Visualizing Cyanobacteria **from Space**

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A web tool highlighting long-term trends and where to sample tomorrow

While naturally part of freshwater ecosystems across the planet, cyanobacteria, or blue-green algae, have expanded in recent decades resulting in blooms that dominate many lakes, rivers, and other water bodies. With many cyanobacteria species naturally producing toxins, this creates potential risks and new management challenges for public health agencies, drinking water facilities, and lake managers. With an increasing need to understand cyanobacteria bloom trends and have up to date information, a valuable screening tool was developed for use in California that provides a new and unique understanding of cyanobacteria blooms by utilizing daily updated satellite data and over a decade of historical images taken from space.

Remote sensing data

Satellite imagery provides a lot more than just pretty true-color imagery like you see in Google Earth. Specialized satellites can estimate not just how much algal biomass exists in large lakes and other waterbodies, but how much cyanobacterial biomass exists, based on the intensity of specific wavelengths of light that reflects back to the satellite. This ability to literally see what human eyes can't, and allows for the detection of cyanobacteria at levels lower that what is observable to the human eye, which allows them to be especially effective as an early warning tool for developing blooms. Using imagery collected roughly every other day by two European Space Agency (ESA) satellites, the National Aeronautical and Atmospheric Administration (NOAA) processes and shares these data to reveal an incredible dataset that can document in near real-time when and where cyanobacteria blooms are occurring and how severe they are.

Following the pioneering use of processed satellite imagery for assessing cyanobacteria blooms in Lake Erie and Florida by NOAA and others (Wynne et al. 2008; Stumpf et al. 2012), California has funded the San Francisco Estuary Institute (SFEI) to develop an interactive Satellite Analysis Tool (cchab.sfei.org) to characterize the seasonality, spatial distribution, and development of harmful algal blooms (HABs) in 250 of the state's largest waterbodies. This tool provides a spatial display of cyanobacteria blooms, easy to understand charts that let you see long-term and short-term trends based on lake-wide statistics, queries relevant field data entered into a public environmental database (CEDEN.org) to allow comparisons to the satellite data, and generates an automatic email notification when satellites detect cyanobacteria concentrations rising above background levels. These features allow for a much better understanding of the status and trends of cyanobacteria blooms and provide a useful screening tool for blooms across California.

Interactive satellite analysis tool

The entry page to the tool provides a map that spans California, allowing users to pan throughout the state's large waterbodies to get an overview of the latest conditions (Figure 1). Satellite data is displayed spatially as estimates of cyanobacteria abundance for each of the individual 300 meter x 300 meter pixels the satellite data is able to repeatedly capture. The pixels are displayed in an easy to understand and color-blind-friendly heat map where warmer colors represent high concentrations and cool colors, lower concentrations of cyanobacteria, allowing the user to intuitively see bloom intensity.

Users can click on a lake, or type in the name of their lake of interest, to quickly navigate to view to the heart of the tool, where spatial and temporal data are separately displayed for the lake of interest (Figure 2).

For each lake, this main page has three features that are displayed: (1) a map on the left showing estimates of the cyanobacteria abundance within each pixel, (2) a long time-series chart in the upper right that plots the lake-wide mean and 90th percentile data for multiple years, and (3) short time-series charts for a detailed view of statistics. These three displays are all linked to a movable "window" within the upper timeline graph that allows the user to quickly select different time periods to dynamically change the data displayed within the map and charts. Scrolling across the long time-series plot reveals data collected by the ESA's MERIS instrument from 2002-2012, and for their OLCI instrument from 2017 to present. This long time-series view is a great way to compare how bloom events change from year to year and quickly get the big picture of cyanobacteria trends across most of the 21st century.

Most users will quickly appreciate the ability to navigate through bloom seasons by changing dates for the window, allowing them to visualize cyanobacteria blooms like they never have before, revealing when and where cyanobacteria blooms develop, how the

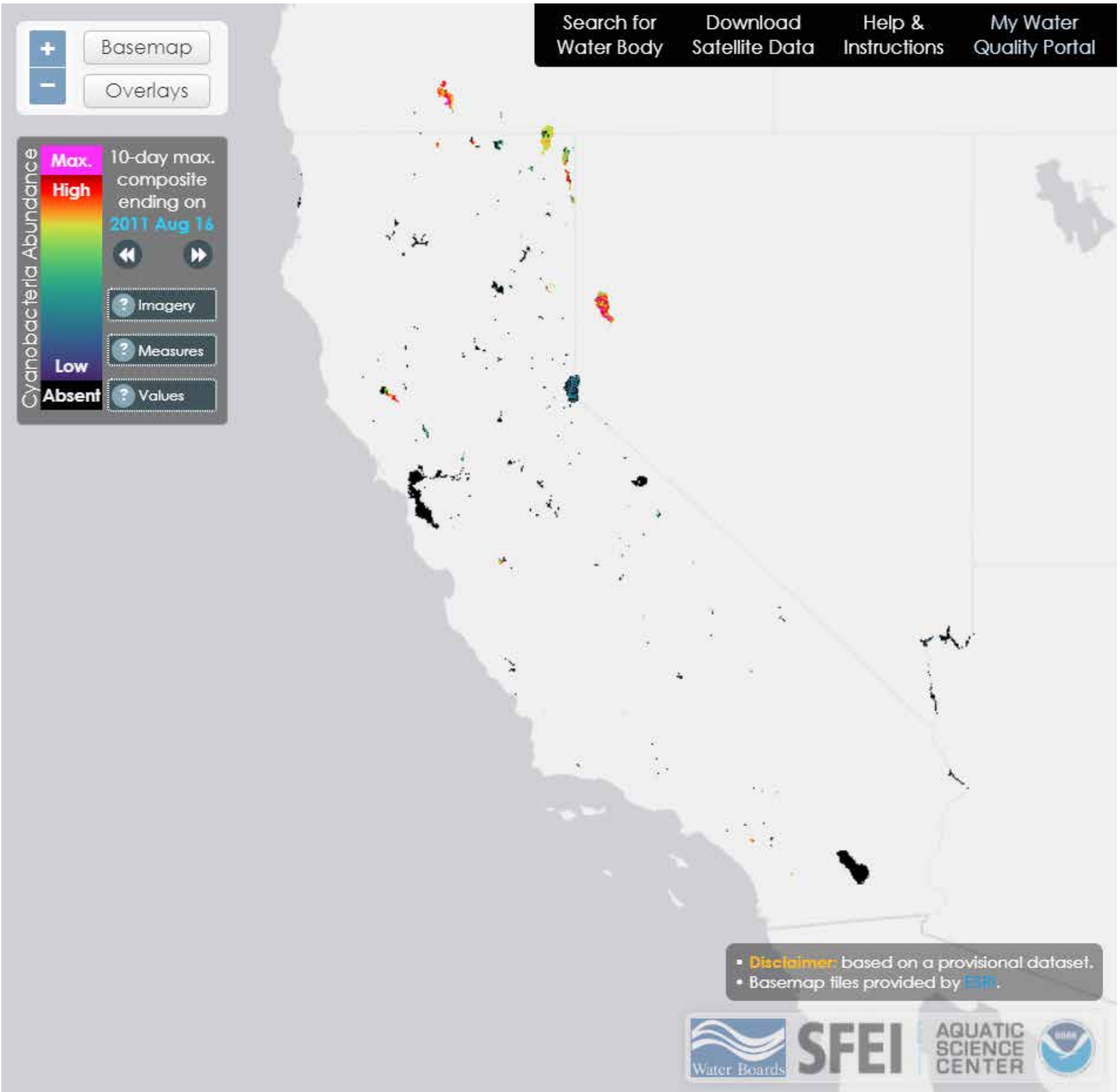

Figure 1. Satellite Analysis Tool entry page displaying status of lakes across California.

bloom grows over time, shift based on wind and currents, and inevitably decline. By navigating to the time just prior to a bloom, you can also select the "play" button on the map legend to watch a daily advancing animation of the map and charts, revealing the fascinating birth, life, and death of a cyanobacteria bloom.

In addition to the satellite-derived statistics and products, selecting the "CEDEN Analytes" tab allows users to query relevant water quality and cyanotoxin data from California's public environmental database CEDEN to display alongside the continuous satellite trend data seen in the short time-series chart, as well as display of each sampling location on the lake map (Figure 3). This comparison of field data, both in time and space, allow users to better see trends in commonly collected data like chlorophyll-a, and how these values track with the trends in the satellite data and spatially depending on where the sample was collected. While there is only a limited amount of relevant data in CEDEN, this querying capacity can be expanded to other public databases in the future.

Where data, charts, or maps are needed outside of the Satellite Analysis Tool, there are a variety of ways to put the information on the tool into reports, emails, or for use in GIS programs. The "Tables" tab can display either satellite or field data in tabular form for viewing or downloading. Charts can also be downloaded, as can the map views as clipped raster images, or within the statewide view, monthly mosaic images for all lakes can be generated for use in ArcGIS and other programs.

Complement to traditional monitoring

The Satellite Analysis Tool is not meant to be used to directly post public health warnings or closures for waterbodies for a few reasons. Most public health thresholds are based on cyanotoxin concentrations, and the satellite measures cyanobacteria abundance and not toxins. Additionally, not all cyanobacteria produce toxins. Rather, managers may see the most value on a day to day basis by using this as a screening tool to complement any regular monitoring programs or help guide event-based monitoring.

With automated processing the morning after each satellite flyover, the tool can provide near-real-time updates on the development, growth, and movement of cyanobacteria blooms. This information can prove critical to understanding whether cyanobacteria blooms are developing, worsening, or shifting towards areas of beneficial uses and can be used to help direct any monitoring resources towards areas of importance. Knowing that there are limited dollars for nearly every monitoring program out there, being able to target monitoring to times and locations when cyanobacteria is detected can lead to much more efficient and effective monitoring programs, ultimately providing better protection for the public and likely fewer expensive non-detections.

Satellite data

With the satellite flying over roughly every other day, occasional clouds and wind events that disperse blooms into deeper water or along shorelines result in highly variable bloom patterns within individual images. This might show a bloom on Monday, no bloom on Wednesday due to clouds, and a bloom again on Friday. To produce more reliable imagery that can account for clouds or other issues, we incorporate all imagery within a ten-day period to produce a running ten-day max composite. Within each ten-day running max composite we capture the maximum value for each pixel from any imagery collected within the previous ten days, then repeat this method every day. This results in timelier data than a static ten-day composites that is only available every ten days and produces a smoother time-series which reveals bloom growth and movement in striking detail.

To ensure that the lake-wide statistics don't get skewed too greatly from a few errant pixels, we require 18 pixels with valid data within each composite to generate any values. For conveying information to public health officials, we often use the 90th percentile value for the lake, which will provide information on what is close to, but not the highest, concentrations within the lake. The mean or median values for the lake while important, may underestimate the risk in any one part of the lake.

One of the complications of using satellite data is that the metric used is one that isn't used by most scientists, the unit-less metric Cyanobacteria Index (CI). While some researchers have been able to establish relationships between CI data and two other more common environmental datasets, Chl-a (ug/L) and the common cyanobacteria *Microcystis sp.* (cells/mL), these conversions can introduce some error and are not used here. Additionally, with the range of CI values being very small numbers (0.00006 - 0.06), getting the data into values that are easier to digest resulted in us creating a Modified CI, where we multiply these CI values by 15,805.18 to produce a much easier to understand range of 1-1000 for our Modified CI. While not used elsewhere, we believe this approach will help translate these important data into a value that is quickly understood by scientists and citizens alike.

Limitations and next steps

While we see great promise from the satellite data, there are a few limitations that can limit its value. The satellites can't see through clouds or fog, limiting its value in some locations and seasons, but we have seen better than expected coverage through wildfire smoke. Also, lakes smaller than 250 acres do not have enough open water pixels to meet our statistical threshold, and narrow lakes often have too many pixels with land/water interface, resulting in invalid data. As technology develops, we hope that additional satellites with better spatial resolution and a similar ability to distinguish cyanobacteria will be able to see blooms in smaller lakes, ponds, and rivers and greatly increase the breadth of use for this type of satellite data.

At this time, the satellite data within the tool are considered provisional since there has yet to be an extensive comparison of the satellite data to field-collected data in California. While the accuracy of the satellite data has been confirmed in other parts of the U.S., the use of this imagery in California brings environmental conditions that haven't yet undergone these comparisons such as high elevation, high salinity, seasonal alkali lakes, and especially clear water. These conditions have challenged the satellite data but through much interaction with NOAA scientists, we believe most of these concerns have been addressed.

With the Satellite Analysis Tool now developed and functioning, we anticipate improvements to this tool in the coming years will make it even more useful. The addition of other environmental databases to query for comparisons to field data, linking to relevant reports and documents for specific lakes, improved access to export raw satellite data, and expanding the tool beyond California are all areas that are being considered. Additionally, the ability to merge this dataset with other satellite data could be helpful in determining relationships to other water quality parameters that might help identify drivers of blooms and how water quality is impacted.

Conclusions

For now, the Satellite Analysis Tool offers a variety of unique features that will complement any existing HAB program. This includes helping managers easily visualize over a decade of imagery, revealing precise details in spatial and temporal trends of cyanobacteria blooms, providing near real-time updates that automatically screen for early detections of blooms to help direct any monitoring activity toward the places and times where blooms are observed, and allowing for easy comparisons to field data entered in a public database. Any way you look at it, the Satellite Analysis Tool can transform your understanding of and ability to respond to cyanobacteria blooms so much that you'll never look at cyanobacteria blooms in the same way again.

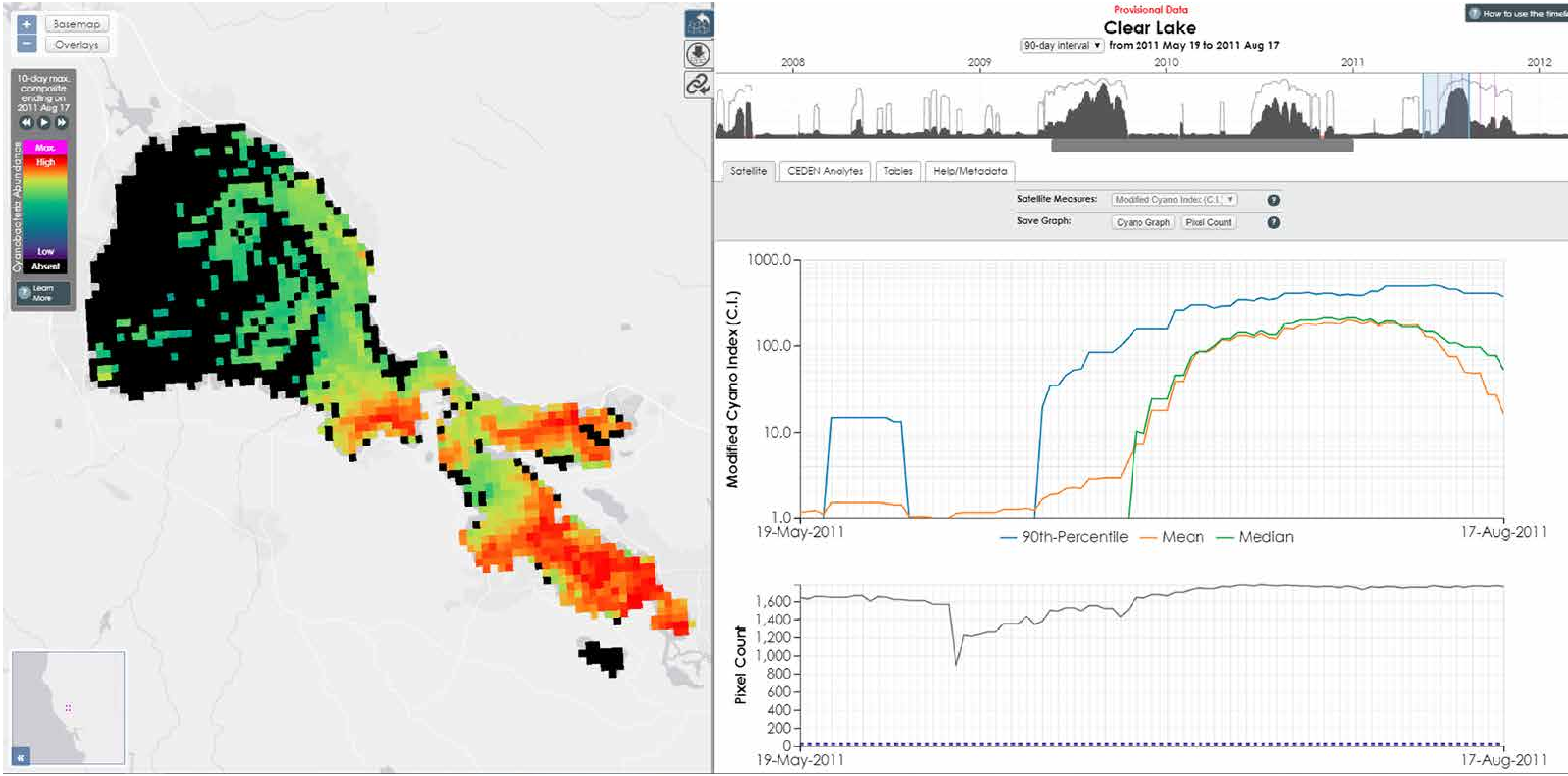

Figure 2. Satellite Analysis Tool display for Clear Lake, CA.

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Randy Turner (pictured at right) is an associate environmental scientist at the San Francisco Estuary Institute. Besides his work on CyanoHABs for SFEI, he works extensively in the Klamath River basin, helping coordinate efforts for a diverse stakeholder driven water quality monitoring and research program.

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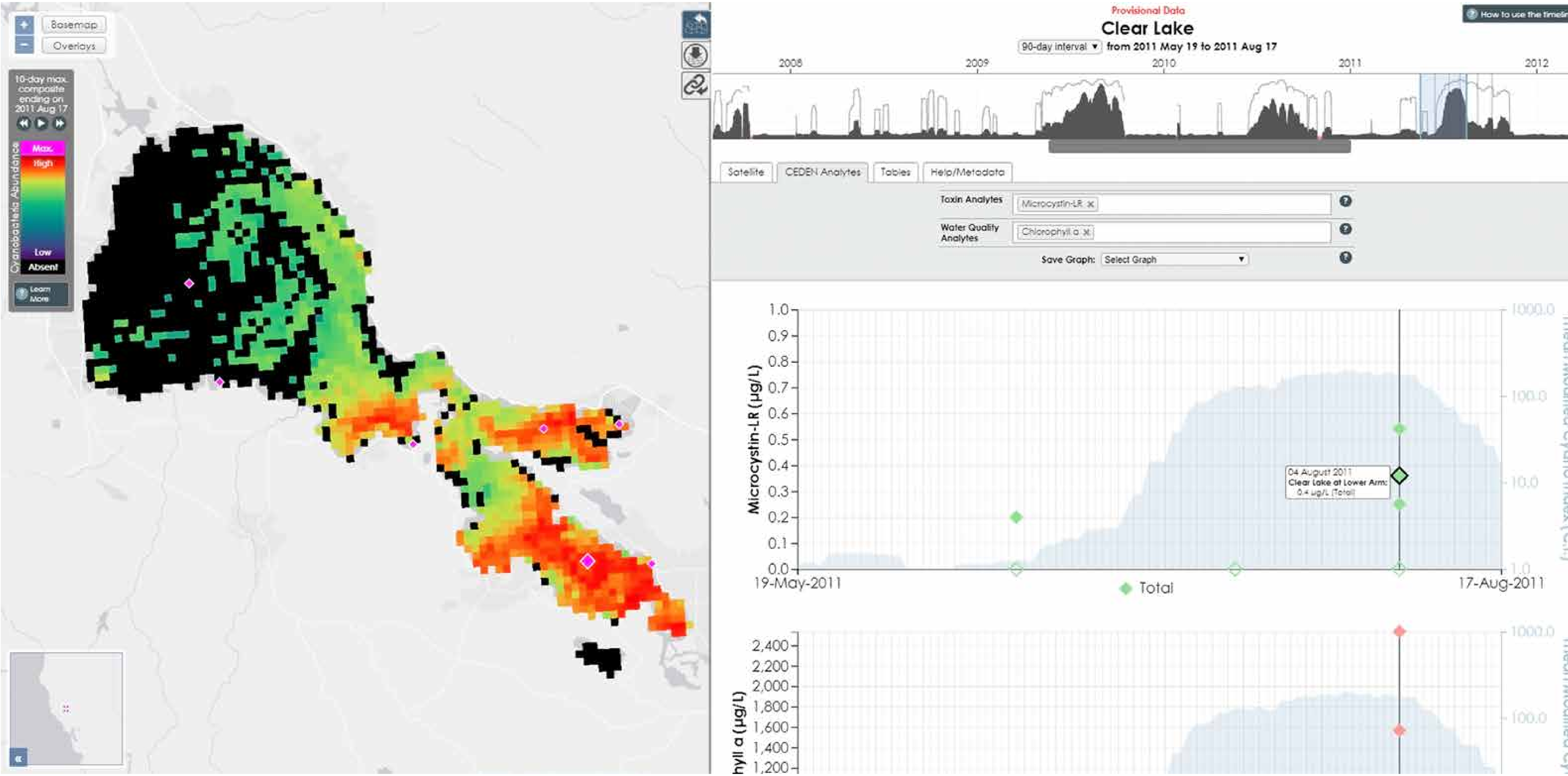

Figure 3. Comparing satellite and field collected data for Chlorophyll-a