Remote Sensing of Water Quality in Laguna del Sauce, Uruguay

In partnership:

PRESIDENCIA
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Introduction

Laguna del Sauce (34°43’ S, 55°13’ W) is a water supply reservoir located in the Department of Maldonado (Uruguay), approximately 15 kilometers west of Punta del Este, and 100 km east of Montevideo. The lagoon covers 50 square kilometers and is 12 kilometers long and 6 kilometers wide. The entire reservoir is formed by a system of three connected lagoons: the Laguna del Sauce proper (4045 ha), Laguna de los Cisnes (205 ha) and Laguna del Potrero (411 ha) (Figure 1). The two main tributaries that contribute water to the reservoir are Arroyo Pan de Azúcar and Arroyo del Sauce, with Arroyo del Potrero being its natural drainage towards the Río de la Plata.

The average flow contributed is approximately 9 m^3/ s. The depth of the reservoir oscillates between 3 and 4 meters with a maximum of 5 meters, and an estimated average volume of water of 153 hm^3. The residence time of water is approximately 195 days.

Laguna del Sauce supplies drinking water to more than 95% of the fixed population (140,000 people) and floating population (it can surpass 400,000 people in the summer season) in Maldonado (cities of Maldonado, Punta del Este, San Carlos, Piriápolis and its peripheral areas) since 1970. The average annual volume of drinking water production from the reservoir is around 52,000 m^3 per day, while in the high season it can reach 100,000 m^3 per day.

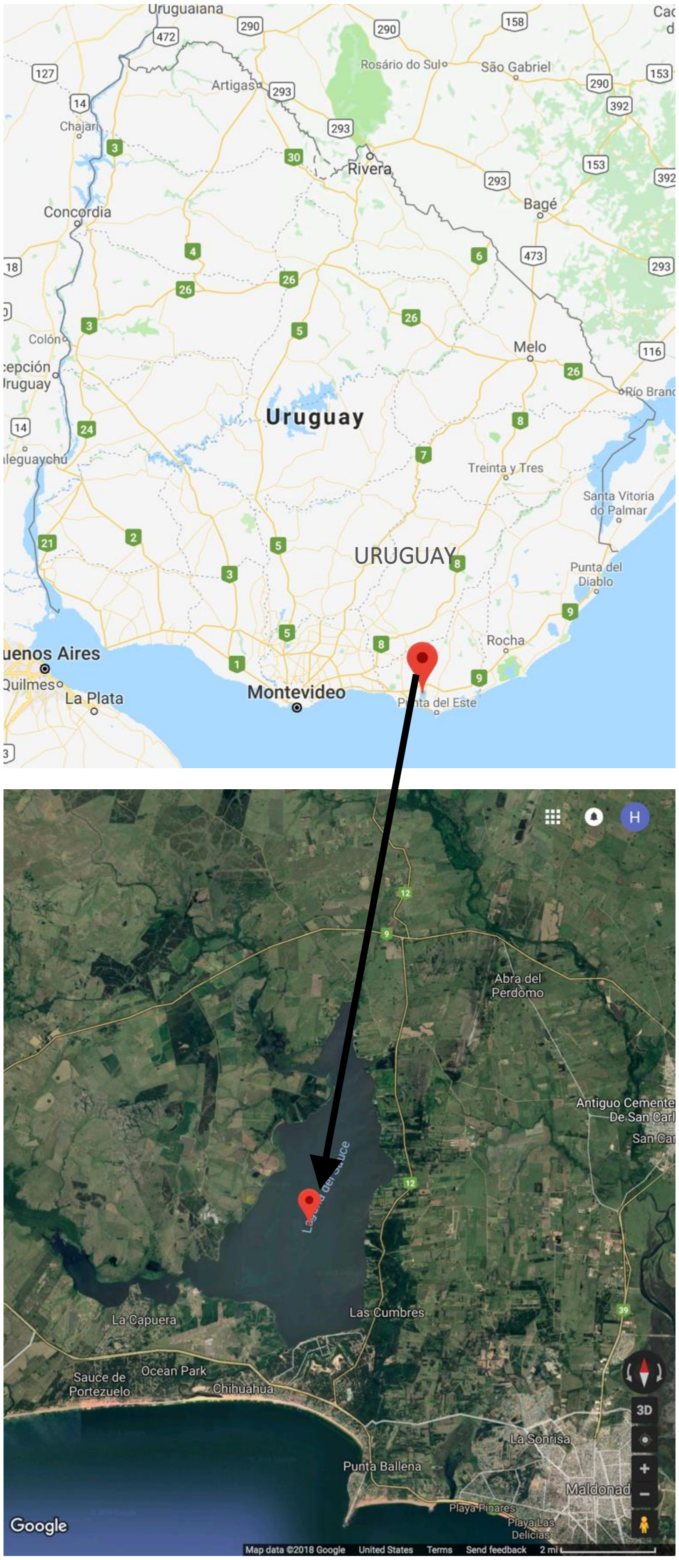


Figure 1: Location of Laguna del Sauce in Uruguay.

The presence of microalgae blooms (cyanobacteria) in Laguna del Sauce has been recorded since the 1960s. Research carried out in different periods agree on the continued and increasing conditions of eutrophication (high concentration of nutrients) of this system. Figure 2 shows the occurrence of high Chlorophyll concentration events that reflect periods of microalgae blooms. Due to these blooms, the potabilization process has presented numerous problems over the years, which have been solved through a considerable transformation of the water treatment plant over the past decade. However, the presence of cyanobacteria continues to pose a potential health risk due to its capacity to produce toxins, which can cause serious disturbances in the supply of drinking water as well as other productive and / or recreational activities. Due to this, improved management of this phenomenon is important for development of the area in the near future.

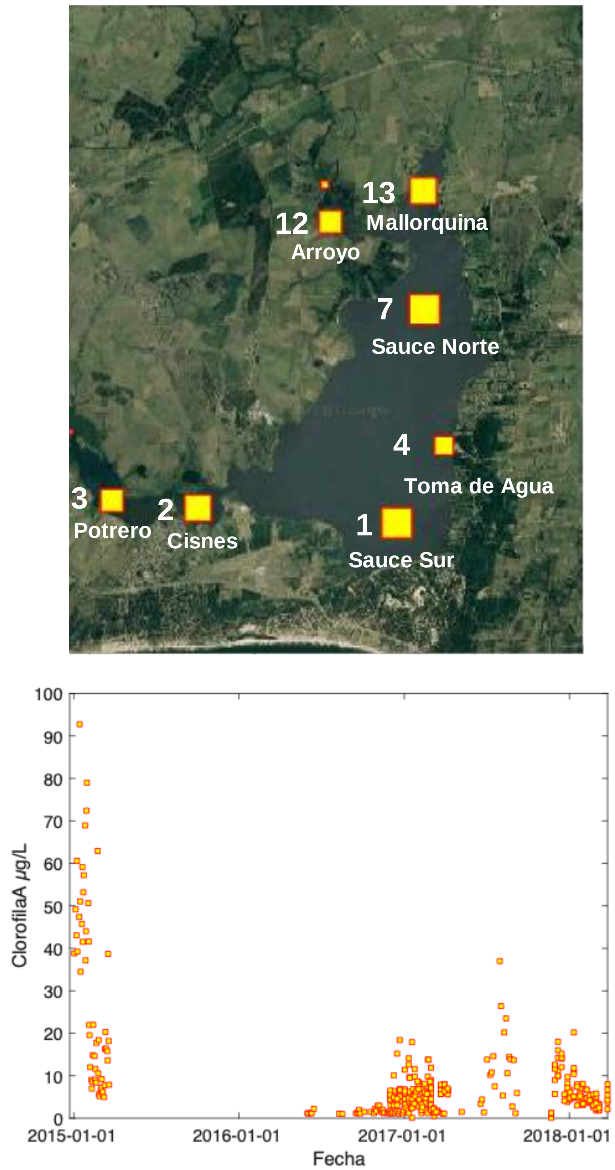


Figure 2: Location of water quality monitoring stations in Laguna del Sauce (above); time series data for Chlorophyll in mg/m^3 (below).

This case study assessed ongoing initiatives to address surface water pollution issues in Uruguay, working in partnership with a team of government agencies charged with water resources management (SNAACC: Secretaría Nacional de Ambiente, Agua y Cambio Climático; MVOTMA: Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente; MGAP: Ministerio de Ganadería, Agricultura y Pesca; OSE: Obras Sanitarias del Estado). Particular focus was placed on a pilot case study application of remote sensing techniques to detection of water quality issues in Laguna del Sauce. This assessment will contribute to a better understanding of options for water quality remote sensing capabilities and needs and assist the government of Uruguay in identifying appropriate remote sensing tools and devise an application strategy to provide information needed to support decision-making regarding the targeting and monitoring of nutrient pollution prevention and mitigation measures.

Remote Sensing of Water Quality in Laguna del Sauce

In-situ data collection is able to provide point estimations of the quality of water conditions in time and space. However, obtaining spatial and temporal variations of quality indicators in large waterbodies through in-situ measurements is practically and costly challenging (Ritchie et al. 2003). Briefly listed below are important limitations associated with conventional methods:

- In-situ sampling of water quality parameters are labor intensive, time consuming, and costly.
- Investigation of the spatial and temporal variations and water quality trends in large waterbodies is impractical.
- Monitoring, forecasting, and management of entire waterbodies might be inaccessible, for example due to the topographic situation.
- Accuracy and precision of collected in-situ data can be questionable due to both field-sampling error and laboratory error.

To overcome these limitations and complement in-situ water quality monitoring efforts, remote sensing can be a useful tool. For decades, remote sensing has evolved towards providing strong capabilities to monitor and evaluate the quality of inland waters (Table 1). Recent investigations have led to obtaining robust correlations between water column reflection (in some cases emission) and physical and biogeochemical constituents, such as transparency, chlorophyll concentration (phytoplankton), and the organic matters and mineral suspended sediments in different waterbodies (El-Din et al. 2013; Giardino et al. 2014; Ritchie et al. 2003, Chipman et al. 2009; Wang et al. 2006). However, remote sensing alone is not sufficiently precise and must be used in conjunction with traditional sampling methods and field surveying. In other words, to obtain a better insight, an integrated use of remote sensing, in-situ measurements and water quality modelling may lead to an increased knowledge of the quality of water systems.

Kallio et al. 2000 highlight four advantages of applying remote sensing in compliance with other water quality monitoring methods:

- Gives a synoptic view of the entire waterbody for more effective monitoring of the spatial and temporal variation
- Makes it possible to have a synchronized view of the water quality in a group of lakes over a vast region.
- Provides a comprehensive historical record of water quality in an area and represents trends over time.
- Prioritizes sampling locations and field surveying times.

Satellite remote sensing-derived estimates are spatially continuous and repeated at regular intervals and can hence be used to increase data availability and complement in-situ point measurements for an improved and integrative monitoring approach. Recent advances in remote sensing technology and analysis have allowed estimation of key water quality constituents from space, including total nitrogen, total phosphorus, chlorophyll-a concentration, colored dissolved organic matter (dissolved organic carbon or total organic carbon), harmful algal blooms (e.g., cyanobacterial toxins or microcystin concentrations), total suspended sediment (or turbidity), and temperature. Combination of multiple sensors and different types of estimation methods can improve the retrieval accuracy of different water quality parameters. Optically active constituents of water that interact with light and change the energy spectrum of reflected solar radiation from waterbodies can be measured using remote sensing (Ritchie et al. 2003). Major water quality parameters as those mentioned above constitute the majority of important indicators of pollution in surface waters. In addition, other water quality parameters such as acidity, chemicals, and pathogens, which do not change the spectral properties of reflected light and have no directly-detectable signals, may be inferable from those detectable water quality parameters with which strong correlations can be found.

Results to Date

It is clear that continued eutrophication of Laguna del Sauce will increasingly impair the numerous ecosystem services it provides. In this work we demonstrate a path to development of water-quality monitoring using publicly-available remote sensing data from satellites Sentinel-2A and Landsat-8. Estimates of Chlorophyll and Turbidity were obtained from atmospherically corrected remote sensing surface reflectance and are regionally tuned using in-situ data available from MVOTMA and scientists from CURE (Colegio Universitario de la Región Este). Chlorophyll and Turbidity were used as proxies for biological productivity (nutrient supply and photosynthetic activity) and concentration of suspended particulates, which are some of the key indicators of water quality. This enables the generation of calibrated maps and time-series data to provide improved insight into the spatial and temporal water-quality dynamics in the reservoir.

Figure 3 shows the results of remote sensing measurements of Chlorophyll and Turbidity along four distinct transects in Laguna del Sauce; these measurements are derived solely from reflectance data from Landsat 8. Higher reflectance values measured by satellites are indicative of lower light absorption, lower photosynthetic activity and thus lower Chlorophyll values, and viceversa. These measurements are useful in discerning spatial trends in water quality, as well as illustrating the gains in spatial resolution obtained by using remote sensing. Once obtained, these "uncalibrated" water quality observations can be compared to in-situ measurements such as those shown in Figure 2.

The satellite spatial coverage of Laguna del Sauce is shown in Figure 4. Figure 5 shows the calibrated correlations between in-situ measurements and satellite derived values of concentrations of Chlorophyll and Turbidity concentrations throughout the reservoir, indicating reasonable agreement.

Satellite (instr.)	Agency	Timeframe	Revisit Time	Resolution [m]	Notes
Landsat-8 (OLI)	USGS / NASA	2H2013 - present	16 days	30	Inland Lakes, Reservoirs and Rivers
Sentinel -2A (MSI)	ESA	2H2015 - present	10 days	10	
Sentinel -2B (MSI)	ESA	2H2017 - present	10 days	10	
Envisat MERIS	ESA	2002 - 2012	3 days	300	Oceans, Regional, Bays and Large Lakes
Sentinel-3A (OLCI)	ESA	2H2016 - present	2 days	300	
Sentinel-3B (OLCI)	ESA	April 25, 2018 (launch)	2 days	300	
EOS Aqua/Terra (MODIS)	NASA	'00/'03 - present	1~2 days	250~500	Oceans, Regional, Basins, Large Bays
SNPP/ JPSS-1 (VIIRS)	NOAA / NASA	1H2015 - present	1 day	~375	
NOAA-20/ JPSS-2 (VIIRS)	NOAA / NASA	2H2017 - present	1 day	~375	
GOES-R	NOAA	2016 - present	15min	1km (640nm 0.5km)	Meteorology

Table 1: Suite of Satellite sensors used in the Laguna del Sauce water quality change analysis.

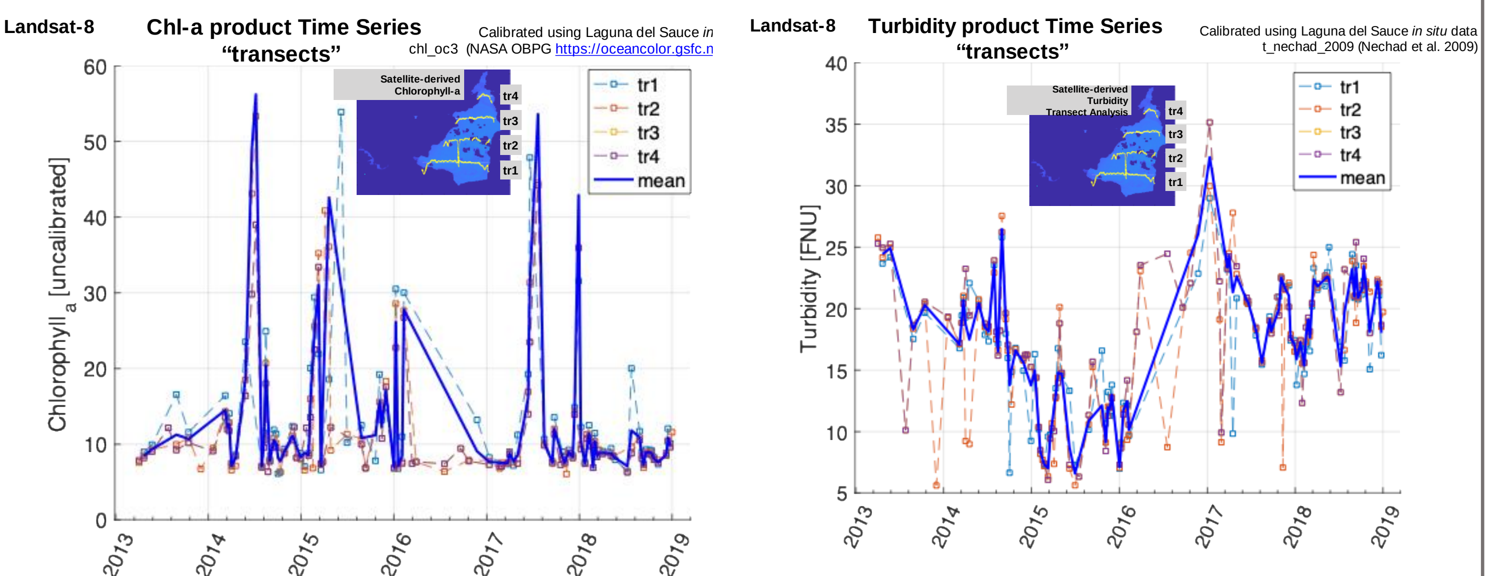


Figure 3: Remote sensing measurements of Chlorophyll and Turbidity along transects in Laguna del Sauce..

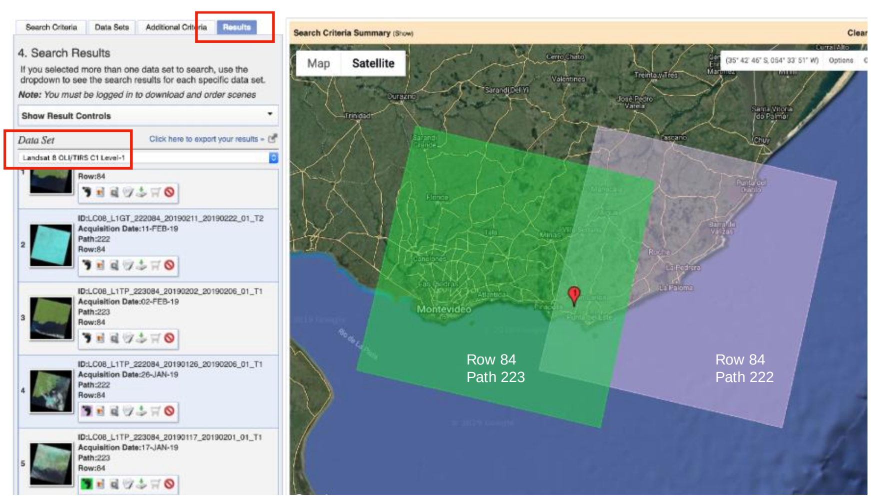
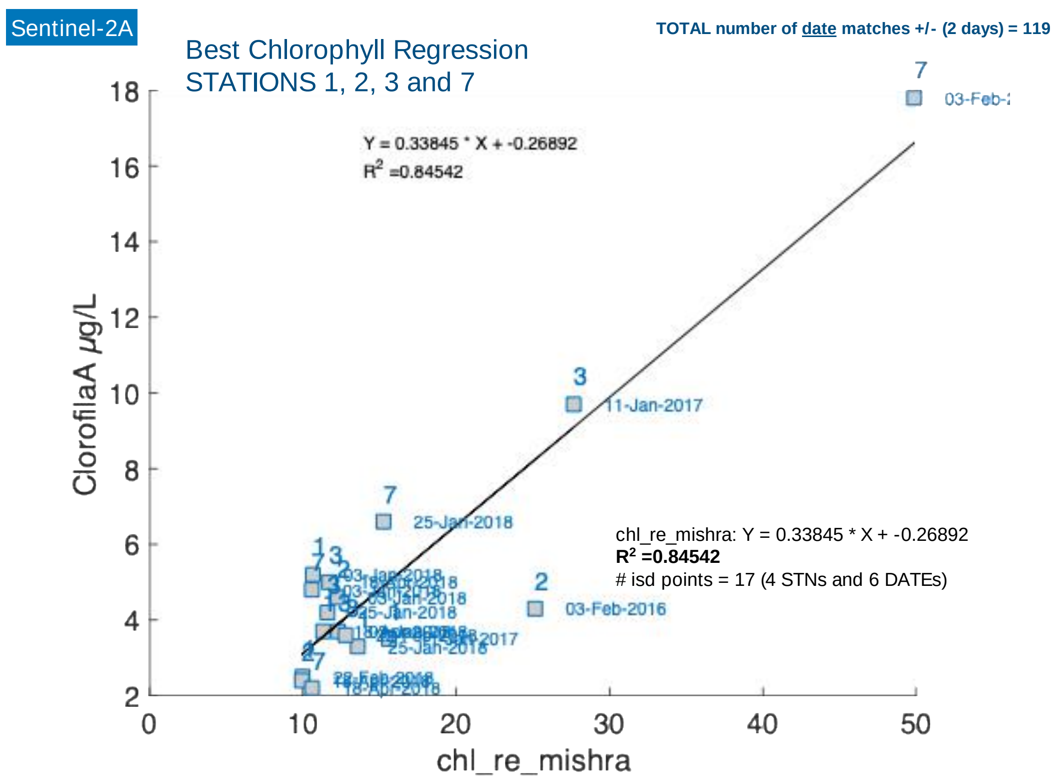


Figure 4: Spatial coverage of Laguna del Sauce by Landsat 8 satellite "tiles".



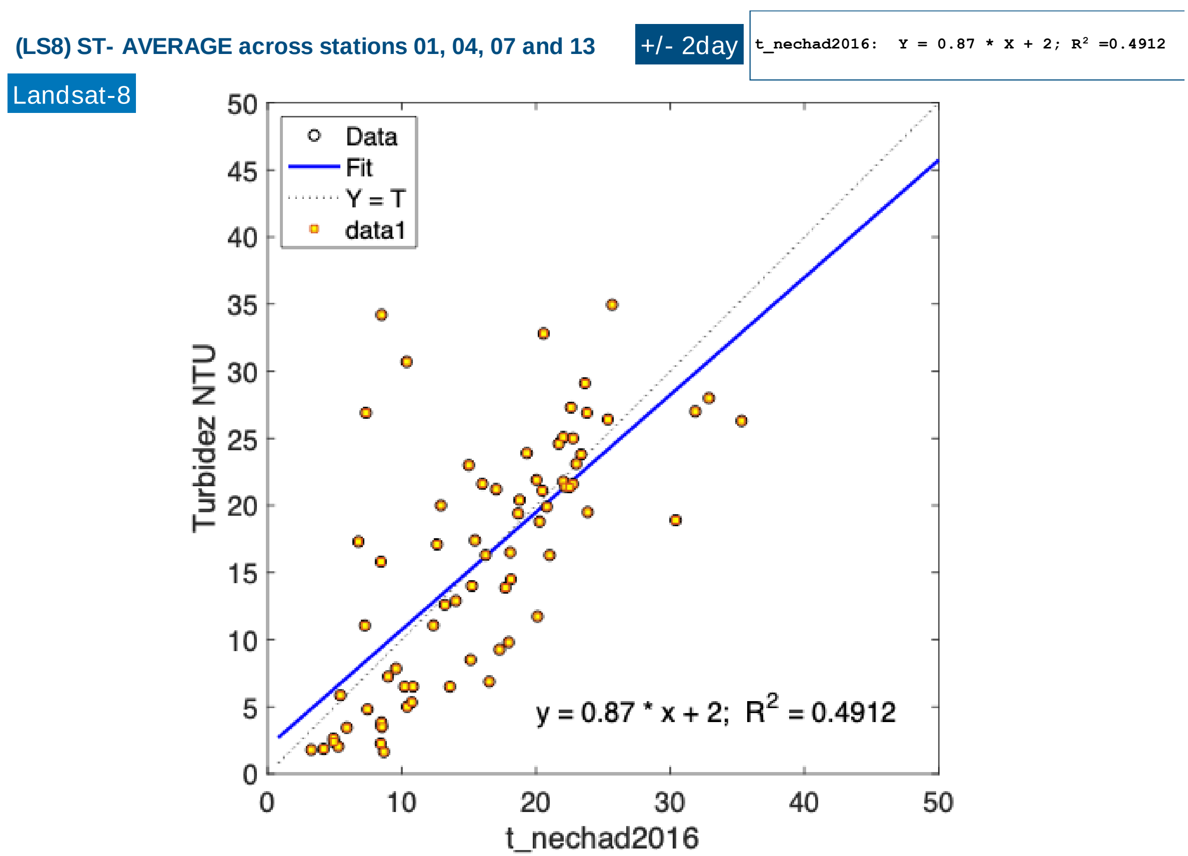


Figure 5: *Correlations between in-situ and remote sensing measurements of Chlorophyll (above) and Turbidity (below).*

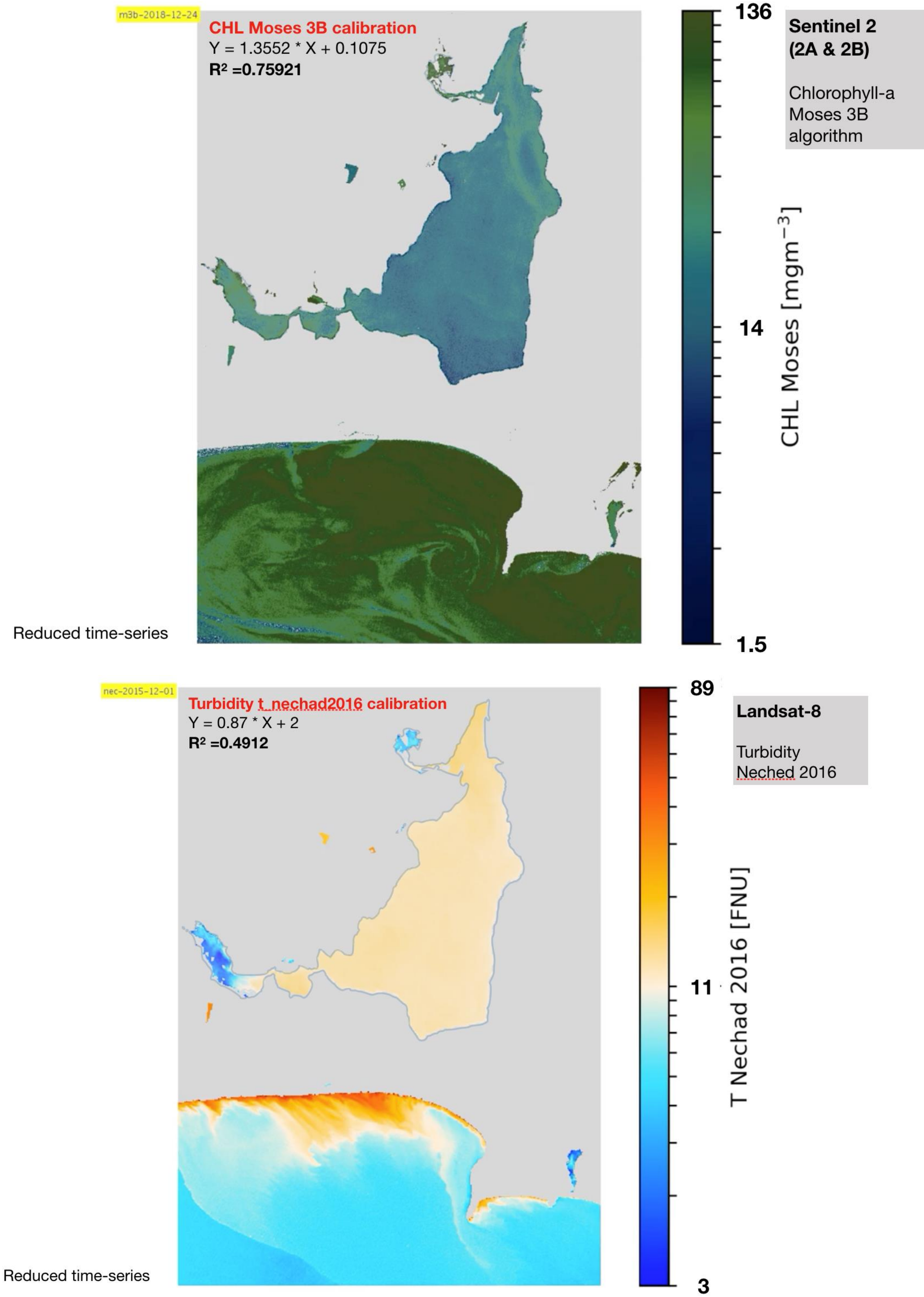


Figure 6: High resolution maps of Chlorophyll (above) and Turbidity (below) for Laguna del Sauce.

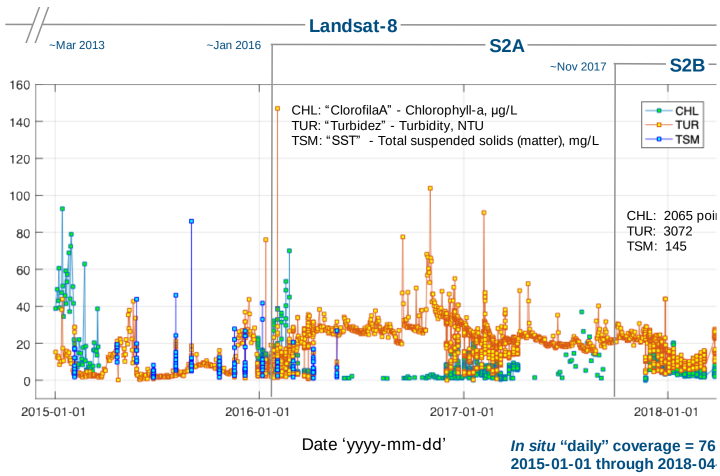


Figure 7: *High resolution time series of water quality parameters for Laguna del Sauce*.

What Controls Water Quality in Laguna del Sauce?

Values of concentration of Chlorophyll and Turbidity at high spatial resolution (10-30 m) were derived from Sentinel-2A and Landsat 8 calibrated algorithms. These values were used to generate the spatial maps shown in Figure 6. These maps show plumes of Chlorophyll and Turbidity in the northern and western sections of the reservoir, near the discharges of the Arroyo del Sauce and Arroyo Pan de Azúcar tributaries, respectively. This pattern of pollution results from hydrologic discharges of pollutants (e.g., nutrients and/or sediments) which are entrained into the interior of the reservoir through the lakes circulation process. These discharges are likely associated with non-point sources of pollution that are typical of land use practices in the watershed that contributes to the reservoir (e.g., agricultural irrigation, fertilizer applications).

In addition to the snapshots depicted in these maps, the remote sensing data can be used to produce high spatial resolution time series of pollution in the lake, as depicted in Figure 7. This allows exploration of temporal trends of water quality pollution in spatial areas of the lake that may be of interest, particularly in managing pollution sources and their discharges to the reservoir.

Some key findings that can be drawn from the introduction of remote sensing water quality data in Laguna del Sauce can be summarized as follows:

- Significant turbidity dynamics are observed in Laguna del sauce over multiple temporal length scales (e.g. LS8 time-series 2013 - 2019) and appear to be the dominant driver of water quality dynamics.
- Inter-annual and seasonal changes with fluctuations of 'low' turbidity < 10 NTU and 'high' turbidity > 20~25 NTU seem primarily related to sediment resuspension of this shallow lake driven by meteorological conditions (wind forcing and rainfall).
- The lake appears to undergo thorough spatial (and presumably) vertical mixing within a matter of days given persistent meteorological conditions.
- Multi-year trends in turbidity observed; e.g. low turbidity domain in 2015, as well as shorter seasonal periods where turbidity is lower, e.g. end of 2013, beginning of 2016.
- Prolonged periods (up to several weeks) of low turbidity <10 NTU, particularly in summer months (Dec-Feb) presumably with higher temperatures (~14°C seasonal temperature variation) precede events with significant biological productivity / HABs (harmful algal blooms).
- The intense HABs appear linked to a combination of environmental and water quality properties: settling of inorganic sediment leading to lower turbidity (periods of no / low wind conditions); several days of increased light availability for photosynthesis (PAR) due to increased water clarity / diminished photon scattering; optimal temperature (> 15~16°C ?) and nutrient balance (low Nitrogen / Phosphorus ratio?). This is hypothesis is supported by Landsat-8 turbidity time series in 2015.

Operationalization of Water Quality Monitoring through Remote Sensing

Remote sensing applications are powerful, low-cost and easily accessible techniques when combined with in situ and meteorological observations. This can result in comprehensive water-quality monitoring and management supported by operational systems which provide automated data ingestion, atmospheric correction and regional calibration.

Satellite data is made public and exchanged by cooperative agreements, between the source government agencies in Europe, USA, Canada, Japan, Korea, etc. Agency data is free. Creating operational information flow is low cost — some development is needed for calibration / validation of atmospheric correction, regional tuning and operational processing towards system reliability.

Remote sensing enables quantitative insight into spatial and temporal dynamics of biogeochemical processes in lakes, estuaries, near coastal and ocean zones; it is a scalable technique across bodies of water, regions and applications.

For Laguna del Sauce, an automated remote sensing data and online visualization system has been developed to serve as a repository of imagery and processing of water quality data. This system downloads and integrates the latest satellite imagery in real-time and thus provides access to the latest data, updating the water quality database to the latest overpass for the Landsat 8 and Sentinel 2 satellites.

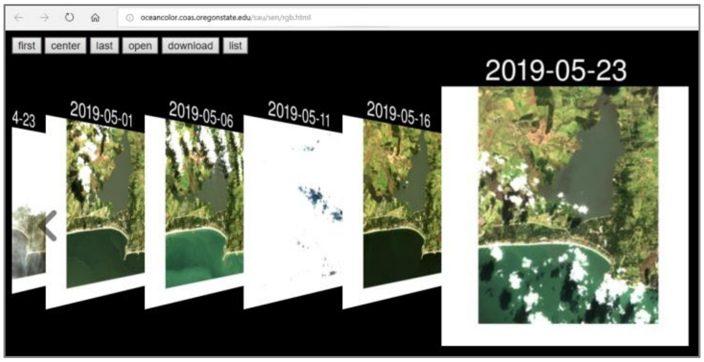


Figure 7: Automated Remote sensing data and visualization system developed for Laguna del Sauce for Landsat and Sentinel Imagery (sentinel imagery displayed in the figure).

The product maps of chlorophyll and turbidity are displayed for each selected image by clicking on the 'open' icon in the online visor. Users can also see the list of available images and download the *.nc (HDF) files, which contain all the water quality product numerical information.

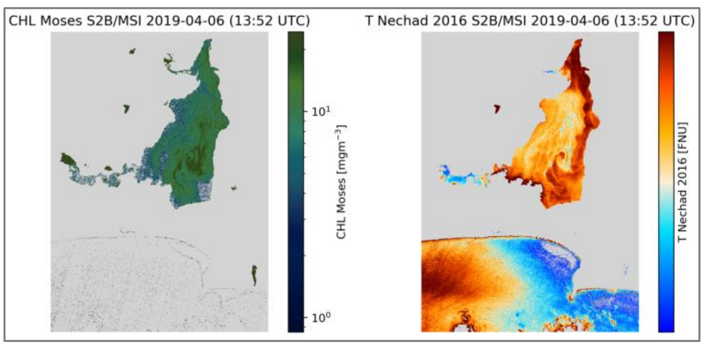


Figure 8: Chlorophyll and turbidity product maps visualized in the online automated water quality monitoring system developed for Laguna del Sauce.

These systems are publicly accessible through the following links: Sentinel-2 (2A and 2B):
http://oceancolor.coas.oregonstate.edu/sau/sen/rgb.html
Landsat-8:
http://oceancolor.coas.oregonstate.edu/sau/lan/rgb.html

Benefits

With increasing presence of remote sensing for water quality monitoring applications in terms of areal coverage, accuracy and free/public data availability, there is an opportunity to operationalize the use of satellite data to complement existing ground-based measurements and information for potentially impaired surface water bodies.

In the case of important water supply reservoirs such as Laguna del Sauce, high spatial and temporal resolution of water quality key parameters, such as Chlorophyll and Turbidity, as explored in this work, can be helpful in identifying the combination of conditions, i.e., rainfall, freshwater inflows into the lake and seasonality in lake turnover, that can lead to harmful algal blooms. This improved knowledge about water quality conditions in the reservoir can help enhance mitigation strategies put in place by OSE to reduce negative impacts to the water treatment plant, which gets clogged with algae when algal blooms are present in Laguna del Sauce.

In this way, operationalizing water quality monitoring through remote sensing can lead to substantial economic savings and contribute to the sustainability of water treatment infrastructure. Similar benefits from the operational use of remote sensing can be achieved as well in terms of near term and future investments in water quality improvements in the Laguna del Sauce system (e.g., design if new infrastructure, retrofits to existing systems).

Challenges

The remote sensing setup used in this case study consisted of primarily computational equipment and training of human resources. Moving forward, an operational water quality monitoring system that incorporates satellite observations would require investments in computational/IT and human resources.

On the computational/IT side, appropriate server and data communications infrastructure is needed to acquire, store, process and visualize water quality data obtained from satellite measurements.

On the human resources side, operationalizing remote sensing monitoring of water quality implies training of staff (e.g., at SNAACC, MVOTMA, MGAP, OSE and CURE) on the processes of: data acquisition from the satellite streams (e.g., Sentinel and Landsat); calibration of algorithm parameters to translate satellite reflectance data into water quality values; integration with ground based data sources; and interpretation, analysis and mapping techniques through GIS platforms already used in country.

Overall, the satellite platform described in this case study provides an excellent basis for development and delivery of calibrated water-quality data products for Laguna del Sauce, and extensible to other important surface water bodies. Together with ground-truth calibration with field observations, the enhanced water quality data system showcased through this work provides significant new insight critical for monitoring of this important reservoir. This system can be operationalized and extended to other important surface water bodies across Uruguay that present similar water quality challenges.

Recommendations for Adoption and Implementation

Successful management of lakes, reservoir, rivers and streams depends on improved monitoring techniques for water quality. The high-resolution satellites (Sentinel-2A/2B and Landsat 8) explored in this work are proven useful to extract complex water quality dynamics from remote sensing reflectance data. The Laguna del Sauce case study highlights the ability to generate new insight about the water quality dynamics from remote sensing, and the benefits of incorporating remote-sensing to the existing streams of in-situ measurements in the reservoir. Research efforts continue under way to develop advanced algorithms and methods for improved data retrieval and new remote sensing instruments towards operational implementation by water agencies like SNAACC, MVOTMA, and OSE.

Building on what has been accomplished, work continues towards the refinement of advanced algorithms to monitor water quality parameters from high-resolution multispectral 'land' instruments such as Sentinel-2A / 2B and Landsat-8. These instruments are essential to develop understanding of complex water-quality dynamics in inland and near-coastal waterways. In Laguna del Sauce, the benefits of using freely available satellite imagery to complement costly in-situ data have been demonstrated here and a satellite-based real-time monitoring system for turbidity and chlorophyll has been developed and is freely accessible online. Additional in situ data (particularly over the full range of variation in Turbidity and Chlorophyll-a) during clear-sky satellite observations will continue to improve the match-up regressions and build a validation data set to refine and complement remote sensing measurements of water quality dynamics over time.

Remote sensing and GIS techniques in conjunction with traditional in-situ sampling are the most effective, cost-effective and reliable tools for monitoring water quality parameters in various surface water bodies (lakes, rivers, groundwater, etc.). In the case of Laguna del Sauce, the techniques developed in this work can be extended to other reservoirs in the country (e.g., Paso Severino), as the footprint of satellites such as Sentinel and Landsat is able to cover larger areas at increasing temporal and spatial resolution.

Monitoring and assessing water quality issues through remotely sensed data can result in effective management of water resources. However, few managerial decisions currently rely on remote sensing-derived water quality evaluations. Instead, most operational methods for monitoring water quality focus on in-situ periodic (boat-based) or continuous (ship-based or buoy-based) measurements, which are often very scarce. The remote sensing technology has advanced a lot in the last years, and all the satellite imagery used in this study is completely free of cost and available to the public. With just a few in-situ measurements, periodic remote sensing data can be processed and calibrated over large spatial areas. Therefore, it is important to understand that a modest investment in remote sensing will represent a large multiplier on the value of in-situ measurements, usually much costlier and more limited in time and space.

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