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ORIGINAL PAPER

A one health google earth engine web-GIS application to evaluate and monitor water quality worldwide

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Abstract

The assessment of water quality using satellite remote sensing has gained significant interest in recent years. Earth Observation data and technologies, particularly through cloud-based platforms like Google Earth Engine (GEE), offer the potential for synoptic coverage and repeated monitoring. This study aimed to develop a Google Earth Engine app for indirect monitoring and assessment of water quality based on Sentinel-2 from a One Health perspective. A JavaScript code was written within GEE to develop a publicly accessible application in order to permit users to indirectly analyze water-bodies world-wide in the spatial–temporal domain. In particular, clouds, shadow and defective pixels were masked out in the entire collection using Quality Assurance (QA) masks. Regarding to the application, named Sen2WQ, several functions were implemented in order to compute: water turbidity (T), chlorophyll (Chl) content, and total suspended solids (TSS) based on established approaches in the scientific literature. The application allows users to map water quality (T, Chl, TSS) within their defined time range and area of interest, displaying time-lapse visualizations, maps, and charts. To validate the app, different remote sensing tools and ground data for these parameters were collected in Italy and worldwide, and Root Mean Squared Error (RMSE) was computed. The results demonstrate the potential of GEE, specifically the Sentinel-2 missions, in monitoring water quality. Sen2WQ may support different figures such as veterinarians in studying animal and wildlife pathologies related to water quality, contributing to a comprehensive One Health approach.

Keywords Google earth engine · Remote sensing · Water quality · App · Sentinel-2 · Water habitat · One Health

Introduction

Nowadays, the monitoring of water quality has become crucial for understanding the conditions of the environment in which human beings, animals and vegetation live in order to reach a real One Health approach (Orusa et al. 2023a, b, c; Carella et al. 2022; Orusa et al. 2019; Orusa et al. 2020). In fact, the evident connection between human and animal health with environmental conditions represents a crucial point for a correct management and conservation of biodiversity all over the world.

Several studies have demonstrated the importance of a balance between these three factors for Public Health and ecosystems preservation (Zinsstag et al. 2011; Gibbs 2014; WHO 2017). Certainly, the collaboration between different researchers is fundamental for a successful and sustainable science (Parker et al. 2016; Parry et al. 2009).

Concerning these aspects, in the last years, the attention of the scientific world to the preservation of aquatic ecosystem is increased, due to different causes. First, it has

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to be considered that the Earth is covered by two-thirds of water, so that it has been iconically defined as a blue marble, because of one of the first picture of the Planet take by astronauts Eugene “Gene” Cernan, Ronald Evans and Harrison Schmitt during the Apollo 17 (Clarke, 1994). Then, aquatic ecosystems play a significant role in the planet's biotic productivity since in the ocean account for 30% of global primary productivity came from plants living there. Therefore, the water represents a perfect proxy for the evaluation of pollution and presence of various forms of contaminants (Karthick et al. 2010).

It is worth to note that water can represent a source of contamination not only in microbiological, but also chemical terms, with important consequences on the state of health of animals, humans, and the environment (Greig et al. 2015). Various pathogens such as viruses, bacteria, and protozoa pose significant microbiological risks, particularly in impoverished regions where inadequate prophylaxis measures and insufficient infrastructure for water collection, management, and disinfection via physical–chemical treatments heighten health risks associated with water consumption (Ashbolt 2015; Ashbolt 2004). Enteric bacteria deriving from fecal contamination of water are among the main risk agents in the absence of sewage treatment plant, for example, and correct management of water resources (Patel et al. 2016).

Regarding the chemical contamination, antibiotics are among the emerging microcontaminants in water with serious effects on the ecosystem and human health (Huang et al. 2011). Their growing presence is related with human activities such as agriculture, phytoculture and livestock farming (Anh et al. 2021; Magureanu et al. 2021; Wu et al. 2020).

Additionally, the increasing depletion of water resources fosters competition between humans and animals. This rivalry arises from the heightened demand for water in primary activities such as agriculture and livestock, juxtaposed with the needs of the tertiary sector and urban areas. These dynamics have significant repercussions on wildlife ecology (Greig et al. 2015; Viani et al. 2023a, b, c; De Marinis et al. 2021; Orusa et al. 2023a, b, c). There was no doubt about the advantages of established water supplies for wildlife. Unfortunately, not much money was spent on monitoring and researching the consequences of water catchments, despite the enormous capital investment in them (Krausman, et al. 2006). This problem was largely debated in the literature (Krausman, et al. 2006; Greig et al. 2015) and different researchers have investigated the effectiveness of water catchments, especially in arid habitats, for some wild animals as for example the desert bighorn sheep (Broyles et al. 1999). The natural water availability is a crucial factor in these types of ecosystem (Epaphras et al. 2008). Moreover, the rising of temperatures in the last years due to climate change can only get worse the situation. A lot of large mammals have to replace their intake of preformed and metabolic water with free water, and climate change will probably reduce the amount of drinking water available in drylands (Fuller et al. 2007). Also small animals need to drink a certain quantity of water for metabolic processes; the difficulty of accessing available water sources (due for example for periods of drought or conflicts with humans for hoarding of resources) can cause dehydration (Walsberg 2000). Although hypovolemia and hyperosmolarity are prevented by inhibiting evaporative cooling, other functions will eventually be compromised and the danger of pathological hyperthermia will grow due to the extra heat storage and early rise in body temperature in the high temperatures. Moreover, the rise of body temperature will increase the possible development of a pathological hyperthermia. Previous researchers have demonstrated how the maximum daily body temperature increase in dehydrated mammals as baboons (*Papio hamadryas*) (Mitchell et al. 2009) and camels (*Camelus dromedarius*) (Bouâouda et al. 2014) in simulated arid area. In this scenario, animal production is related to access to clean water. At the same time rangelands and forests productivity as well as yield from crop are related to water. Focusing only from an anthropic point of view, access to clean water is one of the cornerstones of food security and the SDGs. However, climate change threatens access to quality water. Climate extremes whether linked to droughts or intense rainfall and floods make water monitoring a fundamental aspect for the future. Anthropic pressure adds to the pressure of the climate system on fresh drinking water following the reduction of the global cryosphere and reduction in the duration of the snow cover on the ground in the main world mountain chains. While on one hand developing countries lack infrastructure following an ever-increasing demand with high risks of contamination, on the other, in developed countries, distribution systems and lifestyles cause enormous waste in all sectors (primary, secondary and tertiary) ending up wasting an important resource. However, in both cases, microplastic contamination is now pervasive from glaciers to the oceans and sometimes still difficult to investigate with not only diagnostic but also mapping tools at different scales (Bagliani et al. 2019; Caimotto et al. 2020; Tartaglino et al. 2020).

Therefore, water monitoring is possible though the combination of various technologies, in order to ensure that operations are compliance with all relevant regulations and standards. In particular, researchers can dispone of direct and indirect analysis. Concerning the first one, scientists are able to measure a variety of properties to determine water quality. These include temperature, acidity (pH), dissolved solids (specific conductance), particulate matter (turbidity), dissolved oxygen, hardness and suspended sediment. Each variable reveals something different about the health of a water body.

All these measures are possible with the use of specific laboratory instruments or technologies starting from collected samples or in certain cases can be used direct in the field during the monitoring operations. On the other hand, it is possible to evaluate water quality though indirect tools, such as remote sensing technologies (satellite, drones, etc.…).

In this context, the development of Earth Observation (EO) technologies applied to satellite monitoring allow researchers to assess water quality thought several desktop software like ESA-SNAP toolbox (Samuele et al. 2021; Orusa et al. 2022a). However, cloud-based platform like Google Earth Engine (GEE) permits to scale this indirect analysis easier worldwide (Orusa et al. 2022b). Even if, fewer water quality application are available on GEE, none is based on a scientifically based Geomatics workflow (Vanhellemont et al. 2016; Katlane et al. 2020; Brockmann et al. 2016; Toming et al. 2016; Ouma et al. 2020; Zhao et al. 2020; Ansper et al. 2018).

The color of water is determined by substances in the water, and measuring the color of water allows a retrieval of the water quality. Eutrophic waters appear green, while sediment loaded waters get a brown color.

In the present work, in order to assess the water quality, we consider the water turbidity (T), the chlorophyll content (Chl α) and the total suspended solids (TSS). The water turbidity (T) represents the measurement of water clarity. Suspended particles—such as silt, algae, plankton, and sewage—can cause water to appear cloudy or murky. These particles scatter and absorb light rays rather than allowing light to be transmitted straight through the water. A higher turbidity reading represents cloudier and 'thicker' water with more particles throughout. When water is clear, it has low turbidity levels. Regarding the chlorophyll content (Chl α), it is worth to note that Chlorophyll (Chl) represents an important pigment for photosynthesis. The photosynthetic reaction is mainly divided into three steps: primary reaction, photosynthetic electron transport and photophosphorylation, and carbon assimilation. Chlorophyll a (Chl α) is essential for the primary reaction. Chl a absorb sunlight wavelengths in red–orange light. Concerning the total suspended solids (TSS), they are defined as solids in water that can be trapped by a filter. To measure TSS in laboratory, the water sample is filtered through a pre-weighed filter. Then, the residue retained on the filter is dried in an oven at 103–105 °C until the weight of the filter no longer changes. The increase in weight of the filter represents the TSS. Alternatively, employing spectral analysis of reflectance within specific wavelengths enables the differentiation of TSS.

Highly sensitive multispectral and or hyperspectral cameras, deployed on satellites, aerial flight or drones, allow a quantification of such water constituents from space, at global scale and with a spatial resolution of down to 20–30 s of meters. The retrieval of water constituents, or its optical properties from satellite remote sensed data, is achieved by inversion of the water leaving reflectance spectrum, measured at top of atmosphere and thus requiring a correction for atmospheric effects. This multi-variate problem is extremely challenging and some complex approaches has been suggested in scientific literature to overcome this issue and several atmospheric correction algorithms have been created (Vanhellemont et al. 2016; Brockmann et al. 2016; Toming et al. 2016).

ACOLITE developed to Sentinel-2 (MSI) in two steps: (a) Rayleigh correction for scattering by air molecules, using a Look Up Table generated using 6SV, (b) an aerosol correction based on the assumption of black SWIR bands over water caused by the extremely high pure-water absorption, and an exponential spectrum for multiple scattering aerosol reflectance (Vanhellemont et al. 2016). While, Case 2 Regional Coast Color processor C2RCC (Brockmann et al. 2016) is developed for optically complex Case 2 waters, which use a large database of simulated water leaving radiance and TOA radiances. It is based on neural network technology and has been trained in extreme ranges of scattering and absorption properties (Ansper et al. 2018).

Therefore, the aim of the present work was to develop a GEE app based on a rigorous Geomatics workflow of Earth Observation processing data useful not only to veterinarians but also for other professions (Orusa et al. 2023a, b, c; Sarvia et al. 2021; Orusa et al. 2021), that could indirectly monitor and evaluate water quality from a One Health perspective to face present and future challenges. Finally, the GEE app must have an easy end-user interface without scripting knowledge. Commencing with the opportunities presented by the Space Economy, these objectives hold the potential to facilitate a technological transfer to the veterinarian and health sector. The application was designed to assess water quality in various bodies of water, including lakes, rivers, and seas/oceans. However, during testing, the focus was primarily on lakes due to their significant role in providing freshwater for human and animal activities, including wildlife, and their susceptibility to contamination. Rivers were not included in the testing process due to the potential for spectral mixing issues, especially in smaller rivers, arising from the spectral resolution of Sentinel-2 data. No data was collected in marine areas during testing. However, there is interest in future analyses to evaluate the application's performance in marine environments by comparing data obtained from land-based measurements.

Materials and methods

The GEE app was built in Javascript and implemented directly in the user-interface front-end. The Sentinel-2 (S2) Level-1C collection in GEE was considered also L2A was included but only to display RGB imagery of the location chosen by the end user. It is worth to note that both L1C and L2A products involved the harmonized S2 collection. In order to remove atmosphere noise and detect some water spectral response necessary to derive the qualitative parameters as indirect proxies a routine of ACOLITE and C2RCC (Vanhellemont et al. 2016; Brockmann et al. 2016) algorithms were included into the script pipeline. The atmospheric correction is an important step in remote sensing applications but in the case of aquatic remote sensing the quality can be derived starting from L1C products after performing a careful calibration process in which the atmospheric noise is not always deal as happens for land applications.

ACOLITE is a generic processor developed at RBINS for atmospheric correction and processing for coastal and inland water applications. It currently supports many sensors, among others, Landsat (5/7/8), Sentinel-2 (A/B), Sentinel-3 (A/B), PlanetScope, Pléiades, and WorldView. ACOLITE performs the atmospheric correction by default using the "dark spectrum fitting" approach (Vanhellemont et al. 2016) but can be configured to use the exponential extrapolation (Vanhellemont 2016) according to (https://odnature.naturalsciences.be/remsem/software-and-data/acolite last accessed February 2024). Features include the extraction of rectangular regions of interest (defined by bounding coordinates), calculation of reflectance derived parameters, and the generation of RGB images before and after atmospheric correction. Products are output as geolocated datasets in a NetCDF file and can be exported as GeoTIFF and PNG images. ACOLITE typically makes an atmospheric correction in two stages: (1) a Rayleigh correction for air molecule scattering, based on an exponential spectrum for multiple scattering aerosol reflectance and a Look-Up Table created using 6S; and (2) an aerosol correction based on the assumption of black SWIR bands over water due to the extremely high pure-water absorption. In addition to computing several additional characteristics, ACOLITE produces water-leaving radiance reflectance in the visible and near-infrared bands. Top-of-atmosphere reflectance in Universal Transverse projection are orthorectified, geo-referenced, and radiometrically corrected in Sentinel-2 L1C data. Following Rayleigh correction, a non-water masking is applied to obstruct further processing of land, clouds, glare, and objects like boats. The disguising is carried out with a 2.15% threshold on the 1.6 μm band, which can miss thin clouds, cloud and mountain shadows, and medium sunlight. Since the SWIR bands at 1.6 and 2.2 μm should be dark across all water types, they are automatically employed for the aerosol adjustment. Since there is little signal at this distance wavelengths, the L1C files' (1/10000) digitization, and MSI's comparatively poor signal-to-noise ratio necessitate the use of spatial smoothing filters for these bands. Aerosol type and reflectance will often change over time and space, although not usually at the pixel length scales taken into consideration. After the masking mentioned above, mean spatial averaging is carried out to exclude brilliant SWIR pixels that could otherwise affect the nearby dark (water) pixels. To further lessen the impact of missing or mixed brighter pixels surrounding the masked region, the dilated mask has been filled using the median reflectance measured across water pixels. The signal-to-noise Sentinel-2 MSI has been realized by applying a mean average filter to the SWIR wavelengths. Finally, the coefficients to apply to each band is computed and adopted in the computation of water quality remote sensing indicators. The same concerning on C2RCC, but in this last case, a list of values concerning different atmospheric condition were simply reported into the script.

C2RCC functions as a processor dedicated to atmospheric correction and extraction of water constituents from optical satellite imagery obtained through various sensors. Its foundational methodology, pioneered in 1999, tackles the challenge of atmospheric correction and in-water retrieval using machine learning techniques. This approach involves training artificial neural networks with representative spectra generated by radiative transfer modeling. Initially deployed within the Case-2 Regional processor for specific and generic inland waters, this technology later evolved into the C2RCC processor as part of the ESA DUE CoastColour project (Brockmann et al. 2016). C2RCC is open source and it maintained by the Water Colour Community (https://c2rcc.org/ last accessed February 2024).

In both cases, ACOLITE and C2RCC implements empirical models that resulted from the fit of in-situ data and specific Sentinel-2 spectral bands combinations (Toming et al. 2016; Potes et al. 2018). Moreover, clouds-shadows pixels have been masked out using SCL or QA60 Bitmasks when the first one was not available.

The following proxy water quality spectral indicators have included into the app according to the scientific literature (Katlane et al. 2020; Toming et al. 2016; Ouma et al. 2020; Zhao et al. 2020): water turbidity (T), chlorophyll content (Chl α) and total suspended solids (TSS) expressed, respectively, in FNU, adimensional and μg L^{-1}.

Here below, it has been reported the equation written in Javascript to compute the above-mentioned proxy water indicators from remote sensing. Concerning on water turbidity (T) is computed as reported in Eq. 1:

$$T = \left\{ \beta_t \times \left[\frac{\left(\frac{\lambda_{665nm}}{10000} \times S_{cf} \right)}{\left(1 - \left(\frac{\left(\frac{\lambda_{665nm}}{10000} \times S_{cf} \right)}{\gamma} \right) \right)} \right] \right\} \tag{1}$$

where, β_t: is a coefficient derived from ACOLITE or C2RCC. S_{cf} : is an adimensional scaling factor in fact turbidity is expressed in FNU. In this case the magnitude is equal to 1. γ : is a coefficient derived from ACOLITE or C2RCC. $\lambda_{665\text{nm}}$: is the red band of Sentinel-2.

Concerning on Chlorophyll content (Chl α) is computed considering the generic Normalized Difference Chlorophyll Index (NDCI) and the (Chl α) algorithm (but this last option is not available to end users) as reported in Eqs. 2 and 3:

$$\text{NDCI} = \frac{\rho_{RedEdge1} - \rho_{Red}}{\rho_{RedEdge1} + \rho_{Red}} \tag{2}$$

$$\text{Chl}\alpha = \frac{\left[\left(\frac{\rho_{RedEdge1}}{\rho_{Red}}\right) - \xi\right]}{\nu} \tag{3}$$

where, $\rho_{RedEdge1}$: is the Red edge 1 band corresponding to B5 in Sentinel 2 with a centered wavelength of 703.9 nm (S2A) and 703.8 nm (S2B), respectively. ρ_{Red} : is the Red edge 1 band corresponding to B4 in Sentinel 2 with a centered wavelength of 664.5 nm (S2A) and 665 nm (S2B), respectively. ξ : is a is a coefficient derived from C2RCC or ACOLITE. ν : is a is a coefficient derived from C2RCC or ACOLITE.

Concerning total suspended solids (TSS) is computed according Eq. 5 starting from Eq. 4 expressed in μgL^{-1}.

$$\phi = \left[\rho_{Red} + \left(\frac{\rho_{NIR}}{\rho_{Red}}\right)\right]^{-2} \tag{4}$$

$$\text{TSS} = \left[\left(\phi^2 \times \delta\right) - (\phi \times \in) + \zeta\right] \tag{5}$$

where,

δ : is a coefficient obtained through C2RCC or ACOLITE. ϵ is a coefficient obtained through C2RCC or ACOLITE. ζ : is a coefficient obtained through C2RCC or ACOLITE. The validation of the results was performed detecting the same parameters locally through Sentinel L1C data processed in ESA SNAP toolbox vers.8.0.0 using C2RCC processor in some inland water bodies located worldwide as reported in Fig. 2 (Orusa et al. 2022a; b) by computing the Root Mean Squared Error, as well as the Mean Absolute Error (MAE) as reported into Eq. 6 and 7, respectively. It is worth to note that also some in situ measures were considered to test the reliability of the application in some Italian lakes.

$$\text{RMSE} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(o_i - p_i\right)^2} \tag{6}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n}\left|p_i - o_i\right|}{n} \tag{7}$$

where: n represents the number of samples, while o_i and p_i are the measured values from SNAP toolbox (calculated) or ground measures (observed) and Sen2WQ (predicted) respectively.

Moreover, the data distribution regarding o_i and p_i were plotted through violins plots as reported in the results using Past tool vers. 4.12. It is worth to note that RMSE and MAE were computed in RStudio vers. 2022.02.2 through the packages “Metrics” vers. 0.1.4 (Orusa et al. 2024).

For each lake analyzed in the present study (please see supplementary material) the entire imagery collection ranging from 1 January 2022 to 31 December 2022 were considered both in GEE (Sen2WQ) and SNAP (downloaded locally from official Copernicus portal Scihub https://scihub.copernicus.eu/ last accessed 20 December 2023). In particular, within the time range the median TSS, Chl-α and turbidity were computed and compared in order to compute RMSE in areas of pure water pixels (with a surface at least of 500 m^2). Since in some cases, Sentinel L1C imagery was not available to direct download in Scihub because of the archive was offline, these data were downloaded from the French portal Theia (https://www.theia-land.fr/ last accessed 20 December 2023).

Finally, in order to sum up the entire approach followed a workflow is presented in Fig. 1.

Results

The GEE app was named Sen2WQ—Sentinel-2 Water Quality. A simple user-interface was implemented permitting to set time range and draw an area of interest. The run button permits to display a composite mean map of the variable selected between (i) water turbidity (T), (ii) chlorophyll content (Chl α), (iii) total suspended solids (TSS), (iv) water color simple detection from RGB and then download a chart in.csv or.png format of one of those parameters through the time selected. These indicators are used to define the trophic state on inland waters, which is particularly important when these waters are used for human consumption or leisure activities, for agriculture or industrial purposes and epidemiological studies. Moreover, MAE and RMSE of T, Chl α and TSS were obtained comparing Sen2WQ and SNAP toolbox computed measurements in water bodies spatially located all around the world. Inland waters are essential for the sustainability of the biodiversity on the regions where they are located and, therefore, monitoring its quality is of great importance considering also the rising effect of both climate change and anthropocene. The app can be reached at this link:

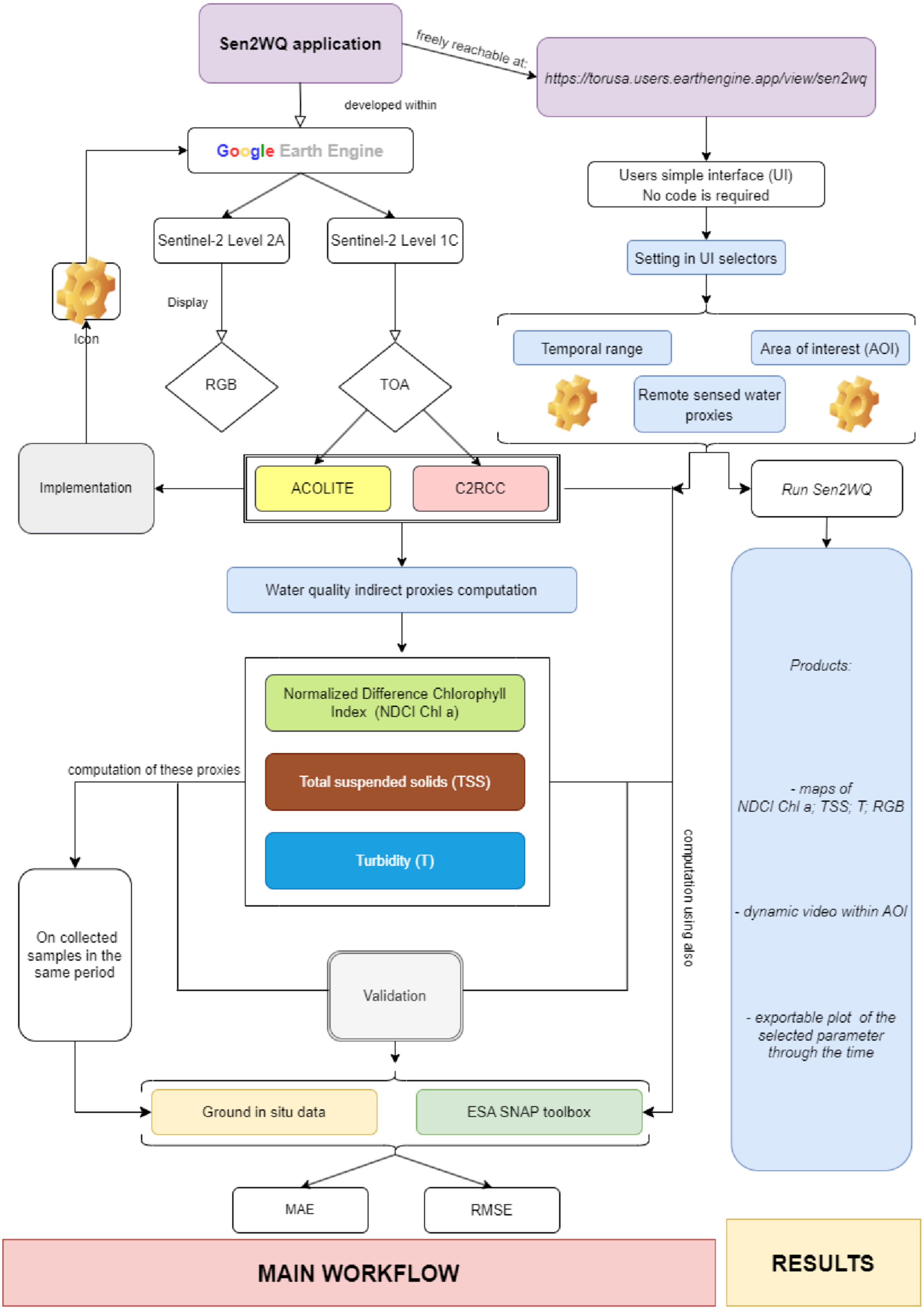
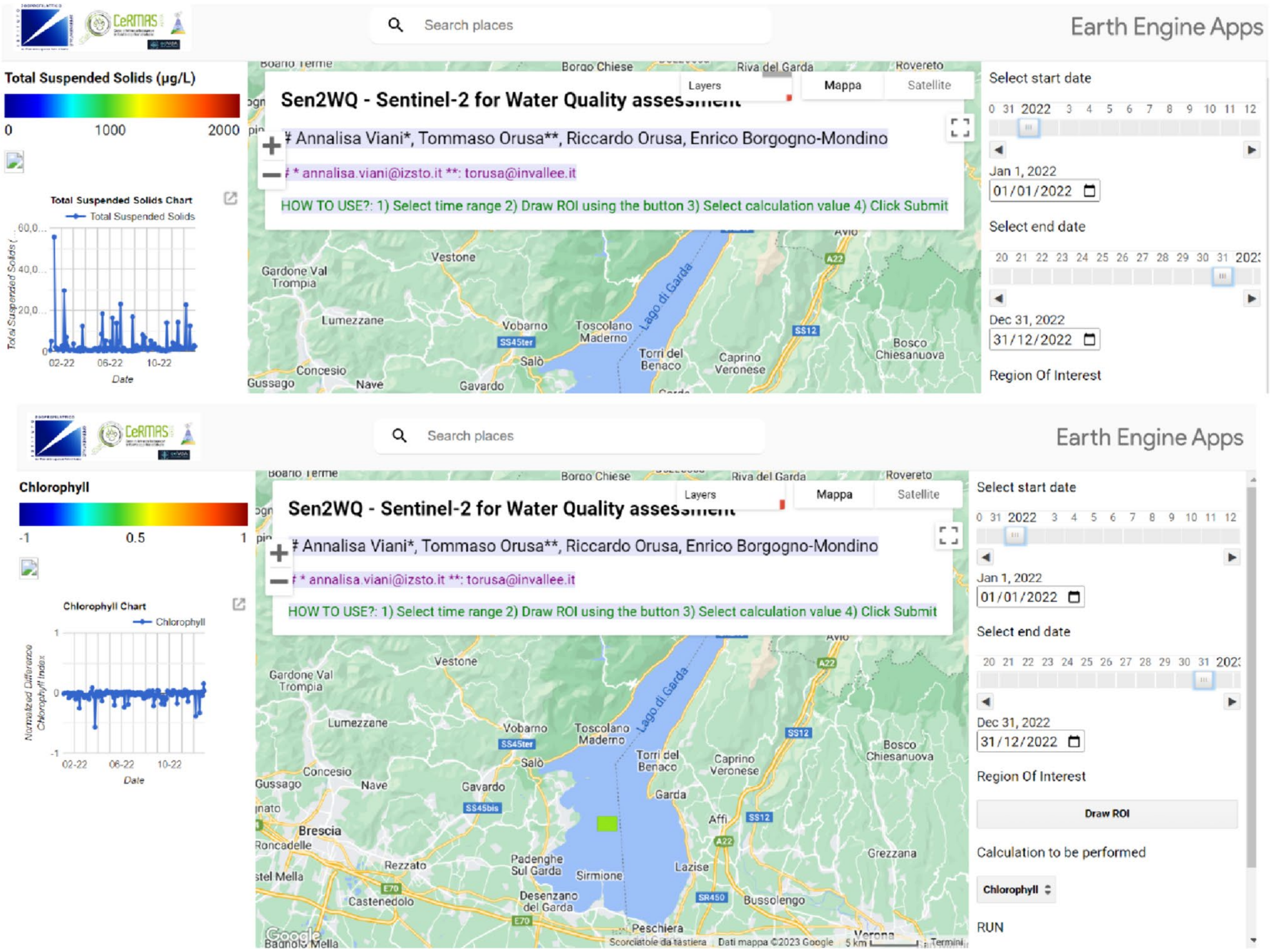


Fig. 1 Flowchart reporting the Sen2WQ approach and description



Sen2WQ - Sentinel-2 for Water Quality assessment

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HOW TO USE?: 1) Select time range 2) Draw ROI using the button 3) Select calculation value 4) Click Submit

Select start date: Jan 1, 2022 01/01/2022

Select end date: Dec 31, 2022 31/12/2022

Calculation to be performed: Chlorophyll

Fig. 2 Dashboard's screenshot from Sen2WQ application within GEE

https://torusa.users.earthengine.app/view/sen2wq (last accessed on 22 December 2023). In Fig. 2, it has been reported an example of the Sen2WQ application.

As previously described in order to validate the results produced with Sen2WQ a random selection of some inland water bodies worldwide located were performed and the water proxies were computed and compared with those retrieved within ESA SNAP toolbox (a table is reported in the supplementary material). In Table 1 below are reported the MAE and RMSE obtained involving the entire water bodies analyzed.

The water proxies computed within Sen2WQ and ESA SNAP toolbox are quite similar as demonstrated by results in Table 1 but also by data distribution (Fig. 3) and their MAEs reported in Fig. 4.

Then, in Fig. 4 has been reported the MAEs of T, Chl α and TSS. Since the variables are expressed in different units of measures, they have been standardized according to Eq. 8, as reported below. This has been done in order to represent the data within the same plot.

Table 1 MAEs and RMSEs computed for water turbidity (T), chlorophyll content (Chl α), total suspended solids (TSS) considering Sen2WQ and ESA SNAP toolbox

	TSS (μgL^{-1})	NDCI Chl-a	Turbidity (FNU)
MAE	2.10	0.03	2.17
RMSE	2.53	0.04	2.80

$$Z = \frac{X - \mu}{\sigma} \quad (8)$$

where, z is the standardized variable, x a given parameter, μ is the mean and σ the standard deviation.

Within the areas analyzed Sen4WQ showed consist results. It is worth to note that no remote sensing or scripting knowledge is required to end users. Furthermore, the application based on cloud computing avoids to lose a lot of time that normally, it would be necessary to compute

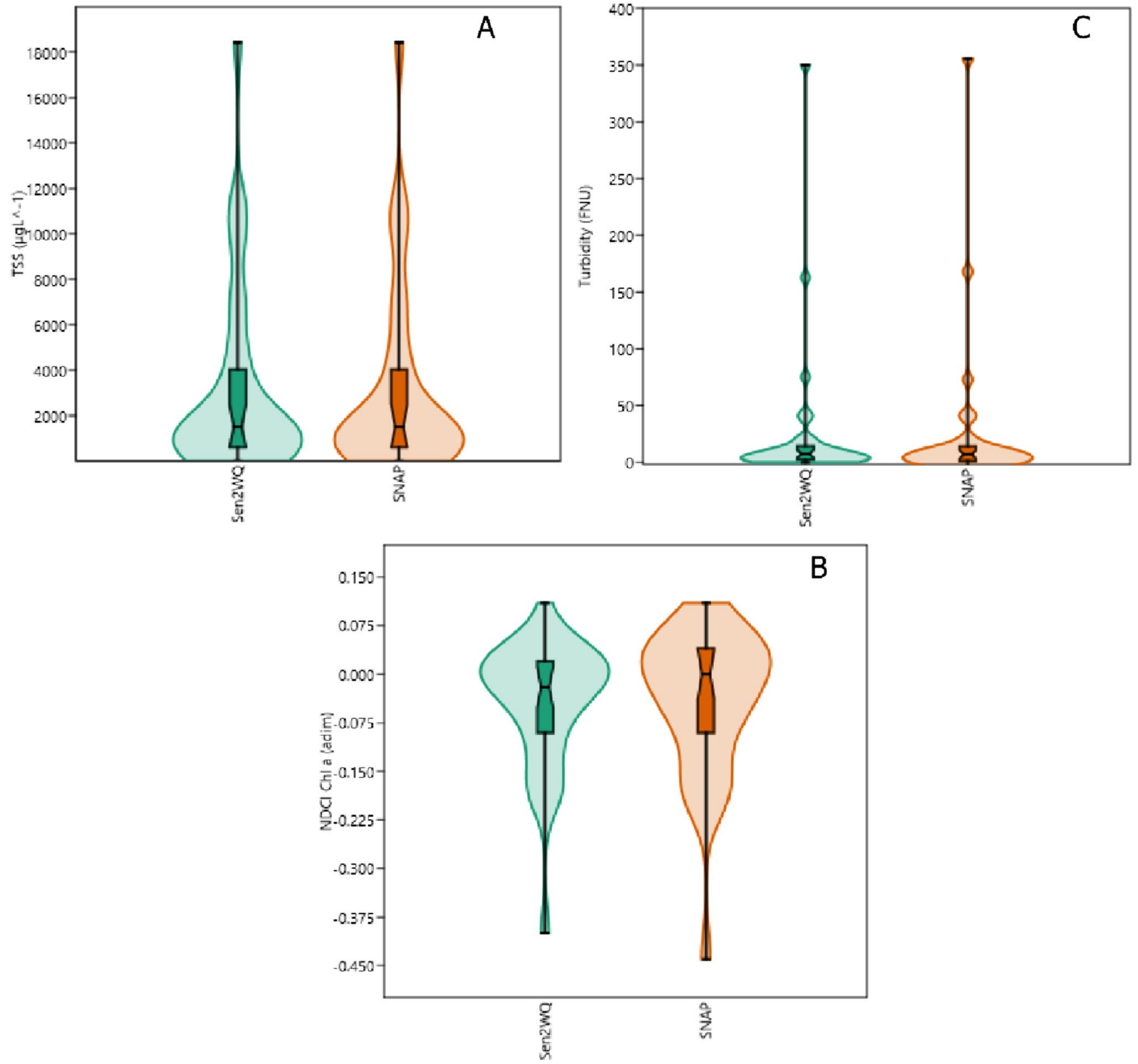

Fig. 3 **A** Total suspended solids (TSS); **B** chlorophyll content (Chl α); **C** Water turbidity (T) data distribution with their relative mean and standard deviation computed using Sen2WQ (in green) and ESA SNAP toolbox (in orange), respectively, in the inland water investigated

the same variable locally and, therefore, it may represent a useful tool to monitor water bodies and their pollutants.

Furthermore, to check the consistency of the results obtained despite the comparison presented in table S1 of supplementary material in which as previously described in both cases data come from remote sensing, in situ measures were included only for two Italian lakes. It is worth to note that ground data collected, were retrieved by European Joint Research Center (JRC) (https://data.jrc.ec.europa.eu/ last access 10 January 2024) and National Research Center that in Italy deals with water issues the CNR IRSA (https://www.irsa.cnr.it/wp/ last access 10 January 2024) portals. In particular, these data were compared by those computed by Sen2WQ. In table S2 in supplementary materials were reported the measures obtained, the consistency of the in-situ dataset and further details, while in Table 2 here below the relative MAEs and RMSEs.

The MAEs and RMSEs calculated in Table 2 show differences between the three water proxies considered. It has to be underlined that using different remote sensing tools they are quite similar, while considering in-situ measures this happens only for chlorophyll content and turbidity. Even

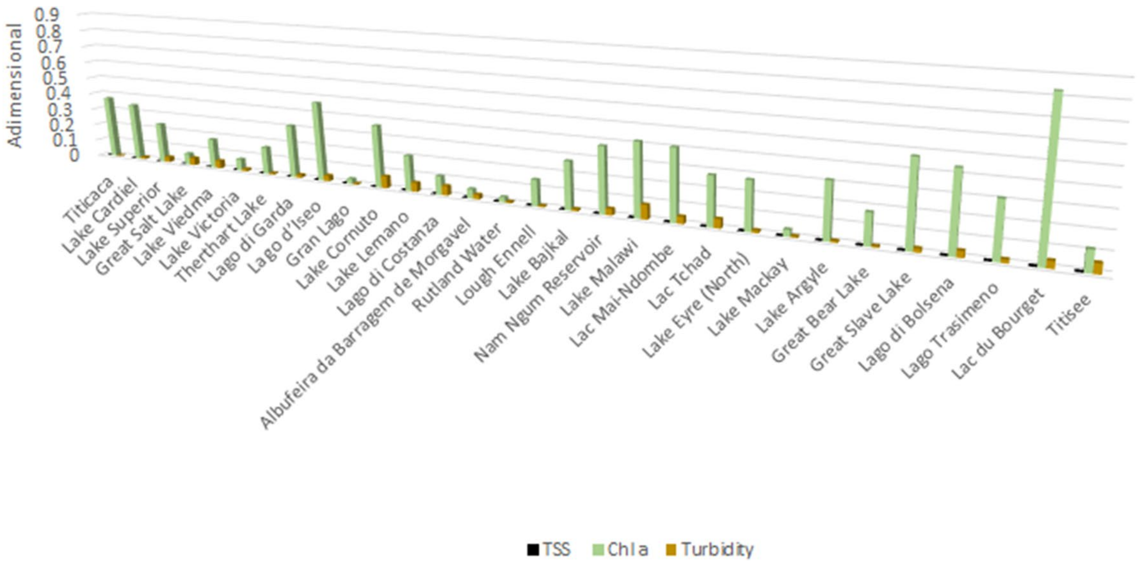

Fig. 4 Standardized MAEs of T, Chl α and TSS

Table 2 MAEs and RMSEs computed for water turbidity (T), chlorophyll content (Chl α), total suspended solids (TSS) considering Sen2WQ and in-situ ground measurements for the Italian lakes investigated

	TSS (μgL^{-1})	NDCI Chl-a	Turbidity (FNU)
MAE	10.95	0.015	0.075
RMSE	10.98	0.016	0.075

if, the results obtained for total suspended solids seem to be acceptable and therefore corroborate the reliability of Sen2WQ, there is a wider difference. A possible explanation may be linked to the greater sensitivity of the analysis instruments conducted on the ground which remain irreplaceable. Although the number of samples on the ground is not large enough to corroborate what has been stated.

Finally, the distribution of TSS, Chl α and T were investigated as reported in Fig. 5 between Sen2WQ and ground measurements collected within the Italian lakes of Garda and Trasimeno which are, respectively, located in the North and Centre of Italy. The data have almost the same distribution the major differences involve TSS and Chl α that also have the major errors as reported in Table 2.

Discussion

The obtained results seem to suggest a validity and technological transferability of *Sen2WQ* to various sectors, thus favoring a concrete One Health approach. However, it should be noted that the number of water bodies to perform the validation involved a small number of lakes despite it is statistically significant considering that it is composed by at least 30 inland water bodies chosen randomly worldwide. Nevertheless, further validation analyzes involving more and more lakes are highly recommended and desirable in the nearer future in particular including ground sample data and laboratory measures of the same variables. At the same time, an implementation of additional parameters and indirect water proxies such as the density of cyanobacteria (C_{ya}), colored dissolved organic matter (CDOM), dissolved organic carbon (DOC) and other *chlorophyll content parameter would be* desirable. Despite everything, the Google Earth Engine application developed seems to be useful in the global monitoring of water bodies at Sentinel spatial resolution (10–20 m in function of the band considered), allowing field analyzes to be directed. For example, in the case of measurement campaigns with a limited budget, as often happens, Sen2WQ would allow technicians to identify, through indirect analyzes based on remote sensing, where to direct their direct analyzes in the field. Or scale measurements collected in the field to satellite measurements through the creation of regression or more complex models. In the latter case, however, the creation of geodatabases (based on the field collection of georeferenced data over time) would certainly allow us to open up application scenarios that are currently only imaginable and such as to strengthen technological transfer and truly widespread and pervasive monitoring of resources water according to a concrete and real One health approach. Today in many technical and scientific sectors, we are witnessing a paradox linked to the intelligent and rational exploitation of technology. In fact, on one hand, it is abused without knowing its real limits and potential, on the other hand we often do

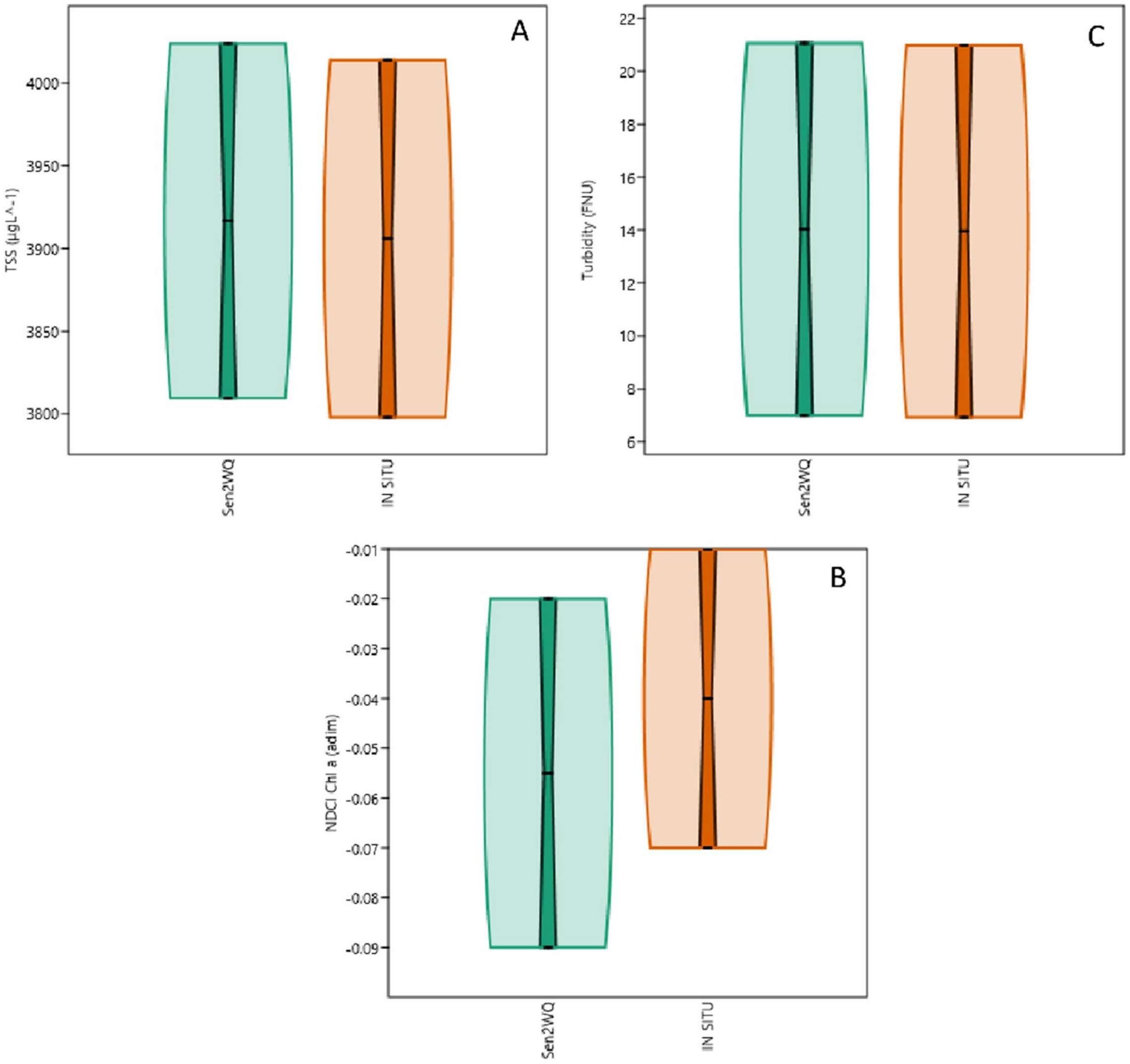

Fig. 5 **A** Total suspended solids (TSS); **B** chlorophyll content (Chl α); **C** Water turbidity (T) data distribution with their relative mean and standard deviation computed using Sen2WQ (in green) and in situ ground measurements (in orange), respectively, in the Italian lakes investigated

not have suitable tools for understanding and managing it with awareness. Technology progresses exponentially and applications often remain limited to a certain sector without opening up to others that could benefit from important implications. However, it should be underlined that, they require continuous updating and awareness of the concrete opportunities or actual limitations. Everything is moving towards the importance of the data that generates information, the problem today is the quality with which I collect that data so that it is scientifically valid and valuable, that it is comparable over time and with different tools and above all that we have knowledge and solid and rigorous tools for its collection. In their absence, it is difficult to achieve real technological transfer and cognitive progress. In fact, the risk is to add noise and confusion to a flood of often approximate scientific information by adopting models or tools that systematically propagate errors and distorted knowledge. The objective of this work was to provide a cloud-based web GIS system and a widely used platform such as Google Earth Engine to support various figures by evaluating the quality of water without ever replacing field analyzes which are essential but which, if anything, goes alongside them or allows us to evaluate and manage situations involving water resources that are difficult to access but which have a crucial ecosystem and animal health value, for example. As illustrated, the application was created with the intention of providing non-experts in remote sensing and scripting with a scientifically rigorous and hopefully safe platform on which they can rely and to complement ordinary analytical and decision-making support tools at various levels. The MAEs and RMSEs obtained seem to corroborate the validity of this tool which we hope can really be useful to various professional figures around the world. It should be remembered that water monitoring applications already exist in Google Earth Engine but none have ever been validated or are based on the implementation of radiative transfer models. Indeed, aquatic remote sensing experts utilize scripts in Python, R, or SNAP to process raw or top-of-atmosphere (TOA) reflectance images from Sentinel-2, despite its limitations in the realm of aquatic ecosystems (hyperspectral data would be better). These scripts enable them to create processing chains and workflows in order to develop EO services. Concerning on Sen2WQ one of the limiting factors at the moment remains the complete implementation of C2RCC directly in the GEE interface in Javascript without calling in there a library written in Phyton and that is only fully reachable in tools like Colaboratory, however, leaving the official GEE application system.

The role of variables like water turbidity, chlorophyll content, and total suspended solids (T, Chl, TSS) in the context of One Health lies in their ability to provide insights into the health of both terrestrial and aquatic ecosystems, which in turn can impact human, animal, and environmental health. Here's how these variables are relevant and how the study has aimed in developing a tool to monitor them according a One Health approach. Water Turbidity (t) refers to the cloudiness or haziness of a fluid caused by large numbers of individual particles suspended in it. High turbidity levels in water bodies can indicate sediment runoff, pollution, or algal blooms, which can have adverse effects on aquatic life. In terms of One Health, turbidity can serve as an indicator of water quality, affecting both human and animal health. For example, high turbidity can interfere with water treatment processes, potentially leading to the presence of harmful pathogens or toxins in drinking water. Additionally, turbid water can impact aquatic species' ability to find food and navigate, ultimately affecting the health of fish populations and other wildlife. It is worth to note both land and aquatic wildlife is a key environmental proxy.

Concerning Chlorophyll Content (Chl), chlorophyll is a pigment found in plants and algae, and its concentration in water can indicate the presence and abundance of phytoplankton, algae, and other aquatic plants. Elevated chlorophyll levels often correlate with eutrophication, a process characterized by excessive nutrient enrichment in water bodies, leading to algal blooms and oxygen depletion. These blooms can produce toxins harmful to both humans and animals, causing issues such as skin irritation, respiratory problems, and even death in severe cases. Monitoring chlorophyll content helps in understanding the dynamics of algal blooms and their potential health impacts on ecosystems and organisms within them pursuing a real One Health approach.

While Total Suspended Solids (TSS) refers to the concentration of particles, both organic and inorganic, that are suspended in water. High TSS levels can result from soil erosion, urban runoff, or industrial discharges, and they can negatively affect aquatic habitats by reducing light penetration, smothering benthic organisms, and impairing fish respiration and reproduction. In terms of One Health, elevated TSS can contribute to the spread of pathogens and contaminants, impacting both human and animal health. For instance, TSS can provide a medium for bacteria and parasites to attach to, potentially leading to waterborne diseases in humans and animals.

By monitoring these variables, even if indirectly using satellite data, doctors and veterinarians can indirectly assess water quality and anticipate potential health risks associated with contaminated or degraded water bodies as well as previously reported address direct analysis with ground measurements. Health care and services, for example, can anticipate outbreaks of waterborne diseases in communities reliant on contaminated water sources by monitoring turbidity and TSS levels. Then, veterinarians can be alerted to potential health issues in livestock or wildlife populations that rely on water bodies for drinking or habitat, based on changes in chlorophyll content indicating harmful algal blooms or other water quality issues. It is important to remember that wildlife hunting, as highlighted in the latest FAO report (Distefano 2005), remains a livelihood for numerous populations and sustains a thriving market in Europe and other continents (Floris et al. 2024). Thus, monitoring environmental variables that affect game is essential for advancing genuine One Health initiatives. Overall, understanding and monitoring these variables play a crucial role in the One Health approach by recognizing the interconnectedness of human, animal, and environmental health and facilitating proactive measures to protect and promote well-being across these domains.

Therefore, a joint work between various sector experts such as geomatics, computer scientists, doctors, veterinarians, chemists, physicists and biologists and more generally environmental scientists can certainly fill the knowledge gap in the veterinarian and health sector about the use and potential of remote sensing and their correct application and exploitation to carry out One Health studies and services (Viani et al. 2023a, b, c; Viani et al. 2023a, b, c; Latini et al. 2021). A correct Geomatics knowledge allows the development and implementation of indirect quality monitoring applications of water, its pollutants and more generally of aquatic ecosystems. A necessity linked not only to the achievement of true One Health and the Sustainable Development Goals (SDGs) but to the present and future challenges that await living species on the planet due to climate change (Orusa et al. 2023a, b, c). Specifically, Sen2WQ can contribute to achieving several (SDGs): Clean Water and Sanitation (SDG 6) in fact the application can provide real-time monitoring and assessment of water quality parameters such as turbidity, chlorophyll-a concentration, and TSS. This information can help identify areas with poor water quality and facilitate targeted interventions to improve access to clean water and sanitation. Life Below Water (SDG 14) by monitoring water quality parameters, the application can help assess the health of aquatic ecosystems, including oceans, lakes and rivers (in this last case, the spatial resolution of Sentinel-2 can be a limit in small water courses due to spectral mixing reasons). This information is crucial for understanding the impacts of pollution and other stressors on marine biodiversity and ecosystems. Life on Land (SDG 15), in fact healthy water ecosystems support terrestrial biodiversity and ecosystem services. Monitoring water quality can help protect habitats and species on land that depend on freshwater resources. By safeguarding water quality, the application contributes to preserving life on land. Good Health and Well-being (SDG 3), access to clean water is essential for human health and well-being. By assessing water quality and identifying potential health risks such as contamination by pollutants or pathogens, the application may support the prevention of waterborne diseases and promote public health. Responsible Consumption and Production (SDG 12) monitoring water quality can inform sustainable water management practices and promote responsible consumption and production. By identifying sources of pollution and promoting efficient use of water resources, the application supports sustainable development and resource conservation. Then, Climate Action (SDG 13), changes in water quality can be influenced by climate change, such as alterations in precipitation patterns, temperature, and extreme weather events. By tracking these changes and their impacts on water quality, the application can support climate adaptation and mitigation efforts. Finally, Zero Hunger (SDG 2), water quality assessment is crucial for sustainable agriculture and food production. Access to clean water is essential for irrigation, livestock watering, and aquaculture and wildlife (as well as game meat) all of which are critical components of food production systems. By monitoring some of the suggested water quality parameters, the application can help ensure the safety and quality of agricultural water sources. This helps to prevent contamination of crops and livestock, reducing the risk of foodborne illnesses. Additionally, the application can assess the health of aquatic ecosystems, including fisheries and aquaculture operations. Healthy aquatic ecosystems support sustainable fisheries and aquaculture practices, which are essential for food security and livelihoods in many communities. By promoting sustainable water management and protecting water resources, the application contributes to enhancing agricultural productivity, resilience, and food security, ultimately supporting the goal of Zero Hunger.

In summary, the One Health Google Earth Engine web-GIS Sen2WQ application for water quality assessment can play a significant role in advancing multiple SDGs by providing valuable information for informed decision-making and promoting sustainable development practices. Managing and monitoring human, animal and plant health starts from an awareness of water resources and a mapping in the domain of time and space through integrated systems that are quick, simple and above all rigorous for the purposes of correct management of water resources.

Conclusions

The development of an application that allows to map water quality defining time range and area of interest represents an important tool for future research studies. In fact, as previously mentioned, it could be used not just as a form of investigation that, indirectly, provide information on human/animal health and environmental conditions. *Sen2WQ* application developed provides an interesting freely open-access web-GIS cloud-based tool for monitoring and assessing water quality according a Geomatics process based on radiative transfer models. The validation has shown an overall RMSEs and MAEs are 2.80 and 2.17 for water turbidity (T), 0.04 and 0.03 for chlorophyll content (Chl α), 2.53 and 2.10 for total suspended solids (TSS). Therefore, water indirect monitoring has to be reinforced by exploiting remote sensing massive technology transfer possibilities, in order to achieve present and future challenged, as well as, pursuing regulations and standards defined by World Health Organization (WHO) passing by those of Food and Agriculture Organization (FAO) and World Organization for Animal Health (WOAH).

The information acquired permit not only to map and study any type of water surface in the World, but hopefully to pursue a One Health Geospatial perspective. It is worth to note that the collaboration between the different sectors of science allowing to explore new research horizons. To realize this scenario, future generations should be increasingly inclined to exchange ideas and concept between universities and research centers of excellence.

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Data availability The data can be requested by sending an email to authors.

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