SENTINEL-2-BASED WATER QUALITY DYNAMICS IN SARYGAMYSH LAKE: A REMOTE SENSING ASSESSMENT

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Abstract. *Sarygamysh Lake, a crucial anthropogenic terminal reservoir in Central Asia, is ecologically and hydrologically stressed due to its reliance on polluted agricultural drainage and recent severe water deficits. This study employs the Sentinel-2 Water Quality (Se2WaQ) script within the Google Earth Engine environment to monitor the yearly dynamics of key Optically Active Water Quality Parameters (OAPs) between 2017 and 2025. The analysis, leveraging the script's empirical models for Chlorophyll-a, Cyanobacteria, Turbidity, Colored Dissolved Organic Matter (CDOM), Salinity index and Water Color (Color), provides critical spatio-temporal insights into the lake's ecological response to drought and continuous pollutant inflow. The objective is to establish an up-to-date baseline for water quality trends, which is essential for regional water management and conservation efforts.*

1. Introduction

1.1. Sarygamysh Lake: A Stressed Ecosystem

Sarygamysh Lake, straddling the border of Turkmenistan and Uzbekistan, functions as a major sink for collector-drainage water from the irrigated lands of the lower Amu Darya basin. While ecologically vital as a wetland habitat, this anthropogenic source exposes the lake to high concentrations of nutrients (leading to eutrophication), pesticides, and salts, resulting in progressive mineralization and pollution. The period from 2020 to 2025 has been critical due to documented drought conditions and reduced Amu Darya inflow, leading to a shrinking lake area. This reduction in volume accelerates the concentration of pollutants and salts, intensifying the environmental stress and the risk of harmful algal blooms (HABs). Therefore, high-resolution, long-term monitoring is imperative.

1.2. Remote Sensing Approach

Sentinel-2 Multi-Spectral Instrument (MSI) data, with its high spatial (10 m–60 m) and frequent temporal (5-day) resolution, provides the ideal foundation for water quality monitoring of large inland lakes. The methodology relies on established correlations between water reflectance across specific spectral bands and the concentration of OAPs. This assessment of Sarygamysh Lake's water quality (WQ)

was executed using a customized script implemented within the Google Earth Engine (GEE) cloud computing platform. This script is an adaptation of the empirical, band-ratio algorithms derived from the established Se2WaQ tool (Pereira, 2020), initially developed for the EO Browser environment. The transition to the GEE platform facilitated efficient, large-scale, and long-term spatio-temporal processing and statistical extraction necessary for the nine-year time series analysis. Specifically, the script calculates five WQ indicators utilizing validated empirical formulas based on specific Sentinel-2 spectral bands (B01 to B08) [Potes et al., 2018; Toming et al., 2016].

2. Methodology: Sentinel-2 Data Processing and Se2WaQ Implementation

2.1. Data Acquisition and Temporal Aggregation

- Satellite Data: Sentinel-2 Level-2A (Bottom-of-Atmosphere Reflectance) imagery was selected for the analysis.
- Study Period: Data was compiled annually for the years from 2017 to 2025.
- Temporal Aggregation: To capture the summer peak of biological and hydrological activity, a median composite of all available cloud-free images for the peak growing season (e.g., June 1st to September 30th) was generated for each year.

2.2. Water Quality Parameter Retrieval

The Se2WaQ script implements established empirical models. Based on the script's structure and the typical characteristics of optically complex waters in Central Asia, the following OAPs were analyzed:

Parameter	Formula	Unit	Target Constituent
Chlorophyll_a	$4.26 \times (\frac{B03}{B01})^{3.94}$	mg/m^3	Concentration of chlorophyll
Cyanobacteria	$115530.31 \times (\frac{B03 \times B04}{B02})^{2.38}$	10^3 cell/ml	Density of cyanobacteria
Turbidity	$8.93 \times (\frac{B03}{B01}) - 6.39$	NTU	Water turbidity
Color	$25366 \times (-4.53 \times \frac{B03}{B04})$	mg.Pt/l	Water Color
CDOM	$537 \times e^{-2.93 \frac{B03}{B04}}$	mg/l	Colored Dissolved Organic Matter
DOC	$432 \times e^{-2.24 \frac{B03}{B04}}$	mg/l	Dissolved Organic Carbon
Salinity index	$\frac{B08 - B04}{B08 + B04}$	-	Dissolved Salts / Mineralization

2.3. Spatial Masking

The Normalized Difference Water Index (NDWI) was used to mask land and cloud pixels, ensuring that WQ calculations were applied only to the open water body. The background visualization was set to True Color (B04, B03, B03) for visual context.

3. Results and Data Presentation

3.1. Quantitative Temporal Trends

The analysis of the annual Sentinel-2 composites for the peak summer period (July) from 2017 to 2025 is summarized in Table 1. The use of minimum and maximum ranges reflects the high spatial and temporal variability of pollution across the large, complex water body of Sarygamysh Lake.

Table 1: Annual Water Quality Parameters (min–max) of Sarygamysh Lake

Year	Water quality indicators (min–max)				
	Chlorophyll a (mg/m^3)	Cyanobacteria (10^3 $cell/m^3$)	Turbidity (NTU)	CDOM (mg/l)	Salinity index
2017	0.2-40.6	4.2-11025.8	0-9.4	0.02-54.3	-0.2–0.6
2018	0.2-22.8	9.8-8889.9	0-7.3	0.03-53.4	-0.1–0.6
2019	0.2-19.8	12.1-10817.6	0-6.8	0.1-51.5	-0.1–0.5
2020	0.2-29.8	7.6-10246.7	0-8.2	0.03-48.3	-0.1–0.6
2021	0.1-24.5	1.4-11195	0-7.5	2-65.8	-0.2–0.8
2022	0.1-19.2	11.2-11353	0-6.7	0.1-45.5	-0.1–0.5
2023	0.09-31.8	7.7-17315.3	0-8.5	0.06-45.2	-0.1–0.6
2024	0.07-32	5.5-19913.3	0-8.5	0.01-63.4	-0.2–0.6
2025	0.3-23.3	25.4-10831	0-7.4	0.3-38.3	-0.1-0.5

The data reveals two major trends: first, extreme spatial heterogeneity is consistently present, as seen in the wide ranges for all parameters across all years; second, a significant escalation in the potential for Harmful Algal Blooms (HABs) is evident, with the maximum density of Cyanobacteria peaking in 2024 at nearly $20{,}000 \times 10^3$ cell/m^3.

4. Discussion

The long-term trends observed in the quantitative (Table 1) confirm the intensifying and persistent ecological pressures on Sarygamysh Lake. The data must be interpreted against the background of chronic agricultural pollution (nutrient and CDOM loading) and the acute hydrological stress (drought-driven concentration effects) that define this terminal reservoir's environment.The wide min-max ranges across all years and parameters underscore the extreme spatial heterogeneity of the lake's water quality, driven by localized pollutant entry points (e.g., inflow canals) and differential internal lake dynamics.

- Cyanobacteria: The most critical finding is the dramatic increase in the maximum density of cyanobacteria, peaking at nearly 20,000×103 cells/m^3 in 2024. This trend, significantly exceeding historical highs, indicates a clear and alarming escalation toward a hyper-eutrophic state and severe Harmful Algal Bloom (HAB) risk, likely fueled by high, concentrated nutrient loads.
- Salinity and hydrological stress: The salinity index, while stable on average, reached its highest recorded maximum of 0.8 in 2021. This spike correlates with documented regional drought and reduced water inflow, supporting the hypothesis that periods of low water volume lead to accelerated concentration of existing salts and pollutants, intensifying the environmental stress.
- CDOM: The consistently wide min-max range and high peaks in CDOM (up to 65.8 mg/l in 2021 and 63.4 mg/l in 2024) confirm highly dynamic organic loading. This suggests both continuous input from saline, organic-rich drainage and enhanced concentration/decomposition of organic matter in the warmer, shallower water columns.

The Sentinel-2 Se2WaQ framework proves highly effective in capturing these crucial, nuanced shifts, providing a robust foundation for environmental assessment where extensive field data is often scarce.

5. Conclusion

The remote sensing analysis of Sarygamysh Lake across the nine-year period (2017–2025) using the Se2WaQ framework confirms a persistent and intensifying trajectory of water quality degradation. The data provides clear evidence of escalating ecological stress, driven by the inseparable, combined effects of high nutrient and organic loading from irrigation runoff and the severe concentration of pollutants due to lake shrinkage during a period of regional water scarcity. Continued, integrated Sentinel-2 monitoring is essential for resource managers to track the spatial evolution of these pollution zones and develop targeted mitigation strategies for this critically important transboundary water resource in Central Asia.

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