Evaluating the feasibility of using Sentinel-2 imagery for water clarity assessment in a reservoir

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Abstract

The new Sentinel-2 satellites present a significant scientific opportunity for the study of water quality. The objective of this study was to evaluate the suitability of Sentinel-2 imagery for estimating and mapping Secchi disk transparency (SDT) in Río Tercero reservoir (Córdoba-Argentina). Field observations and a dataset of atmospherically corrected Sentinel-2 images were used to generate and validate an algorithm to estimate water clarity in the studied reservoir. As a real application of the used methodology, the validated algorithm was used to obtain a spatial representation of water clarity in the reservoir during sampling campaigns. Results demonstrate capabilities of Sentinel-2 mission to make a substantial contribution to the current assessment and understanding of aquatic systems by estimating and mapping a water quality characteristic.

1. Introduction

Lakes and reservoirs have important functions in the environment. Like many other ecosystems, these environments are threatened by the synergistic effects of multiple co-occurring environmental pressures, including human activities, nutrient enrichment, inorganic and organic pollution, and climate change (Palmer et al., 2015; Dörnhöfer and Oppelt, 2016; Ferral et al., 2017; El-Serehy et al., 2018). Therefore, it is imperative to develop new water quality monitoring tools for an efficient management of water resources (Wang et al., 2017).

Satellite remote sensing can improve water quality monitoring and increase the rapid detection of environmental threats, such as eutrophication or harmful algal blooms, due to its time- and cost-effectiveness over large areas as well as remote locations. This is of special interest in the Caribbean and South America region, where there are difficulties in obtaining basic information on water quality (Matthews, 2011; González-Márquez et al., 2018). Furthermore, during the last few years, there is an increasing international interest on the new generation of medium resolution (10–30 m) Earth observation satellites to open a complete new era in the remote sensing of inland waters (Concha and Schott, 2016; Dörnhöfer and Oppelt, 2016; Sovdat et al., 2019). Among these new satellites, the Sentinel-2 mission, developed by the European Space Agency’s (ESA) Copernicus program, provides improved continuity for Landsat and SPOT observations and improves data availability for users since it can be used to support global land services including monitoring vegetation, soil and aquatic systems (Drusch et al., 2012; Du et al., 2016; Wang and Atkinson, 2018).

The Sentinel-2 mission carries a push-broom MultiSpectral Instrument (MSI) aboard Sentinel-2A and Sentinel-2B twin satellites which were launched on 23 June 2015 and 7 March 2017, respectively (Sola et al., 2018). The Sentinel-2 mission presents high spatial resolution, multiple spectral bands, short revisit times, and an open data policy, which has made it a rich satellite data archive available to the general public (Sovdat et al., 2019). The pair of Sentinel-2 satellites presents a significant scientific opportunity for the study of aquatic ecosystems by monitoring and mapping water quality constituents in near shore coastal and inland waters. However, Sentinel-2 derived-products require further community-wide validations to ensure performance under different environmental conditions.

The objective of this study was to evaluate the suitability of Sentinel-2 imagery for estimating and mapping Secchi disk transparency (SDT) in Río Tercero reservoir (Córdoba-Argentina). We focused...
on SDT, a common measurement of water clarity, since it is a widely used metric of lakes and reservoirs water quality closely associated with water quality indicators such as trophic status, chlorophyll-a, lake productivity and total phosphorus (Carlson, 1977; Olmanson et al., 2016; Shang et al., 2016). Further, due to its simplicity and low-cost facilities, SDT is commonly used by many volunteer monitoring programs and it is one of the most widely water quality characteristic estimated by remote sensing (Kloiber et al., 2002; Olmanson et al., 2008).

2. Methodology

2.1. Study area

The Río Tercero reservoir is located in the province of Córdoba (Argentina) (Fig. 1). This reservoir has an area of 46 km², a volume of 10 hm³, a maximum and mean depth of 46.5 and 12.2 m respectively (Mariazzi et al., 1992). The Río Tercero reservoir is divided in two regions by a strait. The western region has three branches where rivers flow, while the eastern region presents the only effluent called Tercero river. The Río Tercero reservoir is one of the most important artificial reservoirs in the central region of Argentina since it plays an important ecological and socio-economical role in the development of cities and towns located nearby. In this sense, the studied reservoir has multiple purposes, such as water supply for approximately 20,000 inhabitants, power generation, flood control, irrigation, tourism and recreational activities (Mariazzi et al., 1992). However, in the last two decades, water quality of the reservoir is declining, reducing its multi-purpose value (Bonansea et al., 2016). In 1986 a nuclear power plant (CNE: 600 MWa) was installed. Water for cooling the nuclear reactor is taken from the middle section of the reservoir and is returned to the western basin by a 5 km long open-sky channel (Bonansea et al., 2015). In 2015, the power plant was stopped since it is in a reconditioning process to extend its useful life.

2.2. Field campaigns

Sampling campaigns were conducted on February 28, 2018; March 14, 2018; August 28, 2018; October 17, 2018; February 14, 2019; and March 24, 2019 at eleven sampling sites (Fig. 1). Coordinates of sample sites were recorded using a GPS device. Water clarity was measured using a standard 20 cm diameter Secchi disk from the shady side of a boat to avoid any undesirable effects of water surface reflection. One-way analysis of variance (ANOVA) was performed as a first approach to compare the significant spatial and temporal variation of SDT values measured in the reservoir (p < 0.05; least significance difference, LSD).

2.3. Remote sensing data and processing

In the present study, the used remote sensing data was acquired by Sentinel-2A and B satellites. As we have previously mentioned, the Sentinel-2 satellites carry the MSI sensor which measures the reflected solar spectral radiance in thirteen spectral bands ranging from the visible (VIS) to the shortwave infrared (SWIR) bands at 3 different spatial resolutions (Table 1). The radiometric resolution of MSI sensor is 12-bit and it incorporates three new red edge spectral bands (RE1, RE2, RE3) which would improve the accuracy of estimating various biophysical variables (Drusch et al., 2012; Traganos and Reinartz, 2018).

Synchronous to fieldwork activities, cloud-free Sentinel-2A/B images of the study area were downloaded from the USGS Global

<table>
<thead>
<tr>
<th>Band specifications for Sentinel-2 MSI sensor.</th>
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</thead>
<tbody>
<tr>
<td><strong>Band</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>1- Aerosol</td>
</tr>
<tr>
<td>2- Blue</td>
</tr>
<tr>
<td>3- Green</td>
</tr>
<tr>
<td>4- Red</td>
</tr>
<tr>
<td>5- Red edge (RE) 1</td>
</tr>
<tr>
<td>6- RE2</td>
</tr>
<tr>
<td>7- RE3</td>
</tr>
<tr>
<td>8- Near infrared (NIR)</td>
</tr>
<tr>
<td>8a- Near infrared narrow (NIRn)</td>
</tr>
<tr>
<td>9- Water vapour</td>
</tr>
<tr>
<td>10- Shortwave infrared (SWIR)/ Cirrus</td>
</tr>
<tr>
<td>11- SWIR-1</td>
</tr>
<tr>
<td>12- SWIR-2</td>
</tr>
</tbody>
</table>
According to Matthews (2011) and Politi et al. (2015) researchers developed many different retrieval algorithms to estimate SDT, due to the fact that the best model varies from one reservoir to another according to water conditions. Thus, we chose not to employ preconceived models to estimate SDT and a wide variety of candidate algorithms were tested. Additionally, different goodness-of-fit measures, including the adjusted R-squared value (R²), the bias (mean difference between estimated and observed SDT), and the root mean square error (RMSE) were calculated to obtain an estimate of the error associated with the estimations. The model with the greatest R² and the lowest Bias and RMSE was selected to retrieve SDT in the entire reservoir surface. The predictive capability of the model was also assessed by comparing the predicted and the observed SDT values of the validation subset by simple regression analysis. Finally, to assess water clarity in the reservoir, quantitative maps were created applying the selected model to the used imagery.

### 3. Results and discussion

#### 3.1. Field data

The basic statistics of SDT measured in Río Tercero reservoir during the sampling campaigns are summarized in Table 2.

ANOVA did not show significant differences between sampling campaigns (p = 0.71). However, this technique indicated significant differences when sampling sites were compared (p > 0.01). Sampling sites located in the western region of the reservoir (Sites 4 to 9) were significantly lower than those located in the eastern region (Sites 1, 2, 3, 10, and 11).

#### 3.2. Algorithms

Regression model was performed using the calibration subset which contained 44 pairs of field and satellite data. Thus, measured SDT values were used to find the best combination of MSI spectral band or band ratios to estimate water clarity in Río Tercero reservoir. Eq. (1) shows the best model developed to predict SDT in the reservoir which included a combination of red edge and near infrared bands of MSI sensor (R² = 0.86):

\[
SDT = 1.79 - 134.15*Band_{RE1} + 157.72*Band_{NIR} + 0.53* \left( \frac{\text{Band}_{RE3}}{\text{Band}_{NIR}} \right)
\]

where Band_{RE1}, Band_{NIR}, Band_{RE3}, and Band_{NIR} are the atmospherically corrected BOA values of MSI spectral bands.

Fig. 2 shows the comparison between field data and SDT values estimated by Sentinel-2 satellite. Fig. 2a, which represents comparison between observed and estimated SDT values used for model development, shows a good fit obtained from regression analysis (R² = 0.85, Bias = 0.03 m, and RMSE = 0.28 m) and a good agreement between the gradient and intercept of the regression line. The capacity of the generated algorithm was also validated comparing values of SDT measured in the field and SDT values predicted by applying the algorithm on BOA values of Sentinel-2 images of the validation dataset (Fig. 2b). In this case, the used goodness-of-fit measures also confirm the robustness and the high predictive capacity of the developed model.

### Table 2

<table>
<thead>
<tr>
<th>Sampling campaign</th>
<th>Acquisition image date</th>
<th>Difference in days</th>
<th>SDT values</th>
<th>Mean ± Sd.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 28, 2018</td>
<td>March 1, 2018</td>
<td>1</td>
<td>2.00 ± 0.74</td>
<td>0.50-3.00</td>
<td></td>
</tr>
<tr>
<td>March 14, 2018</td>
<td>Mach 14, 2018</td>
<td>0</td>
<td>1.83 ± 0.64</td>
<td>0.75-2.50</td>
<td></td>
</tr>
<tr>
<td>August 28, 2018</td>
<td>August 28, 2018</td>
<td>0</td>
<td>1.93 ± 0.86</td>
<td>0.60-3.25</td>
<td></td>
</tr>
<tr>
<td>October 16, 2018</td>
<td>October 17, 2018</td>
<td>1</td>
<td>1.83 ± 0.81</td>
<td>0.50-2.90</td>
<td></td>
</tr>
<tr>
<td>February 14, 2019</td>
<td>February 14, 2019</td>
<td>0</td>
<td>1.60 ± 0.74</td>
<td>0.60-2.50</td>
<td></td>
</tr>
<tr>
<td>March 24, 2019</td>
<td>March 24, 2019</td>
<td>0</td>
<td>2.12 ± 0.81</td>
<td>0.75-3.25</td>
<td></td>
</tr>
</tbody>
</table>

Sd.: Standard deviation.
Algorithm and produce an acceptable error associated with the estimations ($R^2 = 0.81$, Bias = 0.12 m, and RMSE = 0.38 m).

Fig. 3 shows the spatial distribution of simulation mean errors during sampling campaigns. Comparing the mean difference between estimated and observed values of SDT, it was observed that the developed algorithm tended to generate a slight overestimation of SDT values when observed SDT values were low. On the other hand, when observed SDT values were high, the selected algorithm generated an underestimation of SDT values. This is evident in Fig. 3, which shows that in the western region of the reservoir, where lower values of water transparency were found, the overestimation of SDT values was evident by a positive difference between estimated versus observed SDT values. In the eastern region of the reservoir, the negative values of simulated errors demonstrated the underestimation generated by the used algorithm. Figure also shows that the central region of the reservoir presented the lower difference between estimated and observed water transparency values.

3.3. Algorithm implementation

As a real application of remote sensing techniques, the validated algorithm was applied to the used Sentinel-2 imagery obtaining a spatial representation of water clarity in Río Tercero reservoir during sampling campaigns (Fig. 4). This Figure shows that high-quality products can be derived from Sentinel-2 imagery. Coinciding with field data, satellite imagery shows a spatial pattern of water clarity with lower values of SDT in the western region and increasing towards the eastern region of the reservoir. This longitudinal pattern could be associated with river runoff which delivers higher loads of suspended materials and dissolved solids into the western region of the reservoir that decrease the penetration of light and contribute to the reduction of water clarity. This situation is more evident close to river inputs. The opposite situation occurs in the eastern region of the reservoir where deeper waters and rapid sedimentation allow the measure of higher values of SDT. A similar spatial pattern of lower water clarity near river inflows and increasing with distance was found by Bonansea et al. (2015) in this reservoir and by Bazán et al. (2010) and Guan et al. (2011) in different water bodies. Finally, as results show the generated algorithm could be used in the both Sentinel-2 satellites, thus the revisit time over the studied area could be reduced to 5 days, which is a benefit for operational uses and decision-making activities (Pahevan et al., 2017; Sovdat et al., 2019).

Different multi-resolution satellites have been successfully used to estimate water clarity and other water quality variables of inland waters (Matthews, 2011; Villar et al., 2013; Dörnhöfer and Oppelt, 2016). However, as we have previously mentioned, there is an increasing international interest for the evaluation of the potential of new satellite systems and its derived products. In the present study, field data and Sentinel-2 imagery were used to generate a relevant and validated empirical algorithm for estimating and mapping water clarity in one of the most important reservoir of the central region of Argentina. Although we can confirm that the methodology used in the present study is adequate to estimate water clarity, it should be noted that the accuracy of the development algorithm is limited. Thus, for further validation, more simultaneous field observations with overpass time of Sentinel-2 must be compared for improving the accuracy and precision of the coefficients of the generated algorithm. Further, due to the influence of the nuclear power plant on water quality (Bonansea et al., 2015, 2018), we recommend that it must be taken into account when it is operative again for water quality assessment.
4. Conclusions

This study demonstrates capabilities of Sentinel-2 mission to make a substantial contribution to the current assessment and understanding of aquatic systems by estimating and mapping a water quality characteristic in a reservoir of Argentina.

An algorithm to estimate SDT, a common measurement of water clarity, was generated and validated with high goodness-of-fit measures that confirms its robustness and its high predictive capacity ($R^2 = 0.81$, bias $= 0.12$ m, and RMSE $= 0.38$ m). Results also show that the produced water clarity maps enable for the interpretation of the behaviour of the variable in the whole reservoir. However, further research study with a larger data set is needed for a multi-temporal evaluation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2019.102265.

References


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