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Development of Algorithms for Remote Evaluation of Chlorophyll «a» in the Water Bodies of the Dniester River Delta Using Sentinel-2 MSI

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ABSTRACT

Problems Statement and Objective. Intensive economic activity in the Dniester River basin and overregulation of its flow via excessive reservoirs provoke eutrophication and deterioration of the water quality affecting ecosystem biodiversity and threatening public health. To achieve sustainable water quality management, it is proposed to use remote sensing (RS) to estimate chlorophyll «a» concentration as a tool for water bodies monitoring. To consider optical properties of these objects and to determine functional dependences, the concentrations calculated with different algorithms based on RS data are compared with field measurements. The main objective of this study is to select and validate the algorithms for remote estimation of chlorophyll «a» concentration in water bodies of the Dniester River Delta using measurements from the Sentinel-2 Multispectral Instrument (MSI).

Data and Methods. Chlorophyll «a» concentrations obtained from the Dniester Delta water bodies from April to September of 2017–2021 have been used. Also, two types of MSI reflectance were used: top-of-atmosphere (TOA) and surface reflectance (SR). During the selection of optimal algorithms, a literature review was conducted. It was decided to select two types of MSI Sentinel-2 spectral band functional combinations. Also, calculations of chlorophyll «a» concentration by the C2RCC (Case 2 Regional Coast Color) processor in SNAP Sentinel Toolbox platform were used.

Results and Discussion. Exponential-type functional dependences were established during development of the selected two-channel and three-channel models. The proposed functional dependences were verified by comparing the calculated values, as well as obtained by the C2RCC processor, with the chlorophyll «a» concentration in the field samples. Comparison showed an advantage of using the TOA coefficients (compared to SR) for both the two-channel and three-channel models: $R_{p<0.001}=0.92$, $MAPE=28.5$, $RMSE=14.4 \text{ mg/m}^3$ and $R_{p<0.001}=0.93$, $MAPE=27.9$, $RMSE=14.3 \text{ mg/m}^3$, respectively. An underestimation of the chlorophyll «a» concentration calculated by the C2RCC processor was found.

Conclusions. The functional dependences based on two- and three-channel TOA combinations of the Sentinel-2 satellite's MSI spectral bands have been proposed for calculation of chlorophyll «a» concentration in complex inland waters of the Dniester River Delta and the Dniester Estuary. Manual and semiautomatic filtering of cloudy, mist, cloud shadowed, and aquatic vegetation-covered areas from imagery has been proposed as a mandatory calculation step. Chlorophyll «a» concentration calculation by the C2RCC processor in the C2X-COMPLEX version for turbid inland waters should be assessed critically due to the ongoing development of atmospheric correction algorithms. Nevertheless, analysis of the selected functional dependences for various types of complex waters, combined with improvements to the atmospheric correction module, offers significant potential of the C2RCC processor, which uses trainable neural networks, to be used in remote monitoring of inland and coastal waters.

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Introduction

The Dniester River Delta and the Dniester Estuary are transitional water system between the river and the Black Sea. The biotic and abiotic characteristics of these water bodies are constantly influenced by climate change, land use pattern in the catchment area, and the extent of water resource exploitation. Intensive economic activity in the region provokes eutrophication of river water due to enrichment with nutrients caused by constant discharge of agricultural waste and municipal wastewater. Permanent eutrophication and overregulation of the river flow via excessive reservoirs lead to long-term deterioration of water quality, which reduces biodiversity of aquatic ecosystems and the potential for multi-purpose use of water resources, and creates a threat to public health.

Regular spatial and temporal monitoring of the water bodies environmental state is essential for sustainable water quality management under these conditions. Remote sensing (RS) data play a very important role here, offering significant advantages over field monitoring data due to its high spatial resolution, simultaneous coverage of large areas, and data availability. Field monitoring data remain necessary, but in smaller quantities, for verifying RS-based calculations and constructing of empirical models.

A significant number of studies of water bodies using remote sensing have focused on determining the concentration of chlorophyll in water [1, 2, 3], which is used to evaluate an aquatic environment trophic status [4], as well as a quantitative indicator of phytoplankton biomass [5]. However, as shown in [1], when using remote sensing for inland water bodies, an individual approach is required due to the unique optical properties of different aquatic environments. A solution to choose the best functional calculation model could be comparison of RS evaluation of water pigment concentration using different algorithms with the results of field measurements in order to establish a significant relationship.

The main objective of this study is to select and validate an algorithm for remote evaluation of chlorophyll «a» concentrations in water bodies of the Dniester River Delta and the Dniester Estuary using RS data. The following was done for this purpose:

(1) correlation and regression analysis of chlorophyll «a» concentrations determined in water samples in laboratory and calculated using various functional models based on Sentinel-2 satellite Multispectral Instrument (MSI) measurements;

(2) validation and revealing of the specific features of the MSI data-based algorithms using

for construction of chlorophyll «a» concentrations spatial distribution in the studied water bodies.

Material and methods

To achieve the objective, field data on chlorophyll «a» concentration in the water surface layer of the Dniester Estuary, the Dniester River and Lake Tudorovo, obtained by the Regional Centre for Integrated Environmental Monitoring (RCIEM) team of Odesa National I.I. Mechnikov University (ONU) in April-September 2017-2021 under the national research projects and the PONTOS International Project [6] were used (Figure 1).

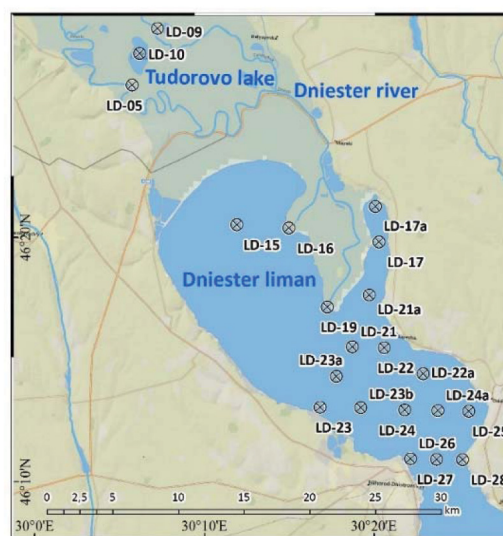


Fig. 1. A complete set of water sampling points from 2017 to 2021 in the Dniester River Delta and the Dniester Estuary, used in this study

Surface water samples for chlorophyll determination were collected at fixed (± 10 m) coordinates directly into sampling containers above optically deep water, i.e. where the water depth was lower than its transparency. During sampling additional parameters, such as temperature, electrical conductivity, water transparency, depth, and others, were measured (Table 1). Within three to four hours the samples were delivered to the RCIEM laboratory, where phytoplankton cells were concentrated through membrane filters and photosynthetic pigment concentrations were determined using the YENWAY-6300 spectrophotometer.

The time period during which the data were collected covered significant part of the natural seasonal and interannual variability of chlorophyll «a» in the inland waters of the Dniester River Delta enabling us to state temporal representativeness of the field data used.

To remotely determine photosynthetic pigments' concentrations in the Dniester Estuary, the Dniester

Table 1

Statistical characteristics of chlorophyll «a» concentrations and other parameters measured during the RCIEM surveys in the Dniester Estuary, the Dniester River and the Lake Tudorovo in 2017–2021

Parameter	Mean	Standard deviation	Median	Min	Max	Dataset Length
Chl «a», mg/m ³	41.7	34.3	34.3	5.0	151.5	50
Depth, m	2.2	0.9	1.9	1.2	5.8	50
Transparency, m	0.5	0.2	0.5	0.2	0.8	50
Temperature, °C	21.8	5.3	23.3	11.9	29.3	50
Conductivity, mSm	1.81	2.15	0.68	0.45	8.85	50

River, and the Lake Tudorovo, high-resolution multispectral sensor (MSI) measurements of the Sentinel-2 satellite for 2017–2021 (hereinafter referred to as images) were used. The MSI produces measurements in 13 spectral bands with spatial resolution of 10 to 60 m per pixel, which allows to obtain an information even for relatively small water bodies. Two types of the MSI products were taken from open sources [7]:

- first level of processing (Level-1C): solar radiation reflectance coefficients at the top of the atmosphere (TOA - Top-of-atmosphere reflectance);
- second level of processing (Level-2A): atmospherically corrected solar radiation reflectance coefficients at the bottom of the atmosphere (BOA - Bottom-of-atmosphere reflectance), now referred to as Surface Reflectance (SR).

In this work, the MSI sensor products from the Copernicus database [7], version 2023, were used. A similar work was conducted [6] in the framework of the PONTOS International Project in 2021, but at that time the Sentinel-2 satellites images of previous versions were used. With the new, latest version of the images used in this work the results of the chlorophyll concentration calculation were significantly different from those presented in [6].

The MSI data and the field samples selection criteria were as follows (Table 2):

- the availability of a field sample of photosynthetic pigments, collected in the spatial

coverage of the image, on the day and the closest possible time of the satellite overflight (less than 4 hours difference);

- the complete absence of clouds, cloud shadows, and mist on the images above the field sampling points to prevent from potential errors in indirect methods of pigment concentration calculation.

According to the literature data [3, 8, 9], remote (satellite) determination of chlorophyll «a» concentration was initially used for the open ocean waters: the blue and green spectral bands were used in indirect empirical and semi-analytical algorithms [10]. The algorithms are based on dependences between reflectance in different parts of the spectrum and the Inherent Optical Properties (IOP) of water, the coefficients of total absorption and backscattering of solar radiation.

Empirical dependences estimate pigments using equation of regression between sample concentration and satellite-derived reflectance [3, 11]. These methods account for regional variability of water properties and have been used by the NASA to obtain chlorophyll «a» concentration with Coastal Zone Color Scanner (CZCS) [10].

Semi-analytical algorithms allow pigment concentrations to be obtained by solving equations from radiative transfer theory [10, 12], separating various components influencing color in natural water and accounting separately

Table 2

List of the Sentinel-2 images for 2017–2021 used for this study

No	Image ID	Date
1	S2B_MSIL1C_20170717T090019_N0205_R007_T35TQM	17.07.17
2	S2A_MSIL1C_20180717T085601_N0206_R007_T35TQM	17.07.18
3	S2A_MSIL1C_20190712T085601_N0208_R007_T35TQM	12.07.19
4	S2B_MSIL1C_20190717T085609_N0208_R007_T35TQM	17.07.19
5	S2B_MSIL1C_20200718T084559_N0209_R107_T35TQM	18.07.20
6	S2B_MSIL1C_20210424T084559_N0300_R107_T35TQM	24.04.21
7	S2A_MSIL1C_20210611T085601_N0300_R007_T35TQM	11.06.21
8	S2A_MSIL1C_20210718T084601_N0301_R107_T35TQM	18.07.21
9	S2A_MSIL1C_20210820T085601_N0301_R007_T35TQM	20.08.21
10	S2A_MSIL1C_20210929T085751_N0301_R007_T35TQM	29.09.21

for the absorption of solar radiation by water, phytoplankton, dissolved organic matter, and non-algal particles.

In shallow, productive, optically complex coastal and inland waters the absorption of phytoplankton pigments in the blue spectral region overlaps and prevents the unambiguous use of this area in calculations. Significant uncertainty in these waters is caused by the dominance of suspended organic detritus and colored dissolved organic matter (CDOM) in the optics of the water column [13].

There are algorithms based on the reflectance peak around 700 nm (red spectral region) and the assumption that the specific absorption coefficient and the fluorescence quantum yield of chlorophyll “a” remain constant [13] for quantitative estimation of chlorophyll concentration in optically complex waters, which also adds uncertainty. In [14] an empirical three-band reflectance model to estimate chlorophyll «a» concentration in turbid productive waters was presented, and in [15] it was developed, which was originally intended for estimation of pigment content in terrestrial vegetation. According to [15], in turbid inland and coastal waters, the models combining spectral reflectance bands should be used, taking into account the absorption band of chlorophyll «a» in the red spectral region and the fluorescence emission of chlorophyll «a» at 685 nm. Sources of uncertainty in this model are the taxonomic composition of phytoplankton, light conditions, nutritional status, and water temperature.

To select the optimal algorithm for evaluating of chlorophyll «a» concentration in turbid productive waters using the Sentinel-2 images we have analyzed, using literature sources, combinations of reflectance coefficients in the 660–753 nm range for the following sensor types: MODIS – Moderate Imaging Spectrometer, MERIS – Medium Resolution Imaging Spectrometer, SeaWiFS – Sea-viewing Wide Field-of-view Sensor, Ocean Optics USB2000 radiometer, and AISA airborne

imaging spectrometer. Then, based on existing studies for various sensors listed in Table 3, two types of spectral band combinations from the MSI Sentinel-2 sensor set were selected for development:

- Two-channel model - $[Chl\ «a»] \sim R_{704 \pm 15} / R_{665 \pm 31}$,
- Three-channel model - $[Chl\ «a»] \sim R_{740 \pm 14} / (R_{665 \pm 31} + R_{704 \pm 15})$,

where $[Chl\ «a»]$ – concentration of chlorophyll «a» in the surface layer of water; $R(\lambda)$ – reflectance coefficients for waves of different lengths (λ).

Another indirect method used in this work is the calculation of chlorophyll «a» in the C2RCC (Case 2 Regional Coast Colour) processor [18], which uses trainable neural networks. The algorithmic foundations of the processor were established by Schiller and Dörffler [19]. The latest modification, the C2X-COMPLEX (C2XC) processor, which showed good results in complex waters [20], was used in this work.

The processor core is a 5-component IOP model of water that takes into account absorption by pigment, detritus, yellow matter, and scattering by “white particles” (lime deposits) and “typical sediment” [18]. The average absorption and scattering spectra of particles in water in the processor are calculated using dataset from the NOMAD database [21], based on a numerous marine field measurements set.

The C2RCC was designed to calculate chlorophyll concentration, Total Suspended Matter (TSM) and other surface water characteristics using data from sensors on the MERIS, Sentinel-3 (OLCI), Sentinel-2 (MSI), and other satellites. The processor is available on the European Space Agency’s SNAP Sentinel Toolbox [22] platform as open-source software. To obtain more accurate results, the processor uses real-world parameters of the aquatic environment, such as salinity and temperature, as well as certain atmospheric characteristics, such as pressure and ozone concentration.

The C2RCC processor is equipped with a built-in atmospheric correction neural network: the

Table 3

Examples of models and fundamental dependences for remote determination of chlorophyll «a» concentration in water for different sensors

Source	Functional dependences forms
Kallio et al., 2003 [16]	Two-channel model (for AISA airborne imaging spectrometer): $[Chl\ «a»] = a * (R(\lambda_1) / R(\lambda_2)) + b$, where $\lambda_1 = 700\text{--}710\text{ nm}$, $\lambda_2 = 660\text{--}665\text{ nm}$
Dall’Olmo & Gitelson, 2005 [15]	Three-channel model (for Ocean Optics USB2000 radiometer): $[Chl\ «a»] \sim [R^{-1}(\lambda_1) - R^{-1}(\lambda_2)] * R(\lambda_3)$, where: $\lambda_1 = 673\text{ (or } 665)\text{ nm}$, $\lambda_2 = 710\text{ nm}$, $\lambda_3 = 740\text{ nm}$
Gitelson et al., 2007 [17]	Two-channel model (for SeaWiFS, MODIS, MERIS): $[Chl\ «a»] \sim R^{-1}(\lambda_1) * R(\lambda_3)$, where: $\lambda_1 = 668\text{--}672$, $\lambda_3 = 713\text{--}722\text{ nm}$
Gilerson et al., 2010 [13]	Two-channel model (for MERIS): $[Chl\ «a»] = [35.75 * R(\lambda_1) / R(\lambda_2) - 19.30]^{1.124}$, where: $\lambda_1 = 708\text{ nm}$, $\lambda_2 = 665\text{ nm}$
Gilerson et al., 2010 [13]	Three-channel model (for MERIS): $[Chl\ «a»] = [113.36 * R(\lambda_3) / (R(\lambda_1) + R(\lambda_2)) + 16.45]^{1.124}$, where: $\lambda_1 = 708\text{ nm}$, $\lambda_2 = 665\text{ nm}$, $\lambda_3 = 753\text{ nm}$

“water” part of the processor receives reflectivity signals from the “atmospheric” part as an input. However, no standard atmospheric correction model exists for inland waters: all existing approaches have limitations. At the same time, atmospheric correction of optical satellite data is a critical step, as the reflectance measured as the top-of-the-atmosphere (TOA) signals must be correctly converted to water reflectance in the bottom of the atmosphere (SR) before practical use. Otherwise, poor atmospheric correction becomes the largest source of error and uncertainty in satellite products based on reflectivity.

For calculations with the proposed functional models and the C2RCC processor the reflectance coefficients $R(\lambda)$ for different spectral regions obtained from Sentinel-2 MSI images with processing levels Level-1C and Level-2A were used. The original images were modified in the SNAP environment: (1) cropping the image coverage area by the study area in order to minimize the calculation time; (2) changing the spatial resolution of the images to 20 m per pixel for all spectral bands.

TOA and SR reflectance coefficients from the Sentinel-2 MSI images and chlorophyll «a» concentration calculated by the C2XC were extracted in SNAP in 3x3-pixel windows, localized at field sampling points in the center. From these nine-pixel windows cells, the cells in which the calculated values of chlorophyll «a» concentration exceeded the 50% of those determined in the field samples were manually discarded. Cells with detected vegetation, mist, and shadow were also rejected. This cell rejection process is based on the fact that the C2XC automatically checks cloud cover using Sentinel-2 MSI spectral band 8 using preset thresholds.

For the remaining cells of the nine-pixel windows the median values of both chlorophyll

«a» concentration calculated using the C2XC algorithm and the TOA and SR reflectance coefficients from the Sentinel-2 MSI products (Level-1C and Level-2A, respectively) modified to 20-meter resolution were used. The median values of the nine-pixel windows were used to minimize the influence of cells with wrong outliers.

Results and discussion

In the process of the two-channel and three-channel models development, the exponential-type functional dependences were established, as shown in Figs. 2-5. Calculations of chlorophyll «a» concentration based on the derived functional dependences are shown next to the model graphs in Figs. 2a-5a.

Graphical and numerical results of calculations of chlorophyll «a» concentration in the surface water layer by the C2XC processor in the SNAP are shown in Fig. 6.

A comparison of the results calculated using different algorithms was analyzed for their correspondence to field data. For each functional model the statistical estimates were calculated: the correlation coefficient R , the mean absolute percentage error (MAPE) (1), and the root mean square error (RMSE) (2) (Table 4):

$$MAPE = 100 \times \frac{\sum_{i=1}^n \left| \frac{y_i - x_i}{x_i} \right|}{N} \quad (1);$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^n (x_i - y_i)^2} \quad (2),$$

where x_i – measured, and y_i – calculated chlorophyll «a» concentration for i -point; N – the quantity of comparing pairs.

MAPE was chosen because it allows for comparison of algorithms regardless of the

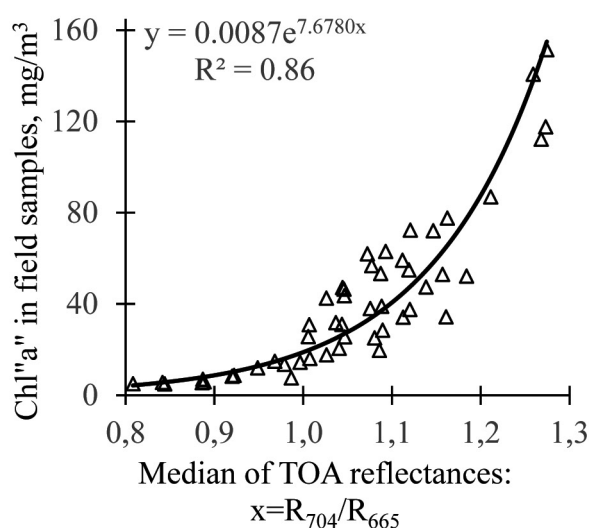


Fig. 2. Functional dependence of chlorophyll «a» concentration on two-channel TOA combination

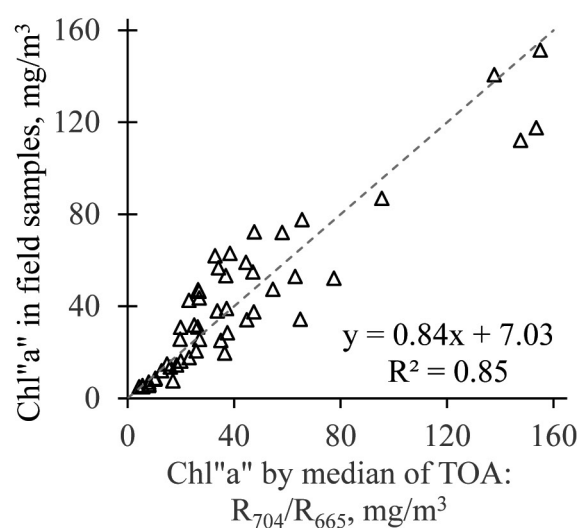


Fig. 2a. Scatterplot of calculated (TOA, two-channel model) and measured chlorophyll «a» concentration

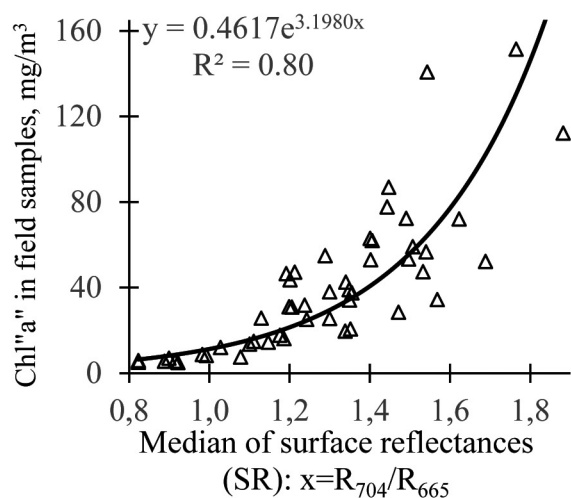


Fig. 3. Functional dependence of chlorophyll «a» concentration on two-channel SR combination

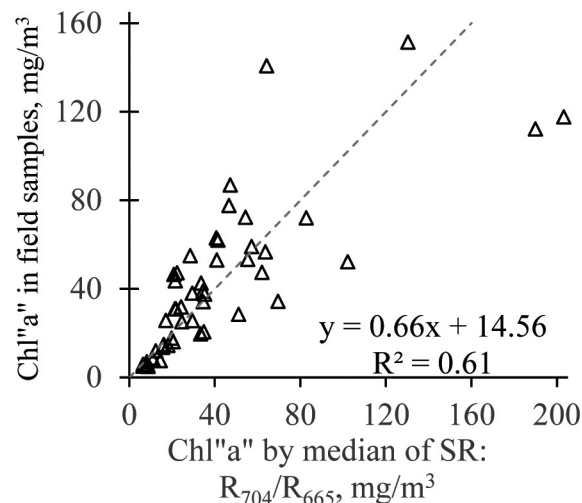


Fig. 3a. Scatter plot of calculated (SR, two-channel model) and measured chlorophyll «a» concentration

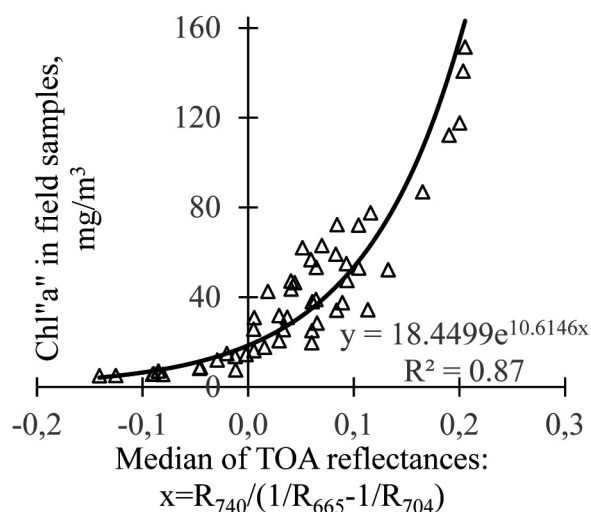


Fig. 4. Functional dependence of chlorophyll «a» concentration on three-channel TOA combination

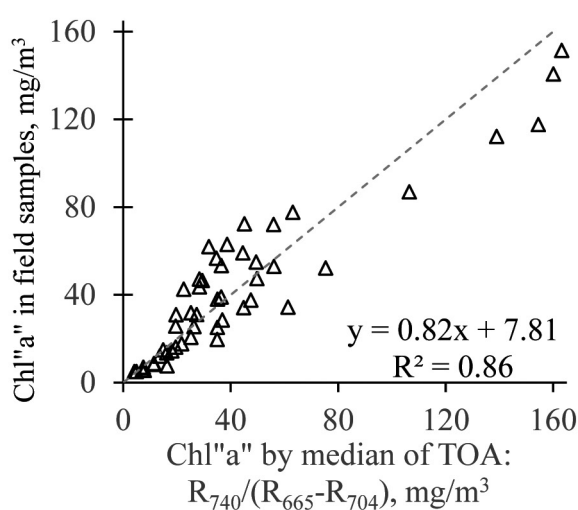


Fig. 4a. Scatter plot of calculated (TOA, three-channel model) and measured chlorophyll «a» concentration

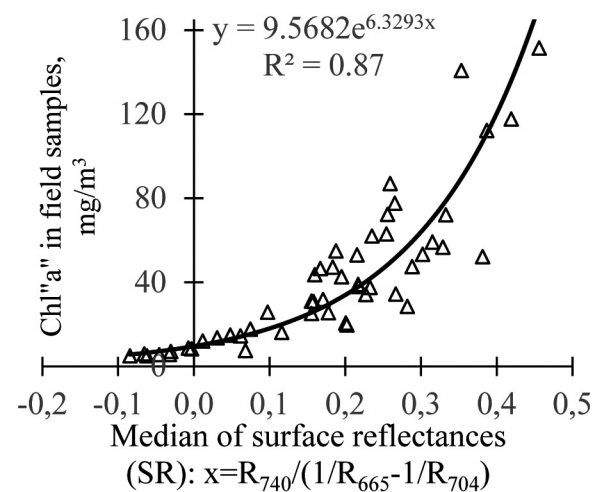


Fig. 5. Functional dependence of chlorophyll «a» concentration on three-channel SR combination

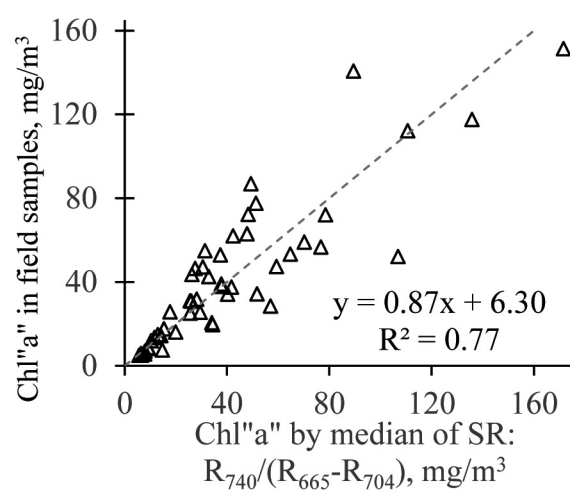


Fig. 5a. Scatter plot of calculated (SR, three-channel model) and measured chlorophyll «a» concentration

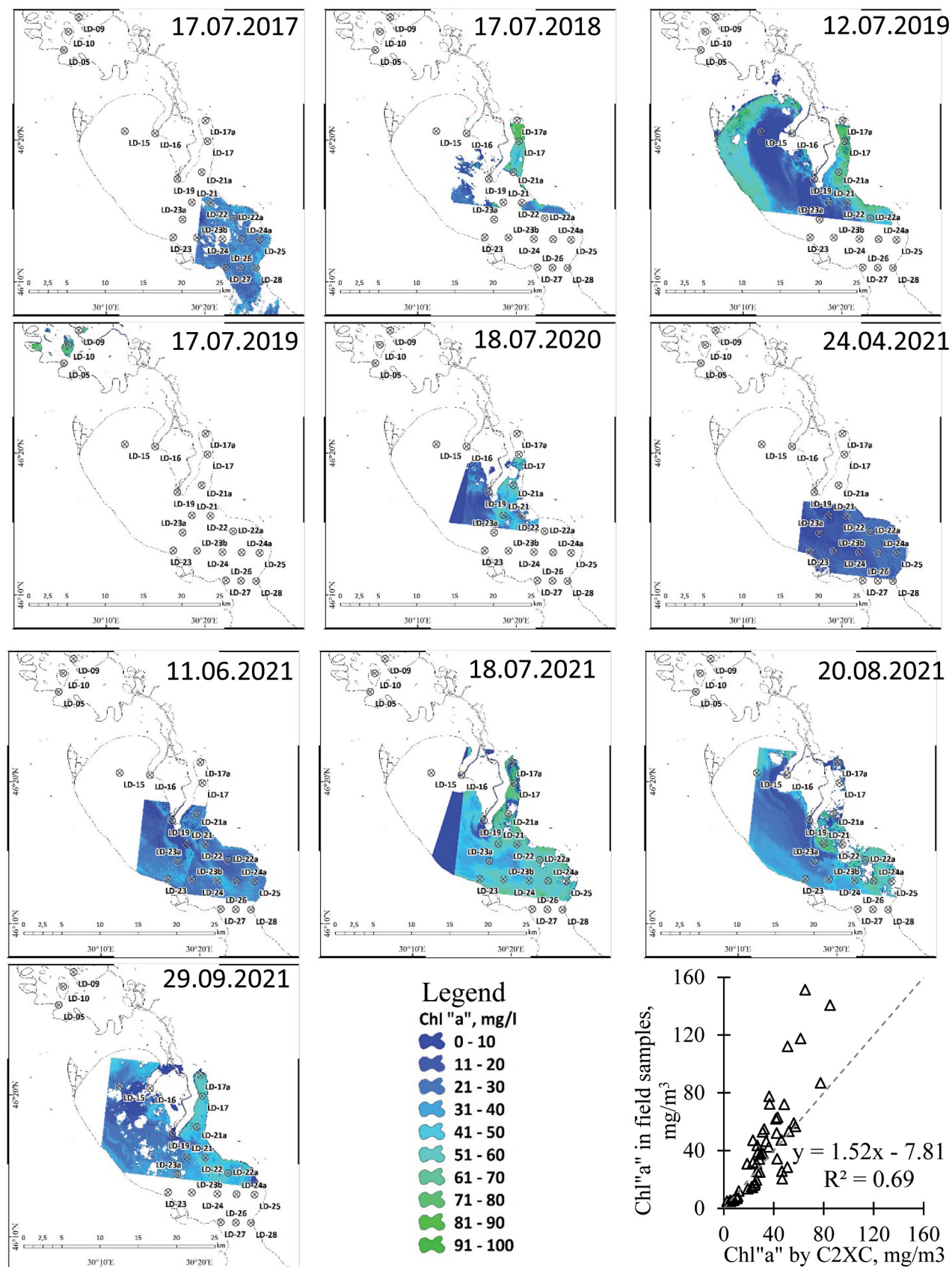


Fig. 6. The C2XC calculated chlorophyll «a» concentration in the Dniester River Delta and estuary in 2017–2021 (on the background of planned sampling points) and the summary scatterplot of calculated (C2XC) and measured concentrations

Table 4

Statistical assessments of accuracy of the chlorophyll «a» concentration calculating based on Sentinel-2 MSI data using different algorithms

Algorithm of Calculation	R ($p < 0.001$)	MAPE	RMSE, mg/m ³
Two-channel model by TOA reflectance	0.92	28.5	14.4
Two-channel model by SR reflectance	0.78	27.8	16.8
Three-channel model by TOA reflectance	0.93	27.9	14.3
Three-channel model by SR reflectance	0.88	35.0	25.2
The C2XC algorithm	0.83	33.6	23.1

selected concentration ranges. Of all the calculation methods considered, those yielding the lowest MAPE and RMSE, as well as the highest correlation coefficients, were selected. This allowed to take into account the strength of linear relationship and the dispersion in the scatterplots of calculated and measured chlorophyll «a» concentrations across the entire range of values, i.e. from 5.0 to 151.5 mg Chl «a»/m³.

As noted above, the reflectance coefficients $R(\lambda)$ by the Sentinel-2 MSI the processing levels Level-1C and Level-2A (i.e. TOA and SR) were used during development of the functional dependence. Pairwise comparison of data series has demonstrated the advantage of the TOA coefficients (in contrast to the SR) using for both two-channel and three-channel models (Table 4). This is especially clearly seen from the correlation coefficients and RMSE's.

A possible explanation for this is the quality of atmospheric correction by the Sen2Cor processor, developed by Telespazio VEGA Deutschland GmbH [23, 24]. This processor performs correction of Sentinel-2 Level-1C (TOA) products to account for the influence of the atmosphere and produces Level-2A (SR) products. Two main Sen2Cor modules are designed to process Level-1C input data: the scene classification module (SCL) and the atmospheric correction module (AC), which deals with the absorption and scattering of light by gas molecules and aerosol particles in the atmosphere. The SCL module, using threshold tests based on TOA coefficients, classifies cirrus and other clouds, their shadows, snow, vegetation, and water. This classification and masking are then applied in the AC module with atmospheric conditions stored in look-up tables (LUTs), which are in turn calculated using libRadtran [25], a library of functions and programs for calculating solar and thermal radiation transport in the Earth's atmosphere. The LUTs were calculated from the spectral responses of Sentinel-2A and Sentinel-2B [24] for a range of sensor and solar geometries, surface elevations, and a variety of atmospheric parameters. AC reads the LUT corresponding to the geographic and spatial location and performs parameter interpolation.

To account for the influence of aerosols in the atmosphere libRadtran suggests to use a basic list of aerosol types with additional specific parameters: rural, urban, marine, desert, fog, winter/summer atmosphere, ozone concentration, visibility, and climate characteristics. However, interpolation is not supported for the aerosol type also included in the LUT, which may lead to errors in atmospheric correction, as our study area is located less than 50 km from the Black Sea coast.

Furthermore, the Sen2Cor processor [24]:

- is not intended for overwater or coastal applications;
- does not contain modules for correcting water surface effects (e.g., sun glares in rough seas);
- does not estimate the optical thickness of aerosols and water vapor above the water surface.

The use of the Sen2Cor processor over water is possible, but requires the use of aerosol optical thickness and water vapor concentration over the nearest land surface, which also affects the result of atmospheric correction over the studied water bodies of the size of the Dniester Estuary and the floodplains of the Dniester River Delta.

The concentrations of chlorophyll «a» calculated by C2XC are clearly underestimated compared to other algorithms (Table 4). This may be due to several factors. Firstly, the C2RCC processor uses only the built-in atmospheric correction of the Sen2Cor processor [24], which operates according to a simplified libRadtran scheme [25]. Secondly, the aerosol optical thickness (AOT) is derived according to a simplified scheme of the method [26] with the aerosol type fixed for land. Evaluating the obtained results, one should agree with [20] that for coastal and inland waters, the problem of eliminating the contribution of atmospheric components (gases, aerosols) in the reflected signal, along with such interference as sun glares, proximity to land, and aquatic vegetation, requires further development of the C2RCC processor in the C2X-COMPLEX version in the form of a more detailed adjustment of the atmospheric correction algorithms and the development of a standardized approach.

It should also be noted that the C2RCC was developed based on the 16 spectral channels of the

MERIS spectrometer [19], whose characteristics were precisely tailored to capture the dynamics of the concentration and composition of phytoplankton pigments and yellow matter. The latest versions of C2RCC, including C2X-COMPLEX, are an adaptation of the original Case 2 Regional Coast Color design to sensors with different sets, characteristics, and bandwidths, such as the Sentinel-2 and Landsat-8 sensors.

Conclusions

To obtain a satisfactory (correlation coefficient of up to 0.93) estimate of chlorophyll «a» concentration in complex inland waters of the Dniester River Delta and the Dniester Estuary based on Sentinel-2 satellite MSI data, we propose using exponential-type empirical functional dependencies for two- and three-channel TOA spectral band combinations, i.e. based on solar radiation reflectivity at the top of the atmosphere (without atmospheric correction). The difference in calculation accuracy between the two- and

three-channel combinations was found to be insignificant, with a slight advantage for the three-channel model.

A mandatory step in preparing TOA reflectance coefficients for use in the proposed functional relationships is the removal of water areas covered by clouds, mist, cloud shadows, and aquatic vegetation from Sentinel-2 images. Thus, manual and semiautomatic preparation of Sentinel-2 MSI data remains a significant element for use in the proposed algorithms.

The calculations of chlorophyll «a» concentration by the C2RCC processor in the C2X-COMPLEX version for turbid inland waters should be assessed critically due to the ongoing development of atmospheric correction algorithms. However, the analysis of the selected functional dependencies for various types of complex waters, combined with the improvement of the atmospheric correction module offers significant potential for the C2RCC processor, which uses trainable neural networks, to automate remote monitoring of inland and coastal waters.

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Розробка алгоритмів дистанційної оцінки хлорофілу «а» у внутрішніх водах дельти річки Дністер з використанням даних Sentinel-2 MSI

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АНОТАЦІЯ

Господарська діяльність у басейні річки Дністер та зарегульованість водного стоку провокують евтрофікацію та погіршення якості води, що впливає на біорізноманіття екосистем та є загрозою для здоров'я населення. З метою стійкого управління якістю води пропонується дистанційне зондування Землі для оцінки концентрації хлорофілу «а». Для урахування оптичних властивостей вод та визначення функціональної залежності застосовано порівняння розрахункових концентрацій з результатами польових вимірів. Метою роботи є підбір та обґрунтування алгоритмів для дистанційної оцінки концентрації хлорофілу «а» у водоймах дельти річки Дністер за даними Multispectral Instrument (MSI) супутника Sentinel-2.

Використані концентрації хлорофілу «а» у водоймах дельти річки Дністер, що отримані у 2017–2021 рр. Використані коефіцієнти відбиття радіації з MSI двох типів: TOA (Top-of-atmosphere reflectance) та атмосферно відкориговані SR (Surface Reflectance). При підборі алгоритмів проаналізовано літературу, на основі чого відібрані два типи комбінацій спектральних смуг MSI. Застосовувався розрахунок концентрації хлорофілу «а» процесором C2RCC на базі SNAP Sentinel Toolbox.

Для відібраних двоканальної та триканальної моделей встановлено функціональні залежності експоненційного типу. Верифікація залежностей проводилася порівнянням розрахункових і отриманих C2RCC величин з польовими концентраціями хлорофілу «а». Порівняння показало перевагу використання даних TOA (порівняно з SR) як за двоканальною, так і за триканальною моделями: $R_{p<0.001}}=0.92$, $MAPE=28.5$, $RMSE=14.4$ мг/м³ і $R_{p<0.001}}=0.93$, $MAPE=27.9$, $RMSE=14.3$ мг/м³ відповідно. Встановлено заниження розрахованих C2RCC величин.

Для розрахунків концентрацій хлорофілу «а» у водоймах дельти річки Дністер запропоновано двоканальні та триканальні TOA-моделі за спектральними смугами MSI Sentinel-2. Розрахунки концентрації хлорофілу «а» процесором C2RCC для вказаних вод пропонується оцінювати критично через наявні алгоритми атмосферної корекції. Тим не менш, аналіз підібраних залежностей у поєднанні з поліпшенням атмосферної корекції дає процесору C2RCC перспективи для автоматизації дистанційного моніторингу.

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дельта річки Дністер, екологічний стан водойм, хлорофіл «а», дистанційне зондування, Sentinel-2 MSI, C2RCC, алгоритм атмосферної корекції, функціональні моделі.