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Biomass Phytoplanktonic in Sem-enclosed Bay of Diégo-Suarez, Madagascar Using Sentinel-2 MSI Satellite: Application to Ocean Color Observations

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Abstract

The use of remote sensing to monitor coastal waters and their current state is of high importance, as fresh waters are the habitat of many species of flora and fauna, and are also important for anthropogenic activities.

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Water quality can be monitored by many parameters, including dissolved suspended matter, phytoplankton, water colour (FU), and dissolved oxygen, while the concentration of Chlorophyll-a (Chl-a) is a representative indicator for proxy phytoplankton and monitoring water quality.

The detection of phytoplankton in water layers, through Chl-a indicators, is an effective method for displaying eutrophication. Numerous scientists and studies have shown that remote sensing data and techniques are capable of monitoring the temporal and spatial distribution and variation of this phenomenon.

This study aimed to investigate the monitoring of waters quality in Diégo-Suarez Bay, in Antsiranana, Madagascar with the application of Chl-a detection algorithm (C2RCC-C2X-Net), by using Sentinel-2 satellite imagery data for the seasons summer (February 14), winter (June 16) and inter-season time (22 October) 2023. The maximum chlorophyll index (MCI) algorithms have been applied to top of atmosphere (TOA) reflectance data, to detect Chl-a and monitor the trophic range of the water. Both algorithms were correlated and resulted in Pearson’s r values up to 0.82. Finally, the Chl-a concentration was estimated by applying an empirical equation that correlates the MCI and Chl-a concentration developed within previous studies.

Those results were further analyzed and interpreted with spatial statistical methods, to understand the spatial distribution pattern of the quality and proxy of biomass phytoplanktonic in our study area. Our results demonstrated that the highest Chl-a concentration was located in the South-west southeast of the Diégo-Suarez Bay during the study period. Sentinel-2 data can be a useful tool for lake managers, in order to estimate the spatial distribution of the Chl-a concentration and identify areas prone to eutrophication, as well as the coastal zones

Keywords: Diégo-Suarez Bay; Chlorophyll-a; MCI sentinel-2; remote sensing; C2X-Net.

1. Introduction

The Diégo-Suarez Bay is a semi-enclosed bay bordering Antsiranana city in northern of Madagascar. The bay provides economic benefits from tourism, traffic maritime to fishing[1].

In these coastal waters are major carbon, nutrients and total suspended Dissolved reservoirs; support diverse species in multiple habitat; provide a wide range of ecosystem services and function as natural barriers for the protection of coastal areas from extreme climate events, including floods, tropical cyclones[2]. Simultaneously, it is under heavy anthropogenic pressure from nearby industries, cities and other inputs from various human activities [1].

An enrichment of nutrients results in an increase in the eutrophication of the sea. Additionally, a growing coastal population is leading to increased anthropogenic pollution that greatly affects coastal [2]. However, these coastal aquatic ecosystems are increasingly vulnerable. The phytoplankton are firstly victims of human activities and natural disasters[3].

The Chlorophyll-a (Chl-a) pigment concentration is common to all microscopic algae in the aquatic ecosystems and considered an indicator of the abundance and quality of phytoplankton biomass also an important parameter to characterize degree of eutrophication in the water [4,5].

Marine phytoplankton play also an important role in global carbon cycle via carbon pump[6] and biogeochemical cycle. The monitoring of water quality using in situ observations of Chl-a and measuring parameter physics and chemics are expensively. Traditional methods of extracting samples from the coastal based on sampling points and subsequent laboratory studies are costly, laborious, and slow; and cannot adequately assess the entire water [5].

To overcome these limitations, the challenge lies in incorporating water quality monitoring methods with regular, almost real-time, cost-effective, automated, and noninvasive approaches with adequate spatiotemporal coverage.

Remote sensing techniques allow various sampling locations to be covered, information on often inaccessible points to be obtained, and quick assessment of the ecological status of the water, which is advantageous over traditional studies involving sampling and subsequent laboratory analysis. The capabilities of these satellite images can be exploited in various areas to survey different phenomena at large scales and detect variations in the water resources in both ground and surface sea [5].

The launch of the first ocean color sensor Coastal Zone Color Scanner (CZCS) in 1978, started for passive satellite ocean color remote sensing[7], the oceanographers and scientists were capable to estimate characteristic physic, chemics, biologics and biogeochemical on global ocean. Satellite technology, including the MultiSpectral Instrument (MSI) sensor onboard Sentinel-2, enables and freely the continuous monitoring of these variables in inland and coastal waters at high spatial and temporal resolutions.

To improve the monitoring of water quality and phytoplankton biomass in the Diégo-Suarez Bay to estimate Chl-a and Total Suspended Matter (TSM) concentrations using C2X-Net neural algorithm.

2. Materials and Methods

2.1. Study area

Diégo-Suarez Bay is situated part the extreme North-East coastal of Madagascar (12°8.486'S-12°19.734'S, 49°22.786'-49°11.106'E) and extends approximately 178.35 Km^2. It was composited 6 Islets (Nosy Volana, Langoro, Lonjo, Loapasana, Koba and Nosy Fano).

Diégo-Suarez Bay is a four-leaf clover'shape and it composed 4 smallest bays: Tonnerre, Cailloux Blancs, Cul de sac Gallois and French bay (**Figure 1**). Additionally, it has also semi-enclosed with connections to the Indian Ocean at Nosy Volana (ST) in Tonnerre Bay.

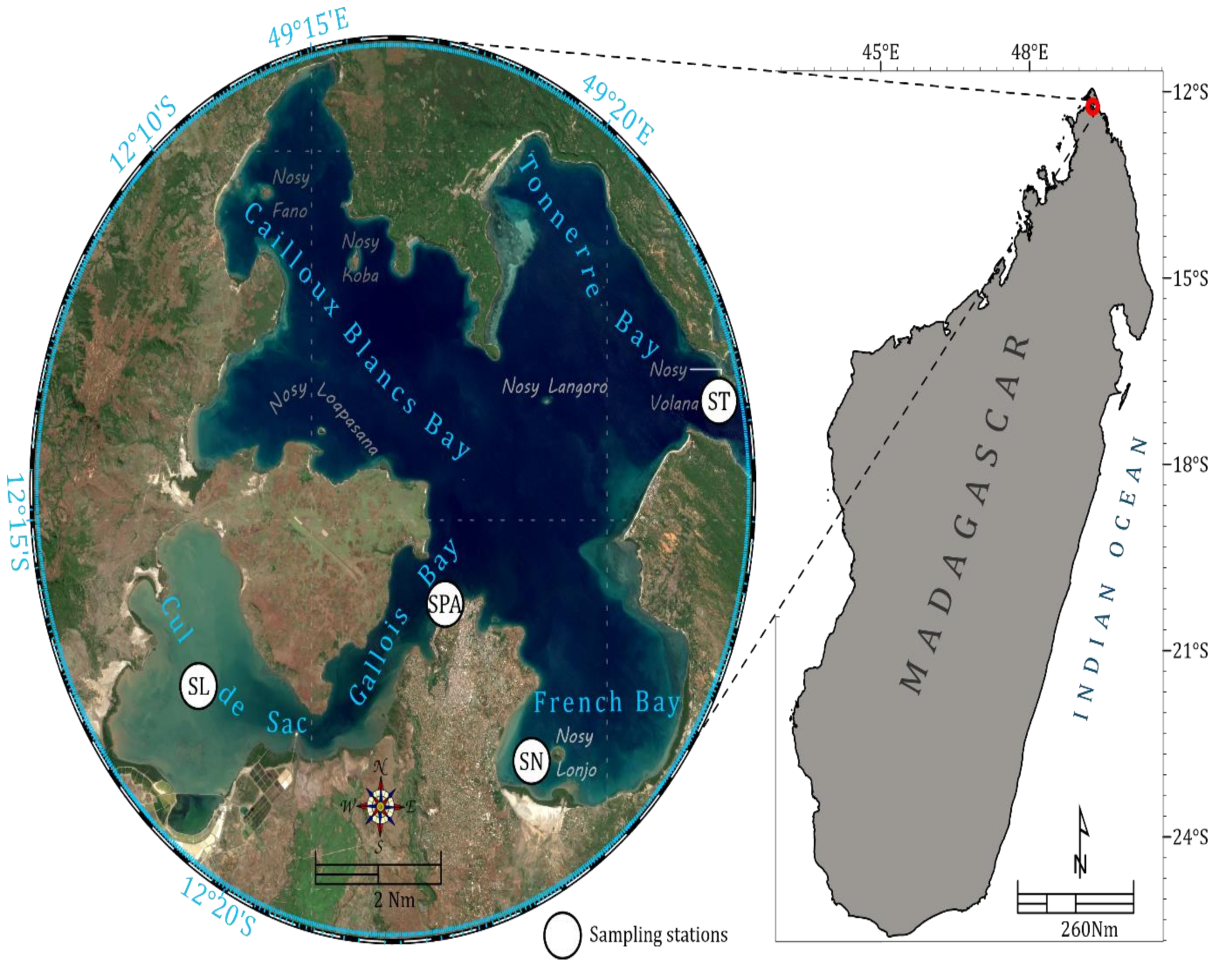

Figure 1: Map of the study area of Diégo-Suarez Bay and in situ sampling locations are represented as white points. (SL) Saline Station, (SPA) Port Station, (SN) Lonjo Station and (ST) Temoin station

Cul de Sac Gallois Bay (SW) is mostly shallow and semi-enclosed. The area is under the influence of effluents from the coastal city of Antsiranana. Rivers are the main sources of pollution from heavy industry in the adjacent areas.French Bay (SE) is mostly semi-enclosed and it communicate of Tonnerre Bay (**Figure 1**). The area is under the influence of effluents from the coastal city of Antsiranana. And river drain via Betahitra. Cailloux Blancs (NW) and Tonnerre Bay (E) are open areas in the Western and communicate with Indian Ocean. Tonnerre Bay with deeper parts of the sea open and it is heavily influenced by currents and waves.

The depth of the bay ranges from 5.3 to 24.3 m at most locations, except for the main shipping channels near Nosy Volana, which are maintained at depths of 22.4 to 78.8m on Tonnerre Bay (**Figure *2***). Betahitra river, Caïman, Antsahalina, Antsahampano, Main, and Maques rivers are drain into Diégo-Suarez at Cul de Sac of Gallois bay. The annual cycle in Diégo-Suarez is characterized by dry season in winter (December–February), an inter-monsoon (March–May), and wet season.

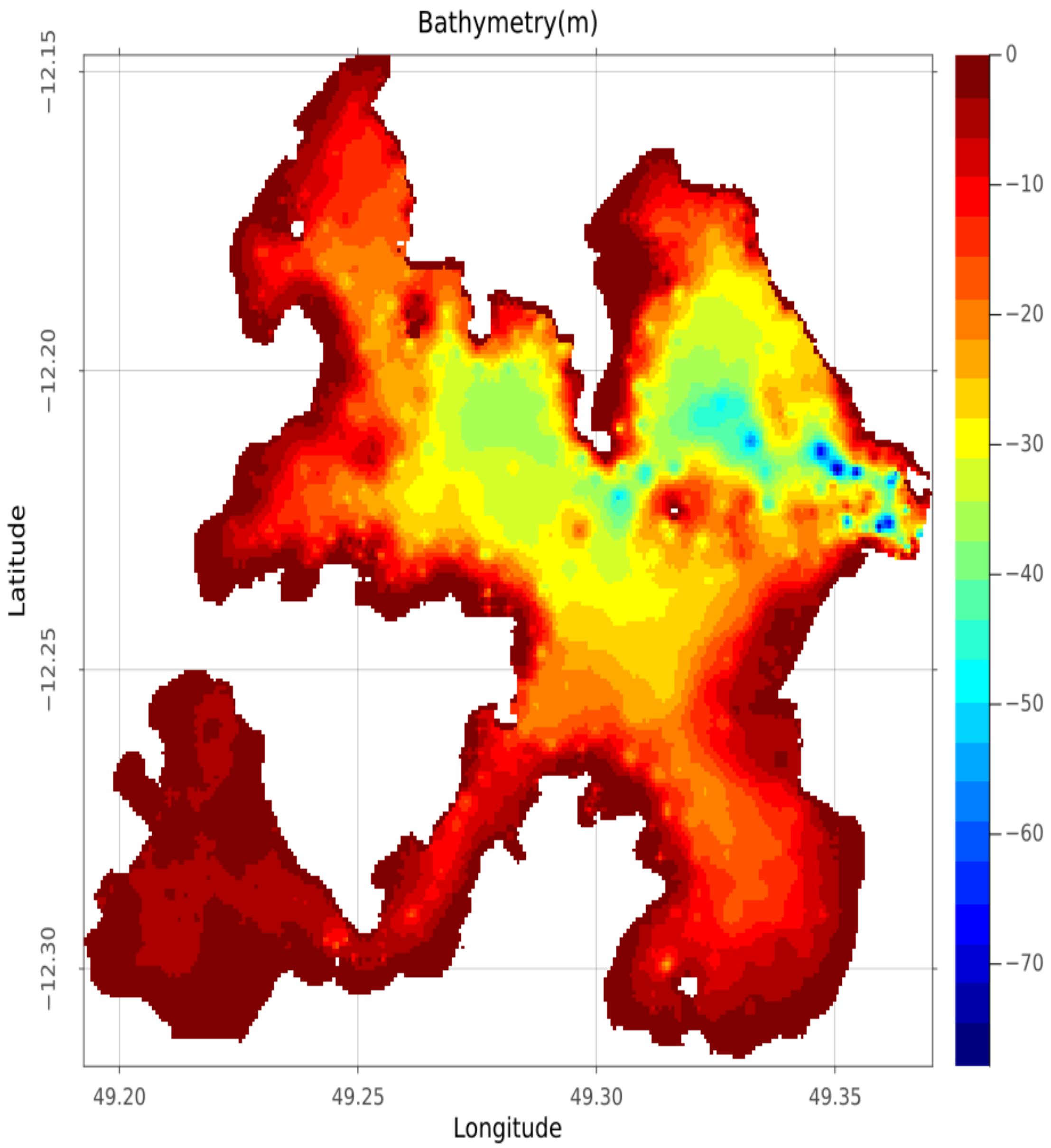

Figure 2: Bathymetry of Diégo–Suarez Bay

2.2. Satellite S2 MSI data

Sentinel-2A and -2B Multispectral Imager (MSI) are satellite of ESA's Copernicus from Earth observation program based on a constellation of two satellites with a swath width of 290 km[8]. The Sentinel-2 (S2) mission provides enhanced continuity to services relying on optical multi-spectral high spatial resolution observations over global land and coastal regions. The S2 mission operates two twin satellites simultaneously: Sentinel-2A and Sentinel-2B respectively operational since 2015 and 2017[5].

Each instrument has a multispectral sensor (MSI) that contains 13 bands, with spatial resolution 10,20 and 60m, Level-1C (L1C) and revisit 5 days at equator[5], [9]. In this study covers the period from February, June and October 2023, with all S2 imagery <30% cloud cover at the L1C processing level were downloaded from the Copernicus Open Access Hub (https://scihub.copernicus.eu). According to [9], L1C product were resampling at 10-20 m spatial resolution of Sentinel-2A and -2B using a scientific image processing toolbox via SeaDAS 9.1. After, these images were processed with AC processors C2RCC (v1.2) in SeaDAS and it a comprehensive software package developed by NASA OB.DAAC for the processing, display, analysis, and quality control of remote-sensing Earth data via (seadas.gsfc.nasa.gov).

The C2RCC was developed by Doerffer and Schiller in 2007 [10] is based on deep learning approaches.

It is a neural-network-based atmospheric correction processor which provides the results of water-leaving reflectance (ρw), inherent optical properties (IOPs), Chl-a, and total suspended matter (TSM)[1,11] and provides the possibility to add additional background information such as salinity, elevation, ozone, temperature, and air pressure[12].

For this study, the salinity and Temperature were set respectively to 34 (PSU) and 27°C which is different from the default setting. Here, the Chl-a and TSM outputs (conc-chla and TSM product) of C2RCC were used. To monitor the eutrophication, we applied detection algorithms, the Maximum Chlorophyll Index (MCI). The MCI was originally developed for MERIS sensor data with the purpose to produce daily data for tracking, detecting, and mapping phytoplankton biomass.

The MCI measures the height of its peak reflectance at 705 nm of the electromagnetic spectrum, while it is used as a baseline for the range between 665 nm and 740 nm regions for Sentinel-2 bands. The width of the peak near 705 nm is associated with high levels of Chl-a in oceans, coastal, and terrestrial waters, as has emerged through surveys and studies. The MCI applied to Sentinel-2 data is described by the following [13] equation:

$$MCI = R_{705} - R_{665} - 0,53*\left(R_{740} - R_{665}\right) \qquad (1)$$

2.3. In situ data

An multiparameter sound 556 MPS was used for the measurement of physicochemical parameter (Total Dissolve Suspended (TDS), pH, Salinity (SAL), Dissolved oxygen (DO) and Sea Surface Temperature (SST). The samples were collected on seasonally (summer (February), Winter (June) and interseason(October) at 04 different locations in Diégo-Suarez Bay (**Figure 1**; n = 12,

Table *1*) as part of an ongoing study.

The FU classification of water colour was estimated using a 3D-printed mini Secchi disk [9,14,15], developed by Bob Brewin and his colleagues [14]. Additional samples 14 February, 24 June and 22 October 2023 were coincided MSI S2 and it used to validate remote sensing observations.

Table 1: Date acquisition of images and in situ observation of this study

	Sentinel -2A			Sentinel-2B	
Season	**Field date**	**Image date**	**Time**	**Image date**	**Time**
				2/14/2023	11:10
Summer		2/19/2023	10:18	2/19/2023	10:18
	2/14/2023		9:15	2/24/2023	6:09
	6/24/2023		9:00	6/4/2023	10:48
Winter		6/19/2023	10:39	6/14/2023	10:47
				6/24/2023	11:59
		10/7/2023	10:48	10/2/2023	13:19
Inter-season		10/27/2023	11:16	10/12/2023	10:55
	10/22/2023		9:26	10/17/2023	10:39
				10/22/2023	9:13

In the laboratory, chlorophyll-a concentration (Chl-a), water samples were filtered through GF/F and filters were subsequently in 90% acetone solvent for 24 h at -20◦C and the concentration of Chl-a [16]. The absorbance in three replicates was measured at 750, 664, 647, and 630 nm in a Double beam UV-Visible (UV-2600, Shimadzu, Japan) spectrophotometer, and then the chlorophyll-a concentration ($mg.m^{-3}$) was calculated according to [17], [18] using a equation:

$$\mathrm{Chl-a(mg.m^{-3})} = \frac{\left[(11,6 * OD_{665}) - (1.31 * OD_{645}) - (0,14 * OD_{630})\right]\nu}{V \times L} \quad (2)$$

OD : absorbance after substraction from the absorbance at 750nm

ν = 15 mL : volume of acetone (mL)

V : volume of filtered water (mL)

L : path length of the cuve (cm)

2.4. Data analyses

Julia 1.10.4 was used to find significant difference in concentration parameters among all stations using one-way Analysis of Variance (1-way ANOVA). Simple linear correlation-regression was established for the relationship between, S2 Chl-a vs in situ Chl-a, MCI vs Chl-a and S2 Chl-a vs S2 TSM. One ways ANOVA and significance values were set at $p < 0.05$ used in this study and its significance ($p < 0.05$) were calculated using linear regression and Student's t-tests following[9]

3. Results

3.1. Physic and chemical in situ

In situ data observation values by stations are showing in **Figure 3**. Seasonally Salinity (PSU) values in SL, SN, SPA and ST stations oscillates respectively 31.10-37.10(34.13±3), 31.75-34.40(32.72±1.46), 29.3-34.10(31.27±2.56) and 33.75-34.36 PSU (34.1±0.32 PSU). In Diégo-Suarez Bay, Dissolved Oxygen (mg. L^{-1}) concentration for each station corresponding with 8.14±1, 8.99±0.47, 7.37±1.44 and 8.62±0. 83mg.L^{-1} respectively in SL, SN, SPA and ST stations. The pH of seawater ranged from 7.91-8.20, 7.22-7.67, 7.80-8.38 and 7.97-8.10 respective in SL (Cul de Sac Gallois bay), SN (French Bay), SPA and ST (Tonnerre Bay) and 31.86±1.23, 31.81±3.23, 23.85±6.63 and 27.910±4.6 g.$L^{-1}$of total dessous suspended. Sea surface temperature change with seasons in Diégo-Suarez. Summer, the SST oscillates 27.2 to 30.1°C; 26-27.33°C in winter and 27.28-27.81°C in interseason of each station. Finally, Forel-Ule classification of water colour (FU) for seawater in Diégo-Suarez Bay range from 4-13 FU. The details of our results per station are summarized in heatmap (appendix).

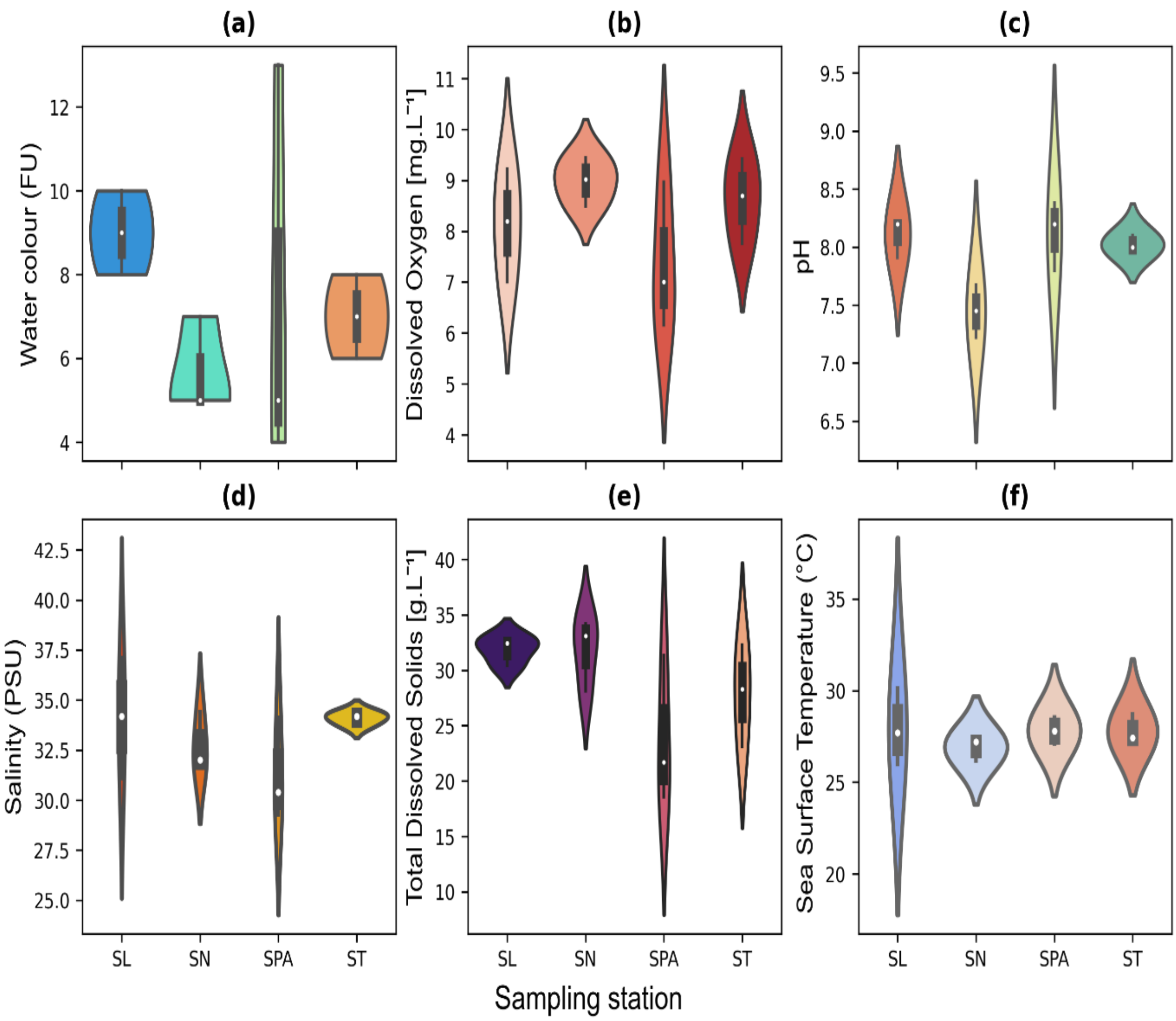

Figure 3 : *In situ* observations. Violin represent the IQR of parameters values, the white dots represent the median, the whiskers represent the minimum and maximum values. (a) water color class [FU]; (b)

dissolved oxygen [DO]; (C) pH; (d) salinity [SAL]; (e) total dissolved solids [TDS]; (f) sea surface temperature [SST]

3.2. Comparison of remote sensing and in situ observations

Earlier studies validating the used satellite retrieval algorithms against the field derived measurements have suggested good performance of these algorithms in various aquatic systems[9]. For this study, the C2RCC algorithm was compared to in situ samples collected between February, June and October 2023 at 4 different locations in Diégo-Suarez (**Figure 1**). For Diégo-Suarez, the Sentinel-2 data for each water quality indicator were compared on days when the sensor passed the study region (n = 12). The analyses of the coefficient of determination and the root-mean-square error (RMSE) showed that Sentinel-2 data generally compared well (r^2= 0.54, p > 0.001 for Chl-a and r^2 = 0.68, for the MCI) with differences between the sensors and in situ data.

The Regression Model Chl-a and TSM The growth of phytoplankton in the water contributes to the increase in turbidity and suspended Matter (TSM). There is a relationship between TSM and Chl-a phytoplankton that can be estimated based on Chl-a. A highest of TSM may inhibit the growth of phytoplankton due to light limitation.

The peak in Chl-a was observed in February in SL station. While, all the other stations in coastal areas, did not exceed 5 mg.m^{-3} Chl-a in June and October 2023.

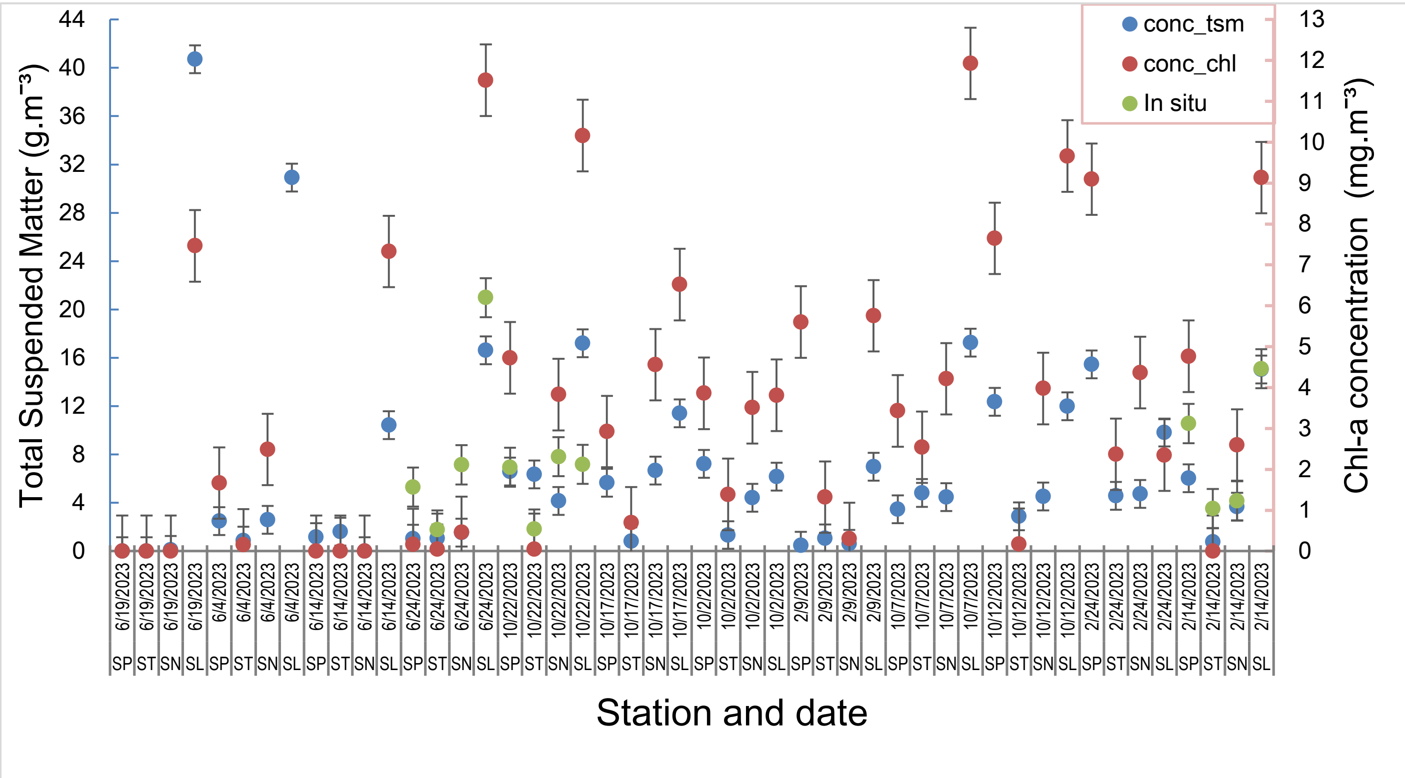

Figure 4: The comparison between remote-sensing and in situ observations of the water quality indicators at 4 locations in Diégo-Suarez Bay. Monthly values (±SD) are given for chlorophyll-a (Chl-a).

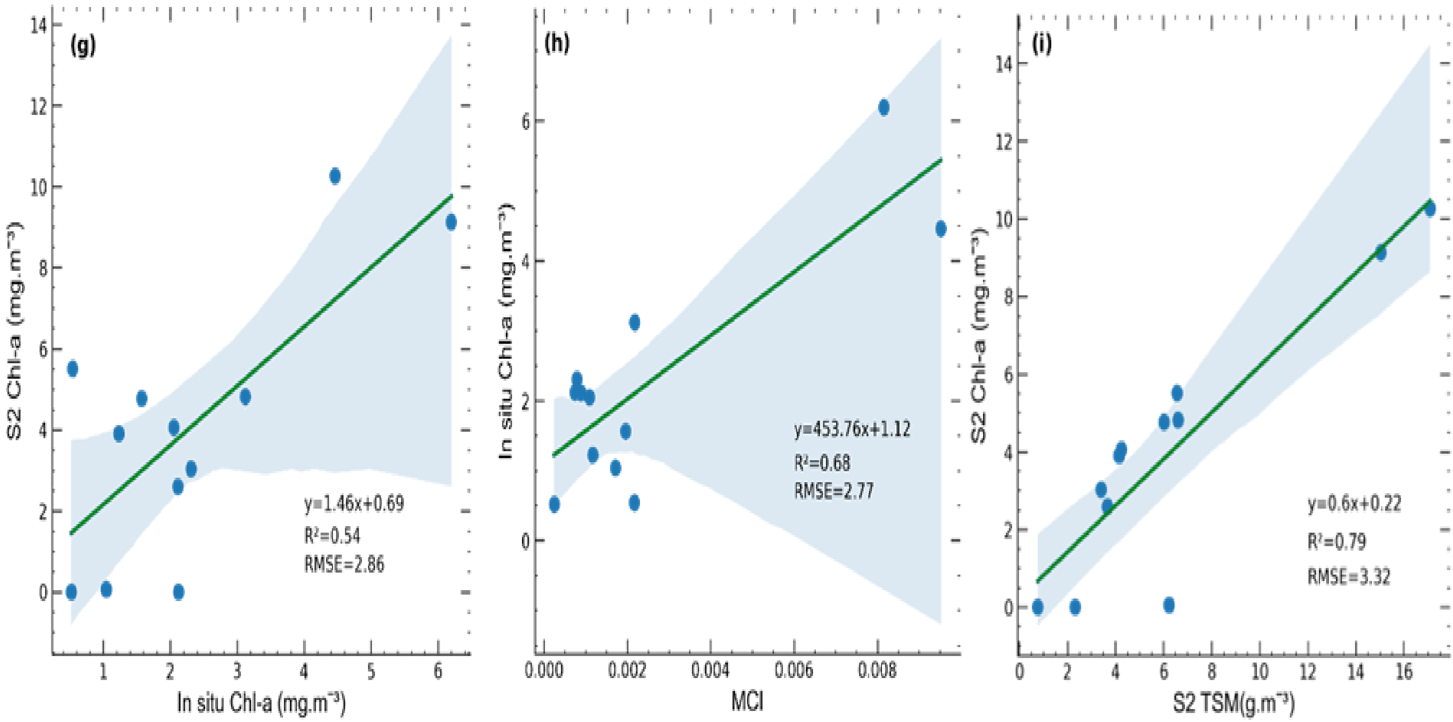

Figure 5: Scatterplot showing matchups between *in situ* Chl-a (mg.m^{-3}) and (g) S2 Chl-a, (h) MCI and (i) S2 Chl-a vs S2_TSM (g.m^{-3})

3.3. Variation spatio-temporel of Chl-a TSM concentration

Although seasonal and inter-annual variations exist, the *in situ* observations from summer were compared with those collected in winter and inter season as part of an ongoing study in (**Figure 4,6**). Chl-a concentrations during the February and October 2023 were considerably lower at some of the northern and central locations in the bay (ST) compared with June, while at other stations similar concentrations were found in both seasons. According to the Total suspended matter concentration, the coastal areas were divided into 4 bays. Tonnerre bay (ST) showed low turbidity (i.e. low concentration of TSM) throughout the time series. In Cailloux Blancs bay, the areas were more turbid during the summer and early winter. In Cul de Sac Gallois bay, which includes the SL and SN stations, showed a peak in TSM concentration before the start of our observation period which likely stems from higher river inputs during the early summer and inter-season as a result of rainfall and windy ("*Varatraza*"). **Figure 1**i shows the comparison of the S2 TSM concentration and the estimated Chl-a with best relationships (R^2=0.79, p<0.5, RMSE=3.32, r=0.80).

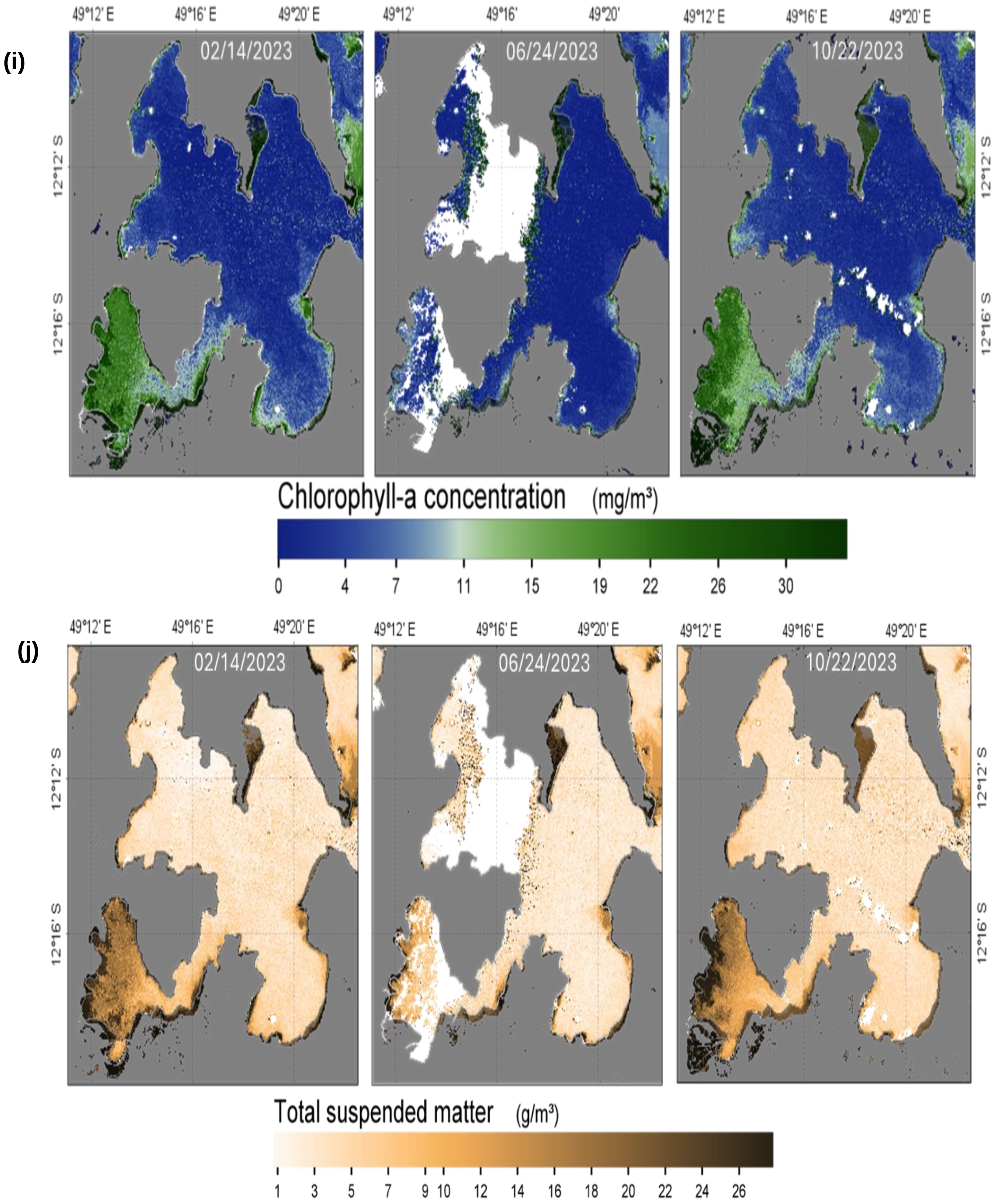

Figure 6: Concentration of (i) Chlorophyll a (Chl-a); (j) total suspended matter (TSM) from S2 Satellite

4. Discussion

Monitoring and managing aquatic resources is necessary to ensure the safety of marine environments[1]. The *in situ* physic and chemical parameters such as salinity (PSU), sea surface temperature (°C), dissolved oxygen ($mg.L^{-1}$) and pH can greatly affect the dynamics of phytoplankton growth and abundance in the water[19] and their spatial and temporal distribution. Seasonally, the Salinity values in SL, SN, SPA and ST stations were presented respectively 34.13±3, 32.72±1.46, 31.27±2.56 and 34.1±0.32 PSU. The highest value of salinity of in ST station it depends position of this locality the permanent renewal of water circulation (communicate of Indian Ocean). The In Diégo-Suarez bay, Dissolved Oxygen concentration for each station corresponding with 8.14±1, 8.99±0.47, 7.37±1.44 and 8.62±0.83 $mg.L^{-1}$ respectively in SL, SN, SPA and ST stations.

The pH of seawater ranged from 7.80-8.38, 7.22-7.67, and 7.97-8.10 respective in Cul de Sac Gallois bay, French Bay and Tonnerre Bay. Sea surface temperature also change with seasons in Diégo-Suarez Bay. In the summer season, the SST oscillates average 30.2°C; 27.32°C in winter and 27.80°C in interseason of each station. This variation of SST characterized a particularly climate of northern of Madagascar.

The use of satellite data in the assessment could be of benefit to monitoring programs as a quicker and more extensive tool for the short- to long-term monitoring of coastal waters. An additional benefit of satellite data to the public is the quicker availability and spatial coverage of information about HABs in contrast to in situ sampling. The first goal of this study was to assess the applicability of the C2RCC. It has been shown to be useful in many different coastal water, for example, in the Baltic Sea[1].

The C2RCC validation resulted in a total of 12 valid Chl-a match-ups. Most of the *in situ* measurements showed Chl-a in the range of 0.52–6.2 $mg.m^{-3}$, whereas the satellite data showed a larger variation in the Chl-a, $5{\times}10^{-4}$–10. 27$mg.m^{-3}$. The Cul de Sac Gallois bay (i.e SL and SPA stations), showed much higher Chl-a than the other coastal areas (SL, $p<0.05$). A strong apparent linear relationship between in situ and S2 Chl-a was found in most of the coastal areas ($R^2=0.54$, RMSE=2.86, $r = 0.73$, df = 12, $p < 0.05$).

The peak in Chl-a was observed in February in SL station. While, all the other stations in coastal areas, did not exceed 5 $mg.m^{-3}$ Chl-a in June and October 2023. The relationship between the in situ Chl-a and the MCI was relatively best ($R^2 = 0.68$, $p < 0.05$).

The estimation of the TSM and Chl-a values from Sentinel-2 imagery using C2RCC from Diégo-Suarez coastal waters on February 14, June 24 and October 22, 2023 ranges respectively from 0.76–15.03 $g.m^{-3}$ (average 6.37 $g.m^{-3}$), 2.32 – 6.55 (average 4.13 $g.m^{-3}$), 4.15-17.09 (average 8.51 $g.m^{-3}$) and $5{\times}10^{-4}$ – 9.14 (average 4.125 $mg.m^{-3}$), $4{\times}10^{-4}$ –5.51(average 3.15 $mg.m^{-3}$) and $6{\times}10^{-2}$ –10.27(average 4.77 $mg.m^{-3}$). S2 MSI has suitable spatial resolution from 10 m, which could support the development of new applications over coastal are for monitoring requirements. The Cul de Sac Gallois bay (SL) is where the highest Chl-a concentrations were measured during February 2023.

This result was similarly of previous research in the Diégo-Suarez Bay described by [20,21] from MODIS Aqua sensor using OC3M algorithm, with respectively 2.7 $mg.m^{-3}$ (February 2020) and 3.6 $mg.m^{-3}$ (February 2018).

Two factors cause the zone to have the highest Chl-a concentrations (phytoplankton biomass): (i) the hydrodynamics of the water, in which the flow circulation configuration is determined by the bathymetry (Cul de Sac Gallois bay is a flatter zone) and wind patterns and it thought sediment from the land; and (ii) the littoral zone receives nutrients exported from its tributary watersheds (Caiman river,…) as well as from a number of camping areas and homes and dump (ordures) without wastewater treatment and wastewater with a poor treatment from the industries (Pêche et Froid de l'Océan Indien (PFOI), Compagnie Salinière de Madagascar (CSM), STAR and SECREEN) in Antsiranana city.

Reference [19] were confirmed the phytoplankton community fluctuates due to uptake of high concentration of nutrients, especially nitrogen in the form of nitrate and phosphorus as phosphate are essential phytoplankton growth.

5. Conclusion

Combining temporal resolution on sentinel-2 with in situ measuring, we can monitor spatial and temporal variations in water quality using space-borne data. S2 MSI has suitable spatial resolution from 10 m, which could support the development of new applications over coastal are for monitoring requirements. With both satellites, S2A and S2B, the temporal resolution of 2 to 3 days provides the possibility to include and analyze more data for testing and for developing new applications for S2 MSI satellites.

Even more, it has the advantage of providing time series and dynamics of Chl-a in coastal area. And the results C2RCC to the high correlation with in situ measurements at bands useable for deriving Chl-a. As Chl-a is one of the main parameters for estimating the ecological status of water and phytoplankton biomass.

These results may provide some guidance to the responsible for safeguarding, conservation, tourism operator and care of ocean and sea in the area to identify areas prone to eutrophication and coastal areas that my influence the water quality and phytoplankton biomass. However, a greater challenge will undoubtedly be proposing physically-based equations to determine water quality parameters independent of the study site, with rapid, simple calibration.

Finally, the option of enriching these results with other sensors data capture frequency of 1 day could improve the detection of high concentrations of Chl-a due to events that occur quickly and activate alerts for local population. Data and the relationships extracted from both S2 can effectively help us to quantify seawater quality and phytoplankton studies. Continuous monitoring of environment parameters and succession phytoplankton biomass (Chl-a) in different seasons may fulfil the overall goal to achieve sustainable healthy ecosystem of Diégo – Suarez Bay,

The limited comparison between remote sensing and *in situ* observations presented in this study showed some similarities as well as discrepancies in the magnitudes of the water quality indicators studied, such that we were obliged to treat them as independent pieces of information, and confine the analyses of remote sensing data to infer relative changes over time.

However, it is worth noting that the relative changes observed through remote sensing and in situ observations were generally consistent with each other. Additionally, the clouds cover presented also an obstacle for satellite observations in our region. Our results highlight the importance of continued and sustained in situ observations of water quality in Diégo-Suarez Bay, to permit more precise match-up data analyses of remote sensing and in situ observations, with a view to developing better satellite retrieval algorithms that are tuned for these regional conditions.

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6. Conflicts of Interest

The authors declare no conflict of interest.

7. Appendix

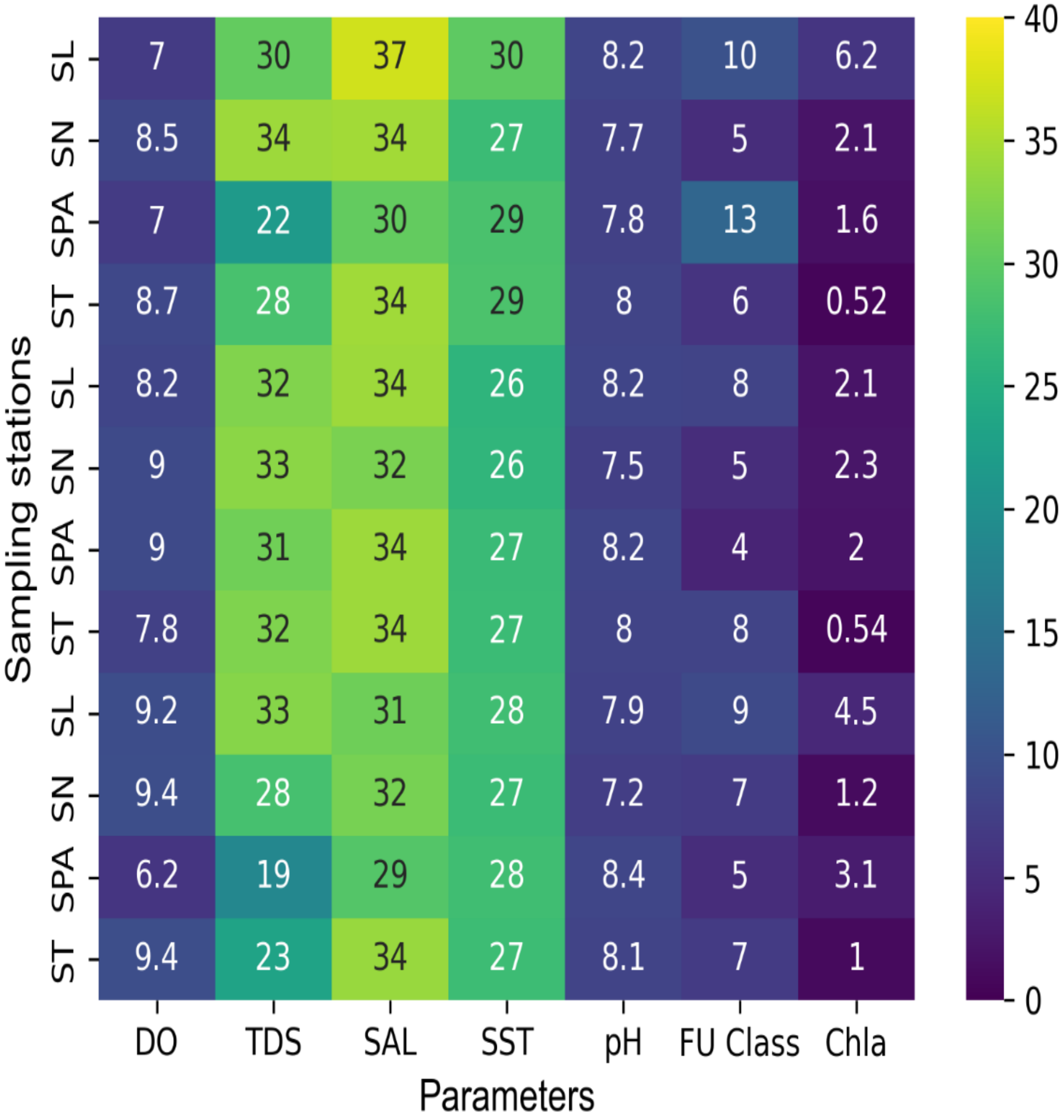

Figure 7: Heatmap of *in situ* observation from Feb14, June 16 and October 22, 2023 in Diégo-Suarez Bay

References

[1] I.-A. Rahn, K. Kangro, A. Jaanus, et K. Alikas, « Application of Satellite-Derived Summer Bloom Indicators for Estonian Coastal Waters of the Baltic Sea », *Applied Sciences*, vol. 13, n° 18, p. 10211, sept. 2023, doi: 10.3390/app131810211.

[2] V. Theenathayalan *et al.*, « Regional Satellite Algorithms to Estimate Chlorophyll-a and Total Suspended Matter Concentrations in Vembanad Lake », *Remote Sensing*, vol. 14, n° 24, p. 6404, déc. 2022, doi: 10.3390/rs14246404.

[3] M. W. Lomas *et al.*, « Phytoplankton optical fingerprint libraries for development of phytoplankton ocean color satellite products », *Sci Data*, vol. 11, n° 1, p. 168, févr. 2024, doi: 10.1038/s41597-024-03001-z.

[4] Y. Cheng et S. Zhang, « The Research on the Variation of Chlorophyll-a in Bohai Sea Based on MODIS Data », in *ESMA 2020*, 2021. doi: 10.1088/1755-1315/714/2/022029.

[5] F. Barraza-Moraga, H. Alcayaga, A. Pizarro, J. Félez-Bernal, et R. Urrutia, « Estimation of Chlorophyll-a Concentrations in Lanalhue Lake Using Sentinel-2 MSI Satellite Images », *Remote Sensing*, vol. 14, n° 22, Art. n° 22, janv. 2022, doi: 10.3390/rs14225647.

[6] A. Bracher *et al.*, « Obtaining Phytoplankton Diversity from Ocean Color: A Scientific Roadmap for Future Development », *Front. Mar. Sci.*, vol. 4, mars 2017, doi: 10.3389/fmars.2017.00055.

[7] G. Wang et J. Moisan, « Remote Sensing of Phytoplankton Pigments », in *Plankton Communities*, L. Pereira et A. Marta Gonçalves, Éd., IntechOpen, 2022. doi: 10.5772/intechopen.95381.

[8] A. Cuartero, J. Cáceres-Merino, et J. A. Torrecilla-Pinero, « An application of C2-Net atmospheric corrections for chlorophyll-a estimation in small reservoirs », *Remote Sensing Applications: Society and Environment*, vol. 32, p. 101021, nov. 2023, doi: 10.1016/j.rsase.2023.101021.

[9] G. Kulk *et al.*, « Effect of Reduced Anthropogenic Activities on Water Quality in Lake Vembanad, India », *Remote Sensing*, vol. 13, n° 9, p. 1631, avr. 2021, doi: 10.3390/rs13091631.

[10] C. Brockmann *et al.*, « Evolution of the C2RCC Neural Network for Sentinel 2 and 3 for the Retrieval of Ocean Colour Products in Normal and Extreme Optically Complex Waters », août 2016. Consulté le: 5 août 2024. [En ligne]. Disponible sur: https://www.semanticscholar.org/paper/Evolution-of-the-C2RCC-Neural-Network-for-Sentinel-Brockmann-Doerffer/cc23d61fc8d72bef80218b6402ef437378793c8e

[11] C. Brockmann *et al.*, « Evolution of the C2RCC Neural Network for Sentinel 2 and 3 for the Retrieval of Ocean Colour Products in Normal and Extreme Optically Complex Waters », août 2016. Consulté le: 5 août 2024. [En ligne]. Disponible sur: https://www.semanticscholar.org/paper/Evolution-of-the-C2RCC-Neural-Network-for-Sentinel-Brockmann-Doerffer/cc23d61fc8d72bef80218b6402ef437378793c8e

[12] A. Ansper et K. Alikas, « Retrieval of Chlorophyll a from Sentinel-2 MSI Data for the European Union Water Framework Directive Reporting Purposes », *Remote Sensing*, vol. 11, n° 1, p. 64, déc. 2018, doi: 10.3390/rs11010064.

[13] Š. Tereza, *RUS Webinar_ Freshwater Quality Monitoring with Sentinel-2* -, (2020).

[14] R. Brewin *et al.*, « A Printable Device for Measuring Clarity and Colour in Lake and Nearshore

Waters », *Sensors*, vol. 19, n° 4, p. 936, févr. 2019, doi: 10.3390/s19040936.

[15] N. Menon *et al.*, « Citizen Science Tools Reveal Changes in Estuarine Water Quality Following Demolition of Buildings », *Remote Sensing*, vol. 13, n° 9, Art. n° 9, janv. 2021, doi: 10.3390/rs13091683.

[16] E. Coria-Monter, M. A. Monreal-Gómez, D. A. Salas de León, et E. Durán-Campos, « Water masses and chlorophyll-a distribution in a semi-enclosed bay of the southern Gulf of California, Mexico, after the "Godzilla El Niño" », *Arab J Geosci*, vol. 12, n° 15, p. 473, août 2019, doi: 10.1007/s12517-019-4636-1.

[17] J. D. H. Strickland et T. R. Parsons, *A manual of sea water analysis*, vol. 1. in Bulletin ; no. 125, no. W. E. RICKER N. M. CARTER, vol. 1. Ottawa: Fisheries Research Board of Canada, 1965.

[18] J. D. H. Strickland et T. R. Parsons, « A Practical Handbook of Seawater Analysis, 2nd edition. », 1972, doi: 10.25607/OBP-1791.

[19] S. A. Azad et V. J. Jinau, « Spatial Distribution of Dissolved Inorganic Nutrients and Phytoplankton around Kota Kinabalu Wetland, Sabah, Malaysia », *ABC*, vol. 10, n° 04, p. 113-126, 2020, doi: 10.4236/abc.2020.104009.

[20] S. F. Mahatsiaro *et al.*, « Estimation of Chlorophyll-a concentration in Diégo-Suarez bay using Aqua-MODIS sensor », in *The Trevor Platt Science Symposium and training, 7-11 August 2023, Plymouth, United Kingdom*, Plymouth, UK, 2023.

[21] A. Landy Soambola *et al.*, « Biological and oceanographic analyzes of intoxication by marine animal consumption (Imac) precursors in diego suarez bay and northern-east of madagascar », p. 96-103, 2018. [En ligne]. Disponible sur: https://www.researchgate.net/publication/330543968