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Estimation of chlorophyll concentration on surface water bodies from hyperspectral satellite data

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Abstract

This research contributes to advancing the measurement and monitoring of crucial biogeophysical parameters, serving as both qualitative and quantitative indicators for the assessment of natural surface conditions. Leveraging hyperspectral satellite sensors, the primary objective is to enhance the management of natural resources. A key focus of this investigation is the concentration of chlorophyll, a pivotal indicator for assessing phytoplankton abundance and algal biomass in aquatic environments. Chlorophyll concentration emerges as a valuable metric for gauging water quality, understanding the biophysical state of water bodies, discerning trophic levels, and evaluating the eutrophication status of water. The imperative to estimate chlorophyll concentration through satellite-derived data stems from inherent limitations in in-situ measurements. Traditional field measurements conducted by pertinent Regional Environmental Protection Agency entities are labor-intensive, allowing for only a sparse sampling frequency, typically limited to a few measurements annually. Furthermore, these in-situ measurements offer data at specific points, potentially overlooking the spatial variability of chlorophyll concentration across water bodies. By leveraging hyperspectral satellite technology, this research aims to overcome these limitations, providing a more comprehensive and spatially distributed understanding of chlorophyll concentration. This holistic approach not only enhances the efficiency of resource management but also contributes to a more nuanced comprehension of the dynamic ecological processes within aquatic ecosystems.

1. Introduction

The term "pollution," as defined by Legislative Decree 152/06 Article 74, refers to the "direct or indirect introduction, as a result of human activity, of substances or heat into the air, water, or soil, which can harm human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, disrupting, defacing, or deteriorating recreational values or other legitimate uses of the environment". According to the Department of Civil Protection website, pollution sources can be categorized into three types:

- **Civil**: Originating from urban discharges when water flows without any treatment into rivers or directly into the sea.
- **Industrial**: Comprising various substances dependent on industrial production.
- **Agricultural**: Linked to the excessive and improper use of fertilizers and pesticides, which, being generally water-soluble, penetrate the soil and contaminate aquifers.

Polluted waters pose a serious risk to human health and ecosystem quality, as pollutants enter the food chain, causing diseases and deformities. Sustainable water availability and management are among the sustainable development goals. Specifically, Goal 6.3 aims to improve water quality by 2030, reducing pollution, chemical releases, and increasing wastewater treatment before discharge into water bodies. Goal 6.6 focuses on protecting water-related ecosystems. Freshwater ecosystems underpin global water security but face threats from human activities and climate change. The European Water Framework Directive (2000/60/EC) urges member states to achieve good status in water

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bodies by 2027, necessitating the reduction of anthropogenic pollution and the restoration of ecosystems. Goal 14 also aims to reduce or prevent all forms of marine pollution, particularly from nutrients, and to sustainably manage and protect the marine and coastal ecosystem. To gauge progress, continuous monitoring of key biological, physical, and chemical parameters is crucial for understanding the ecological state of water bodies.

This work contributes to the measurement and monitoring of biogeophysical parameters using hyperspectral satellite sensors. These sensors provide both qualitative and quantitative indicators of natural surface conditions. Advanced space technologies, such as the PRISMA satellite in the European Copernicus project, play a vital role in studying Earth, offering real-time and non-intrusive monitoring capabilities.

The study focuses on estimating water quality parameters in lagoon and marine surfaces, specifically chlorophyll concentration in the Venice lagoon (Italy) and nearby marine zones from 2019 to 2022. Utilizing hyperspectral data processed by a neural network, inspired by the biological function of the human brain, overcomes challenges associated with in-situ chlorophyll concentration estimation.

In this research, neural networks significantly enhance chlorophyll concentration monitoring, addressing the limitations of in-situ measurements and providing a more comprehensive understanding of water body dynamics.

2. Method

A neural network is created to estimate chlorophyll concentration from PRISMA satellite data.
The network comprises layers: the Input layer receives external data, the Hidden layer processes information, and the Output layer collects results.
Neural networks can be Single Layer Perceptron (SLP) or Multi-Layer Perceptron (MLP). SLP is simple, offering binary output, while MLP, with hidden layers, uses non-linear transformations and backpropagation.
The activation function adds non-linearity; common ones include sigmoid and hyperbolic tangent functions.
Neural networks generalize learning, vital for complex tasks. Designing a network involves defining inputs/outputs, generating training data, determining structure, and training. The training phase employs backpropagation to adjust weights iteratively.

2.1. Dataset creations

The dataset integrates Sentinel-3 and PRISMA data. Sentinel 3 chlorophyll data was used as ground truth; using the Water Full Resolution product, 22 Sentinel-3 products between 2019 and 2022 were selected.

The PRISMA (PRecursore IperSpettrale della Missione Applicativa) satellite, a groundbreaking initiative by the Italian Space Agency (ASI), represents a significant milestone in the field of Earth observation. Successfully launched on March 22, 2019, PRISMA carries with it a state-of-the-art hyperspectral sensor, setting new standards for high-resolution imaging across numerous spectral bands. This hyperspectral capability empowers PRISMA to unravel intricate details in electromagnetic signatures, facilitating comprehensive analyses of Earth's diverse surfaces and dynamic atmosphere. The satellite's advanced technology enhances our ability to study and understand environmental changes, monitor vegetation health, and investigate variations in mineral composition. PRISMA's contributions extend across diverse domains, from agriculture to water quality, making it a crucial asset in the realm of Earth observation.

The Sentinel-3 Ocean and Land Colour Instrument (OLCI) leads the forefront of the European Space Agency's Sentinel-3 mission, epitomizing state-of-the-art capabilities for Earth observation. Integral to the Copernicus program, Sentinel-3 OLCI assumes a pivotal role in surveilling the well-being of Earth's oceans and land surfaces. Deployed alongside the Sentinel-3A satellite in February 2016, and later complemented by the Sentinel-3B in April 2018, OLCI serves as a medium-resolution imaging spectrometer specifically crafted to capture a diverse array of spectral bands. With its adeptness in recording radiance and reflectance from the Earth's surface, OLCI facilitates the tracking of crucial environmental parameters, spanning ocean color and surface water quality.

For PRISMA data relevant reflectance values were downloaded. Selecting bands crucial for chlorophyll estimation involved referencing absorption spectra and literature. Ten VNIR bands were chosen.

The final dataset structure includes a random set of points on the selected dates, their S3 chlorophyll values and PRISMA reflectance values for selected bands. This data set was divided 60% for the training phase and 40% for the validation phase, which in turn was divided by 55% for the validation phase and 45 % for the testing phase.

2.2. Network structure

By doing a several simulations, also varying the number of intermediate layers, the configuration that reports the minimum error value is shown in Figure 1.
The performance metrics used on validation and test set are the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).

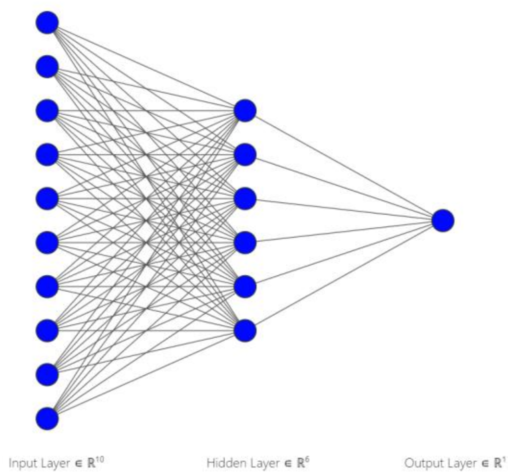

Figure 1. Neural network configuration

3. Results

The neural network created was applied to PRISMA images over the Venice lagoon for determination of chlorophyll concentration maps.
The areas of greatest interest within the lagoon are the city of Venice (1) and Venice Marco Polo airport (2).

Figure 2. Area of interest

Figure 3. Venice Marco Polo airport

The following results were obtained for the date of August 2, 2021.

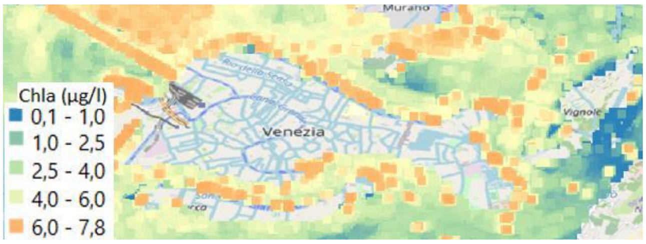

Figure 4. Trend in chlorophyll concentration on 12 August 2021 in the city of Venice

The highest concentrations for the city of Venice are found along the coasts, reaching approximately 8 µg/l. This demonstrates how anthropogenic presence can alter the normal chlorophyll concentration. In the central zone of the lagoon, characterized by limited water exchange, the concentration varies between 2 µg/l and 6 µg/l. In the area where the lagoon connects to the Adriatic Sea, the concentration reaches a maximum value of 1 µg/l. The Mediterranean Sea, in fact, is considered an oligotrophic basin due to its very low chlorophyll concentrations.

Figure 5 confirms what was said previously, there is an increase in the concentration of chlorophyll along the coast of the airport. The concentration reaches a maximum value of approximately 8 µg/l and decreases as the distance from the coasts increases, where concentration values even lower than unity are recorded.

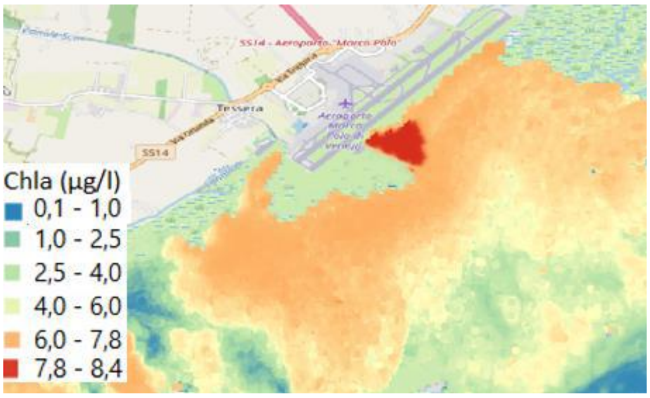

Figure 5. Trend in chlorophyll concentration on 12 August 2021 near the airport

4. Discussion

The analyses conducted unveiled a pronounced issue of eutrophication in the examined waters. During the winter period, the extent of the area impacted by elevated chlorophyll concentration is more substantial. The transition from winter to spring marks the occurrence of phytoplankton "blooms." In contrast, during the summer season, the combination of vertical stratification, leading to diminished nutrient supply in deeper layers, and elevated temperatures results in lower chlorophyll concentrations. This observation contributes valuable insights to the understanding of seasonal variations in phytoplankton dynamics, emphasizing the significance of environmental factors in shaping chlorophyll levels in aquatic ecosystems.

5. Conclusion

In exploring the proposed study, we initially addressed the concern of pollution in surface water bodies, a prevalent issue affecting numerous water systems. Our specific focus centered on the eutrophic condition of these bodies, resulting from the excessive and uncontrolled discharge of nutrients. To meet the objectives outlined in Directive 2000/60/EC, meticulous monitoring of various biophysical parameters becomes imperative for enhancing resource management and quality. The conducted experiments underscored the substantial relevance of neural networks in both the study and surveillance of resources, often relying on specific and constraining observations.

Of particular note is the potential offered by remote sensing in environmental monitoring and the remarkable adaptability of neural networks, making them applicable to a wide array of distinct case studies.

Through the application of the network to various cases of interest, criticalities in chlorophyll concentration were identified, particularly in the coastal regions, characterized by an ecologically poor-sufficient state and zones exhibiting a pronounced eutrophic condition.

The capability to generate, nearly in real-time, a map illustrating the trend in chlorophyll concentration for the designated area holds significant importance. This information proves valuable for the implementation of strategies and measures directed at safeguarding and enhancing the available resources.

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