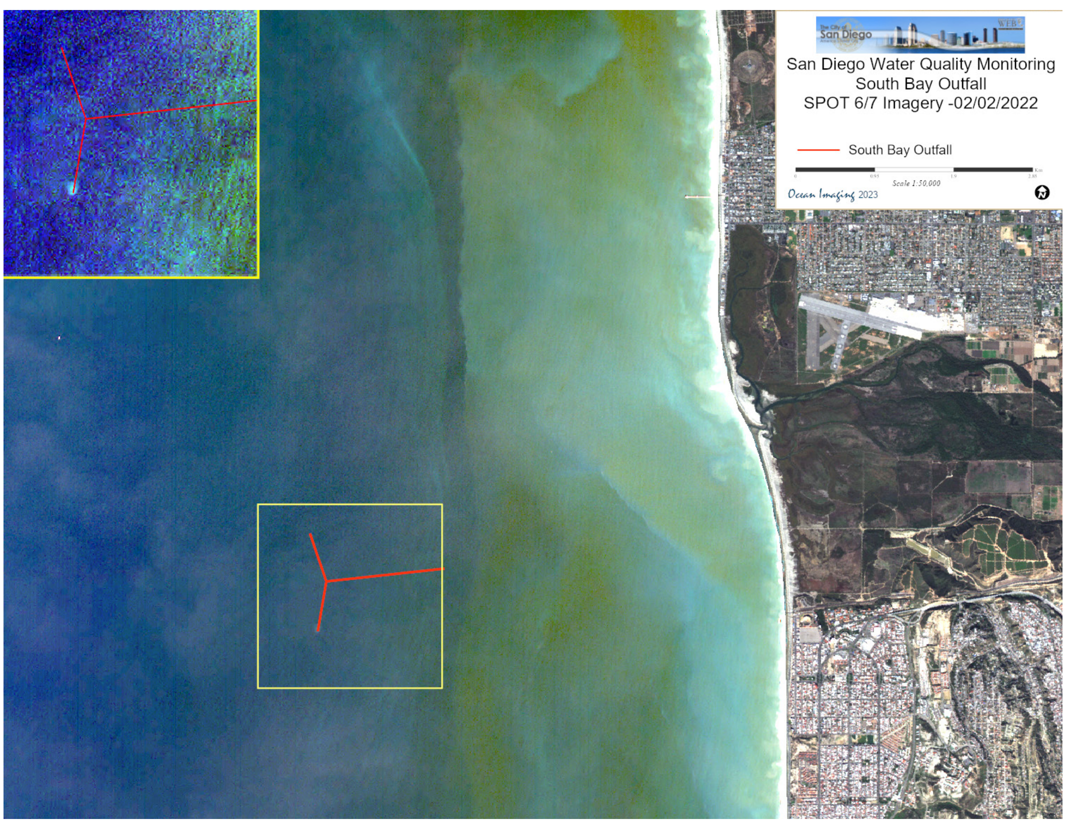
APPENDIX A – HIGH RESOLUTION SATELLITE IMAGERY SHOWING SBOO-RELATED WASTEWATER PLUME






The City of San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 02/02/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023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South Bay Outfall
SPOT 6/7 Imagery -02/02/2022
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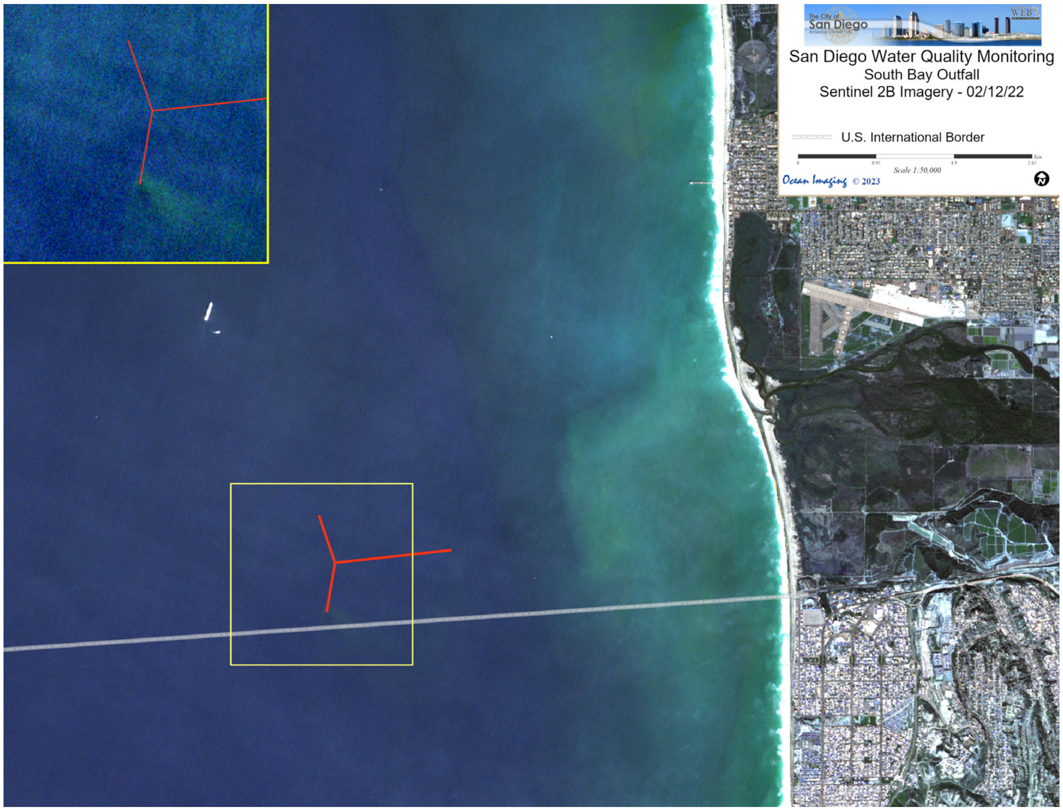
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Sentinel 2B Imagery - 02/12/22
U.S. International Border
Scale 1:50,000
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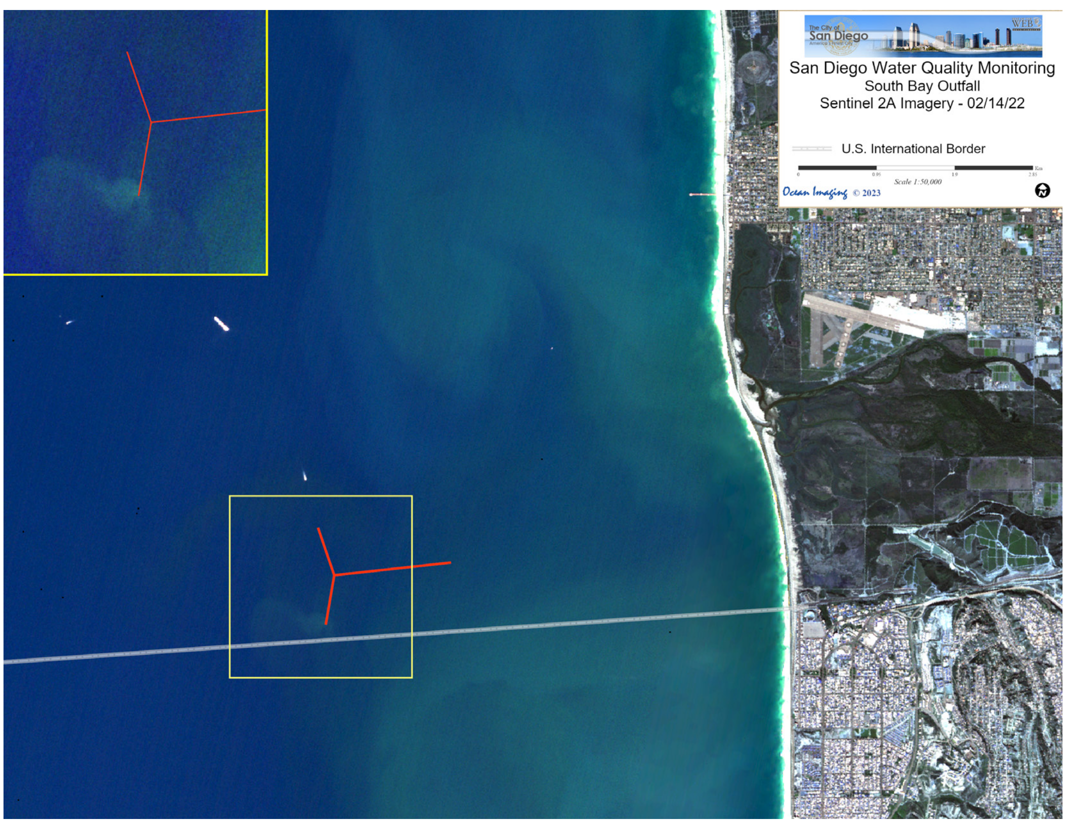
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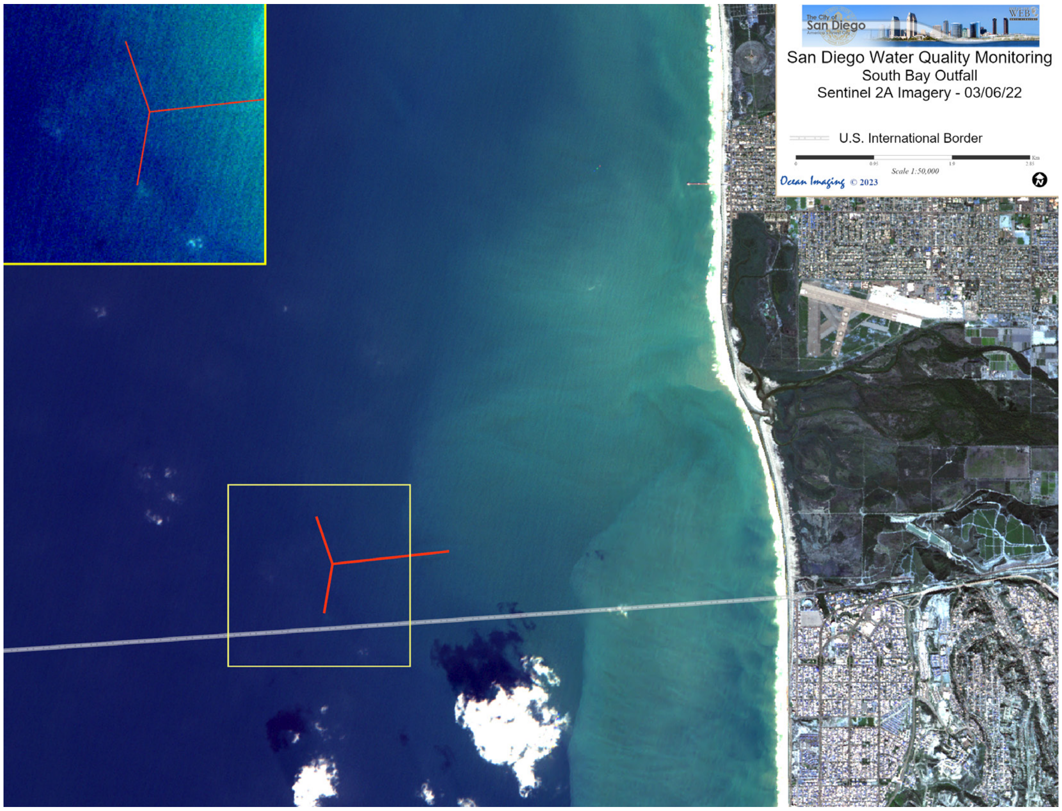
Ocean Imaging © 2023


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2A Imagery - 03/06/22
U.S. International Border
Scale 1:50,000
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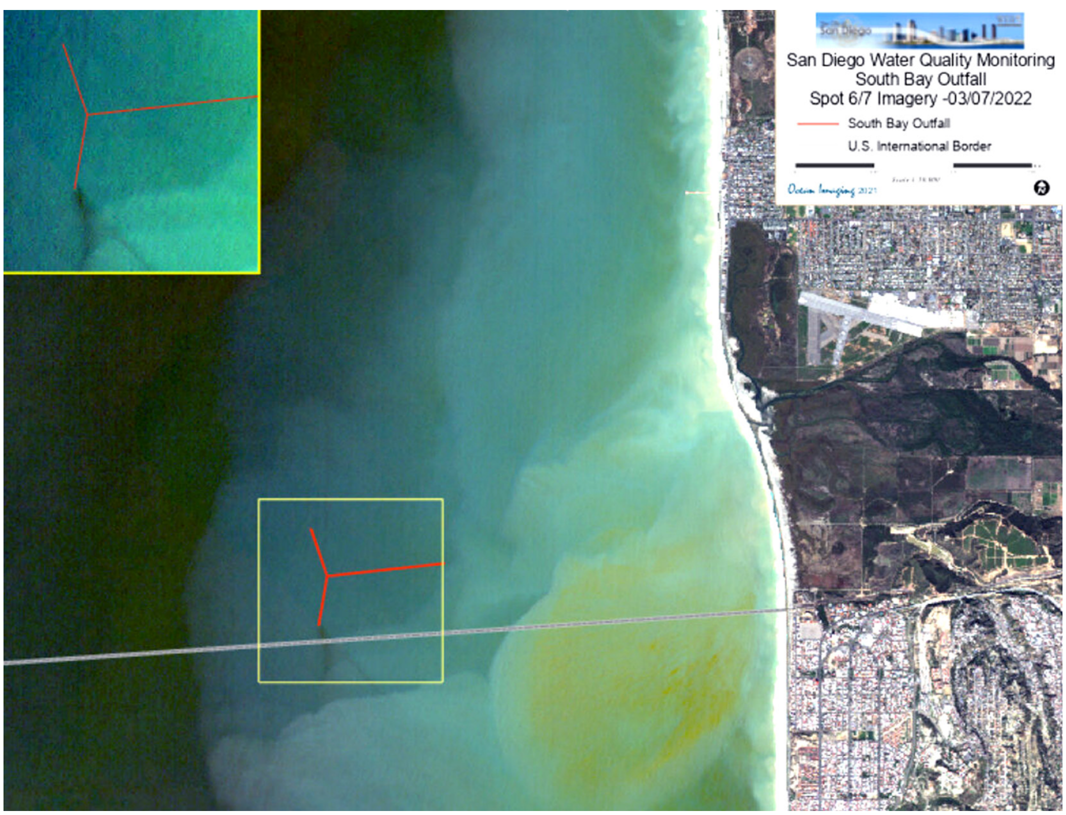
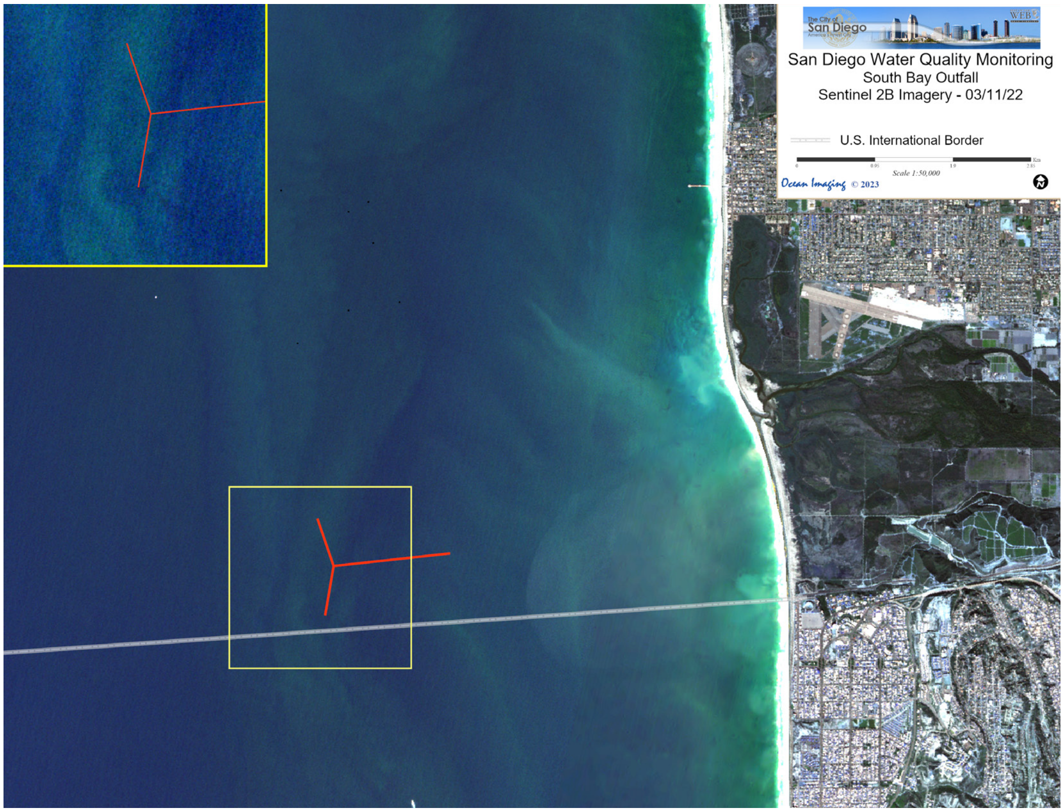
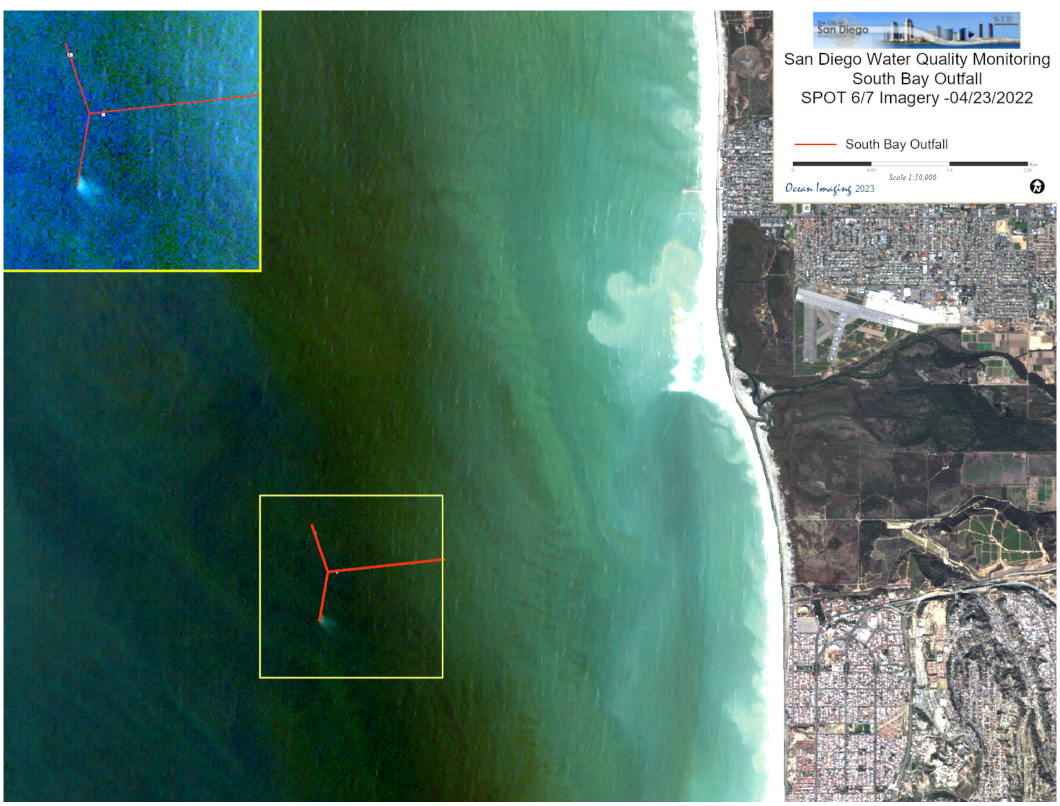
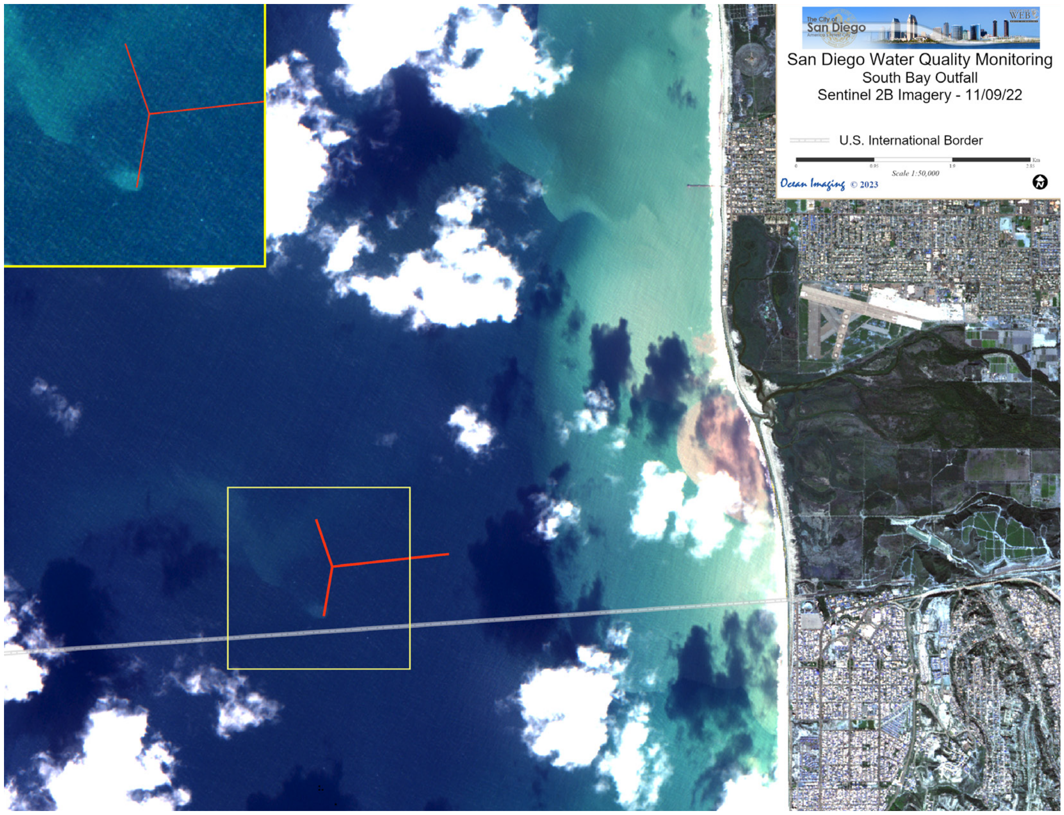

San Diego Water Quality Monitoring
South Bay Outfall
Spot 6/7 Imagery -03/07/2022
South Bay Outfall
U.S. International Border


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 03/11/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023


San Diego Water Quality Monitoring
South Bay Outfall
SPOT 6/7 Imagery -04/23/2022
South Bay Outfall
Scale 1:50,000
Ocean Imaging 2023


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 11/09/22
U.S. International Border
Scale 1:50,000
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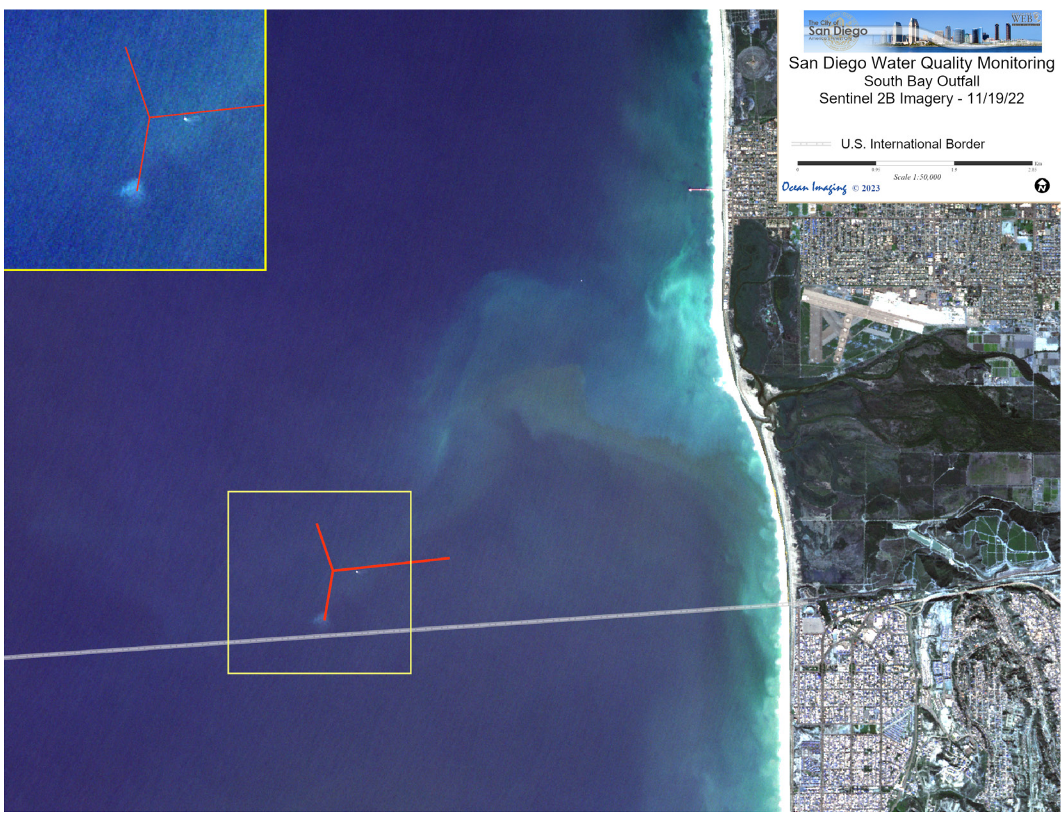
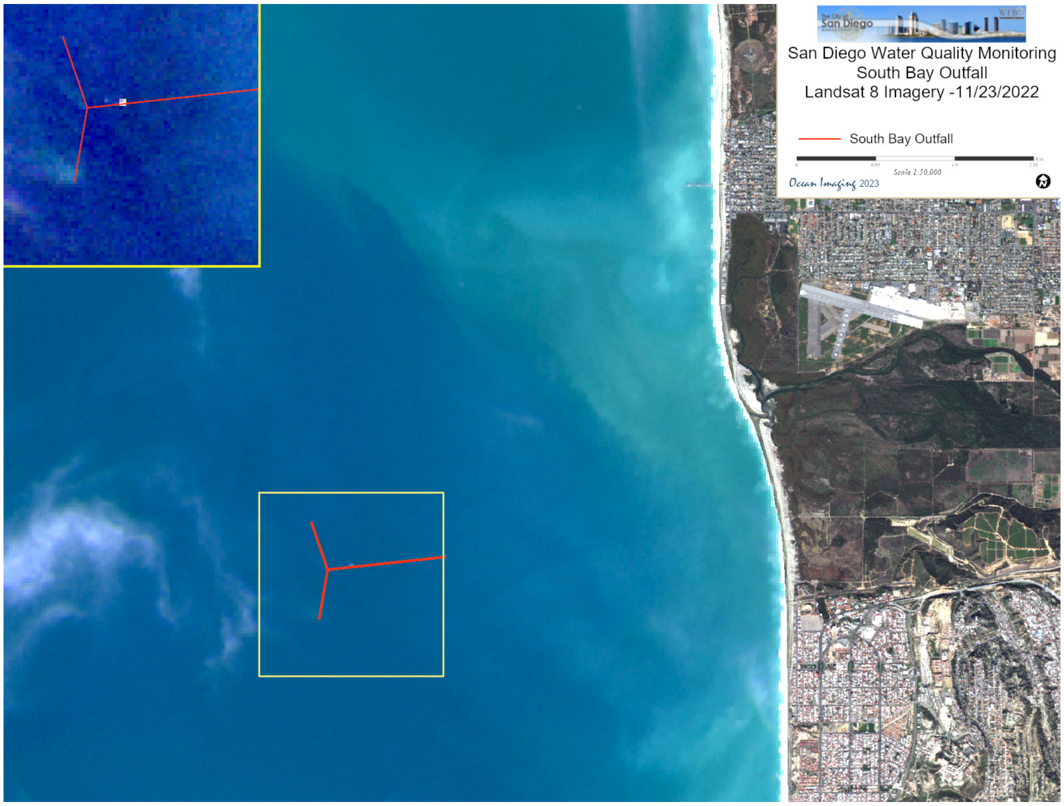
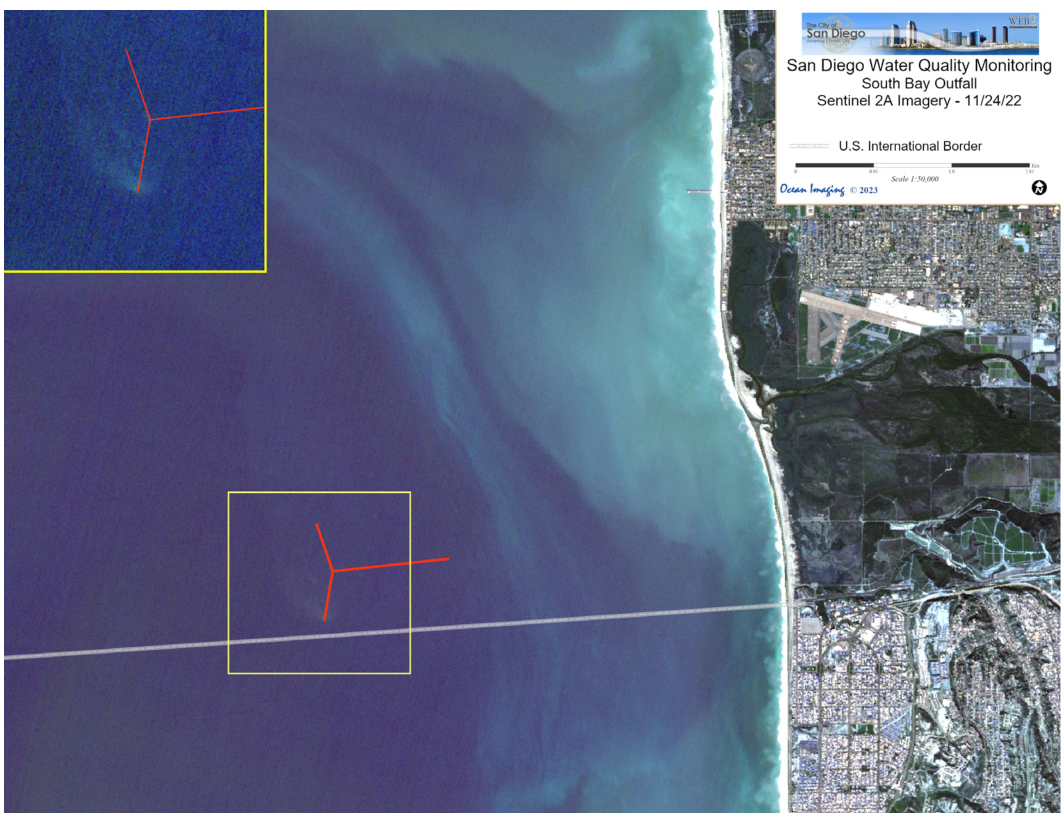
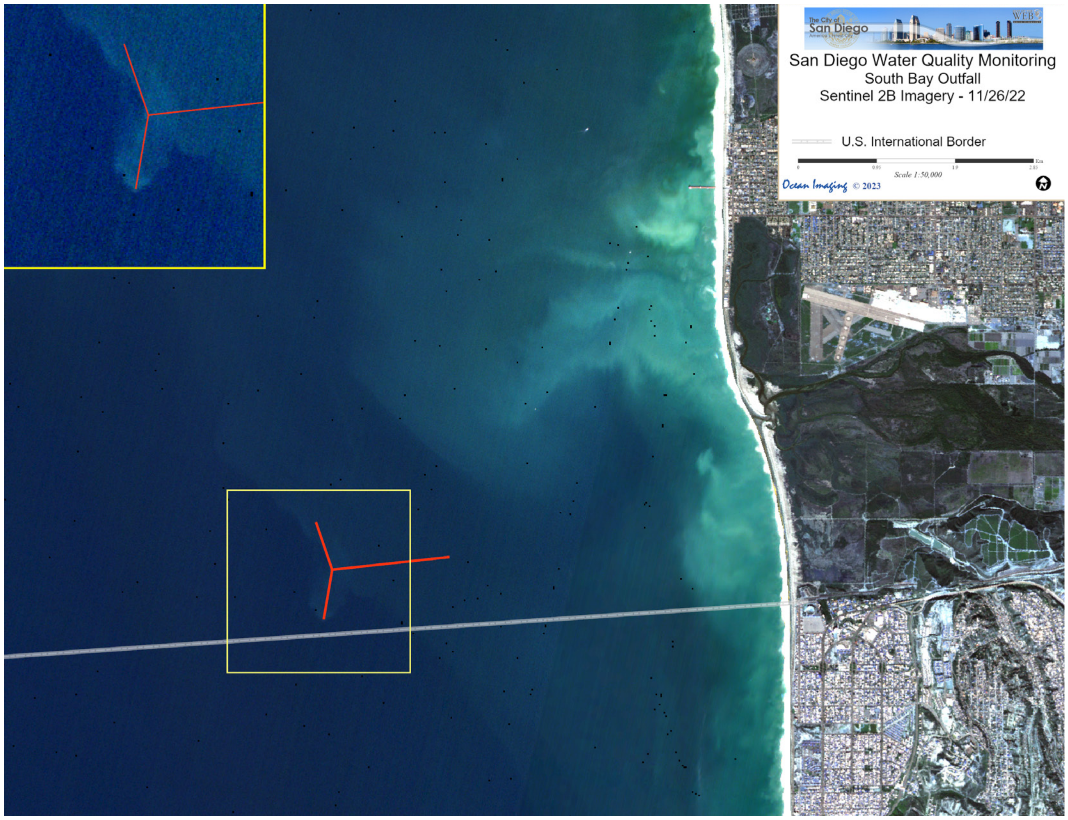
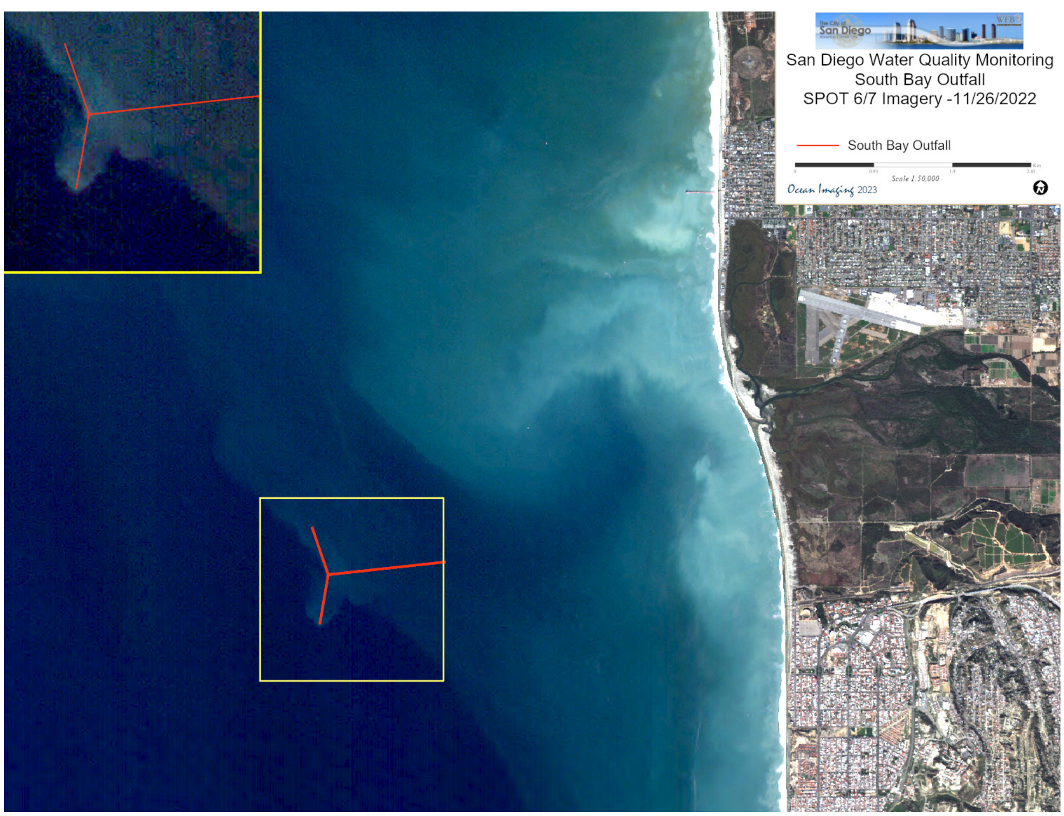

San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 11/19/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023


San Diego Water Quality Monitoring
South Bay Outfall
Landsat 8 Imagery -11/23/2022
South Bay Outfall
Ocean Imaging 2023


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2A Imagery - 11/24/22
U.S. International Border
Ocean Imaging © 2023


The City of San Diego
America's Finest City
WEB
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 11/26/22
U.S. International Border
0
0.95
1.9
2.85
Km
Scale 1:50,000
Ocean Imaging © 2023
N


The City of San Diego
WEB
San Diego Water Quality Monitoring
South Bay Outfall
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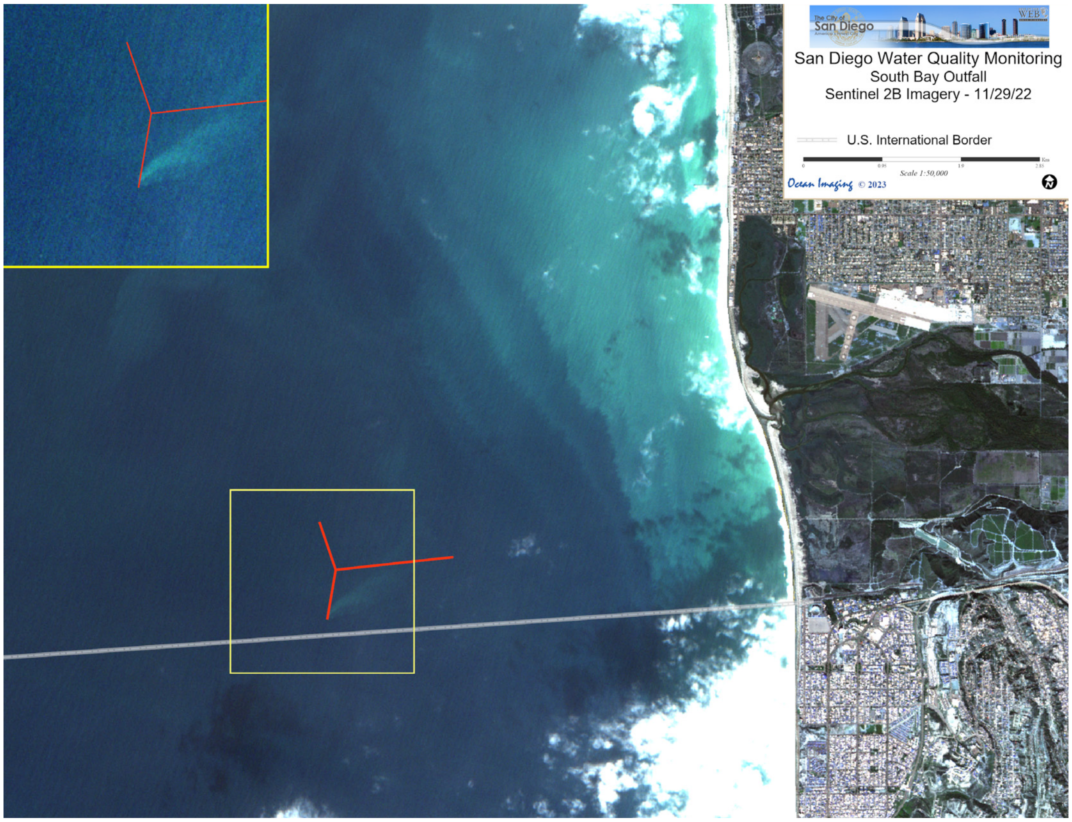
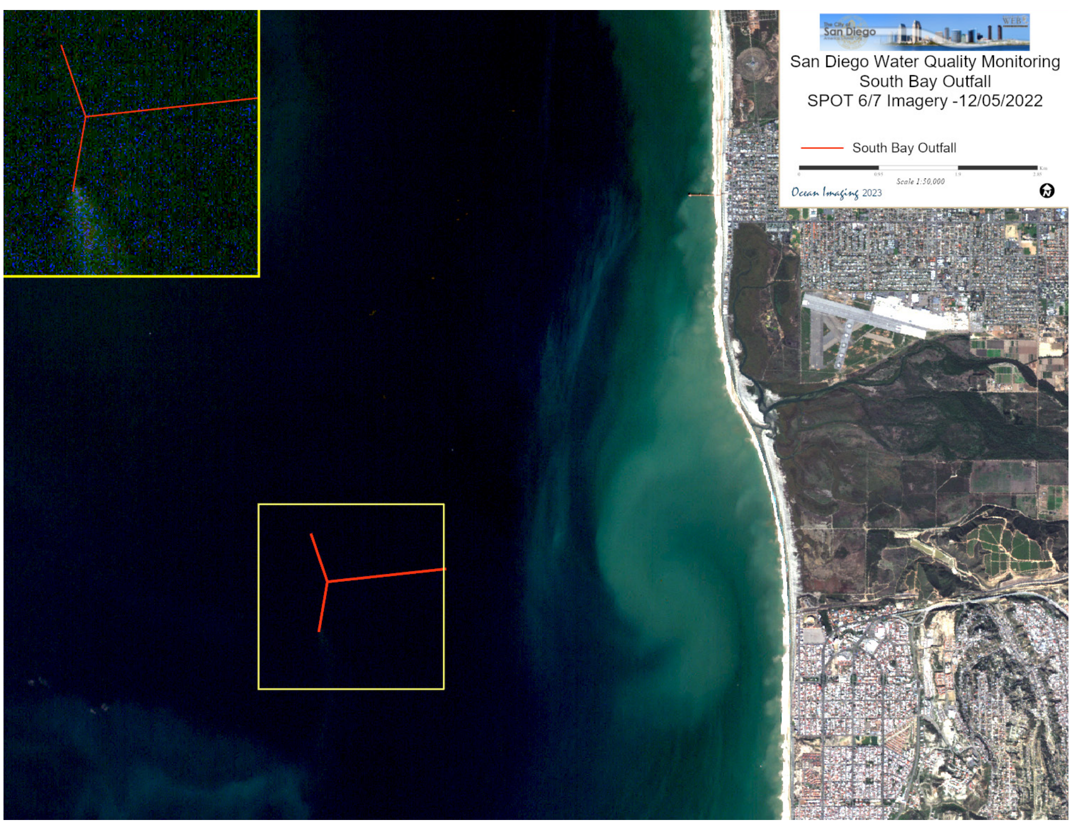
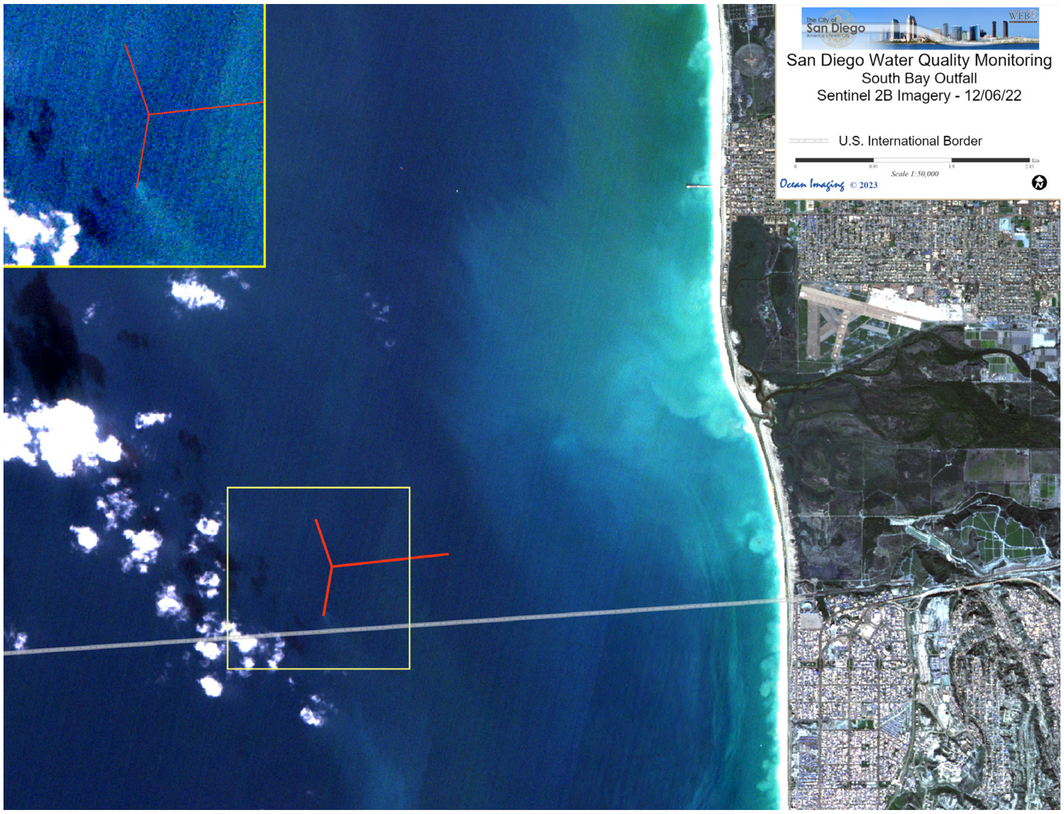
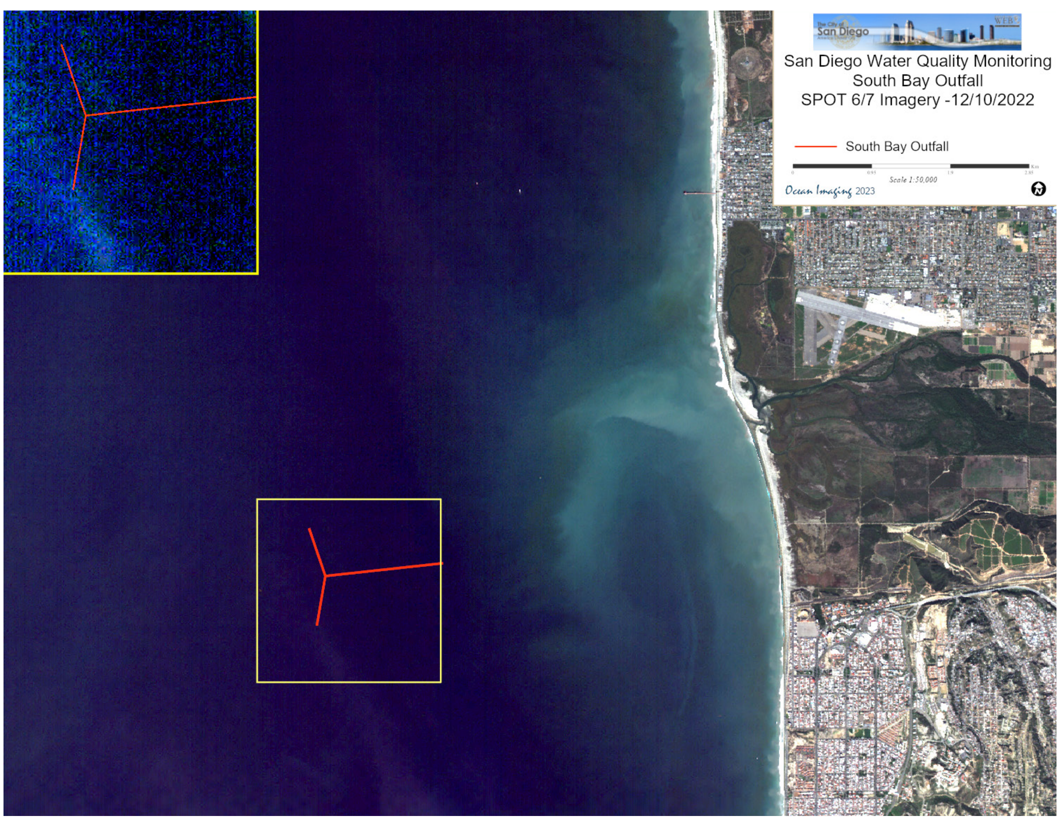
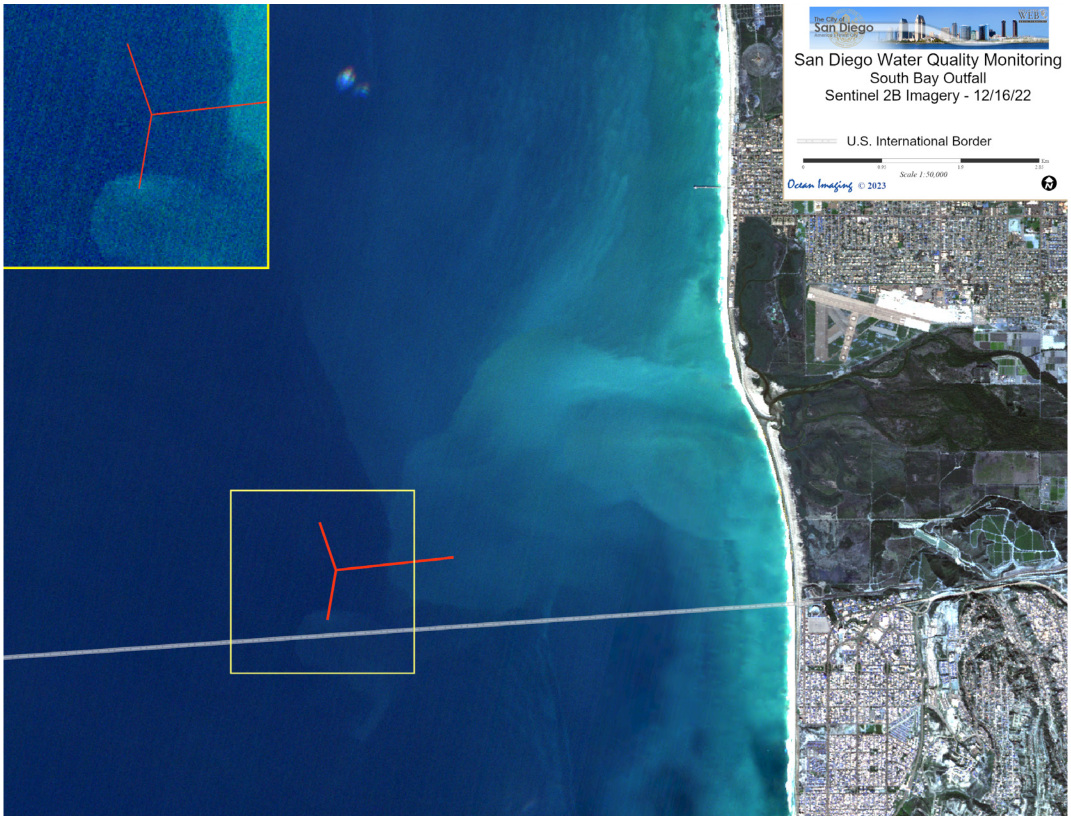

The City of San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 11/29/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023


The City of San Diego
San Diego Water Quality Monitoring
South Bay Outfall
SPOT 6/7 Imagery -12/05/2022
South Bay Outfall
Scale 1:50,000
Ocean Imaging 2023


San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 12/06/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023


San Diego Water Quality Monitoring
South Bay Outfall
SPOT 6/7 Imagery -12/10/2022
South Bay Outfall
Scale 1:50,000
Ocean Imaging 2023



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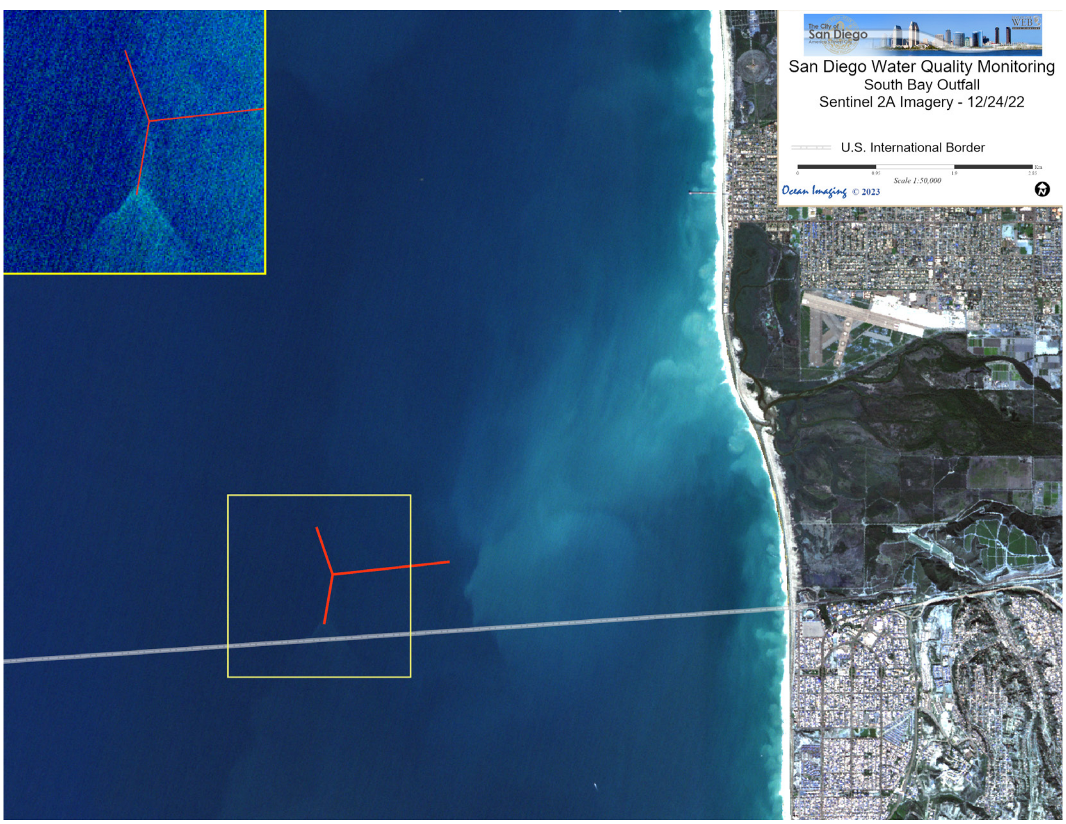
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2B Imagery - 12/16/22
U.S. International Border
Scale 1:50,000
Ocean Imaging © 2023



The City of San Diego
San Diego Water Quality Monitoring
South Bay Outfall
Sentinel 2A Imagery - 12/24/22
U.S. International Border
Scale 1:50,000
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