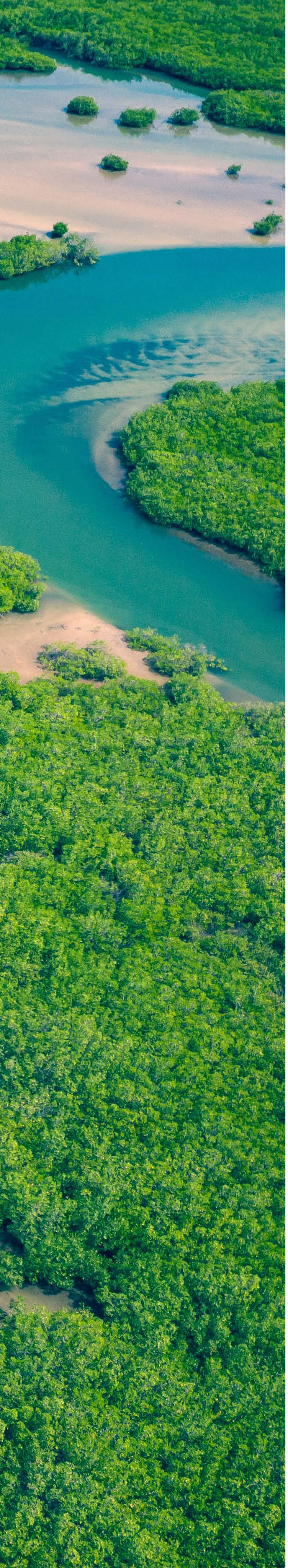
Gybe

Impact of COVID lockdown on Water Quality:
Remote Sensing analysis of four locations.
Inter-American Development Bank Report



Gybe | Know your water

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STUDY OVERVIEW

This study introduces Gybe's remote sensing (RS) methods for monitoring of water quality in support of measuring, understanding and managing impacts in sensitive water bodies that are part of Inter-American Development Bank (IDB) Latin America and Caribbean (LAC) portfolio. More specifically, this study pilots the use of a satellite-imagery-based data collection and processing that operationalizes the creation of location-specific water quality (WQ) data set, which has not been generally available until now. In addition to providing a baseline assessment of water resources at four select locations over time, these products will be used to rapidly assess changes in water quality conditions resulting from socio-economic changes introduced by local and regional response to the Covid-19 pandemic & associated lockdown conditions.

This study provides stakeholders with a new comprehensive measurements basis, and historical trends, that can be used to inform impact monitoring. It also provides a retrospective dataset against which the economic effects felt by varying Covid-19 lockdown measures can be compared.

The monitoring and analytical tools demonstrated here provide decision makers and stakeholders with a new comprehensive measurement basis and historical trends that can be used to inform impact or progress monitoring for existing projects and further water and sanitation investments aimed at improving water quality. Importantly, this study also provides a retrospective dataset against which the economic effects felt by varying Covid-19 lockdown measures can be compared. The data sets resulting from this demonstration can further be compared with other socio-economic, land-use and water and sanitation utilization data-sets to assess both the near term, event based changes such as onset of Covid-19 restriction measures, or longer-term impact assessments.

The methods used allow for easy-to-scale and systematic monitoring, analytics and reporting across the IDB-LAC portfolio, increasing efficiency in tactical and strategic decision making. The specific focus of this study is to implement an automated RS data processing chain enabling detection of phytoplankton abundance (chlorophyll-a) as a proxy for pollution by organic and inorganic nutrients, as well as sediments (and turbidity or water 'clarity').

These water quality parameters are typically driven by land-erosion and runoff processes and also often contain other pollutants from urban environments such as untreated or partially treated sewage or effluent.

Excess nutrient loading, and urban runoff and wastewater pollution due to inadequate sanitation are some of the major water quality issues identified across the IDB-LAC portfolio.

The data production was tailored to specific reservoir, river and estuarine systems of interest to stakeholders and thus provides a comprehensive analysis and dataset for a suite of water quality parameters. Additionally, this pilot leverages the historical remote sensing data archives to provide a baseline trend and variability assessment for water quality within these watersheds. Information about access to the data archive generated in this work for further analysis and assimilation is described in the appendix.

The water bodies selected for this study are as follows:

- **Guanabara Bay** at Rio de Janeiro, Brazil;
- **Lake Titicaca** in Bolivia and Peru;
- **Ypacarai Lake** near Asuncion, Paraguay; and
- The **Rio Reconquista Basin** near Buenos Aires, Argentina.

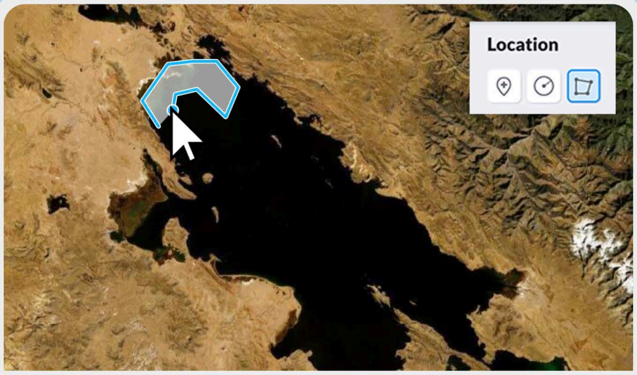
Finally, this study will help build capacity and strengthen activities undertaken by IDB staff in their use of RS and GIS tools to improve water quality management.

VIRTUAL GAUGES
DATA AT ANY LOCATION OF INTEREST

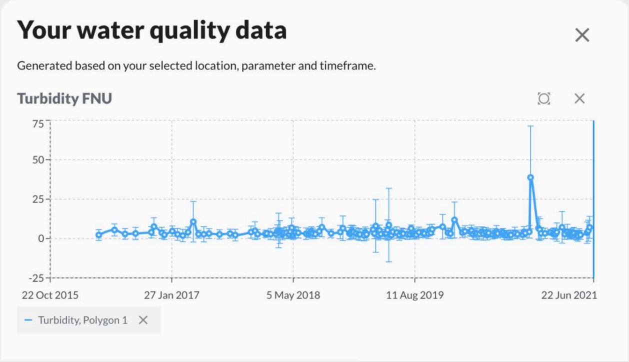
Virtual gauges are well defined points or areas of interest on a datamap. They allow us to generate time series data for any location of interest in a body of water, based on historic data from satellite images, going back to 2016.

First, we define a location of interest, and generate a shapefile for that specific area. Next, a time series is generated per water quality parameter for that area. This time series shows the median levels in the defined location over the timeframe of the available historical satellite data.

In this way, virtual gauges allow us to generate time series for any point or area that is of interest on the datamaps, as if we had placed a gauge there physically.



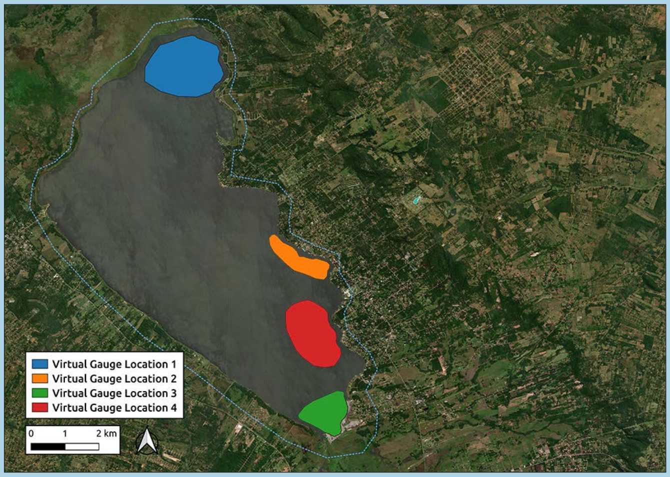
1. Select any location on the map



2. A time series chart is generated for that location, for each water quality parameter

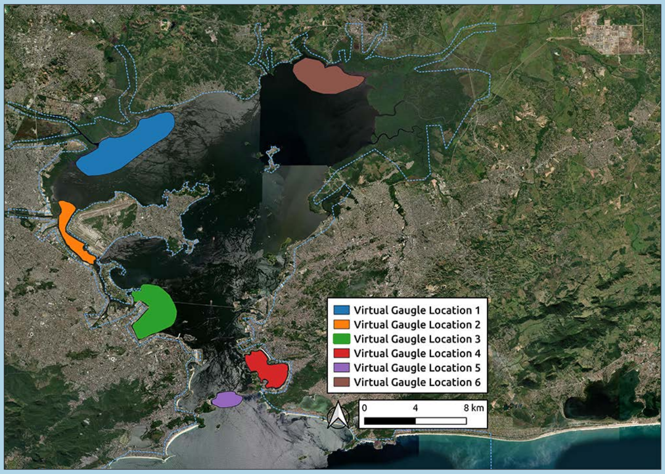
In this report, Virtual Gauge locations depended on feedback from IDB staff when available, with a preference for areas close to densely populated regions and at least 50 meters across in rivers. Those at Ypacarai Lake were selected with a focus on being directly downstream from densely populated areas where tourism dominates (Virtual Gauges 2 & 4), as well as at the natural in-flow and out-flow locations (Virtual Gauges 1 & 3). At Guanabara Bay, Virtual Gauges were established at the major outflow points from heavily populated and polluted waterways (Virtual Gauges 1, 2, 3, 4), as well as at points where natural flow patterns can be observed (Virtual Gauges 4 & 5). In Rio Reconquista Basin, Virtual Gauge locations 1, 2, & 3 were selected because they can summarize in-flow/out-flow activity within the Rio Reconquista basin, while Virtual Gauges 4 & 5 were used as auxiliary measures of activity in the adjoining basins within the Buenos Aires metropolitan area. At Lake Titicaca, all Virtual Gauges were established based on being downstream from some significant population, as well as being located within the shallower and geographically isolated bays that characterize the lake.

SITES AND **LOCATIONS OF INTEREST**



YPACARAI LAKE

- 4 Locations of interest defined (=virtual gauges)
- Central Department, Paraguay

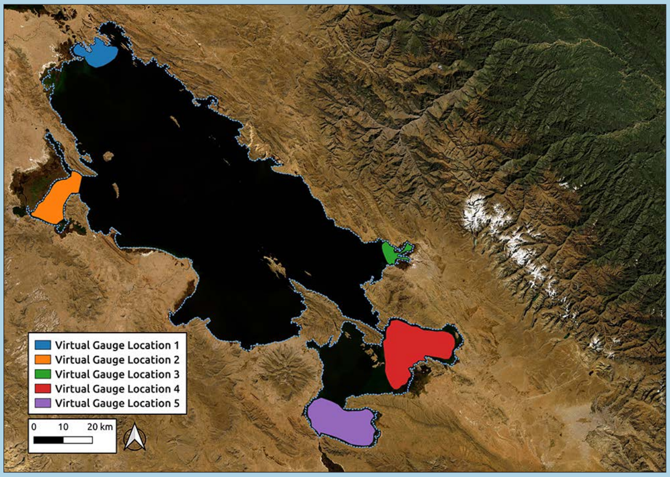


GUANABARA BAY

- 6 Locations of interest defined (=virtual gauges)
- Rio De Janeiro, Brazil

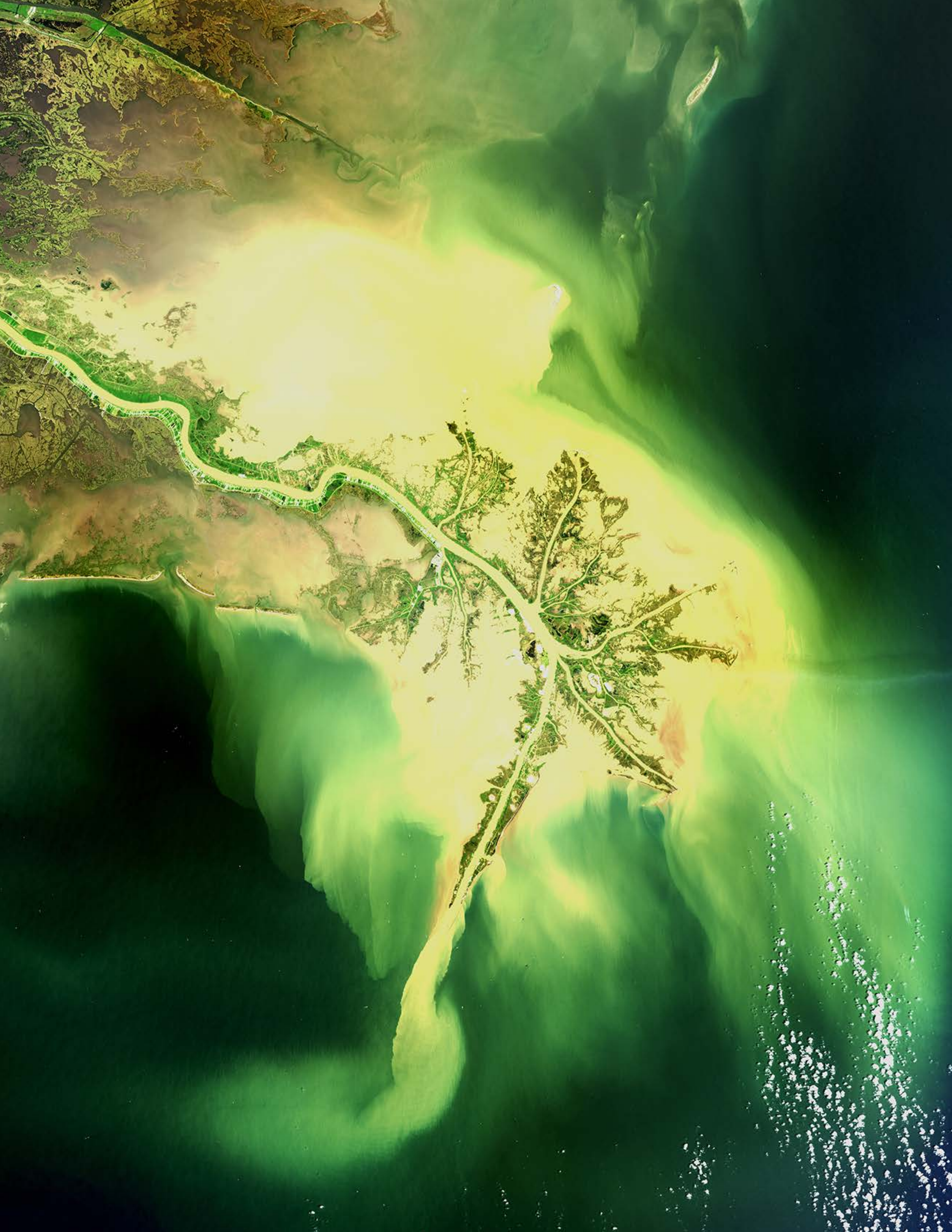
RIO RECONQUISTA BASIN

- 5 Locations of interest defined (=virtual gauges)
- Buenos Aires, Argentina



LAKE TITICACA

- 5 Locations of interest defined (=virtual gauges)
- Bolivia and Peru



OUR METHODS

REMOTE SENSING DATASETS

Satellite imagery datasets are acquired from the European Space Agency's Sentinel 2 A & B platforms, which are capable of producing a high-resolution (10-20 m) multispectral (490-865 nm) image at the same location on Earth every 5 days. These imagery data are distributed free for public use, and are used as the starting point for Gybe's satellite data processing pipeline.

For this pilot study, three different water quality metrics are calculated and used for the assessment of each water body; Chlorophyll-*a*, Turbidity, and Suspended Matter.

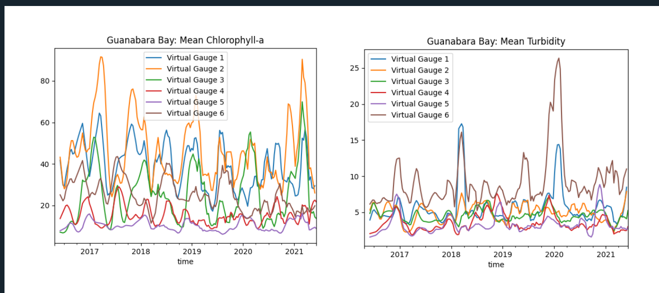
This pipeline ingests the raw top-of-atmosphere imagery, corrects for atmospheric effects, calculates a suite of WQ metrics, and creates a data repository for use across different display and analysis platforms. For more information on methods and processes, see Appendix A. For this pilot study, three different WQ metrics are calculated and used for the assessment of each water body.

1. Chlorophyll-a measures the concentration of phytoplankton growing in the water and is expressed in milligrams per cubic meter (mg/m^3). Water quality problems associated with changes in this water quality parameter are typically caused by nutrient pollution.

2. Turbidity the optical clarity of the water and is supplied in Formazin Nephelometric Units (FNU).

3. Suspended Matter measures the concentration of fine particles, both inorganic and organic, that are suspended in the water and is supplied in units of grams per cubic meter (g/m^3). Water quality problems associated with changes in this water quality parameter are typically caused by sediment pollution.

All resulting water quality product datasets are geo-referenced, cloud-screened, and adjusted to account for localized water extent changes over time.

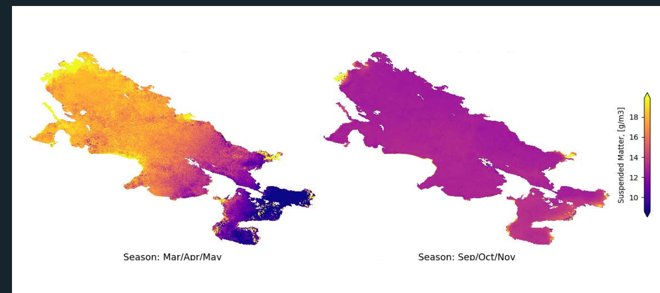


VIRTUAL GAUGES

Goal: generate time series based on specific, well defined areas of interest in the water body.

A Virtual Gauge is a specific geographic region of interest in which water quality parameters are temporally assessed in greater detail than viable across the entire water body. The goal of establishing Virtual Gauge locations is to extract data that enables rapid, flexible, and relevant investigation into areas where known WQ issues exist.

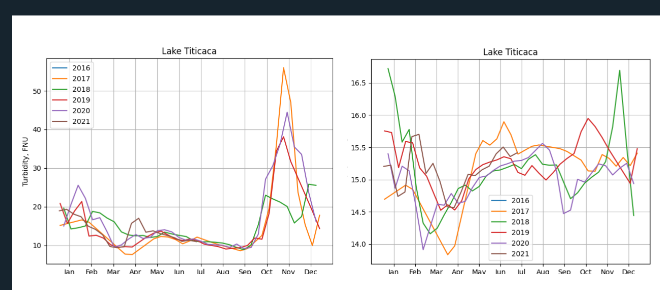
To establish a Virtual Gauge location, we first collect information from local experts and the scientific literature about where WQ issues originate or tend to occur. Examples of this information include official WQ sampling locations, citizen science reports, known point source polluters, areas where rivers are input into a reservoir, or locations of critical infrastructure (e.g. drinking water or hydro-power intake locations). Then, a spatially referenced area is created that reflects both the research and a statistically relevant pixel sample size.



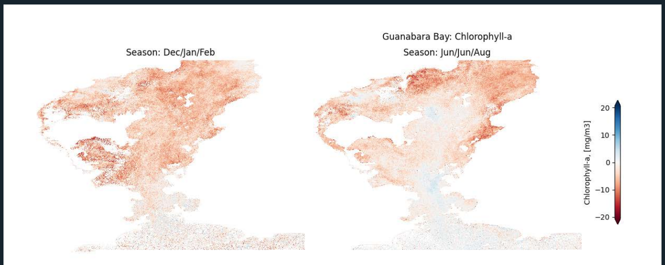
SEASONAL TRENDS

Goal: identify seasonal effects on water quality parameter values.

1. Spatial seasonal trends
We created maps illustrating the average seasonal changes across the entire water body. First, water quality values across the full archival time series were grouped into four three month intervals. Then values were averaged through time to produce maps that highlight the seasonal differences. This allows for identifying periods during the year or location within the water body where trends are noticeable, providing a method to link hydrological and land processes, or prevailing meteorological conditions. Seasonal and meteorological drivers not only impact the urban and rural runoff, but can influence the hydro-dynamics (water mixing) including flooding, storm surge, sewage flows and light available for photosynthesis, and more generally photochemical processes within the watershed.



2. Temporal seasonal trends
To further illustrate the differences within seasons and across years, we plot water quality time series data split by each year. Plots are produced for the entire water body as well as for each Virtual Gauge locations.



WATER QUALITY CHANGES FROM COVID-19 LOCKDOWN

Goal: identify water quality changes per parameter, before compared to after the Covid-19 lockdown, on 19 March 2020.

Changes to WQ stemming from Covid-19 lockdown restrictions were assessed from Gybe's remote sensing data using a series of simple one-way analysis of variance (ANOVA) tests. Differences in pre- and post-Covid-19 conditions were tested for at each WQ metric at each virtual gauge location, with pre-Covid-19 lockdown defined as all time series data before March 19, 2020.

While the timing and length of lockdown measures varied across the sites (Appendix C), a general assumption that lockdown measures ebbed and flowed starting in March 2020 combined with a seasonally-based division of data allowed for an as accurate as possible approach to comparing pre- vs. post-Covid-19 trends.

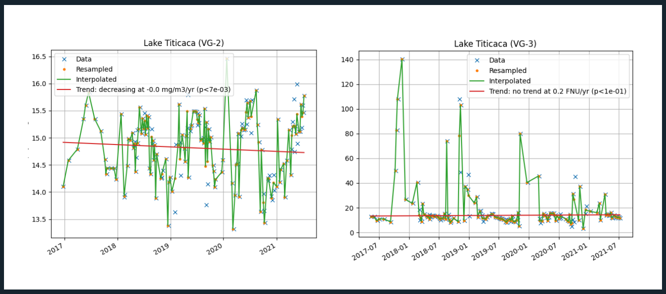
Both pre- and post-Covid-19 datasets were separated into three-month seasons, with tests performed on each season to control for seasonal variations. Significant differences between conditions were recorded with a 'p-value' less than 0.05.

Separately, an assessment of Covid-19 lockdown related differences in WQ was conducted across the entire water body to illustrate general trends not associated with virtual gauge locations.

For this, pixel-wise differences were calculated across the entire water body using images down-sampled to 30 m pixels. The resulting images illustrate where changes in WQ are observable.

Here the pixels where statistically significant differences that coincide with the period pre and post onset of Covid-19 are color coded; blue areas indicate locations where an increase in the water quality parameter is observed and red indicates areas where the specific water quality parameters are lower.

As expected, these changes have some seasonal patterns that could be enhanced by seasonal environmental differences or the timing and severity of lockdown requirements and resulting changes in economic activity.



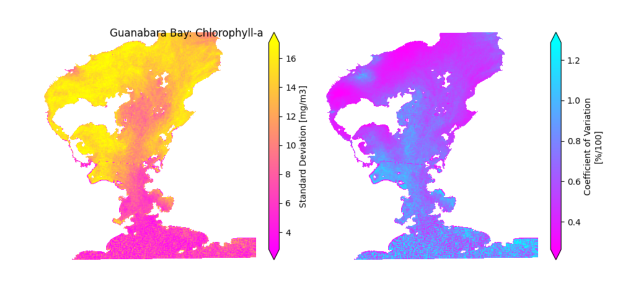
LONG TERM TRENDS

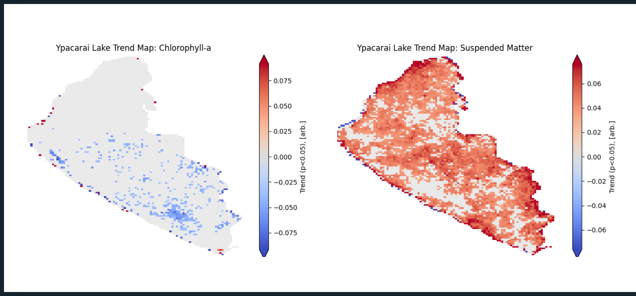
Mann-Kendall Trend Test

Goal: identify whether a water quality parameter is increasing or decreasing over time in a specific area.

We apply a seasonally adjusted Mann-Kendall Trend Test (Hirsch et al., 1982) to Virtual Gauge locations. First, the median water quality parameter value is calculated across a Virtual Gauge location for each image date. Then, a Mann-Kendall test is applied to the full archival time series which provides the direction, magnitude, and statistical significance of potential trends at that location.

The outcome indicates whether the time series data at that location has a consistent increasing or decreasing trend.





VARIATION MAPS

Goal: quantify where water quality values are consistently high, low, and have high variability over time.

We created Variation Maps for each water body and water quality parameter. This process calculates the median, standard deviation, and coefficient of variation on a pixel-wise basis through time.

The product is a map that shows the spatial distribution of these summary statistics through time. These maps can be used to locate areas that stand out with consistently different water quality patterns or areas with high variability. Either of these areas could be locations that are valuable indicators of important processes, or can be used as locations for more detailed monitoring

TREND MAPS

Goal: visualize where temporal trends in water quality parameters are occurring.

Next, extending the concept of Variation Maps, we create Trend Maps to visualize where temporal trends in water quality parameters are occurring.

First, data across the entire water body is spatially binned by averaged to approximately 100m resolution.

Then, a linear regression is applied along the temporal axis for each bin; a three-sigma outlier filtering process is used to remove outliers.

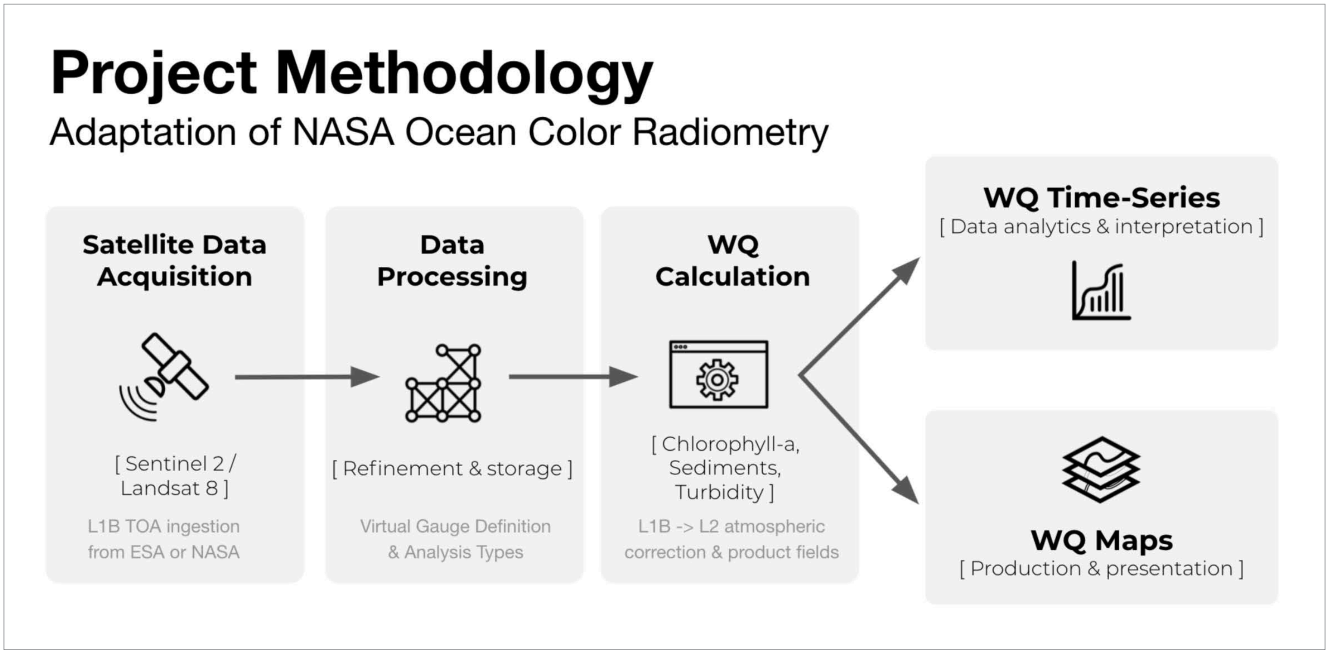
Finally, the linear trends are visualized on a map where statistically significant (p-value below 5%) values are colorized based on direction and intensity.

Similarly to the Spatial Statistics maps, colorized areas can be used to understand areas or locations where long-term trends indicate a linear trend in underlying water quality over multiple years showing increasing environmental pressures on the ecosystems, or successful implementation of policies, land-use practice or water and sanitation projects.

PROJECT **METHODOLOGY**

At the core of this pilot study is a dense satellite time series dataset continuously collected over each of the four sites since early 2016. The two Sentinel 2 satellites orbit asynchronously to provide a new image of a location on the earth's surface every 5 days at the equator (2-3 days at the mid-latitudes). Each image has 13 unique spectral bands available in a resolution of 10-60m, depending on the band.

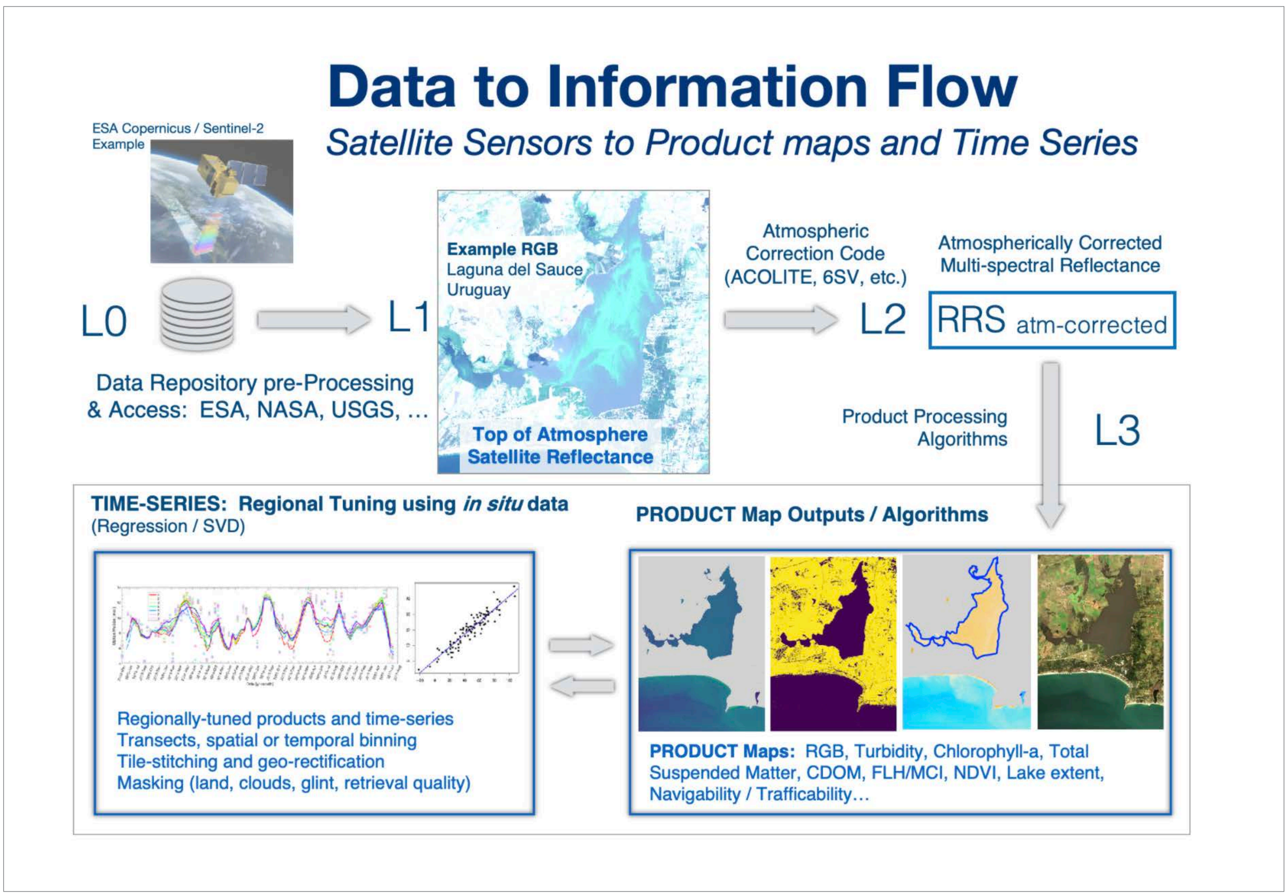
These multi-spectral images provide a snapshot of the earth's surface beyond the visible red, green, and blue spectral bands available from a typical consumer-grade digital camera image. For example, the amount of water present in vegetation canopies can be calculated using spectra invisible to the human eye, the near infrared and shortwave infrared bands on Sentinel 2A (8A, 11, and 12).



However, before any calculations can be performed, each image acquired by the sensor on-board a Satellite above the earth's atmosphere needs to be georeferenced (assigning geographical coordinates to each image pixel) and calibrated for intensity changes across the detector over time.

NASA and other space agencies have established protocols for how this is done, and following NASA nomenclature these top-of-atmosphere corrected images are referred to as processing level "L0". To make these images useful for calculating water quality parameters, the images must undergo a process that removes the effects of the atmosphere present between the satellite sensor and the earth or water surface. This process, termed atmospheric correction, implements a series of algorithms to reduce or eliminate the effects of atmospheric absorption and backscatter on the image, yielding a more accurate representation of the earth's surface.

The resulting images contain values for the remote sensing reflectance (abbreviated as Rrs) of the water body, which are referred to as "L1" in the commonly-adopted NASA nomenclature. These processed images can then be used to derive a variety of data products. Gybe uses proprietary approaches to achieve accurate corrections and robust reflectances at the L1 level.



Academic approaches commonly rely on atmospheric correction processes based on open source methods developed for inland and coastal water applications, such as the Royal Belgian Institute of Natural Sciences' (RBINS) Acolite processor, the National Aeronautics and Space Administration's (NASA) SeaDAS processor (https://odnature.naturalsciences.be/remsem/software-and-data/acolite; https://github.com/acolite/acolite; https://seadas.gsfc.nasa.gov/).

The full image collections, also referred to as archives, containing the atmospherically corrected imagery and Rrs values, are used to calculate the three water quality (WQ) products in this pilot study; Chlorophyll-a, suspended matter, and turbidity concentrations.

These WQ products are obtained by applying relatively standard algorithms developed in the open scientific literature specifically for detecting the makeup of inland coastal waters.

- Chlorophyll-a concentrations, which are measured in milligrams per cubic meter (mg/m^3), are calculated using normalized difference chlorophyll index (NDCI) developed by Mishra (2012).
- The NDCI algorithm can be used to detect algae concentrations and blooms using the red and red-edge spectral bands.
- Suspended matter and turbidity concentrations are measured in grams per cubic meter (g/m^3) and Formazin Nephelometric Units (FNU), respectively, and are both derived from the methodology developed by Nechad et al. (2010) for detecting total suspended matter (TSM) concentrations on the water surface.

It is important to note that the data in this report is not calibrated or validated against ground measurements, which is an effort deemed out of scope of this pilot in part due to inconsistent availability of water quality data across the four pilot sites. Gybe normally uses proprietary atmospheric correction approaches, water quality retrieval algorithms and data fusion with ground-based data to derive robust and quantified water quality parameters.

The analyses used in this pilot study relied on the pixel-wise time series data extracted from the entire water surface across each site. Having datasets that were dense in both the spatial (10 m pixels) and temporal (1 new image roughly every 5 days) dimensions facilitated analyses that could focus on establishing WQ baselines, quantifying changes in temporal trends, and illustrating patterns in spatial distributions. Trends over time and within seasons were established using simple time series plots constructed from the average or median WQ data product value across the entire water surface or else constrained to Virtual Gauge locations. Moving average filters were applied to time series data to both smooth spikes and interpolate across small gaps (https://en.wikipedia.org/wiki/Moving_average).

Quantifying the direction and magnitude of trends in the time series data is important to contextualizing any significant annual fluctuations. To do so a seasonally adjusted Mann-Kendall trend test was used to assess the presence, direction, and magnitude of a trend in the larger time series. Mann-Kendall tests are used to look through an entire dataset and quantify whether there is a significant fundamental change in the trend, regardless of the nature of the data distribution (i.e. no assumptions for a normal distribution) or linearity of the trend (i.e. it could be a non-linear trend) (Meals et al., 2011). In this pilot study, seasonally adjusted Mann-Kendall trend tests were applied to each WQ dataset averaged across each Virtual Gauge location. The results quantified the long-term behavior at each Virtual Gauge location and helped differentiate the dynamics at locations where water inputs and outlets occurred.

The spatially-oriented portion of the analyses focused on highlighting locations where WQ metrics were higher, lower, and changing over time.

The Seasonal Mean, Spatial Variation, and Spatial Trend maps relied on pixel-wise average (or median) values taken through time and projected onto a geographically referenced surface.

- Seasonal Mean maps perform a simple grouped average of all data in a season across the entire water surface.
- Spatial Variation maps calculate a pixel-wise median, standard deviation, and coefficient of variation through time across the entire water surface.
- Spatial Trend maps calculate a simple pixel-wise linear regression through time across the water surface, highlighting the pixels in which there is a significant (upward or downward) trend. In effect, these methods provide a way to quantify where there are WQ issues and if they change over time. For example, consistently high and increasing turbidity values at the location in a reservoir where a creek empties could direct resources for mitigation and restoration activities higher in the watershed.

GYBE

SUMMARY OF **PROJECT RESULTS**

APPLICABILITY

Remote Sensing applied to monitoring of water quality in lakes, rivers and reservoirs is a valuable emerging technology that can provide geospatial information about water clarity, nutrient, bacterial and industrial pollution from urban and rural sources. The methodology deployed by Gybe using cloud computing allows rapid monitoring deployment and scalable coverage across numerous watersheds and geographies.

This significantly lowers the costs of obtaining water quality information compared to laborious water sampling and collection methods. Furthermore, satellite data acquisition and processing is automated and available continuously across the globe, and new data are automatically analyzed and contextualized within seasonal or historical trends. This allows investments in water and sanitation infrastructure to be valued on the basis of realized regional and community benefits, and allows operators of water systems to reduce risks and lower operational and management costs.

This pilot study used remote sensing to determine if changes in human activity due to the Covid-19 lockdown measures of 2020-2021 could be detected in resulting water quality indicators across four sites in the IDB-LAC portfolio. **The hypothesis is that changes in industrial, commercial, and residential occupancy would be reflected in key water quality metrics measured across the pilot sites.**

To locate and measure these changes, Gybe conducted a series of one-way ANOVA (analysis of variance) statistical tests comparing the full historical archive of remote sensing data before and after the onset of Covid-19 lockdown measures across a range of locations. Gybe also produced maps that highlight locations within each site where noted differences are observed following the implementation of Covid-19 lockdown conditions.

Although this report presents a comprehensive analysis of this entirely new source of water quality data across the sites and locations of interest, a more detailed analysis can be performed by looking at different time-frames (e.g. entire data set or monthly aggregates) within these watersheds.

Additional insights may be unravelled by further combining Gybe's data set with other sources of information including local sensors, information from water and sanitation utilities and a more detailed analysis of the timing of location conditions and their local impacts.

COVID-19 FINDINGS

Results of this study show that remote sensing can be used to detect minor and more significant changes in the clarity of water (turbidity), sediment transport (total suspended matter), and algae (Chlorophyll-*a*) concentrations at specific locations during the period coinciding with the Covid-19 lockdown. The timing and duration of lockdown measures vary based on location; Buenos Aires, Argentina from early March to late July 2020, Asuncion, Paraguay from early March to late May 2020, La Paz/El Alto, Bolivia from early April to late May, and Rio de Janeiro, Brazil during May 2020. Location-specific timelines are provided in Appendix C. In many locations these changes were statistically significant, relative to baseline years prior to 2019. Additionally, the difference maps showed where the most pronounced changes occurred across each of the sites and some of the areas were significant in extent. It is important to note that across all four sites in this pilot, there are no consistent trends in magnitude, spatial extent or direction of changes. This is likely explained by the diversity of the four water systems in this pilot and complexity of local land-use, mix of runoff (urban & agricultural & intertidal), as well as the prevailing or seasonal hydrological and meteorological conditions.

KEY TAKEAWAY

The most significant changes that were observed, in relation to the Covid-19 restrictions, generally occur in areas directly adjoining or downstream from densely populated areas.

Findings summary per site:

Rio de Janeiro (Guanabara Bay)

Significant differences in water quality were observed at several locations in Guanabara Bay (Rio de Janeiro) corresponding to a time-frame generally coincident with Covid-19 lockdown measures, which are summarized in Appendix C. The most pronounced changes in water quality and lock-down measures occurred in the month of May 2020, as discussed in the results section.

Lake Titicaca

Significant differences in water quality coincident with Covid-19 lockdown measures have also been observed at several locations across Lake Titicaca. Significant changes in post- Covid-19 water quality are temporarily observed in isolated areas downstream from the larger population centers in La Paz, Achacachi, Desaguadero, and Puno. During the same time, the offshore parts of lake Titicaca seem to follow normal seasonal trends during the Covid-19 period.

Buenos Aires (Rio Reconquista Basin)

The Reconquista River Basin, which includes the municipality of Buenos Aires, also highlights locations where changes in water quality appear significant and correlated to the timing of Covid-19 restrictions. Primary lockdown measures in the Buenos Aires region between March and July 2020 appear to precede the increased Chlorophyll-a concentrations across several analysis locations during Dec 2020 & Jan/Feb 2021, which could be indicative to higher untreated or partially treated wastewater production during the lockdown period.

It is also important to note that since 2016 - the start of the Sentinel 2 archive - there is an underlying trend of increasing eutrophication (as observed from increasing Chlorophyll-a concentrations) at specific locations selected in this study (Virtual Gauges 1 and 3).

Ypacarai Lake, Paraguay
There were no statistically significant changes observed in water quality parameters pre- and post-Covid-19 lockdown measures at any of the study locations on Ypacarai Lake. However, seasonal differences and long-term increasing trends for suspended sediments across all locations of interest in this pilot are quite notable. The increased sediments could be indicative of long-term increase in nutrient loading from agriculture, which could be driving further eutrophication of this lake. With limited urban development and a population of approximately 350,000 surrounding this waterbody, the impact of Covid-19 restrictions appears to be minimal.

Generally, the statistically significant changes described above, coinciding with the Covid-19 onset and in the vicinity of urban areas, are not generally observed farther downstream or off-shore, as the waters get mixed and diluted. This further indicates that the observed changes are likely caused by the implemented Covid-19 measures and human-induced changes in urban (residential and industrial) and also rural (agricultural) demands on the water and sanitation systems. In order to isolate more localized changes, the remote sensing data generated from this pilot should be integrated with additional local contexts and datasets describing the extent, timing and type of impacts that were observed with regards to water and sanitation locally. Additionally, higher spatial and temporal resolution satellite datasets and local sampling data could be used to build on this local context to provide a highly local or personalized look into human-influence changes and trends in water quality at specific locations.

DISCUSSION AND NEXT STEPS
Given the significant growth in available low-earth orbit satellite imagery - or aerial imagery - platforms used for observation from private companies such as Planet Labs and public agencies such as NASA, ESA and others, significant improvements are expected in how often new images are generated. Daily revisits for larger > 5~10 km water areas are already possible. Satellite imagery from commercial platforms is available at 1 meter spatial resolution, enabling access to narrower rivers (>10~20 meter width) and smaller ponds and lakes. Continuous monitoring through the supplimental use of sensors, especially in smaller river, streams, and canals could be particularly be helpful to pinpoint sanitation and waste-water treatment hotspots, which in turn could inform more localized spatial extents where to Covid-19 impacts could be more concentrated.These results and remote sensing technology in general, can be a useful addition to the toolkit used by infrastructure, and water and sanitation teams in general or more specifically to understand the impacts due to Covid-19 restrictions.

The new datasets generated in this pilot can help provide insight in three key areas:
1. Inputs on where to measure and optimal in situ sampling rates
Remote sensing results pinpoint locations of high activity and variability throughout the year, helping to optimise the effectiveness of on the ground sampling by ensuring sampling is happening in the most interesting places.
2. Where to plan and develop future remediation or investment efforts
These data can also be used to identify locations where problems are most frequently occurring, as well as understanding the mitigation or remediation measures that should be applied. In addition to location, the scale of the needed intervention can be determined based on modeled or predicted impacts, and then verified during project implementation.

3. Inputs to help understand the ecological impact of construction, civil engineering or other infrastructure projects.

This remote sensing dataset on water quality gives us insight on what seasonal fluctuations are to be expected, and how levels of different water quality parameters are shifting over the long term. By combining this dataset with the timing and location of engineering projects, or interventions, meteorological and specifically rainfall data, as well as land use change information more generally, we can reach a more complete understanding of the downstream water quality and other environmental impacts from various projects.

Beyond this report document, as a deliverable of the pilot, Gybe is providing the Inter American Development Bank's Water and Sanitation teams with download-access to the full water quality datasets and analyses generated during this pilot project. Access to this information is described in the appendix. The teams are also conducting a series of workshops to explore further applications for these data to identify other potential impact areas or data-sets that support or enhance the conclusions relating to Covid-19 impacts. Additionally, Gybe is providing the Inter American Development Bank's staff with trial access to the GybeMaps™ platform to allow local teams to perform data exploration tasks or visualize results for specific areas outside of the analysis covered in this report.

This analysis of the water quality data sets can be extended, but integrating local in-situ water quality data, or additional data on meteorological and hydro-dynamics, as well as quantified geospatial datasets describing specific changes resulting from Covid-19 socioeconomic restrictions across the locations, or other data sets as they become available. Local water-quality in situ data would allow validating and calibrating the satellite based retrievals to get more quantitative results and the meteorological and hydrological data sets could provide additional context on the relationships between water quantity and quality.

Additionally, geospatial information about wastewater infrastructure quality, waste outflow locations and changes in population movement during the lock-down could be used to identify locations for study further upstream within the urban system, before significant mixing or dilution occurs. Other data indicating domestic water consumption or transportation data could also be used as proxies for the severity and duration of changes that were implemented in response to the Covid-19 pandemic and its multiple waves of infections. These additional data-sets and analysis would allow these findings to be applied towards more quantitative and finer resolution scales in time and space.

Finally, for further validation of the findings in this report, it may be useful to evaluate the post-pandemic time-period as normal population movement resumes and compare that time frame with a return to baseline conditions in water quality parameters. This would require taking a post-pandemic period of at least 12 months as a new baseline for comparison with data before and during the Covid-19 pandemic restrictions.

RESULTS SUMMARY
YPACARAI LAKE

Located ~30 km east of Paraguay's capital city Asuncion, Ypacarai Lake is a major source of drinking and irrigation water for the region as well as serving as a popular tourist attraction.

With a relatively large surface area (60 km²), average depth of 1.72 m, and location in a subtropical climate, the lake has long suffered from eutrophication and intense algal blooms (Moreira et al., 2018). Additionally, a steadily increasing population with limited access to a formal sewer network results in high organic nutrient loads flowing into the lake. While the wetland areas at the north (Yukyry Creek) and south (Pirayu Creek) can filter some of this load, relatively low flow rates from the only outflow point (Salado River) further contribute to algal blooms (Marti et al., 2017).

Consistently high Chlorophyll-a concentrations are observed across the entire lake (Figure 1) throughout the entire time series, with notably high values during an algal bloom in March of 2017 (Figure 2).

There is a slight seasonal variation in Chlorophyll-a concentrations with higher values from June through August (Figure 3), and over the entire time series there is no statistically significant upward trend or downward trend.

Separately, there are significantly increasing trends in suspended matter and turbidity values at all four Virtual Gauging locations across the lake throughout the entire time series (Figure 4).

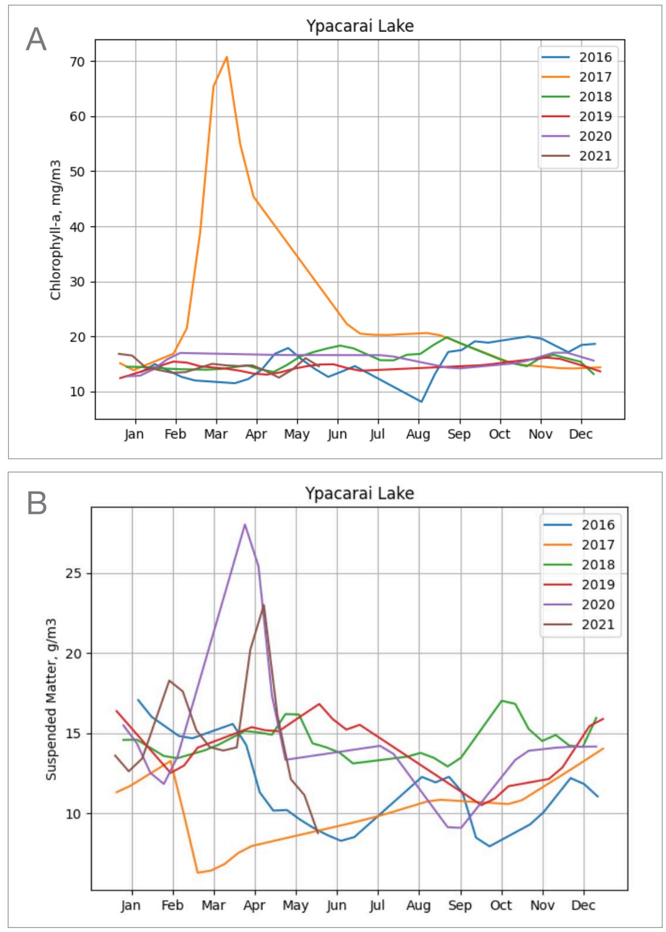


Figure 1: Panels A and B show the annual trends in Chlorophyll-a and suspended matter concentrations, respectively, across the entire Ypacarai Lake. Consistent levels of Chlorophyll-*a* concentrations appear to correspond to the lake's subtropical location, shallow depth, and low turnover rate.

A significant spike in Chlorophyll-a concentration shows an inverse relationship with suspended matter during an algal bloom in early-mid March 2017. This supports the idea that clear water conditions can predicate intense algae growth and subsequent bloom events.

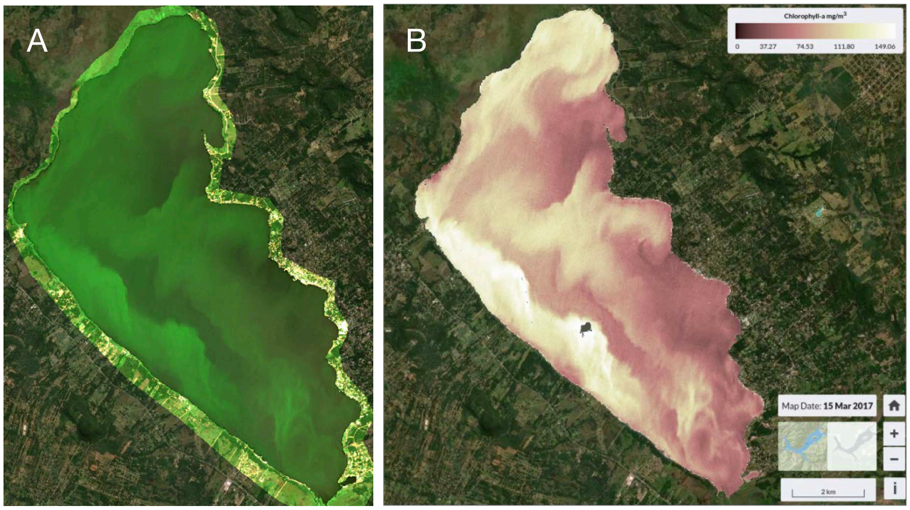


Figure 2: An intense algal bloom imaged on March 15, 2017; Panel A shows the corrected RGB image while Panel B shows the calculated Chlorophyll-a product. While the average value across the entire reservoir is ~70 mg/m^3, some locations approached 150 mg/m^3. This is a significant deviation from the normal values, which range from 10-20 mg/m^3 between 2016 until present. Importantly, this bloom event occurred when lower than normal suspended matter concentrations were observed across the entire reservoir. This demonstrates an inverse relationship between Chlorophyll-a and suspended matter concentrations, and supports the idea that more clear water allows for increased algae production.

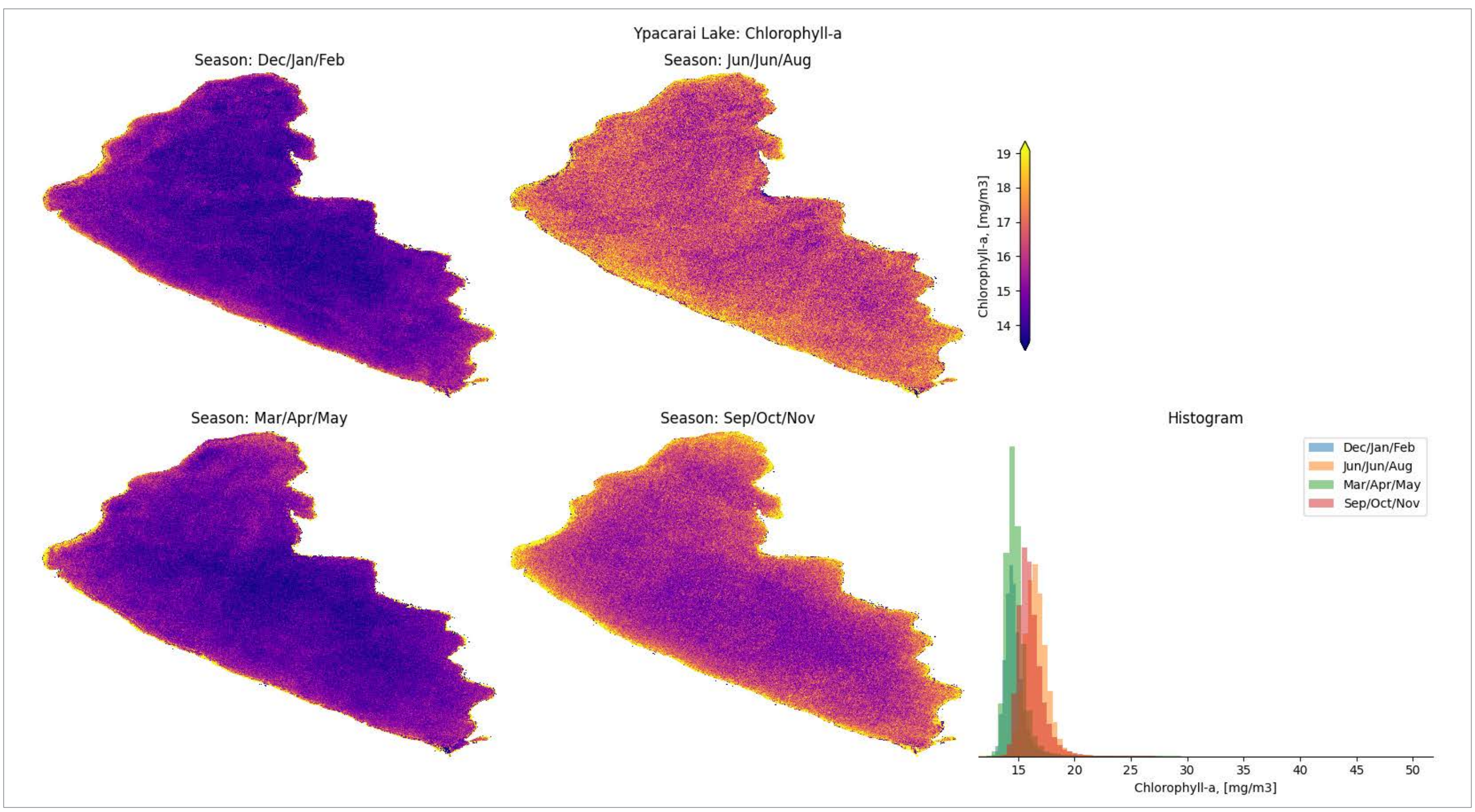


Figure 3: Seasonally partitioned mean Chlorophyll-*a* concentrations across Ypacarai Lake. Each surface depicts the mean pixel value across the entire site throughout a three-month period. While there is some localized spatial variation, the small size of this site leads to rather consistent values across the entire area.

Figure 4: Mann-Kendall trend analysis for suspended matter concentrations at all Virtual Gauge locations at Ypacarai Lake show an increasing trend since 2016. These increasing trends in suspended matter occur while there are no or decreasing trends in Chlorophyll-a concentrations at the same Virtual Gauge locations. Despite the anomalous algal bloom, this could point to how higher overall suspended matter concentrations mitigate algae growth across the entire water body.

There were no significant differences found between WQ metrics pre- and post-Covid-19 lockdown measures at any Virtual Gauge location on Ypacarai Lake. However, maps illustrating the pixel-wise mean difference between pre- and post-Covid-19 across the entire water surface show observable differences based on season (Figure 5).

From March-May of 2020, there is a relatively neutral change signal in Chlorophyll-a, while for suspended matter there is an overall decreasing trend.

This decreasing trend continues for suspended matter concentrations into June/July/August before heading in the opposite direction from September 2020 through February 2021.

This change in signal could be attributed to limited human activity during the initial lockdown restrictions, then increased travel to the region as people began to work remotely and vacation in the region.

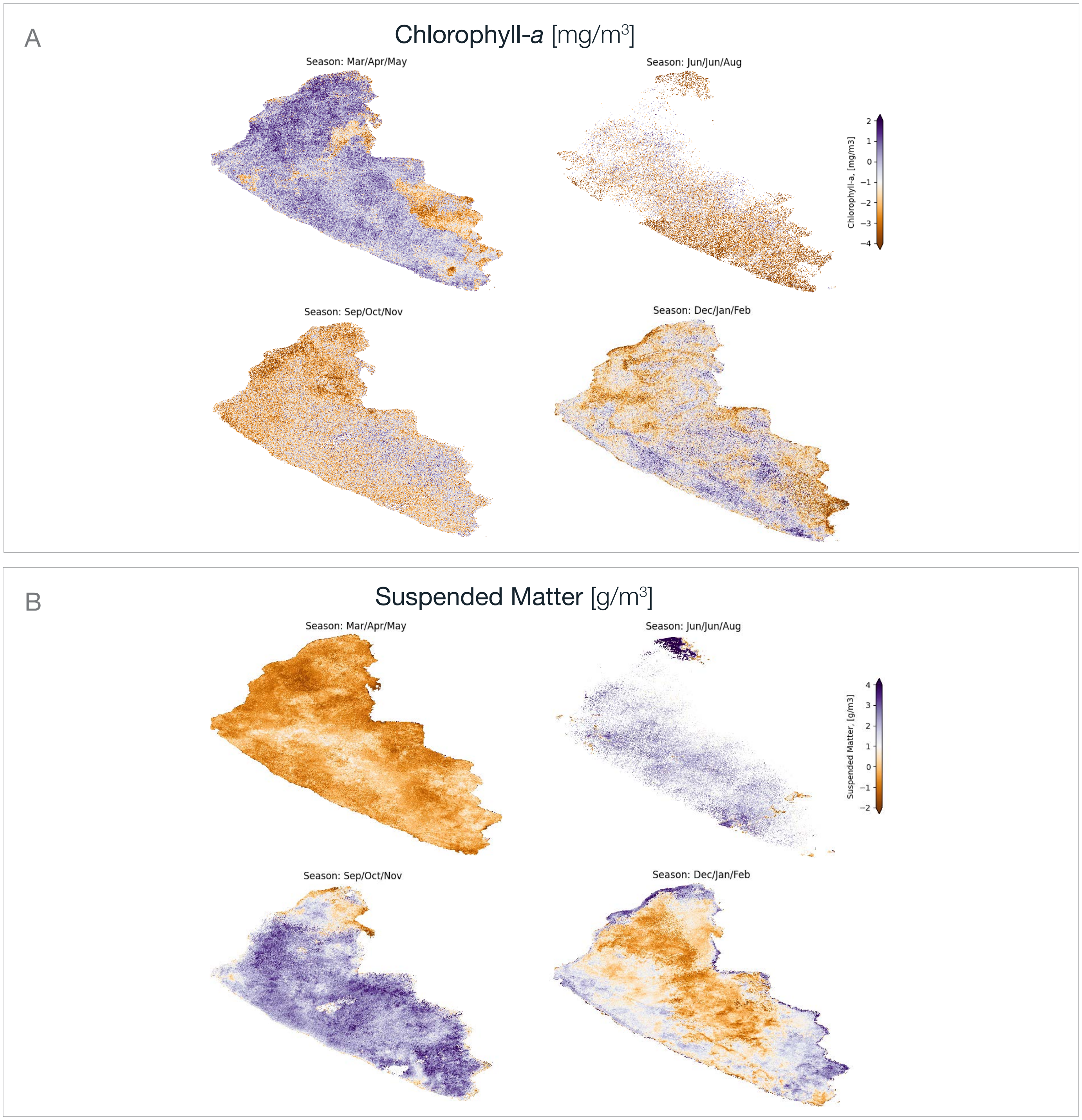


Figure 5: Pixel-wise differences between pre- and post Covid-19 lockdown measures in Chlorophyll-a (Panel A) and suspended matter (Panel B) concentrations across Ypacarai Lake. Each 10m pixel depicts the difference in mean WQ metric values between the pre- and post-Covid-19 time frames.

Negative pixel values are areas where there was a significant reduction in a WQ metric when comparing pre- vs. post-Covid-19 lockdown restrictions. Panel B shows that when comparing the months of June/July/August, suspended matter concentrations decreased significantly across the entire water body. This trend then reversed course and increased into the months of September/October/November before becoming more mixed into the months of December/January/February 2020-2021.

While these maps likely reflect some of the regular seasonal signal, the significant differences between pre- and post-lockdown conditions should be further investigated.

RESULTS SUMMARY
GUANABARA BAY

Guanabara Bay is a 384 km² area surrounded by several of Brazil's major metropolitan areas and roughly 8.6 million people, many of whom reside in the city of Rio de Janeiro.

About 84% of the bay is less than 10m deep, with the remaining portion a deep main channel that leads out to the Atlantic Ocean; these properties in turn hamper the internal circulation of the water within the bay (Kjerfve et al., 1997).

Significant land-use change away from the natural estuarial ecosystems to heavy industrial and residential has led to widespread ecological degradation in water quality in the bay (Fisatrol et al., 2015). Unfiltered organic waste from sewage outfalls draining dense residential development has led to severe eutrophication and a significant decline in marine life (Carreira et al., 2002; Nepomuceno et al., 2006).

High Chlorophyll-a levels tend to be observed at locations draining dense residential and industrial development, which correspond to Virtual Gauge locations 1, 2, and 3 (Figure 6). Patterns at these locations also follow a seasonal trend, with higher concentrations occurring during the warmer and wetter months, especially November through March for locations 2 and 3 during a period of higher solar radiation in the southern hemisphere.

This data set could be used to design a monitoring plan to better understand the key sources of nutrients and organic matter resulting in eutrophication.

As an outlet for several major unobstructed rivers, annual trends in turbidity and suspended matter concentrations align with the rainiest months, from December to March, and are particularly noticeable at Virtual Gauge location 6 (Figure 7). There were significant differences in WQ metrics that correspond with the general timing of Covid-19 lockdown measures at several Virtual Gauge locations in Guanabara Bay.

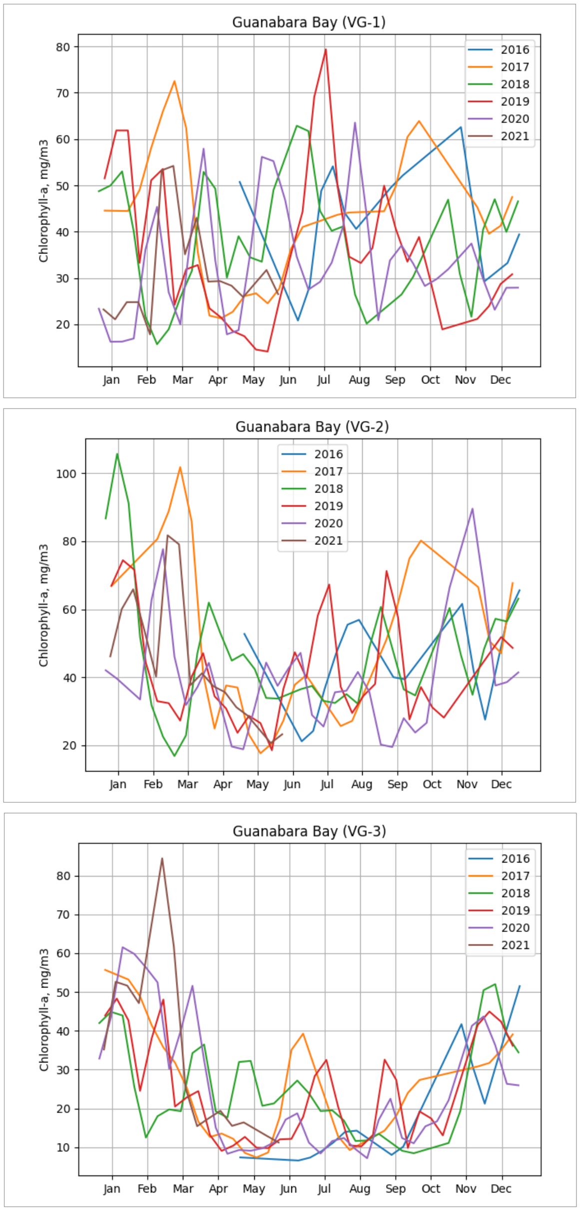
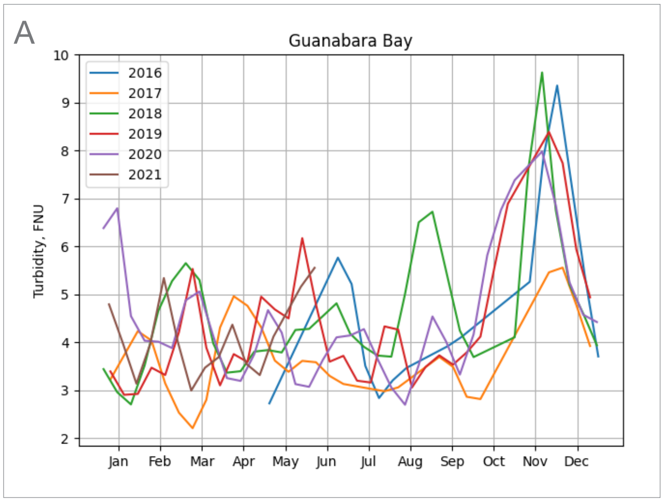


Figure 6: Annual trends in Chlorophyll-a concentrations at Virtual Gauge locations 1, 2, and 3 across Guanabara Bay. This shows a strong seasonal pattern where algae blooms are prevalent in the southern hemisphere summer, and higher amounts of photosynthetic radiation and higher nutrient runoff.

Lockdown measures affecting Rio de Janeiro are summarized in Appendix D, and were limited to the month of May 2020 for the context of this study.



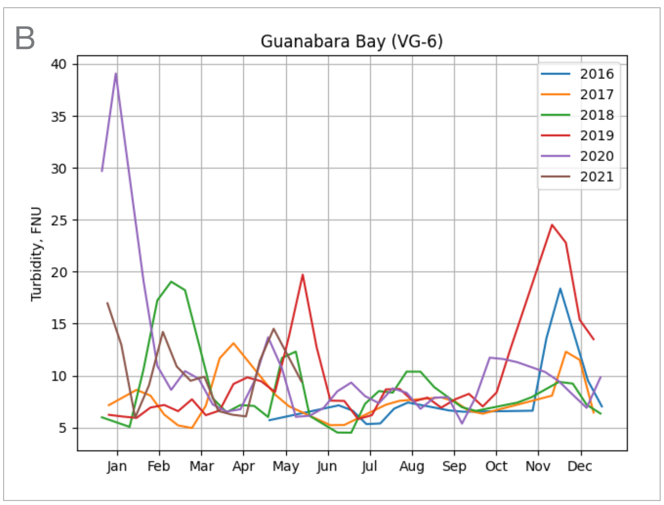


Figure 7: Panel A shows the annual trends in turbidity across the entire Guanabara Bay. Higher levels starting in November appear to correspond with higher precipitation inputs to the watershed. Panel B shows the same trends at Virtual Gauge location 6, where many rivers empty into the bay.

Overall, there were few instances of statistically significant changes in WQ metrics at Virtual Gauge locations (Table 2), however significant trends at these locations are further observed and corroborated across the entire water surface (Figure 8).

In particular, post Covid-19 lockdown conditions show overall reductions in Chlorophyll-*a* concentrations across much of Guanabara Bay, with significant reductions at Virtual Gauge locations 1 and 6.

Reductions in Chlorophyll-*a* concentrations at Virtual Gauge 1 at the location of the outlet of the heavily polluted Rio Iguacu, could be caused by changes in industrial and residential discharges at varying stages of lockdown restrictions.

However, at Virtual Gauge location 4, the increase in Chlorophyll-a concentrations during the active lockdown period (Mar/Apr/May 2020) could be tied to increased residential effluent from people being at home. Table g1 summarizes the locations with statistically significant ($p < 0.05$) differences between pre and post Covid-19 lockdown measures, with the site-wide differences illustrated in maps of the entire water surface across the site (Figure 8).

Overall, Figure 8 indicates that Chlorophyll-*a* concentrations appear to significantly decrease across the entire bay throughout Covid-19 onset and lockdown timeframe, which could indicate generally lower nutrient levels across the bay. However, due to size and complexity of the inputs into the bay, pinning down the origin of these changes is less straightforward, and requires narrowing the analysis to areas where local and more detailed understanding of restrictions in place during Covid-19 in concert with demographic and economic geospatial data.

More variable conditions along the western shoreline near Rio de Janeiro suggest that effects from lockdown measures may be localized and dependent on the enforcement of and compliance with restrictions in these areas, coupled with quality of water and sanitation infrastructure in those locations.

In particular, the area near Virtual Gauges 1 and 2 has opposing patterns in suspended matter concentrations between March/April/May and December/January/February.

The decrease in suspended matter concentrations during March/April/May (2020) appears to correspond with the official lockdown period in Rio de Janeiro (May 5 - May 24, 2020) as outlined by IDB staff (Appendix D). Decreased suspended matter concentrations during this time may correlate with decreased industrial wastewater output. While the increases later on during December/January/February (2021) points to relaxed lockdown measures and increased activity overall (Appendix D).

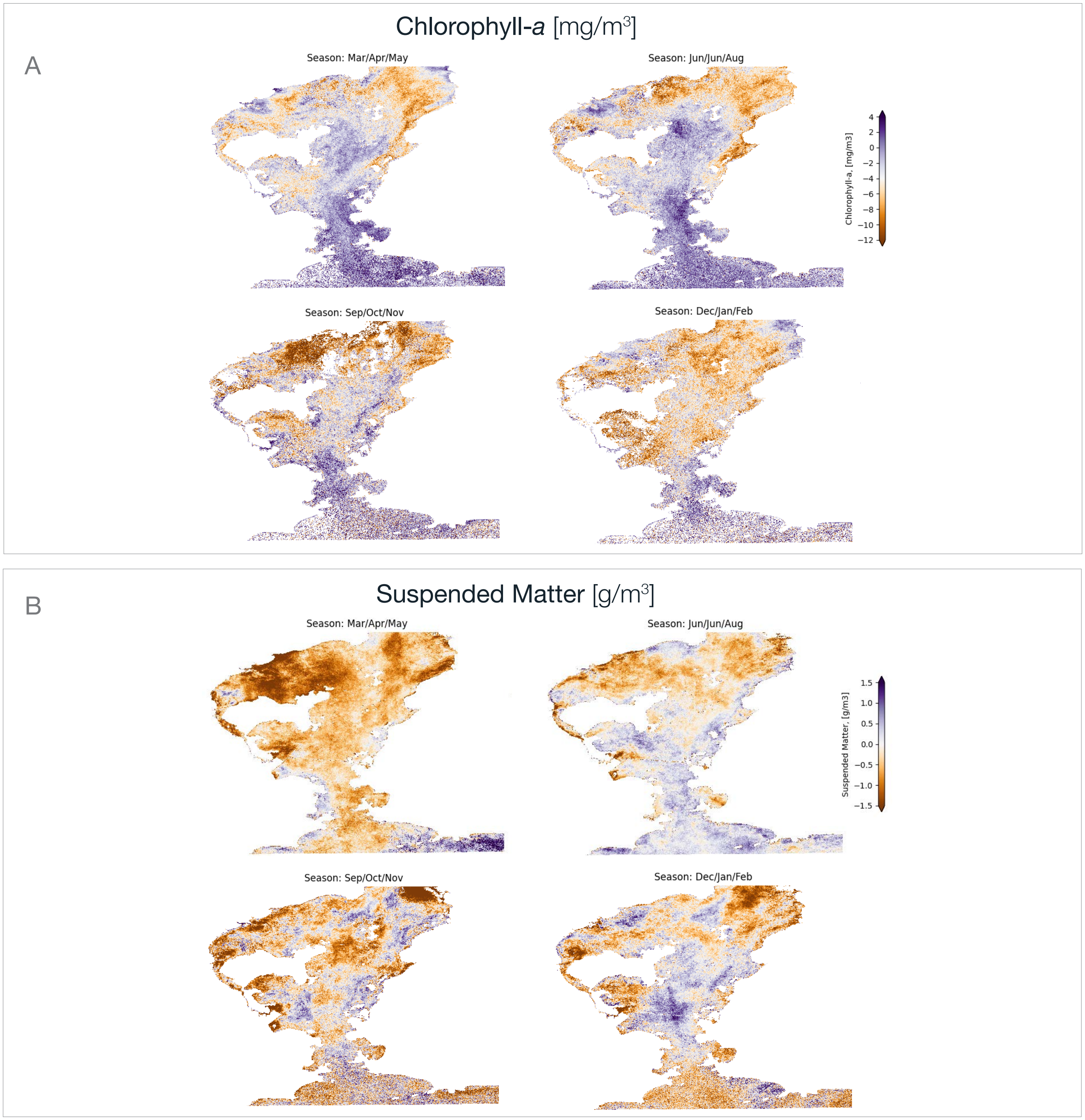
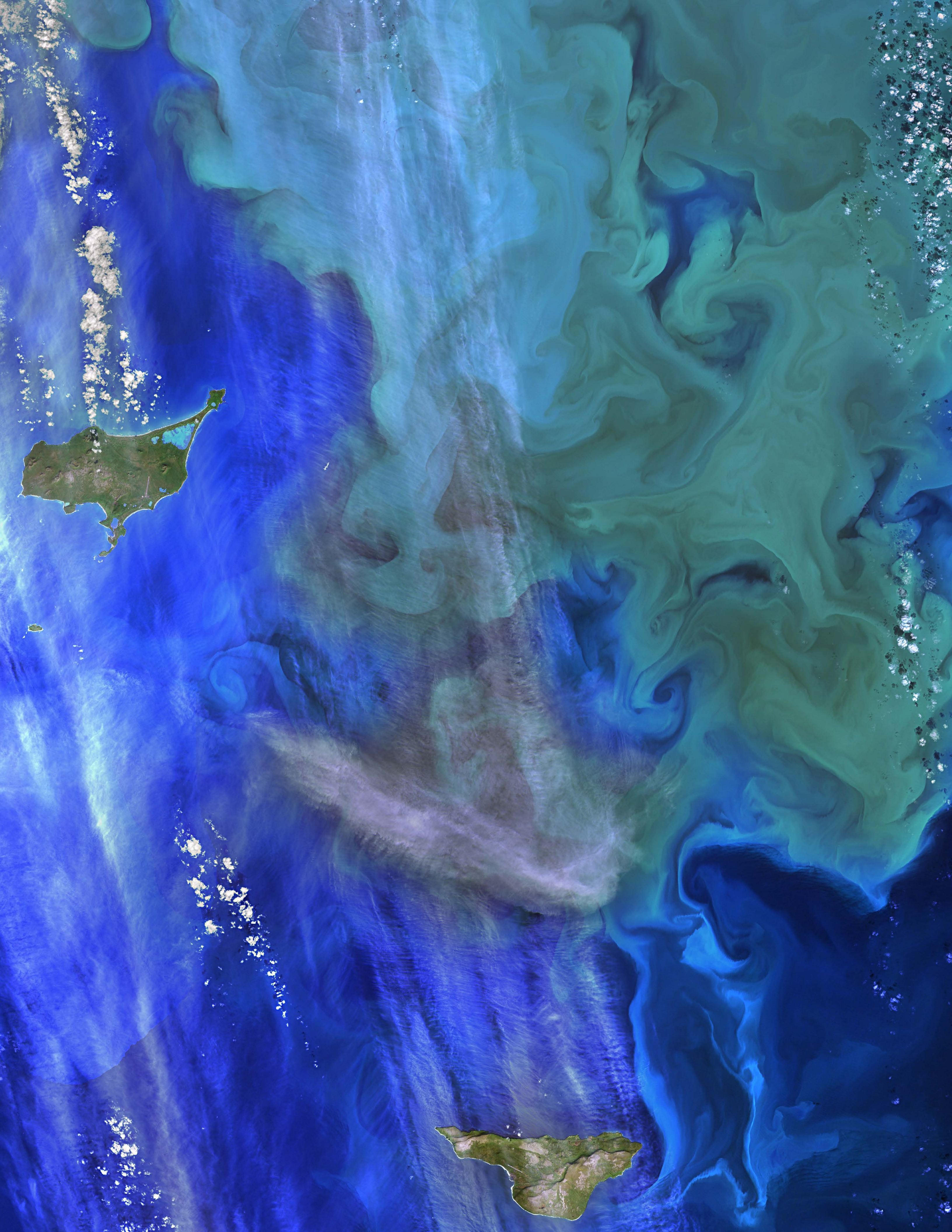


Figure 8: Pixel-wise differences between pre- and post Covid-19 lockdown measures in Chlorophyll-a (Panel A) and suspended matter (Panel B) concentrations across Guanabara Bay. Each 10m pixel depicts the difference in mean WQ metric values between the pre- and post-Covid-19 time frames.

Location	Parameter	Timeframe	Change
1	Chlorophyll-a	Sep/Oct/Nov (2020)	Decrease
1	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Decrease
4	Chlorophyll-a	Mar/Apr/May (2021)	**Increase**
4	Susp. Matter & Turbidity	Dec/Jan/Feb (2020-2021)	Decrease
6	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Decrease

Table 2.



RESULTS SUMMARY
RIO RECONQUISTA BASIN

The Rio Reconquista Basin houses around 11% of Argentina's population, comprising 33% of the Buenos Aires metropolitan area, and as a result faces considerable pollution from industrial wastewater and untreated sewage from informal residential settlements *(Castañé et al., 2006; de Cabo et al., 2000).*

Regional and international programs, including those funded by the Inter-American Development Bank (IDB), have implemented measures to improve both wastewater and flood control infrastructure throughout the basin *(Janches et al., 2014).*

Importantly, this includes channelization of the Rio Reconquista through the densely populated area between Roggero Dam (Lago San Francisco) and the Rio Lujan. While such channelization helps control flows from the dam through the urban areas, it can also concentrate polluted runoff (Figure 9).

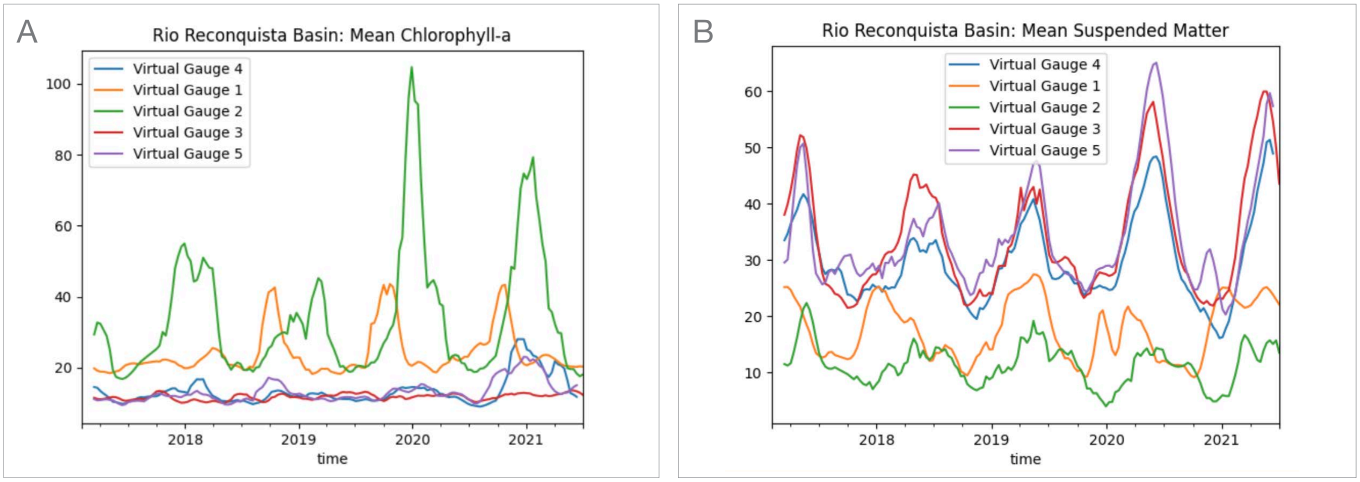
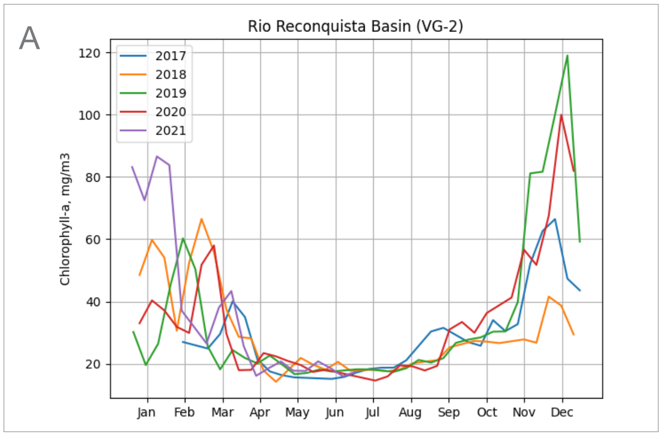


Figure 9: Full time series of Chlorophyll-*a* (Panel A) and suspended matter (Panel B) concentrations across the Rio Reconquista Basin, with each line corresponding to a different virtual gauge location. Interestingly, the conveyance of water through the Rio Reconquista can be observed in the lag between water leaving Lago San Francisco (Virtual Gauge 1) and flowing through the confluence with the Rio Lujan (Virtual Gauge 2). The overall higher concentrations of Chlorophyll-a at Virtual Gauges 1 and 2 (Panel A) are due to the greater input of nutrients that trigger algae growth from the urbanized watershed, coupled with lower overall volume of water in this part of the system. The opposite effect is observed in suspended matter concentrations (Panel B), where the inherent presence of suspended sediments is higher at locations where water volume is greater and there are greater inputs from non-urbanized sources.

Strong seasonal trends in all WQ metrics are observed across the entire site, and are particularly pronounced at the specific Virtual Gauge locations (Figure 10).

To effectively monitor WQ metrics in this area, both over the long term and resulting from Covid-19 lockdown measures, Virtual Gauges locations 1, 2, and 3 were established at strategic points. Starting with those specific to the Rio Reconquista, Virtual Gauges 1-3 were established at Lago San Francisco, the lower section of Rio Reconquista, and the outlet of the Rio Lujan, respectively.



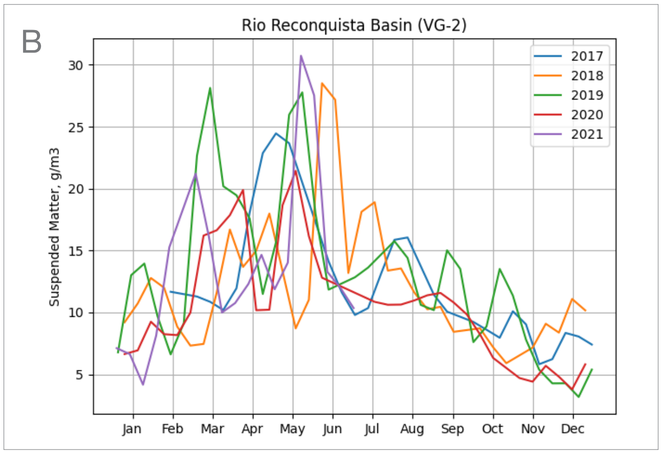


Figure 10: Annual trends in Chlorophyll-a and suspended matter concentrations at Virtual Gauge location 2. Higher levels of Chlorophyll-a (Panel A) from November to March appear to correspond with higher Austral summer temperatures. While higher suspended matter concentrations (Panel B) are observed into the wetter months of February to April.

To characterize the adjoining basins in the Buenos Aires metropolitan region, Virtual Gauges 4 and 5 were established at the outlet of the Matanza River and downstream from the city of La Plata, respectively. All Virtual Gauge locations were selected based on input from IDB stakeholders, being of a certain size (> 50m wide), and proximity to densely populated areas.

There were significant differences found in WQ metrics observed from Covid-19 lockdown measures at several Virtual Gauge locations in the Reconquista River Basin (Table 3).

Primary lockdown measures in the Buenos Aires region took place between March-July 2020, with the full extent summarized in Appendix D. Of note are the increased Chlorophyll-a concentrations at Virtual Gauges 1, 2, and 3 during Dec/Jan/Feb 2020-2021 of post Covid-19 lockdown.

These differences are also observed in maps illustrating the simple difference in mean values between pre- and post-Covid-19 around the Virtual Gauge locations (Figure 12).

While this could point to greater residential wastewater production during lockdown measures, there has also been increasing Chlorophyll-*a* concentrations at Virtual Gauge locations 1 and 3 since 2016 (Figure 11).

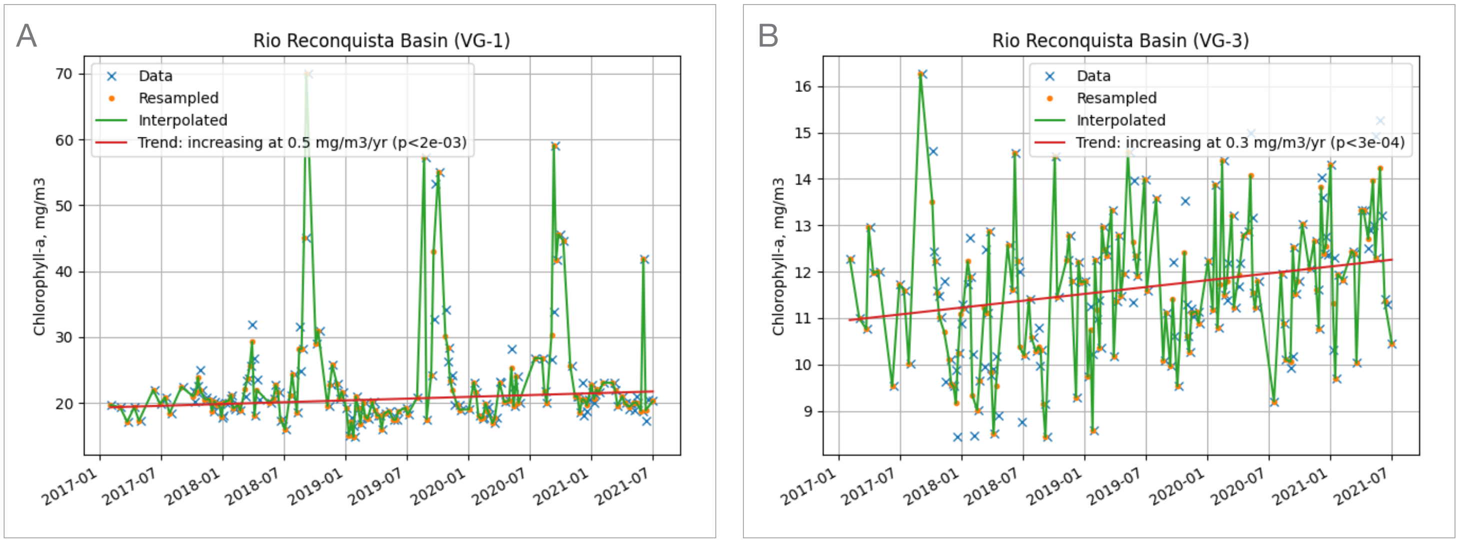
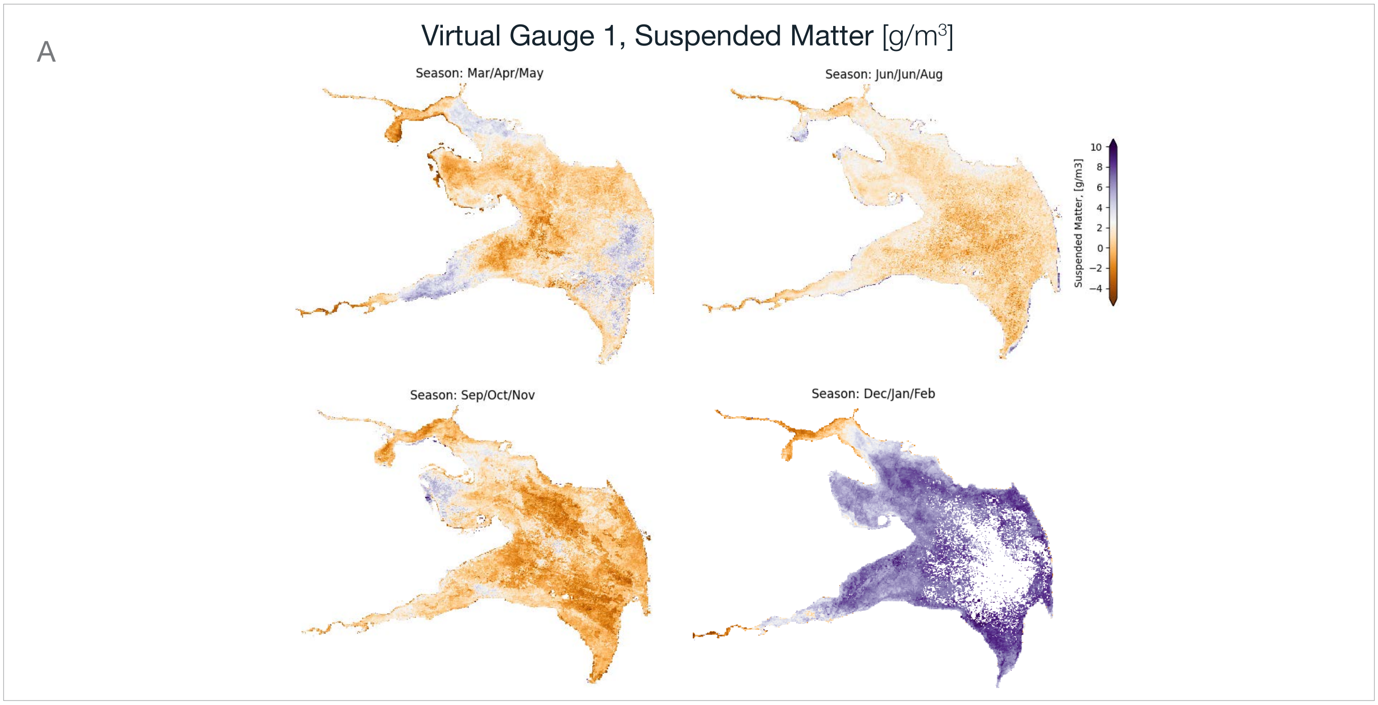


Figure 11: Long term trends in Chlorophyll-a concentrations at Virtual Gauges 1 and 3 in Rio Reconquista Basin show a slight upward trend across the entire time series data set.
These upward trends could be in part due to increased runoff of organic compounds from agricultural practices occurring throughout the watershed, which would provide fuel for algae growth.

Location	Parameter	Timeframe	Change
1	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Increase
2	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Increase
2	Susp. Matter & Turbidity	Dec/Jan/Feb (2020-2021)	Decrease
3	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Increase
3	Chlorophyll-a	Mar/Apr/May (2020)	Increase
3	Susp. Matter & Turbidity	Dec/Jan/Feb (2020-2021)	Decrease
4	Chlorophyll-a	Sep/Oct/Nov (2020)	Increase
4	Turbidity	Dec/Jan/Feb (2020-2021)	Decrease
4	Turbidity	Jun/Jul/Aug (2020)	Increase
4	Turbidity	Mar/Apr/May (2020)	Increase
5	Chlorophyll-a	Jun/Jul/Aug (2020)	Increase
5	Turbidity	Dec/Jan/Feb (2020-2021)	Decrease
5	Turbidity	Jun/Jul/Aug (2020)	Increase
5	Turbidity	Mar/Apr/May (2020)	Increase

Table 3



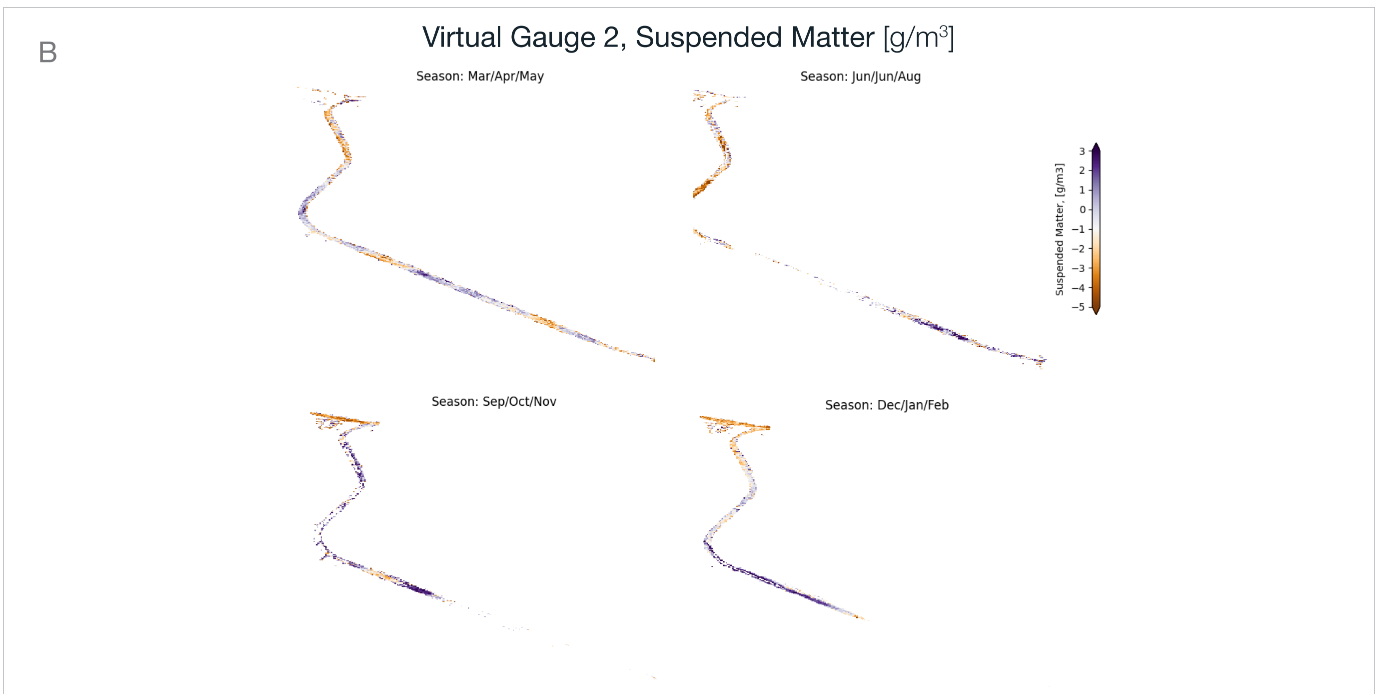


Figure 12: Figure r2: Pixel-wise differences between pre- and post Covid-19 lockdown measures in suspended matter concentrations at Virtual Gauge locations 1 (Panel A) and 2 (Panel B) in the Rio Reconquista Basin. Each 10m pixel depicts the difference in mean WQ metric values between the pre- and post-Covid-19 timeframes. Panel A shows slight increases in suspended matter concentrations in parts of the reservoir from March until November, then a more substantial increase into December and the early parts of 2021. Panel B shows decreased suspended matter concentrations at a few locations throughout Virtual Gauge location 2 during March/April/May and June/July/August 2020. Of note is the decrease during March/April/May 2020 towards the upstream end of Virtual Gauge location 2, where the Parque Industrial Tigre is located. Later on in June/July/August 2020, when regional lockdown restrictions begin to ease (Appendix D), the suspended matter concentrations begin to increase in this same area.

RESULTS SUMMARY
LAKE TITICACA

As the largest freshwater lake in South America, Lake Titicaca is integral to the high plateau regions of Peru and Bolivia where much of the population is dependent on the lake for cultural, agricultural, and economic activities.

Increased untreated outflows from industrial and residential development have compromised larger ecosystem health, and led to bi-national government programs aimed at implementing sanitation projects at key places around the lake (Duquesne et al., 2021).

In particular, the shallower areas in the southern (Rio Katari outlet), far western (Puno Bay), far eastern (near Achacachi), and northern portions (Rio Ramis) all are subject to decreased water quality and algal blooms (Cruz et al., 2010; Komárková et al., 2016). Consequently, higher Chlorophyll-a concentrations are observed at Virtual Gauge locations that align with these shallower areas (Figure 13).

Interesting to note is the strong seasonal variation at some locations, while others remain consistent throughout the years. Both the strong variation and consistency at these locations could be in part to wind-driven water circulation patterns from the winds predominantly being from the north and west. Similarly, these patterns are observed in turbidity and suspended matter concentrations at the same Virtual Gauge locations (Figure 14).

In the Lake Titicaca region, the only official Covid-19-related lockdown measures were in effect in La Paz/El Alto (Virtual Gauge location 4) during April-May 2020 (Appendix D). There were significant differences in WQ metrics observed from Covid-19 lockdown measures at several Virtual Gauge locations in Lake Titicaca (Table 4), however significant trends at these locations are further observed and corroborated across the entire water surface (Figure 15).

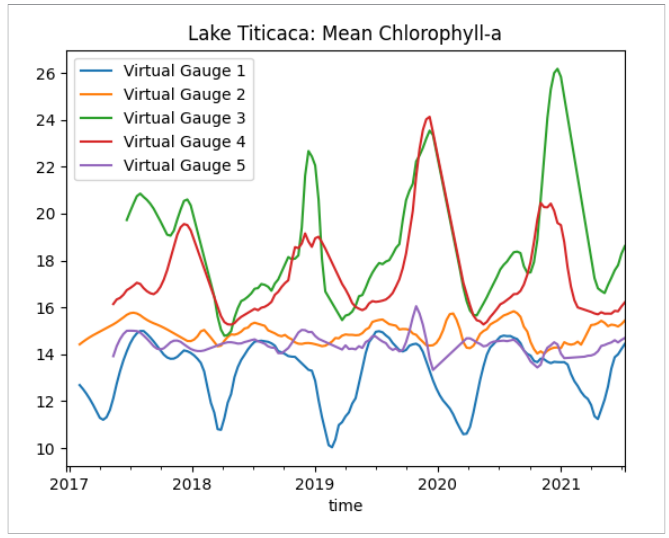


Figure 13: Full time series of Chlorophyll-a values at all Virtual Gauge locations throughout Lake Titicaca. The strong seasonality in Virtual Gauges 1, 3, and 4 could in part be due to their locations downstream from significant population centers and the increased organic pollutants that might be running off from these locations and contributing to higher Chlorophyll-a concentrations from algal blooms.

The lack of strong seasonal signals at Virtual Gauge locations 2 and 5 could also be in part due to lower nutrient levels. In these locations, there is likely less wind-driven movement on the water surface, since the predominant wind direction is out of the west, which typically creates conditions well suited for surface algal bloom formation.

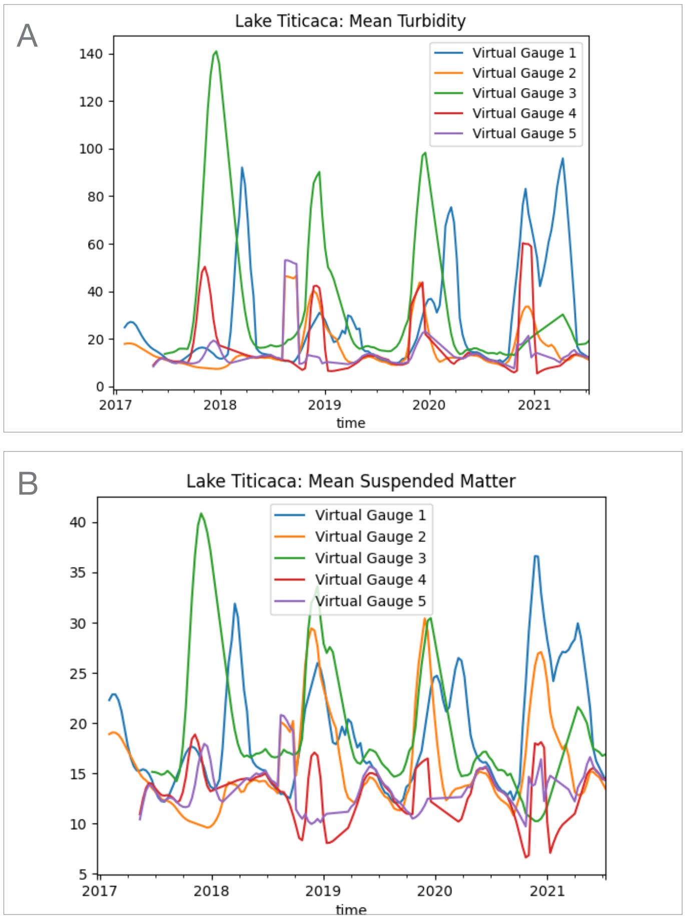


Figure 14: Full time series of turbidity and suspended matter values at all Virtual Gauge locations throughout Lake Titicaca. During the later part of 2020 and into 2021, turbidity and suspended matter concentrations at Virtual Gauge location 3 decreased to below normal levels. This decrease also mirrored an increase in Chlorophyll-a concentrations at that same location. This perhaps indicates that limited industrial activity contributed to a reduction in runoff while increasing the likelihood of algal growth in clearer waters.

In particular, post Covid-19 conditions show isolated areas with clear changes in WQ metrics, and these areas tend to be downstream from the larger population centers in La Paz, Achacachi, Desaguadero, and Puno. In addition to corresponding with the Virtual Gauge locations, these areas tend to be isolated from the main lake area and in bays and inlets. Despite active lockdown measures in La Paz/El Alto during April-May 2020 (Appendix D), no significant effects on WQ metrics were observed. However, there were significant differences found at the adjacent Virtual Gauge locations (3 & 5) downstream of Achacachi and Desaguadero, respectively. A further analysis about local implications of the lock-down measures in terms of population movement and impacts on water and sanitation infrastructure utilization would help explain these differences. Table t1 summarizes the significant ($p < 0.05$) differences between pre and post Covid-19 lockdown measures, with the site-wide differences illustrated in maps of the entire water surface across the site (Figure 15).

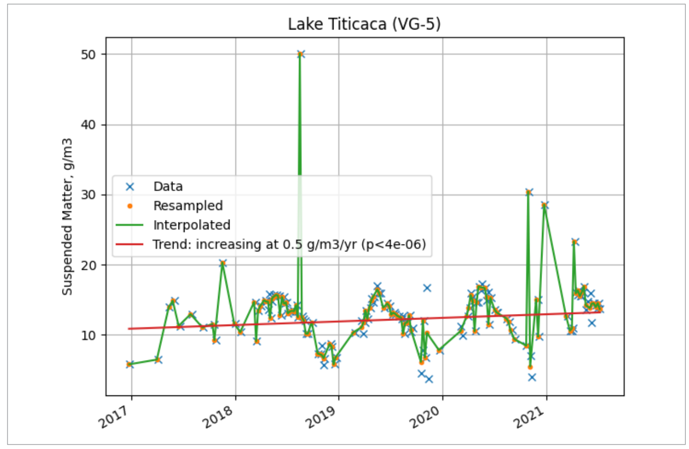


Figure 16: Mann-Kendall trend analysis of suspended matter levels at Virtual Gauge location 5, which corresponds to the south-western portion of Lago Menor.

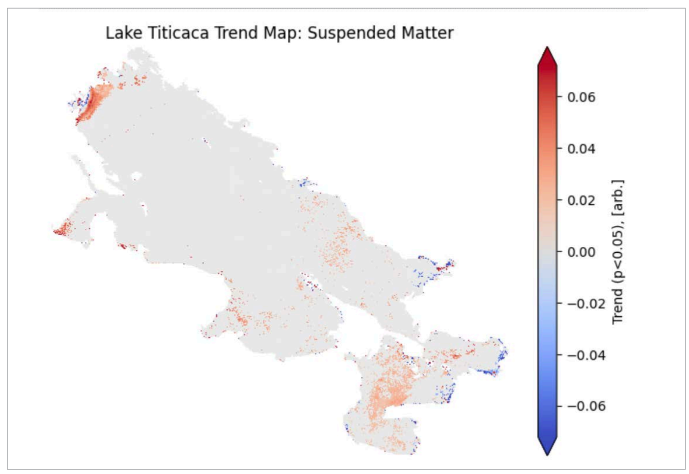
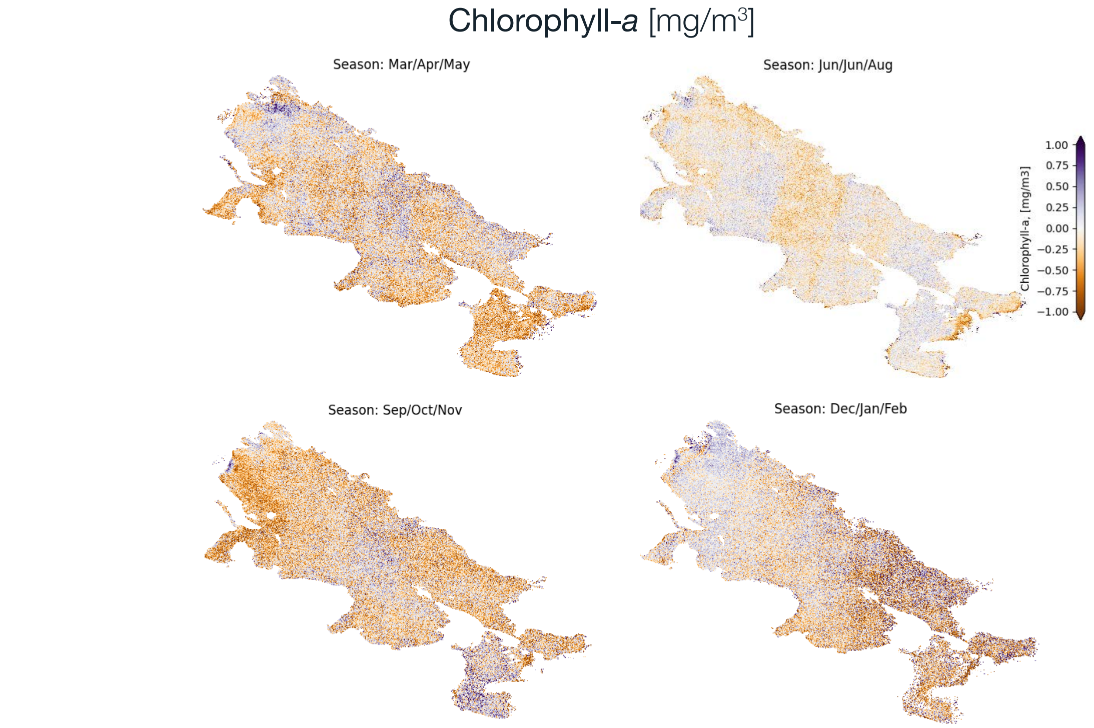


Figure 17: Trend Map showing the direction and magnitude of the long term trends in suspended matter across Lake Titicaca.

Location	Parameter	Timeframe	Change
1	Chlorophyll-a	Dec/Jan/Feb (2020-2021)	Increase
2	Chlorophyll-a	Jun/Jul/Aug (2020)	Increase
2	Chlorophyll-a	Sep/Oct/Nov (2020)	Decrease
3	Chlorophyll-a	Mar/Apr/May (2020)	Increase
5	Susp. Matter & Turbidity	Dec/Jan/Feb (2020-2021)	Increase
5	Susp. Matter & Turbidity	Mar/Apr/May (2020)	Increase

Table 4.

A



B

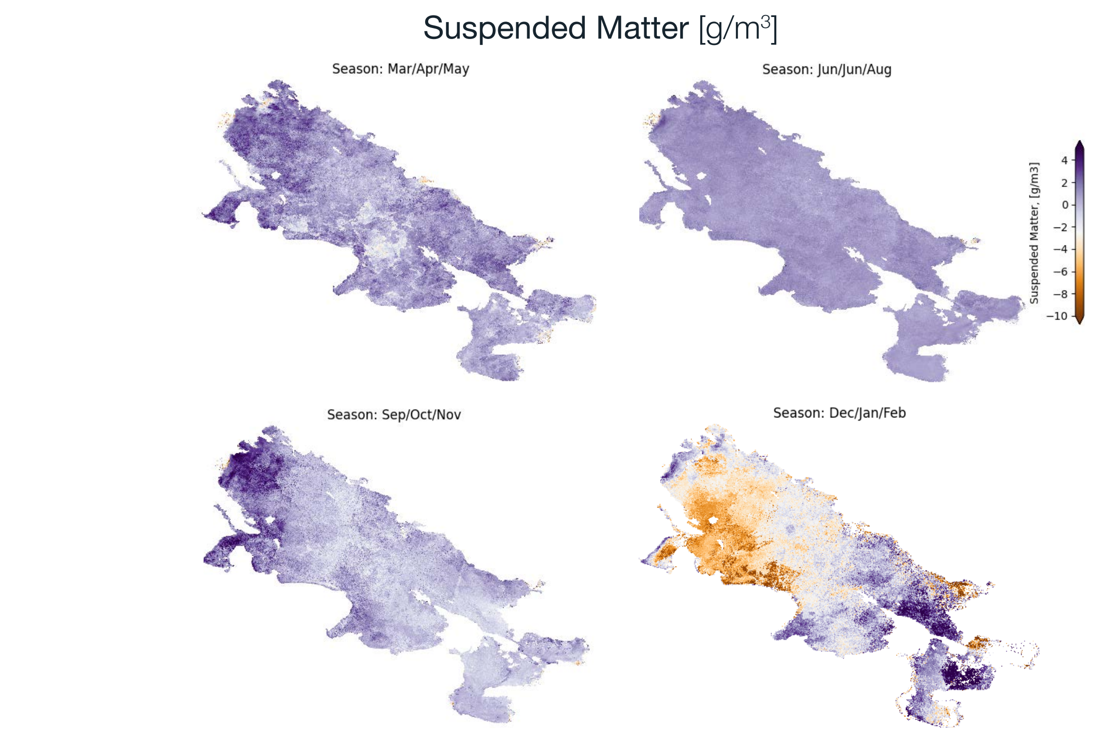


Figure 15: Pixel-wise differences between pre- and post Covid-19 lockdown measures in Chlorophyll-a (Panel A) and suspended matter (Panel B) concentrations across Lake Titicaca. Each 10m pixel depicts the difference in mean WQ metric values between the pre- and post-Covid-19 time frames. Little to no significant changes were observed across the entire lake from March through August, then from September to November significant increases in suspended matter concentrations were observed near the areas that correspond with Virtual Gauges 1, 2, and 4. Following this, there was a significant decrease in suspended matter near Virtual Gauge locations 3 and 4 from December 2020 through February 2021.

OUR

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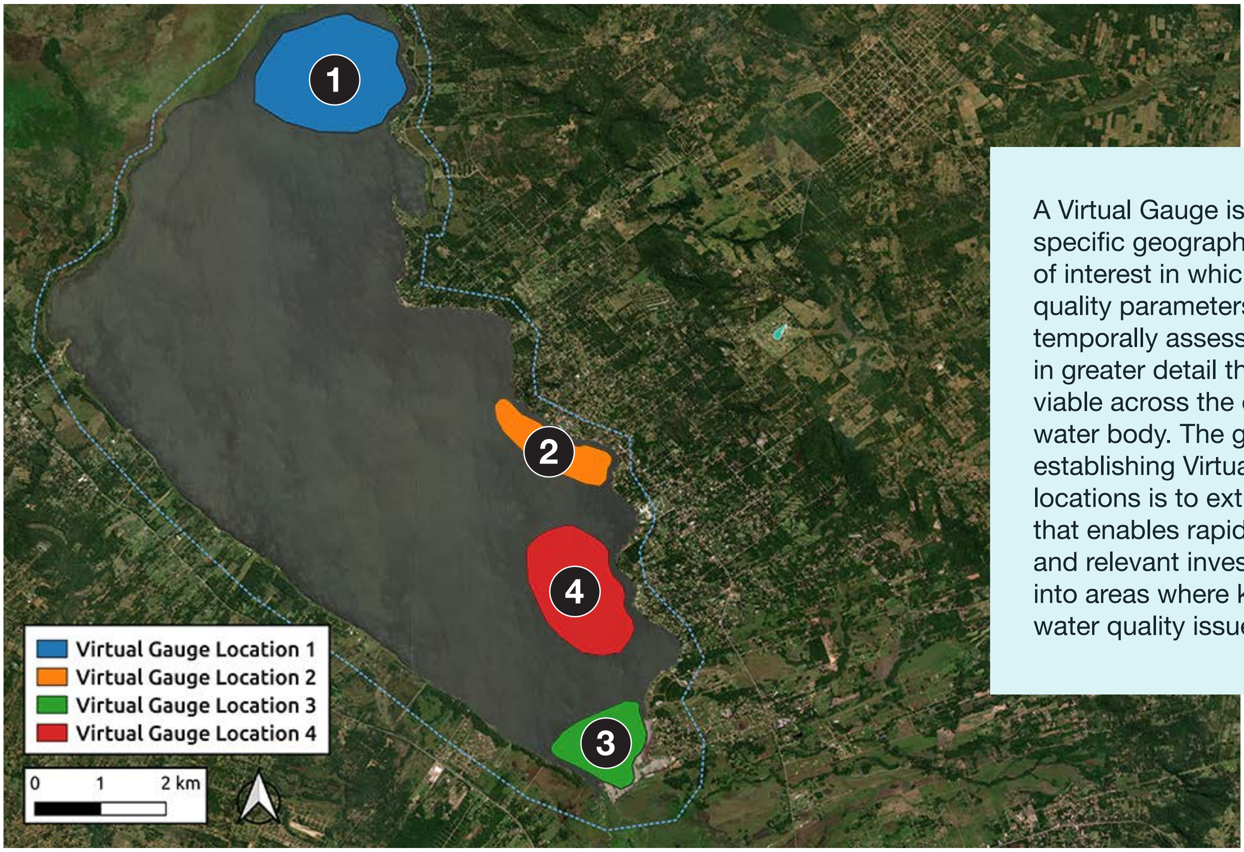
APPENDIX A1 Ypacarai Lake

APPENDIX A1
YPACARAI LAKE

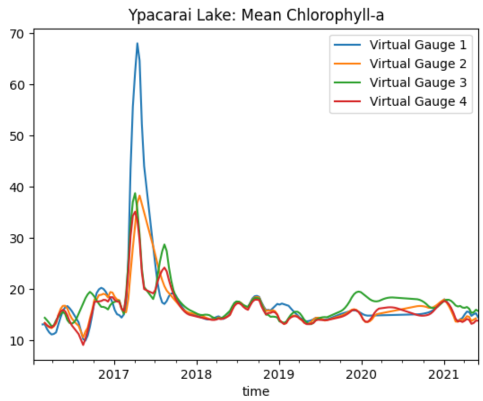
1. Virtual Gauges

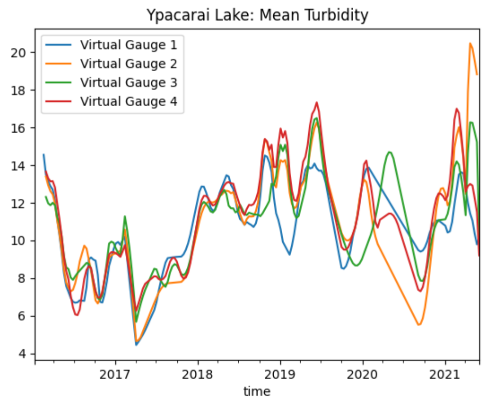
Change over time at key locations across the lake

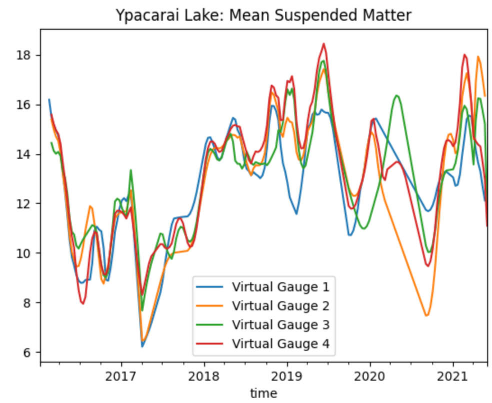
From 2015 to today, at all 4 locations of interest in Ypacaraí Lake.



A Virtual Gauge is a specific geographic region of interest in which water quality parameters are temporally assessed in greater detail than viable across the entire water body. The goal of establishing Virtual Gauge locations is to extract data that enables rapid, flexible, and relevant investigation into areas where known water quality issues exist.



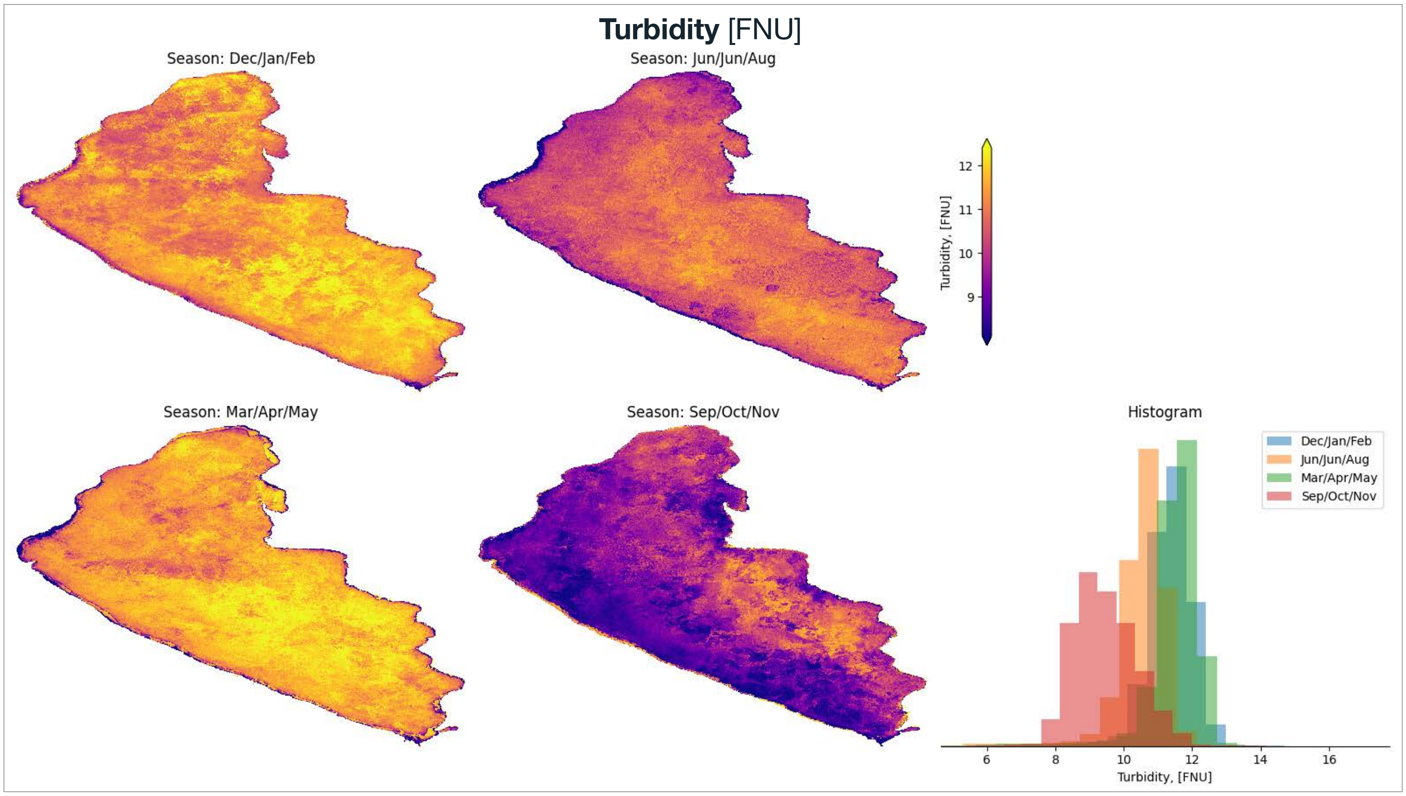


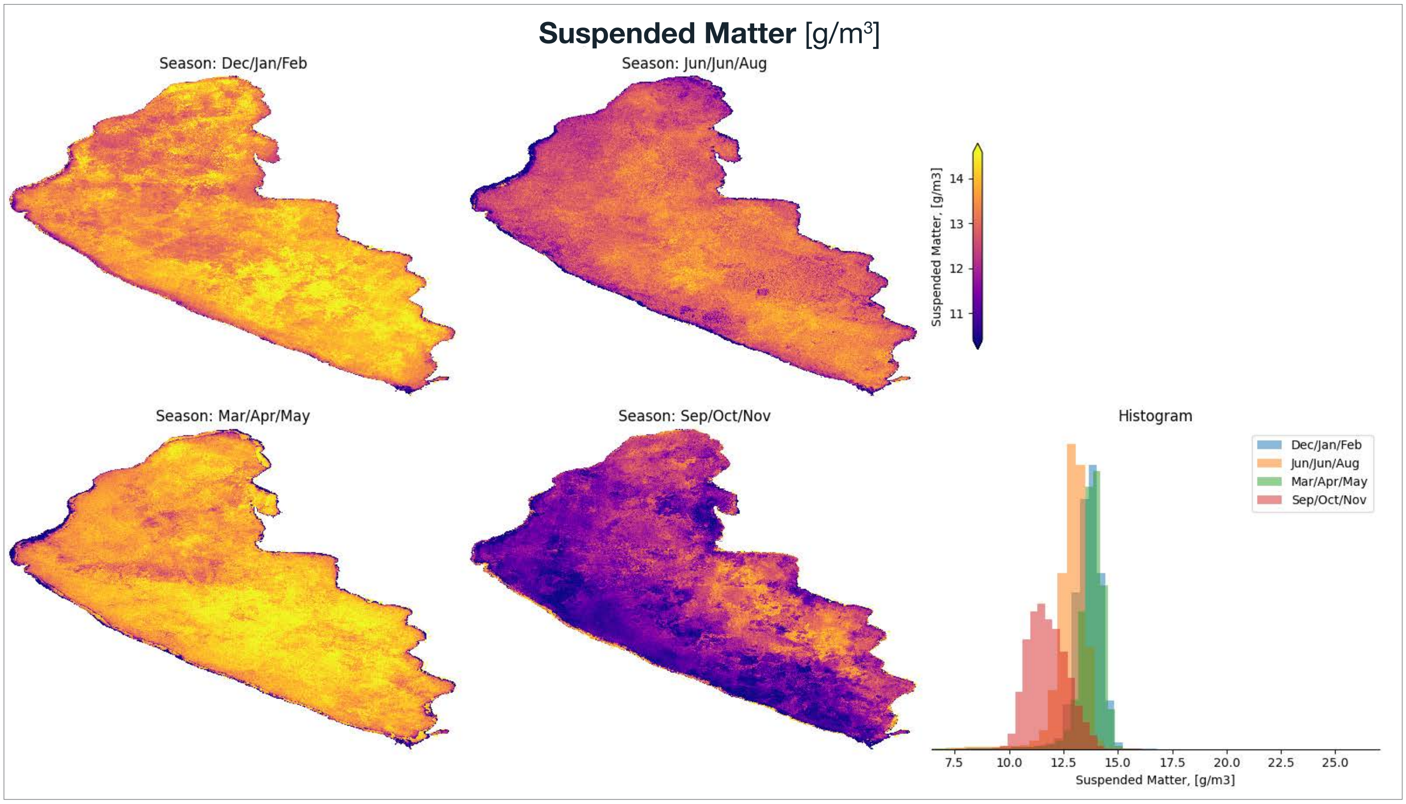


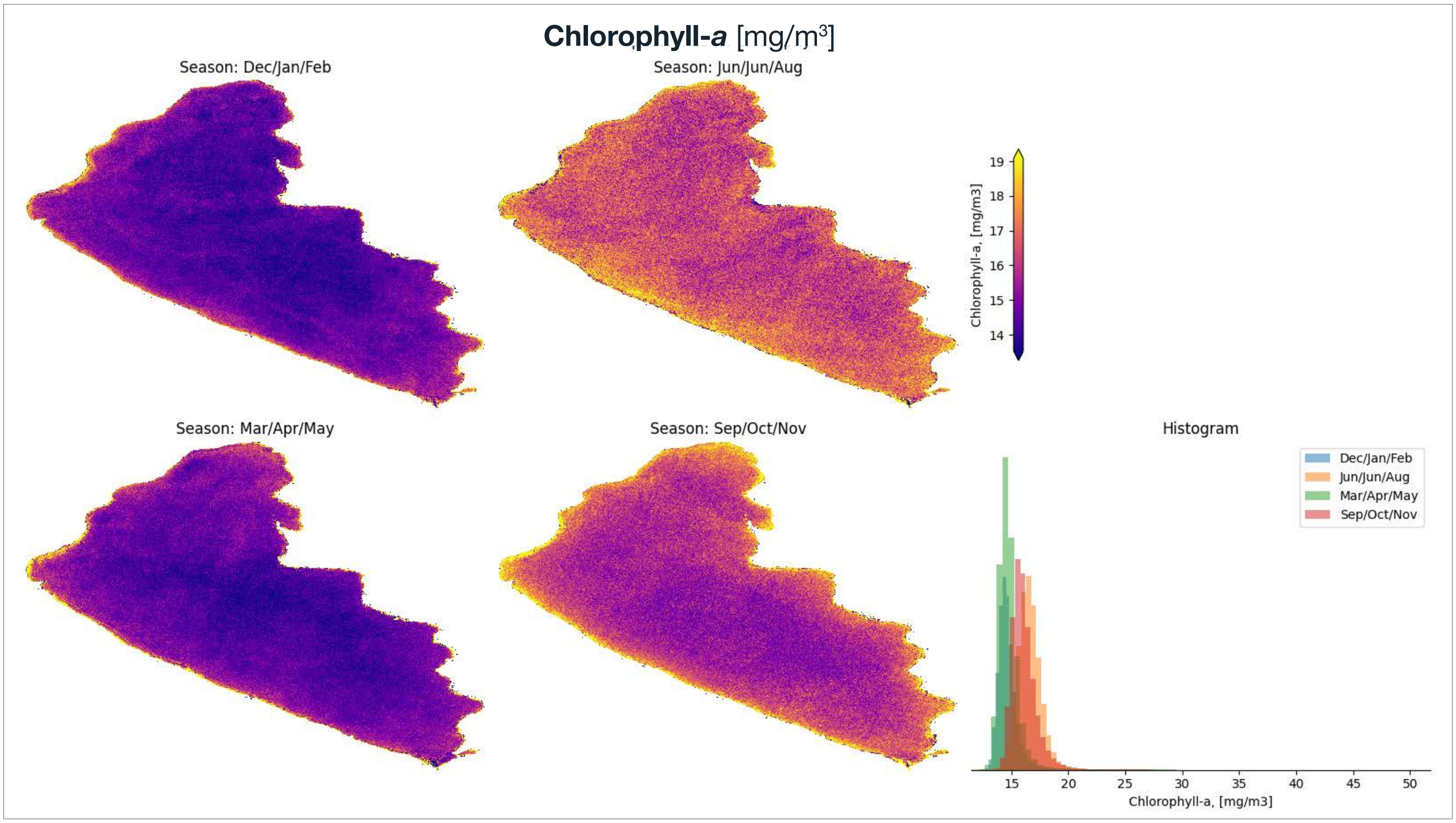
2. Seasonal Trends

2.1: Spatial Seasonal Trends

Maps illustrating the average seasonal variation across the entire water body.

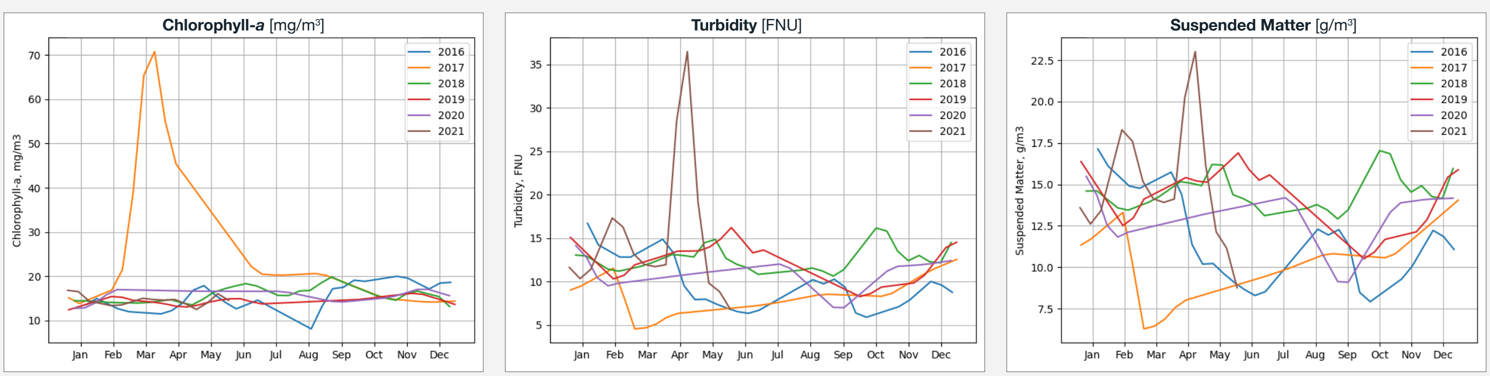






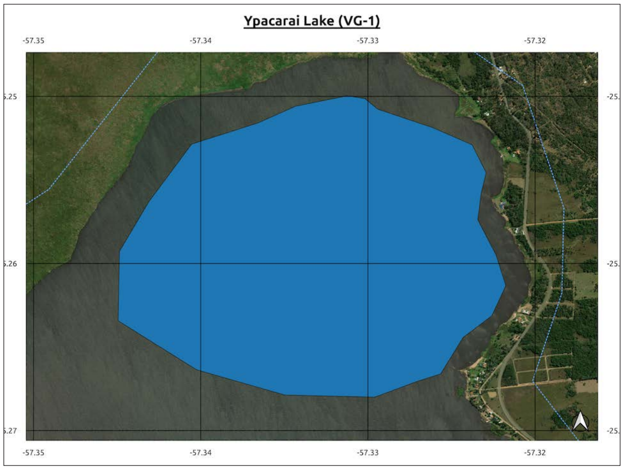
2.2a Temporal Seasonal Trends: Entire Waterbody

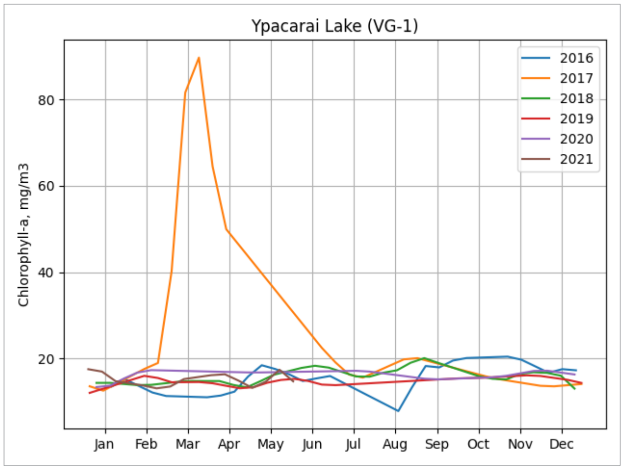
Water quality time series data split by each year: seasonal variation per parameter, across the whole reservoir.

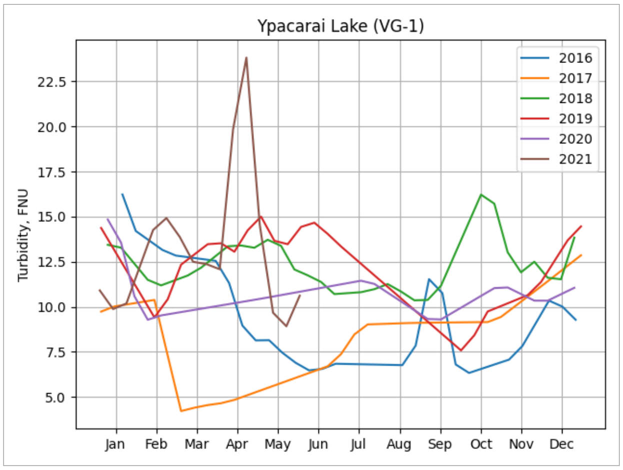


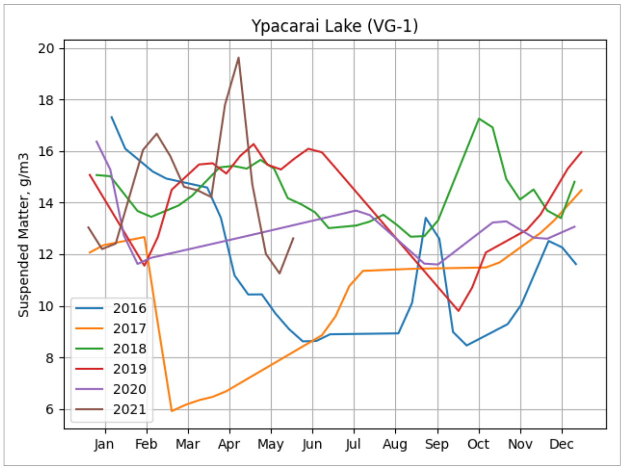
2.2b Temporal Seasonal Trends: Per Virtual Gauge (location of interest)

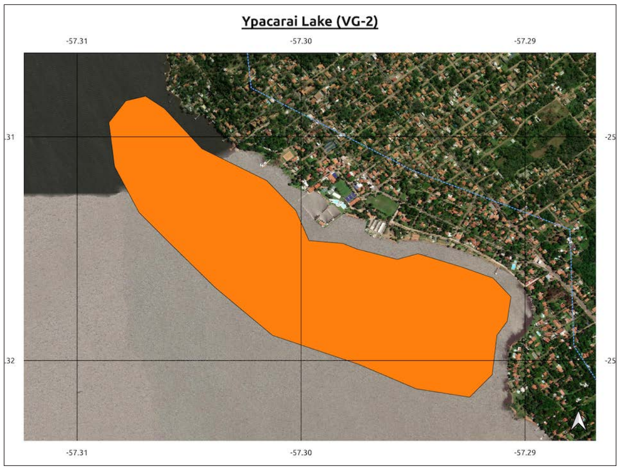
Water quality time series data split by each year: seasonal variation per parameter, per virtual gauge (area of interest)

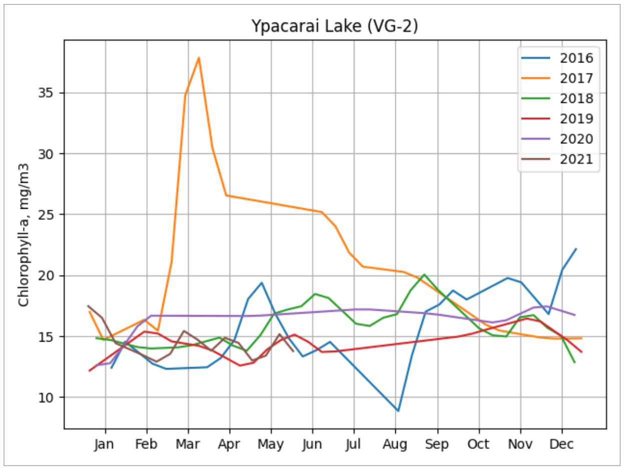

Ypacarai Lake (VG-1)
-57.35
-57.34
-57.33
-57.32

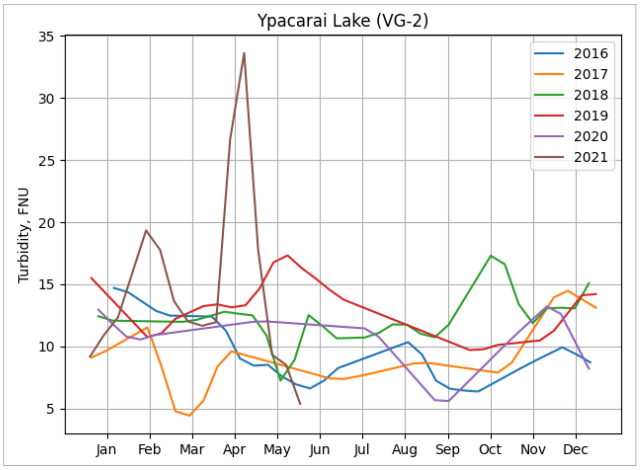

Ypacarai Lake (VG-1)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

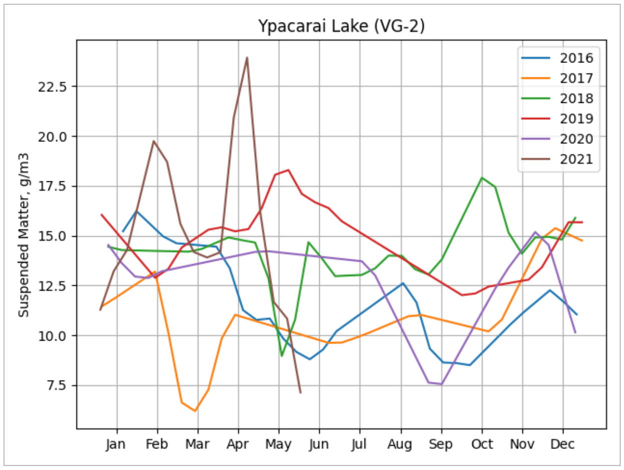

Ypacarai Lake (VG-1)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

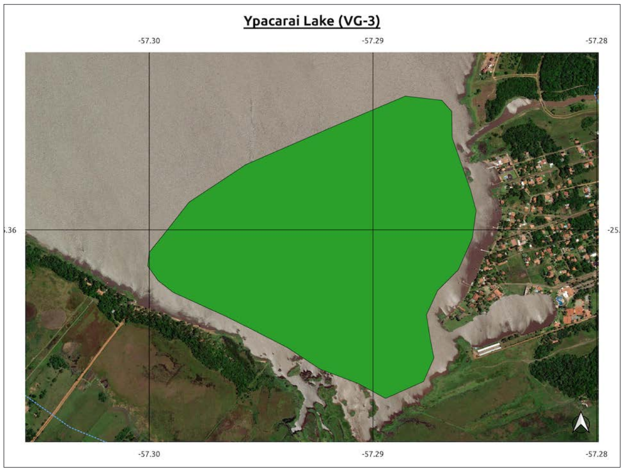

Ypacarai Lake (VG-1)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

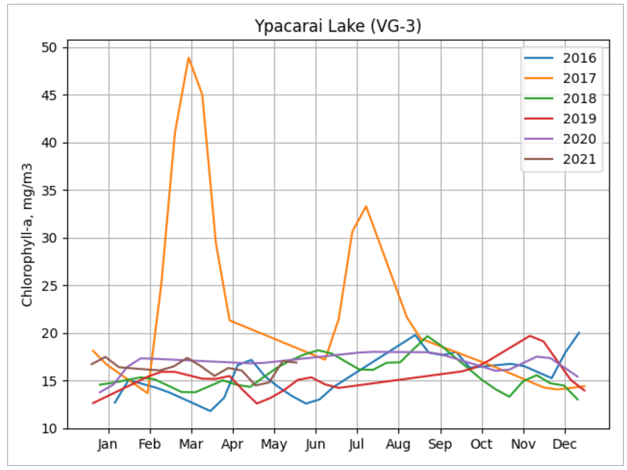

Ypacarai Lake (VG-2)
-57.31
-57.30
-57.29

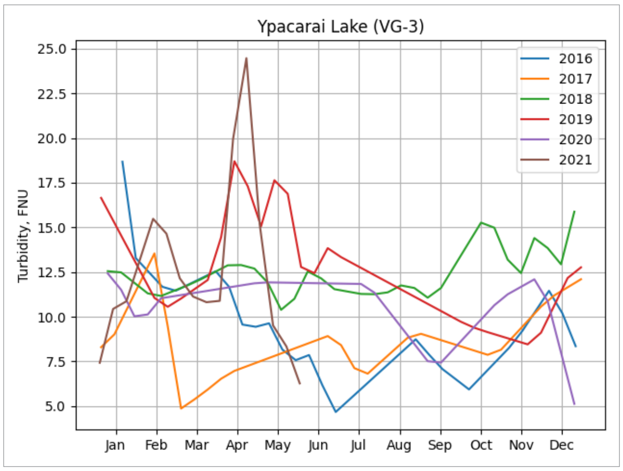

Ypacarai Lake (VG-2)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

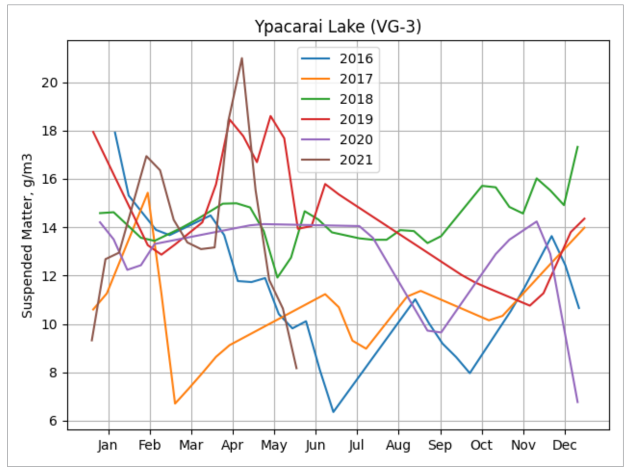

Ypacarai Lake (VG-2)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

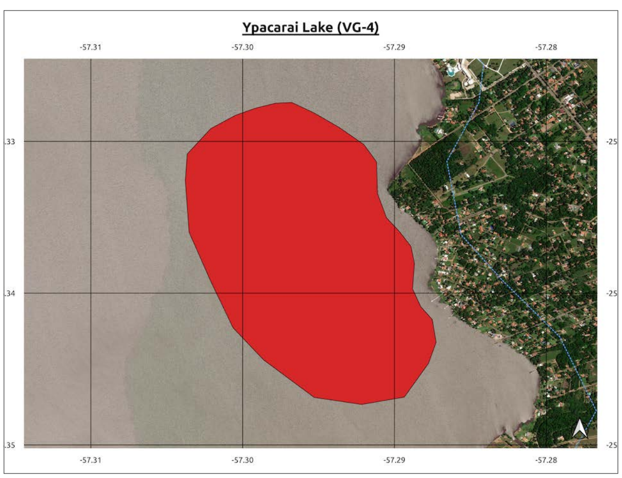

Ypacarai Lake (VG-2)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

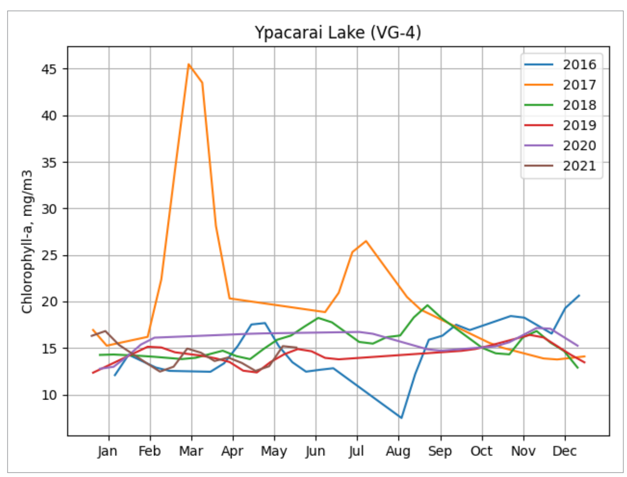

Ypacarai Lake (VG-3)
-57.30
-57.29
-57.28

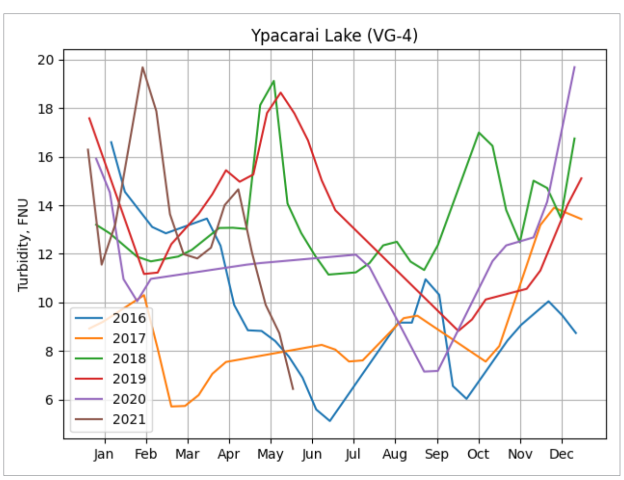

Ypacarai Lake (VG-3)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

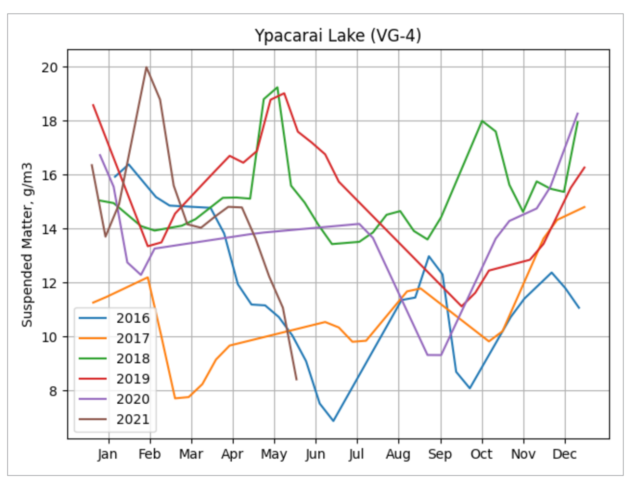

Ypacarai Lake (VG-3)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

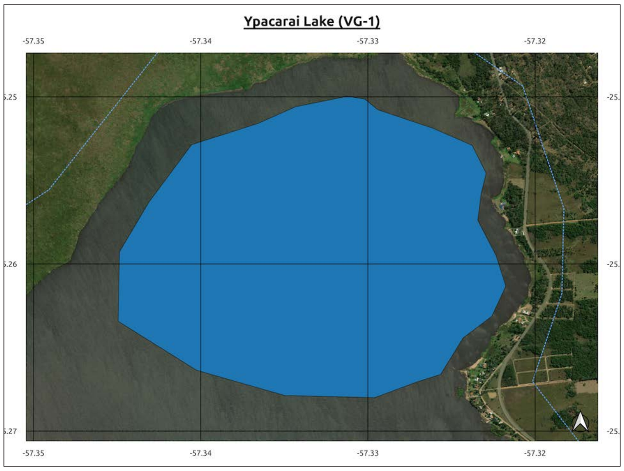

Ypacarai Lake (VG-3)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

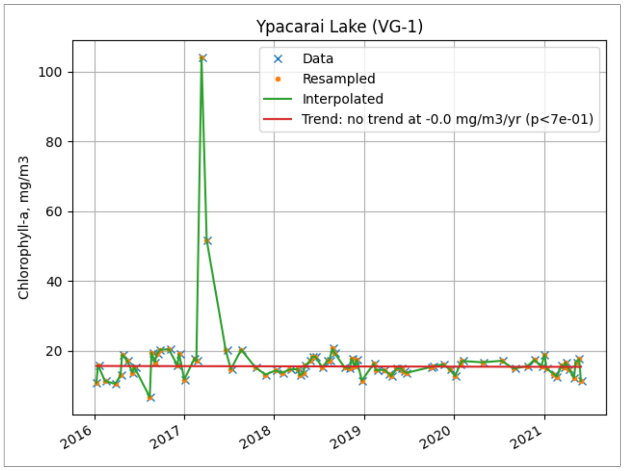

Ypacarai Lake (VG-4)
-57.31
-57.30
-57.29
-57.28

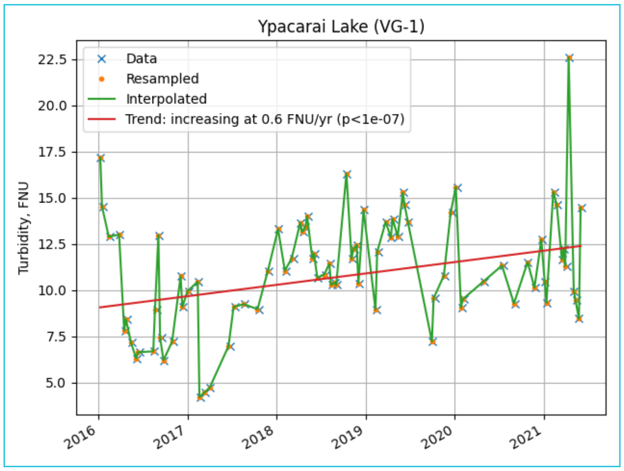

Ypacarai Lake (VG-4)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

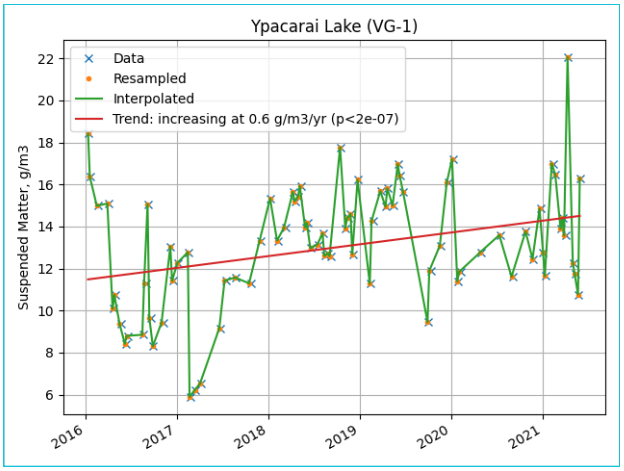

Ypacarai Lake (VG-4)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

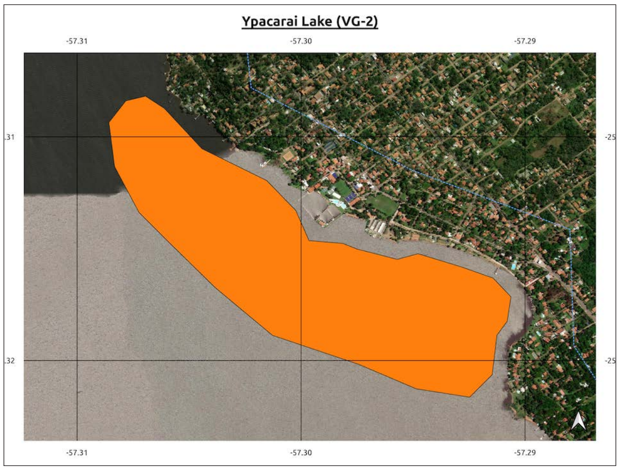

Ypacarai Lake (VG-4)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

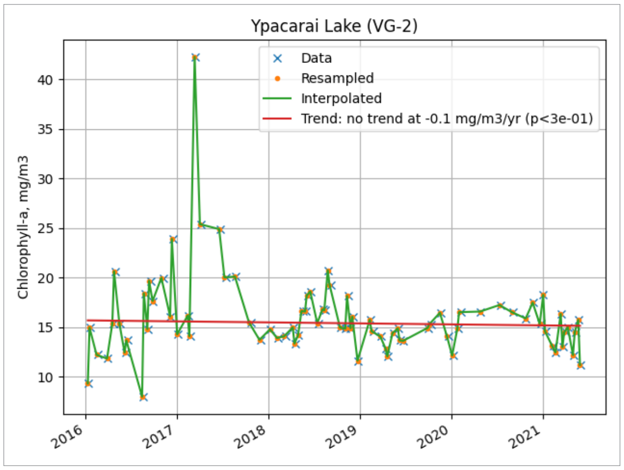

Ypacarai Lake (VG-1)
-57.35
-57.34
-57.33
-57.32

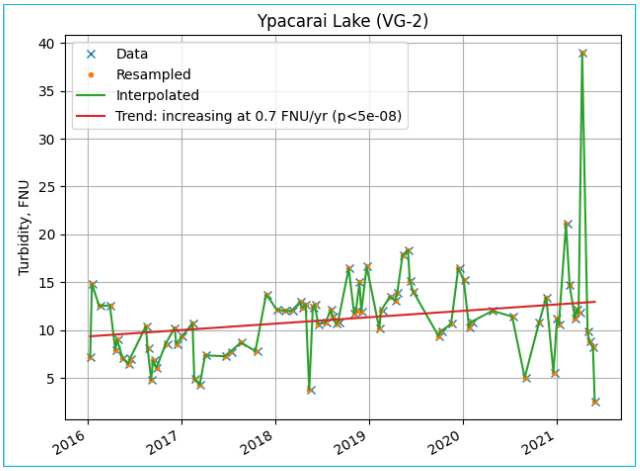

Ypacarai Lake (VG-1)
Data
Resampled
Interpolated
Trend: no trend at -0.0 mg/m3/yr (p<7e-01)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021

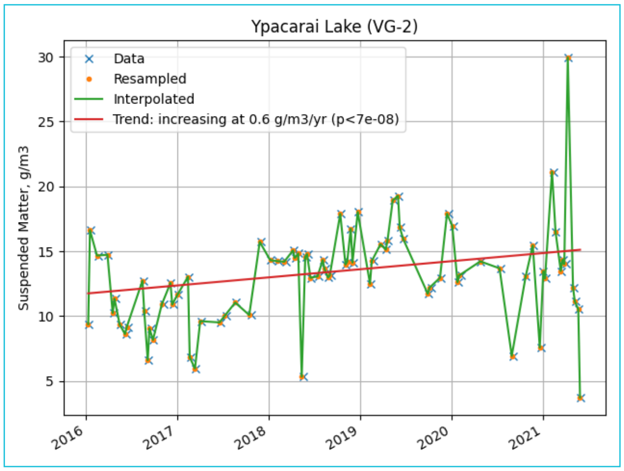

Ypacarai Lake (VG-1)
Data
Resampled
Interpolated
Trend: increasing at 0.6 FNU/yr (p<1e-07)
Turbidity, FNU
2016
2017
2018
2019
2020
2021

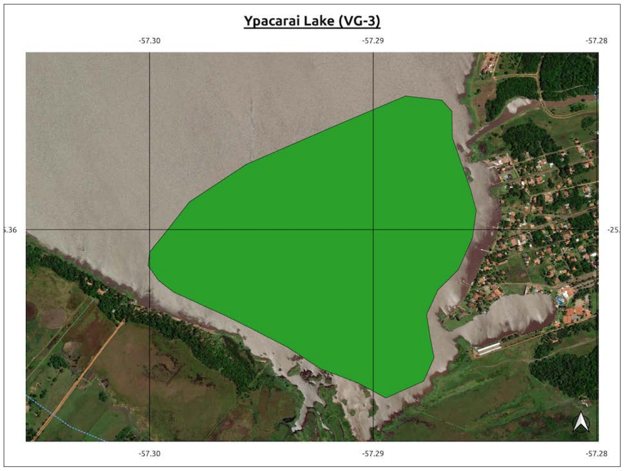

Ypacarai Lake (VG-1)
Data
Resampled
Interpolated
Trend: increasing at 0.6 g/m3/yr (p<2e-07)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021

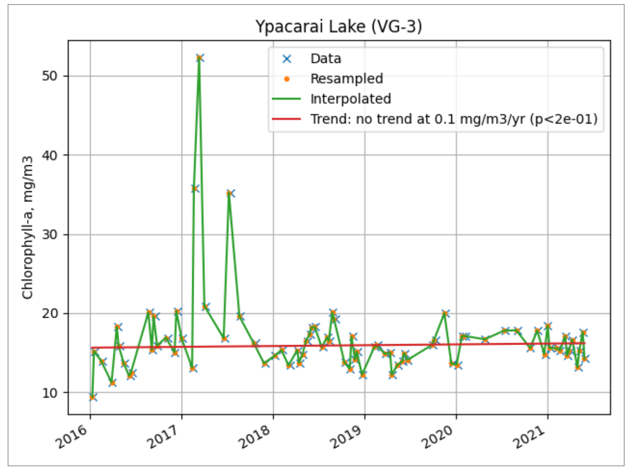

Ypacarai Lake (VG-2)
-57.31
-57.30
-57.29

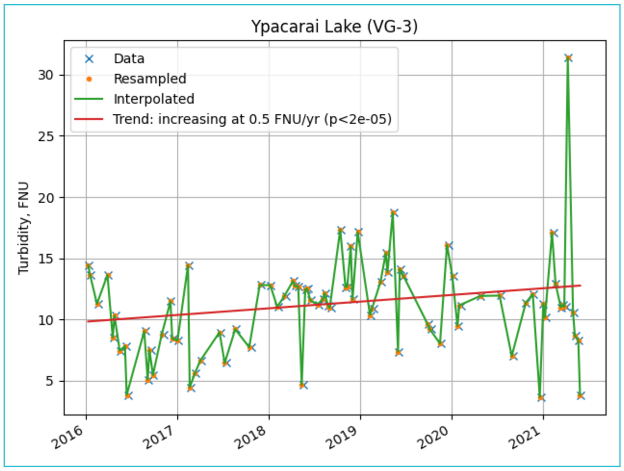

Ypacarai Lake (VG-2)
Data
Resampled
Interpolated
Trend: no trend at -0.1 mg/m3/yr (p<3e-01)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021

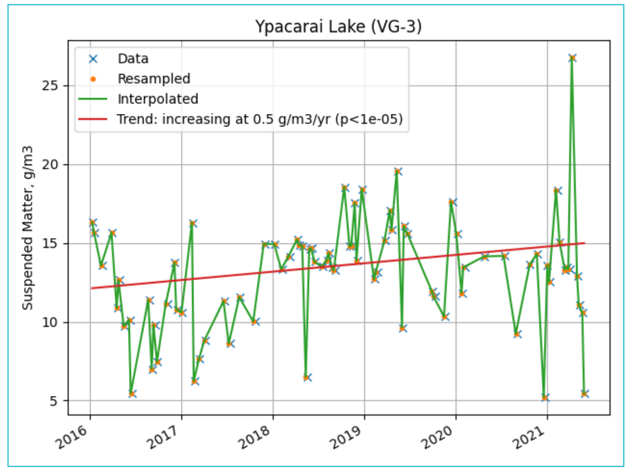

Ypacarai Lake (VG-2)
Data
Resampled
Interpolated
Trend: increasing at 0.7 FNU/yr (p<5e-08)
Turbidity, FNU
2016
2017
2018
2019
2020
2021

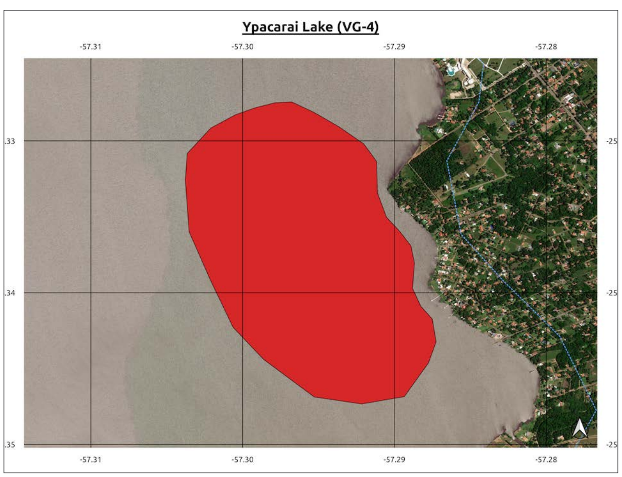

Ypacarai Lake (VG-2)
Data
Resampled
Interpolated
Trend: increasing at 0.6 g/m3/yr (p<7e-08)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021

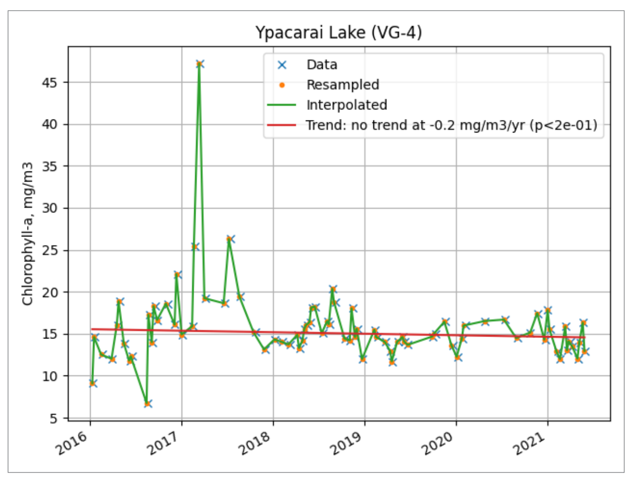

Ypacarai Lake (VG-3)
-57.30
-57.29
-57.28

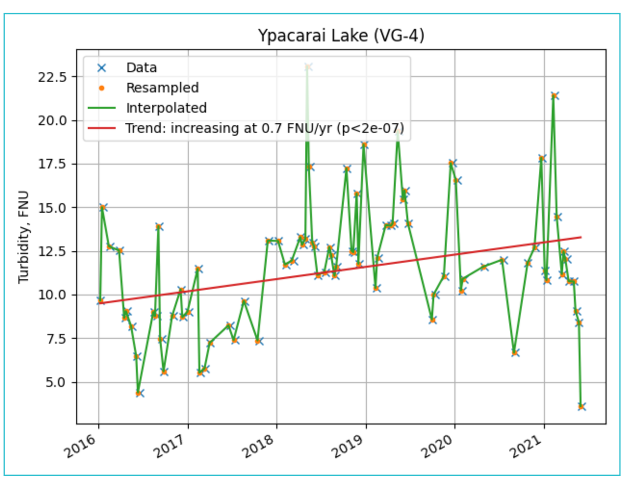

Ypacarai Lake (VG-3)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: no trend at 0.1 mg/m3/yr (p<2e-01)
2016
2017
2018
2019
2020
2021

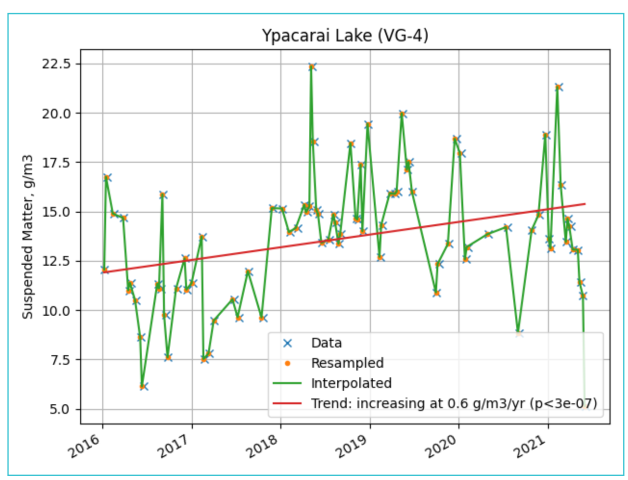

Ypacarai Lake (VG-3)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: increasing at 0.5 FNU/yr (p<2e-05)
2016
2017
2018
2019
2020
2021


Ypacarai Lake (VG-3)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: increasing at 0.5 g/m3/yr (p<1e-05)
2016
2017
2018
2019
2020
2021


Ypacarai Lake (VG-4)
-57.31
-57.30
-57.29
-57.28


Ypacarai Lake (VG-4)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: no trend at -0.2 mg/m3/yr (p<2e-01)
2016
2017
2018
2019
2020
2021


Ypacarai Lake (VG-4)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: increasing at 0.7 FNU/yr (p<2e-07)
2016
2017
2018
2019
2020
2021

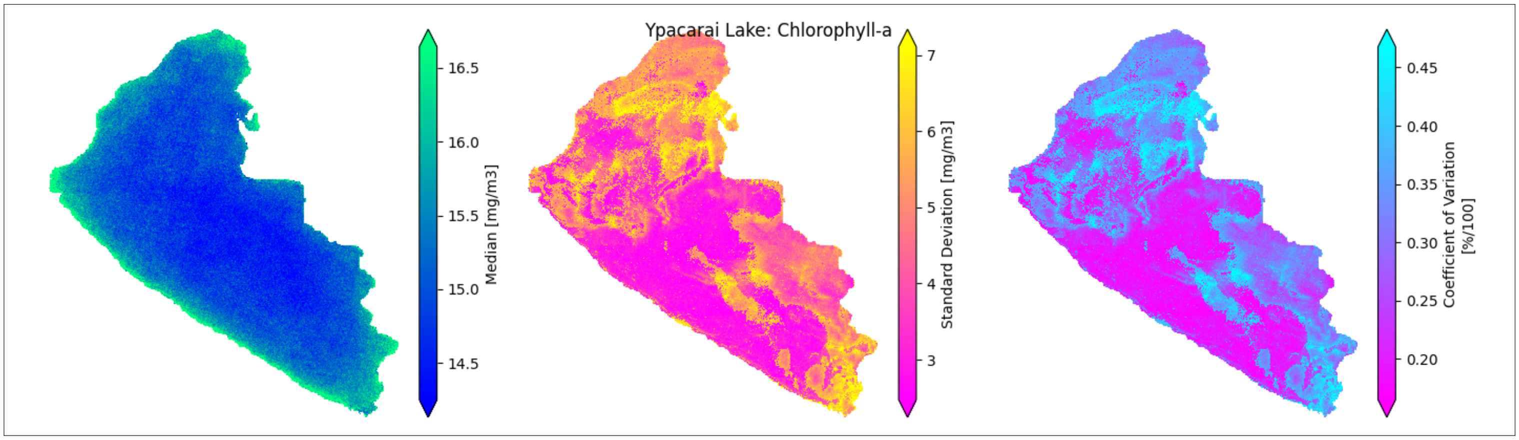

Ypacarai Lake (VG-4)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: increasing at 0.6 g/m3/yr (p<3e-07)
2016
2017
2018
2019
2020
2021

4. Variation Maps

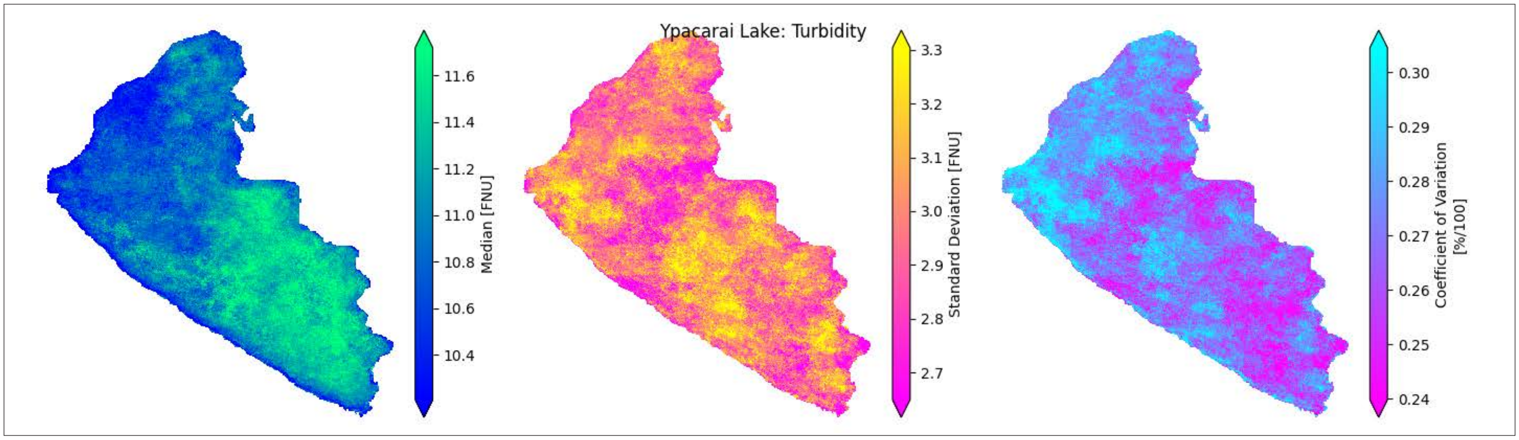
We created Variation Maps for each water body and water quality parameter. This process calculates the median, standard deviation, and coefficient of variation on a pixel-wise basis through time. The product is a map that shows the spatial distribution of these summary statistics through time.

Median | **Standard Deviation** | **Coefficient of Variation**

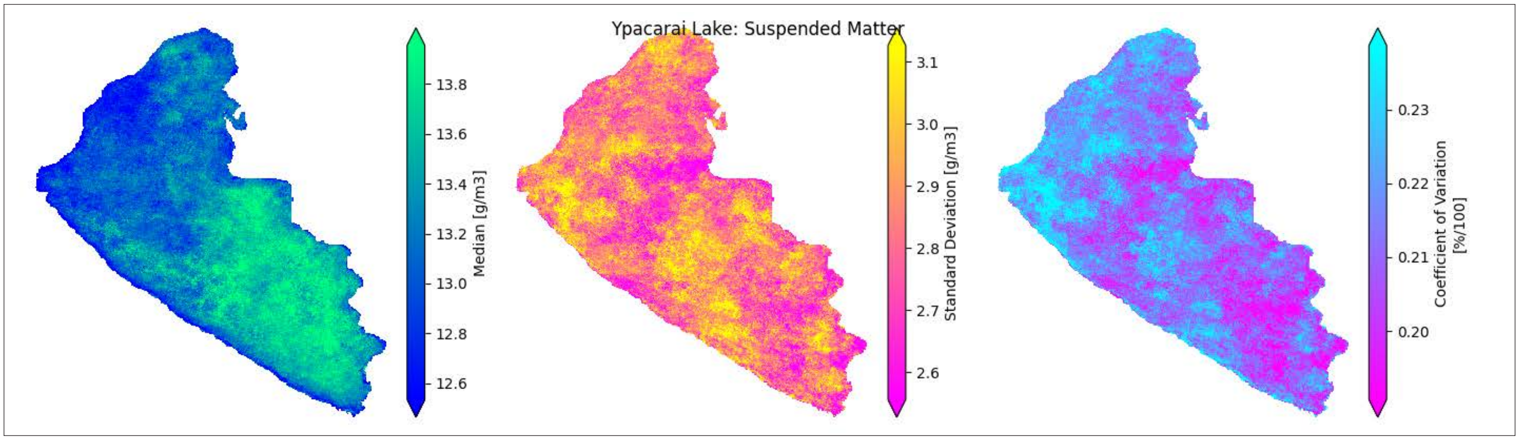
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



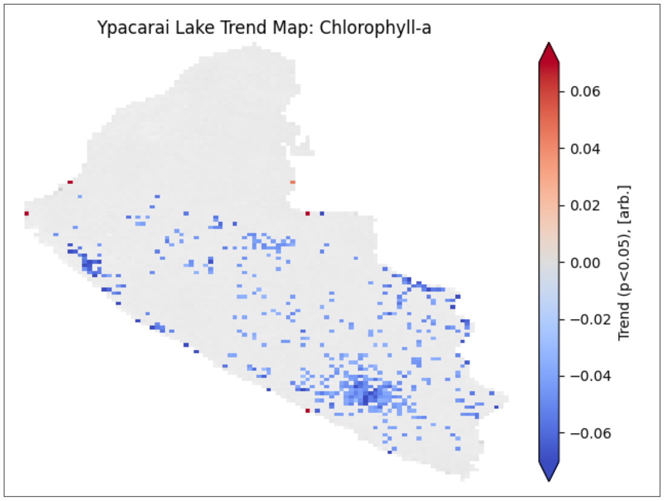
4.3 Suspended Matter [g/m^3]



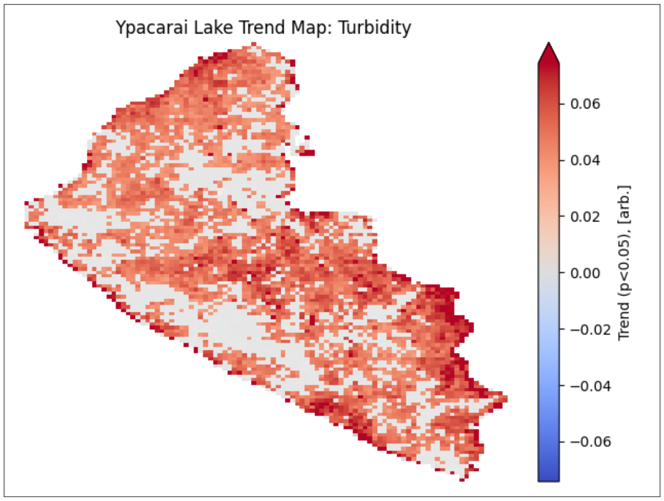
5. Trend Maps

We create Trend Maps to visualize where temporal trends in water quality parameters are occurring. First, data across the entire water body is spatially binned by averaged to approximately 100m resolution. Then, a linear regression is applied along the temporal axis for each bin, a three-sigma outlier filtering process is used to remove outliers. Finally, the linear trends are visualized on a map where statistically significant (p-value below 5%) values are colorized based on direction and intensity.

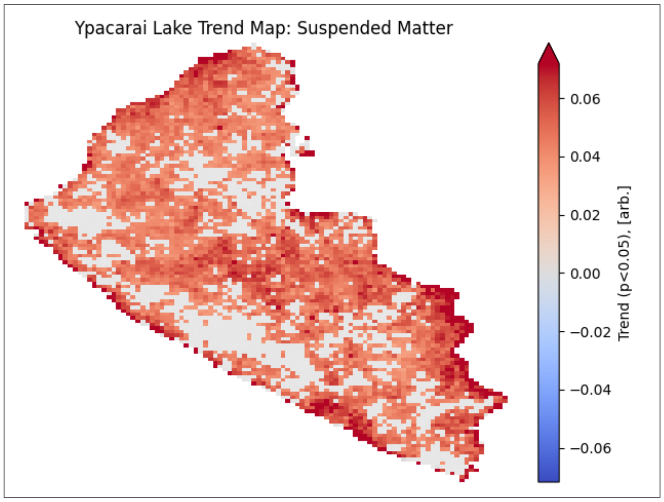
5.1 Chlorophyll-*a*
[mg/m³]



5.2 Turbidity
[FNU]



5.3 Suspended Matter
[g/m³]

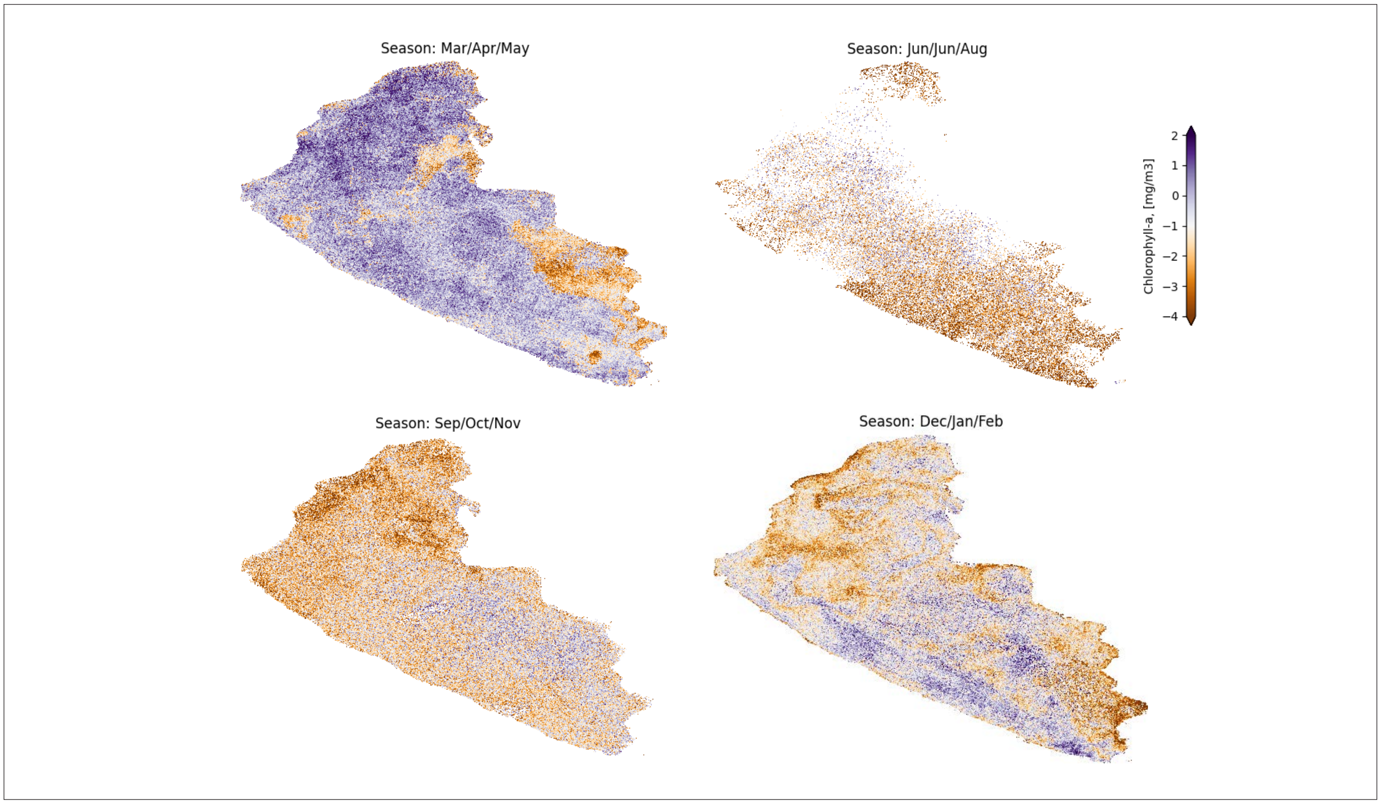


6. Difference Maps

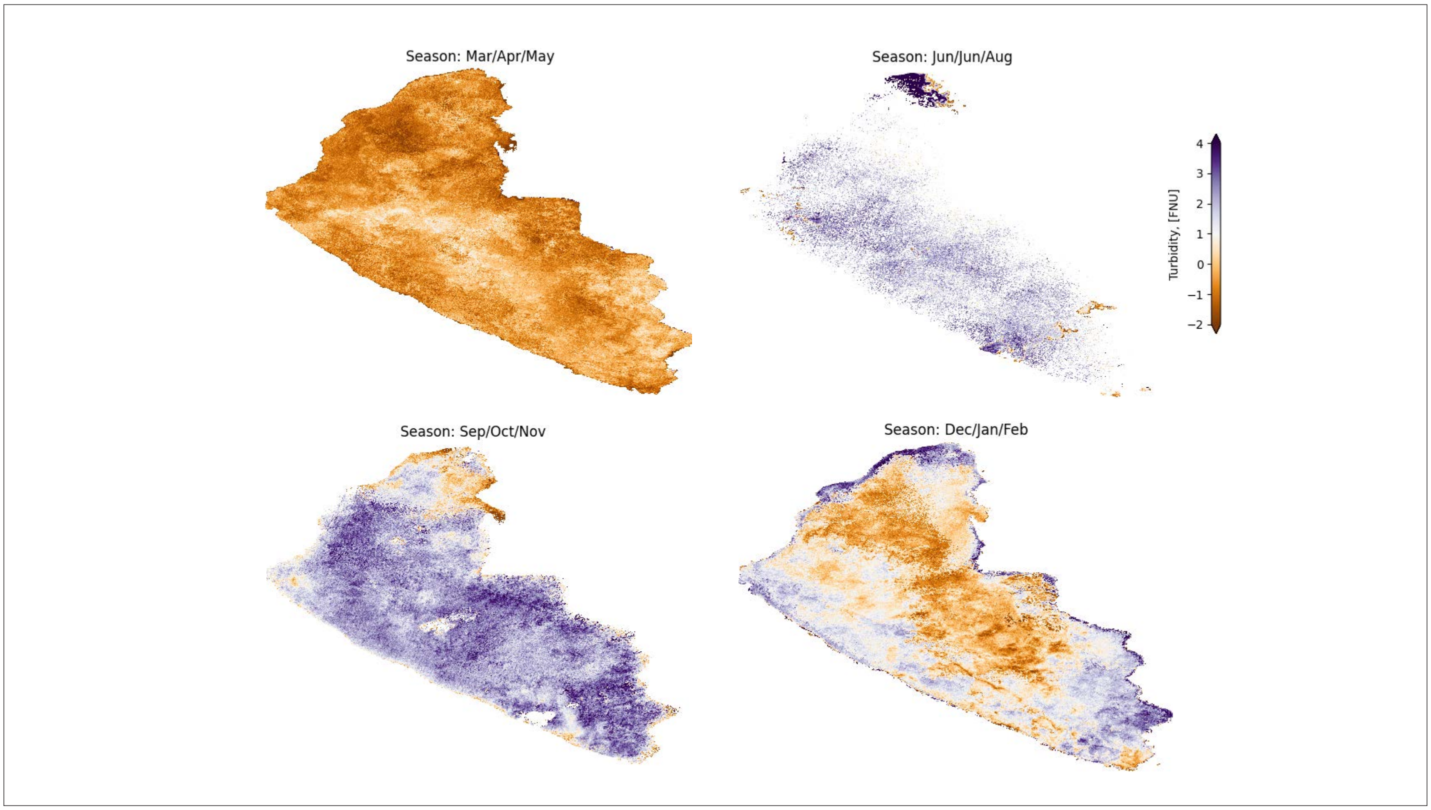
Changes to WQ stemming from Covid-19 lockdown restrictions were assessed using a series of simple one-way analysis of variance (ANOVA) tests. Differences in pre- and post-Covid-19 conditions were tested for at each WQ metric at each virtual gauge location, with pre-Covid-19 lockdown defined as all time series data before March 19, 2020. Both pre- and post-Covid-19 datasets were separated into three-month seasons, with tests performed on each season to control for seasonal variations. Significant differences between conditions were recorded with a 'p-value' less than 0.05.

Separately, an assessment of Covid-19 lockdown related differences in WQ was conducted across the entire water body to illustrate general trends not associated with virtual gauge locations. For this, pixel-wise differences were calculated across the entire water body using images downsampled to 30 m pixels. The resulting images illustrate where changes in WQ are observable.

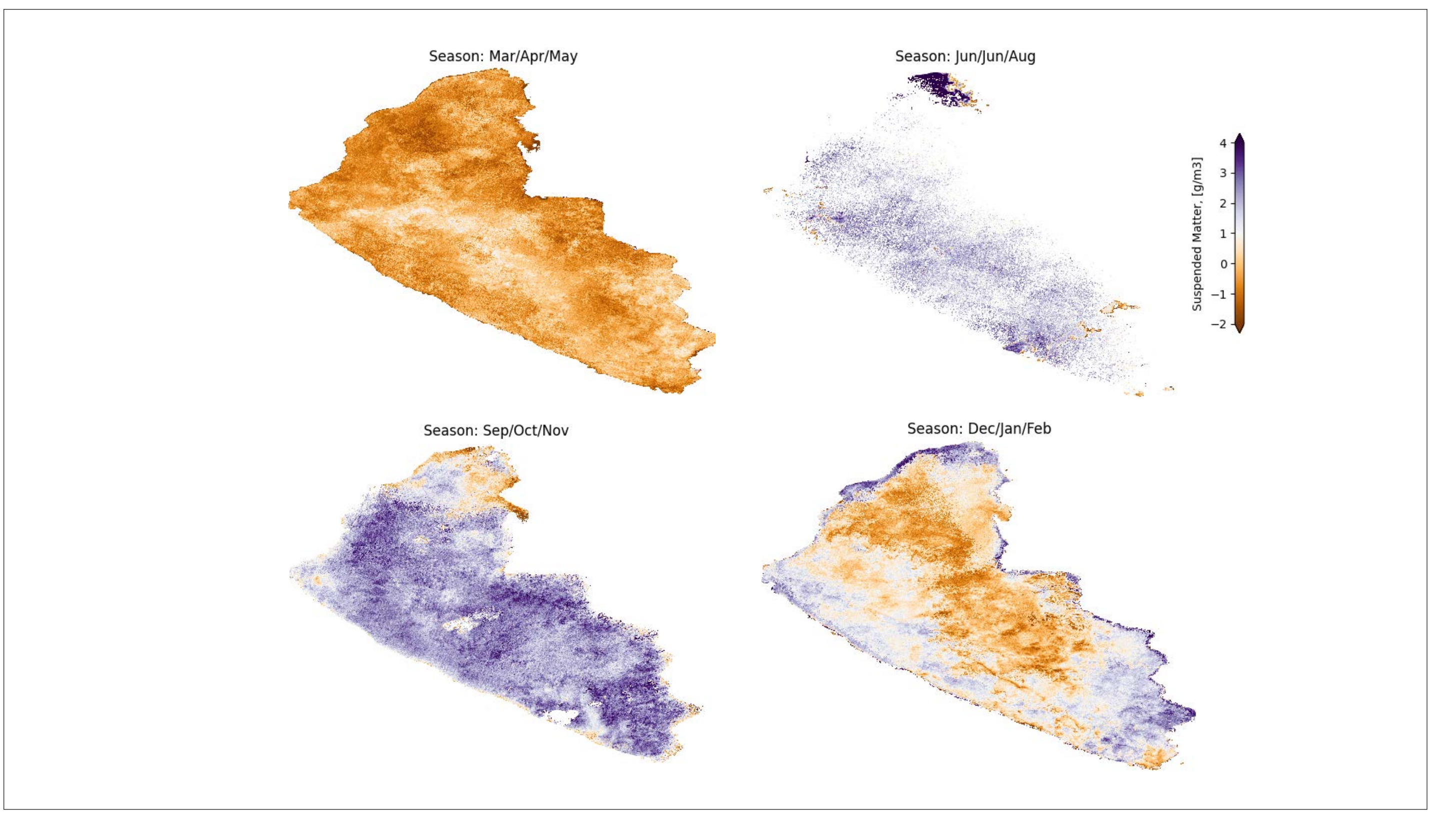
6.1 Chlorophyll-*a* [mg/m^3]



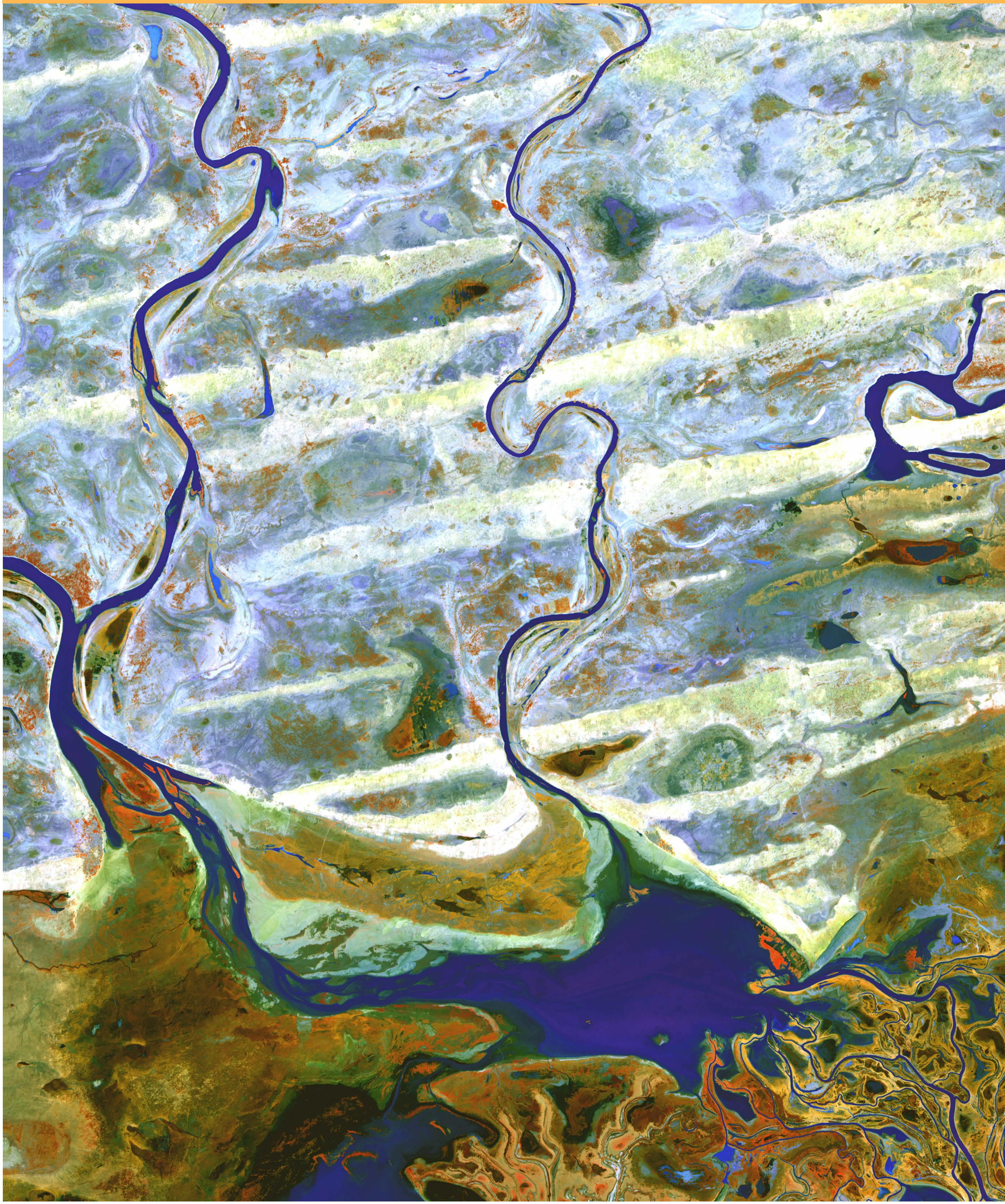
6.2 Turbidity [FNU]



6.3 Suspended Matter [g/m^3]



APPENDIX A2 Guanabara Bay



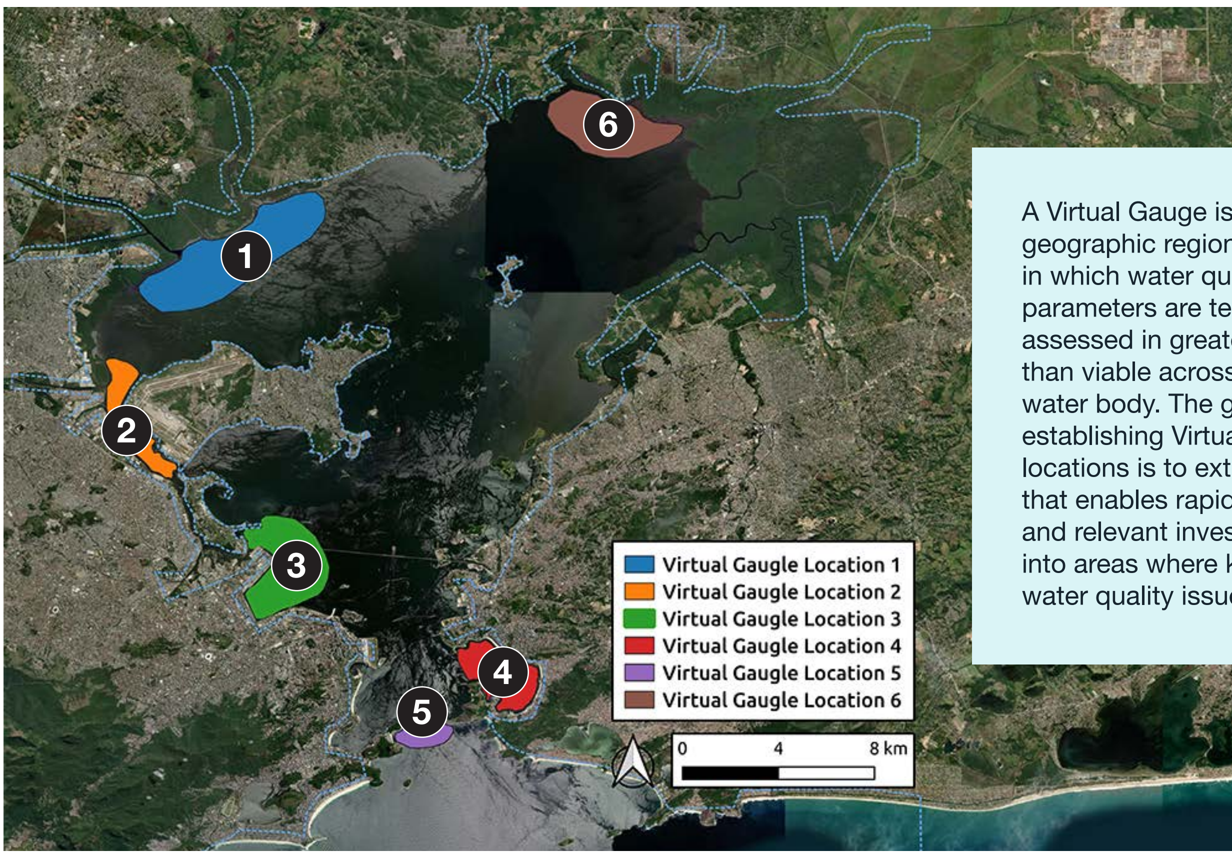
APPENDIX A2

GUANABARA BAY

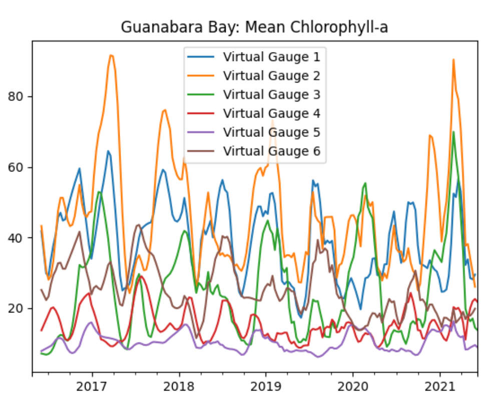
1. Virtual Gauges

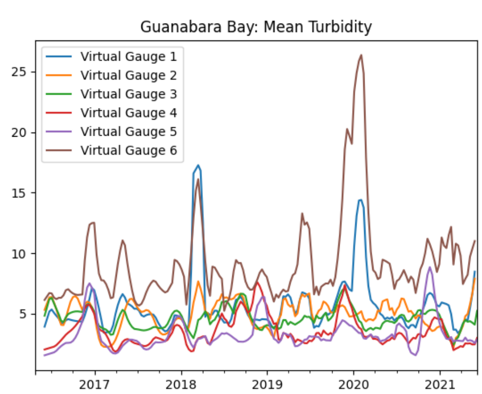
Change over time at key locations across the bay

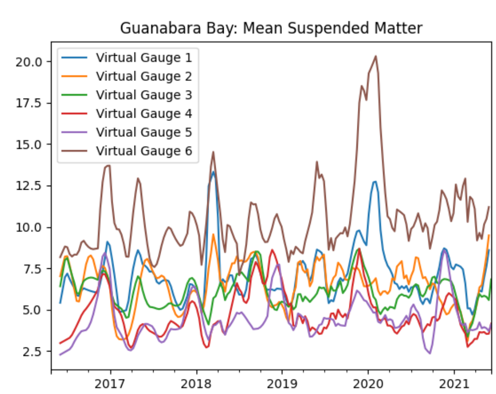
From 2016 to today, at all 6 locations of interest across the Gaunabara Bay.



A Virtual Gauge is a specific geographic region of interest in which water quality parameters are temporally assessed in greater detail than viable across the entire water body. The goal of establishing Virtual Gauge locations is to extract data that enables rapid, flexible, and relevant investigation into areas where known water quality issues exist.



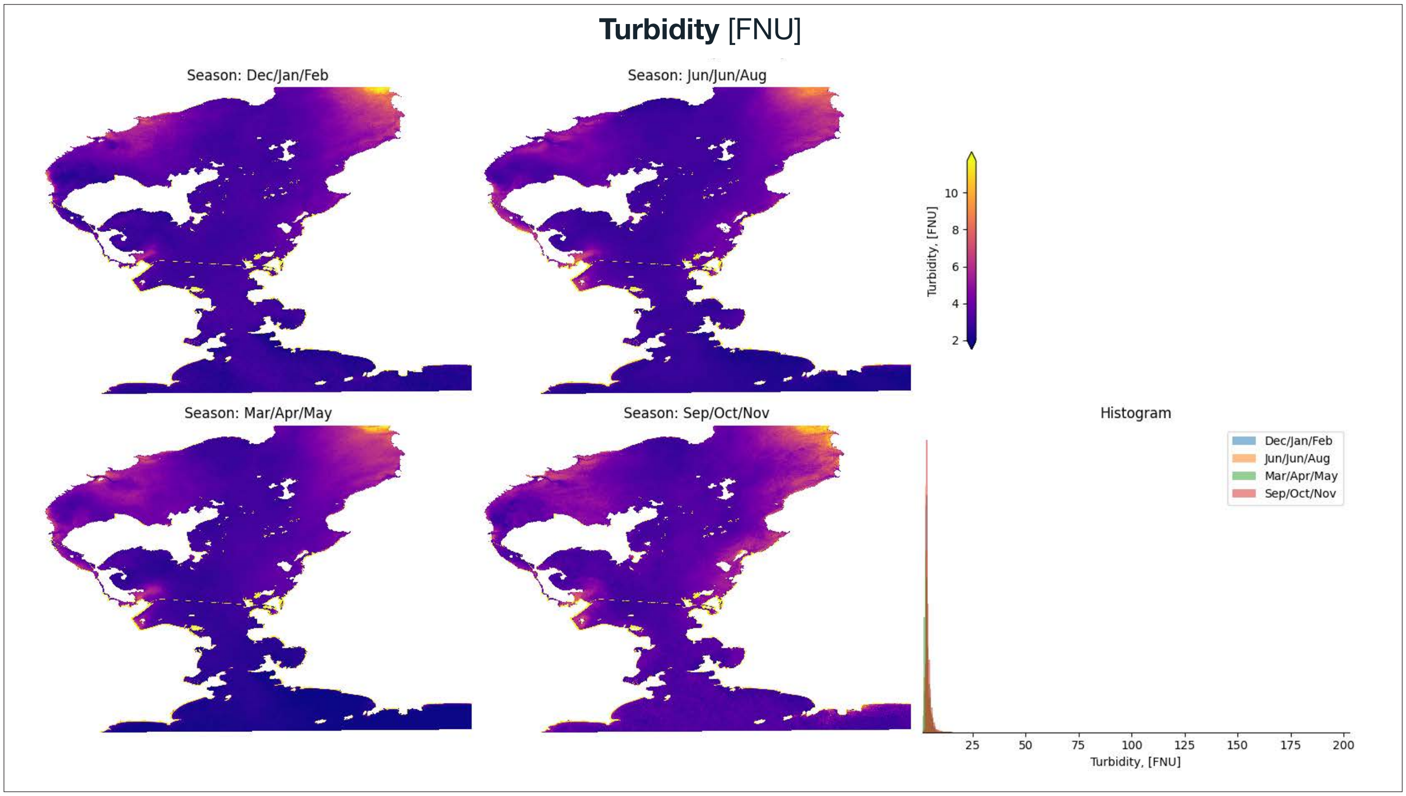


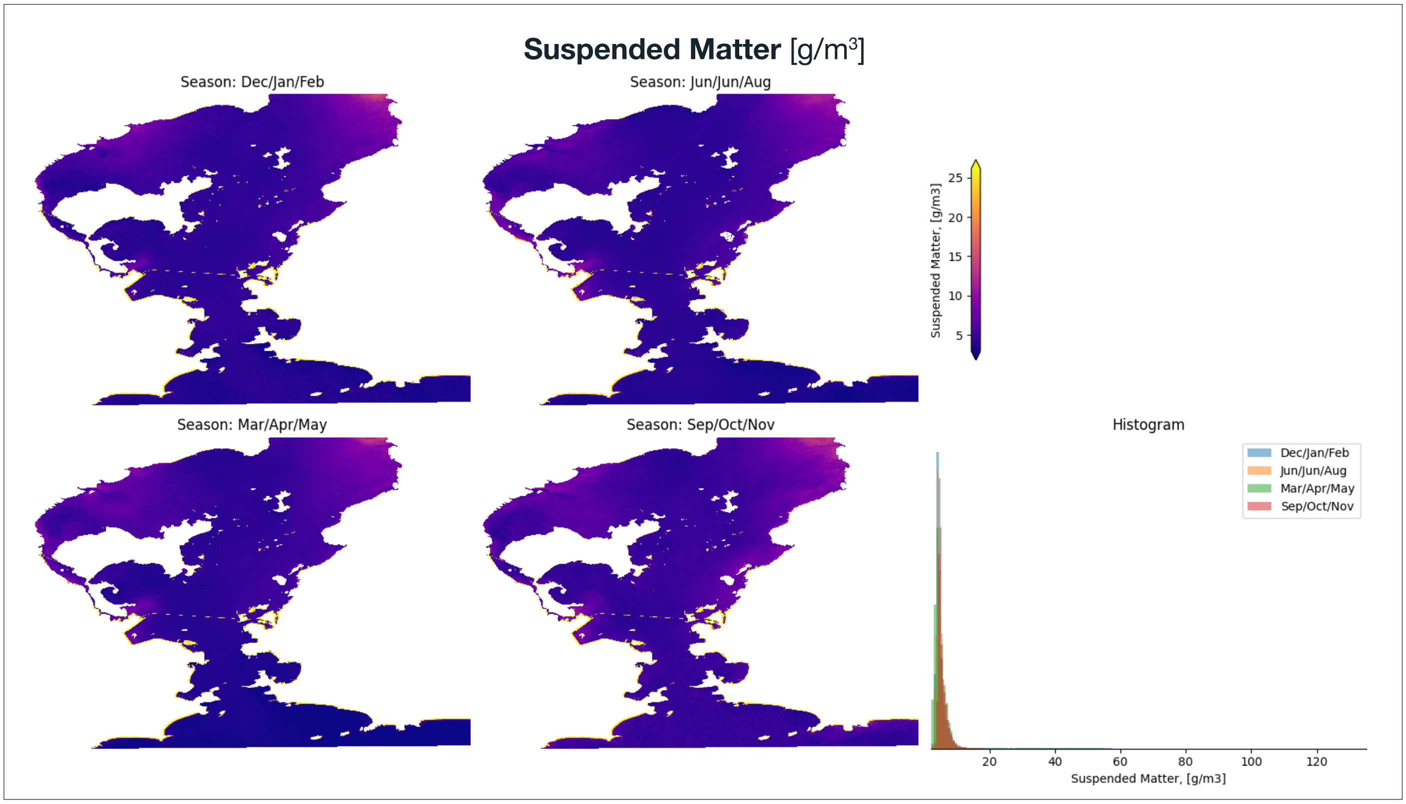


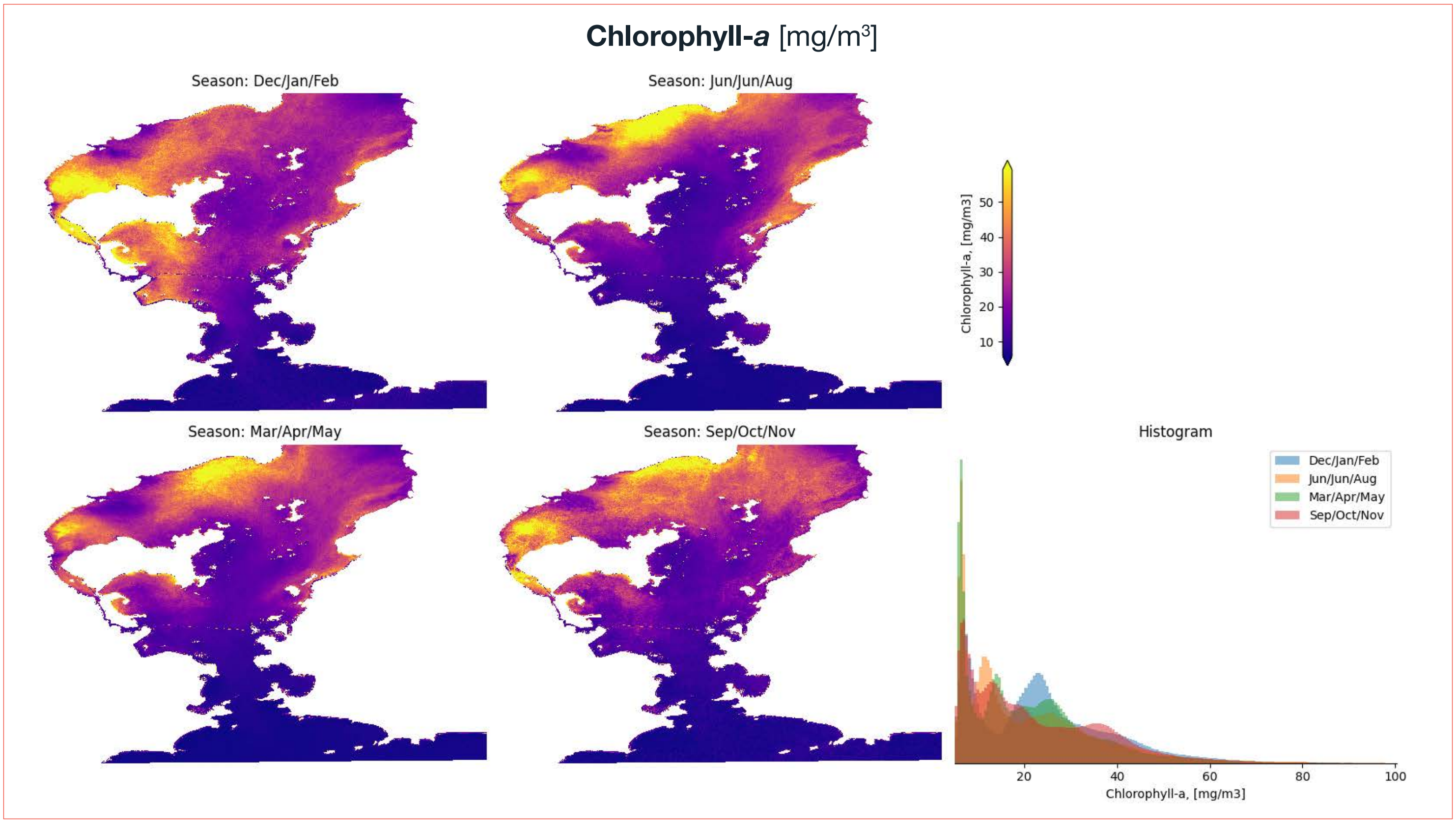
2. Seasonal Trends

2.1: Spatial Seasonal Trends

Maps illustrating the average seasonal variation across the entire water body.

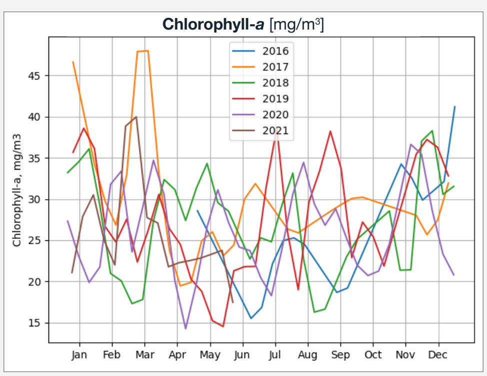


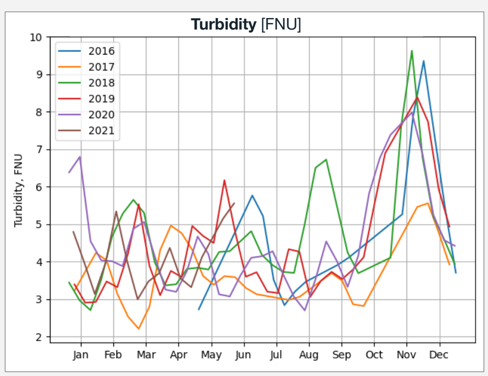


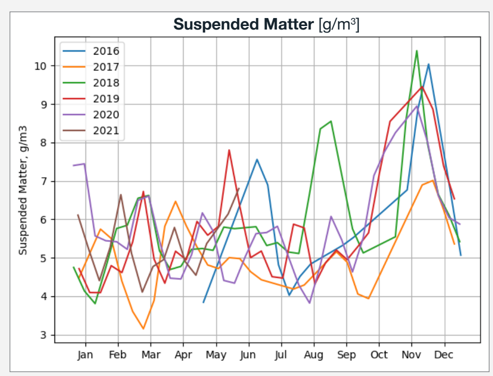


2.2a Temporal Seasonal Trends: Entire Waterbody

Water quality time series data split by each year: seasonal variation per parameter, across the whole reservoir.

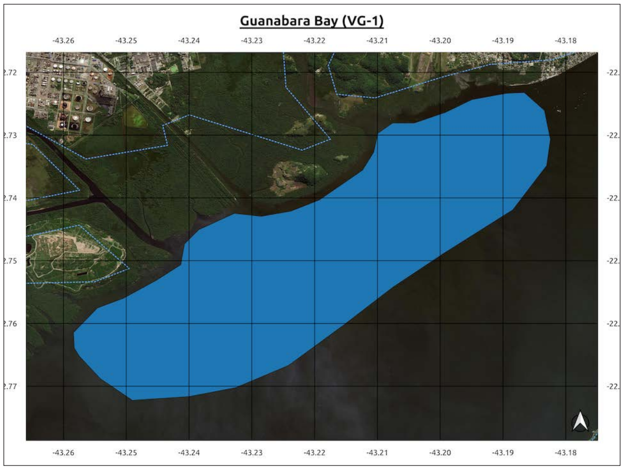


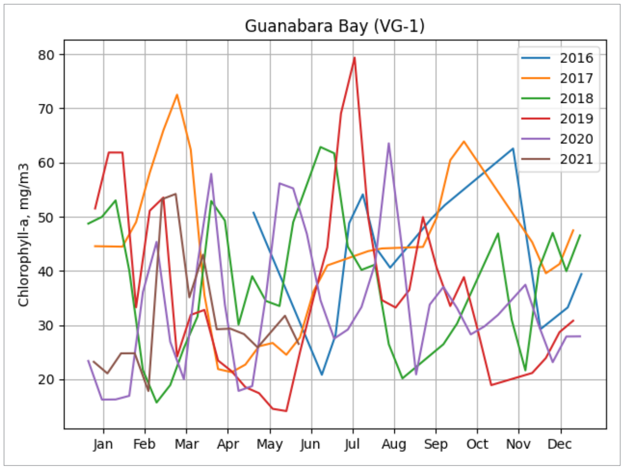


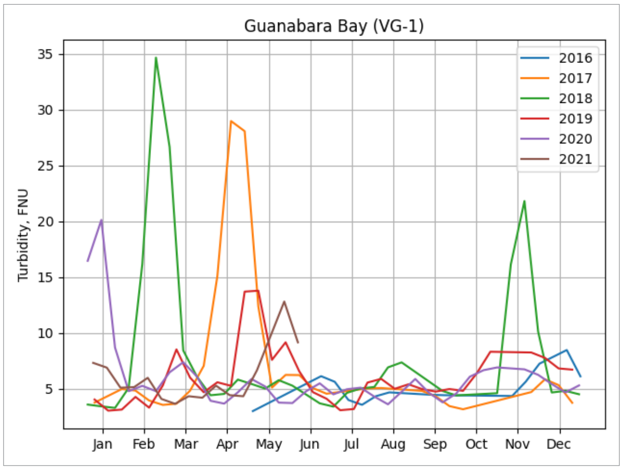


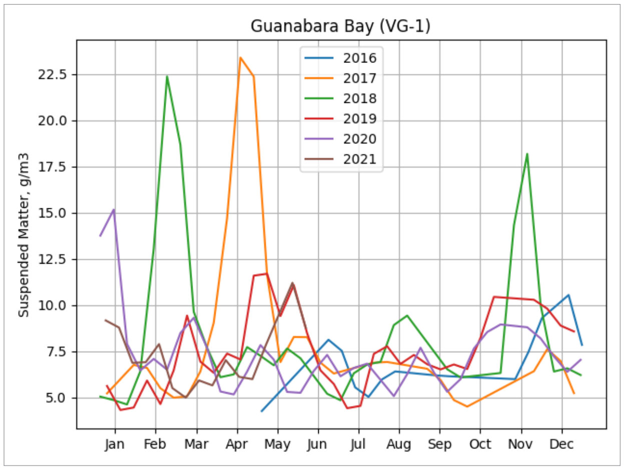
2.2b Temporal Seasonal Trends: Per Virtual Gauge (location of interest)

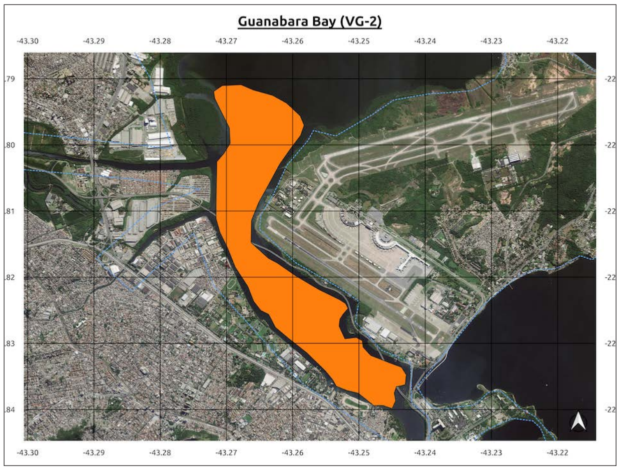
Water quality time series data split by each year: seasonal variation per parameter, per virtual gauge (area of interest) (see following pages).

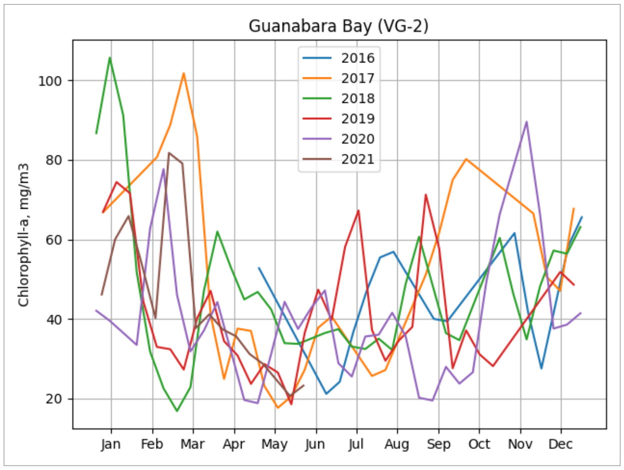

Guanabara Bay (VG-1)

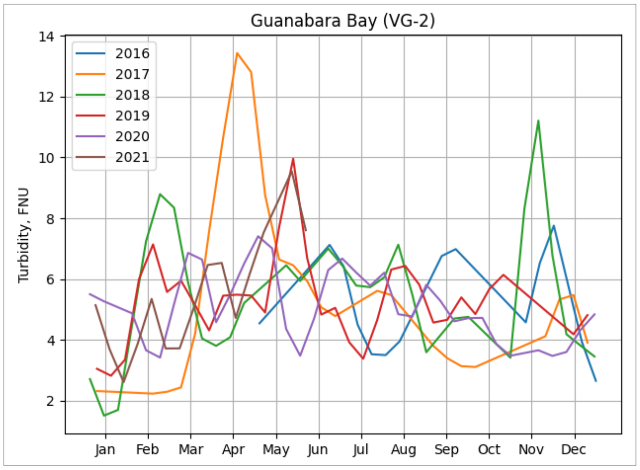

Guanabara Bay (VG-1)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

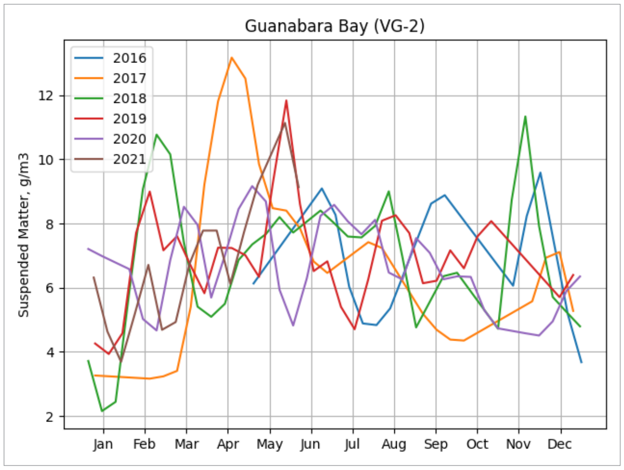

Guanabara Bay (VG-1)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

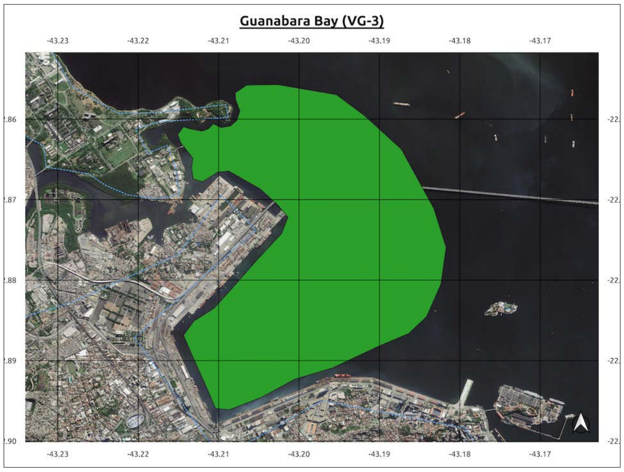

Guanabara Bay (VG-1)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

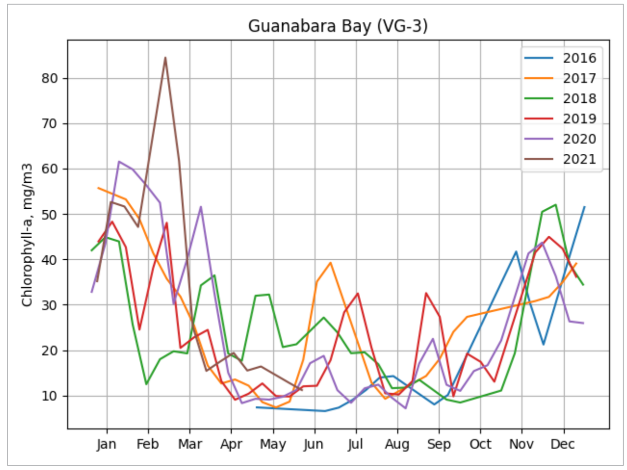

Guanabara Bay (VG-2)

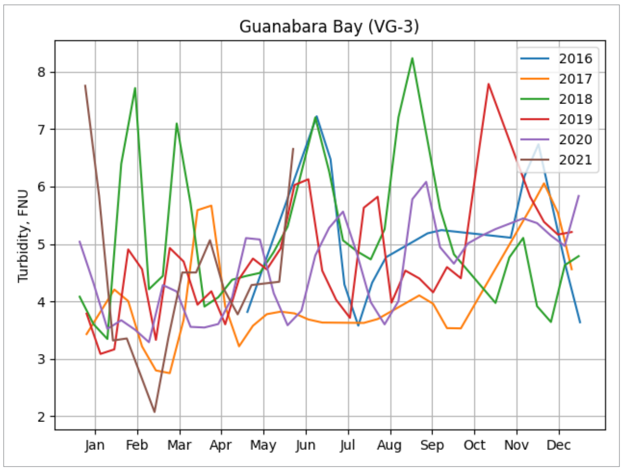

Guanabara Bay (VG-2)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

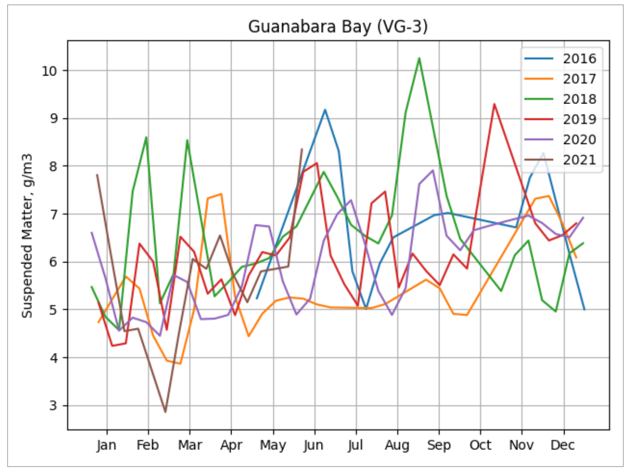

Guanabara Bay (VG-2)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

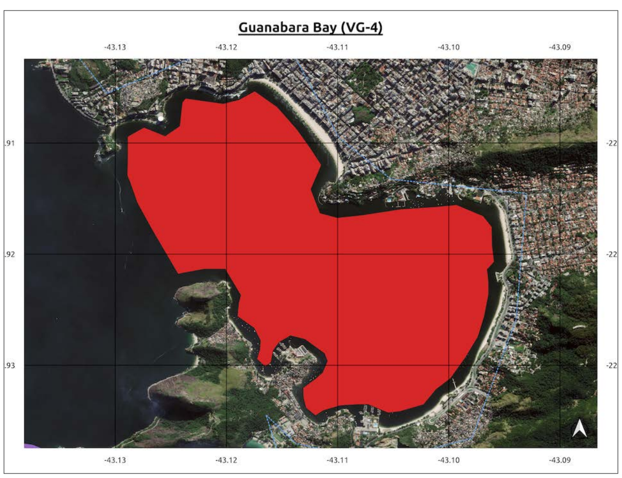

Guanabara Bay (VG-2)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

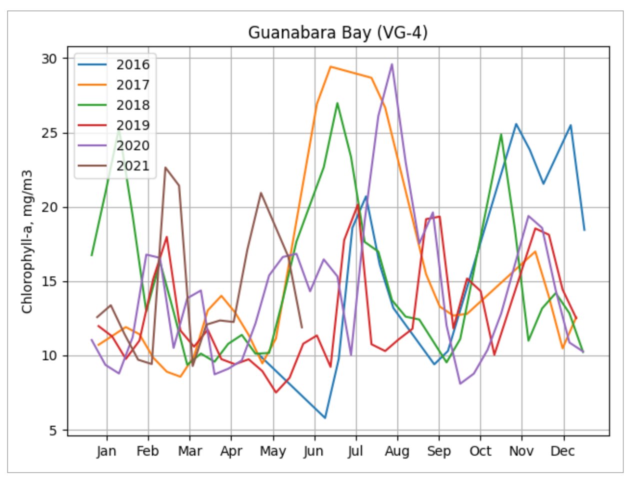

Guanabara Bay (VG-3)

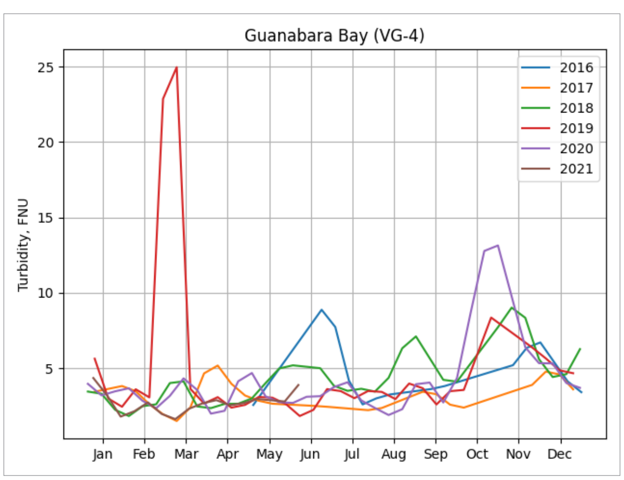

Guanabara Bay (VG-3)
Chlorophyll-a, mg/m3
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

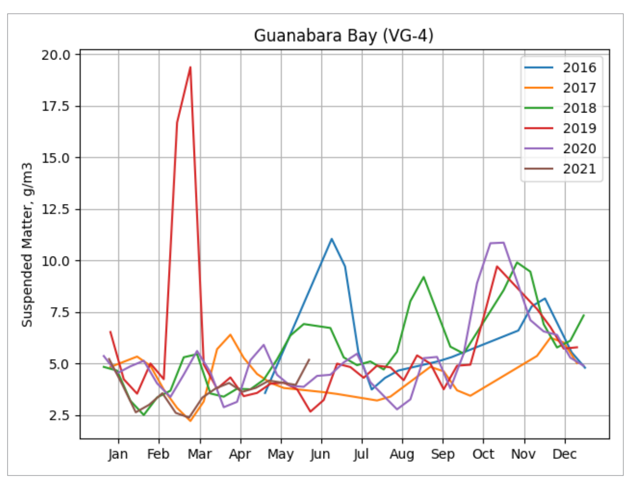

Guanabara Bay (VG-3)
Turbidity, FNU
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

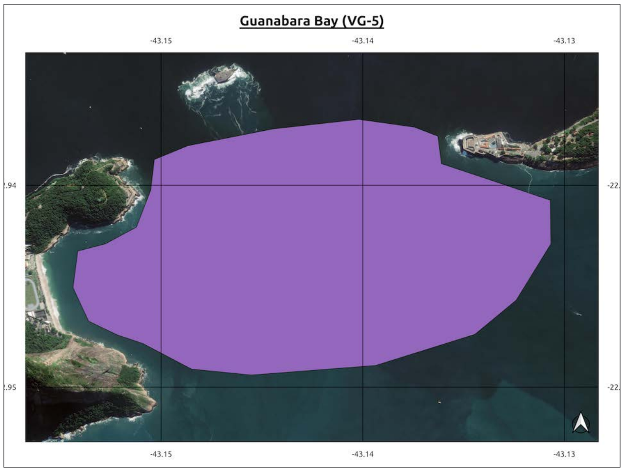

Guanabara Bay (VG-3)
Suspended Matter, g/m3
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

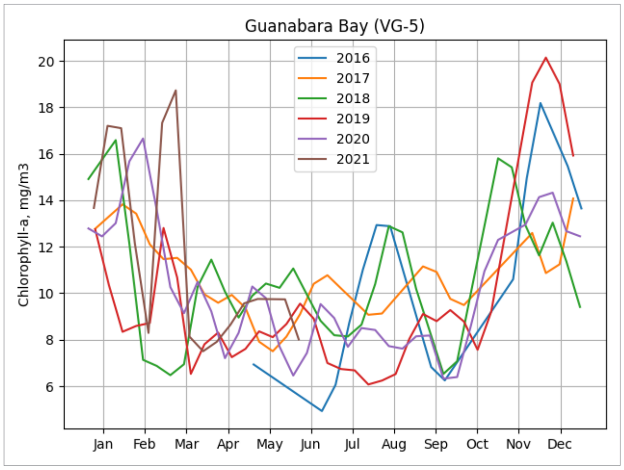

Guanabara Bay (VG-4)

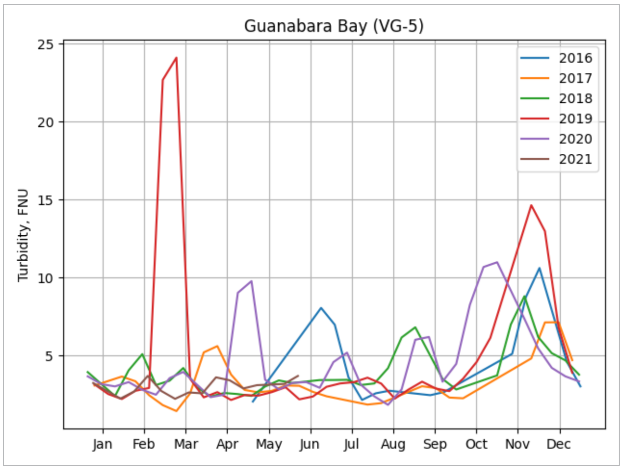

Guanabara Bay (VG-4)
Chlorophyll-a, mg/m3
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

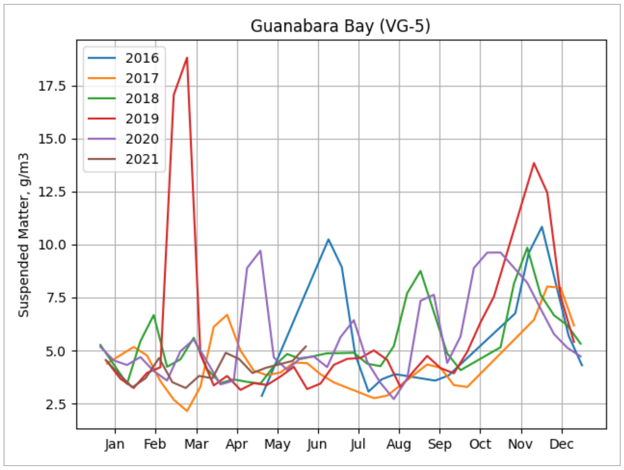

Guanabara Bay (VG-4)
Turbidity, FNU
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

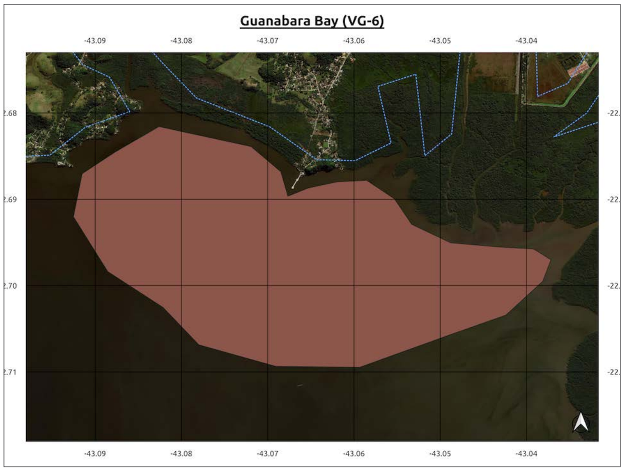

Guanabara Bay (VG-4)
Suspended Matter, g/m3
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2016
2017
2018
2019
2020
2021

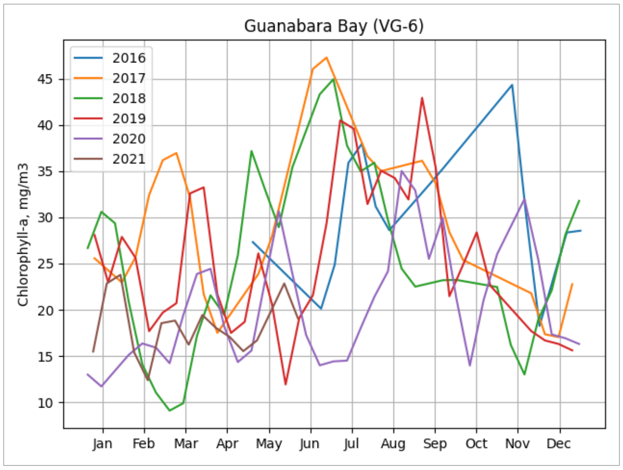

Guanabara Bay (VG-5)
-43.15
-43.14
-43.13

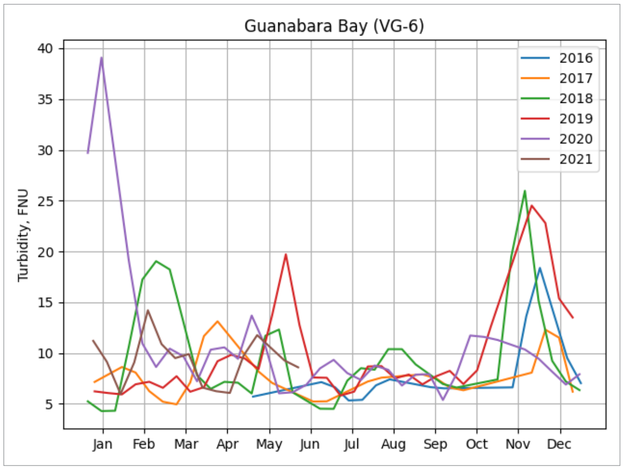

Guanabara Bay (VG-5)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

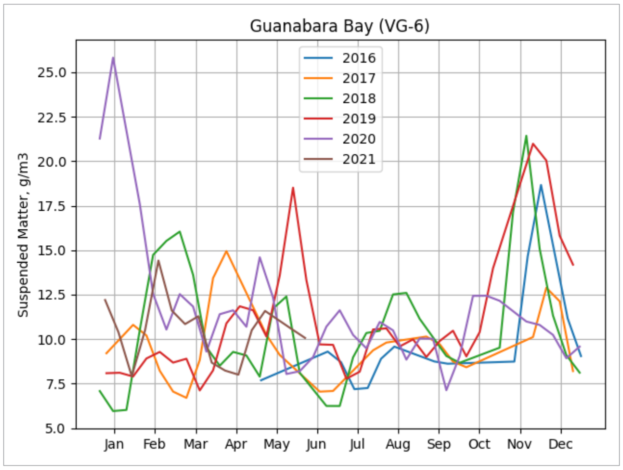

Guanabara Bay (VG-5)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Guanabara Bay (VG-5)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Guanabara Bay (VG-6)
-43.09
-43.08
-43.07
-43.06
-43.05
-43.04

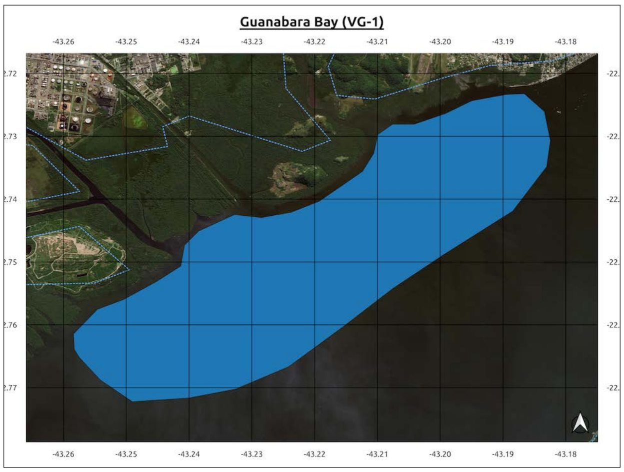

Guanabara Bay (VG-6)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

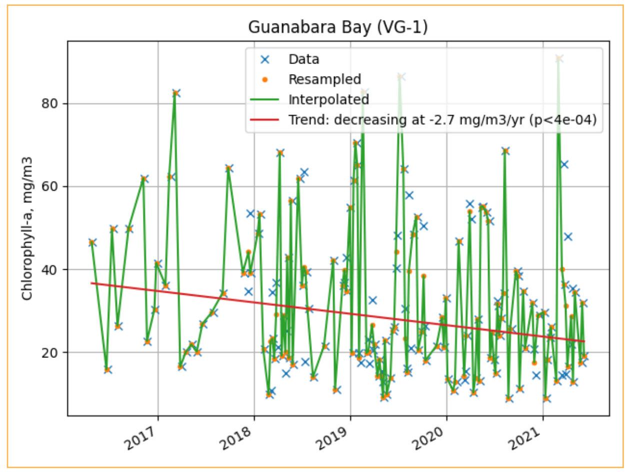

Guanabara Bay (VG-6)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

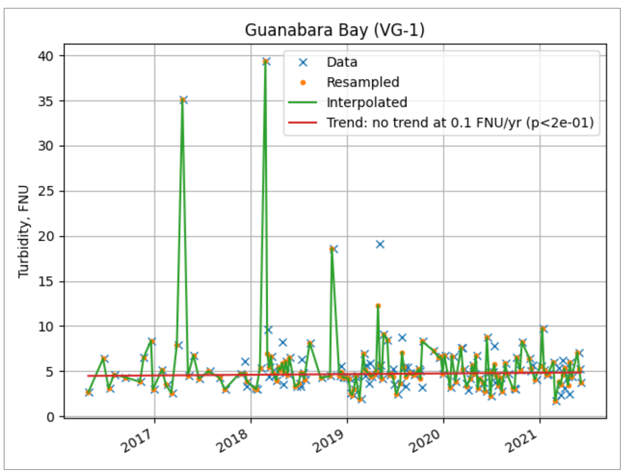

Guanabara Bay (VG-6)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

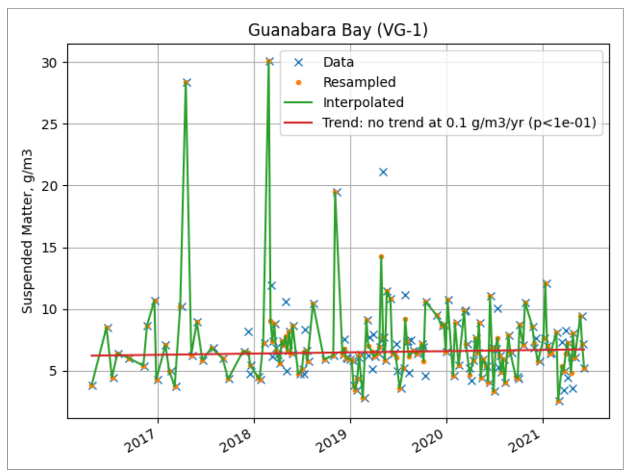
3. Long term trend analysis

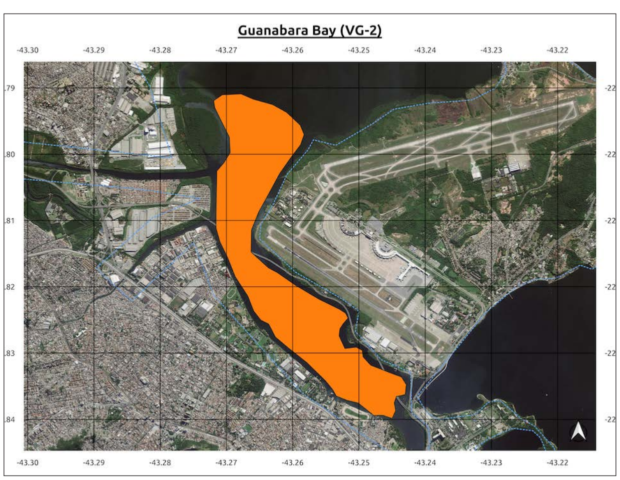
We apply a seasonally adjusted Mann-Kendall Trend Test to Virtual Gauge locations. First, the median water quality parameter value is calculated across a Virtual Gauge location for each image date. Then, a Mann-Kendall test is applied to the full archival time series which provides the direction, magnitude, and statistical significance of potential trends at that location. The outcome indicates whether the time series data at that location has a consistent increasing or decreasing trend.

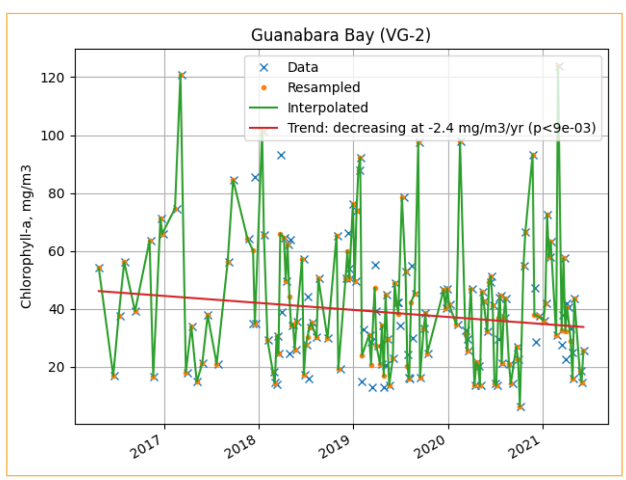


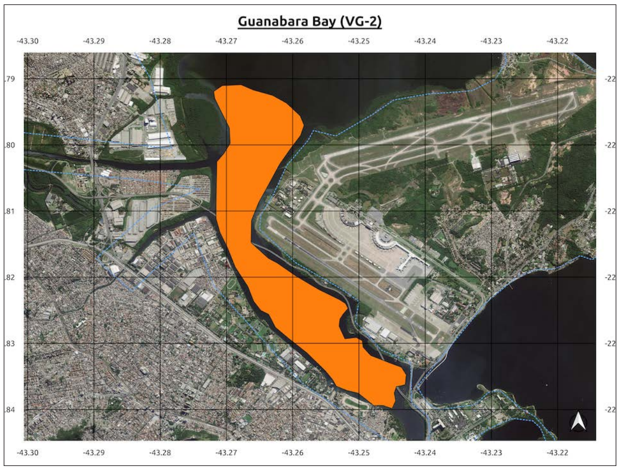


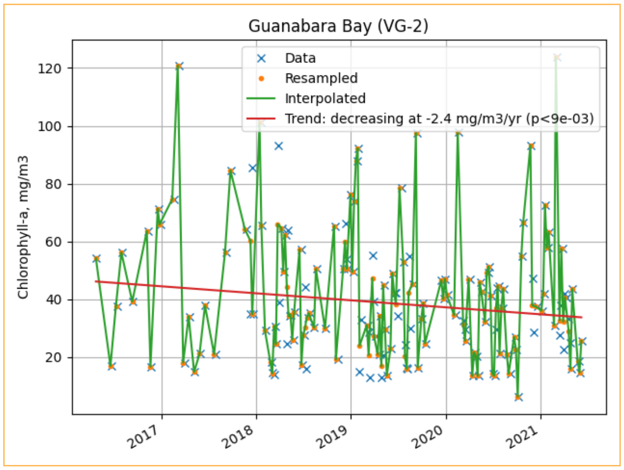


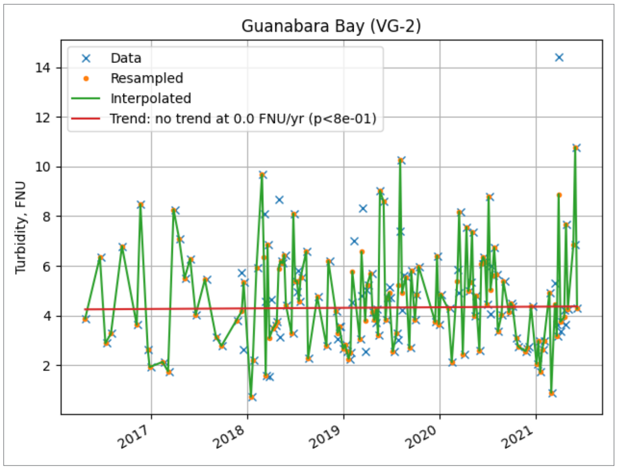


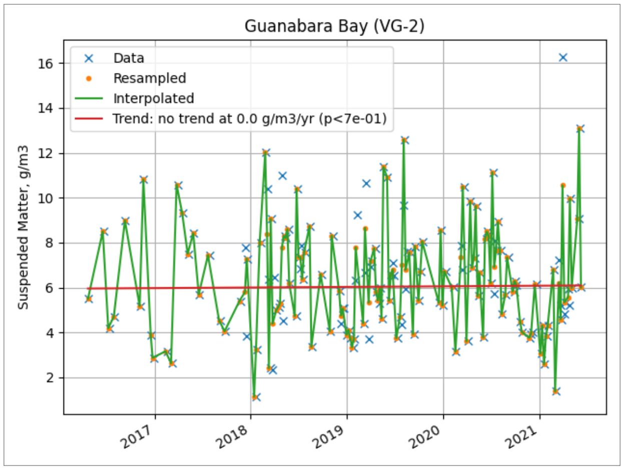


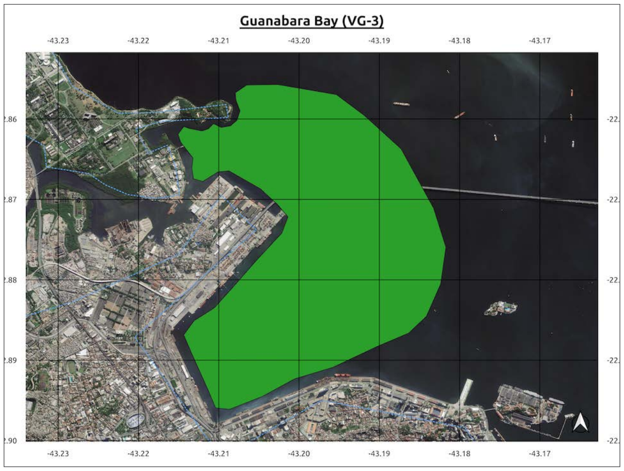


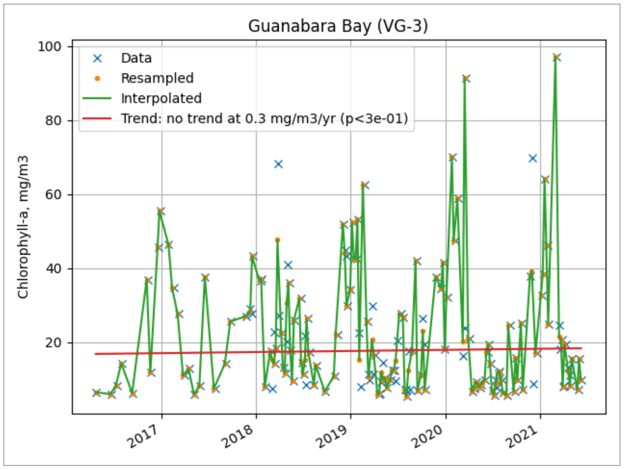

Guanabara Bay (VG-2)
-43.30
-43.29
-43.28
-43.27
-43.26
-43.25
-43.24
-43.23
-43.22

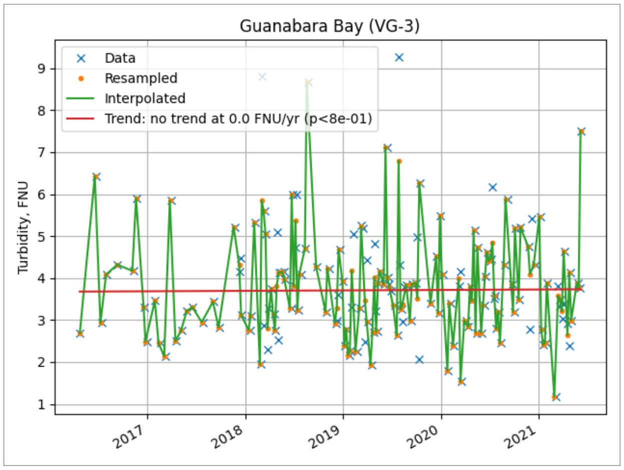

Guanabara Bay (VG-2)
Data
Resampled
Interpolated
Trend: decreasing at -2.4 mg/m3/yr (p<9e-03)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021

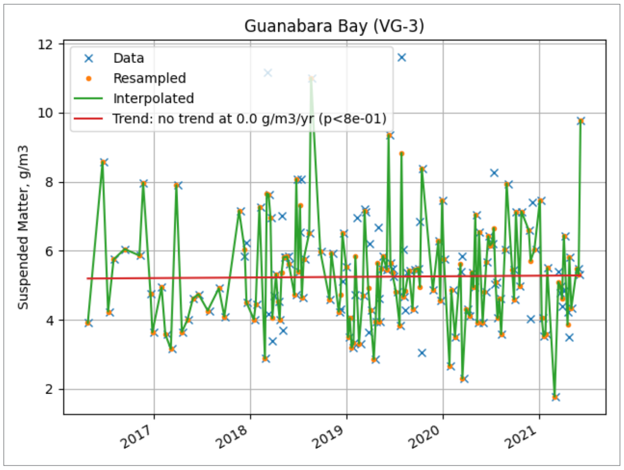

Guanabara Bay (VG-2)
Data
Resampled
Interpolated
Trend: no trend at 0.0 FNU/yr (p<8e-01)
Turbidity, FNU
2017
2018
2019
2020
2021

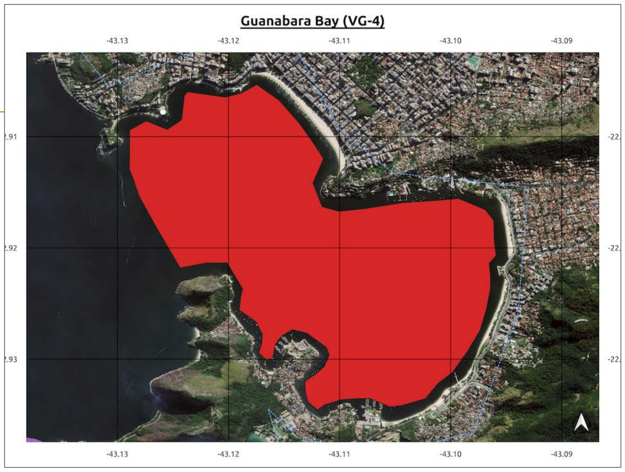

Guanabara Bay (VG-2)
Data
Resampled
Interpolated
Trend: no trend at 0.0 g/m3/yr (p<7e-01)
Suspended Matter, g/m3
2017
2018
2019
2020
2021

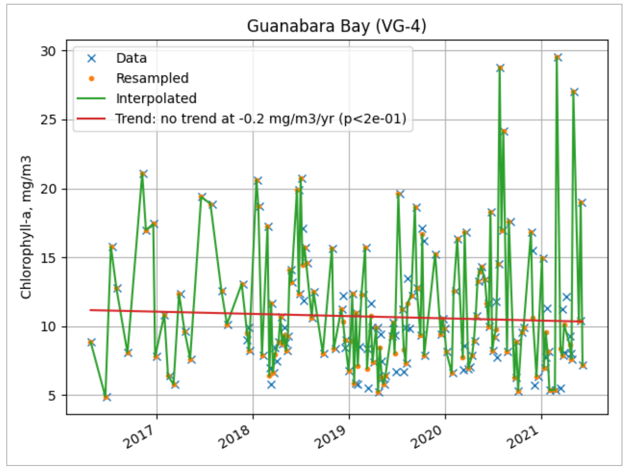

Guanabara Bay (VG-3)
-43.23
-43.22
-43.21
-43.20
-43.19
-43.18
-43.17

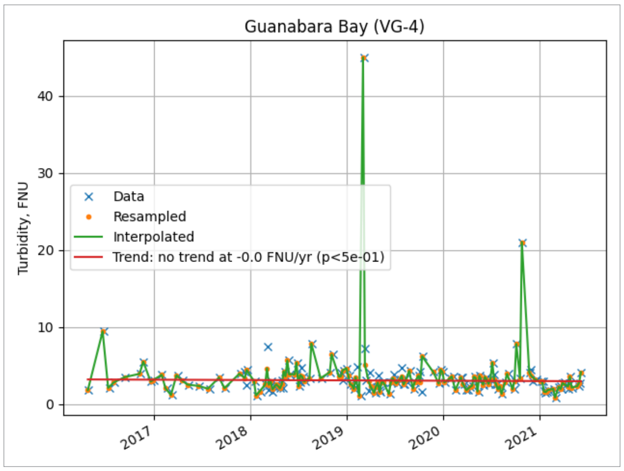

Guanabara Bay (VG-3)
Data
Resampled
Interpolated
Trend: no trend at 0.3 mg/m3/yr (p<3e-01)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021

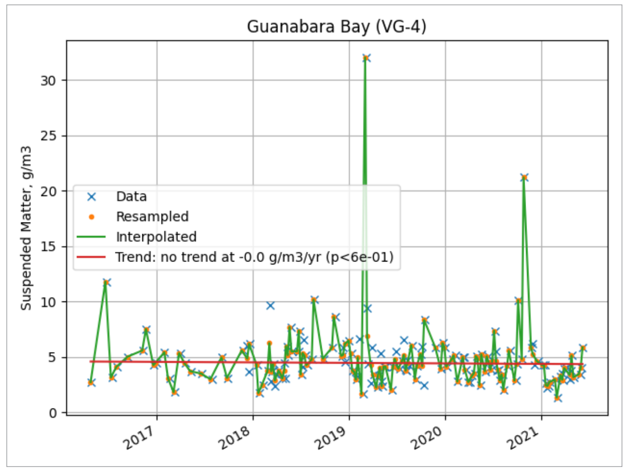

Guanabara Bay (VG-3)
Data
Resampled
Interpolated
Trend: no trend at 0.0 FNU/yr (p<8e-01)
Turbidity, FNU
2017
2018
2019
2020
2021

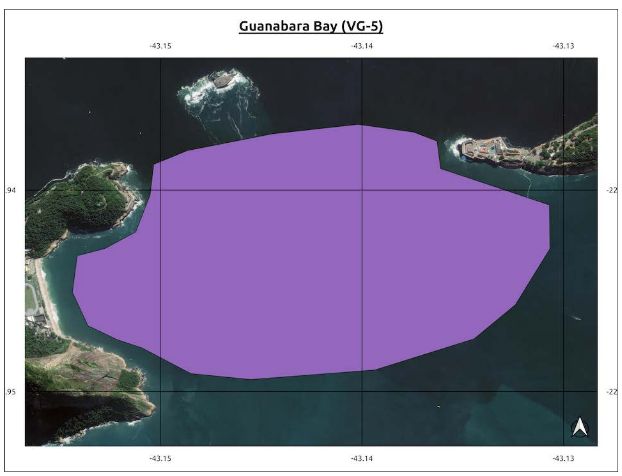

Guanabara Bay (VG-3)
Data
Resampled
Interpolated
Trend: no trend at 0.0 g/m3/yr (p<8e-01)
Suspended Matter, g/m3
2017
2018
2019
2020
2021

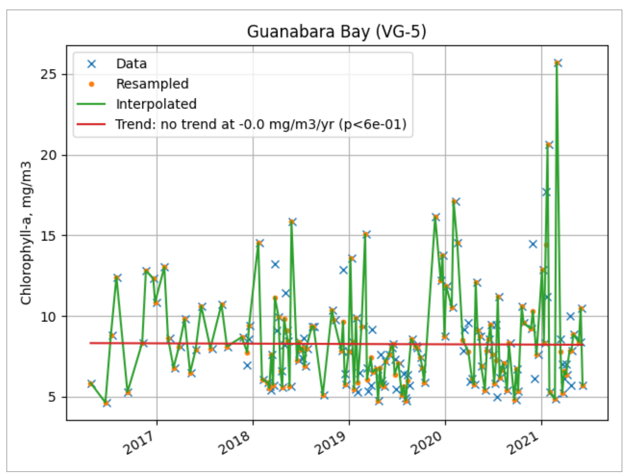

Guanabara Bay (VG-4)

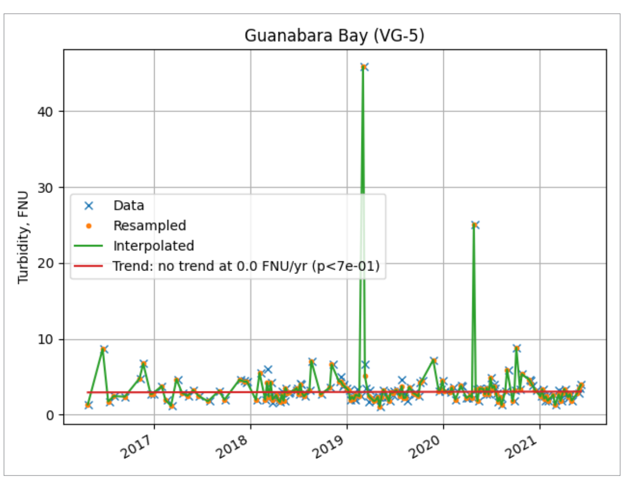

Guanabara Bay (VG-4)
Data
Resampled
Interpolated
Trend: no trend at -0.2 mg/m3/yr (p<2e-01)
Chlorophyll-a, mg/m3

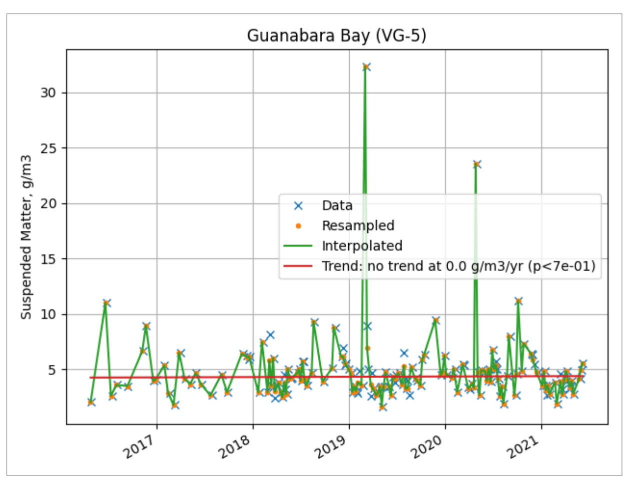

Guanabara Bay (VG-4)
Data
Resampled
Interpolated
Trend: no trend at -0.0 FNU/yr (p<5e-01)
Turbidity, FNU

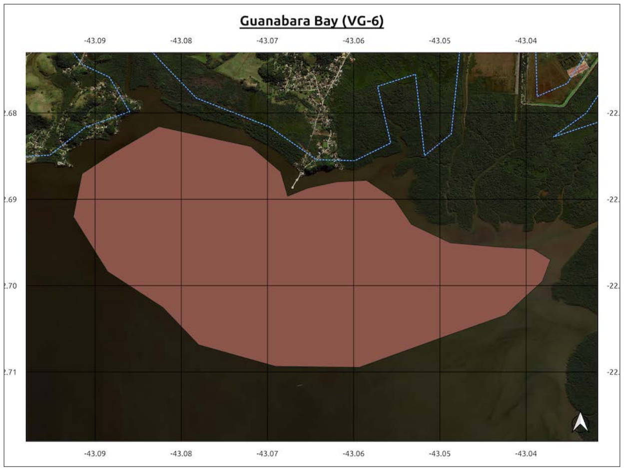

Guanabara Bay (VG-4)
Data
Resampled
Interpolated
Trend: no trend at -0.0 g/m3/yr (p<6e-01)
Suspended Matter, g/m3

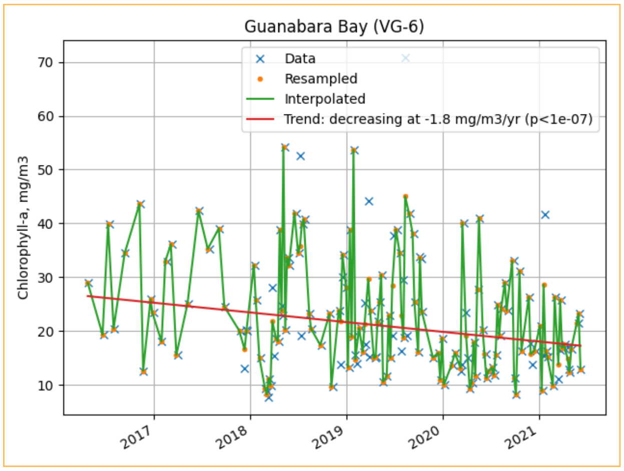

Guanabara Bay (VG-5)

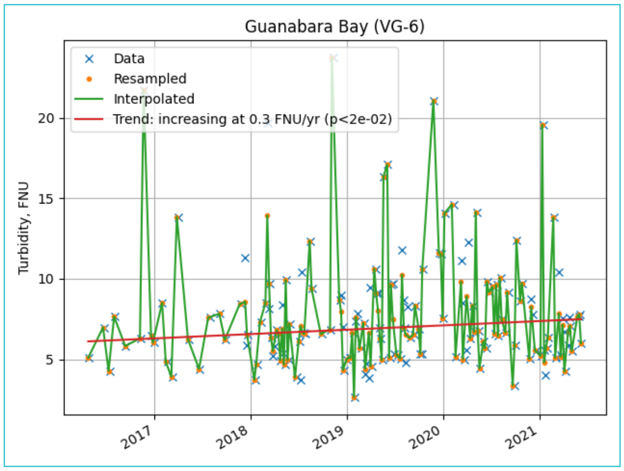

Guanabara Bay (VG-5)
Data
Resampled
Interpolated
Trend: no trend at -0.0 mg/m3/yr (p<6e-01)
Chlorophyll-a, mg/m3

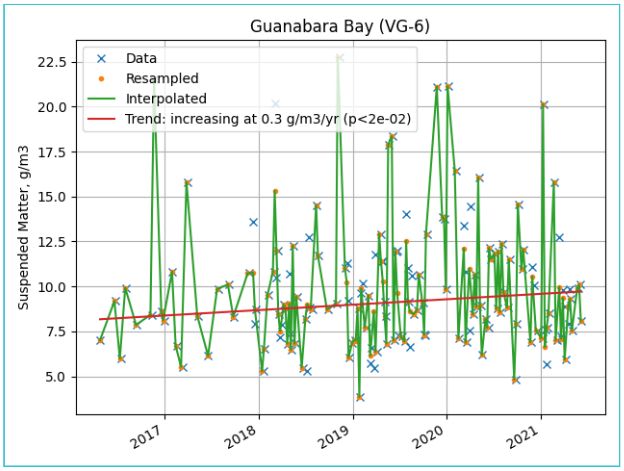

Guanabara Bay (VG-5)
Data
Resampled
Interpolated
Trend: no trend at 0.0 FNU/yr (p<7e-01)
Turbidity, FNU


Guanabara Bay (VG-5)
Data
Resampled
Interpolated
Trend: no trend at 0.0 g/m3/yr (p<7e-01)
Suspended Matter, g/m3


Guanabara Bay (VG-6)
-43.09
-43.08
-43.07
-43.06
-43.05
-43.04


Guanabara Bay (VG-6)
Data
Resampled
Interpolated
Trend: decreasing at -1.8 mg/m3/yr (p<1e-07)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021


Guanabara Bay (VG-6)
Data
Resampled
Interpolated
Trend: increasing at 0.3 FNU/yr (p<2e-02)
Turbidity, FNU
2017
2018
2019
2020
2021

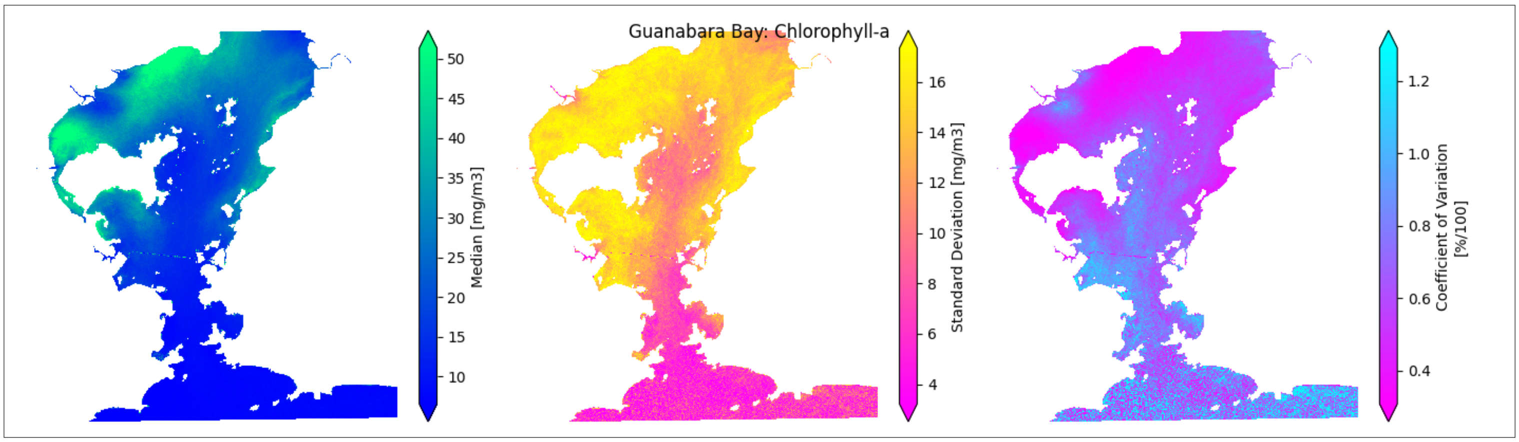

Guanabara Bay (VG-6)
Data
Resampled
Interpolated
Trend: increasing at 0.3 g/m3/yr (p<2e-02)
Suspended Matter, g/m3
2017
2018
2019
2020
2021

4. Variation Maps

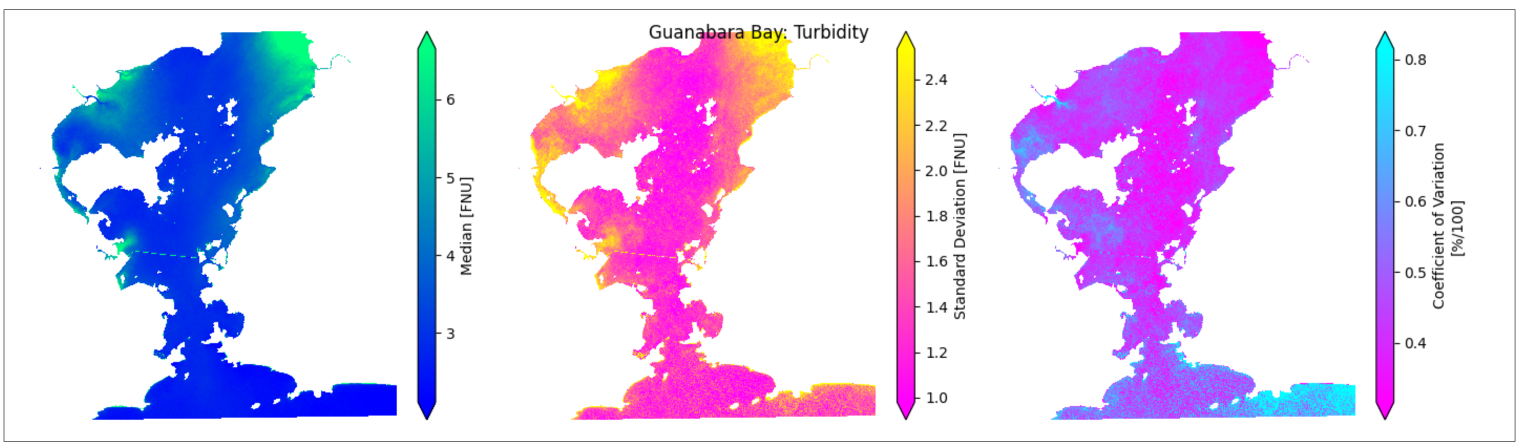
We created Variation Maps for each water body and water quality parameter. This process calculates the median, standard deviation, and coefficient of variation on a pixel-wise basis through time. The product is a map that shows the spatial distribution of these summary statistics through time.

Median | **Standard Deviation** | **Coefficient of Variation**

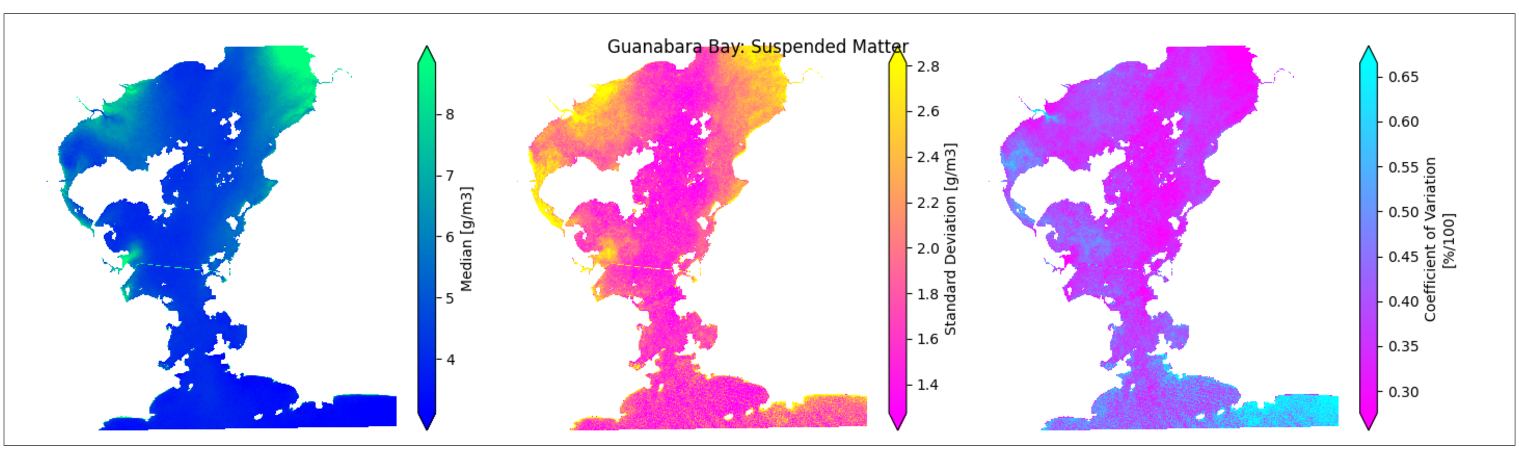
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



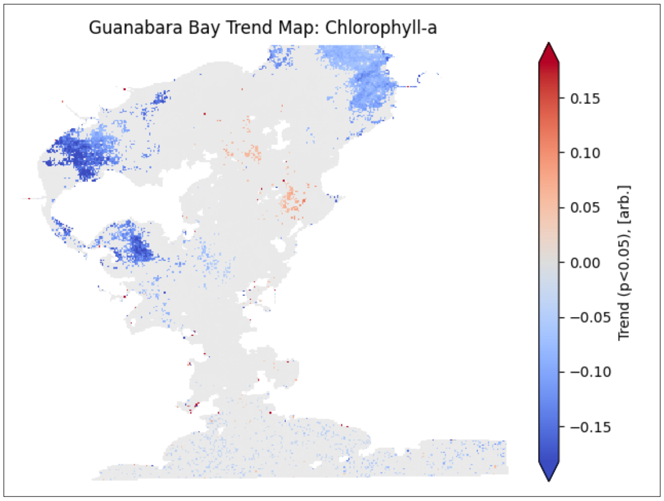
4.3 Suspended Matter [g/m^3]



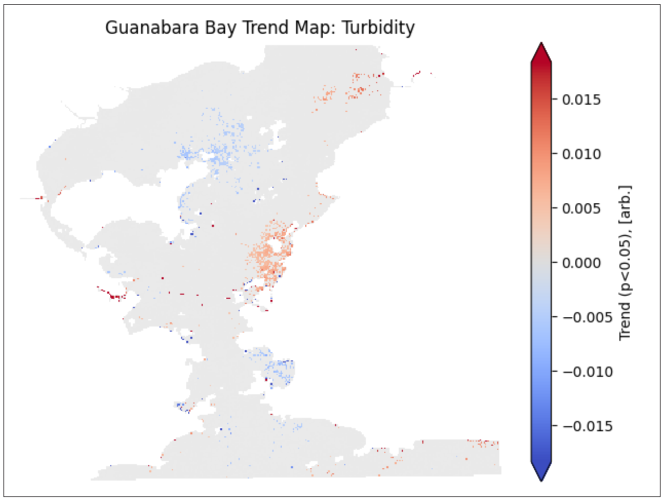
5. Trend Maps

We create Trend Maps to visualize where temporal trends in water quality parameters are occurring. First, data across the entire water body is spatially binned by averaged to approximately 100m resolution. Then, a linear regression is applied along the temporal axis for each bin, a three-sigma outlier filtering process is used to remove outliers. Finally, the linear trends are visualized on a map where statistically significant (p-value below 5%) values are colorized based on direction and intensity.

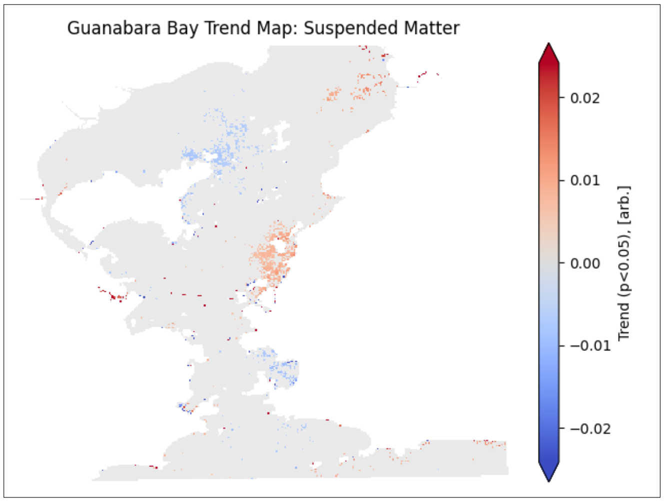
5.1 Chlorophyll-*a*
[mg/m³]



5.2 Turbidity
[FNU]



5.3 Suspended Matter
[g/m³]

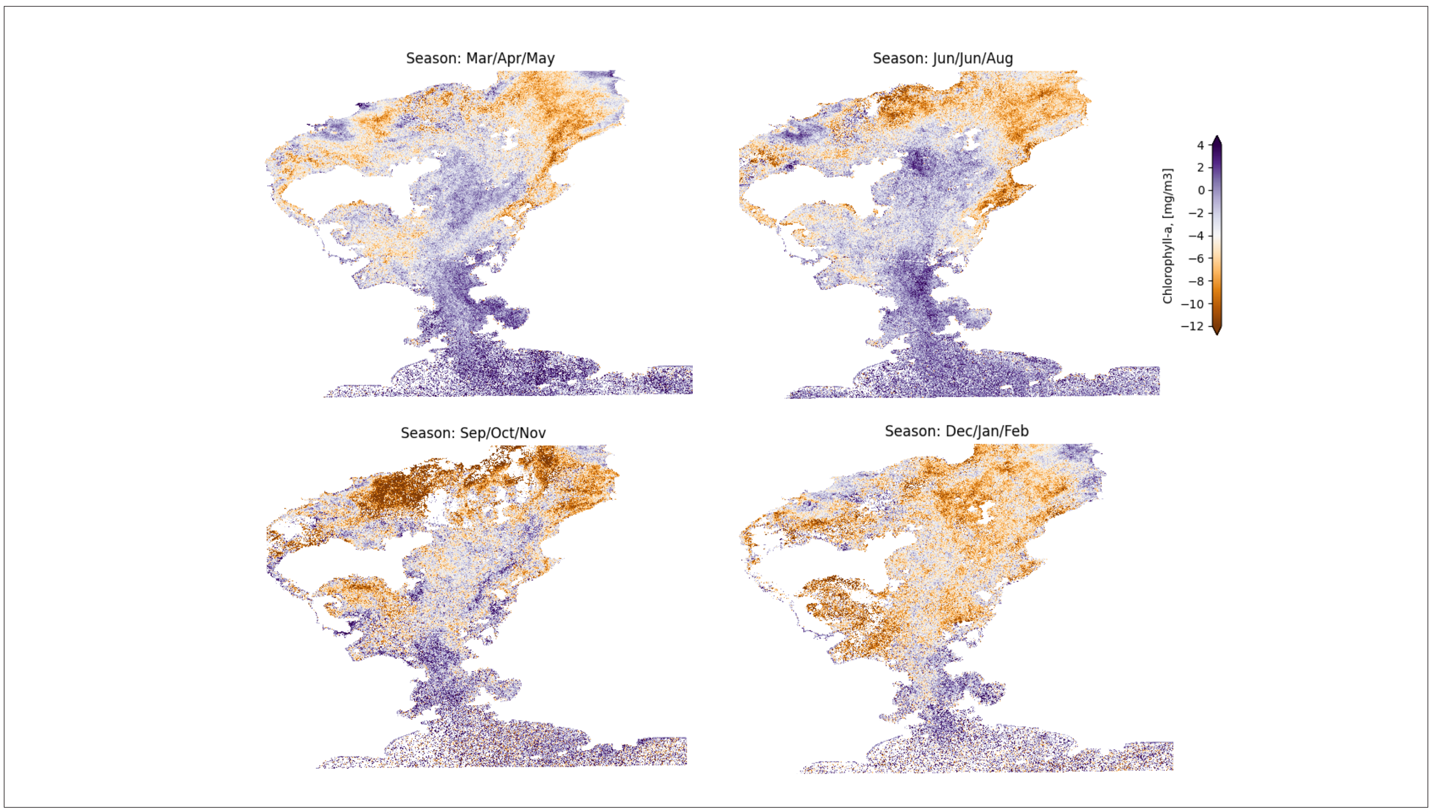


6. Difference Maps

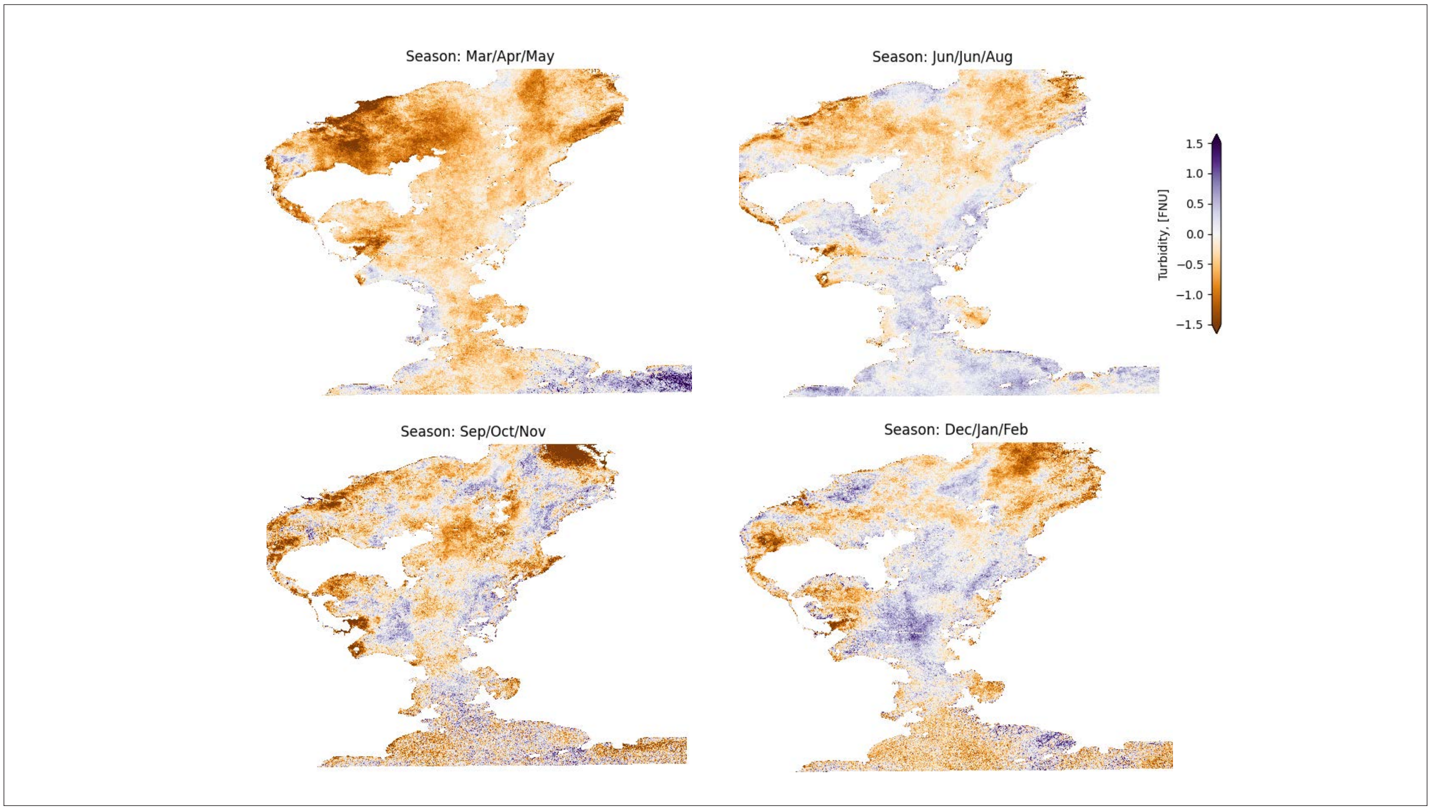
Changes to WQ stemming from Covid-19 lockdown restrictions were assessed using a series of simple one-way analysis of variance (ANOVA) tests. Differences in pre- and post-Covid-19 conditions were tested for at each WQ metric at each virtual gauge location, with pre-Covid-19 lockdown defined as all time series data before March 19, 2020. Both pre- and post-Covid-19 datasets were separated into three-month seasons, with tests performed on each season to control for seasonal variations. Significant differences between conditions were recorded with a ‘p-value’ less than 0.05.

Separately, an assessment of Covid-19 lockdown related differences in WQ was conducted across the entire water body to illustrate general trends not associated with virtual gauge locations. For this, pixel-wise differences were calculated across the entire water body using images downsampled to 30 m pixels. The resulting images illustrate where changes in WQ are observable.

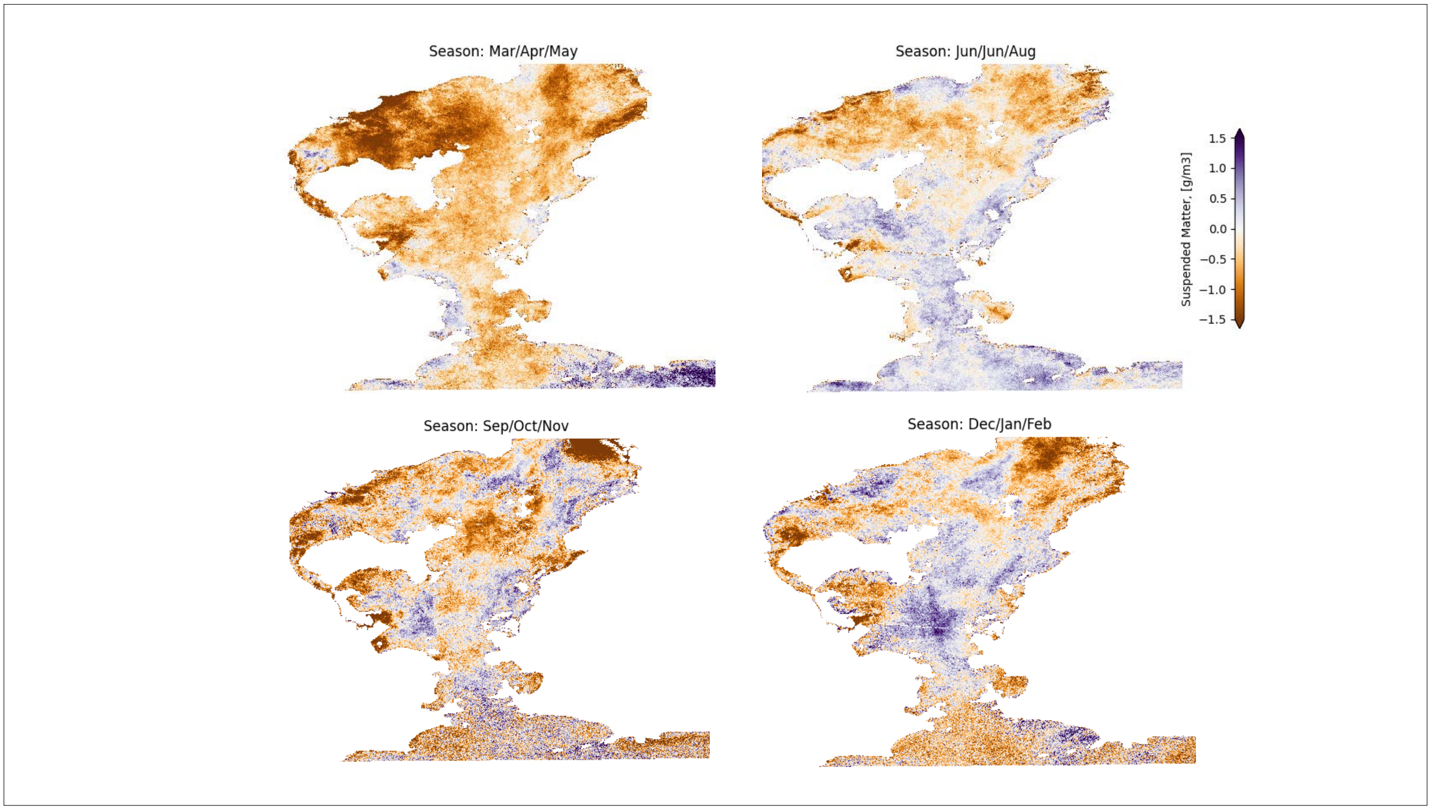
6.1 Chlorophyll-*a* [mg/m^3]



6.2 Turbidity [FNU]



6.3 Suspended Matter [g/m^3]



APPENDIX A3 Rio Reconquista Basin

APPENDIX A3

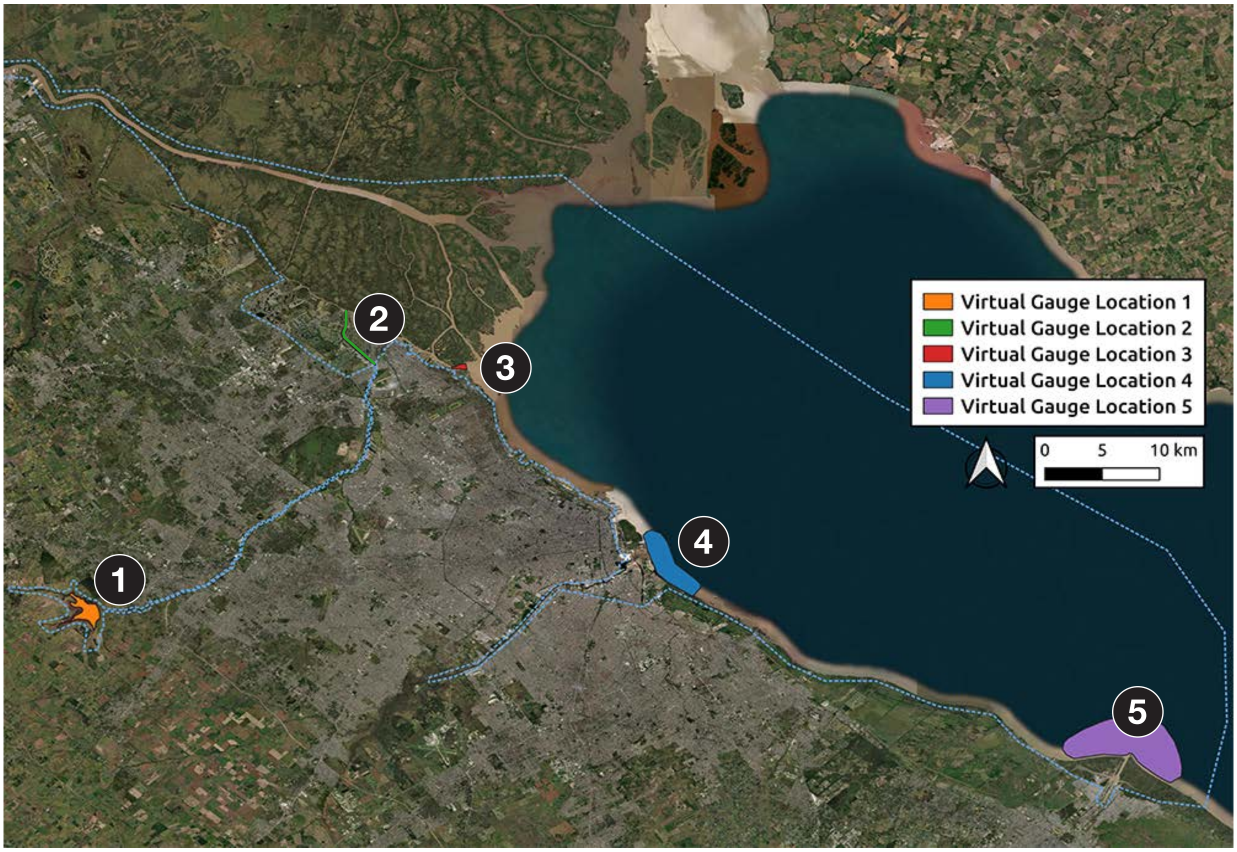
RIO RECONQUISTA BASIN

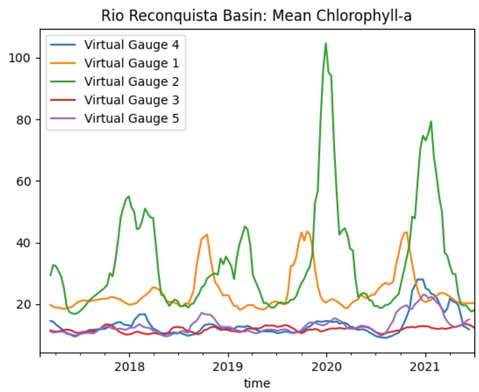
A Virtual Gauge is a specific geographic region of interest in which water quality parameters are temporally assessed in greater detail than viable across the entire water body. The goal of establishing Virtual Gauge locations is to extract data that enables rapid, flexible, and relevant investigation into areas where known water quality issues exist.

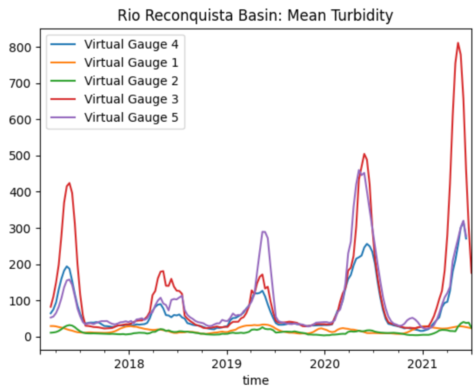
1. Virtual Gauges

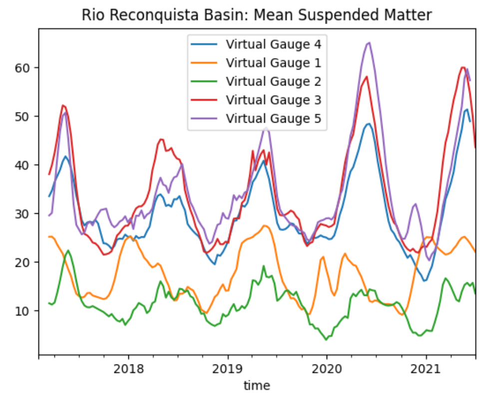
Change over time at key locations across the basin

From 2017 to today, at all 5 locations of interest in the Rio Reconquista Basin.





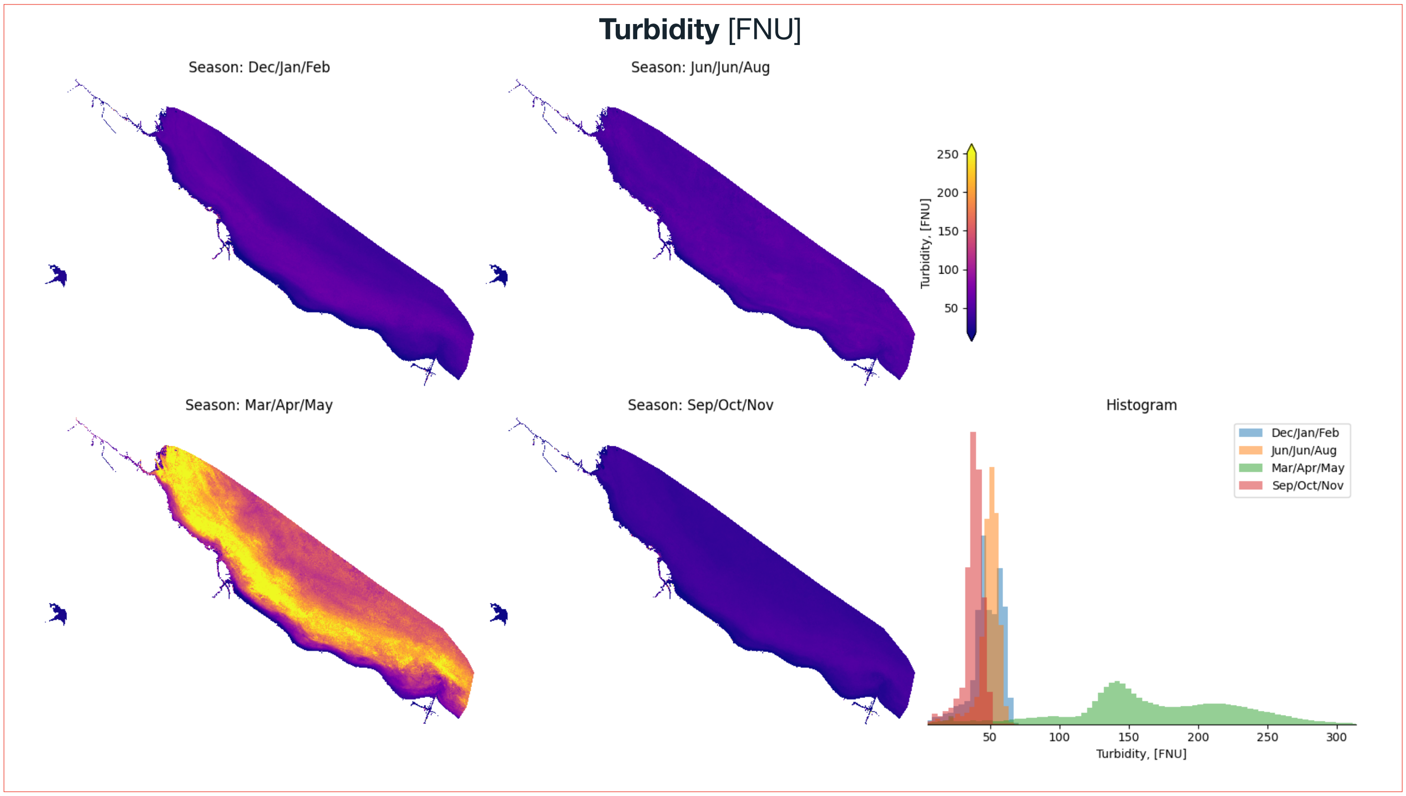


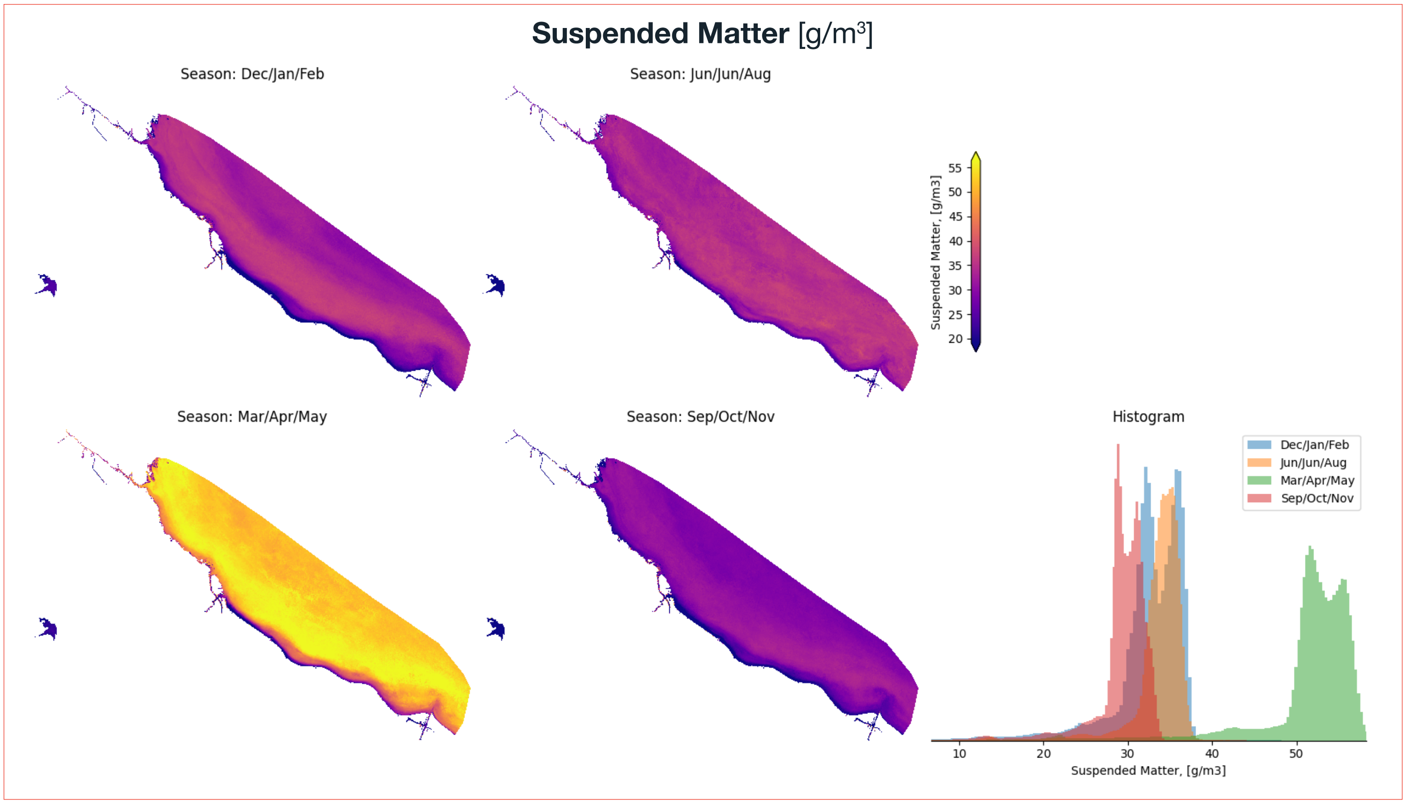


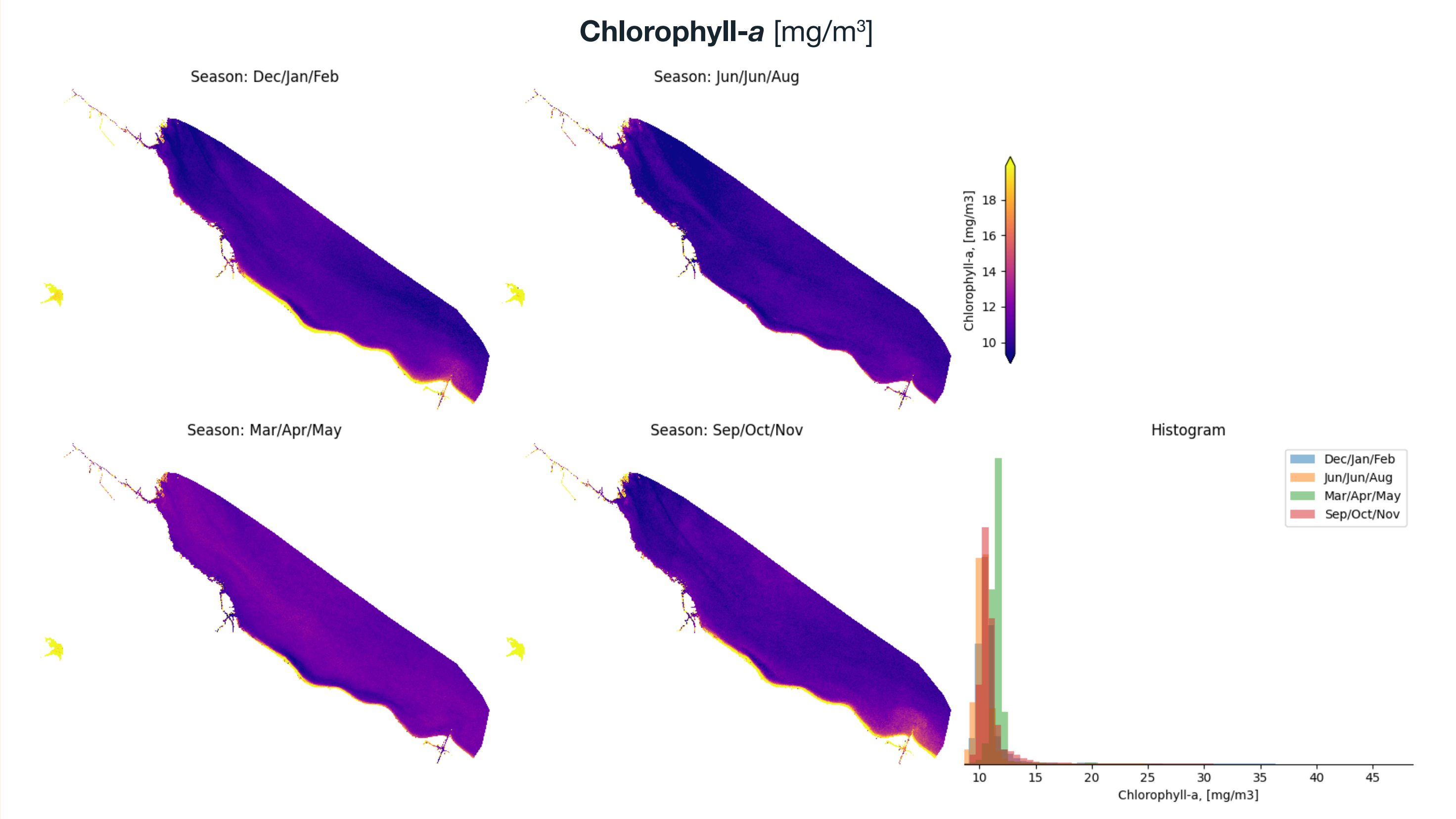
2. Seasonal Trends

2.1: Spatial Seasonal Trends

Maps illustrating the average seasonal variation across the entire water body.

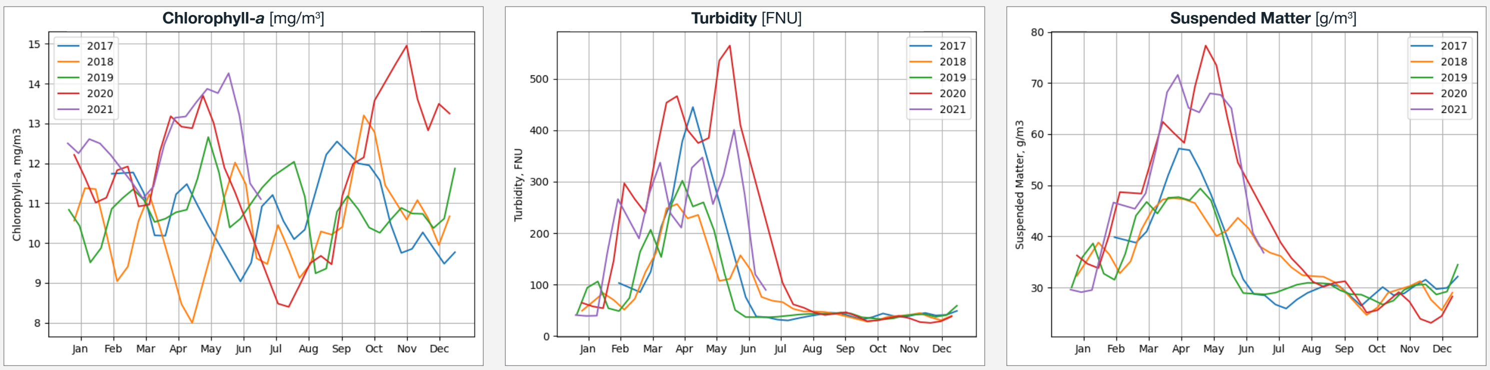






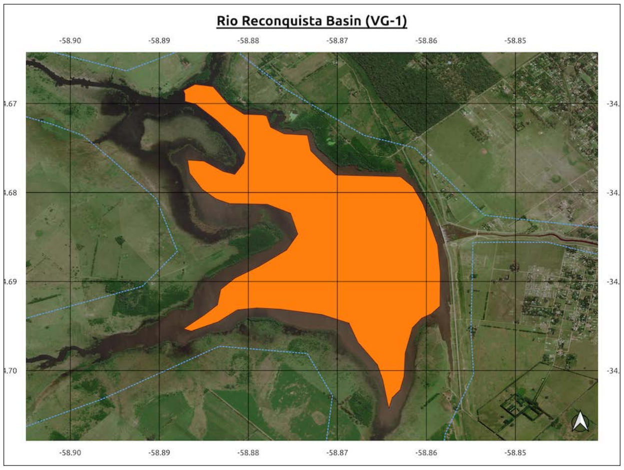
2.2a Temporal Seasonal Trends: Entire Waterbody

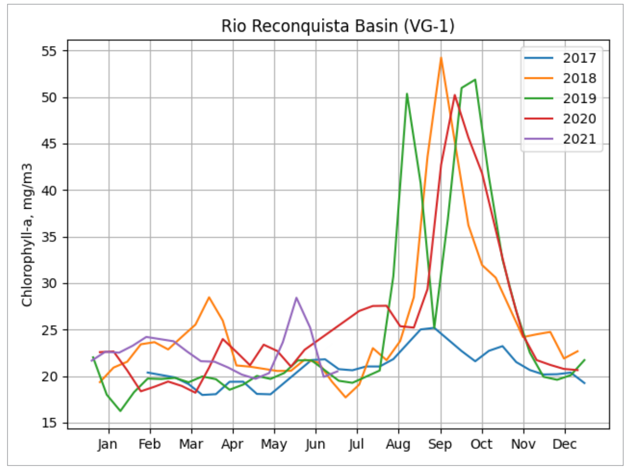
Water quality time series data split by each year: seasonal variation per parameter, across the whole reservoir.

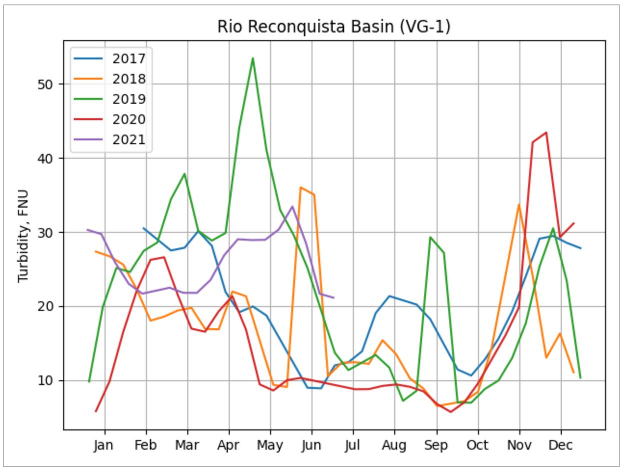


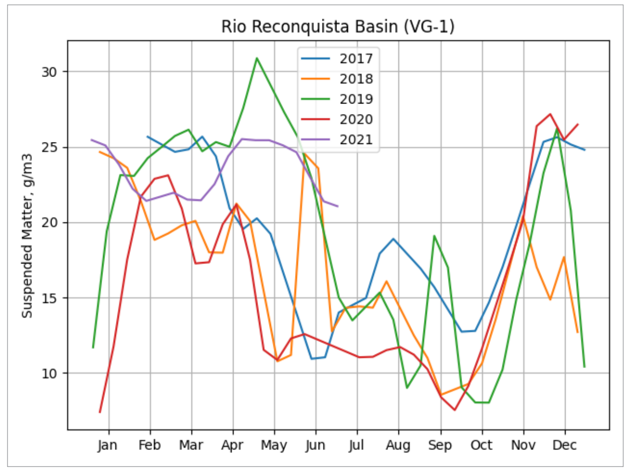
2.2b Temporal Seasonal Trends: Per Virtual Gauge (location of interest)

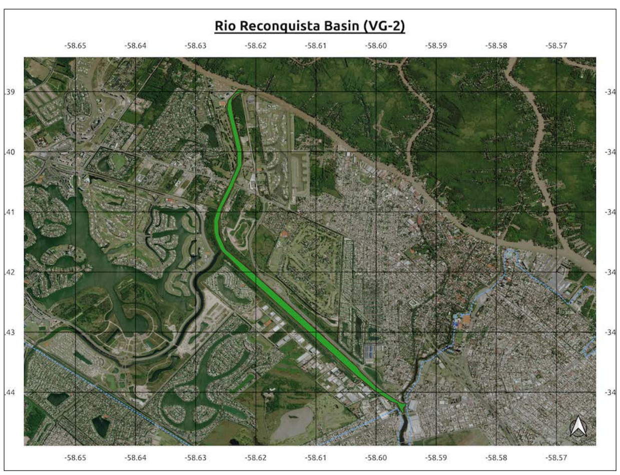
Water quality time series data split by each year: seasonal variation per parameter, per virtual gauge (area of interest) (see following pages).

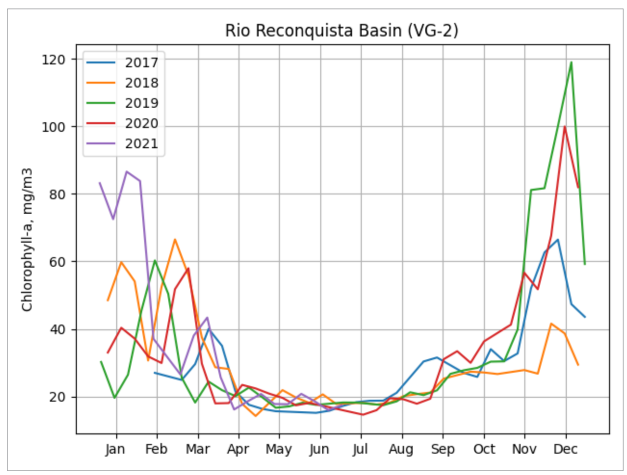

Rio Reconquista Basin (VG-1)
-58.90
-58.89
-58.88
-58.87
-58.86
-58.85

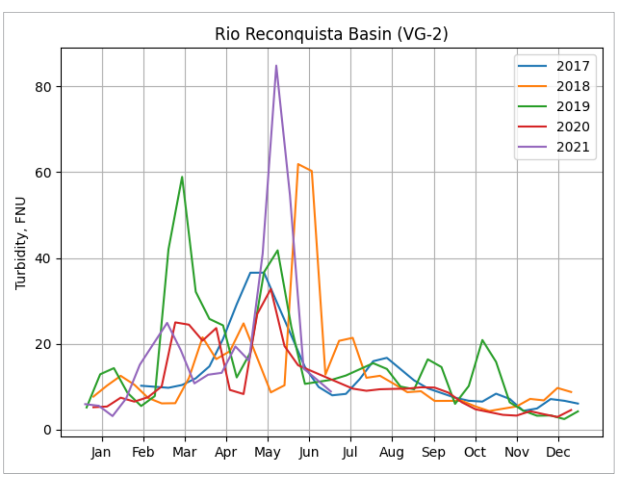

Rio Reconquista Basin (VG-1)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

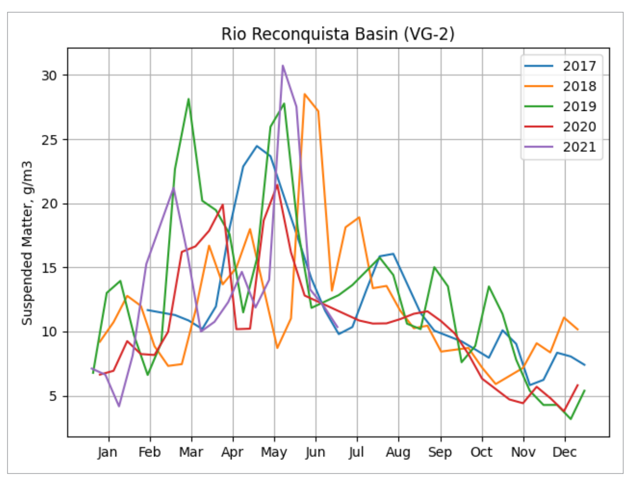

Rio Reconquista Basin (VG-1)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

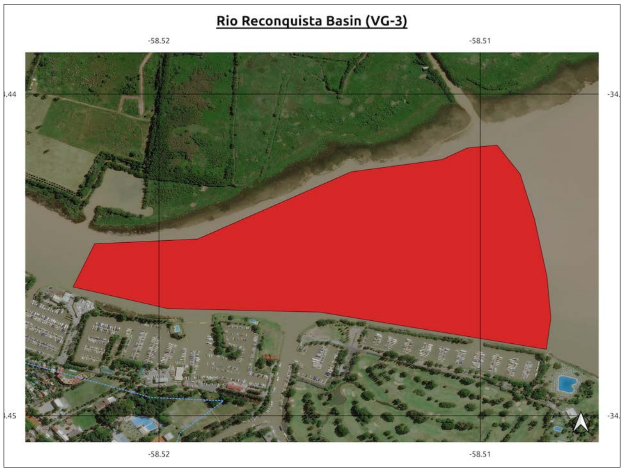

Rio Reconquista Basin (VG-1)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

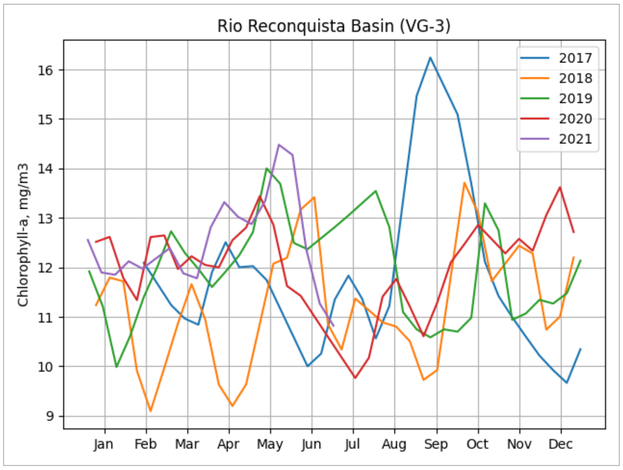

Rio Reconquista Basin (VG-2)
-58.65
-58.64
-58.63
-58.62
-58.61
-58.60
-58.59
-58.58
-58.57

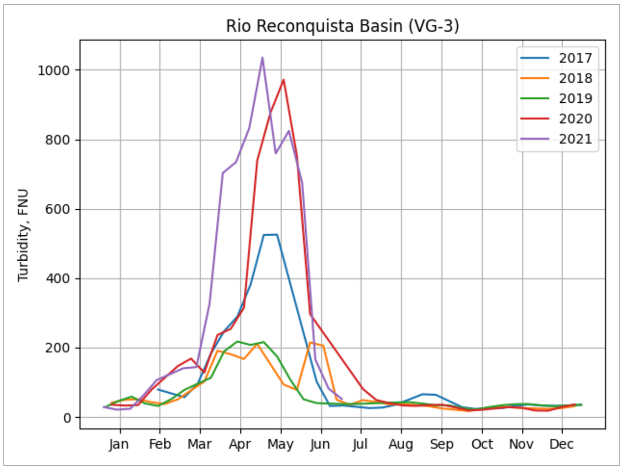

Rio Reconquista Basin (VG-2)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

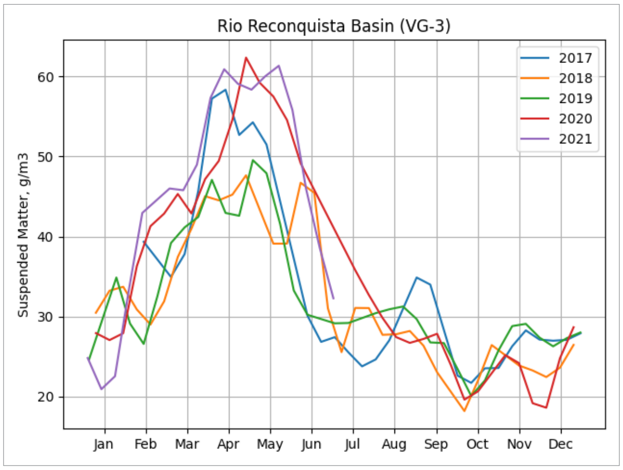

Rio Reconquista Basin (VG-2)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

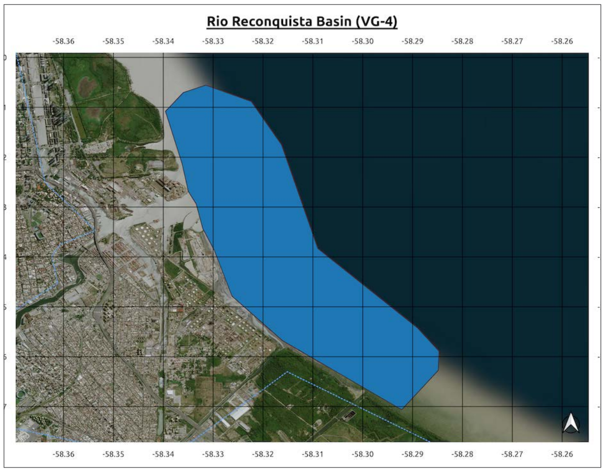

Rio Reconquista Basin (VG-2)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

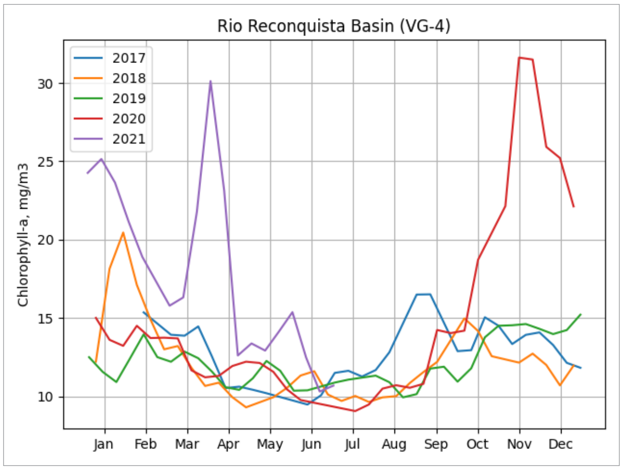

Rio Reconquista Basin (VG-3)
-58.52
-58.51

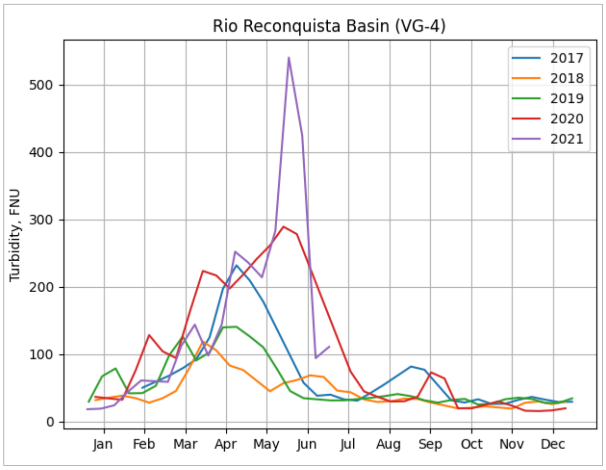

Rio Reconquista Basin (VG-3)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

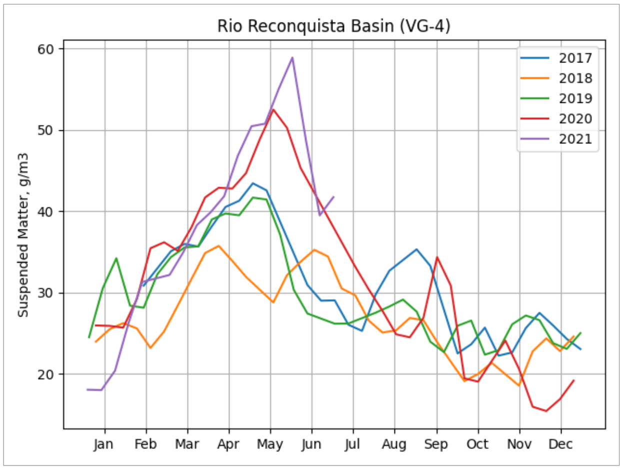

Rio Reconquista Basin (VG-3)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

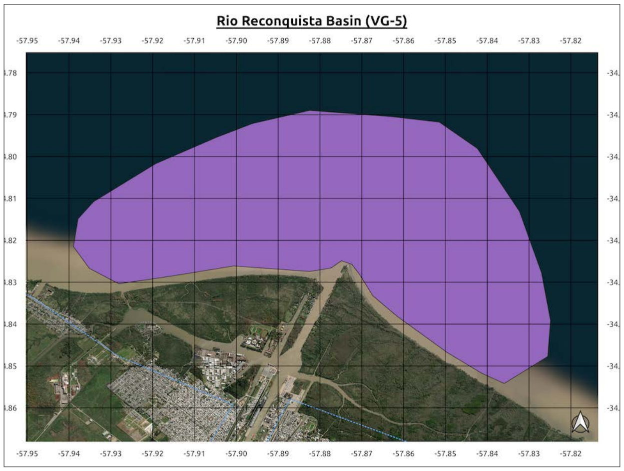

Rio Reconquista Basin (VG-3)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

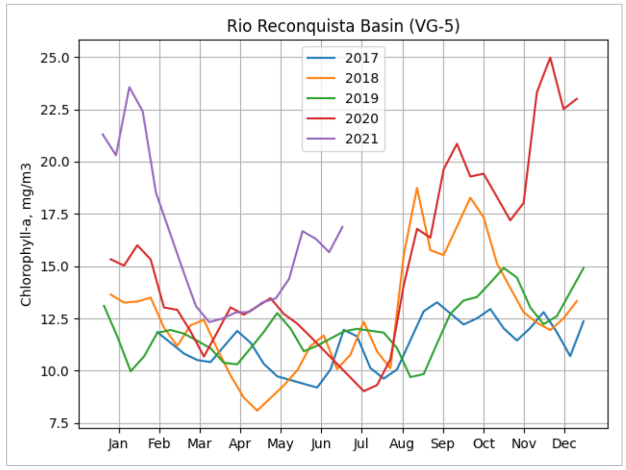

Rio Reconquista Basin (VG-4)
-58.36 -58.35 -58.34 -58.33 -58.32 -58.31 -58.30 -58.29 -58.28 -58.27 -58.26

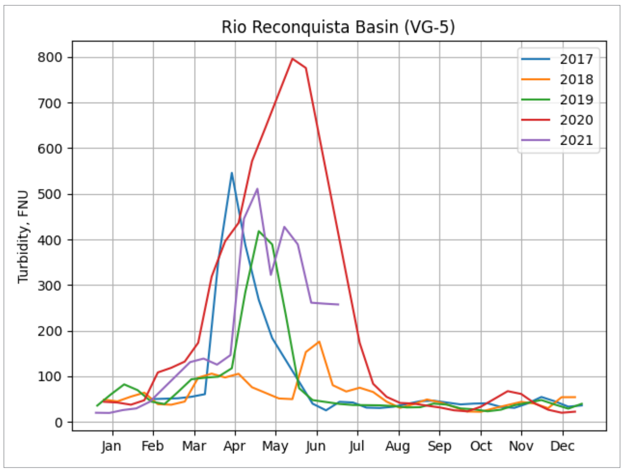

Rio Reconquista Basin (VG-4)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

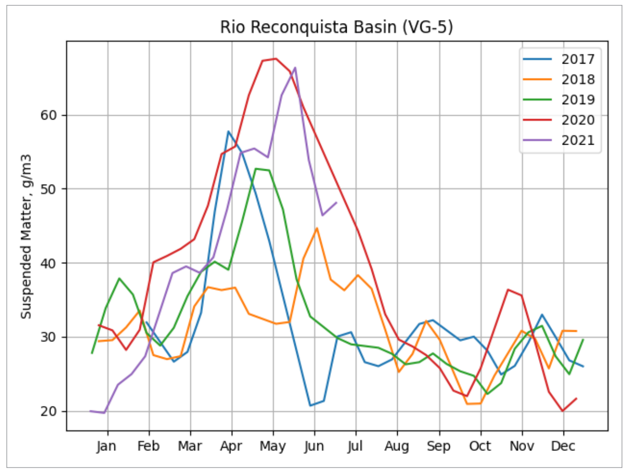

Rio Reconquista Basin (VG-4)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Rio Reconquista Basin (VG-4)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Rio Reconquista Basin (VG-5)

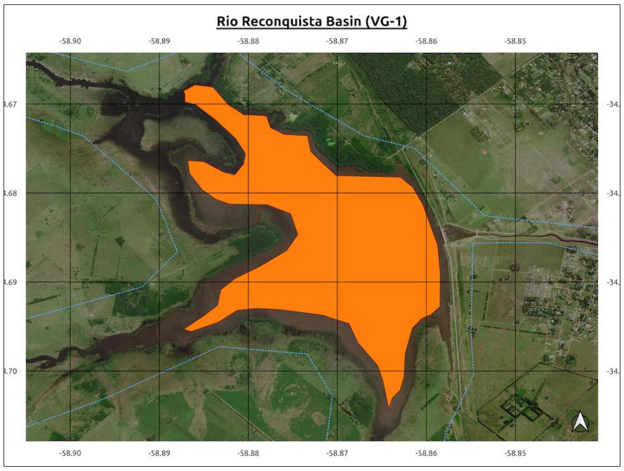

Rio Reconquista Basin (VG-5)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

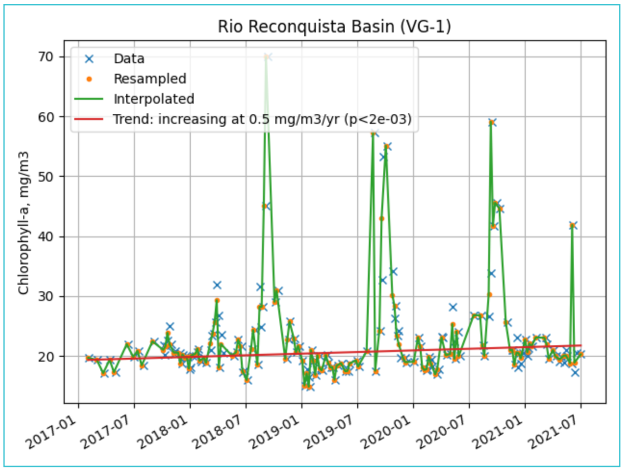

Rio Reconquista Basin (VG-5)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

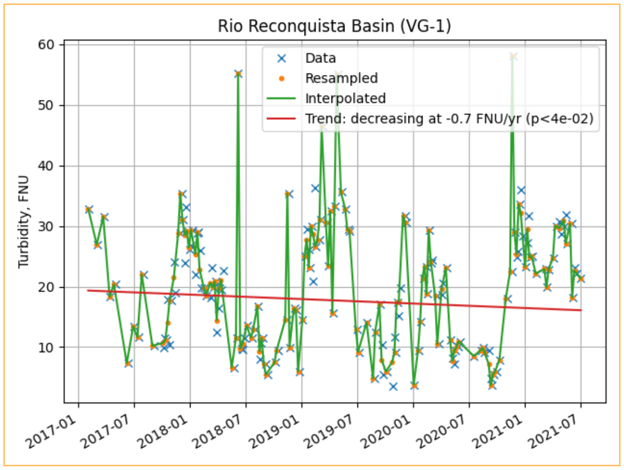

Rio Reconquista Basin (VG-5)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

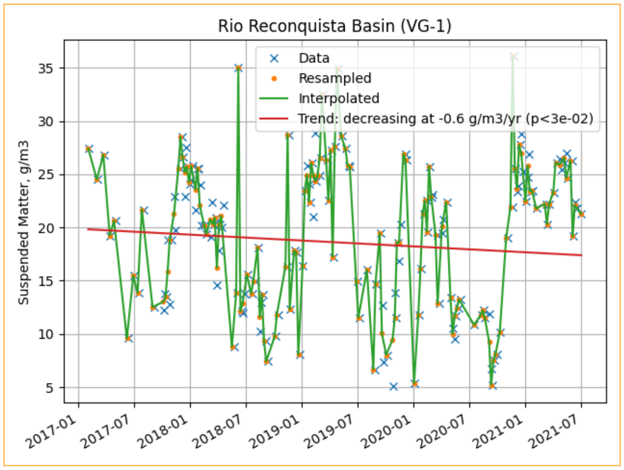
3. Long term trend analysis

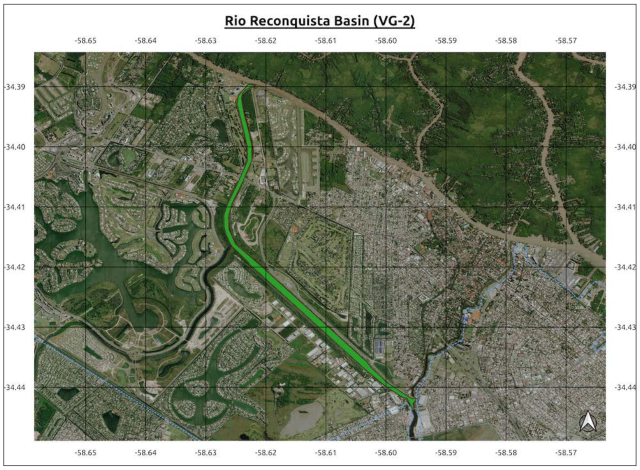
We apply a seasonally adjusted Mann-Kendall Trend Test to Virtual Gauge locations. First, the median water quality parameter value is calculated across a Virtual Gauge location for each image date. Then, a Mann-Kendall test is applied to the full archival time series which provides the direction, magnitude, and statistical significance of potential trends at that location. The outcome indicates whether the time series data at that location has a consistent increasing or decreasing trend.

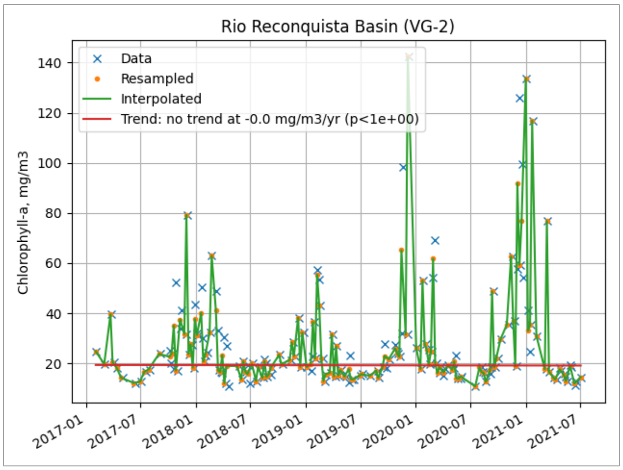


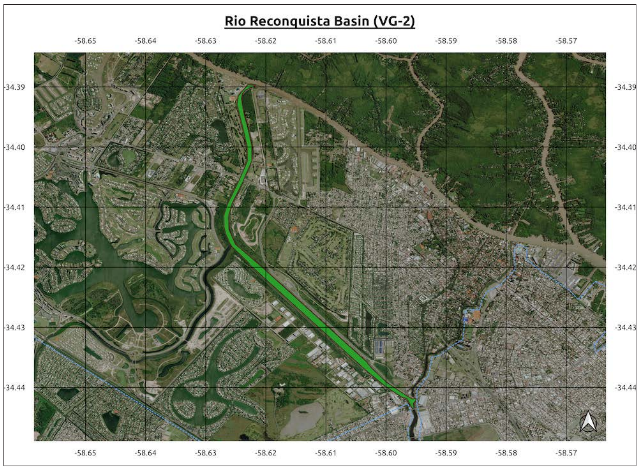


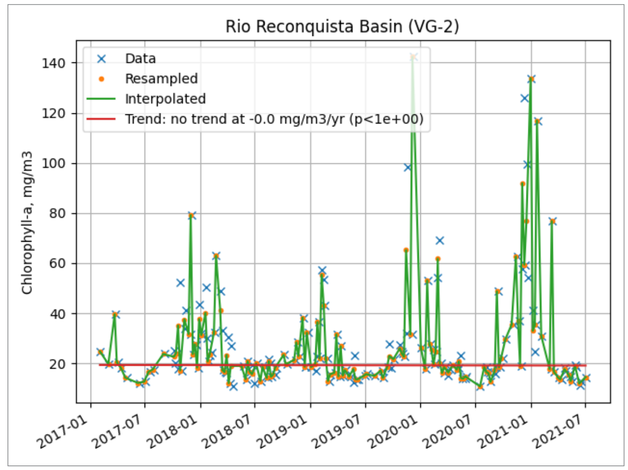


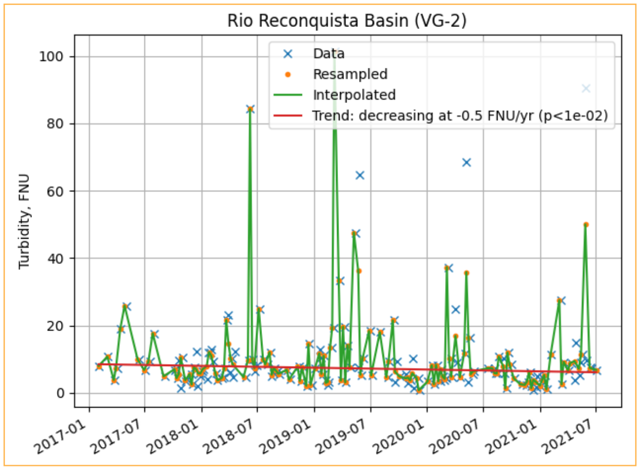


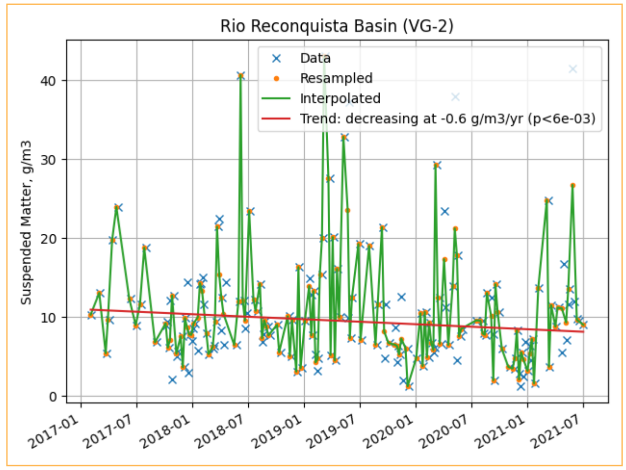


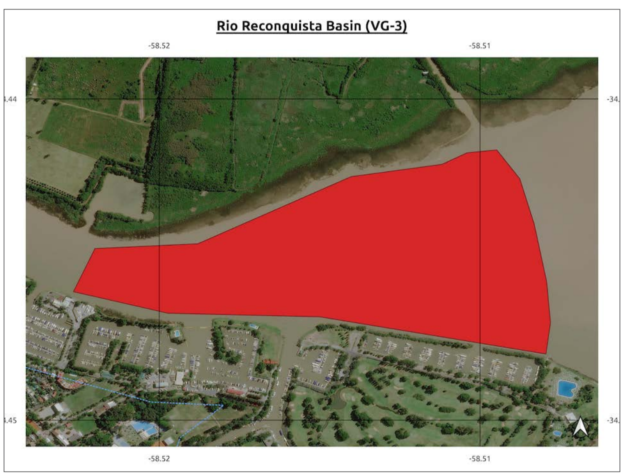


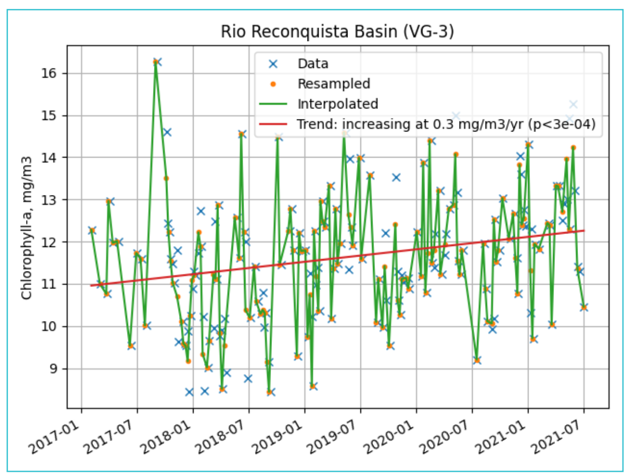

Rio Reconquista Basin (VG-2)

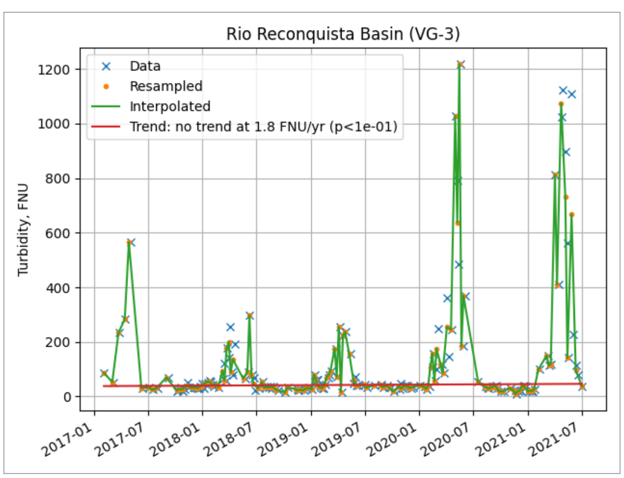

Rio Reconquista Basin (VG-2)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: no trend at -0.0 mg/m3/yr (p<1e+00)

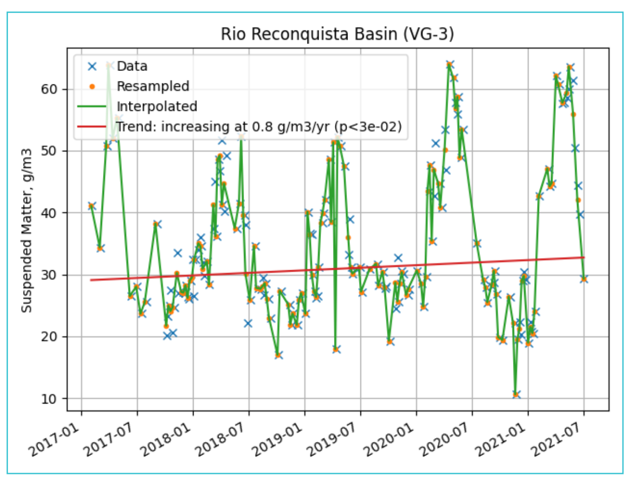

Rio Reconquista Basin (VG-2)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: decreasing at -0.5 FNU/yr (p<1e-02)

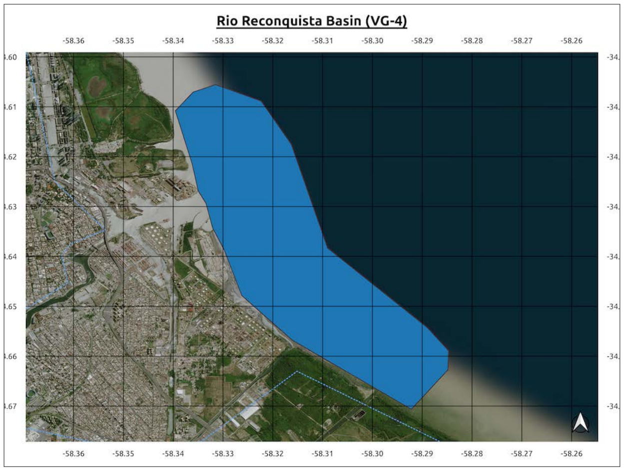

Rio Reconquista Basin (VG-2)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: decreasing at -0.6 g/m3/yr (p<6e-03)

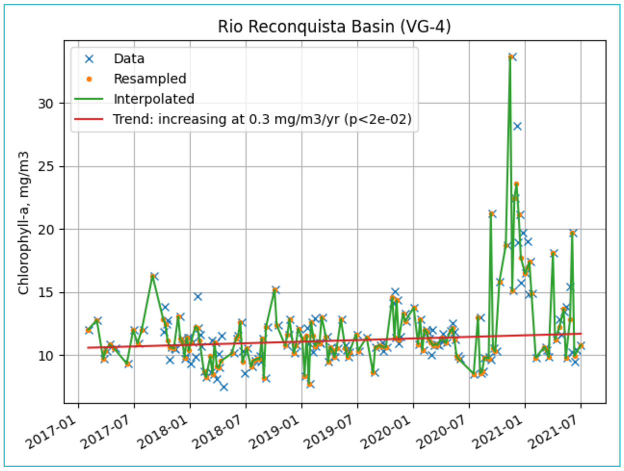

Rio Reconquista Basin (VG-3)

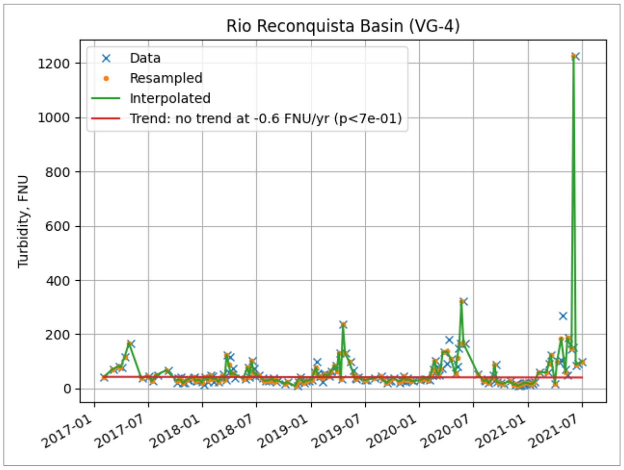

Rio Reconquista Basin (VG-3)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: increasing at 0.3 mg/m3/yr (p<3e-04)

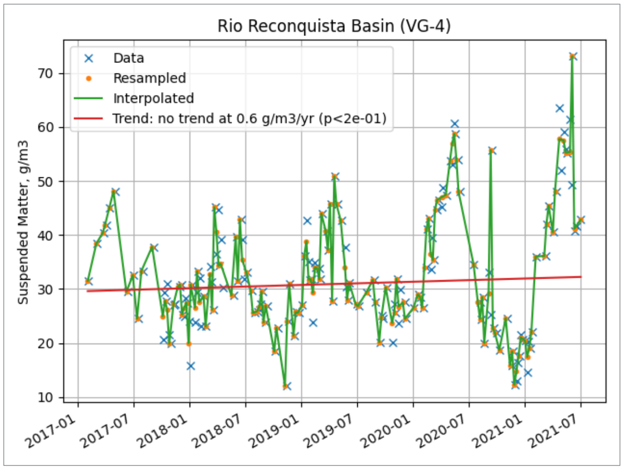

Rio Reconquista Basin (VG-3)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: no trend at 1.8 FNU/yr (p<1e-01)

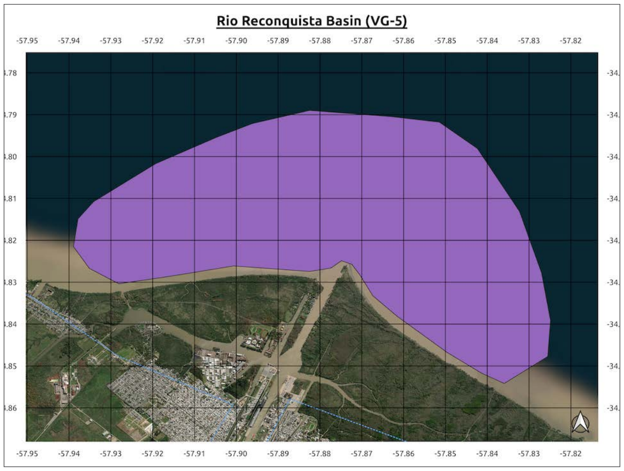

Rio Reconquista Basin (VG-3)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: increasing at 0.8 g/m3/yr (p<3e-02)

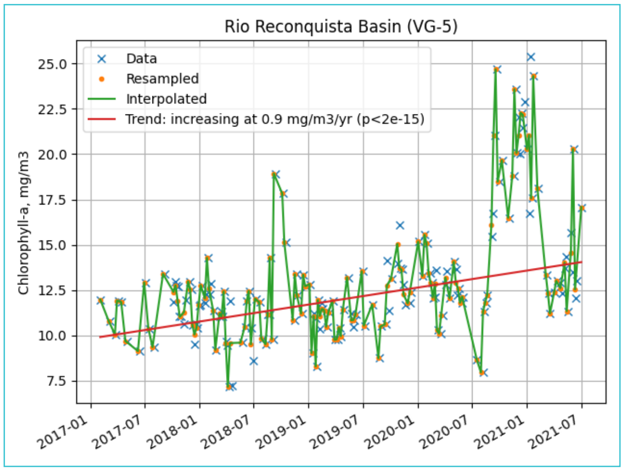

Rio Reconquista Basin (VG-4)

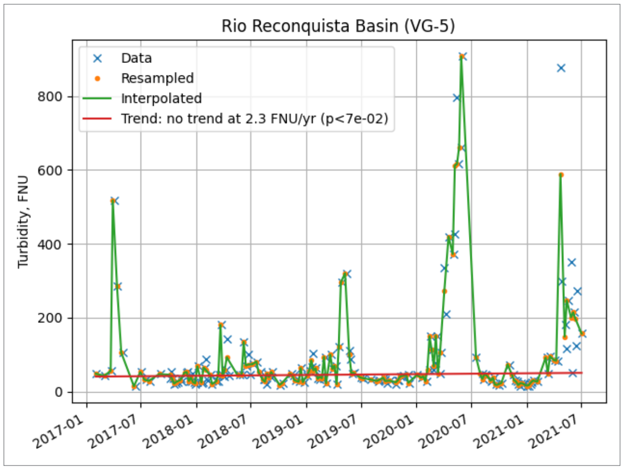

Rio Reconquista Basin (VG-4)
Data
Resampled
Interpolated
Trend: increasing at 0.3 mg/m3/yr (p<2e-02)
Chlorophyll-a, mg/m3

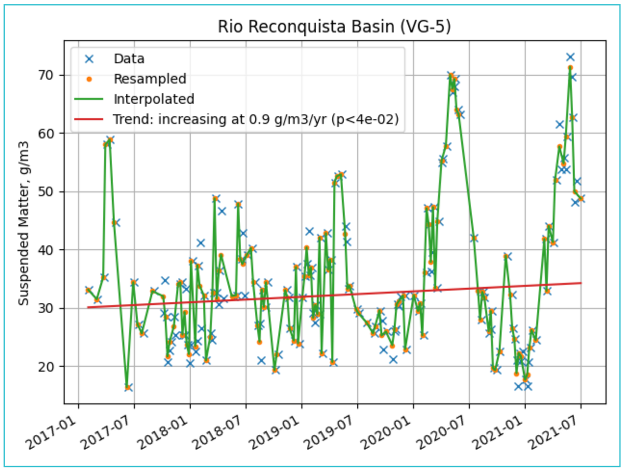

Rio Reconquista Basin (VG-4)
Data
Resampled
Interpolated
Trend: no trend at -0.6 FNU/yr (p<7e-01)
Turbidity, FNU


Rio Reconquista Basin (VG-4)
Data
Resampled
Interpolated
Trend: no trend at 0.6 g/m3/yr (p<2e-01)
Suspended Matter, g/m3


Rio Reconquista Basin (VG-5)


Rio Reconquista Basin (VG-5)
Data
Resampled
Interpolated
Trend: increasing at 0.9 mg/m3/yr (p<2e-15)
Chlorophyll-a, mg/m3


Rio Reconquista Basin (VG-5)
Data
Resampled
Interpolated
Trend: no trend at 2.3 FNU/yr (p<7e-02)
Turbidity, FNU


Rio Reconquista Basin (VG-5)
Data
Resampled
Interpolated
Trend: increasing at 0.9 g/m3/yr (p<4e-02)
Suspended Matter, g/m3

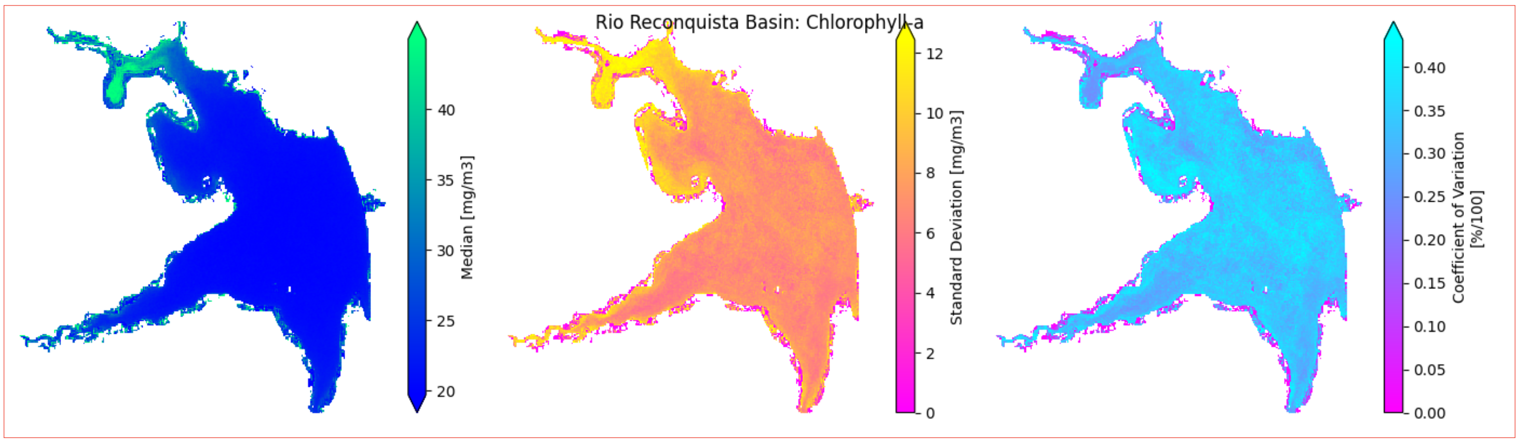
4. Variation Maps

We created Variation Maps for each water body and water quality parameter. This process calculates the median, standard deviation, and coefficient of variation on a pixel-wise basis through time. The product is a map that shows the spatial distribution of these summary statistics through time.

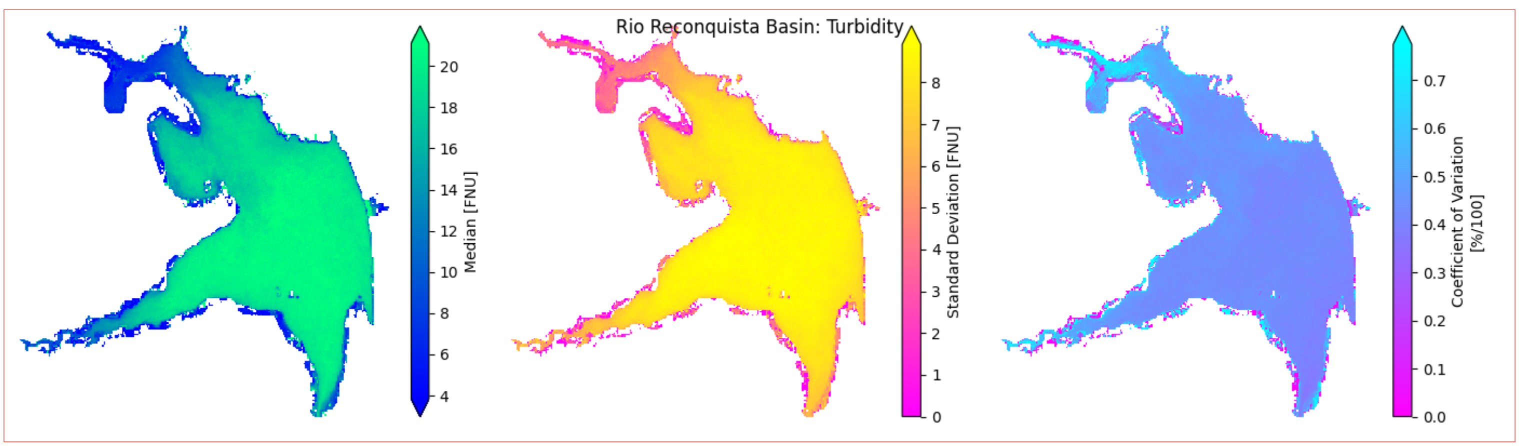
VIRTUAL GAUGE 1
First location of interest

Median | **Standard Deviation** | **Coefficient of Variation**

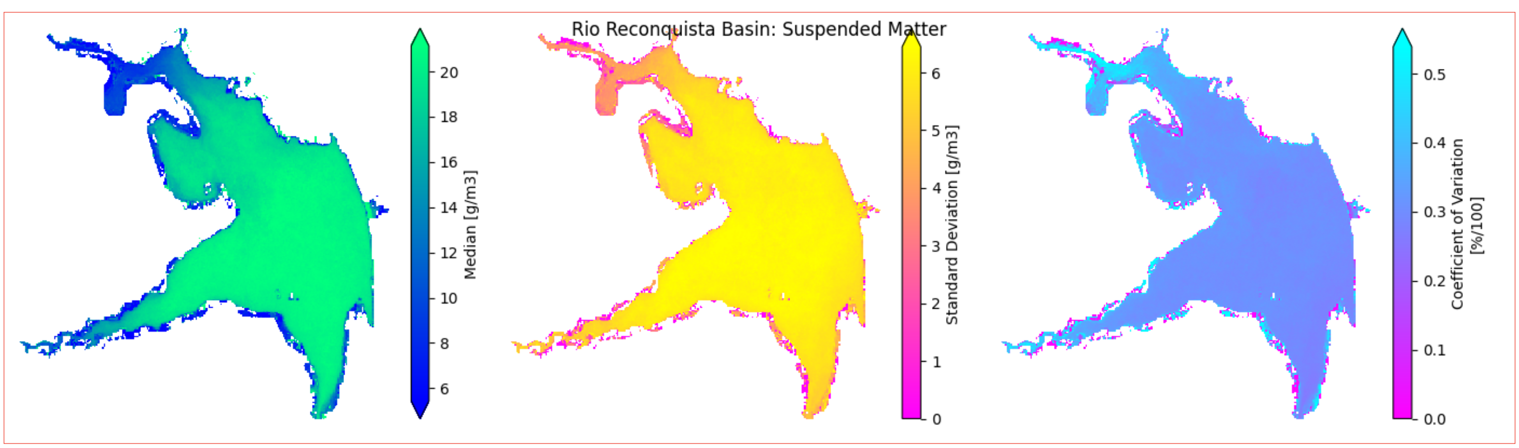
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



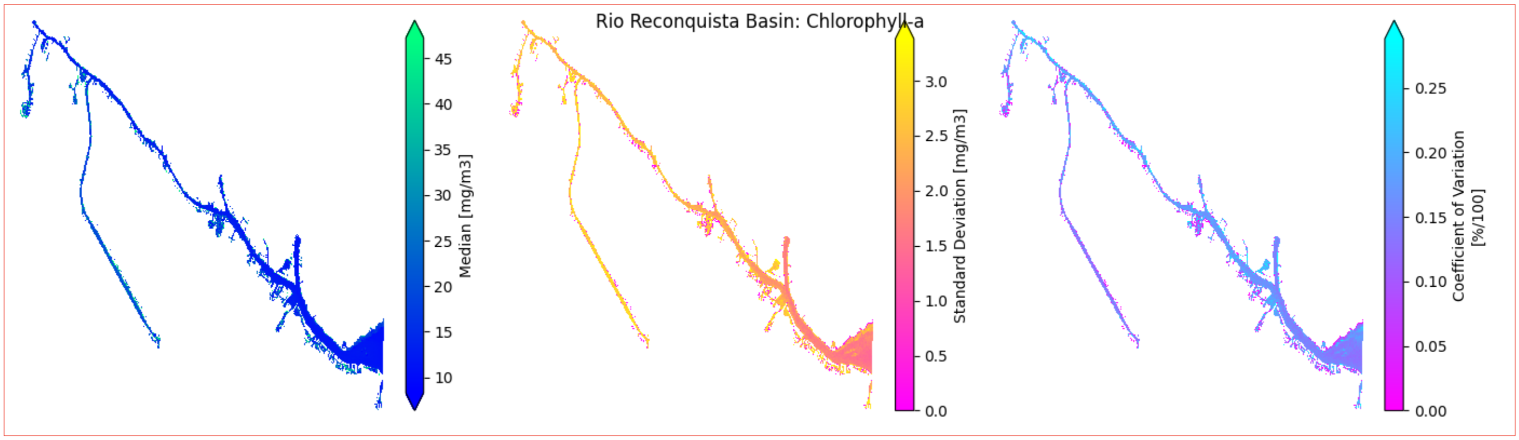
4.3 Suspended Matter [g/m^3]



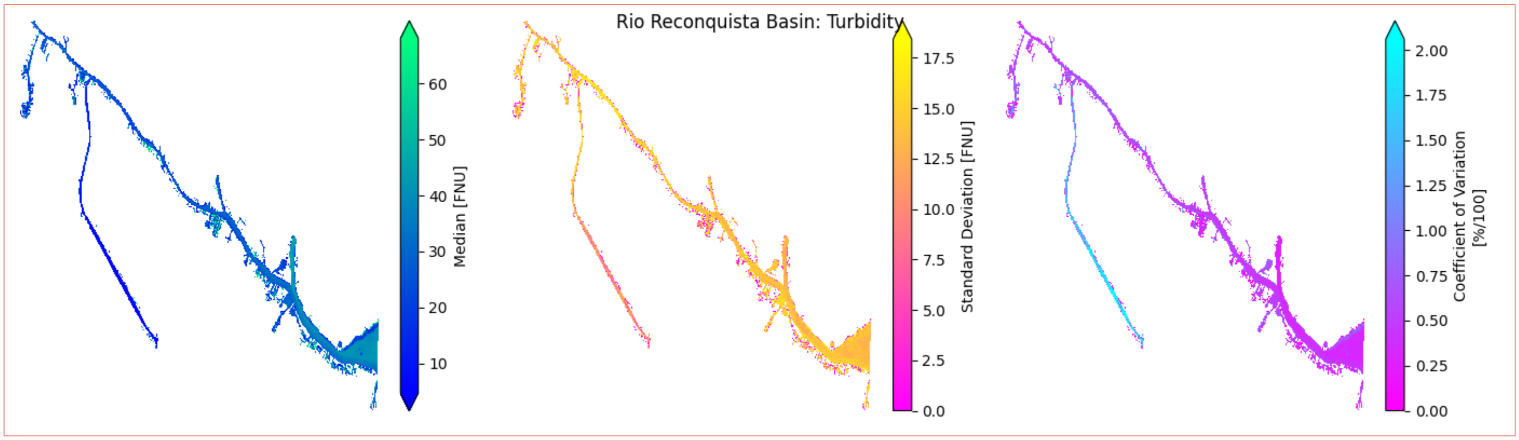
VIRTUAL GAUGE 2 and 3
Second and third locations of interest

Median	Standard Deviation	Coefficient of Variation

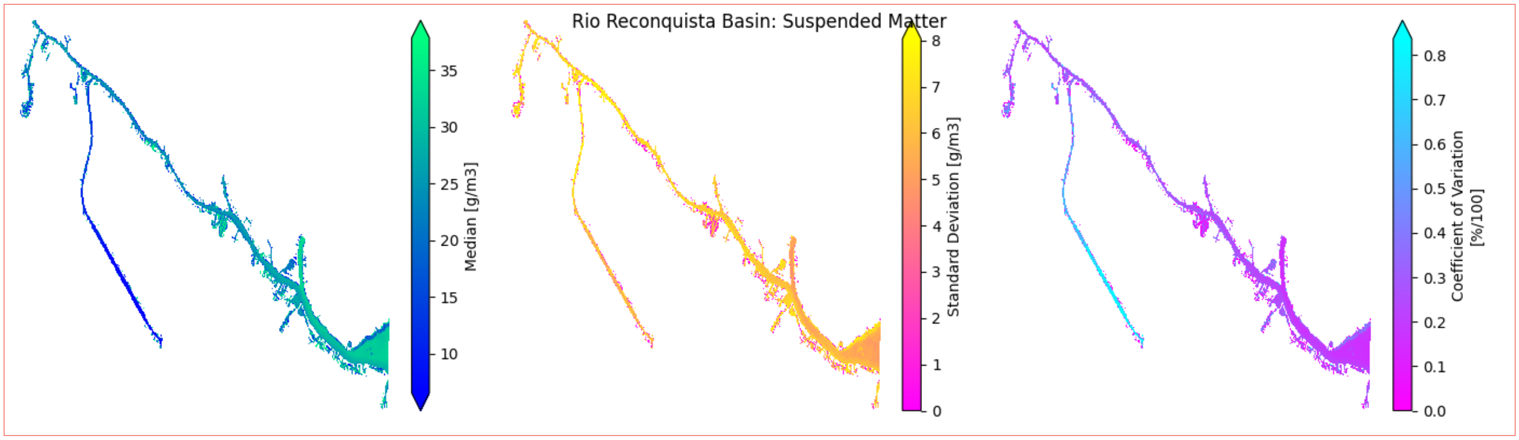
4.1 Chlorophyll-*a* [mg/m³]



4.2 Turbidity [FNU]



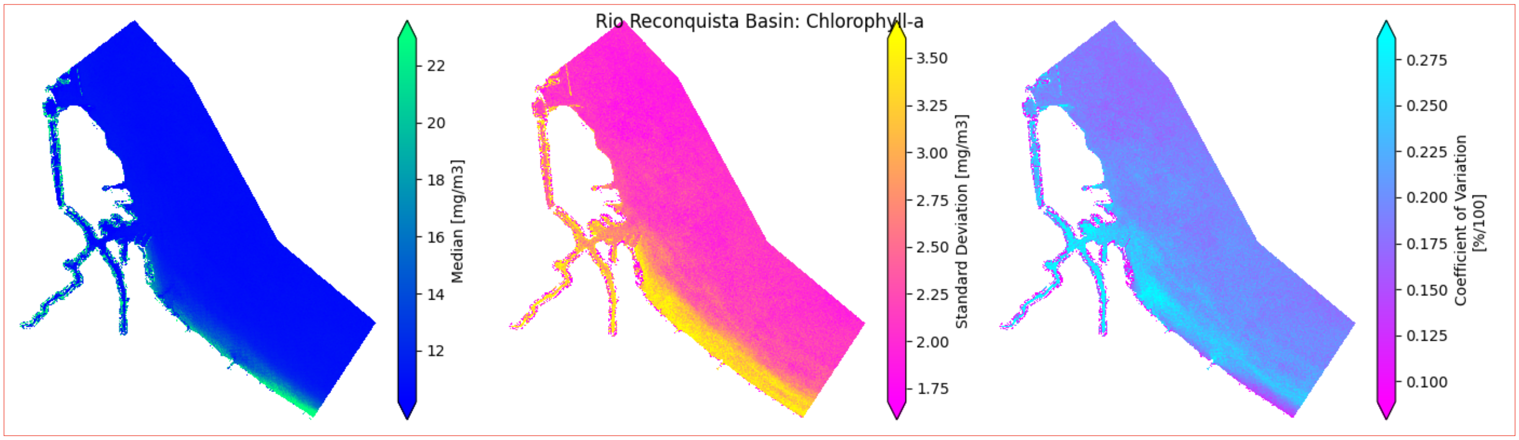
4.3 Suspended Matter [g/m³]



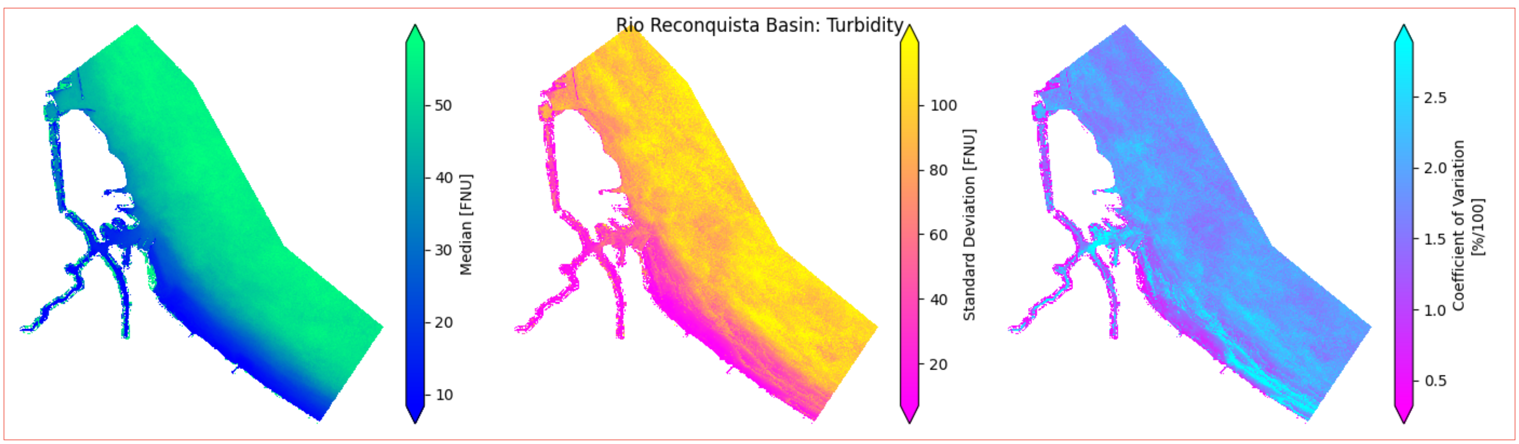
VIRTUAL GAUGE 4
Fourth location of interest

Median | **Standard Deviation** | **Coefficient of Variation**

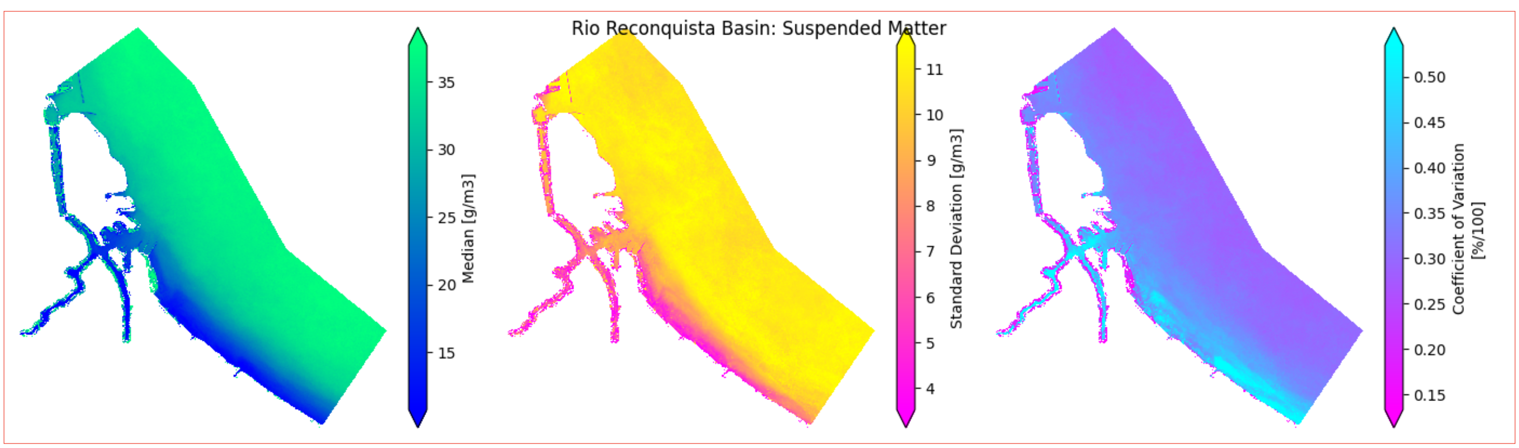
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



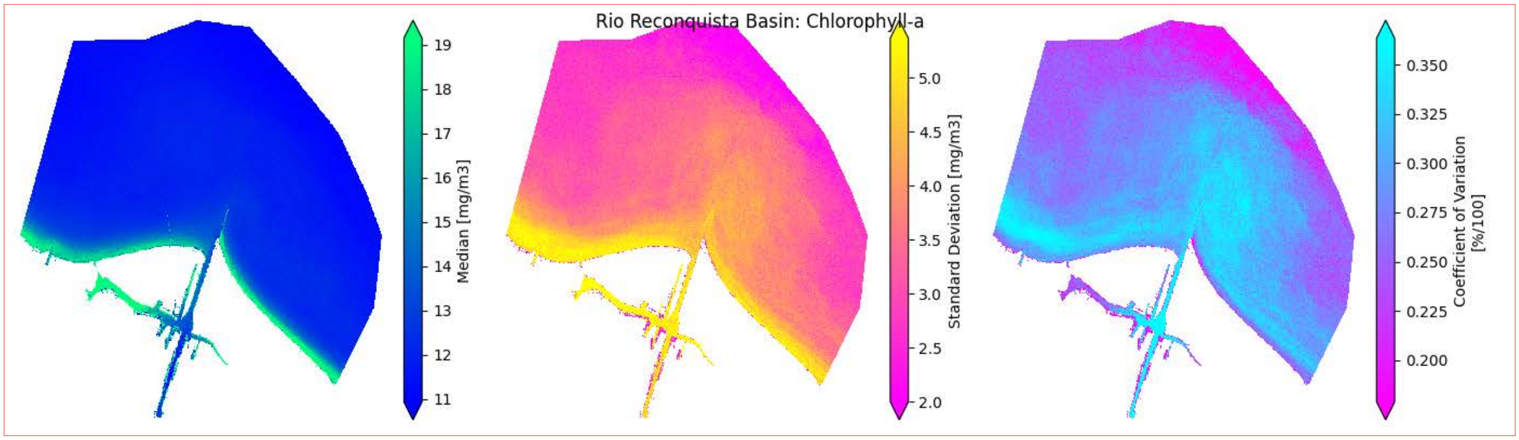
4.3 Suspended Matter [g/m^3]



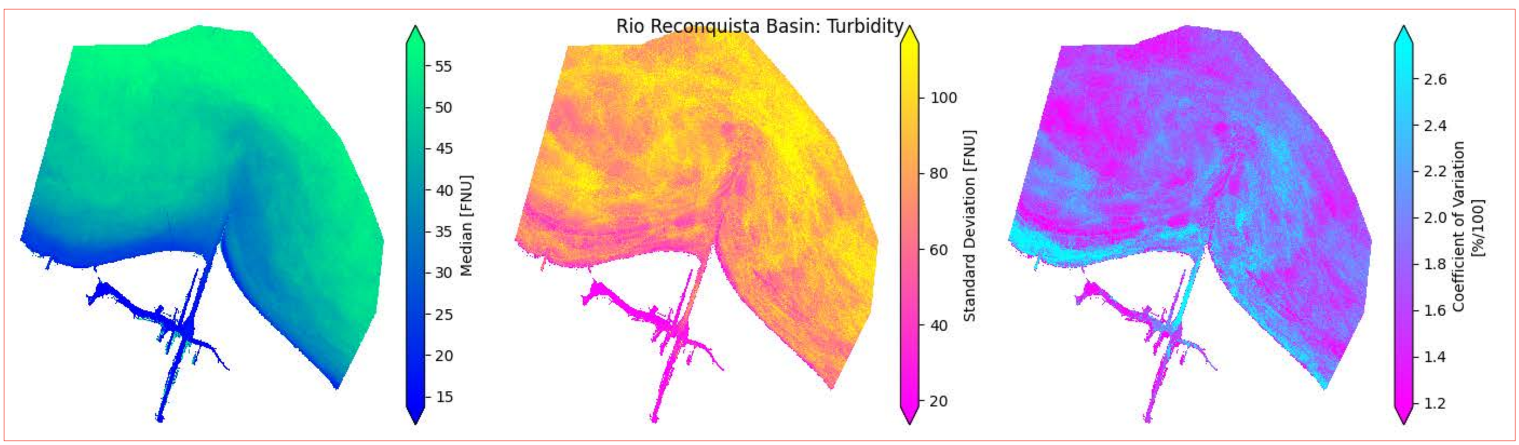
VIRTUAL GAUGE 5
Fifth location of interest

Median **Standard Deviation** **Coefficient of Variation**

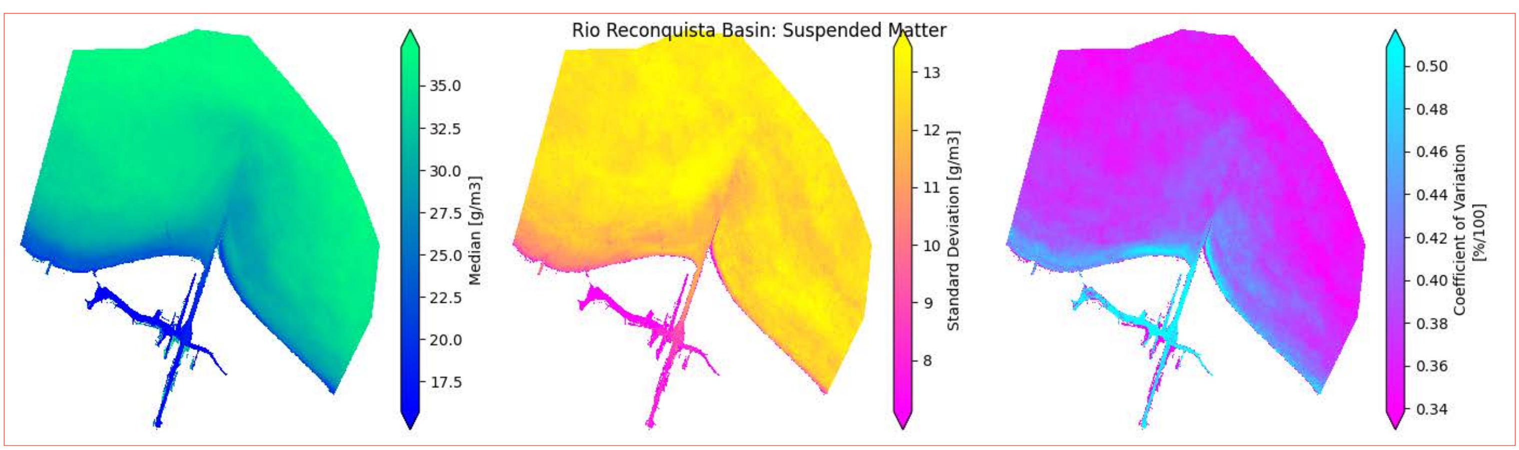
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



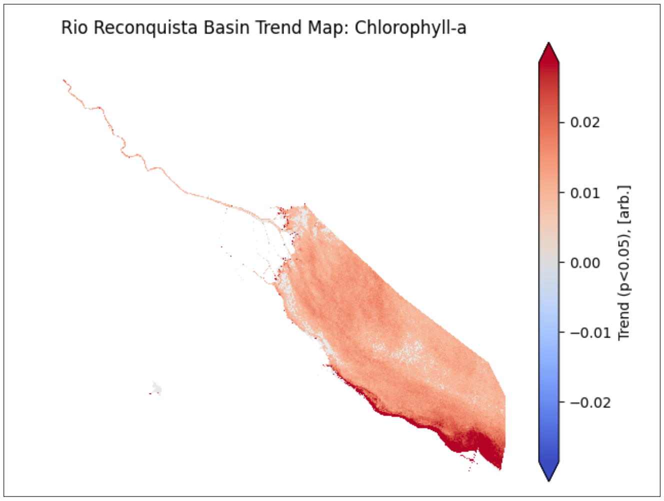
4.3 Suspended Matter [g/m^3]



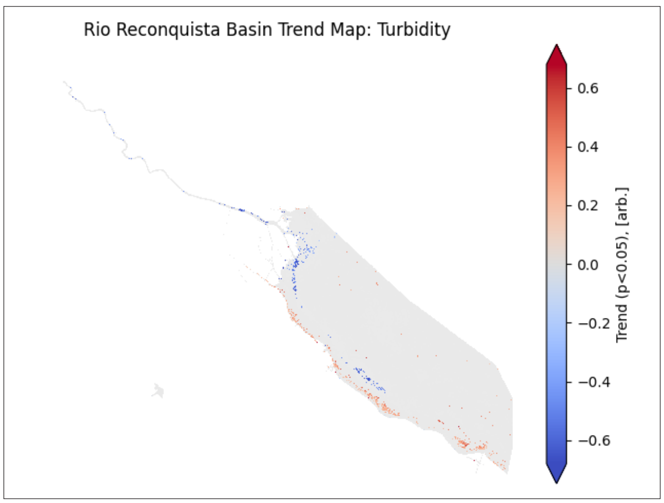
5. Trend Maps

We create Trend Maps to visualize where temporal trends in water quality parameters are occurring. First, data across the entire water body is spatially binned by averaged to approximately 100m resolution. Then, a linear regression is applied along the temporal axis for each bin, a three-sigma outlier filtering process is used to remove outliers. Finally, the linear trends are visualized on a map where statistically significant (p-value below 5%) values are colorized based on direction and intensity.

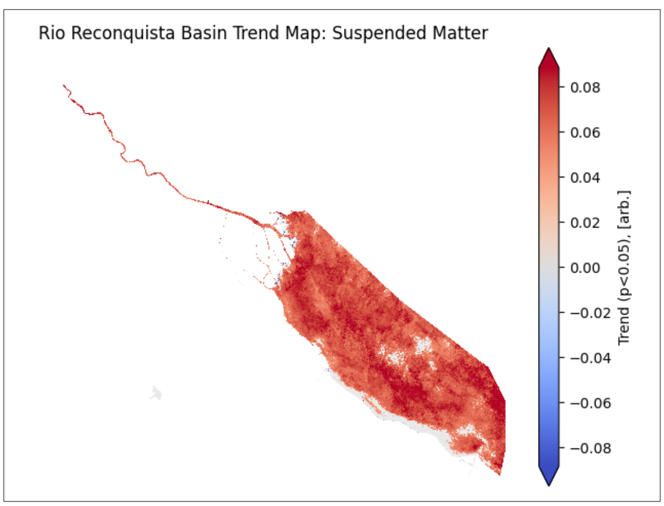
5.1 Chlorophyll-*a*
[mg/m^3]



5.2 Turbidity
[FNU]



5.3 Suspended Matter
[g/m^3]



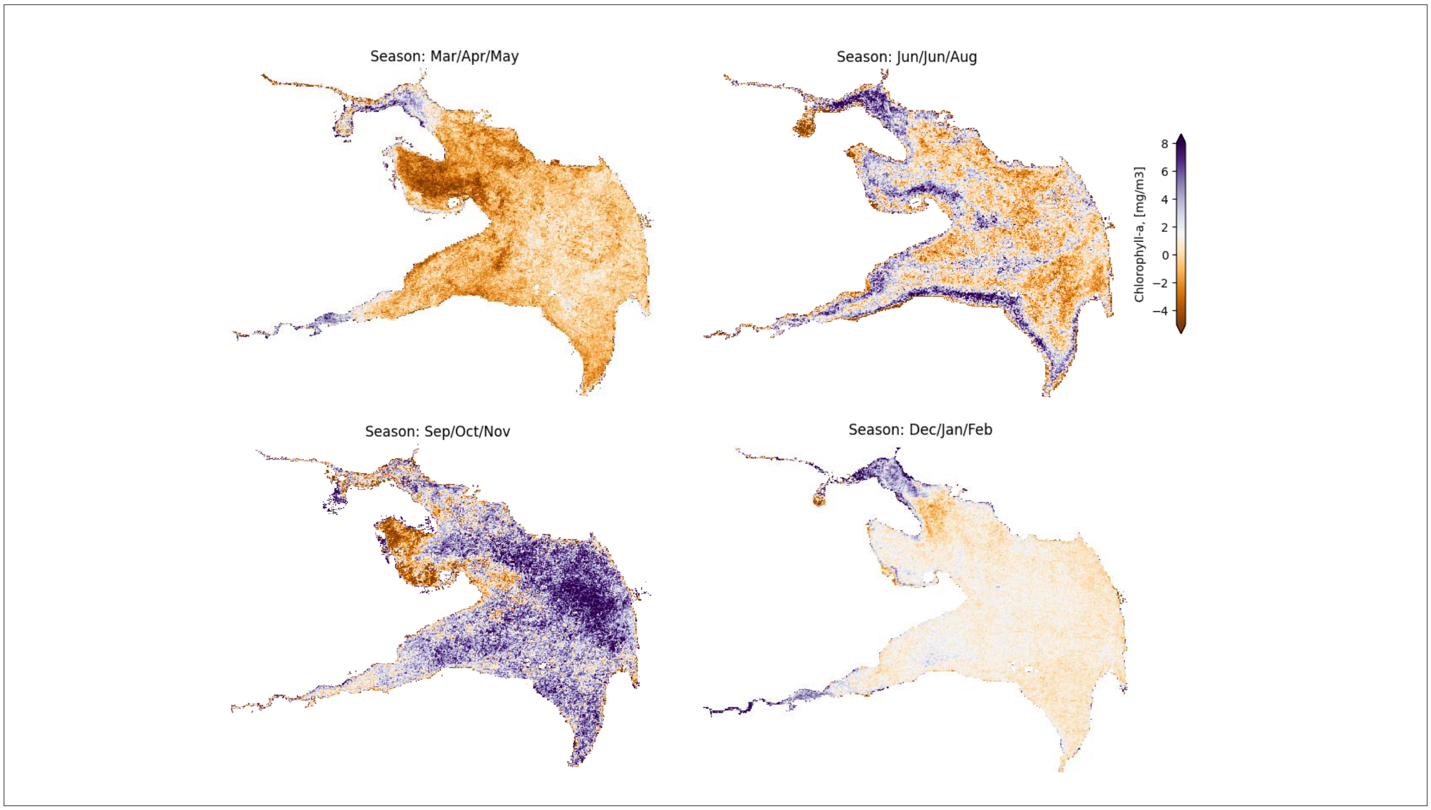
6. Difference Maps

Changes to WQ stemming from Covid-19 lockdown restrictions were assessed using a series of simple one-way analysis of variance (ANOVA) tests. Differences in pre- and post-Covid-19 conditions were tested for at each WQ metric at each virtual gauge location, with pre-Covid-19 lockdown defined as all time series data before March 19, 2020. Both pre- and post-Covid-19 datasets were separated into three-month seasons, with tests performed on each season to control for seasonal variations. Significant differences between conditions were recorded with a ‘p-value’ less than 0.05.

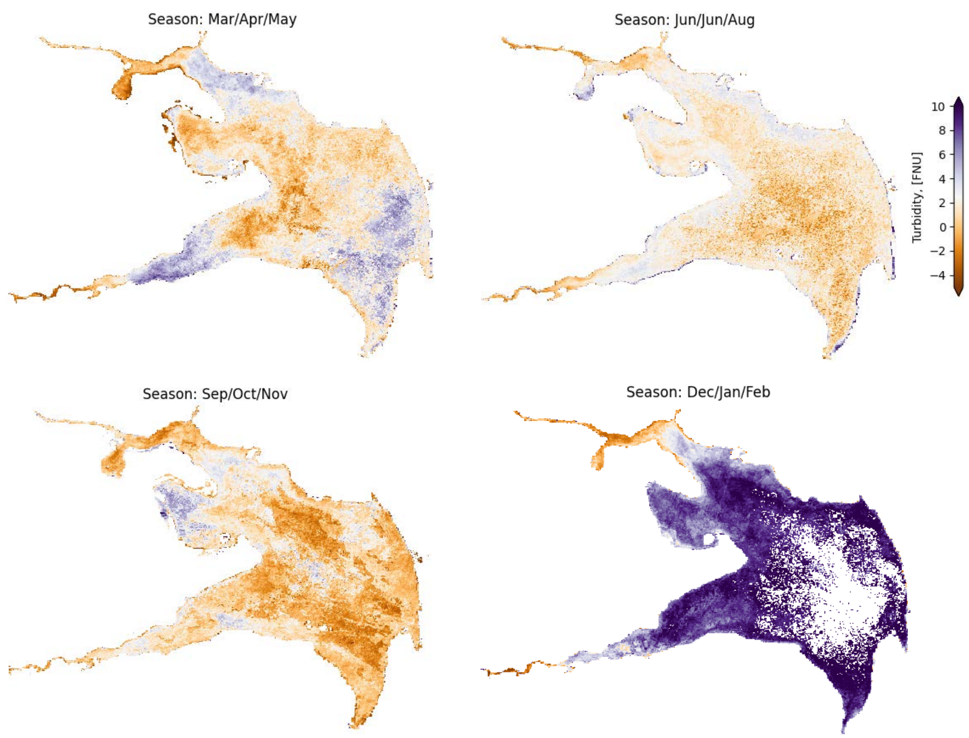
Separately, an assessment of Covid-19 lockdown related differences in WQ was conducted across the entire water body to illustrate general trends not associated with virtual gauge locations. For this, pixel-wise differences were calculated across the entire water body using images downsampled to 30 m pixels. The resulting images illustrate where changes in WQ are observable.

VIRTUAL GAUGE 1
First location of interest

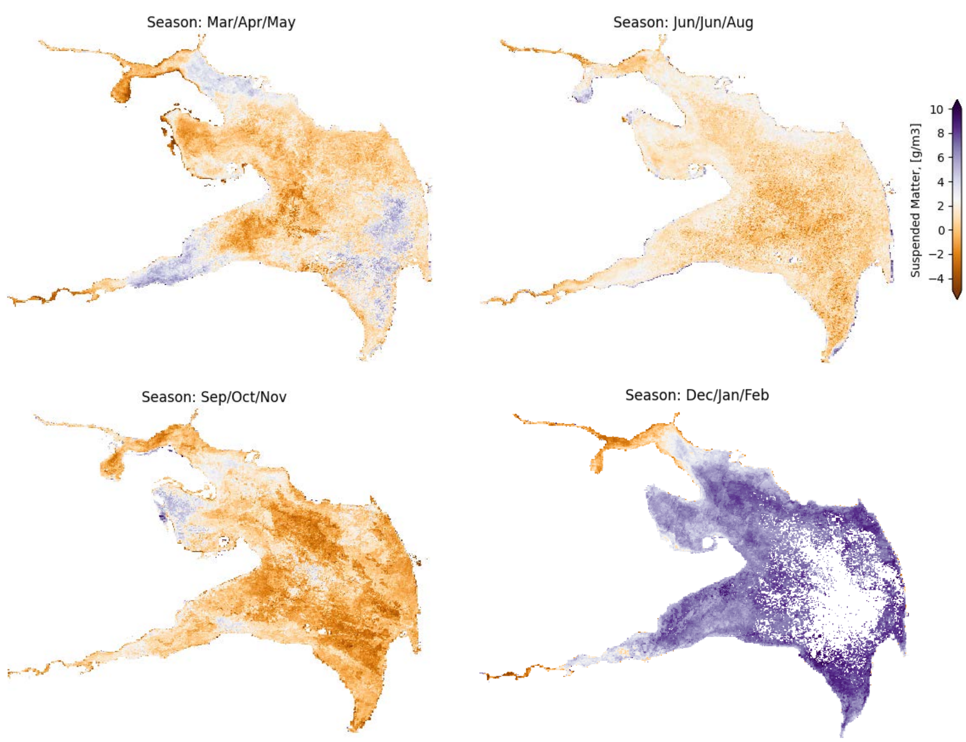
Chlorophyll-*a* [mg/m^3]



6.2 Turbidity [FNU]

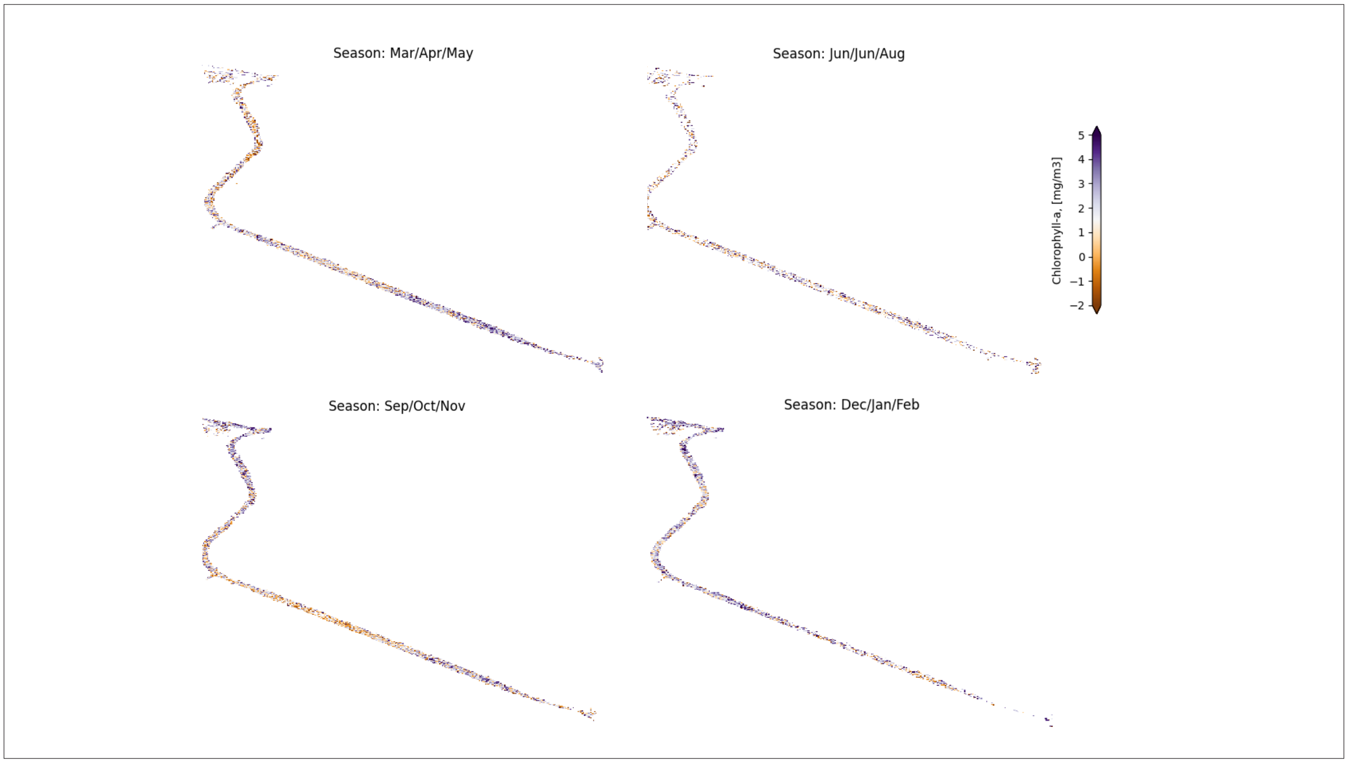


6.3 Suspended Matter [g/m³]

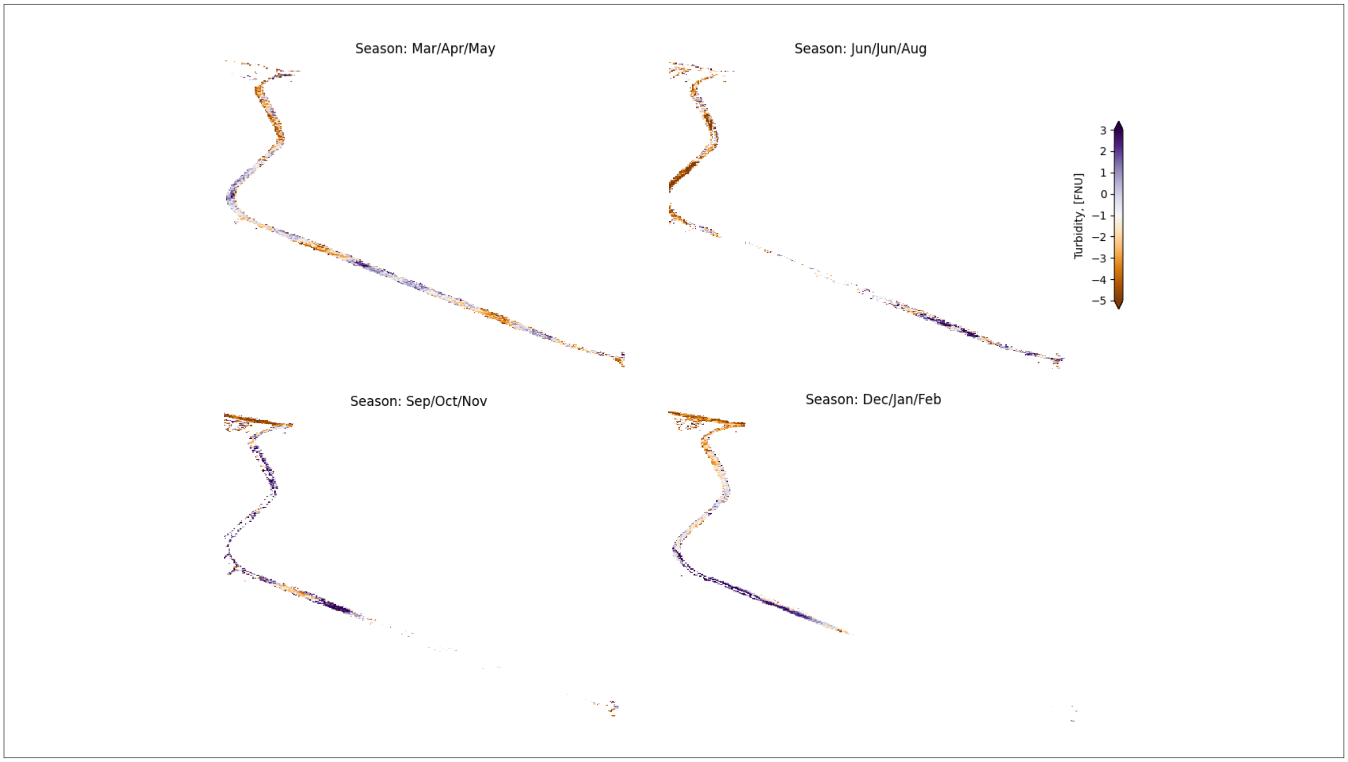


VIRTUAL GAUGE 2
Second location of interest

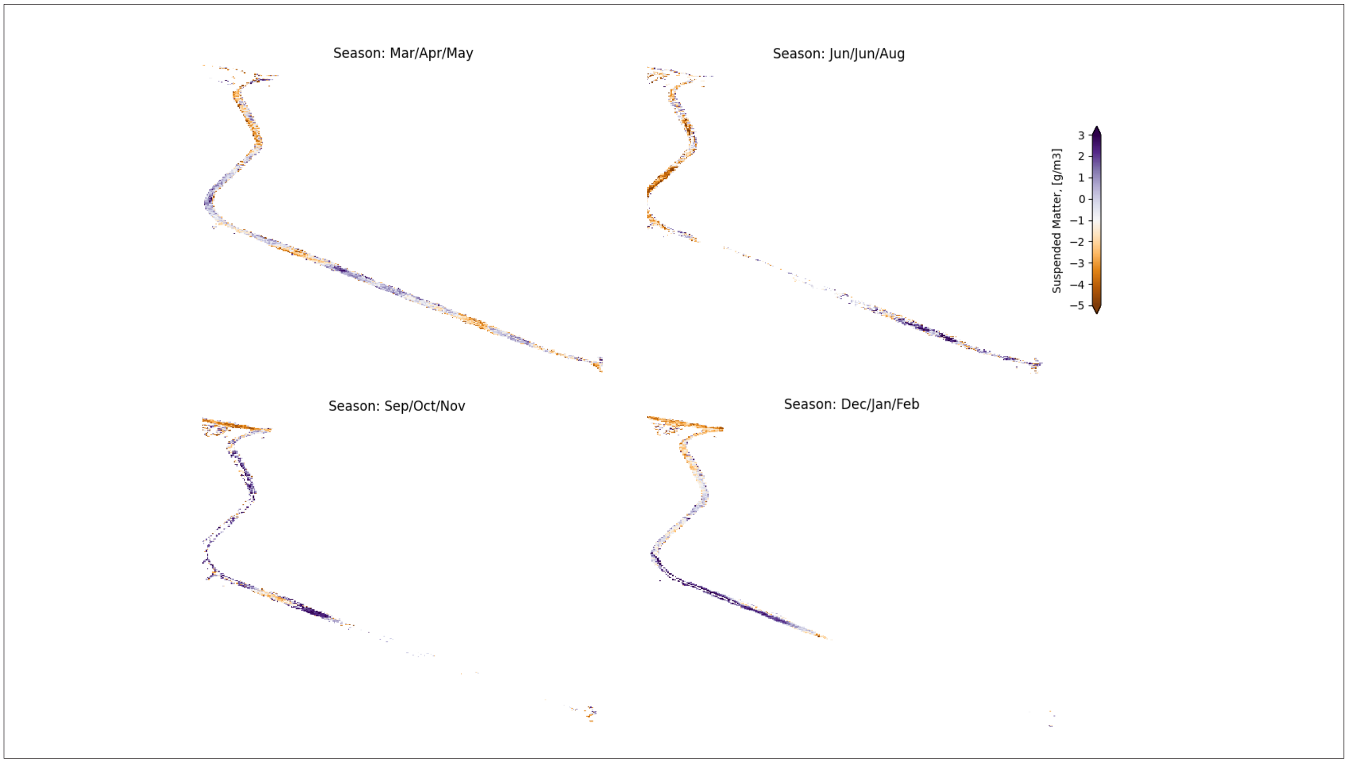
Chlorophyll-*a* [mg/m³]



Turbidity [FNU]

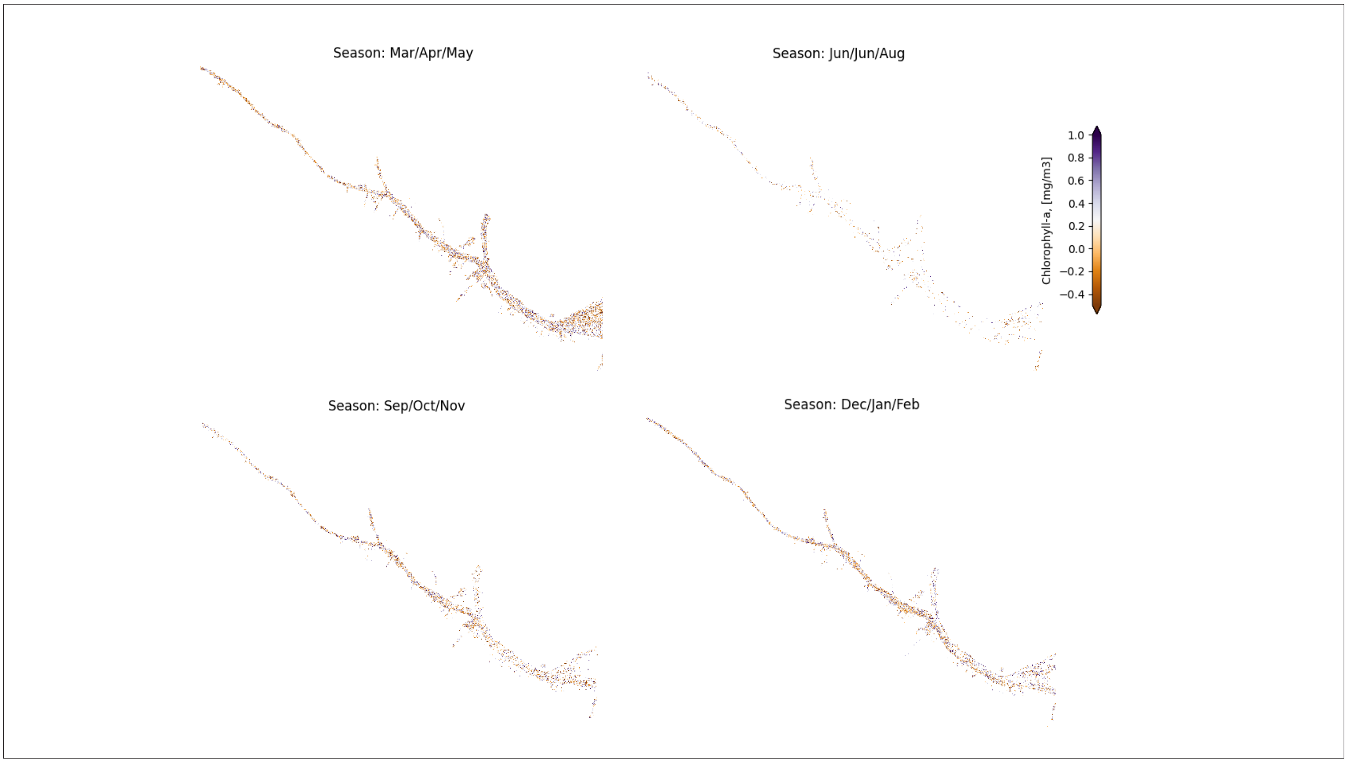


Suspended Matter [g/m³]

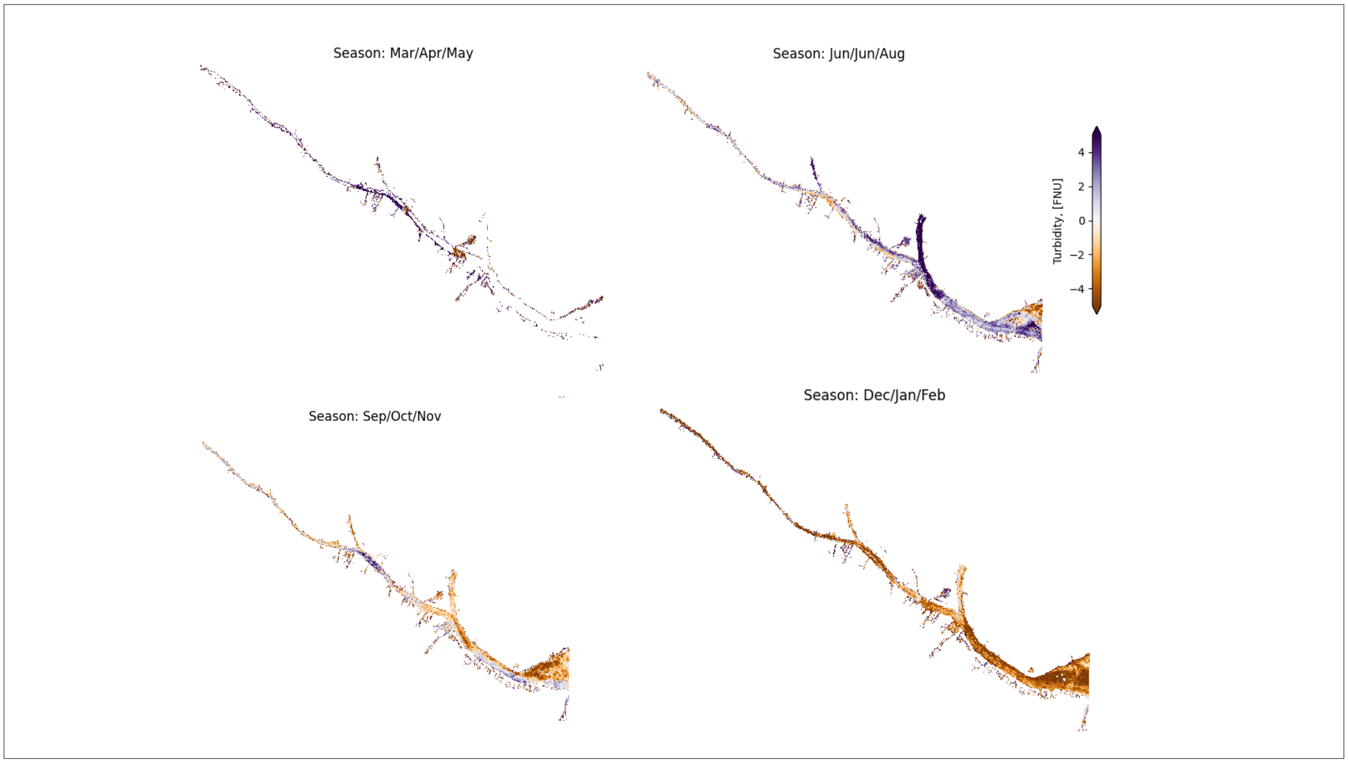


VIRTUAL GAUGE 3

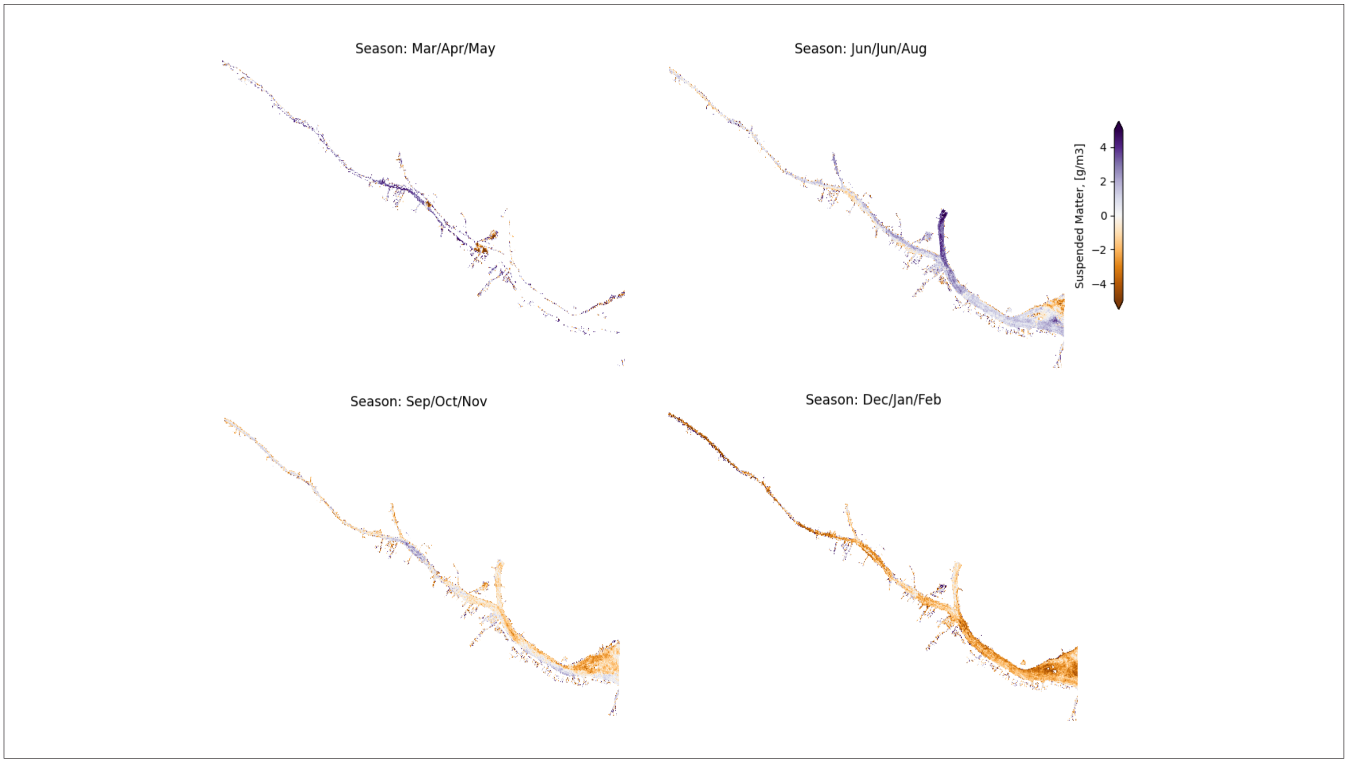
Chlorophyll-*a* [mg/m³]



Turbidity [FNU]

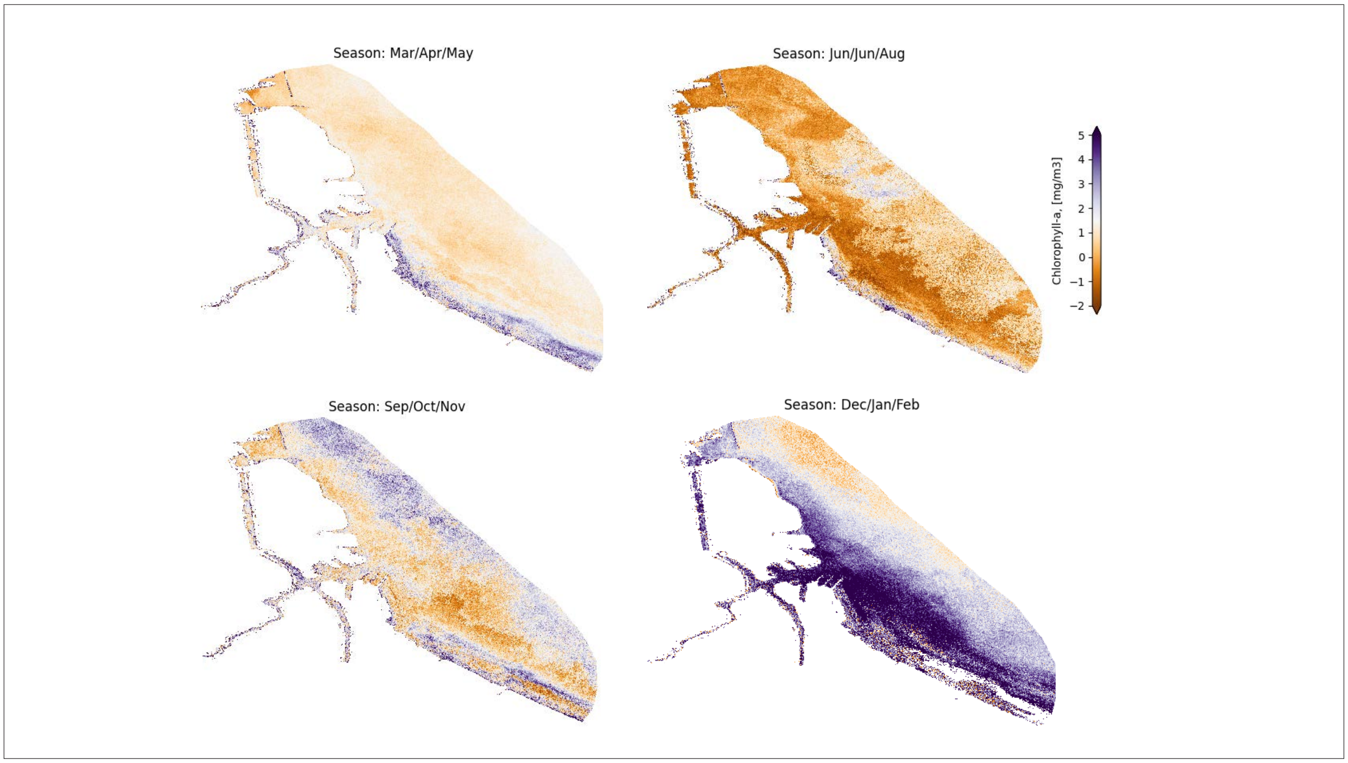


Suspended Matter [g/m³]

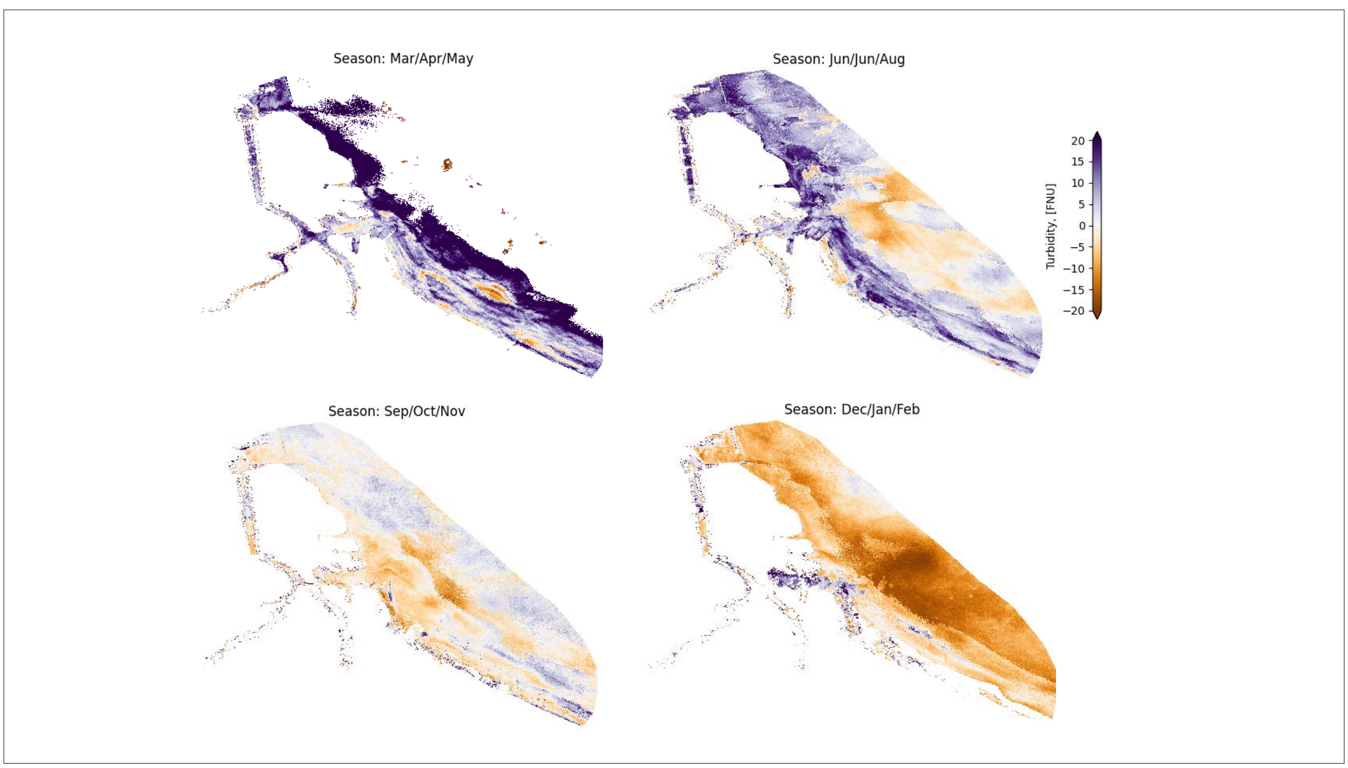


VIRTUAL GAUGE 4

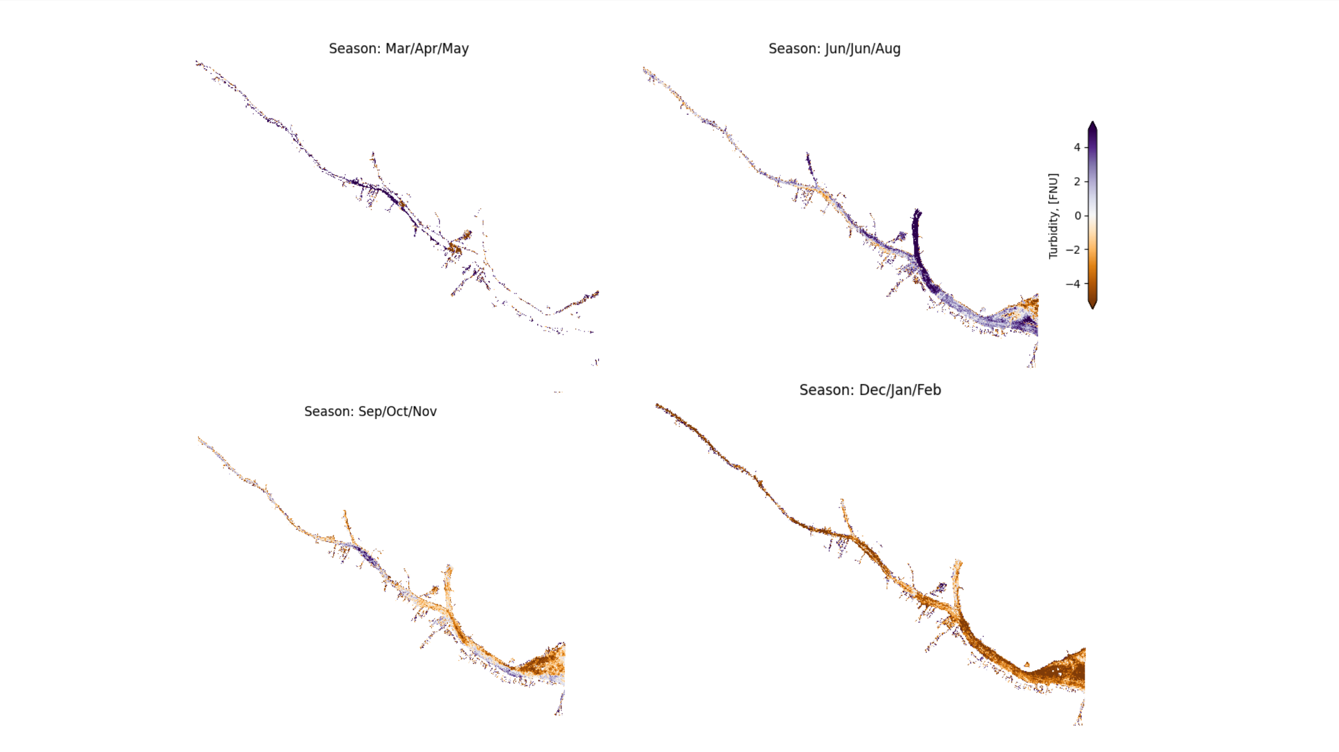
Chlorophyll-*a* [mg/m³]



Turbidity [FNU]

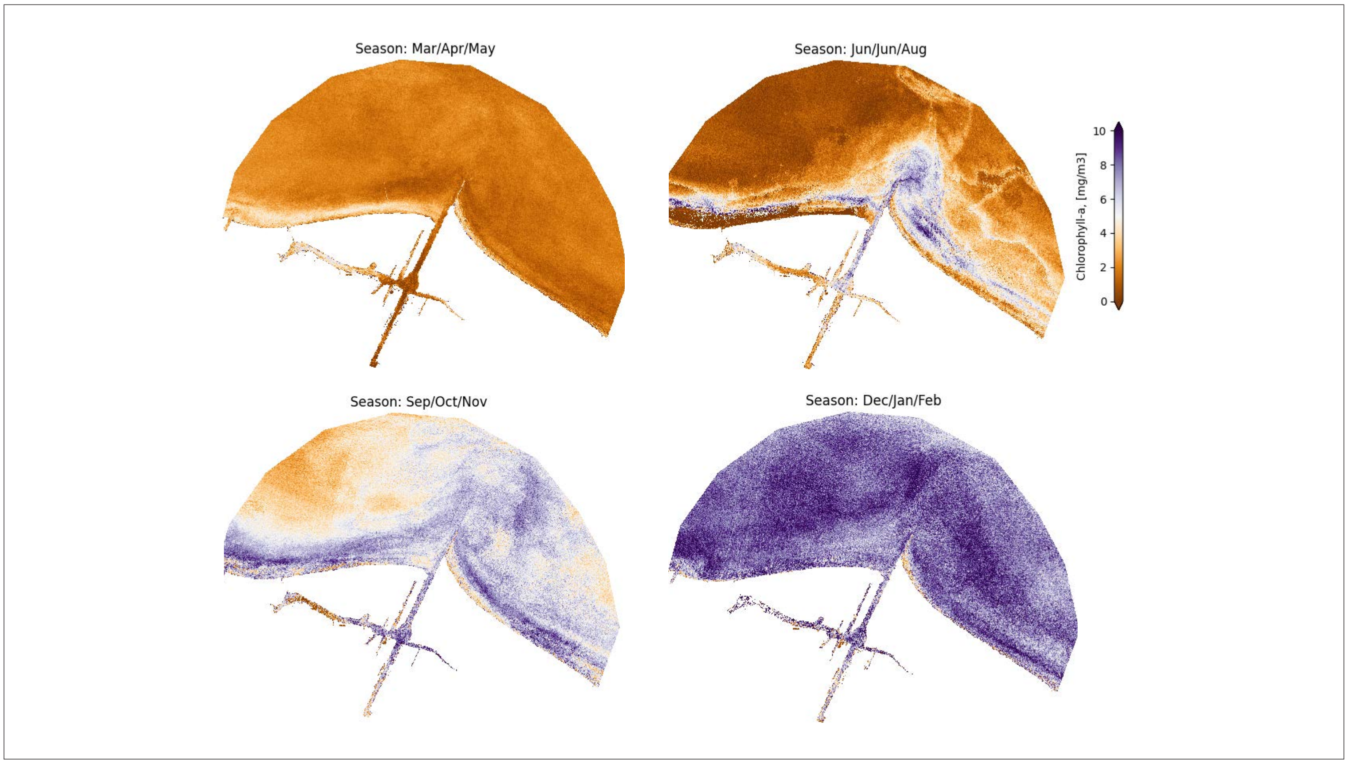


Suspended Matter [g/m³]

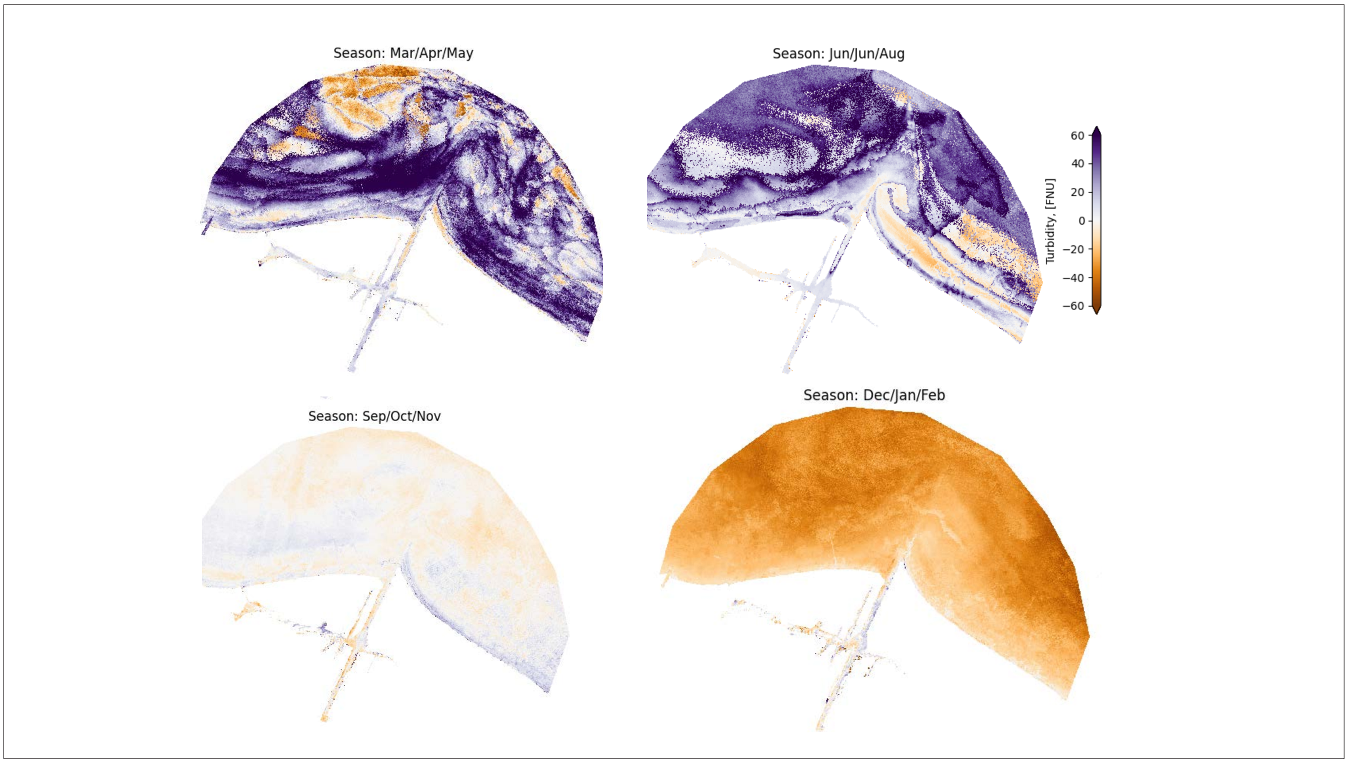


VIRTUAL GAUGE 5

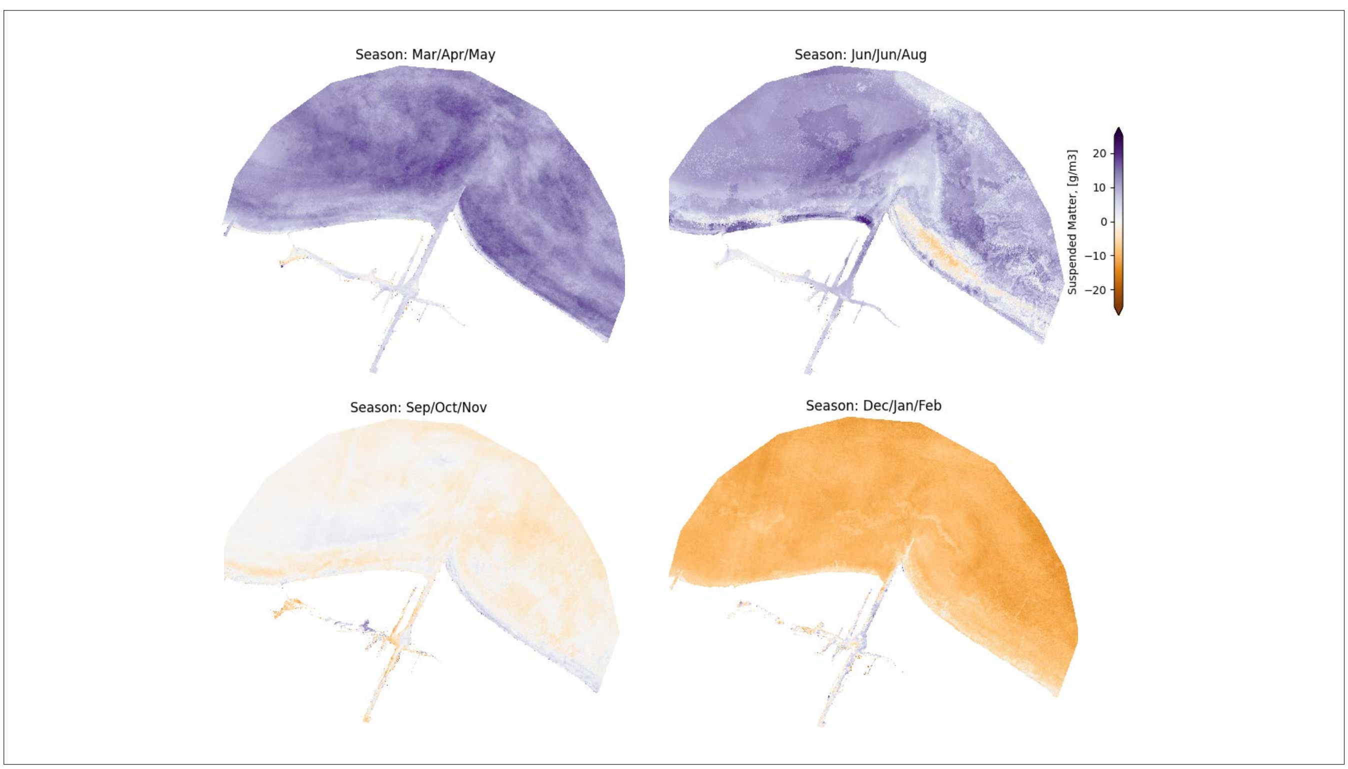
Chlorophyll-*a* [mg/m³]



Turbidity [FNU]



Suspended Matter [g/m³]



APPENDIX A4 Lake Titicaca

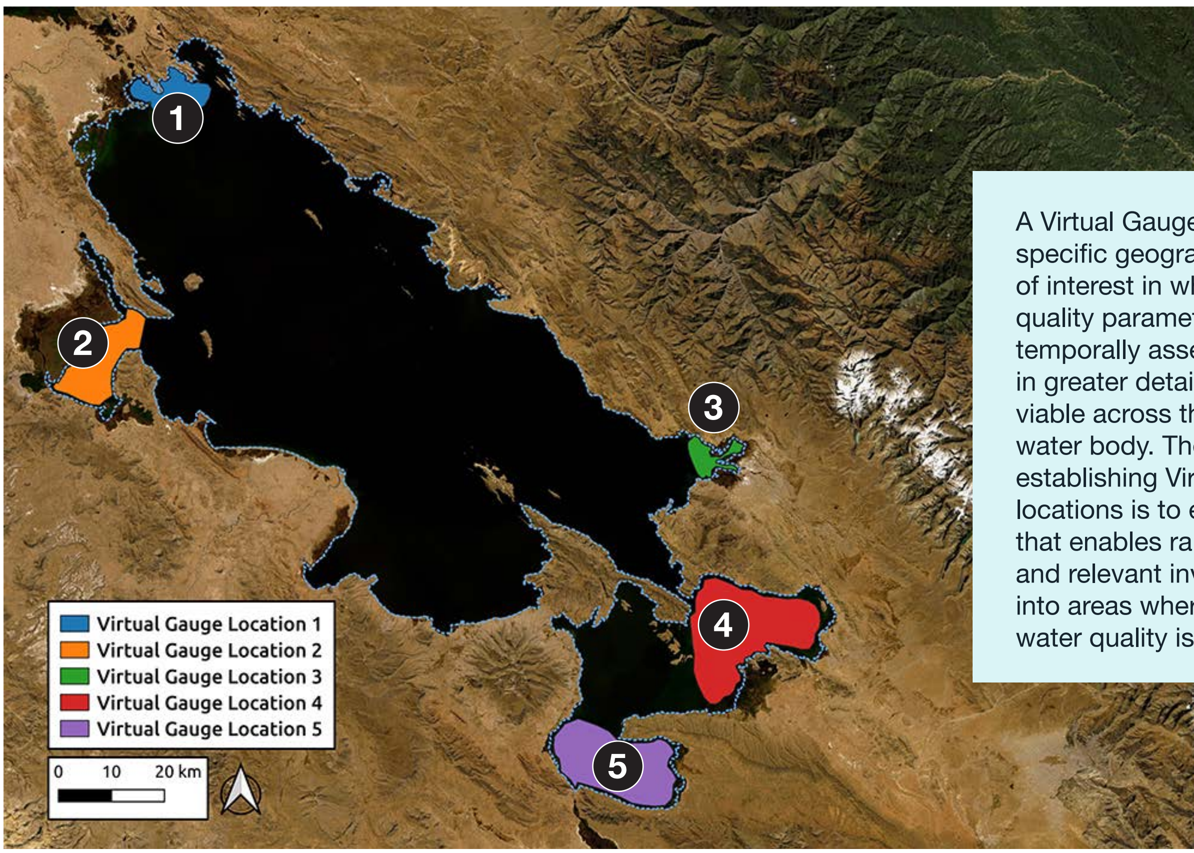
APPENDIX A4

LAKE TITICACA

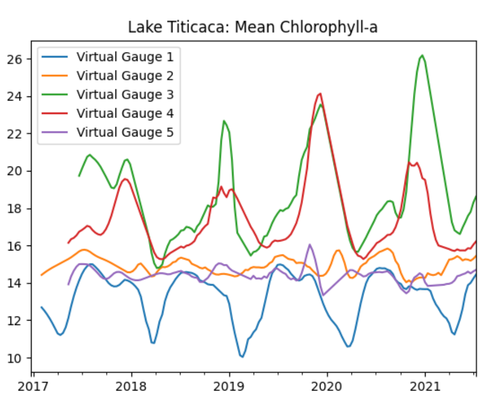
1. Virtual Gauges

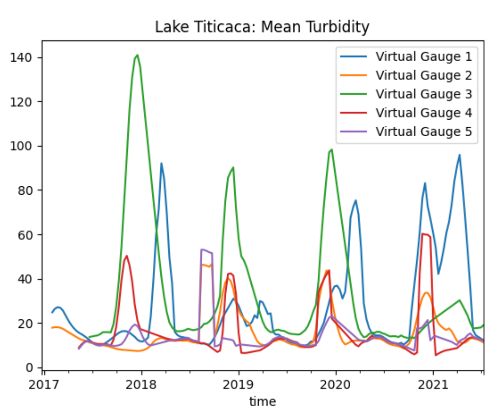
Change over time at key locations across the reservoir

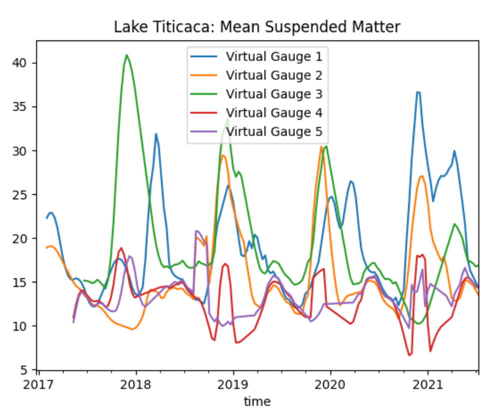
From 2016 to today, at all 5 locations of interest at Lake Titicaca.



A Virtual Gauge is a specific geographic region of interest in which water quality parameters are temporally assessed in greater detail than viable across the entire water body. The goal of establishing Virtual Gauge locations is to extract data that enables rapid, flexible, and relevant investigation into areas where known water quality issues exist.





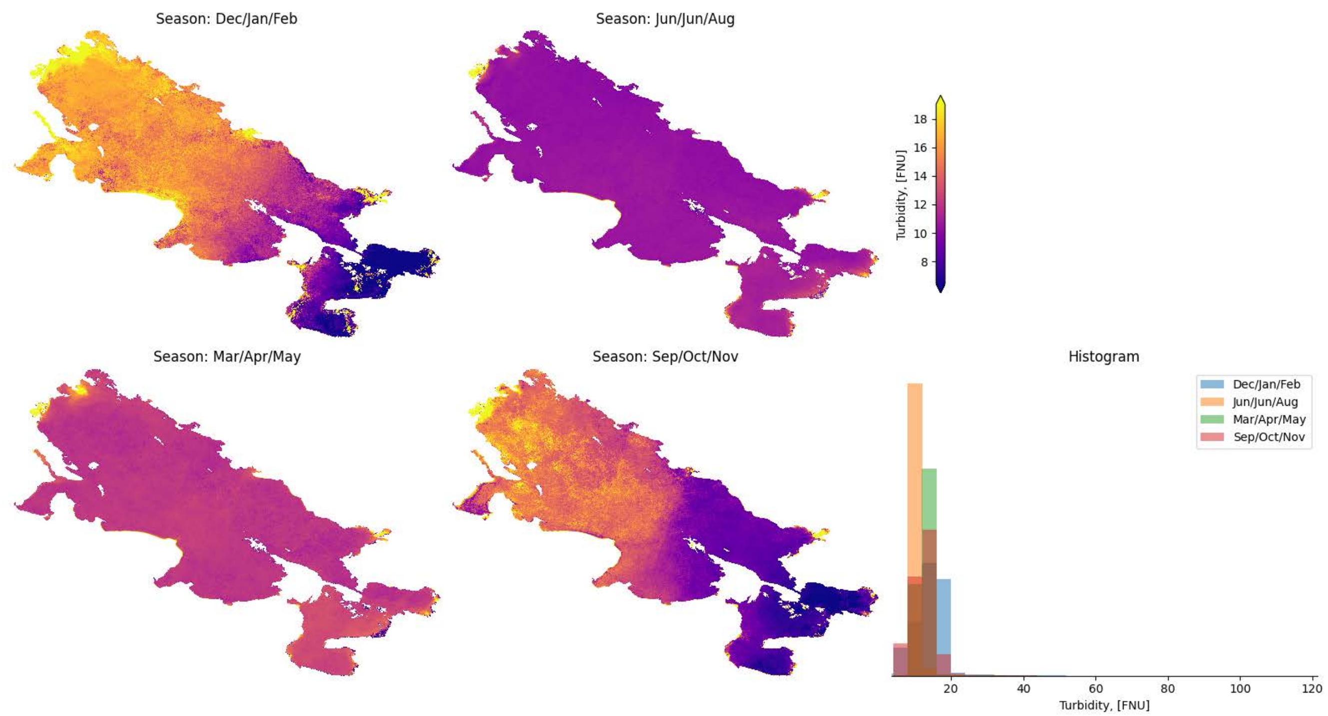


2. Seasonal Trends

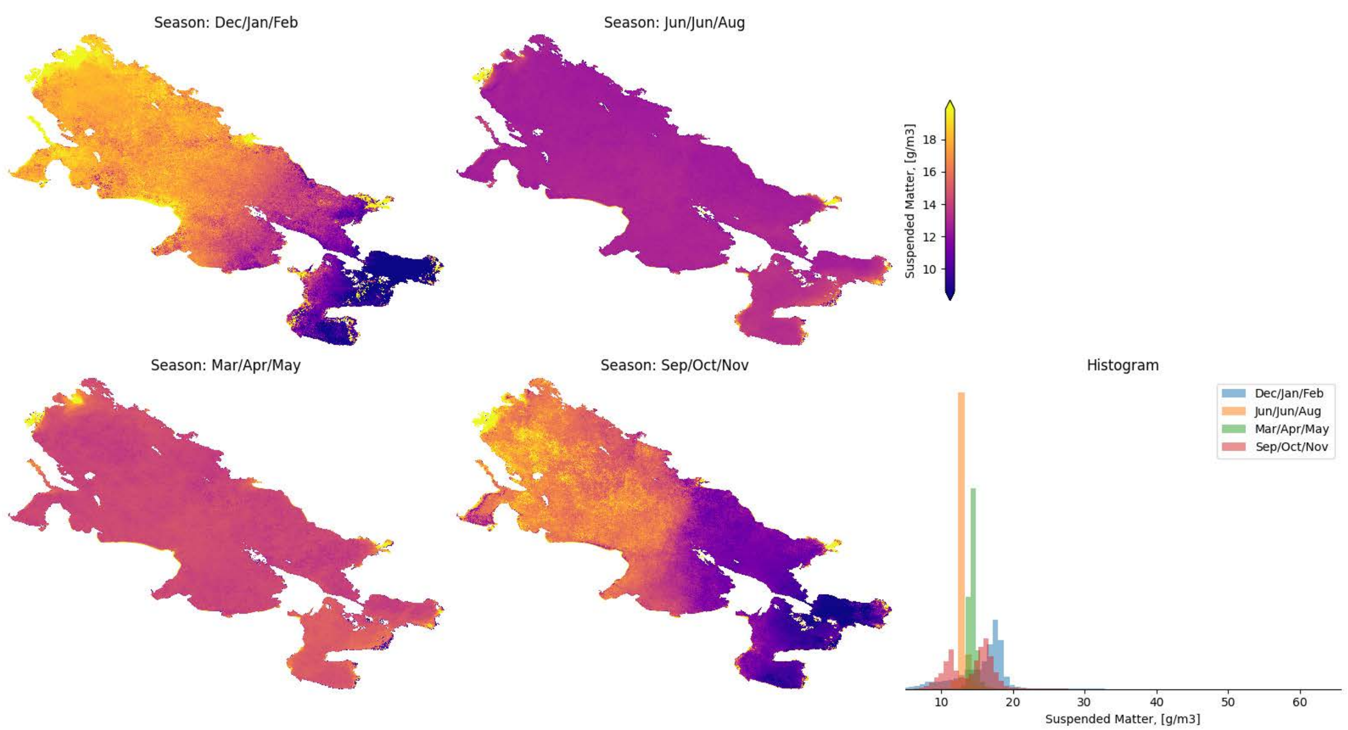
2.1: Spatial Seasonal Trends

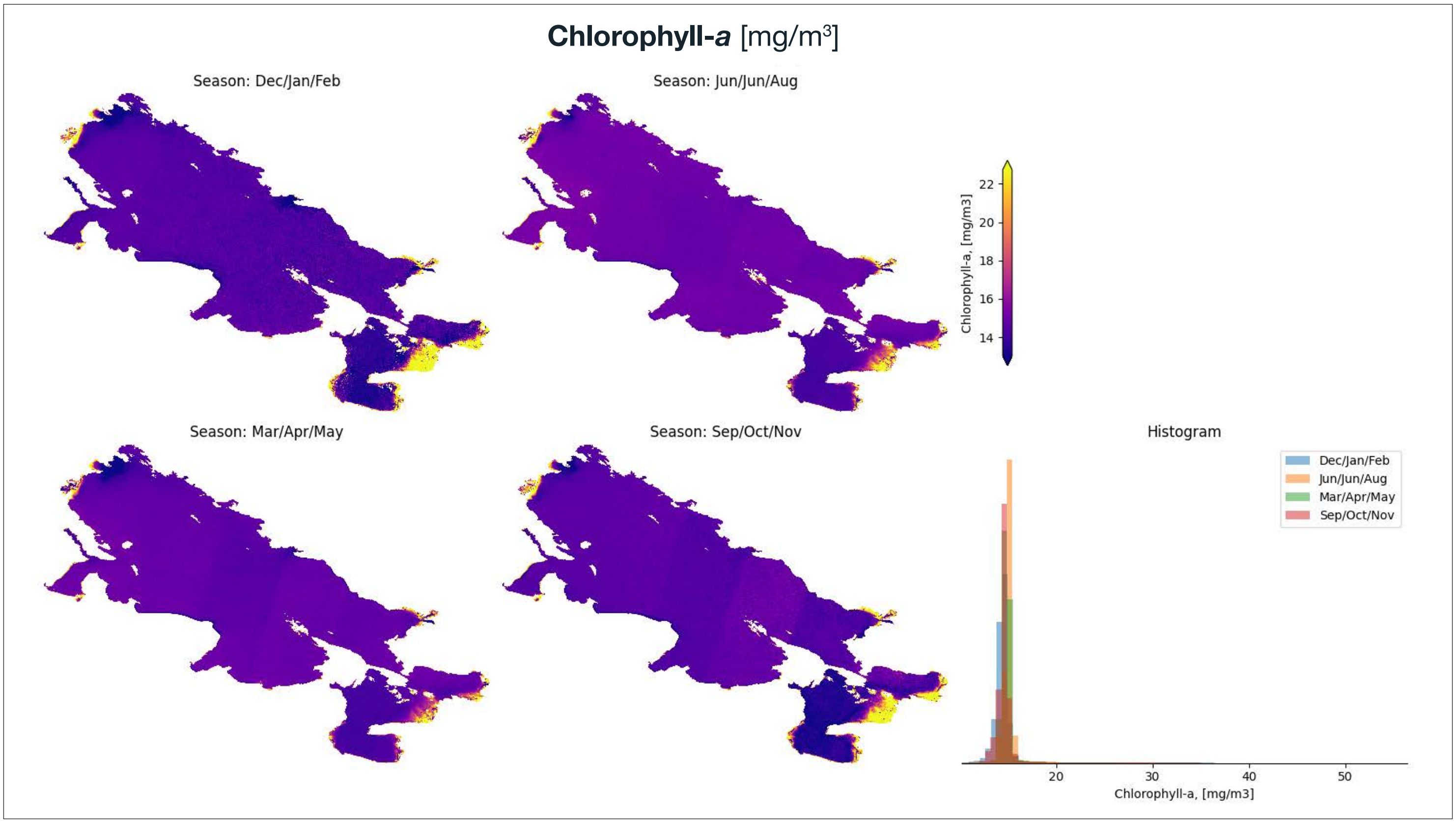
Maps illustrating the average seasonal variation across the entire water body.

Turbidity [FNU]



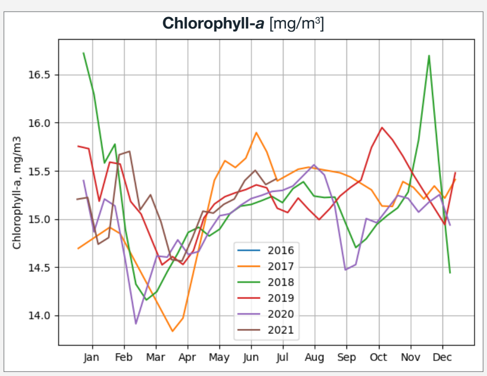
Suspended Matter [g/m³]

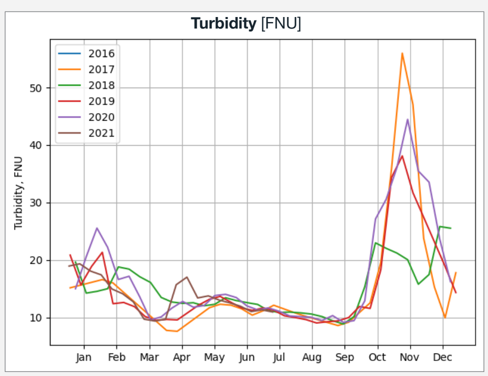


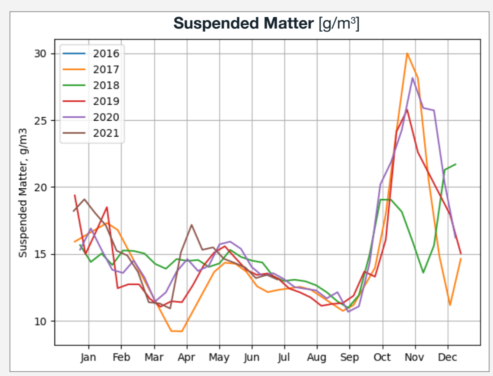


2.2a Temporal Seasonal Trends: Entire Waterbody

Water quality time series data split by each year: seasonal variation per parameter, across the whole reservoir.

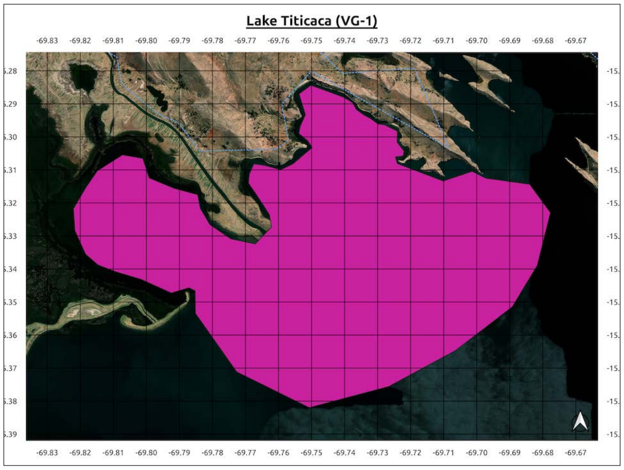


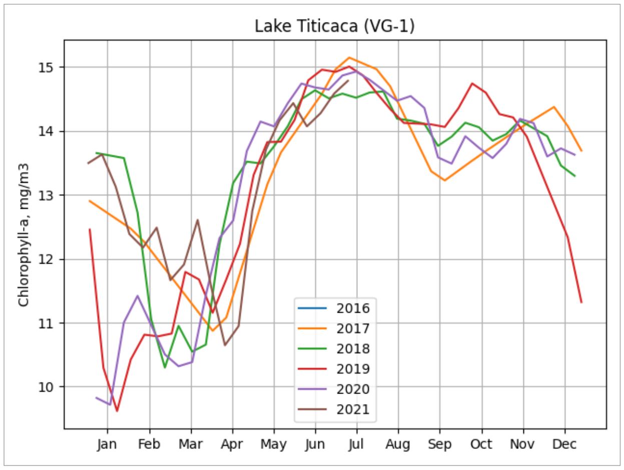


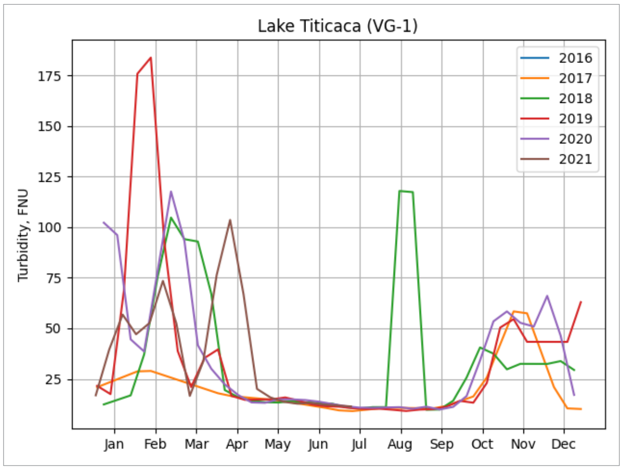


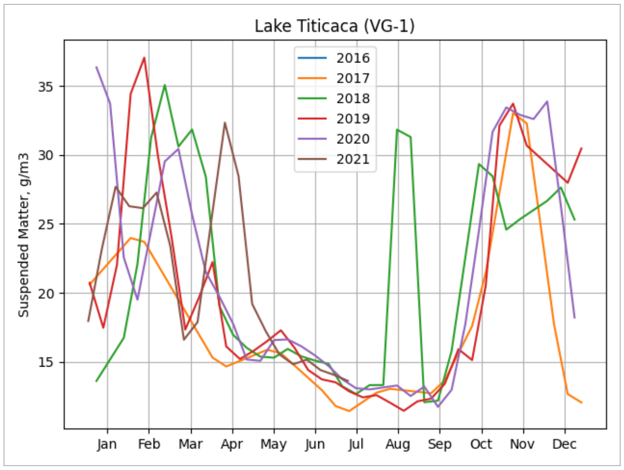
2.2b Temporal Seasonal Trends: Per Virtual Gauge (location of interest)

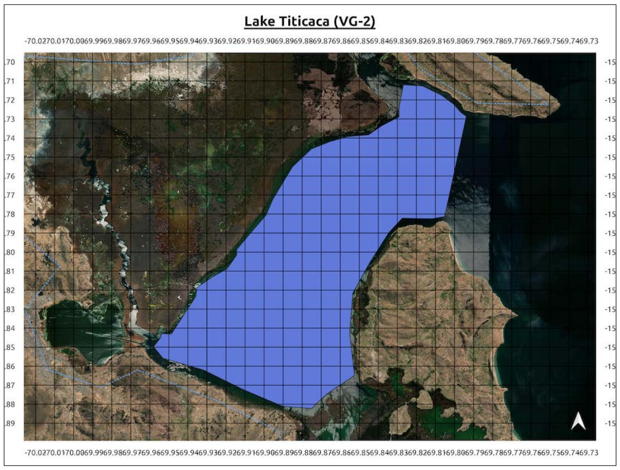
Water quality time series data split by each year: seasonal variation per parameter, per virtual gauge (area of interest) (see following pages).

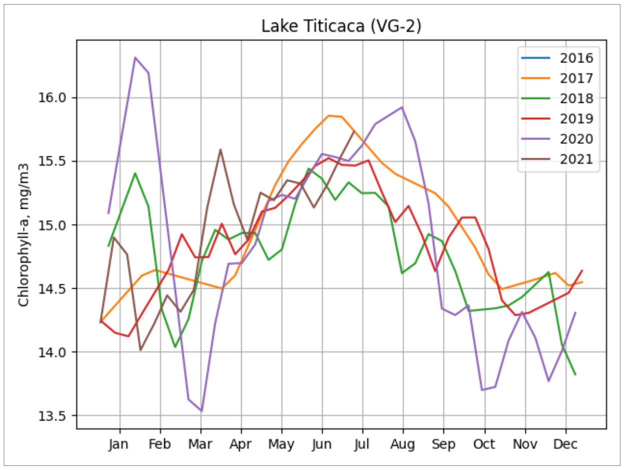

Lake Titicaca (VG-1)

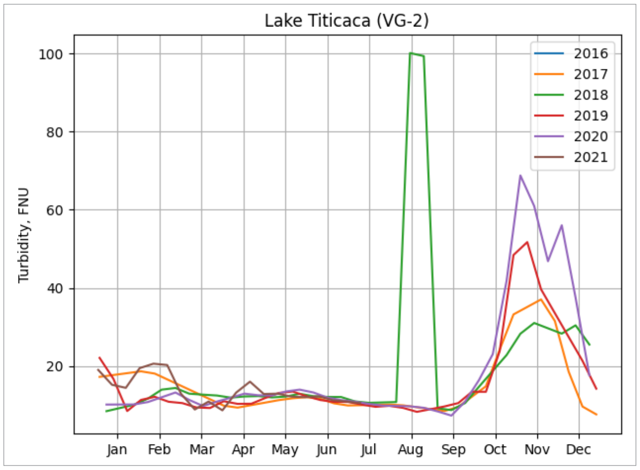

Lake Titicaca (VG-1)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

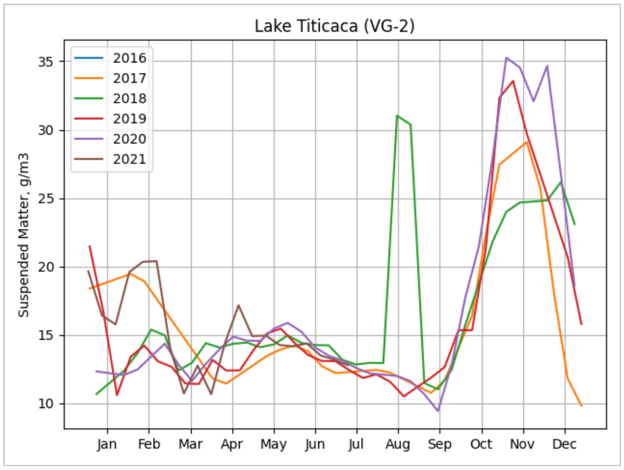

Lake Titicaca (VG-1)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

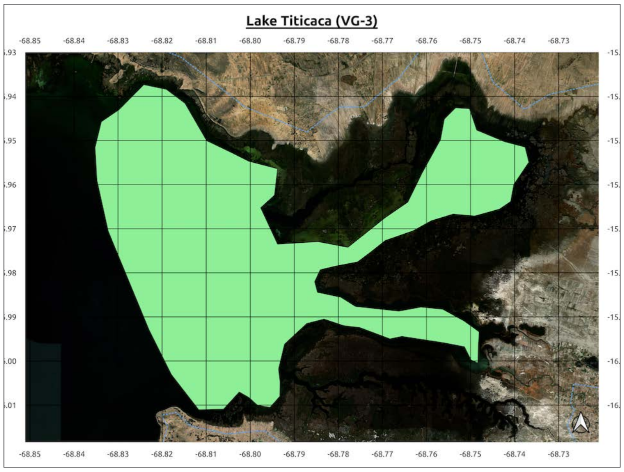

Lake Titicaca (VG-1)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

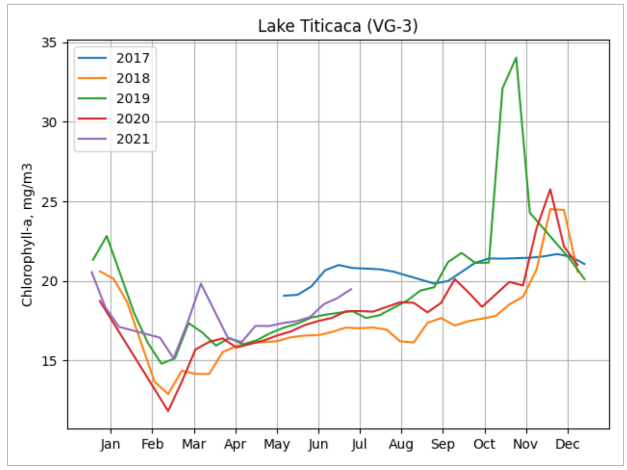

Lake Titicaca (VG-2)

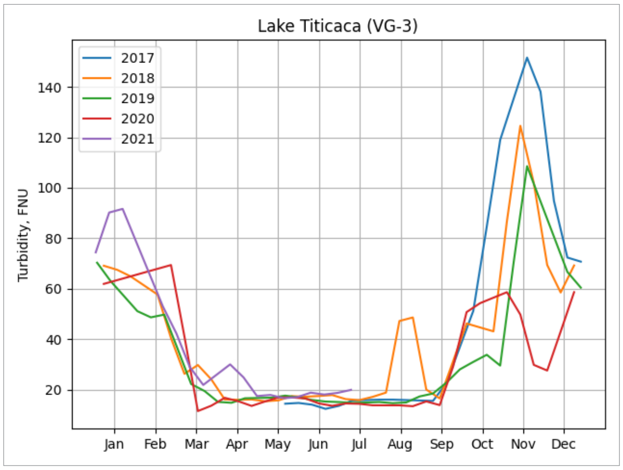

Lake Titicaca (VG-2)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

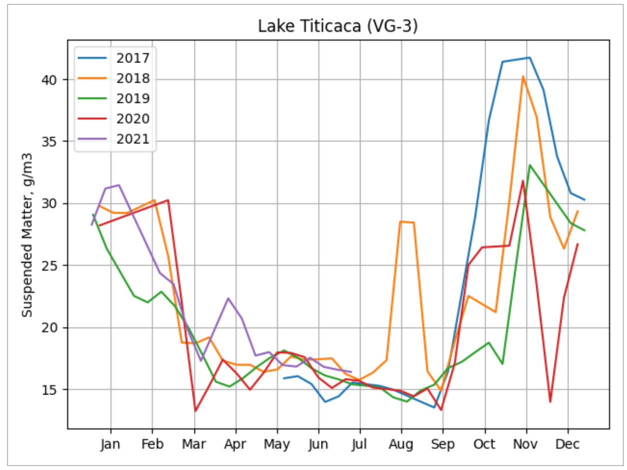

Lake Titicaca (VG-2)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

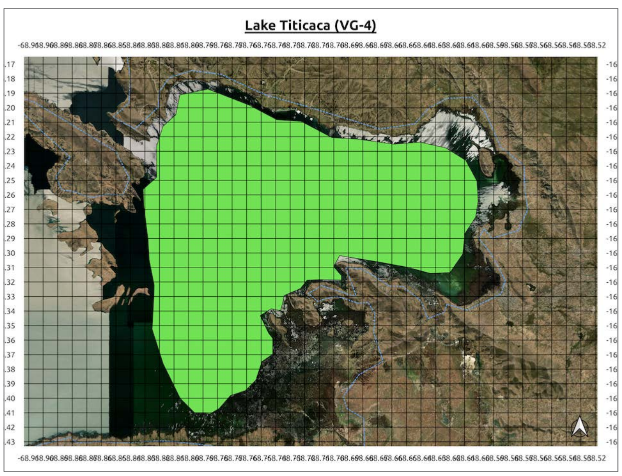

Lake Titicaca (VG-2)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

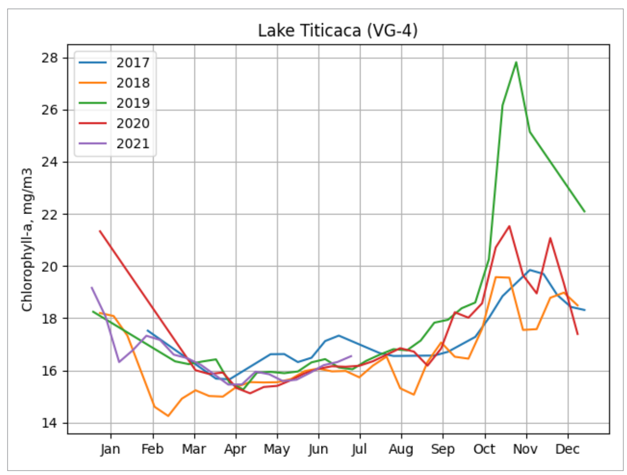

Lake Titicaca (VG-3)

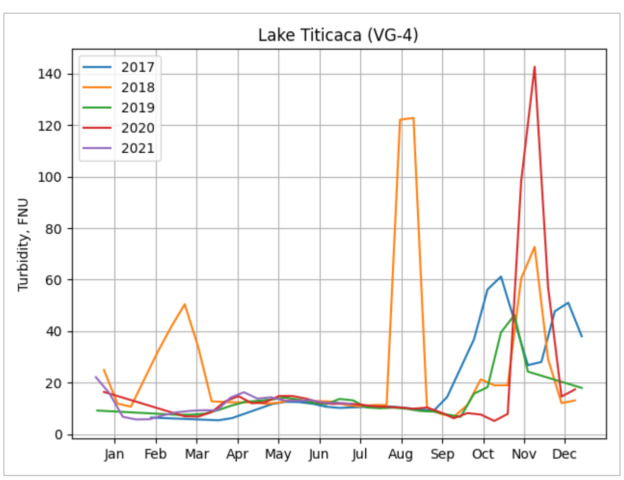

Lake Titicaca (VG-3)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

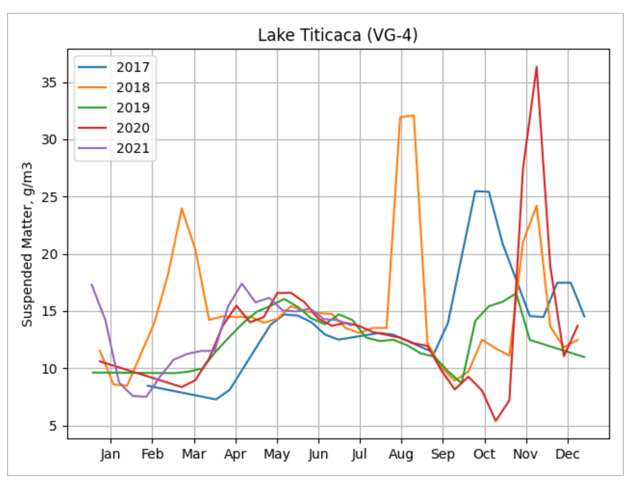

Lake Titicaca (VG-3)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

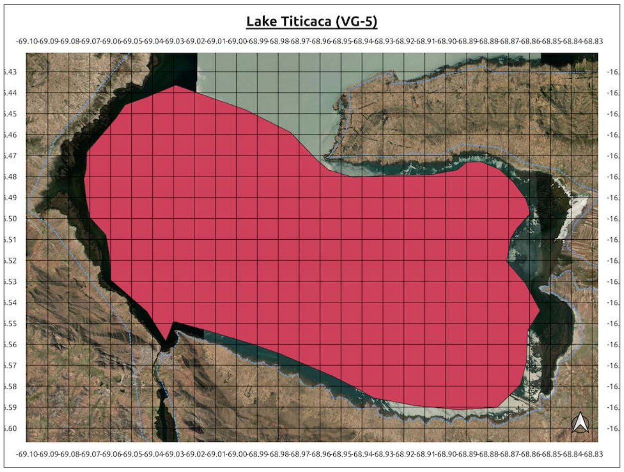

Lake Titicaca (VG-3)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

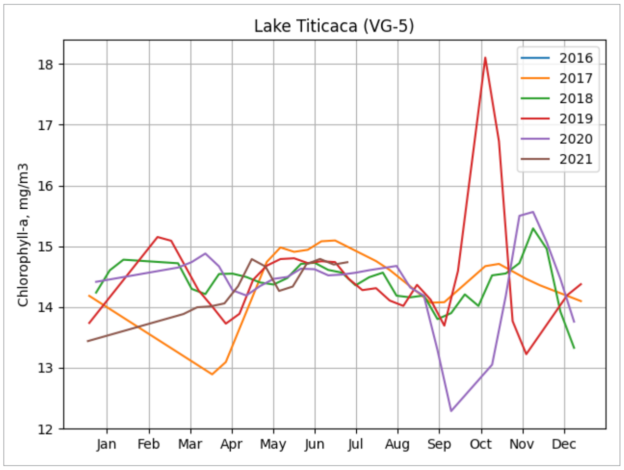

Lake Titicaca (VG-4)

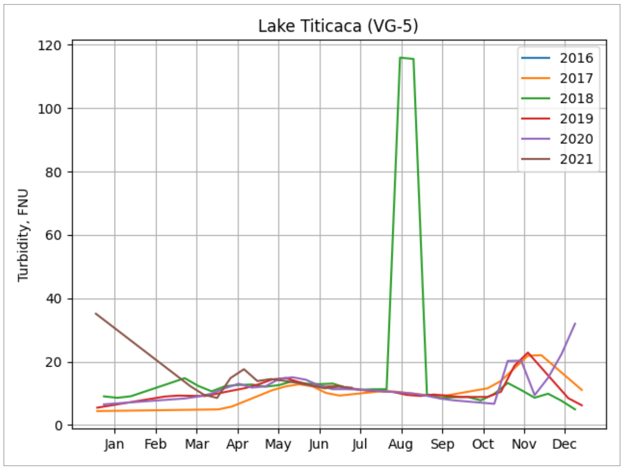

Lake Titicaca (VG-4)
Chlorophyll-a, mg/m3
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

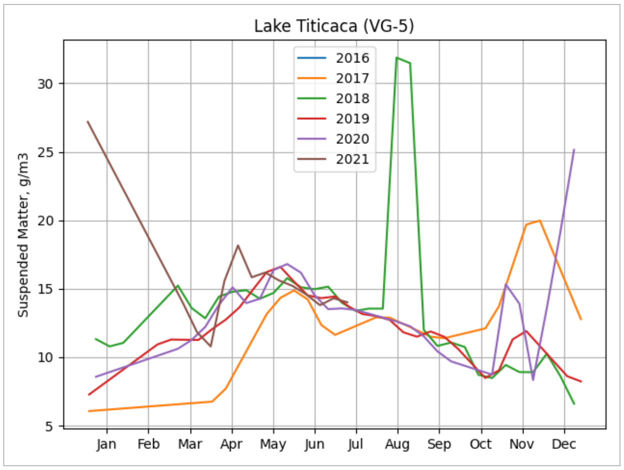

Lake Titicaca (VG-4)
Turbidity, FNU
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Lake Titicaca (VG-4)
Suspended Matter, g/m3
2017
2018
2019
2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Lake Titicaca (VG-5)

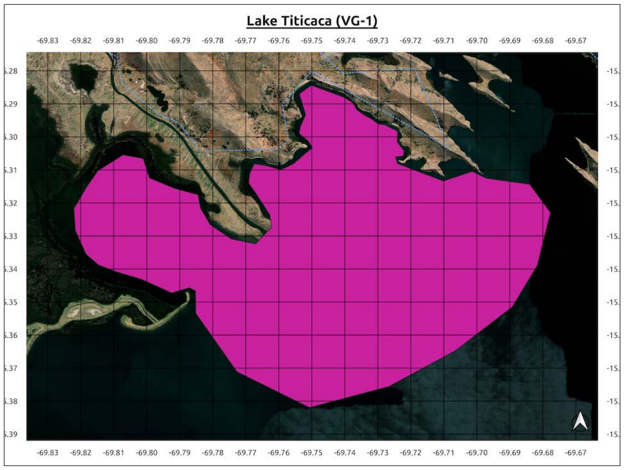

Lake Titicaca (VG-5)
Chlorophyll-a, mg/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

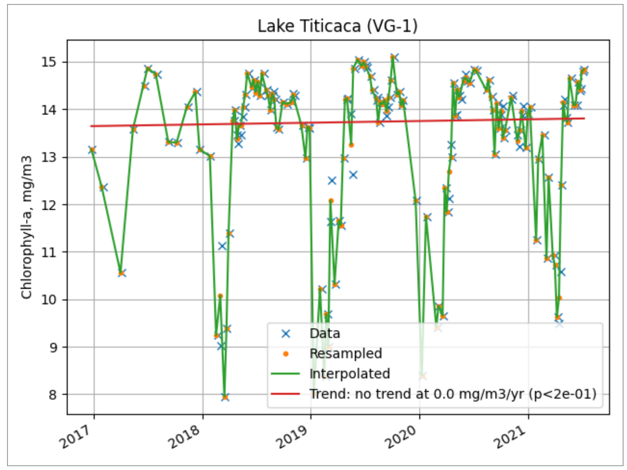

Lake Titicaca (VG-5)
Turbidity, FNU
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

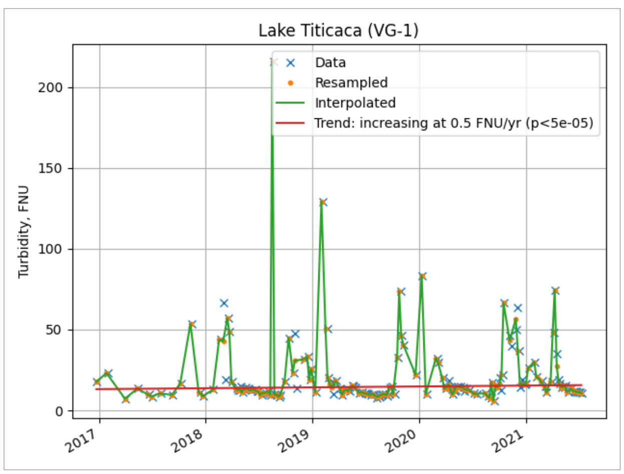

Lake Titicaca (VG-5)
Suspended Matter, g/m3
2016
2017
2018
2019
2020
2021
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

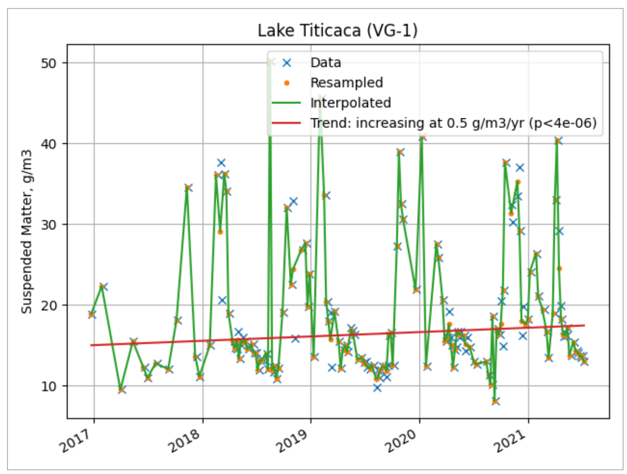
3. Long term trend analysis

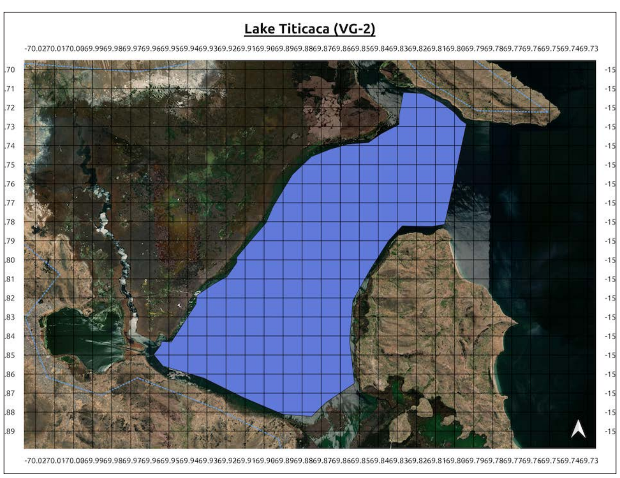
We apply a seasonally adjusted Mann-Kendall Trend Test to the Virtual Gauge locations. First, the median water quality parameter value is calculated across a Virtual Gauge location for each image date. Then, a Mann-Kendall test is applied to the full archival time series which provides the direction, magnitude, and statistical significance of potential trends at that location. The outcome indicates whether the time series data at that location has a consistent increasing or decreasing trend.

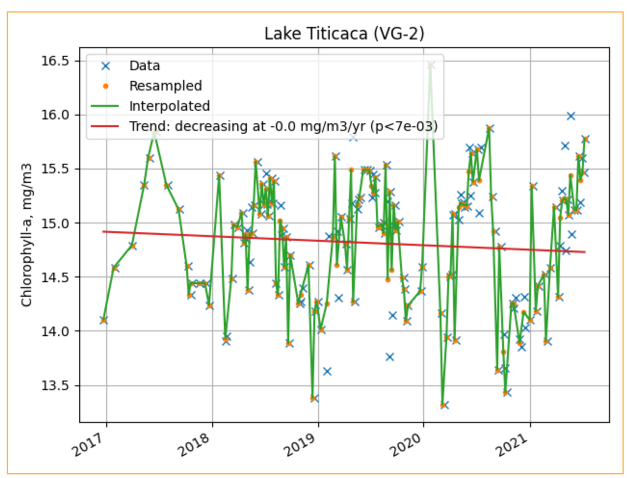


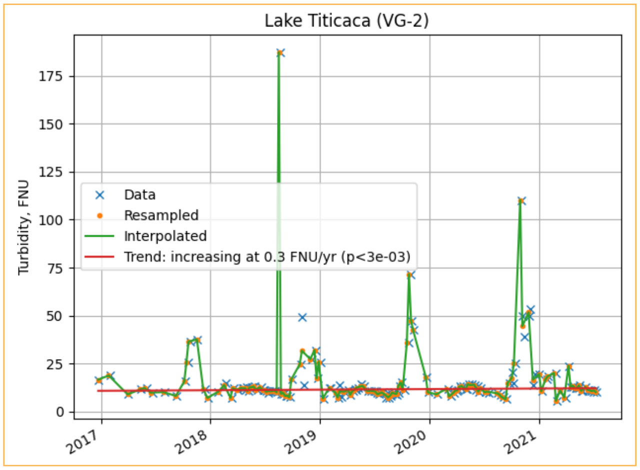


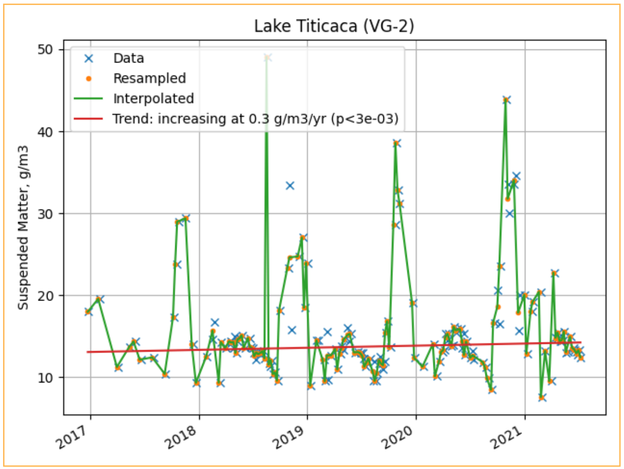


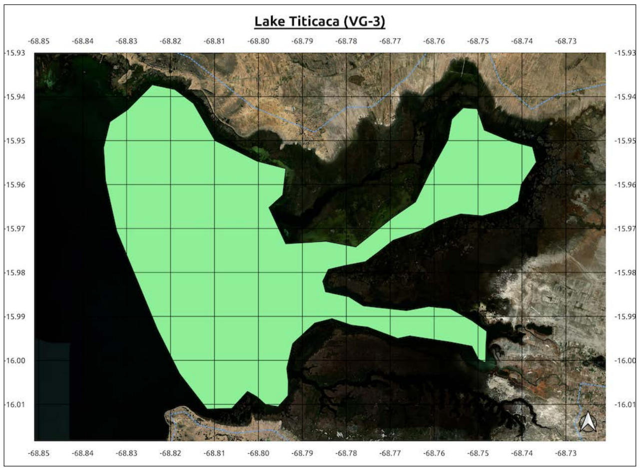


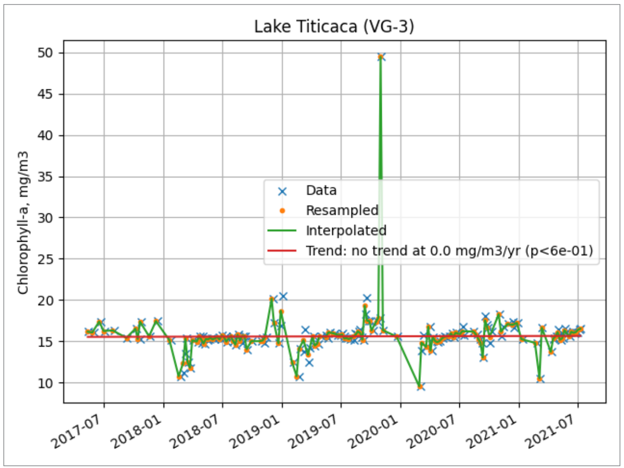


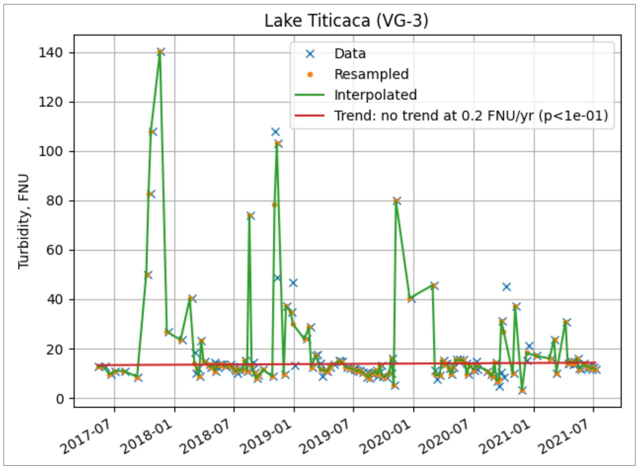


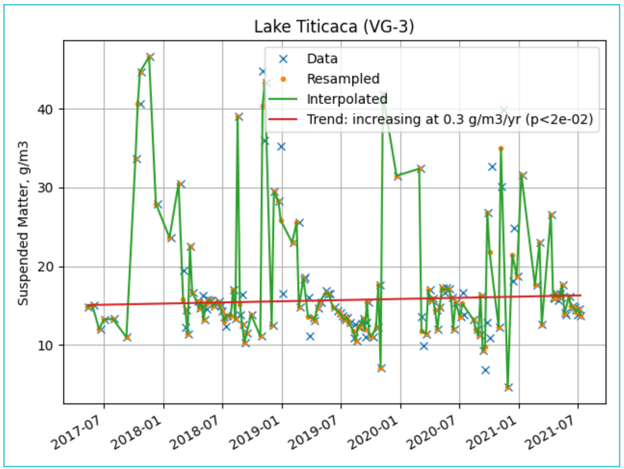

Lake Titicaca (VG-2)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: increasing at 0.3 FNU/yr (p<3e-03)
2017
2018
2019
2020
2021

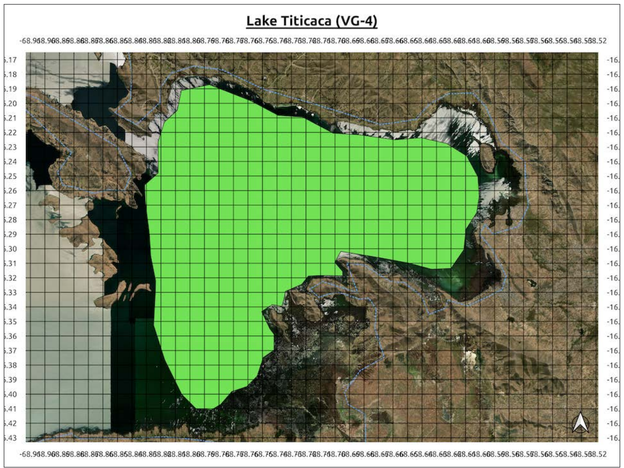

Lake Titicaca (VG-2)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: increasing at 0.3 g/m3/yr (p<3e-03)
2017
2018
2019
2020
2021

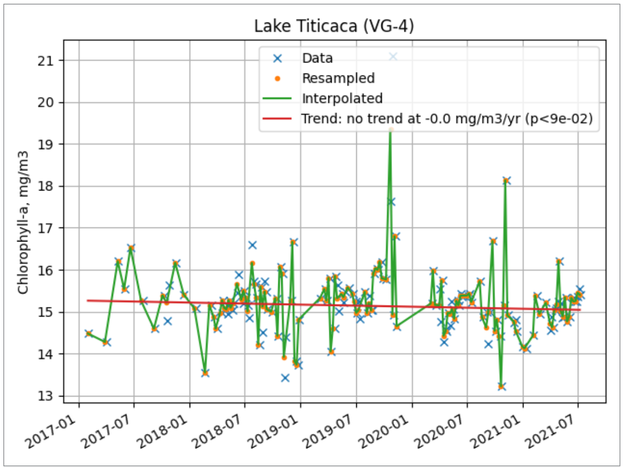

Lake Titicaca (VG-3)

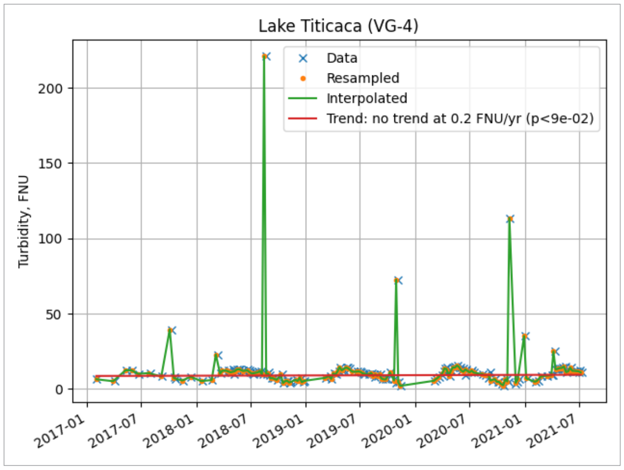

Lake Titicaca (VG-3)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: no trend at 0.0 mg/m3/yr (p<6e-01)
2017-07
2018-01
2018-07
2019-01
2019-07
2020-01
2020-07
2021-01
2021-07

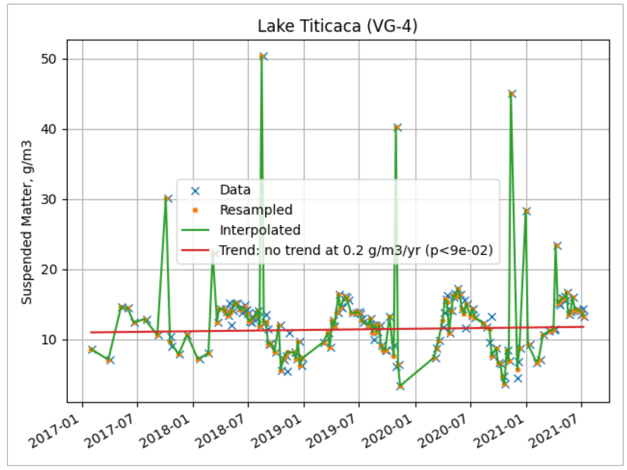

Lake Titicaca (VG-3)
Turbidity, FNU
Data
Resampled
Interpolated
Trend: no trend at 0.2 FNU/yr (p<1e-01)
2017-07
2018-01
2018-07
2019-01
2019-07
2020-01
2020-07
2021-01
2021-07

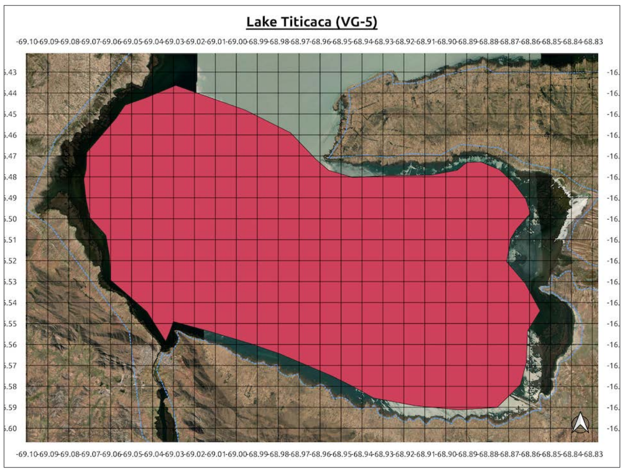

Lake Titicaca (VG-3)
Suspended Matter, g/m3
Data
Resampled
Interpolated
Trend: increasing at 0.3 g/m3/yr (p<2e-02)
2017-07
2018-01
2018-07
2019-01
2019-07
2020-01
2020-07
2021-01
2021-07

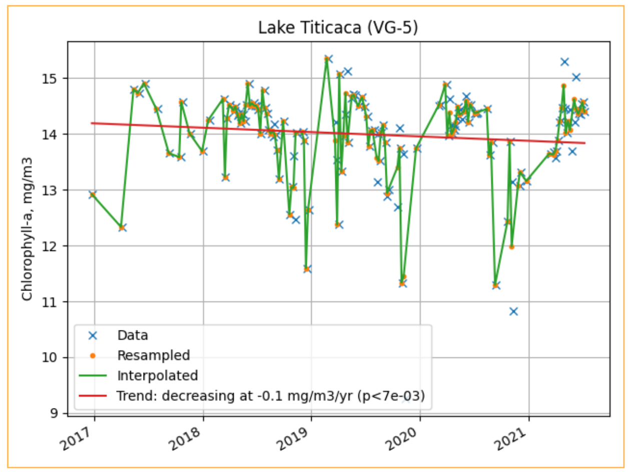

Lake Titicaca (VG-4)

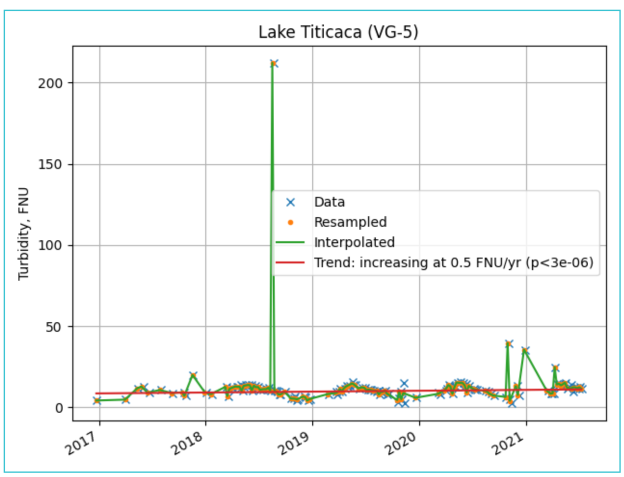

Lake Titicaca (VG-4)
Chlorophyll-a, mg/m3
Data
Resampled
Interpolated
Trend: no trend at -0.0 mg/m3/yr (p<9e-02)
2017-01
2017-07
2018-01
2018-07
2019-01
2019-07
2020-01
2020-07
2021-01
2021-07

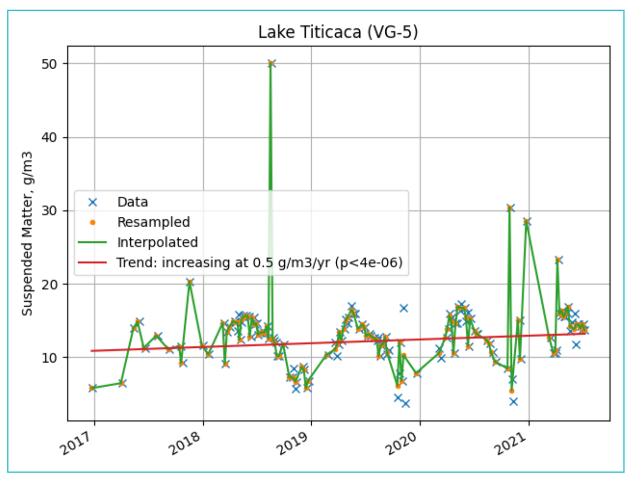

Lake Titicaca (VG-4)
Data
Resampled
Interpolated
Trend: no trend at 0.2 FNU/yr (p<9e-02)
Turbidity, FNU


Lake Titicaca (VG-4)
Data
Resampled
Interpolated
Trend: no trend at 0.2 g/m3/yr (p<9e-02)
Suspended Matter, g/m3


Lake Titicaca (VG-5)


Lake Titicaca (VG-5)
Data
Resampled
Interpolated
Trend: decreasing at -0.1 mg/m3/yr (p<7e-03)
Chlorophyll-a, mg/m3


Lake Titicaca (VG-5)
Data
Resampled
Interpolated
Trend: increasing at 0.5 FNU/yr (p<3e-06)
Turbidity, FNU


Lake Titicaca (VG-5)
Data
Resampled
Interpolated
Trend: increasing at 0.5 g/m3/yr (p<4e-06)
Suspended Matter, g/m3

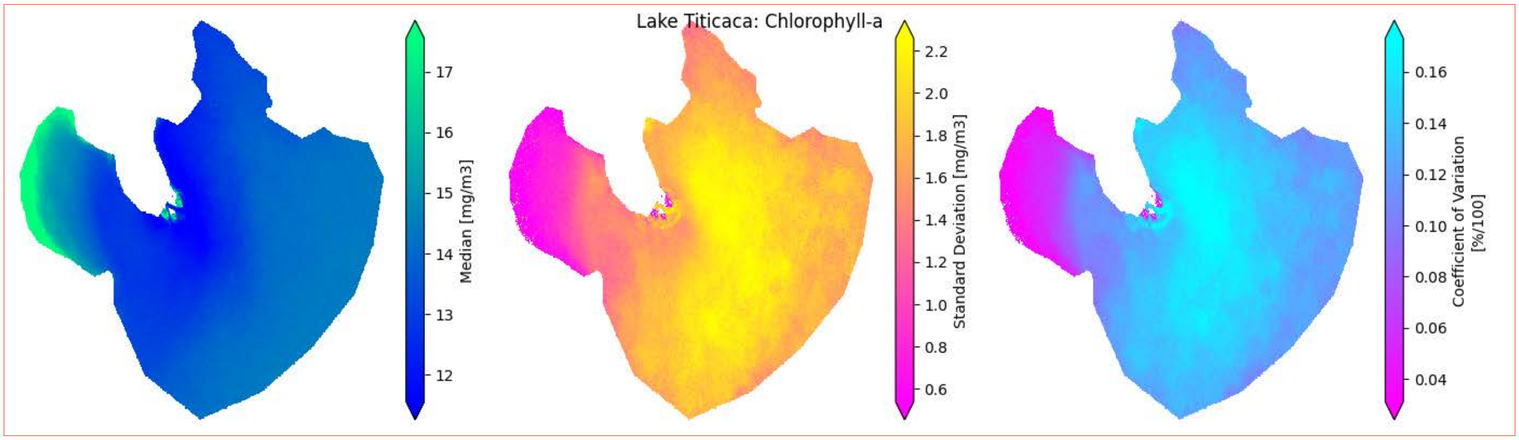
4. Variation Maps

We created Variation Maps for each water body and water quality parameter. This process calculates the median, standard deviation, and coefficient of variation on a pixel-wise basis through time. The product is a map that shows the spatial distribution of these summary statistics through time.

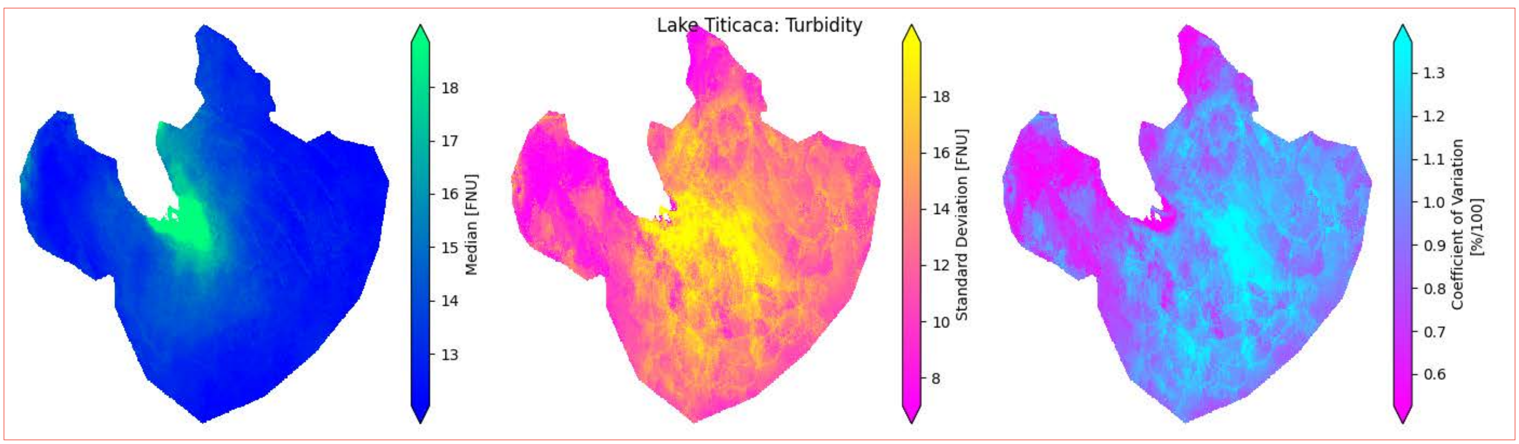
VIRTUAL GAUGE 1
First location of interest

Median **Standard Deviation** **Coefficient of Variation**

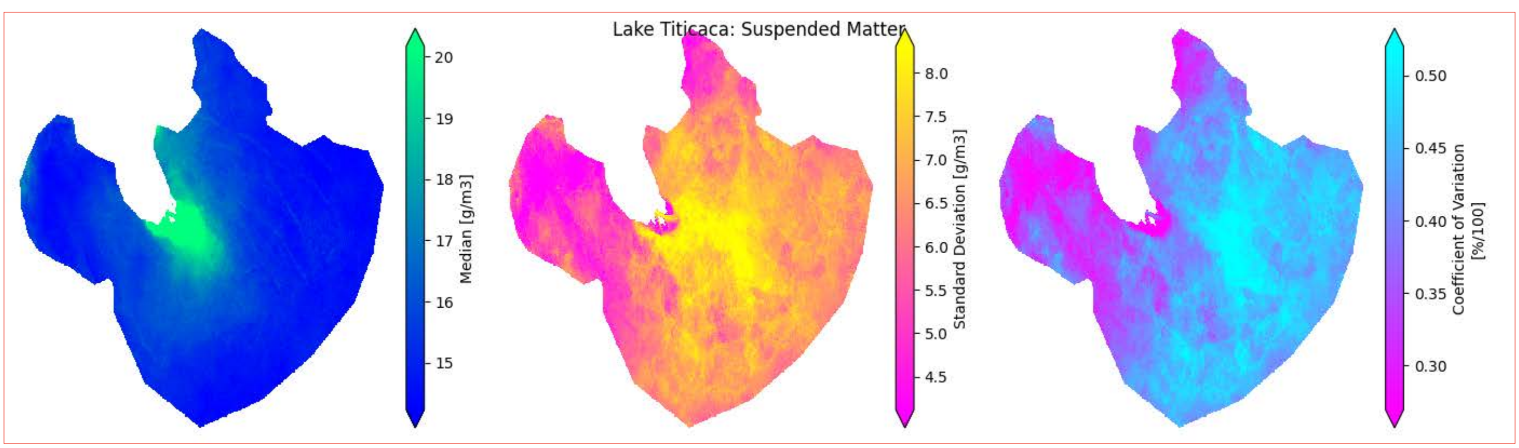
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



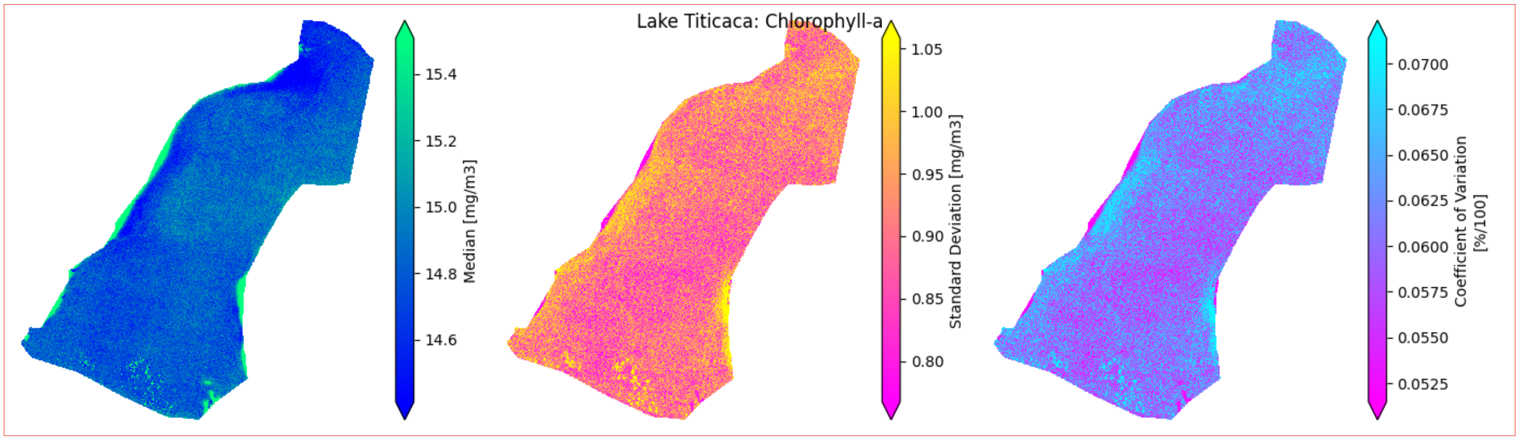
4.3 Suspended Matter [g/m^3]



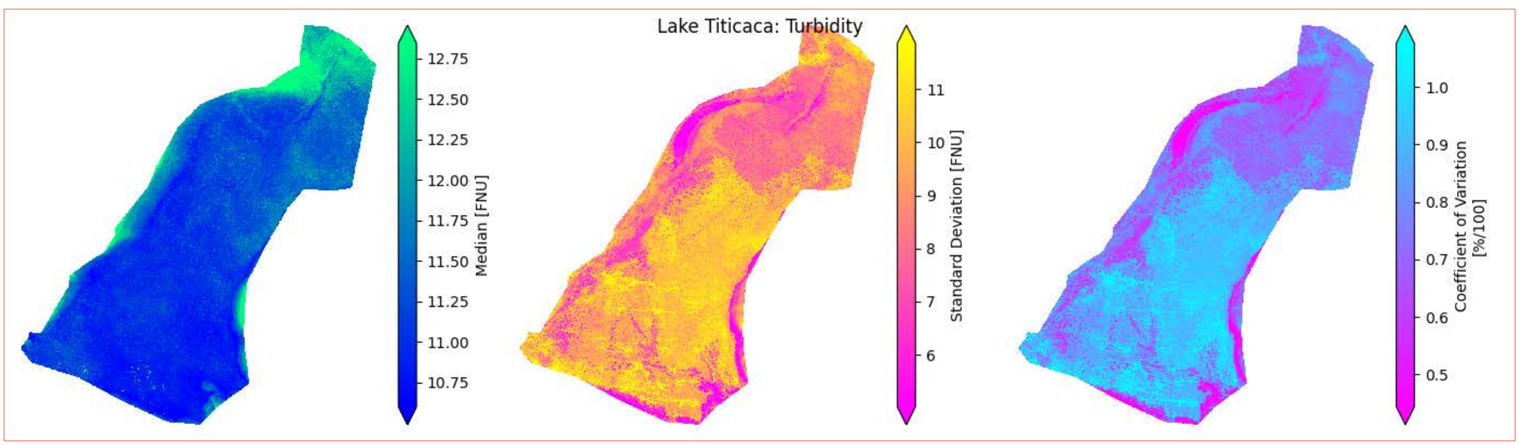
VIRTUAL GAUGE 2
Second location of interest

Median | **Standard Deviation** | **Coefficient of Variation**

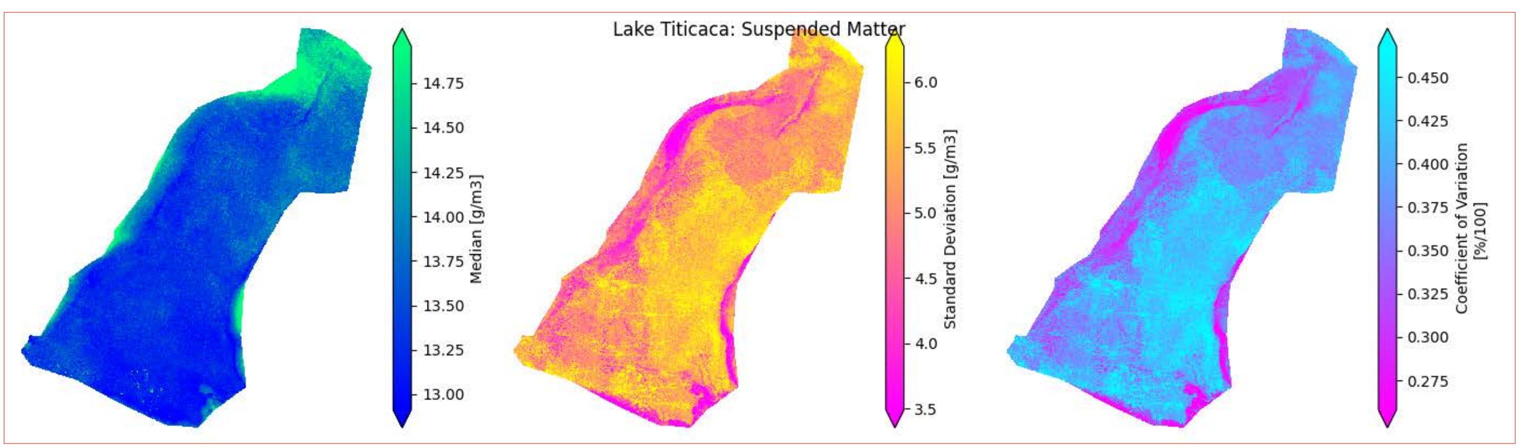
4.1 Chlorophyll-*a* [mg/m³]



4.2 Turbidity [FNU]



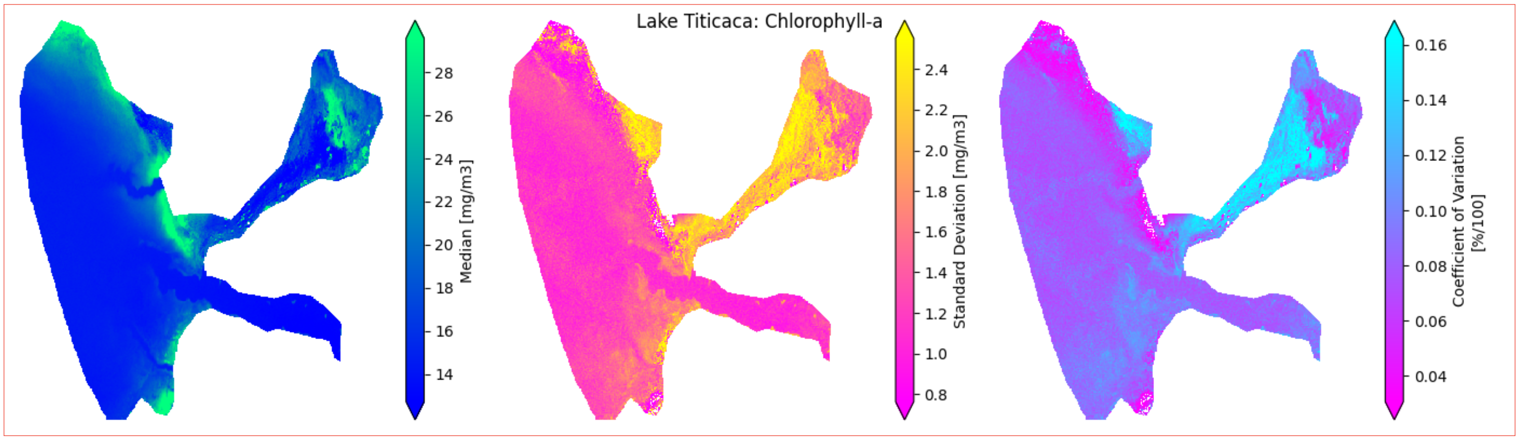
4.3 Suspended Matter [g/m³]



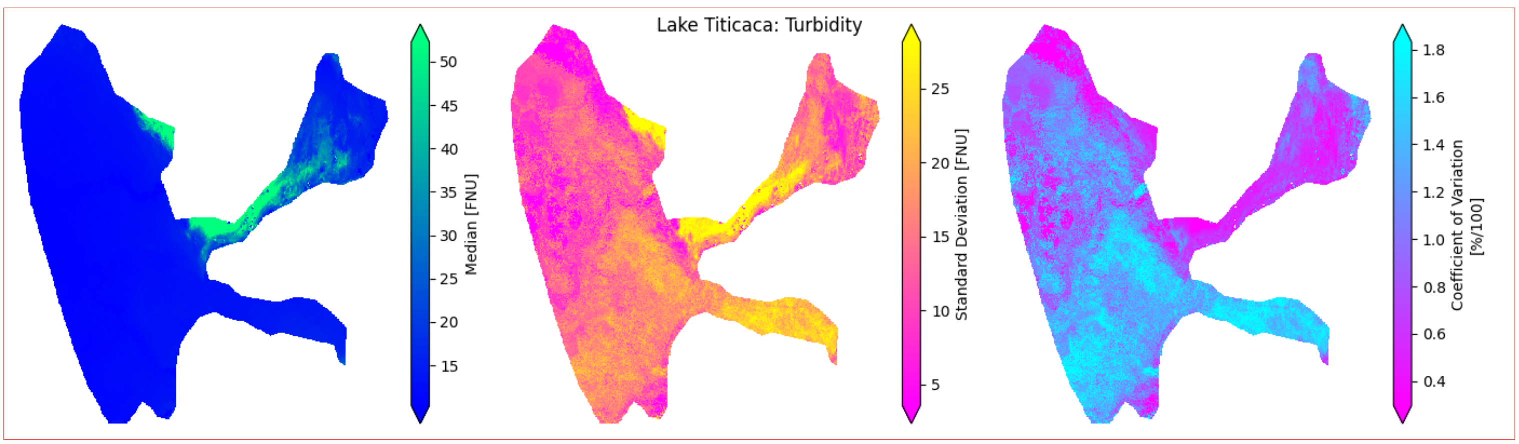
VIRTUAL GAUGE 3
Third location of interest

Median | **Standard Deviation** | **Coefficient of Variation**

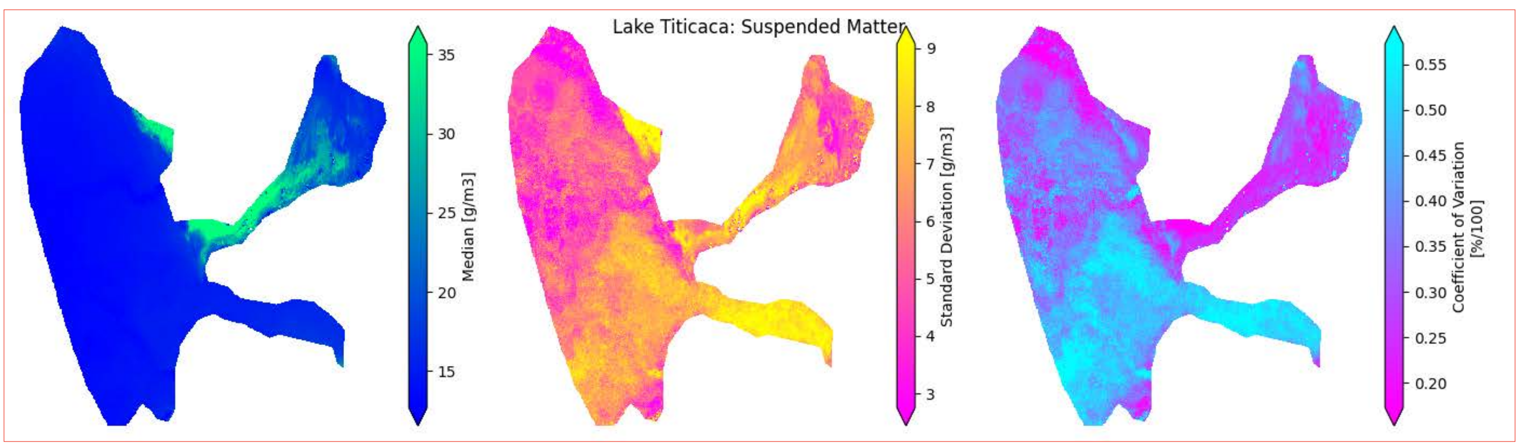
4.1 Chlorophyll-*a* [mg/m³]



4.2 Turbidity [FNU]



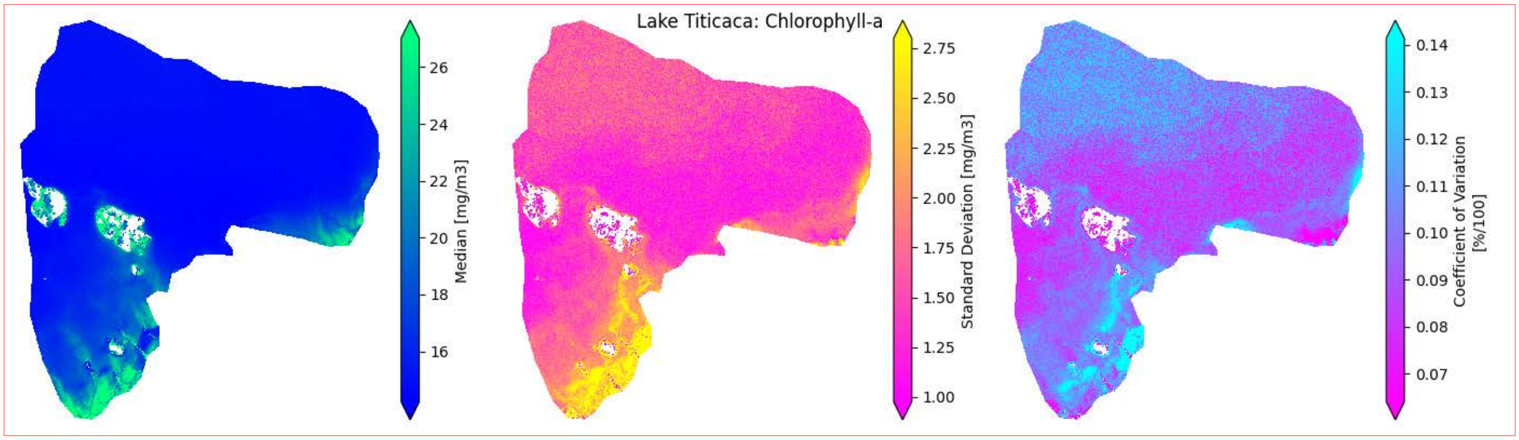
4.3 Suspended Matter [g/m³]



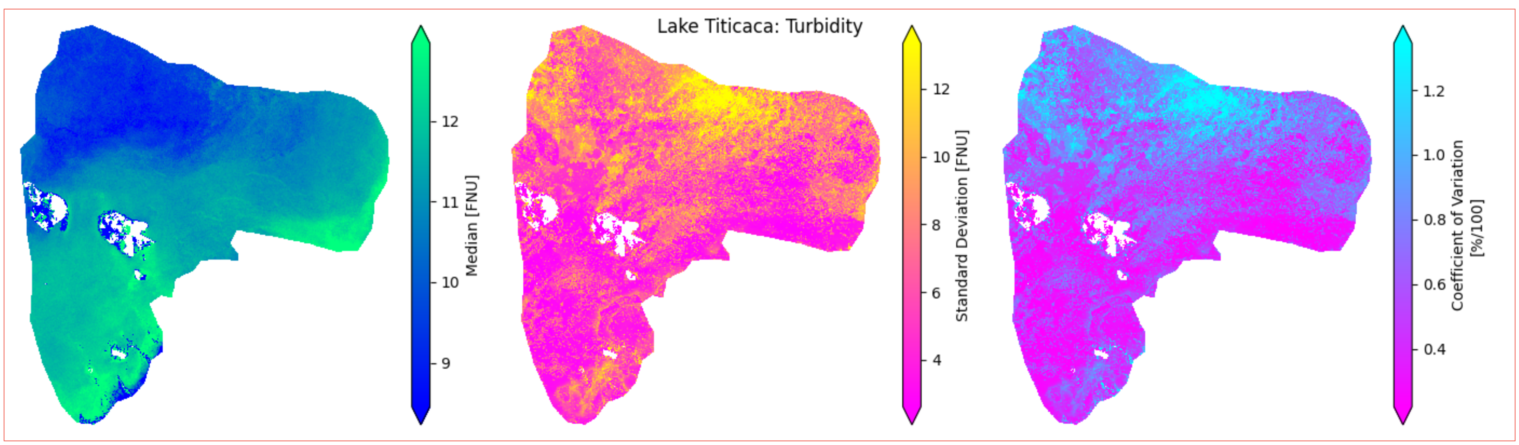
VIRTUAL GAUGE 4
Forth location of interest

Median | **Standard Deviation** | **Coefficient of Variation**

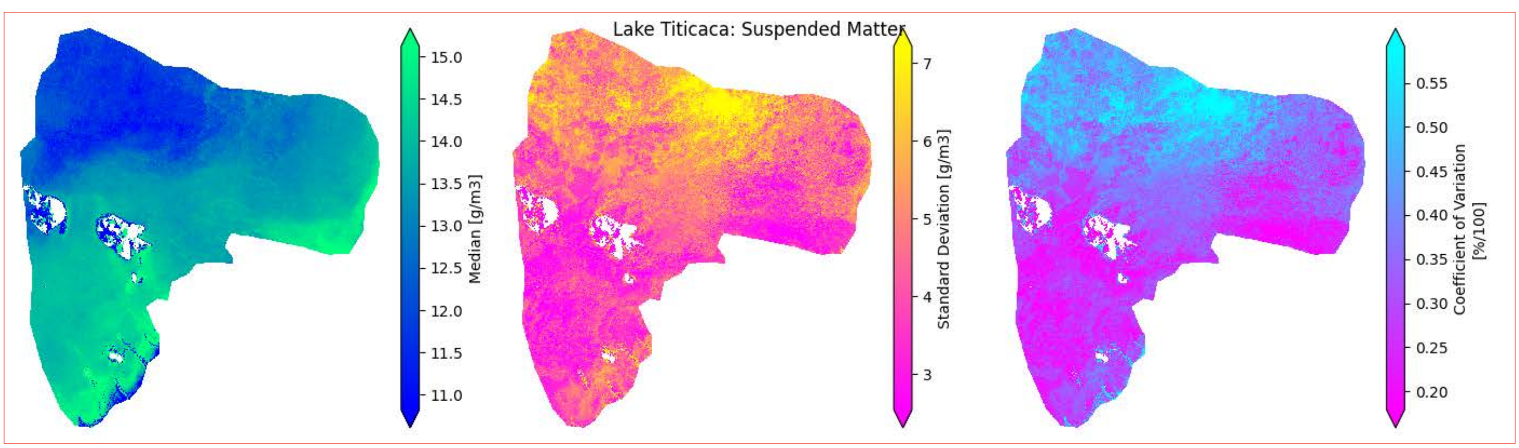
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



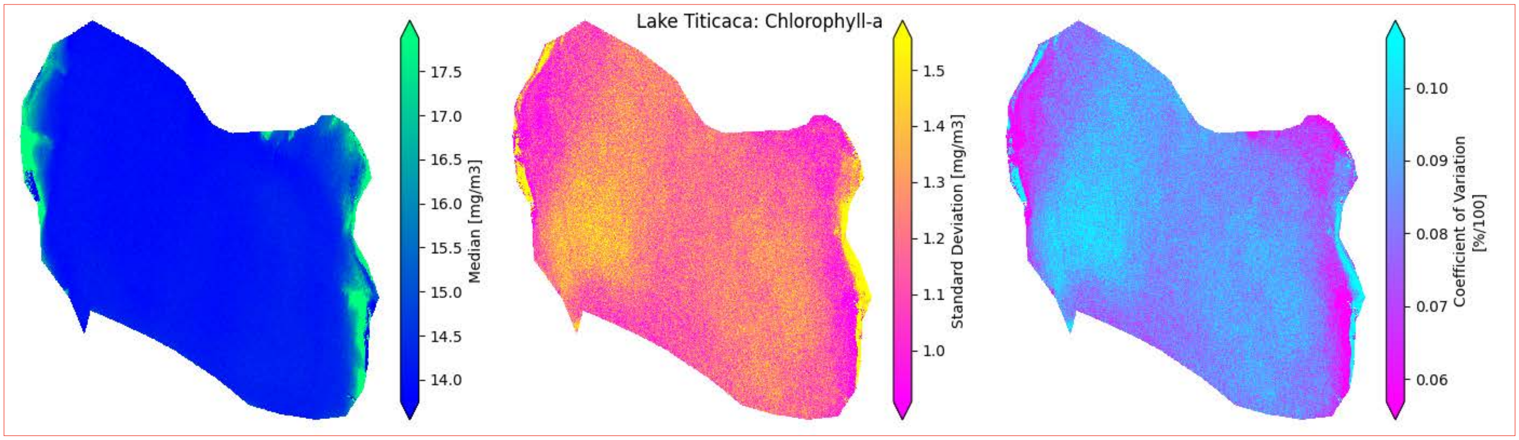
4.3 Suspended Matter [g/m^3]



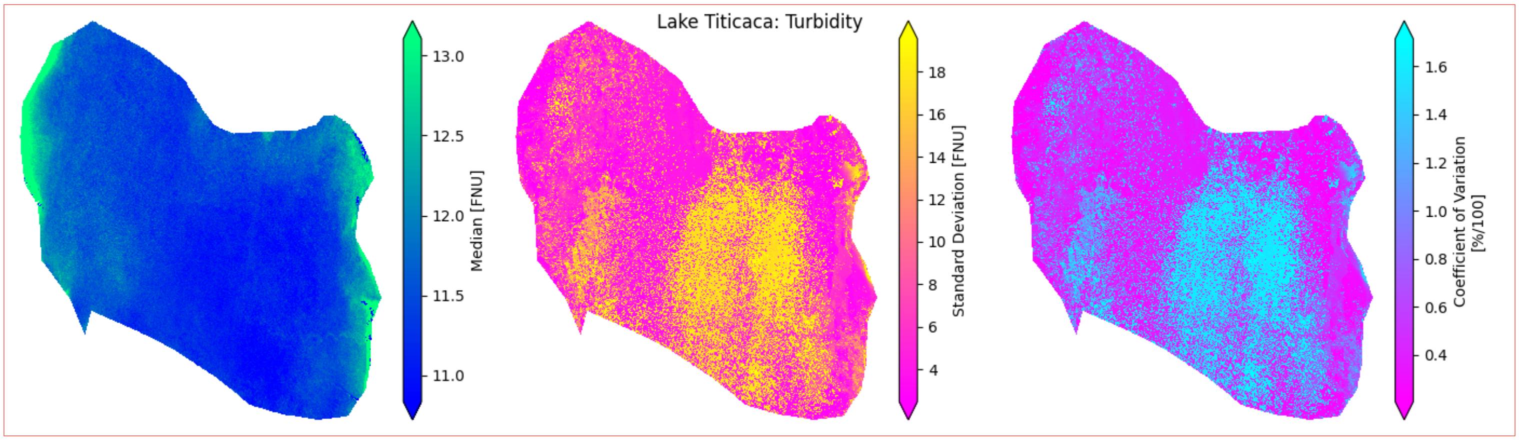
VIRTUAL GAUGE 5
Fifth location of interest

Median	Standard Deviation	Coefficient of Variation

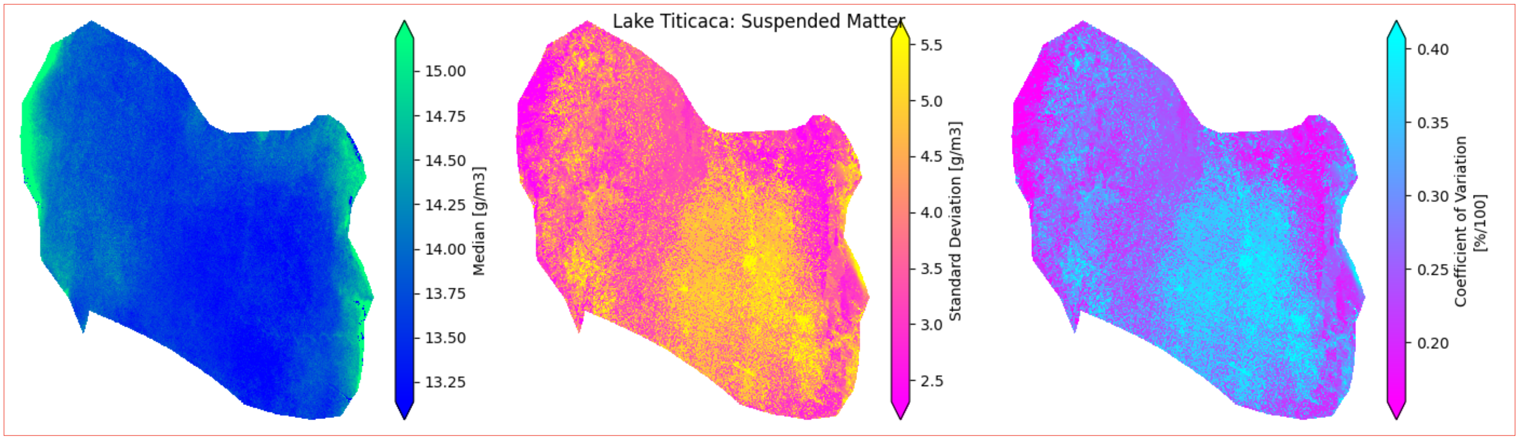
4.1 Chlorophyll-*a* [mg/m³]



4.2 Turbidity [FNU]



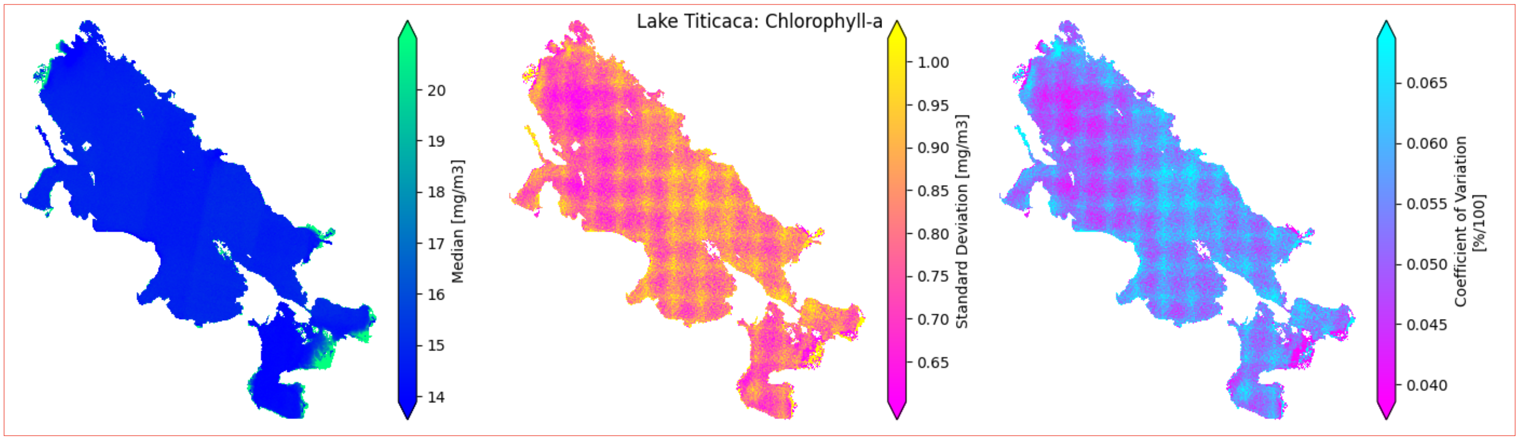
4.3 Suspended Matter [g/m³]



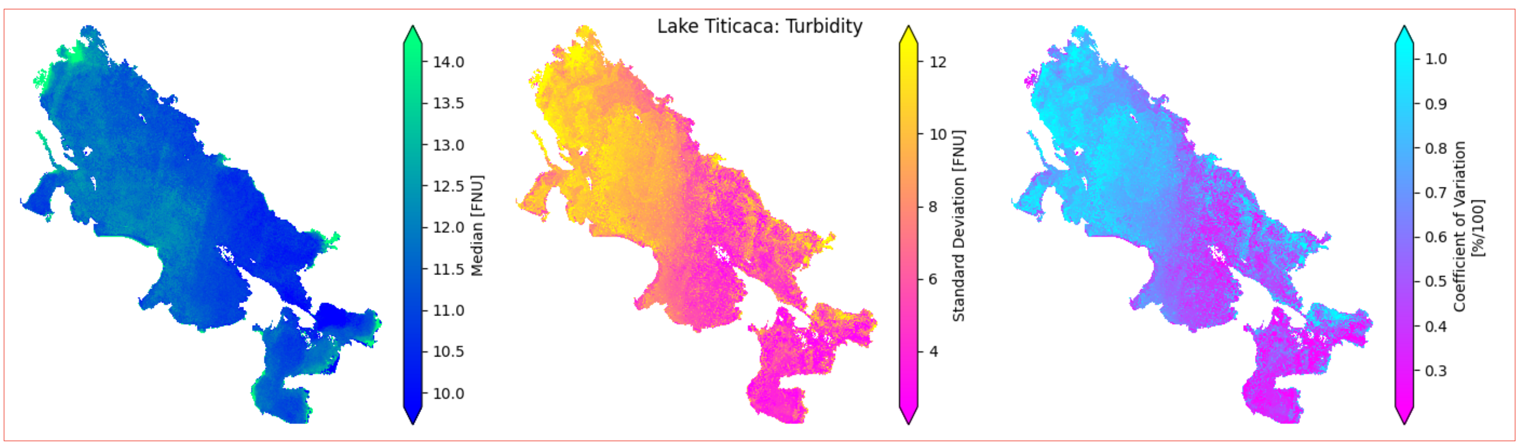
Entire Lake Overview,
Lake Titicaca

Median | **Standard Deviation** | **Coefficient of Variation**

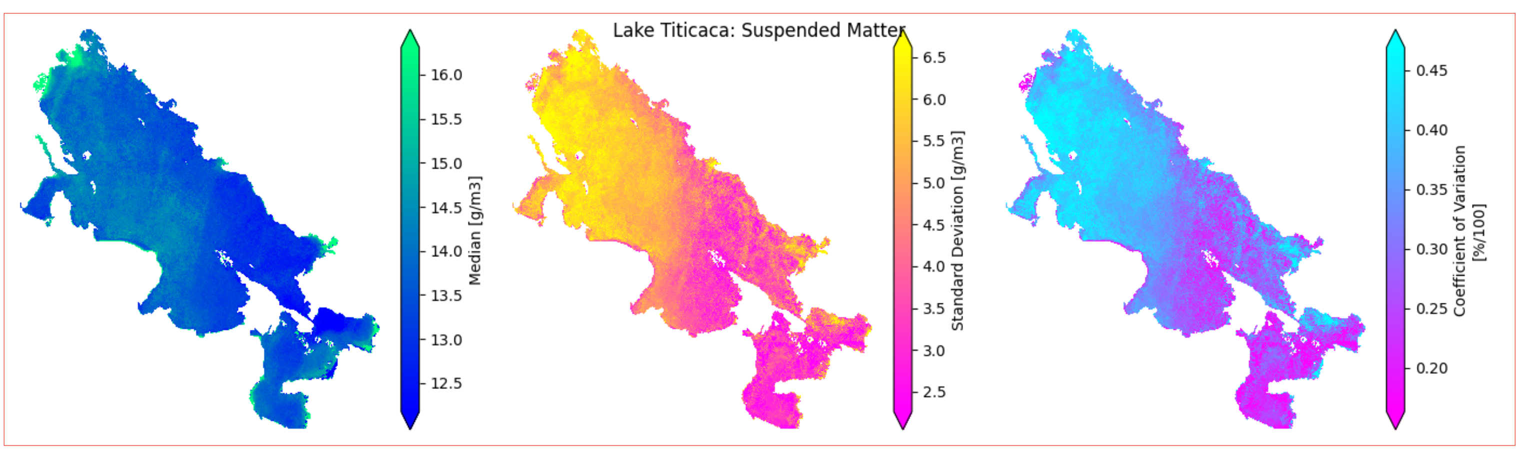
4.1 Chlorophyll-*a* [mg/m^3]



4.2 Turbidity [FNU]



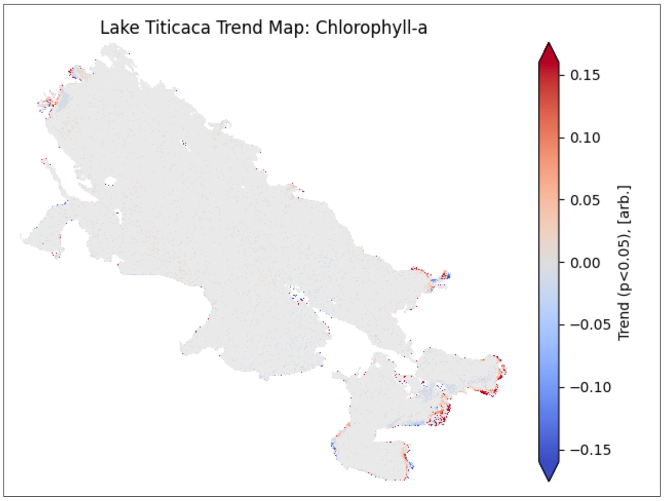
4.3 Suspended Matter [g/m^3]



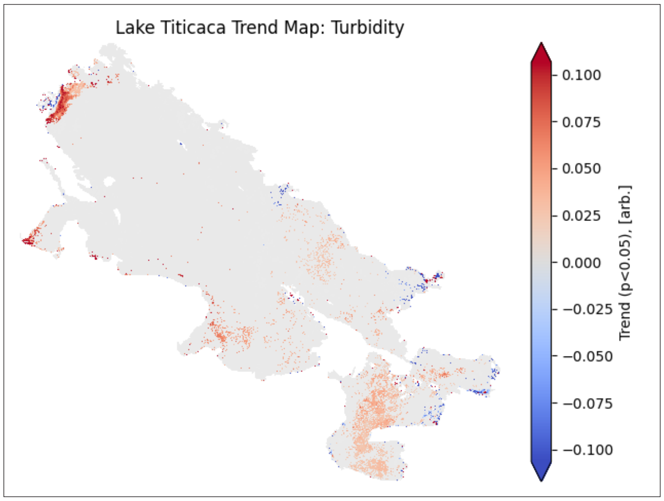
5. Trend Maps

We create Trend Maps to visualize where temporal trends in water quality parameters are occurring. First, data across the entire water body is spatially binned by averaged to approximately 100m resolution. Then, a linear regression is applied along the temporal axis for each bin, a three-sigma outlier filtering process is used to remove outliers. Finally, the linear trends are visualized on a map where statistically significant (p-value below 5%) values are colorized based on direction and intensity.

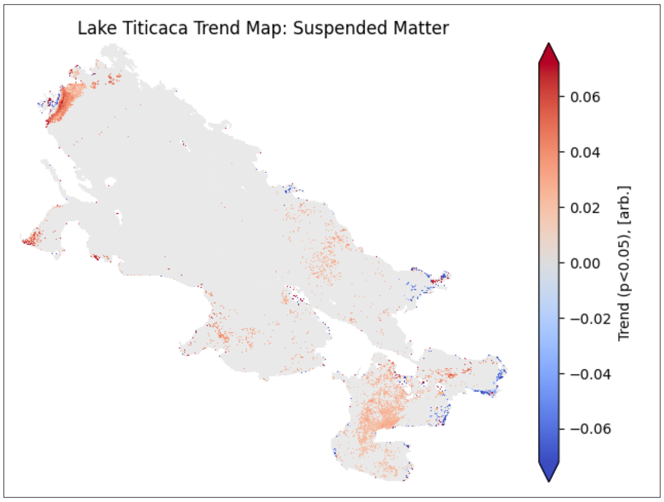
5.1 Chlorophyll-*a* [mg/m³]



5.2 Turbidity [FNU]

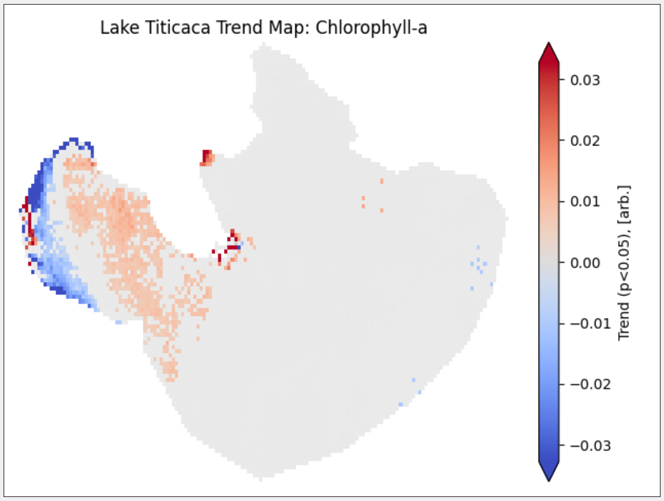


5.3 Suspended Matter [g/m³]

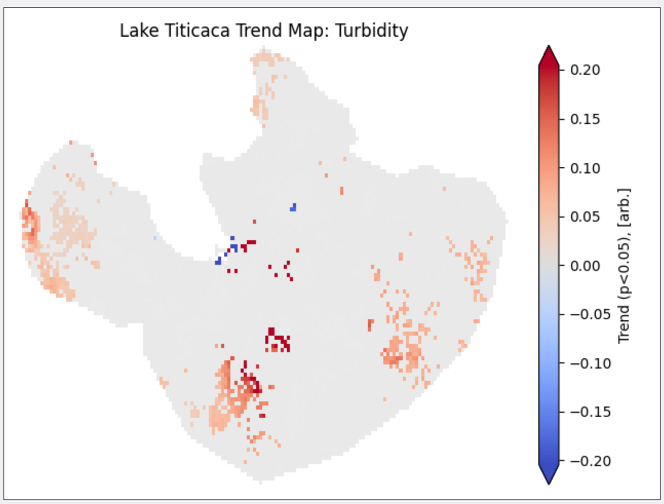


Virtual Gauge 1

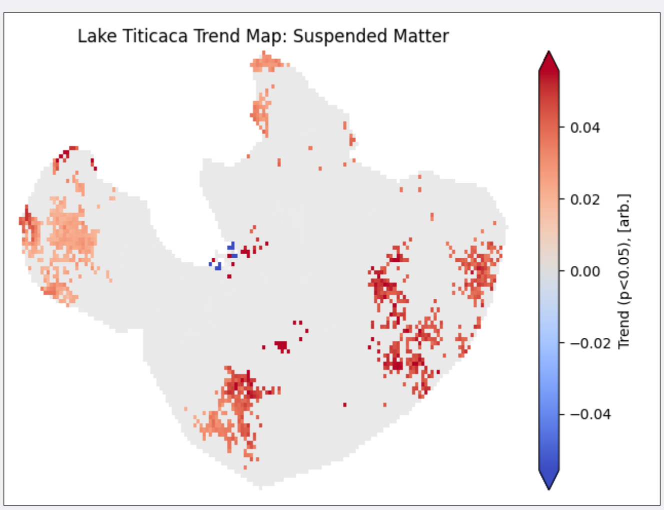
5.1.1 Chlorophyll-*a* [mg/m³]



5.2.1 Turbidity [FNU]

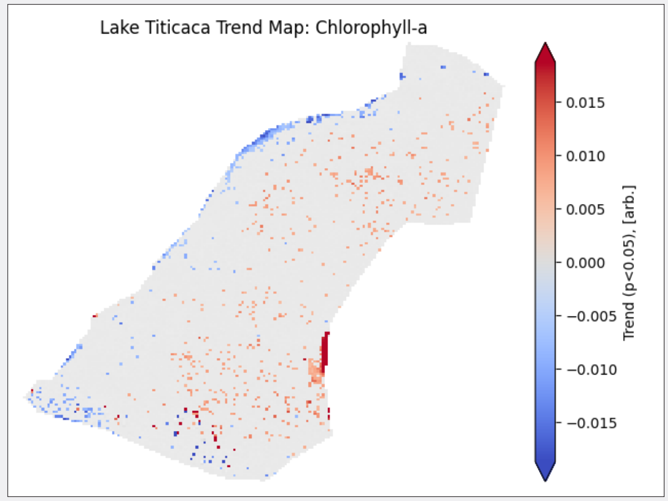


5.3.1 Suspended Matter [g/m³]

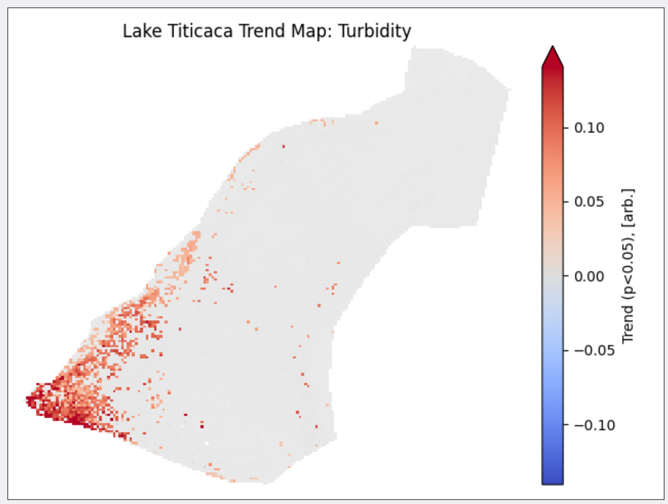


Virtual Gauge 2

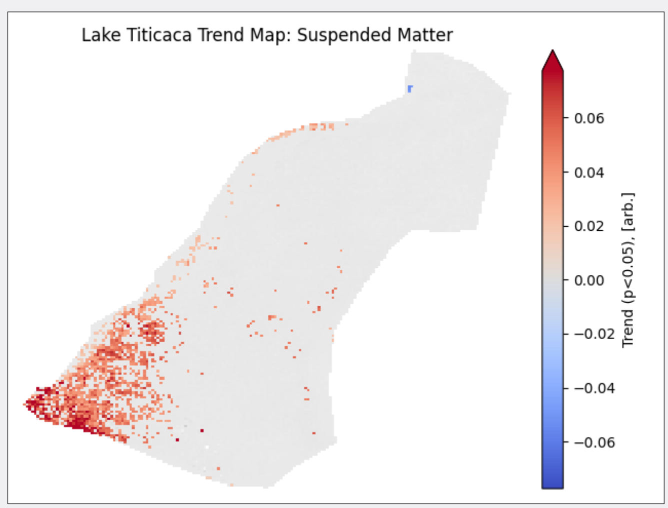
5.1.2 Chlorophyll-*a* [mg/m³]



5.2.2 Turbidity [FNU]

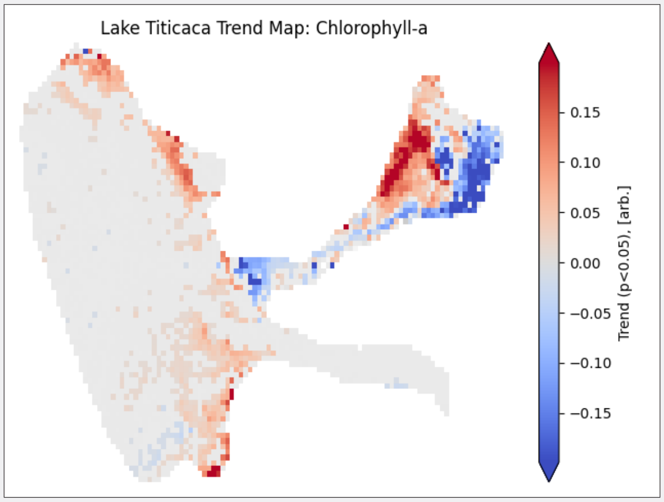


5.3.2 Suspended Matter [g/m³]

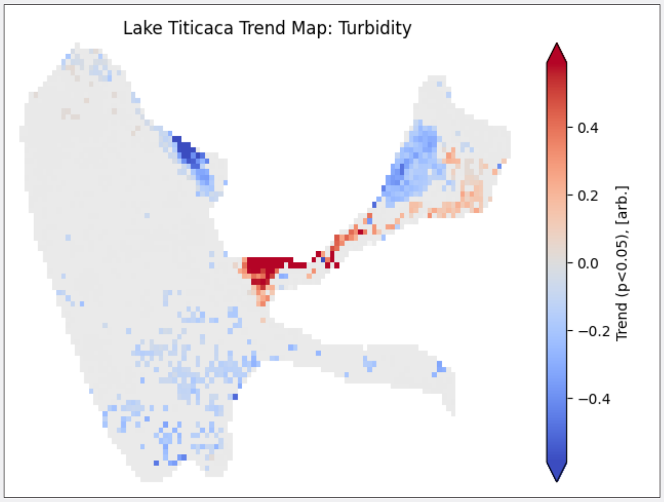


Virtual Gauge 3

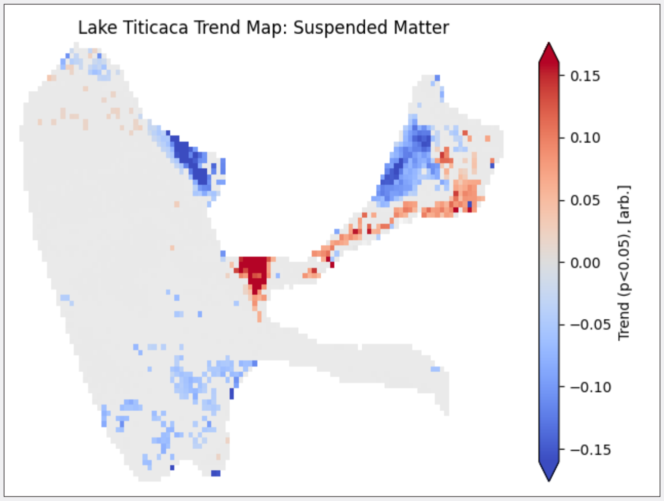
5.1.3 Chlorophyll-*a* [mg/m³]



5.2.3 Turbidity [FNU]

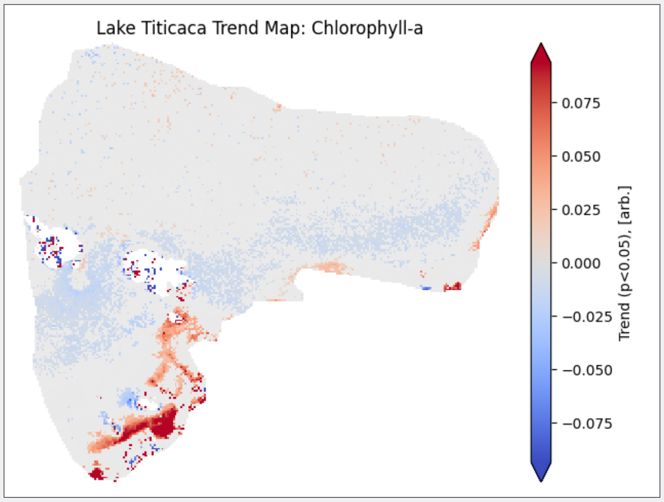


5.3.3 Suspended Matter [g/m³]

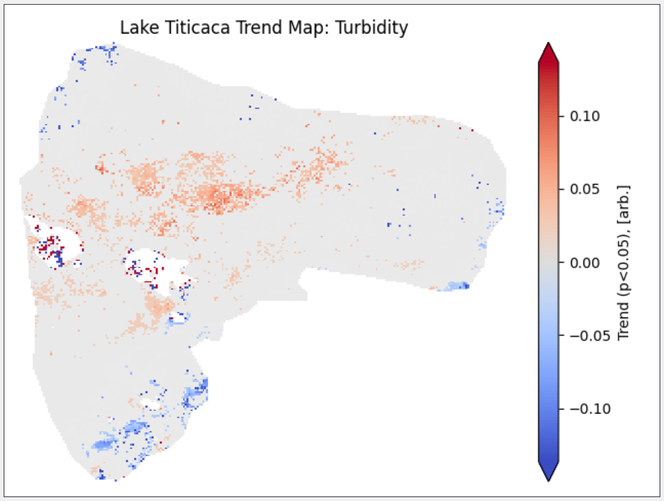


Virtual Gauge 4

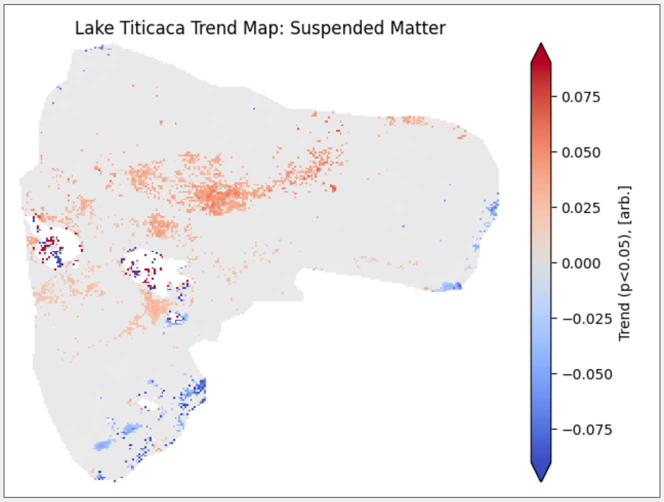
5.1.4 Chlorophyll-*a* [mg/m³]



5.2.4 Turbidity [FNU]

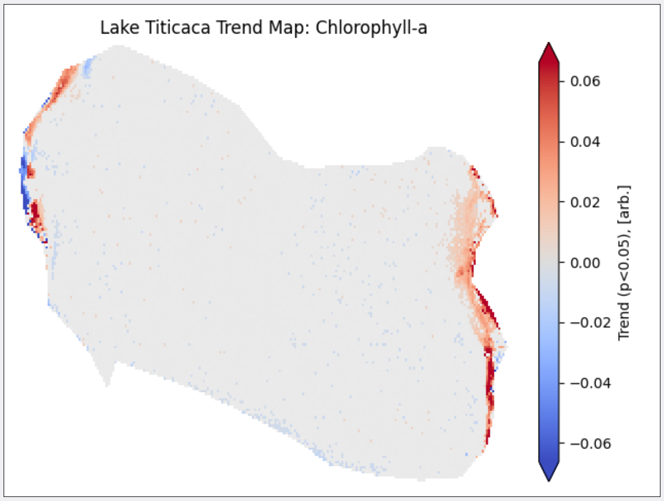


5.3.4 Suspended Matter [g/m³]

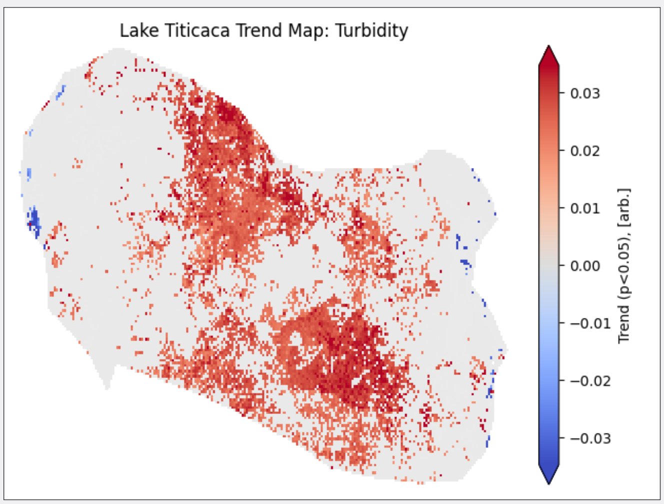


Virtual Gauge 5

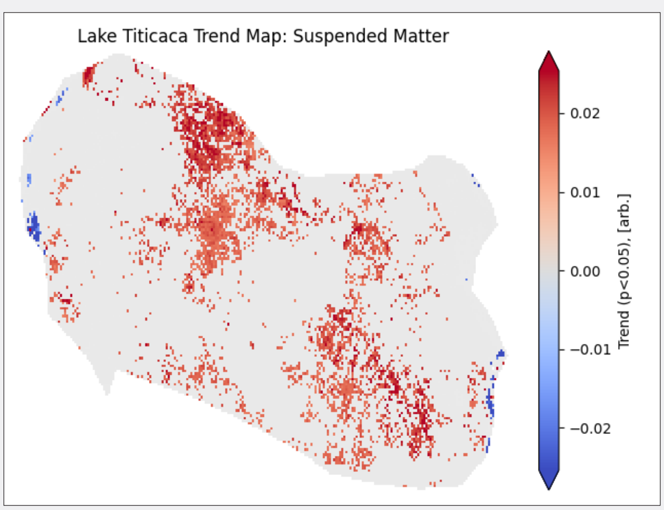
5.1.5 Chlorophyll-*a* [mg/m^3]



5.2.5 Turbidity [FNU]



5.3.5 Suspended Matter [g/m^3]

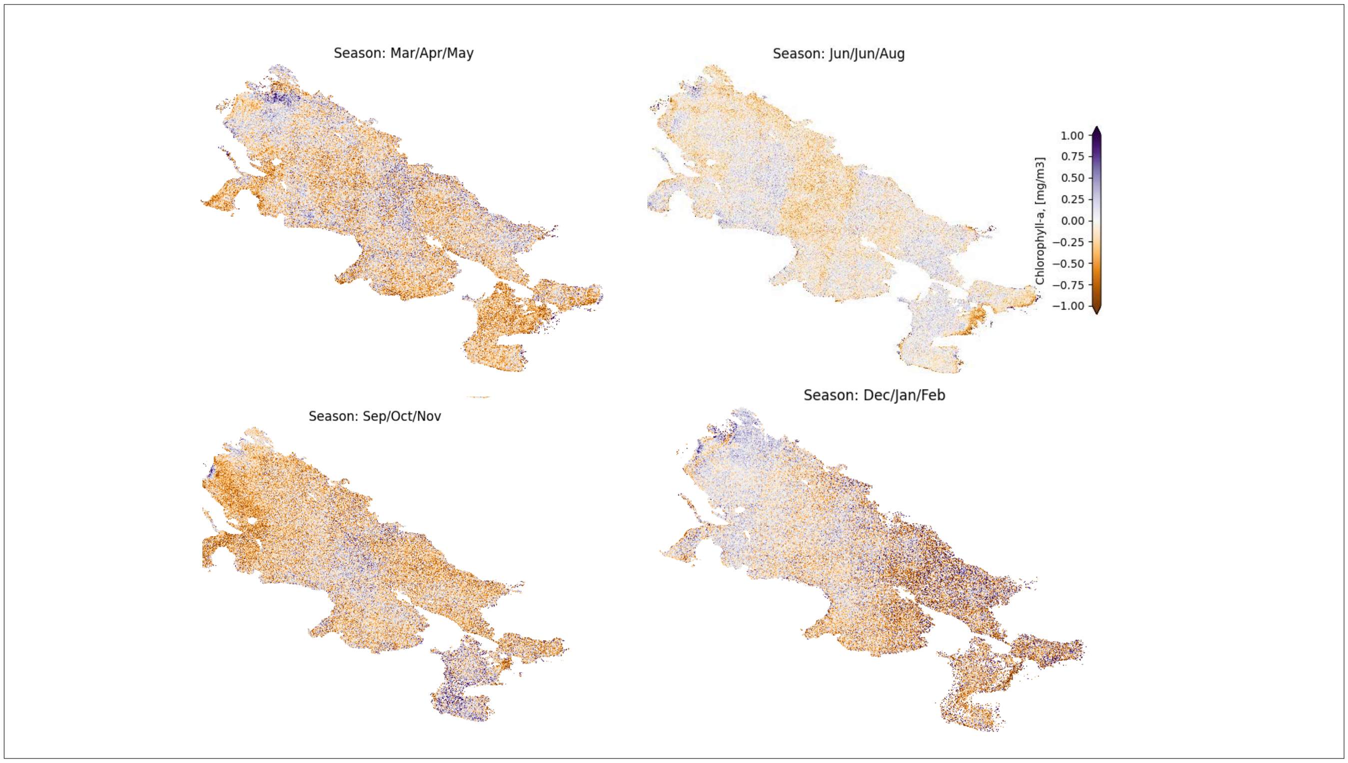


6. Difference Maps

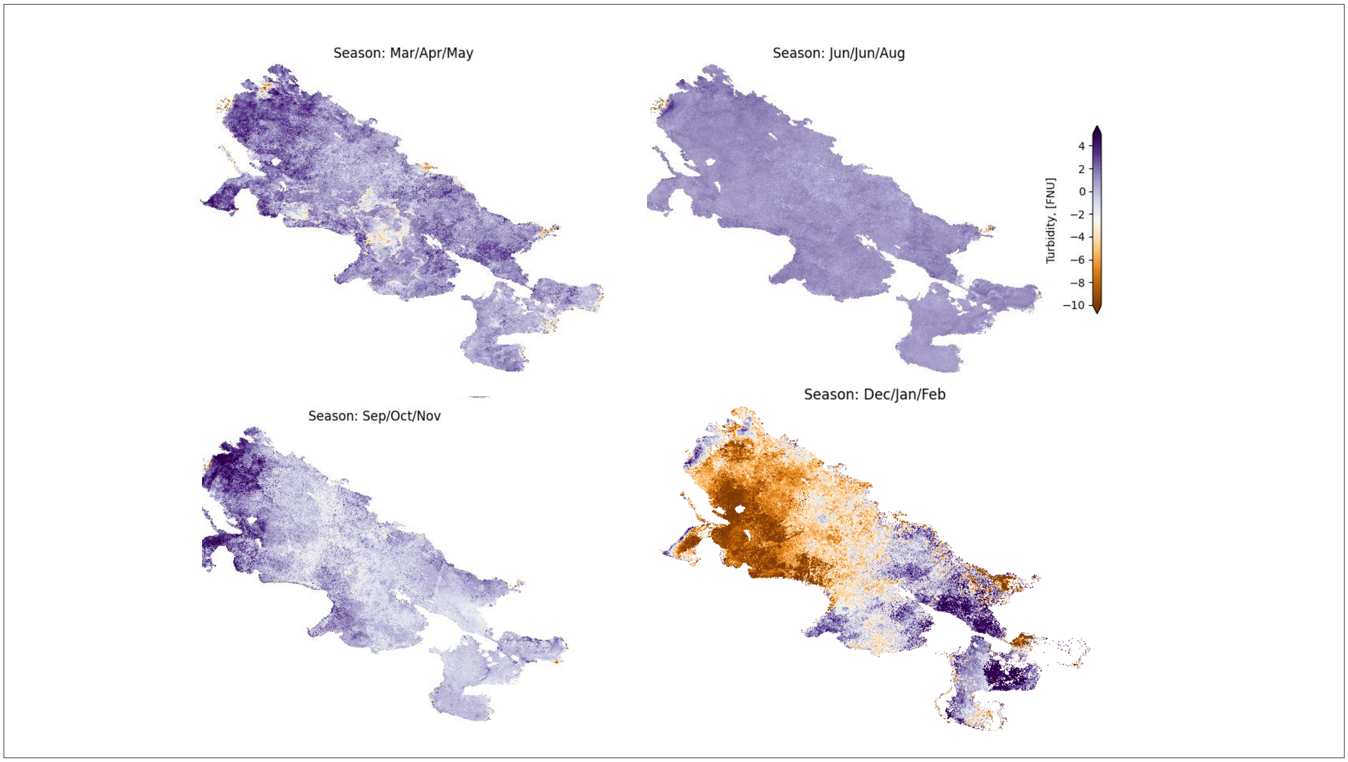
Changes to WQ stemming from Covid-19 lockdown restrictions were assessed using a series of simple one-way analysis of variance (ANOVA) tests. Differences in pre- and post-Covid-19 conditions were tested for at each WQ metric at each virtual gauge location, with pre-Covid-19 lockdown defined as all time series data before March 19, 2020. Both pre- and post-Covid-19 datasets were separated into three-month seasons, with tests performed on each season to control for seasonal variations. Significant differences between conditions were recorded with a ‘p-value’ less than 0.05.

Separately, an assessment of Covid-19 lockdown related differences in WQ was conducted across the entire water body to illustrate general trends not associated with virtual gauge locations. For this, pixel-wise differences were calculated across the entire water body using images downsampled to 30 m pixels. The resulting images illustrate where changes in WQ are observable.

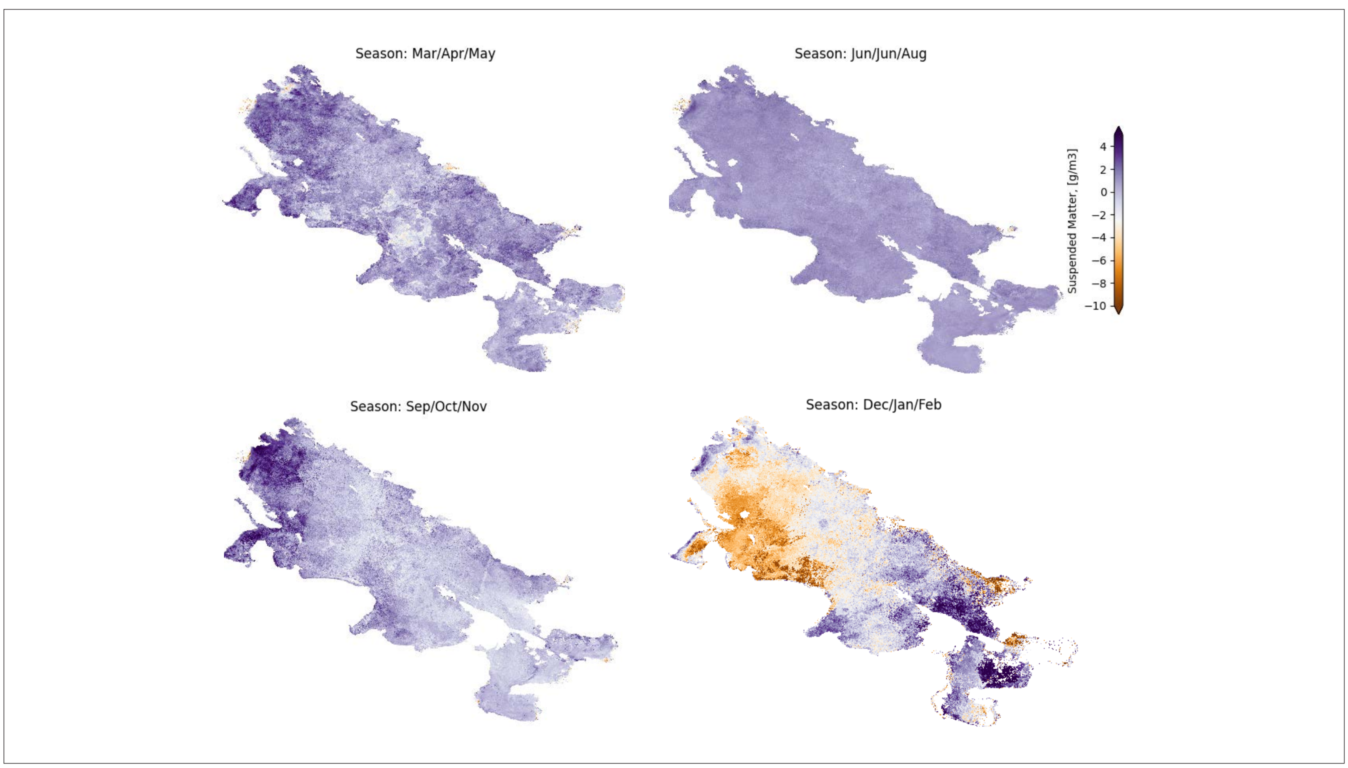
6.1 Chlorophyll-*a* [mg/m^3]



6.2 Turbidity [FNU]



6.3 Suspended Matter [g/m^3]



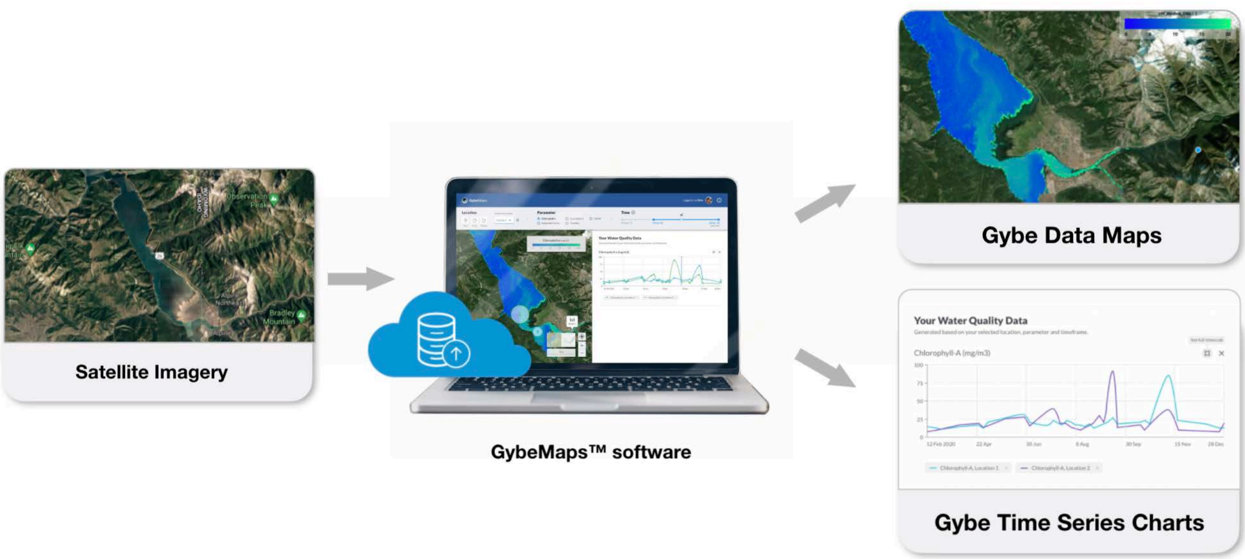
APPENDIX B.

Project Team and Background

PROJECT TEAM
OVERVIEW

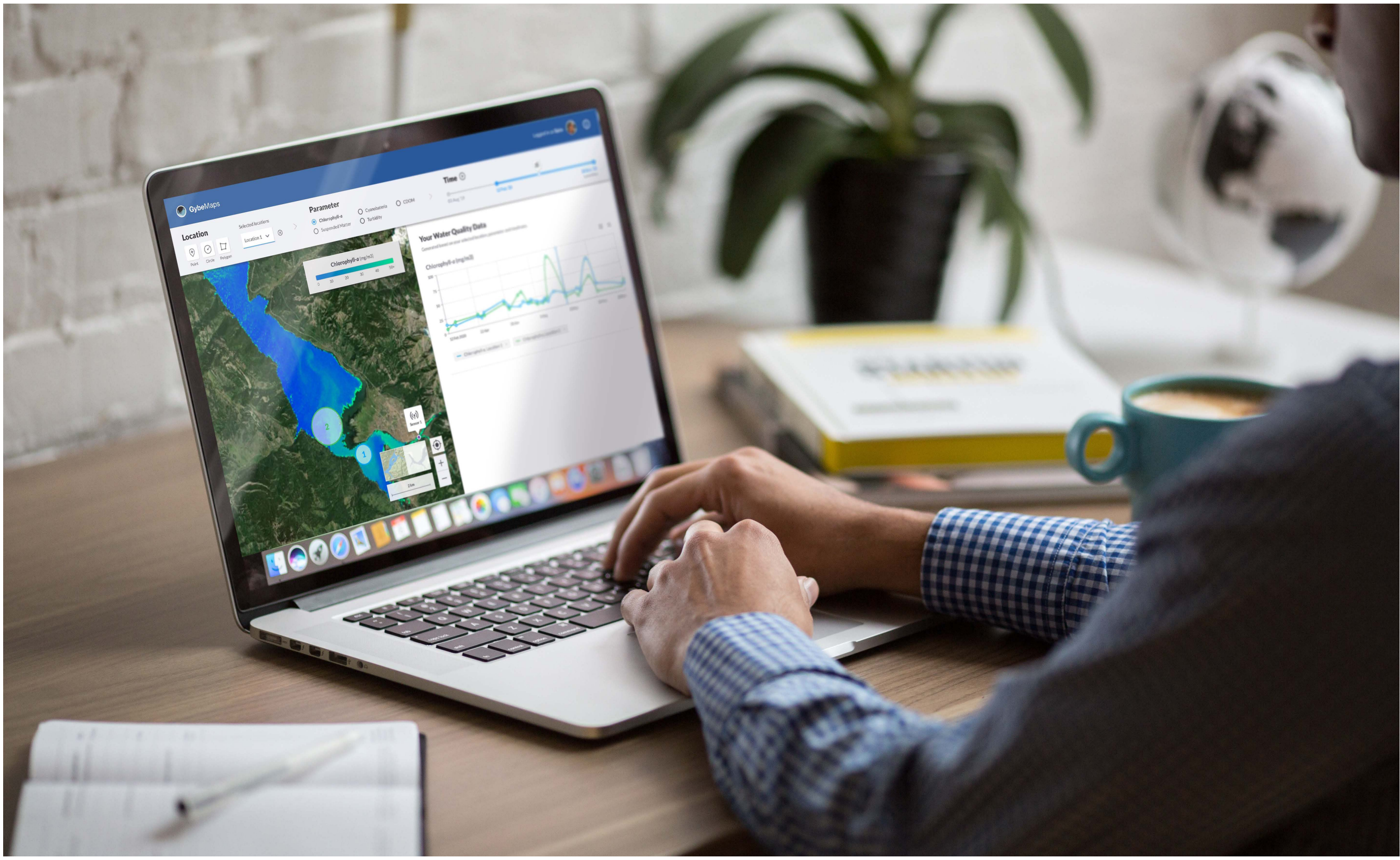
Gybe (Flying Gybe Inc) is a US based technology start-up founded in June 2019, backed by Techstars in Partnership with The Nature Conservancy and Anheuser-Busch InBev through their 100+ Accelerator and the US Department of Energy. Gybe currently provides automated water quality monitoring services based on satellite remote sensing imagery in combination with Gybe's proprietary ground sensor data.

The combined data sets and analytics are delivered through GybeMaps™, an easy to use web platform providing near-real time continuous information for a range of local municipalities, NGOs and private sector customers in the US. Gybe's customers include drinking water and hydro-power utilities, international infrastructure investment NGOs, food & beverage multinationals and conservation NGOs, including The Nature Conservancy.



Gybe currently provides water quality monitoring services to TNC science teams in Louisiana and North Carolina to quantify impacts of conservation and management actions in the Mississippi River basin and on the Cape Fear River, and to develop new methods for tracking and mapping non-point source pollution.

Gybe's experience in measuring water quality from satellite data was demonstrated previously with consulting work in Mexico and Uruguay. In Mexico, the team has worked to assess ongoing initiatives to address surface water pollution around the country, working in partnership with CONAGUA, the national agency charged with water resources management.



Particular focus of this work was placed on identifying a pilot case study application of RS techniques to detection of nutrient related pollution, i.e., Nitrogen, Phosphorus, Chlorophyll-*a*, as those are major water quality issues that have been identified by CONAGUA in terms of pollution of major water sources around the country.

In Uruguay, members of Gybe's team recently completed a case study application in Laguna del Sauce, which supplies water to a number of cities in Maldonado, serving over 400,000 people in peak season. This reservoir has increasingly shown signs of eutrophication, such as algae blooms and overall decreasing water quality, which is affecting water treatment infrastructure as well as public health. Parts of the work in Uruguay and Mexico are published in knowledge briefs by The World Bank.

For additional information on Gybe's autonomous water quality monitoring products, please refer to the web-site: **www.gybe.eco**
or contact by email: **info@gybe.eco**.

Project Team

Ivan Lalović (Chief Executive Officer)

Ivan led engineering, product and customer teams for a number of Fortune 50 and 500 companies including HP, AMD and ASML and worked with semiconductor manufacturers like Intel, IBM and Samsung to achieve higher performance computing and communications. He is now focused on building technologies that transform how we monitor, understand and manage water issues. Ivan is an author of more than 50 papers and 23 US patents.

Dr. Nicholas Tufillaro (Chief Technology Officer)

Nick's career has straddled industry and academia, and has included work at Los Alamos National Labs, HP Labs, Otago University and Oxford. Since 2009, he has focused on applying remote sensing to monitor water resources as a research professor at Oregon State University. His list of publications and patents is available at aquahue.net

Dr. Adam Belmonte (Project Lead, R&D Programs)

Adam is a remote sensing scientist with a diverse background in technological applications for water resource management. Throughout his personal and professional experiences he has chased water in its many forms, from urban green infrastructure to agricultural water rights to snow melt in forests. He is driven to provide actionable, forward-thinking solutions to ensure global long term water security.

Dr. Philipp Grötsch (Head of Product Development)

Philipp is a physicist who has devoted his career to environmental monitoring with a focus on water quality. For most of his professional life, he's been bridging the gap between cutting-edge scientific research and its timely application to real-life problems in industry. His mission is to raise environmental awareness and advance the transition to a data-driven green economy.

Sara De Moitié (Head of Design)

Sara De Moitié is a strategic and user centered designer. She has experience in marketing, UX, UI and graphic design, working at every stage across the design and development process, from front end strategy to detailed design and development. She has also worked as a coach for startups and has taught design thinking in several university courses, including a year long master's course at Aalto and Stanford University.

APPENDIX C.

Covid lockdown information

APPENDIX D

LOCKDOWN INFO

1. Buenos Aires, Argentina

La cuarentena obligatoria (Buenos Aires):
17/03/2020 - 07/11/2020

Un confinamiento breve para atajar la segunda ola de coronavirus (Buenos Aires):
22/03/2021-31/03/2021

<table>
<tr><th colspan="10">2020</th><th colspan="9">2021</th></tr>
<tr><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>July</th><th>Aug</th><th>Sep</th></tr>
<tr><td colspan="5">Cuarentena Obligatoria</td><td colspan="7">Buenos Aires pasa al esquema de Distanciamiento Social.</td><td>Confin.</td><td>Solo finde</td><td colspan="5">Distanciamiento Social.</td></tr>
</table>

Breve confinamineto en 2021: 22/05/2021. De esta forma se restringe la circulación en esas zonas del país, permitiendo únicamente circular en las cercanías a los domicilios entre las 6 y las 18 hs, salvo razones especialmente autorizadas. Las personas deberán permanecer en sus residencias habituales y solo podrán desplazarse para aprovisionarse de artículos de limpieza, medicamentos y alimentos y otros artículos de necesidad en los comercios esenciales. Queda suspendida la presencialidad en las actividades económicas, industriales, comerciales, de servicios, culturales, deportivas, religiosas, educativas, turísticas, recreativas y sociales. Estas medidas regirán desde el sábado 22 de mayo a las 0 horas hasta el domingo 30 de mayo inclusive. A partir de ese día y hasta el 11 de junio, se continuarán con las medidas vigentes hasta el 21 de mayo, retomando las restricciones mencionadas el fin de semana correspondiente a los días 5 y 6 de junio.

Source: Central Government website - medidas gobierno
https://www.argentina.gob.ar/coronavirus/medidas-gobierno

2. Asunción, Paraguay

La cuarentena total, denominado oficialmente Aislamiento Preventivo General:
20/03/2020 - 03/05/2020

Cuarentena intelignete (Asunción):
04/05/2020 - 24/05/2020 (fase 1)
25/05/2020 - 14/06/2020 (fase 2)
15/06/2020 -22/08/2020 (fase 3)

Cuarentena social (Asunción):
23/08/2020 - 04/10/2020

Nueva Normalidad:
05/10/2020 - hoy

Zonas rojas (Asunción):
18/03/2021 - 26/03/2021
27/04/2021 - 10/05/2021

2020										2021								
Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
Cuarentena Total		CI F1*	CI F2*	CI F3*		Cuarentena social		Nueva normal				Zona Roja		Zona Roja				

Cuarentena total
Paraguay (incluyendo Asunción) entró en cuarentena total el 20 de marzo de 2020 al confirmarse la transmisión comunitaria en el país, restringiéndose totalmente la libre circulación, a excepción de casos de necesidad o urgencia y quedaron exceptuados ciertos trabajadores, especialmente de servicios básicos (supermercados, farmacias, estaciones de servicio, entre otros). Toque de queda: 24 hs.

Cuarentena intelignete
La 'Cuarentena Inteligente', denominada oficialmente 'Plan de Levantamiento Gradual del Aislamiento Preventivo General', consiste en la liberación de ciertos sectores laborales (y por fases) para la activación paulatina y monitoreada de la economía, bajo estrictas medidas sanitarias que fue presentado el 24 de abril y que rige desde el 4 de mayo. Está compuestas por cuatro fases, en el que cada 21 días se analizará la situación epidemiológica y la conducta cívica para ir liberando las demás fases gradualmente. (fase 1: de preparación, fase 2: leve, fase 3: moderada). Toque de queda: 21:00 a 05:00 (fase 1,2) / 23:00 a 05:00 (domingos a jueves) 00:00 a 05:00 (viernes y sábados) (fase 3)

Cuarentena social
El 20 de agosto de 2020, el ministro de Salud Julio Mazzoleni anunció que desde el lunes 24 de agosto hasta el domingo 6 de septiembre regiría nuevas restricciones, especialmente para el ámbito social, llamado ""Cuarentena Social"", a ser aplicadas en Asunción y el departamento Central por quince días. El 4 de septiembre es prorrogada hasta el 20 de septiembre. El 18 de septiembre es prorrogada hasta el 4 de octubre. Toque de queda: 20:00 a 05:00

Nueva Normalidad
Según lo anunciado el 2 de octubre de 2020 por el ministro de Salud, se deja atrás las fases de la Cuarentena en todo el país, para avanzar a una especie de nueva normalidad conocida como el ""modo covid de vivir"", liberando la mayor parte de las actividades pero manteniendo los cuidados sanitarios. Toque de queda: 00:00 a 05:00

Zonas rojas
El 18 de marzo al 26 de marzo de 2021, el Ministerio de Salud Pública y Bienestar Social señaló como ""zonas rojas"" los districtios incluyendo Asunción. El 27 de abril al 10 de mayo de 2021, el Gobierno volvió a establecer nuevas medidas en las zonas rojas, incluyendo Asunción. Toque de queda: 20:00 a 05:00"

Source: MINISTERIO de SALUD PÚBLICA y BIENESTAR SOCIAL
https://www.mspbs.gov.py/dependencias/portal/adjunto/36a471-DecretoN3478MedidasSanitarias.pdf
https://dgvs.mspbs.gov.py/
https://es.wikipedia.org/wiki/Confinamiento_por_la_pandemia_de_COVID-19_en_Paraguay#cite_note-10"gobierno

3. La Paz/El Alto, Bolivia

Cuarentena total:
29/04/2020 - 31/05/2020*
(not as strict as other countries or Oruro and Santa Cruz)

Cuarentena dinámica:
01/06/2020 - 31/08/2020
*16/07/2020 - 19/07/2020 (cuarentena rígida)

Post confinamiento:
01/09/2020 -

2020										2021								
Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
	Cuarentena total		Cuarentena dinámica			Post confinamiento												

Cuarentena dinámica en la Paz: la presente Ley Municipal establece una serie de medidas que deben ser aplicadas para prevenir la propagación y contagio comunitario del COVID-19 en el Municipio de La Paz, conforme la población vaya retomando sus actividades, con autorización estatal y bajo regulación de la normativa vigente; a cuyo efecto, se establecen facultades del Órgano Ejecutivo Municipal del Gobierno Autónomo Municipal de La Paz, a ser ejercidas en el marco de la Cuarentena Dinámica Condicionada, haciendo uso de sus atribuciones, determinará parámetros mínimos e indispensables de responsabilidad y cultura ciudadana de los habitantes del municipio.

Post Confinamiento: En el marco del ingreso a la fase post confinamiento establecida en el Decreto Supremo N° 4314, se disponen medidas a ser implementadas a partir del 1 de septiembre de 2020 en el Municipio de La Paz, conforme a lo dispuesto) ." e .los artículos siguientes del presente Decreto.
El horario permitido para la circulación peatonal, se extiende de horas 05:00a 20:00 de lunes a viernes.

*although the second wave hit hard La Paz around Nov-Dec 2020, they refused to decree a quarantine.

Source: Observatorio Covid 19 - La Paz gobierno
http://observatoriocovid19.lapaz.bo/observatorio/index.php/component/phocadownload/category/11-politico

4. Rio de Janeiro, Brazil

2020 Lockdown in Rio:
10/05/2020 - 24/05/2020

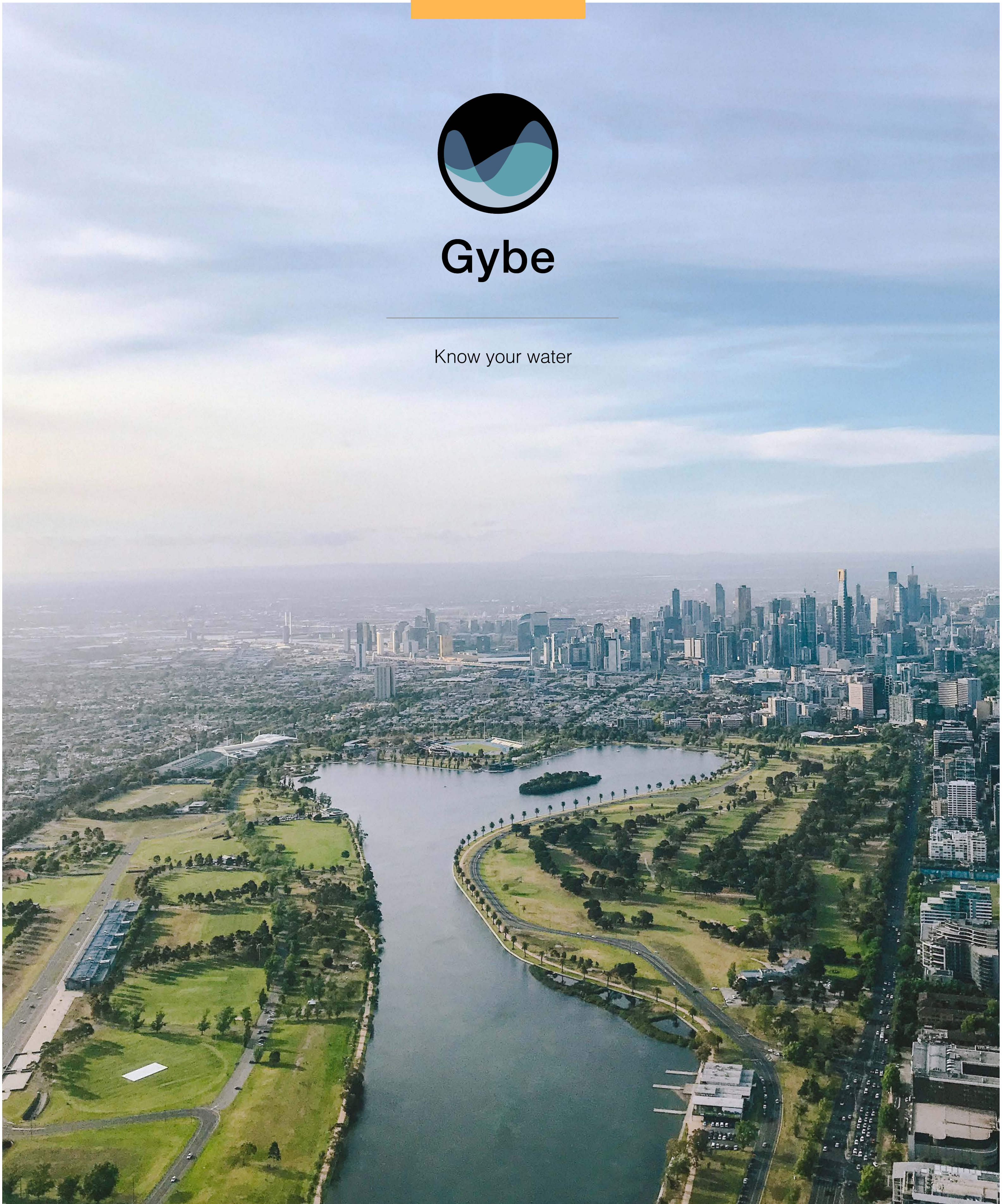
2021 Lockdown in Rio:
20/03/2021 - 04/04/2021

2020										2021								
Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
		Lock-down										Lock-down						

2020: No Rio de Janeiro, o lockdown foi adotado no município de Niterói, por um decreto do prefeito Rodrigo Neves (PDT), com previsão de início após o Dia das Mães (10 de maio). só será permitida apenas a passagem de profissionais de saúde e da segurança do trabalho, salvo os casos urgentes de cidadão comum. O bloqueio terá início no dia 18 de maio, com término previsto para o dia 24.

2021: Em 19 de março, a Prefeitura de Campos dos Goytacazes, no Norte Fluminense, anunciou o fechamento do comércio da cidade, no qual começou em no dia seguinte. De acordo com o município, desde o dia 19, a localidade está com 100% de ocupação nos leitos clínicos e de UTI e vive a iminência da falta de medicamentos específicos para intubação de pacientes e a possível falência do sistema funerário. O documento publicado restringe, até o dia 4 de abril, o funcionamento de bares, quiosques, depósitos de bebidas, restaurantes, lanchonetes, pizzarias e similares.

Sources
https://pt.wikipedia.org/wiki/Lockdown_no_Brasil_em_2020
https://pt.wikipedia.org/wiki/Lockdown_no_Brasil_em_2021



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