

Retrieval of Total Suspended Matter in Inland Water Bodies via EnMAP and PRISMA Spaceborne Hyperspectral Imagery: A Dual Neural Network Approach Trained on Decadal In-Situ Spectroscopy

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Abstract

Total Suspended Matter (TSM) is a primary indicator of water quality. Yet, its ecological impact is dictated by its composition—specifically the ratio between Suspended Particulate Inorganic Matter (SPIM) and Suspended Particulate Organic Matter (SPOM). In Mediterranean reservoirs, where agricultural runoff and seasonal algal blooms create complex optical mixtures, retrieving these components separately is essential for distinguishing between mineral sediment transport and organic productivity. Traditional multispectral sensors struggle to decouple the distinct scattering and absorption signatures of organic and inorganic fractions. This research motivates the use of spaceborne imaging spectroscopy, leveraging the high spectral resolution of EnMAP and PRISMA to perform a simultaneous retrieval of both fractions through a dual Neural Network (Dual-NN) inversion strategy. The networks were trained using a historical dataset spanning two distinct periods (2001–2007 and 2017–2019) consisting of 163 in situ samples collected during pan-Iberian campaigns, and independently evaluated with validation data and satellite matchups ($n=36$ for PRISMA and $n=19$ for EnMAP) between 2023 and 2024. The models demonstrated a high capacity to simultaneously resolve mineral sediment transport versus algal organic productivity. Finally, spatial application over continental water bodies of the Iberian Peninsula confirmed the physical-optical coherence of the hyperspectral inversions, paving the way for operational monitoring in future missions like ESA CHIME.

1. Introduction

1.1 Context and Problem Statement

Total Suspended Matter (TSM) represents the mass concentration per unit volume of suspended particles in water, encompassing both inorganic particles of mineral origin (Suspended Particulate Inorganic Matter—SPIM) and organic components derived from detritus and phytoplanktonic biomass (Suspended Particulate Organic Matter—SPOM) (Matthews, 2011; Bilotta and Brazier, 2008). In continental and transitional aquatic ecosystems, pronounced variations in the concentration and composition of TSM directly influence the light penetration regime, the thermal balance of the water column, the transport of particle-bound pollutants, and the consumption of dissolved oxygen associated with the decomposition of organic matter (Bilotta and Brazier, 2008; Bukata et al., 1995).

In the Mediterranean basin, these optical-ecological processes are intensified by anthropogenic pressures, such as diffuse agricultural nutrient inputs that lead to eutrophication, and by global climate change, characterized by prolonged drought periods interspersed with high-intensity torrential rainfall events (Paerl et al., 2019). This extreme alternation favours water erosion in the basins and increases the mineral sediment load in reservoirs and coastal lagoons.

Satellite remote sensing of water quality is based on the interaction of the solar spectrum with Optically Active Components (OACs) present in the water body (Bukata et al., 1995). However, the discrete spectral resolution of traditional multispectral sensors imposes severe restrictions on robustly separating the scattering produced by the mineral fraction from the combined

absorption and backscattering processes caused by organic biomass. The consolidation of recent spaceborne hyperspectral missions, such as the Precursore IperSpettrale della Missione Applicativa (PRISMA) and Environmental Mapping and Analysis Program (EnMAP), offers a density of consecutive bands in the visible and near-infrared (VNIR, 400–900 nm) ideal for discriminating fine spectral features (Niroumand-Jadidi et al., 2020; Chabrilat et al., 2024).

1.2 Background and Preliminary Study

In our preliminary study published in *ISPRS Annals* Soria-Perpinyà et al. (2026), we investigated the capability of PRISMA and EnMAP spaceborne hyperspectral sensors to quantify TSM and differentiate its constituent organic and inorganic fractions across Spanish inland waters using targeted spectral indices. That work demonstrated that the fine spectral resolution of both instruments allows for the identification of key diagnostic features in the water-leaving reflectance (R_{rs}) spectra, as illustrated in Figure 1.

In optically complex inland waters, phytoplankton often acts as the primary OAC driving spectral variability in the VNIR domain. In our preliminary study, we found that the spectral response of TSM is characterized by two distinct features: a green reflectance minimum in the 550–600 nm range, where mineral particles increase backscattering (Pierson and Strömbeck, 2001), and a pronounced NIR peak around 700 nm, which shifts between 693 and 744 nm as TSM concentration increases due to phytoplankton cell scattering and high water absorption.

Guided by these bio-optical mechanisms and systematic algorithm optimization, the index formulations were established as follows:

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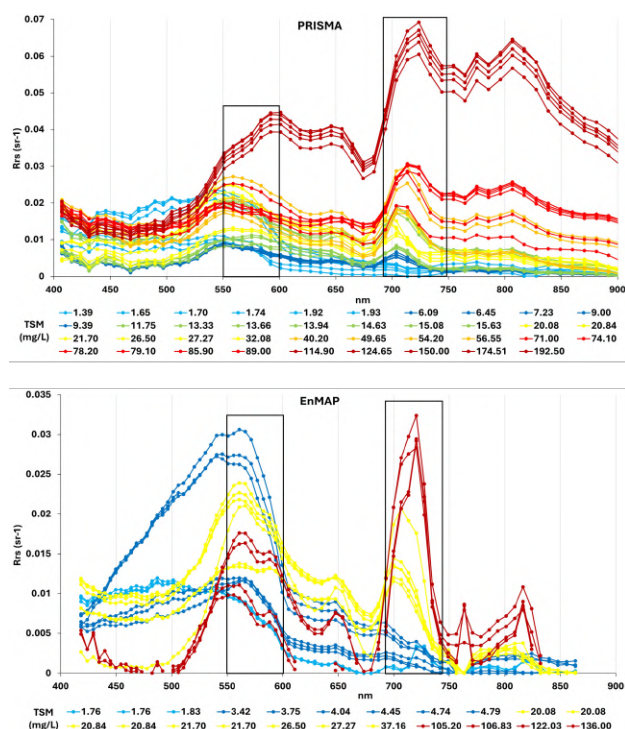


Figure 1. R_{rs} spectra of sampling sites from PRISMA (top) and EnMAP (bottom) images, where the spectral curves are color-coded according to their corresponding TSM concentration values. Boxes mark peaks of interest. Reproduced from Soria-Perpinyà et al. (2026).

1. **Organic Fraction (SPOM):** Formulated using a single spectral band centered at 714 nm to capture the shift of the red-edge reflectance peak. For PRISMA, a linear model with a zero intercept ($R^2 = 0.91$) was calibrated to avoid negative concentration retrievals, whereas a power-law function achieved optimal fit for EnMAP ($R^2 = 0.97$).
2. **Inorganic Fraction (SPIM):** Formulated using a band ratio between the red-edge scattering onset (~ 705 nm) and the green absorption minimum (~ 550 nm). Exponential fits yielded the highest performance: for PRISMA, bands centered at 703.7 nm and 550.9 nm were selected ($R^2 = 0.91$), while for EnMAP, bands at 706.6 nm and 550.7 nm provided optimal agreement ($R^2 = 0.98$).

In Soria-Perpinyà et al. (2026), combining the independently retrieved organic and inorganic components ($TSM = SPOM + SPIM$) yielded highly accurate estimates across both sensors, achieving normalized root mean square errors (NRMSE) below 9% for PRISMA and below 5% for EnMAP.

1.3 Research Objectives and Scope

Building upon the empirical spectral index formulations established in preliminary studies, this work advances towards a dual neural network (Dual-NN) architecture designed to capture non-linear bio-optical interactions and enhance operational full-scene mapping.

The primary objective of this study is to develop and validate a Dual-NN inversion framework for the simultaneous retrieval of

both the overall concentration (TSM) and constituents—specifically the inorganic and organic fractions—of suspended particulate matter in inland water bodies using spaceborne hyperspectral imagery from PRISMA and EnMAP. Furthermore, this research aims to evaluate the robustness, transferability, and performance of the proposed Dual-NN strategy across a wide trophic spectrum and diverse optical regimes in the eastern Iberian Peninsula.

2. Materials and Methods

2.1 Study Site and In Situ Data Sets

Two complementary data sets were used for the development and evaluation of the inversion models:

1. **Historical training data set (2001–2019):** Composed of 163 sampling stations collected within the framework of previous pan-Iberian campaigns. Data were acquired across the INTA and CEDEX projects (2001–2007) as well as the ESAQS project (2017–2019), incorporating laboratory analyses of SPIM/SPOM and water remote sensing reflectance $R_{rs}(\lambda)$ at a 1 nm resolution (400–900 nm). The spatial distribution of these sampling stations used to train the neural networks is depicted in Figure 2 (top).
2. **Satellite validation data set (2023–2024):** Composed of dedicated field campaigns coinciding with overpasses of the PRISMA ($n = 36$) and EnMAP ($n = 19$) satellites. The time gap between field measurements and satellite acquisitions was strictly kept within a ± 3 -day window.

The geographical validation framework encompasses seven aquatic systems in the Iberian Peninsula exhibiting diverse trophic states and optical complexity. On one hand, highly eutrophic and turbid water bodies were included, notably the coastal lagoon of the Albufera of Valencia (a shallow system with a regulated hydrological regime for rice cultivation) and the Bellús and Beniarrés reservoirs. On the other hand, oligotrophic and mesotrophic reservoirs characterized by clearer waters were sampled, such as Benagéber, Contreras, Sitjar, and Tous (see Figure 2, bottom).

To avoid soil-water mixing and coastal adjacency effects, all sampling points were located at a minimum distance of 100 m from the shore.

2.2 Laboratory Protocol and Bio-optical Analysis

Suspension mass determination was carried out by standardized gravimetric analysis (APHA, 1992). The volume of water filtered through pre-weighed glass fibre filters was dried at 105°C for 1 hour to determine the TSM concentration. Subsequently, the filters were subjected to muffle furnace calcination at 460°C for 2 hours to eliminate the organic fraction (SPOM). The remaining mass corresponded to the inorganic fraction (SPIM), allowing the organic fraction to be derived by direct difference ($SPOM = TSM - SPIM$).

2.3 Hyperspectral Image Processing

Level 2 atmospherically corrected products were processed: the L2D product for PRISMA (spectral coverage of 66 VNIR bands) and the L2A product for EnMAP (101 VNIR bands), both with a spatial resolution of 30 m (Bresciani et al., 2022; Chabrilat

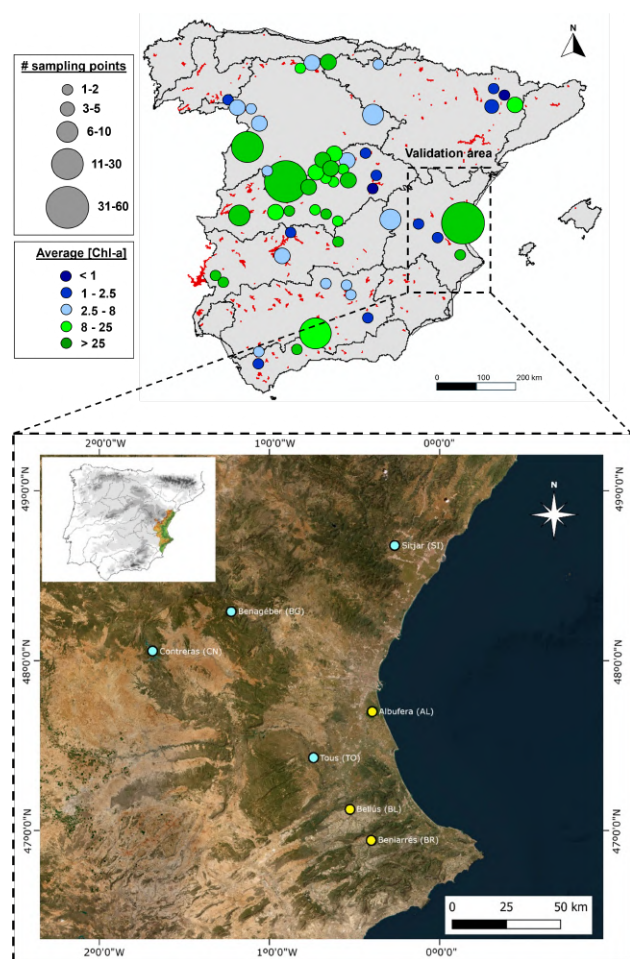


Figure 2. Geographical distribution of the study sites across the Iberian Peninsula in WGS84 geographic coordinate system (latitude/longitude), illustrating the historical training stations from the INTA, CEDEX, and ESAQS campaigns (top) alongside the target reservoirs used for PRISMA and EnMAP satellite validation during the 2023–2024 field campaigns (bottom).

et al., 2024). R_{rs} values were obtained by dividing the atmospherically corrected reflectance by π . Spectral extraction per sampling location was performed by averaging a 3×3 pixel window centred on the *in situ* coordinates.

2.4 Dual-NN Model Architecture

Spectral channels within the Short-Wave Infrared (SWIR) region were excluded from the inversion architecture. Crucially, the *in situ* radiometric database utilized to construct the synthetic training space spans the 400–900 nm spectral range at a 1 nm spectral resolution; extending the network inputs beyond 900 nm would introduce ungrounded extrapolation. Furthermore, pure liquid water exhibits near-complete solar absorption in the SWIR spectrum, and significant SWIR backscattering occurs almost exclusively under extreme turbidity regimes (e.g., highly sediment-laden estuaries like the Río de la Plata) rather than typical inland water bodies.

To exploit the full spectral information available, a dual inversion strategy was designed based on multilayer perceptron neural networks independently optimized for SPIM and SPOM across the VNIR spectral region. Both sub-networks share a compact topology consisting of two hidden layers with 32 and

16 neurons, respectively, utilizing the hyperbolic tangent (tanh) activation function to model smooth, non-linear bio-optical responses. Unlike traditional narrowband-ratio indices or single-channel models, this architecture processes the entire continuous spectral curve. This enables the SPIM network to capture multi-band spectral shape variations and subtle non-linear scattering interactions to isolate inorganic particulates, while allowing the SPOM network to dynamically learn complex relationships associated with algal biomass, pigment absorption, and organic scattering features across diverse optical water types.

Both neural networks were trained using the synthetic hyperspectral dataset spectrally convolved with the specific instrument spectral response functions (ISRF) of PRISMA and EnMAP. Following recommendations by Braga et al. (2022), the first three blue spectral bands of PRISMA were excluded from the training and inversion process due to potential atmospheric correction residual errors and lower signal-to-noise ratios in the deep blue region. Finally, TSM was derived additively by summing the individual predictions from both independent sub-networks ($TSM = SPIM + SPOM$).

To rigorously assess the predictive performance and operational scalability of the Dual-NN architecture, the models were independently validated using the matchup database gathered during the 2023–2024 field campaigns. This validation set spans field measurements synchronized with actual PRISMA ($n = 36$) and EnMAP ($n = 19$) spaceborne overpasses across the evaluated Iberian aquatic systems.

The end-to-end processing workflow, model optimization, and statistical validation (see Figure 3) were implemented in Python. Neural network architectures, hyperparameter tuning, and cross-validation procedures were developed using the `scikit-learn` machine learning library, alongside NumPy and SciPy for numerical computations and spectral convolution routines.

3. Results

3.1 Bio-optical Sampling Campaigns for Model Training and Validation

A comprehensive dataset of *in situ* limnological and bio-optical parameters was compiled to train and independently validate the Dual-NN model for estimating SPIM, SPOM, and TSM. The field measurements encompass a wide dynamic range of water quality conditions across Spanish inland water bodies, capturing diverse trophic states and optical regimes.

For model calibration and algorithm training, a total of $n = 163$ coincident radiometric and water sample measurements were utilized. As summarized in Table 1, the calibration dataset spans more than one order of magnitude in concentrations, with TSM values ranging from 0.67 to 162.30 mg/L (mean = 16.94 mg/L , median = 4.49 mg/L). This broad gradient ensures robust neural network learning across both clear and highly turbid waters. SPOM constitutes the primary organic fraction across the calibration sampling stations (mean = 10.98 mg/L), whereas SPIM exhibits a lower overall mean concentration (6.16 mg/L) but significant variability (standard deviation = 11.59 mg/L), reflecting episodic mineral inputs.

To evaluate model performance under actual satellite acquisition scenarios, independent validation subsets matched with spaceborne hyperspectral observations were extracted. Table 2

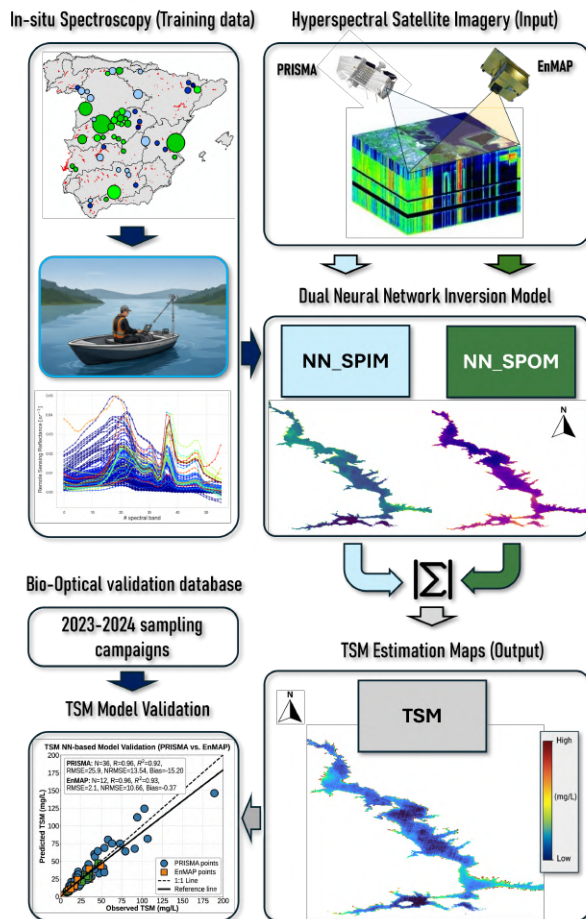


Figure 3. End-to-end processing framework for SPIM, SPOM, and TSM retrieval from hyperspectral imagery. The pipeline integrates in situ radiometric measurements collected across Spanish inland water bodies with PRISMA and EnMAP hyperspectral satellite observations. Neural Network algorithms are applied to retrieve SPIM and SPOM spatial maps, which are combined to derive TSM distribution maps and validated against satellite observations.

presents the descriptive statistics of the *in situ* water quality data coupled to the quasi-synchronous overpasses of PRISMA ($n = 36$) and EnMAP ($n = 19$). The PRISMA-matched dataset covers elevated concentration ranges, with TSM reaching up to 192.50 mg/L (mean = 44.34 mg/L , std = 50.25 mg/L). Similarly, the EnMAP validation subset reflects moderately turbid to highly turbid conditions, with TSM averaging 32.58 mg/L and maximum values of 136.00 mg/L . In both satellite match-up subsets, SPOM accounts for the dominant organic component, consistent with the calibration dataset distribution.

3.2 Calibration of the Dual-NN Models

To evaluate the accuracy and consistency of the developed neural network models, predicted concentrations (y_{pred}) were benchmarked against observed *in situ* values (y_{true}) for both SPIM and SPOM. Figure 4 details the validation scatter plots and error metrics across the PRISMA and EnMAP match-up datasets.

Overall, the algorithms demonstrated robust predictive capabilities, with data points closely aligned along the 1 : 1 reference line across low-to-high turbidity gradients. For the PRISMA retrieval performance (Figure 4, top), the SPOM model achieved

Table 1. Descriptive statistics of the *in situ* water quality parameters used for calibration ($n = 163$).

Sensor / Metric	TSM (mg/L)	SPOM (mg/L)	SPIM (mg/L)
Mean	16.94	10.98	6.16
Median	4.49	1.40	2.60
Minimum	0.67	0.04	0.28
Maximum	162.30	96.80	75.40
Std. Dev.	28.84	20.16	11.59

Table 2. Descriptive statistics of the *in situ* water quality parameters coupled to PRISMA ($n = 36$) and EnMAP ($n = 19$) used for validation.

Sensor / Metric	TSM (mg/L)	SPOM (mg/L)	SPIM (mg/L)
PRISMA			
Mean	44.34	26.13	18.21
Median	20.84	14.48	8.37
Minimum	1.39	0.79	0.60
Maximum	192.50	84.38	108.13
Std. Dev.	50.25	26.61	26.02
EnMAP			
Mean	32.58	19.17	13.41
Median	20.46	14.43	5.92
Minimum	1.76	0.09	0.98
Maximum	136.00	78.73	75.40
Std. Dev.	42.58	24.69	19.19

a coefficient of determination (R^2) of 0.757 with a root mean square error (RMSE) of 9.932 mg/L (NRMSE = 10.26%), slightly outperforming the SPIM retrieval ($R^2 = 0.72$, RMSE = 6.132 mg/L , NRMSE = 8.19%). Both constituents exhibited stable regression slopes ($y = 0.78x + 2.45$ for SPOM and $y = 0.75x + 1.48$ for SPIM), indicating minimal systematic bias in PRISMA retrievals across varying organic and inorganic loads.

A higher retrieval fidelity was obtained for the EnMAP match-ups (Figure 4, bottom). The SPOM estimation achieved exceptional agreement with ground observations, yielding an R^2 of 0.946, a mean absolute error (MAE) of 2.001 mg/L , and a normalized error (NRMSE) below 4.3%. Similarly, the SPIM model demonstrated high precision ($R^2 = 0.854$, RMSE = 4.116 mg/L , NRMSE = 5.49%). The linear fits for EnMAP ($y = 0.92x + 0.82$ for SPOM and $y = 0.86x + 0.98$ for SPIM) exhibit slopes close to unity, highlighting the strong capacity of EnMAP's spectral configuration to decouple organic and inorganic fractions in complex inland waters.

3.3 Validation of the Dual-NN Models

The evaluation of the adjusted models' performance was carried out by comparing the predicted estimates against the *in situ* validation data for both sensors. Table 3 details the statistical-quantitative validation metrics reached by the Dual-NN models.

3.4 Spatial Mapping and Retrieval Distribution of SPIM, SPOM, and TSM

To assess the spatial consistency and mapping capabilities of the Dual-NN architectures across contrasting optical regimes, the trained models were successfully applied to full-extent PRISMA and EnMAP hyperspectral scenes covering all seven reservoirs and aquatic systems included in the validation dataset (Albufera, Benagéber, Bellús, Beniarres, Tous, Contreras, and Sitjar).

For conciseness and to select the optimal scenes in terms of cloud-free coverage and negligible sun glint, Figures 5 and 6

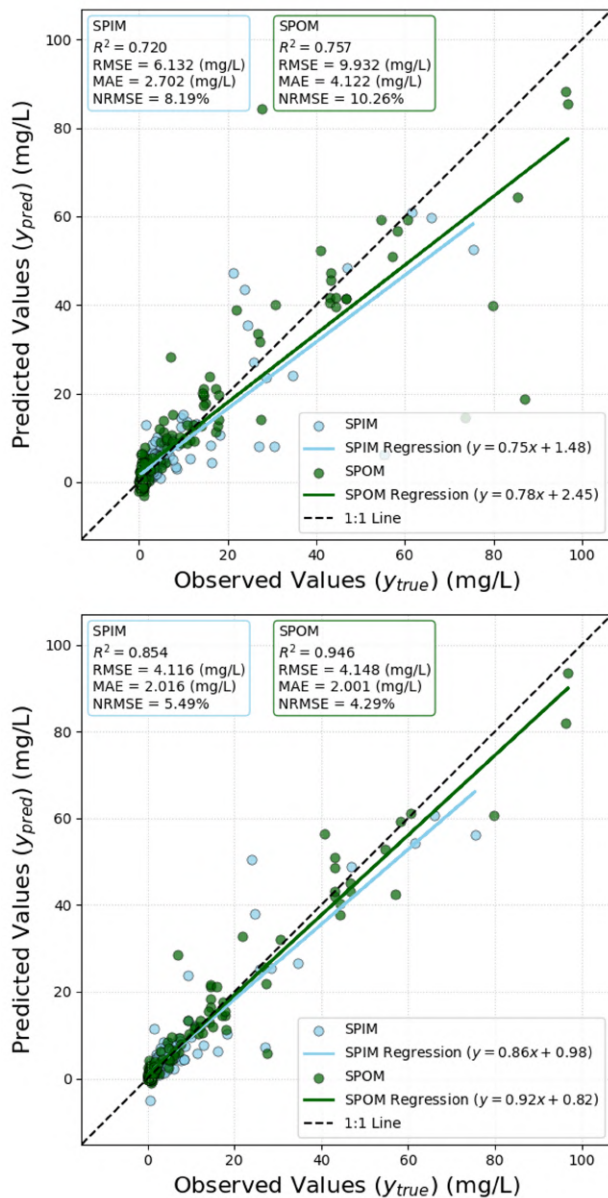


Figure 4. Validation scatter plots of predicted versus observed concentrations for SPIM and SPOM. Comparison between predicted (y_{pred}) and observed (y_{true}) values for SPIM (light blue), and SPOM (dark green) for **PRISMA** (top) and **EnMAP** (bottom) models. The solid lines represent the linear regression fits, while the dashed line indicates the 1 : 1 reference line. Performance statistics (R^2 , RMSE, MAE, and NRMSE) are inset for each parameter.

illustrate the derived concentration maps (SPIM, SPOM, and TSM) for two representative systems at opposite optical extremes: the hypertrophic Albufera of Valencia lagoon (PRISMA) and the oligotrophic Benag ber reservoir (EnMAP). Furthermore, although complete pairs of PRISMA and EnMAP scenes were acquired on different dates for the Albufera, Benag ber, and Bell s water bodies, the retrieved concentration distributions remained highly consistent between sensors and representative of each system’s bio-optical regime, showcasing the cross-sensor reliability of the Dual-NN workflow.

The spatial distribution of the retrieved constituents demon-

Table 3. Validation performance metrics (R^2 , RMSE in mg/L , NRMSE in %, and Bias in mg/L) for SPIM, SPOM, and total TSM (TSM = SPIM + SPOM) dual neural network models across PRISMA and EnMAP sensors.

	R^2	RMSE	NRMSE	Bias
SPIM				
PRISMA	0.87	10.1	11.10	3.14
EnMAP	0.79	1.8	21.54	1.43
SPOM				
PRISMA	0.82	16.8	20.12	10.48
EnMAP	0.92	1.9	13.25	1.9
TSM				
PRISMA	0.92	25.9	13.54	15.2
EnMAP	0.93	2.1	10.66	0.37

strates smooth, spatially coherent patterns without pixel-level noise or edge artifacts, confirming the generalization stability of the Dual-NN framework. Overall, the derived maps effectively capture the distinct bio-optical conditions of the evaluated water bodies:

- **Hypertrophic Regime (Albufera of Valencia – PRISMA):**

As depicted in Figure 5, the Albufera lagoon exhibits elevated overall turbidity and high constituent magnitudes characteristic of a shallow, highly productive hypertrophic ecosystem. The decoupled products successfully delineate internal bio-optical variability, with high SPOM concentrations dominating the central open water area due to persistent phytoplankton biomass. Higher TSM levels are observed near shallow shoreline areas and canal inputs, where wind-driven sediment resuspension and runoff are prominent.

Notably, the full-scene PRISMA retrieval identifies active water pixels in the agricultural surrounding zones. Due to seasonal farming practices and field flooding, the model correctly processes flooded paddy rice fields as water surfaces, mapping high constituent concentrations influenced by shallow water depth, heavy organic loads, and suspended sediment.

- **Oligotrophic Regime (Benag ber Reservoir – EnMAP):**

In contrast, the EnMAP retrieval over the deep oligotrophic Benag ber reservoir (Figure 6) shows consistently low concentration ranges across all parameters. The predicted TSM map reveals a clear longitudinal gradient along the reservoir’s main axis, with slightly higher SPIM concentrations localized near the upstream river inflow, while SPOM remains uniformly low throughout the main body, reflecting clear-water, low-productivity conditions.

Ultimately, this framework successfully unmixes organic and inorganic fractions across orders of magnitude in concentration, delivering accurate, high-resolution geospatial intelligence for diverse inland aquatic ecosystems.

4. Discussion

4.1 From Empirical Spectral Indices to a Pan-National Dual-NN Paradigm

A critical aspect when evaluating retrieval architectures is the trade-off between local empirical performance and global model generalizability. In our preliminary study (Soria-Perpiny  et

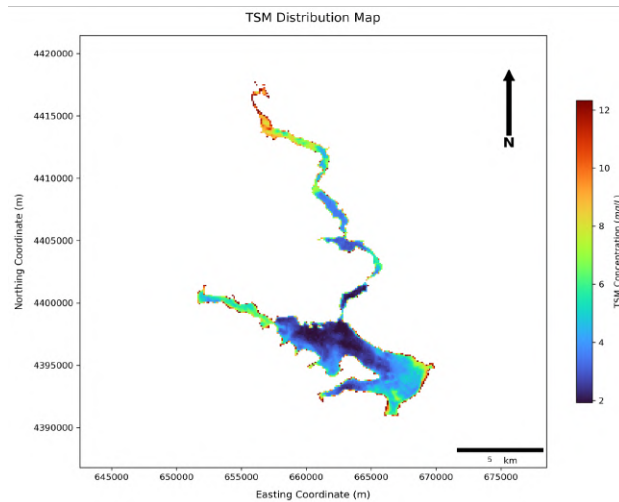
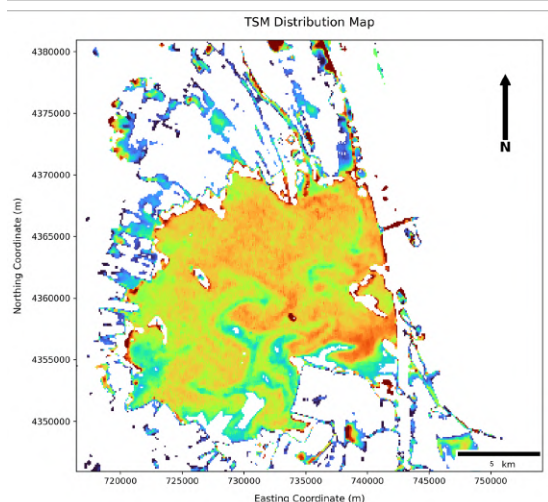
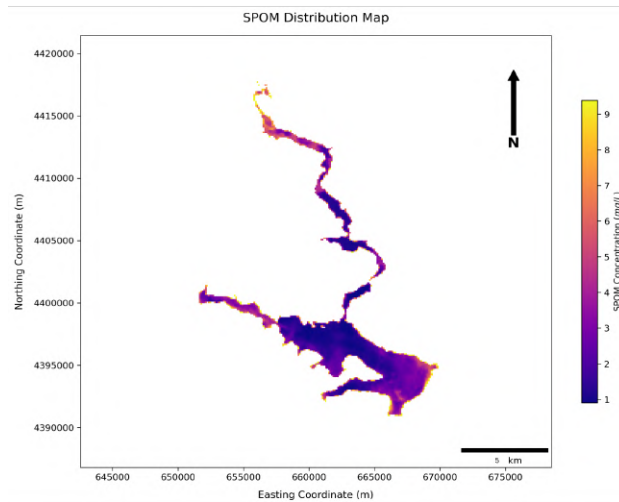
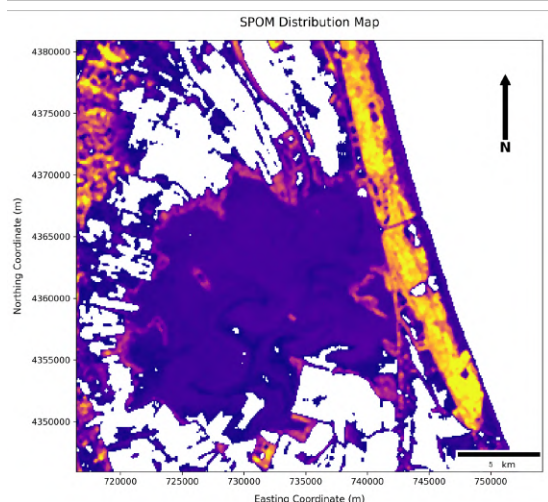
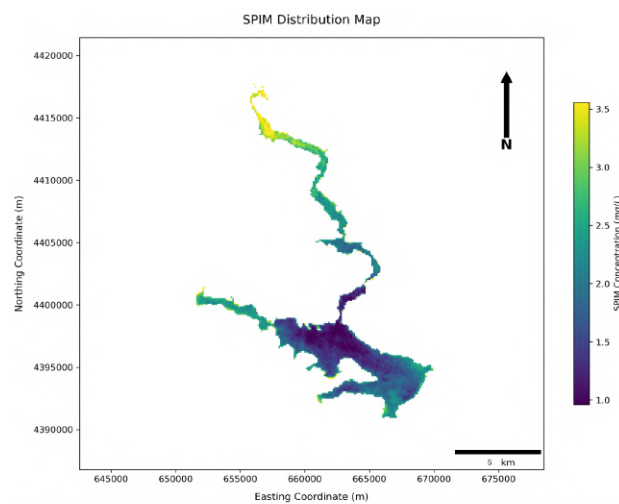
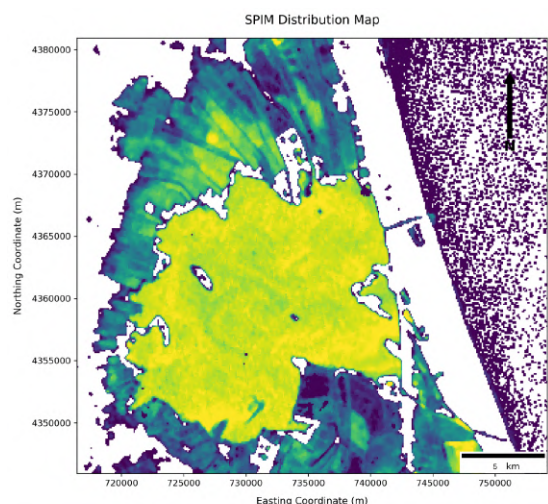


Figure 5. Spatial distribution maps of water constituent concentrations (SPIM, SPOM, and additive TSM) in UTM zone 30N projection system (ETRS89 datum), retrieved from a PRISMA hyperspectral image acquired over the hypertrophic Albufera of Valencia lagoon on November 22, 2023.

Figure 6. Spatial distribution maps of water constituent concentrations (SPIM, SPOM, and additive TSM) in UTM zone 30N projection system (ETRS89 datum), retrieved from an EnMAP hyperspectral image acquired over the oligotrophic Benagéber reservoir on June 10, 2024.

al., 2026), targeted spectral indices yielded exceptional statistical fits for local datasets (NRMSE < 9% for PRISMA and < 5% for EnMAP). However, as is inherent to empirical formulations, those indices were strongly calibrated to specific bio-optical co-variances—such as the high correlation between

chlorophyll-*a*, SPOM, and SPIM observed in the preliminary sampling sites—making them prone to performance degradation when applied beyond their specific calibration domain or across shifting optical regimes.

In contrast, the Dual-NN framework introduced in this work trades minor empirical optimizations for unmatched versatility, operational robustness, and wide-range applicability:

- **Decoupling Bio-Optical Co-variances:** Unlike empirical spectral indices that rely on fixed correlations between pigments and minerals, the Dual-NN leverages a pan-national synthetic training set to learn multi-spectral, non-linear features. This enables dynamic unmixing of organic and inorganic fractions even when typical constituent correlations break down (e.g., sediment resuspension or post-bloom decay).
- **Dynamic Range and Overfitting Mitigation:** Empirical fits often suffer from local overfitting or saturation at extreme values. The Dual-NN architecture seamlessly spans an order of magnitude in concentration—from clear oligotrophic waters ($\text{TSM} < 5 \text{ mg/L}$) to hyper-turbid systems ($\text{TSM} > 50 \text{ mg/L}$)—without requiring site-specific recalibration.
- **Pan-National Transferability and Sensor Interoperability:** Although dedicated Dual-NN models were trained for each sensor to match their specific spectral band configurations, both share a unified architecture and are trained on the same pan-national synthetic bio-optical distributions. This consistent design strategy avoids heuristic, sensor-specific empirical fits (e.g., linear vs. power-law functions) and ensures cross-sensor stability and coherent spatial mapping across both PRISMA and EnMAP scenes.

Therefore, while empirical spectral indices serve as valuable benchmarks for regional assessment, the Dual-NN paradigm represents a crucial step toward scalable, automated, and pan-national inland water quality monitoring frameworks capable of operational deployment without local retraining.

4.2 Performance and Unmixing Capability of the Dual-NN Framework

The validation results demonstrate that the proposed dual-NN architecture effectively addresses the challenging task of decoupling SPIM and SPOM from TSM in optically complex inland waters. Standard bio-optical algorithms often struggle in inland environments due to the overlapping spectral signatures of mineral sediment, phytoplankton pigments, and colored dissolved organic matter. By training dedicated sub-networks for the inorganic and organic fractions, the model achieves high retrieval accuracy across contrasting sensor architectures.

As summarized in Table 3, the framework achieves strong coefficients of determination ($R^2 > 0.79$) and moderate RMSE across all constituent models. Notably, SPOM retrievals exhibited remarkable performance in EnMAP ($R^2 = 0.92$, $\text{RMSE} = 1.9 \text{ mg/L}$), benefiting from EnMAP's superior signal-to-noise ratio and narrow spectral bandwidths in the VNIR region, which are critical for resolving subtle absorption peaks associated with organic pigments. The lower relative error observed in EnMAP compared to PRISMA (NRMSE = 13.25% vs. 20.12%) further underscores the advantage of high-radiometric-quality hyperspectral imagery for subtle bio-optical characterization.

The additive TSM model yielded exceptional performance for total particulate mass estimation, reaching $R^2 = 0.92$ and 0.93 for PRISMA and EnMAP, respectively. The absence of systematic bias in the additive TSM estimations of the EnMAP

TSM model (e.g., Bias = 0.37 mg/L) confirms that decoupling the constituent fractions into distinct, physically sound sub-models does not accumulate residual error but rather stabilizes the global mass balance retrieval.

4.3 Cross-Sensor Robustness and Limnological Consistency across Water Bodies

A major challenge in inland water remote sensing is the transferability and robustness of retrieval models across sensors featuring distinct spatial resolutions, radiometric performance, and asynchronous acquisition timings. In this study, the Dual-NN workflow was applied to full-extent PRISMA and EnMAP scenes to map SPIM, SPOM, and TSM across all seven target aquatic systems, covering a broad limnological gradient: from the shallow, hypertrophic Albufera of Valencia lagoon, to mesotrophic environments such as Bellús and Beniarres reservoirs, to clear-water oligotrophic and mesotrophic systems including Benagéber, Contreras, Sitjar, and Tous reservoirs.

For simplicity and visual clarity, spatial maps representing opposite optical extremes are highlighted in this manuscript (PRISMA for Albufera and EnMAP for Benagéber). Crucially, non-simultaneous acquisitions from both sensors were processed for Albufera, Benagéber, and Bellús. Despite the difference in acquisition dates and sensor characteristics, the retrieved spatial distributions exhibit strong cross-sensor consistency. More importantly, the retrieved concentration levels closely align with the known bio-optical regimes and seasonal dynamics observed in the *in situ* validation datasets.

The derived maps successfully capture the full dynamic range of water constituent concentrations—spanning more than one order of magnitude between the clear-water conditions of Benagéber ($\text{TSM} < 5 \text{ mg/L}$) and the hyper-turbid regime of L'Albufera ($\text{TSM} > 50 \text{ mg/L}$). This demonstrates that the synthetic training space effectively encompasses the optical extremes encountered in natural inland waters, preventing model saturation in hyper-productive environments while maintaining high sensitivity in oligotrophic, low-turbidity waters.

4.4 Spatial Dynamics and Environmental Contextual Effects

The spatial distribution maps (Figures 5 and 6) confirm that the Dual-NN model reproduces realistic, spatially coherent limnological features without high-frequency spatial noise or edge artifacts.

In the deep, oligotrophic Benagéber reservoir (Figure 6), retrieved values remain uniformly suppressed across all parameters, capturing a distinct longitudinal spatial gradient marked by subtle SPIM elevations confined to the riverine inlet. In stark contrast, the hypertrophic Albufera lagoon (Figure 5) is characterized by widespread, elevated SPOM magnitudes concentrated in the central zone of the lagoon as a result of enduring algal biomass. Concurrently, localized surges in TSM emerge along shallow littoral margins and irrigation channel outlets, where hydrodynamic resuspension and terrestrial runoff heavily influence the water column.

Crucially, full-scene retrievals over the Albufera basin revealed elevated constituent concentrations in the agricultural lands surrounding the lagoon. Rather than model degradation, these features correspond to seasonal flooding of paddy rice fields,

where shallow water layers cover rich organic soils. The Dual-NN model successfully identified these flooded pixels as aquatic surfaces, retrieving high SPOM and SPIM values driven by soil organic matter dissolution, shallow sediment resuspension, and agricultural runoff. Recognizing these agricultural water bodies is vital for regional water management, as agricultural drainage channels serve as the primary vector for nutrient loads entering the lagoon ecosystem.

4.5 Limitations and Operational Perspectives

While the Dual-NN architecture demonstrates robust retrieval capability, certain operational limitations remain. First, atmospheric correction over turbid or small inland waters remains a primary source of retrieval uncertainty. Residual surface reflectance errors, particularly in the blue spectral region or due to uncorrected adjacency effects near narrow shorelines, can propagate into the neural network inversion.

Second, while the additive formulation $TSM = SPIM + SPOM$ preserves conservation of mass, severe sun glint or extreme bottom reflectance in shallow, ultra-clear waters can alter spectral steepness, potentially leading to overestimation of inorganic fractions. Future developments will focus on integrating automated pixel-level uncertainty bounds directly into the neural network architecture (e.g., via Bayesian Neural Networks or Gaussian Process regression fallbacks) to provide end-users with spatial confidence layers alongside constituent concentration maps.

5. Conclusions

Performance metrics demonstrate that the Dual-NN framework successfully decouples particulate fractions across the evaluated trophic gradient. In particular, the fine spectral resolution of EnMAP and PRISMA enabled the retrieval of key narrow-band spectral features, allowing the networks to effectively differentiate mineral backscattering from organic absorption signatures. High determination coefficients ($R^2 > 0.90$) achieved for the combined TSM product across both satellite platforms validate the additive inversion strategy.

The observed discrepancy in error metrics (i.e., lower RMSE in EnMAP compared to PRISMA) primarily stems from the larger size and greater optical diversity of the validation dataset associated with PRISMA overpasses, which captured a broader range of water types across Mediterranean systems. Overall, this research underscores the capacity of spaceborne imaging spectroscopy to resolve the optical complexity of continental waters, confirming its clear advantage over conventional multispectral sensors in discriminating organic productivity from mineral sediment transport.

Furthermore, integrating long-term, spatially representative in situ datasets with machine learning architectures provides the generalization robustness required for operational monitoring, thereby reducing reliance on site-specific calibrations. This approach establishes a scalable and reliable framework for water quality assessment using next-generation hyperspectral missions like the upcoming ESA CHIME.

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