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Sustainability in Aquatic Ecosystem Restoration: Combining Classical and Remote Sensing Methods for Effective Water Quality Management

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Abstract: The utilization of Effective Microorganisms (EMs) for lake restoration represents a sustainable approach to enhancing water quality and rebalancing the ecology of aquatic ecosystems. The primary objective of this study was to evaluate the effects of two bioremediation treatment cycles employing EM-enriched biopreparations on water quality in the Siemiatycze lakes. Specifically, this research analyzed various parameters, including dissolved oxygen, transparency, chlorophyll-a, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD5), total phosphorus, total nitrogen, and suspended matter (SM), across eleven designated sampling locations. Additionally, this study employed remote sensing techniques, leveraging Sentinel-2 satellite imagery and the Maximum Chlorophyll Index (MCI), to detect and quantify algal blooms, with a particular focus on elevated chlorophyll-a concentrations. This comprehensive approach aimed to provide a holistic understanding of the impact of biotechnological reclamation on aquatic ecosystem restoration and sustainability. The study's findings indicated a significant improvement in water quality in all lakes, with enhanced water clarity and oxygen profiles. Further, remote sensing studies indicated a reduction in algal blooms, particularly those with high chlorophyll-a concentrations. A considerable decrease in water eutrophication intensity was observed due to diminished nutrient concentrations. The improvements in water parameters are likely to enhance the living conditions of aquatic organisms. These results demonstrate the effectiveness of using EM-enriched biopreparations in the bioremediation of lakes, providing a sustainable approach to enhancing water quality and balancing aquatic ecosystems.

Keywords: bioremediation; blue urban infrastructure; NDR modeling; satellite data processing; water parameters; remote sensing evaluation

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Citation: Mazur, R.; Kowalewski, Z.; Głowienka, E.; Santos, L.; Jakubiak, M. Sustainability in Aquatic Ecosystem Restoration: Combining Classical and Remote Sensing Methods for Effective Water Quality Management. *Sustainability* **2024**, *16*, 3716. https://doi.org/10.3390/su16093716

Received: 20 February 2024
Revised: 20 April 2024
Accepted: 22 April 2024
Published: 29 April 2024

1. Introduction

Water reservoirs are a crucial part of the city's blue–green infrastructure, with water bodies often representing an important part of the urban landscape, usually associated with green natural areas. Urban residents increasingly appreciate both artificial and natural ponds and lakes, which hold a secondary unique urban blue infrastructure value, determined by the range of provided ecosystem services [1,2]. In areas under anthropogenic pressure, ecosystem services provided by blue infrastructure are an important component of public expectations, where the community perceives sustainable urban development with mandatory preservation, restoration, and revitalization of such water bodies. The provision of ecosystem services by water bodies is dependent on their proper trophic state and biological balance. These areas are mostly shallow reservoirs that receive an excessive nutrient supply from surface runoff or watercourses polluted by human activities [3]. As a result, these reservoirs and waterways require reclamation and maintenance efforts. Furthermore, considering the changing continental climate conditions, policymakers must take steps to reduce the exploitation of the environment and restore its biological balance if urban aquatic ecosystems are to provide meaningful, long-term benefits to society. Microbiological restoration of lakes using Effective Microorganisms (EMs) represents a natural and sustainable approach to improve water quality and restore the ecological balance of aquatic ecosystems. EMs comprise a consortium of beneficial microorganisms, including lactic acid bacteria, yeast, and phototrophic bacteria, that exert a positive influence on the natural microbial community in lakes [4–6]. The application of EMs in lake restoration has demonstrated its capacity to enhance the decomposition of organic matter, decrease the concentration of pollutants such as nitrogen and phosphorus, and increase the availability of nutrients for aquatic organisms. EMs also help to improve the dissolved oxygen content of water by promoting photosynthesis and limiting the accumulation of organic matter, which otherwise consumes oxygen during decomposition [7].

In the restoration of lakes using EMs, a culture of microorganisms is prepared in a liquid medium and subsequently introduced into the lake. These microorganisms colonize the lake environment and compete with harmful microorganisms, thereby enhancing water quality and mitigating the risk of harmful algal blooms and other adverse environmental impacts [7]. However, it is essential to note that EMs should be a component of an integrated lake restoration approach, which may encompass measures like reducing nutrient inputs and controlling pollution sources. Moreover, the efficacy of EMs may vary based on the specific conditions of the lake and its surrounding ecosystem, necessitating a thorough assessment and consultation with experts before using this technique [8]. Overall, the application of effective microorganisms in lake restoration may be an effective and sustainable approach to improving water quality and restoring the ecological balance of aquatic ecosystems [8–11].

For the fieldwork, we considered a region situated within agricultural regions, particularly the Kamionka and Mahomet River valleys in Poland, which have primarily faced contamination from surface runoff nutrients and organic pollution; the Kamionka River also receives treated wastewater from the Municipal Company Ltd. in Siemiatycze [12,13]. During the past decade, water monitoring has highlighted a significant decline in water quality across all reservoirs [12], with the deterioration notably decreasing the leisure usability of the reservoirs. These factors have led to progressive water eutrophication, contributing to summer blooms of blue–green algae emerging, along with an increase in other bacteria that pose health risks to individuals using the reservoirs for recreational purposes, in particular swimming.

Economic development plans for the region primarily targeted tourism and ecotourism, capitalizing on the area’s cultural and ecological significance. However, the poor water quality acted as a deterrent for potential tourists and anglers seeking recreational activities in bathing or fishing areas. The reservoir, already in an advanced stage of eutrophication, suffered from turbid water, intense seasonal algal blooms, and considerable sedimentation. The noticeable putrid odor around the lakes signaled deteriorating conditions, with a substantial oxygen deficit during summer leading to severe ecosystem damage including the extinction of invertebrates and local fish within the reservoirs, impairing the aquatic ecosystem.

In response to the water quality decline, the mayor of Siemiatycze took steps to restore the reservoirs, contacting a team of experts to identify an effective strategy to enhance water quality. The treatment method selection criteria prioritized minimal environmental disturbance and long-term effectiveness, thus respecting a predefined budget and resulting in the choice of Effective Microorganisms as a treatment solution. The first revitalization of the reservoirs in Siemiatycze using Effective Microorganisms took place in 2013 and 2014. The second revitalization was conducted in 2016 and 2017 in response to deteriorating water quality parameters. The purification of water reservoirs aimed to restore their functionality and entice tourists to designated recreational areas. These reservoirs are vital components for both tourism (cultural services) and maintaining the flow of water (supporting services). The three artificial lakes, namely Kamionka (reservoir I) and Mahomet (reservoirs II and III), are situated within the proglacial stream valleys and are characterized as small shallow reservoirs (Table 1). Constructed in 1978, these facilities were intended for multiple functions including retention, recreation, ecological balance, and economic purposes [12,13].

Table 1. Morphometric characteristics of Reservoirs I, II, and III in Siemiatycze.

Water Reservoir	Location	Date of Restoration	Surface Area [m^2]	Volume [m^3]	Maximum Depth [m]	Average Depth [m]	Water Flow Types	Flow Velocity	River Tributary
Siemiatycze Dam Reservoir	Siemiatycze	2016–2017	274,000	548,000	5.1	2	Exorheic reservoir	Slow	Kamionka and Mahomet

Conventional lake revitalization methods often target only a limited set of aspects related to specific problem solving, e.g., sedimentation is solved with dredging. However, given the considerable deterioration of the reservoirs and the need to improve various quality and structural parameters of the aquatic ecosystem, these methods are considered a "band-aid", and rather inadequate if ecosystem-level results are expected. Dr. Sitarek's (EM) microbiological bioremediation method has emerged as the most promising solution [7,14]. This approach relies on microbial biopreparations that, upon biological activation, effectively reduces water contaminants. The microbiological bioremediation process involves selecting appropriate biopreparations of directional microorganism strains (allochthonous strains) within the Effective Microorganism (EM) framework [15,16]. These customized biopreparations specifically address the unique characteristics of water pollution. These consortiums of microorganisms from bio-mixtures significantly catalyze the breakdown of organic pollutants in water and improved the quality parameters of surface waters [9,17].

At a global scale, the use of biological preparations containing consortia of microorganisms has enabled the efficient breakdown of organic compounds, facilitating swift water treatment and the advanced mineralization of bottom sediments [7]. These methods represent pioneering advances in environmental biotechnology, particularly employing biotechnological approaches that have triggered the activation of natural self-purification mechanisms. These bioremediation techniques fall under the category of non-invasive biomanipulation methods in the aquatic environment, operating in a 'bottom-up' direction [8,18]. In the literature, other modern methods of decontamination of water bodies are thoroughly described, e.g., the removal of micropollutants via the nanofiltration process [19]. According to Siuda and Chróst, the effectiveness of these reclamation methods employing microbiological preparations quantified by the cost-benefit ratio, delivers a remarkably high result, reaching 75–80% success [20].

The objective of this study was to evaluate the alterations in the Siemiatycze lakes' water quality after two bioremediation treatment cycles using biopreparations enriched with Effective Microorganisms. This research analyzed a set of water quality parameters—including dissolved oxygen, transparency, chlorophyll-a, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD5), total phosphorus, total nitrogen, and suspended matter (SM)—across eleven designated sampling locations. Additionally, this study employed remote sensing techniques, leveraging Sentinel-2 satellite imagery and the Maximum Chlorophyll Index (MCI), to detect and quantify algal blooms, with a particular focus on elevated chlorophyll-a concentrations. This comprehensive approach aimed to provide a holistic understanding of biotechnological reclamation's impact on aquatic ecosystem restoration and sustainability.

2. Materials and Methods

2.1. Study Area

2.1.1. The Terrain Conditions

The Mahomet River water catchment spans a total surface area of 59.48 square meters, while the Kamionka River catchment covers 49.79 square meters. Despite similar sizes and terrain conditions, variations in land use forms contribute to the diverse surface areas of both catchments. Land cover mapping occurs in cycles every 6 years and is integrated into the CORINE land cover database. The land-use patterns within both catchments exhibit comparable trends. Predominantly, areas classified as mixed cover have the largest share in both catchments, with the percentages of other land use forms being significantly lower (Table 1).

2.1.2. Microbiological Bioremediation Assumptions

The method used in these reservoirs was based on achieving a biological balance in the aquatic environment while eliminating the effects of eutrophication and improving water quality. To achieve this balance, biopreparations primarily contained water, and a mixture of lactic acid bacteria, phototrophic bacteria, yeast, sugar cane molasses, fermented wheat bran, and minerals were used to reduce eutrophication and improve the overall quality of water in the reservoirs. The biopreparation used for the Siemiatycze lakes' reclamation had a composition that is currently registered under the name ACS ODO-1.

Most microorganisms contained in the EM biopreparation metabolize organic compounds into mineral compounds to produce carbon dioxide and water. Strains of lactic acid bacteria (the dominant group in EM preparations) carry out the process of converting simple sugars into lactic acid and other by-products, such as carbon dioxide, ethanol, and acetic acid. These decomposition products stimulate autochthonous microorganisms to actively metabolize under conditions of low dissolved oxygen concentration. Lactic acid bacteria (*Lactobacillus* and *Bifidobacterium*) slow down the development of pathogenic microorganisms and accelerate the biodegradation of organic matter. Under aerobic conditions, lactic acid bacteria produce hydrogen peroxide (H_2O_2) as a result of the action of flavoprotein oxidase and NADH peroxidase. Hydrogen peroxide is an unstable compound that breaks down into oxygen and water; this process is likely responsible for the increased concentration of oxygen in the lower zone. In the composition of EM biopreparations, there are strains of fungi capable of efficiently decomposing lignocellulosic compounds (from plant residues), while simpler compounds are further metabolized by bacteria (from the group of facultative anaerobes). *Lactobacillus* sp. can degrade simple organic compounds in oxygen-deprived conditions and stimulate autochthonous microorganisms to actively metabolize, especially in conditions of low dissolved oxygen concentration. Actinobacteria present in biopreparations actively penetrate the depths of sediments (soft organic fractions), altering their structure and activating the process of biological mineralization. Phototrophic bacteria utilize hydrogen sulfide in metabolic processes, and by its oxidation, reduce local odor nuisance. Phototrophic bacteria also produce oxygen, increasing its content in the bottom sediment zone and stimulating highly efficient aerobic autochthonous microorganisms' metabolism. Another group of microorganisms included in microbiological preparations are yeasts (*Saccharomyces*). These organisms produce enzymes involved in the decomposition of organic matter and compounds that are most often a breeding ground for lactic acid bacteria and actinomycetes (*Actinomycetes*). Additionally, microelements present in biopreparations serve as a stimulating factor for decomposition processes, enhancing the efficiency of metabolism and the rapid growth of autochthonous organisms present in the aquatic environment [6,9–11,21–23].

The revitalization of the Siemiatycze lakes included a double application of EMs. The first series of bioremediation treatments were performed in 2013 and 2014, starting in early June. Further revitalization treatments were undertaken in 2016 and 2017. Each time, 5000 dm^3 of microbial biopreparation was introduced into lake waters. The biopreparation's stock solution was prepared by utilizing samples of contaminated lake water. The infusion process involved employing the injection method from a boat using exhaust pumps. The introduction of the biopreparation targeted zones close to the lake bottom, aiming for the effective use of organic carbon and nutrients in both water and sediments by the consortia of microorganisms. Note that the optimal metabolic activity of the selected microorganisms requires a water temperature above 5 °C.

2.1.3. Selection of Sampling Areas

The assessment of the bioremediation process in Reservoirs I, II, and III was based on a water quality analysis conducted by the AGH University in Krakow. Ten representative sampling points were selected within the Siemiatycze reservoir complex. Sampling points 1 to 5 were situated along the flow path of the larger Reservoir II, while 6 to 8 were taken from Reservoir I, and points 9 to 10 were located within Reservoir III (Figure 1).

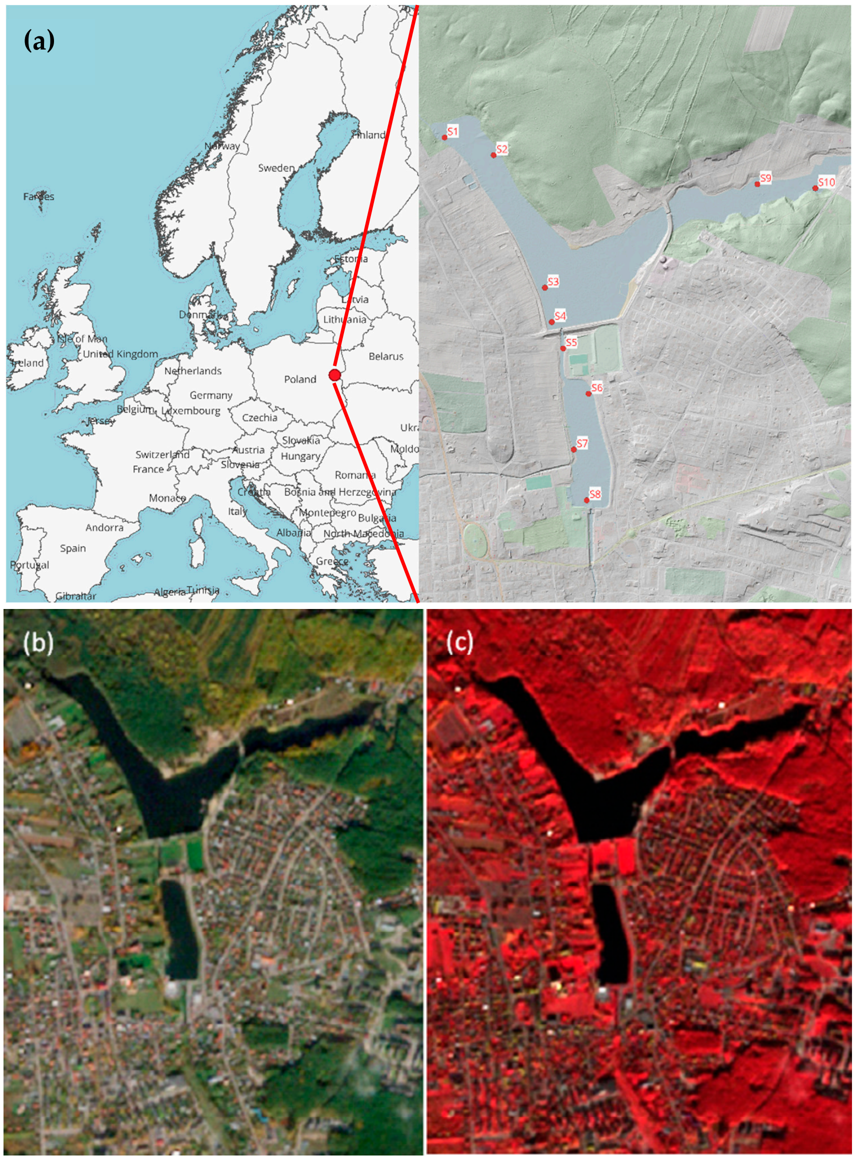

Figure 1. Study area and remote sensing composites: (**a**) an overview map of the study area in Europe with a focus on the Siemiatycze reservoir, overlaid with the distribution of measurement points (S1–S10) (base map source: OpenStreetMap); (**b**,**c**) Sentinel-2 image composites of the Siemiatycze area: (**b**) The natural color composite using channels B4 (red), B3 (green), and B2 (blue); (**c**) The false-color infrared composite highlighting vegetation, using channels B8 (near-infrared), B4 (red), and B3 (green).

2.2. Data

2.2.1. Land Cover Data

Corine Land Cover (CLC) is an established program initiated by the European Union, aimed at providing consistent information on land cover across Europe. The CLC datasets are a product of the European Environment Agency (EEA) and are part of the Copernicus Land Monitoring Service. The CLC inventory is created using satellite imagery as the primary data source and is updated periodically, typically in five- to six-year intervals [24].

In the context of our study that focused on the Siemiatycze reservoir, the CLC data were instrumental in providing a detailed and accurate representation of land cover distribution within the catchment areas. The specific datasets used in this research were derived from the most recent CLC succession of updates, which reflects land cover status in the years 1990, 2000, 2006, and 2012. These datasets were crucial for understanding the spatial distribution of various land cover types, such as agricultural land, forests, urbanized areas, and water bodies, and their potential influence on the water quality of the reservoir.

The CLC data were integrated into our study through a series of geospatial data analysis procedures performed using Geographic Information System (GIS) tools in QGIS 3.32 software. Firstly, the CLC vector data were acquired for the Siemiatycze region and these data were then overlaid with the catchment area boundaries of the Siemiatycze reservoir to extract relevant land cover information. Subsequently, the land cover classes within the catchment areas were quantified to assess their proportional distribution and potential impact on surface runoff and nutrient loading into the water bodies (Table 2).

Table 2. Surface area of land cover/land use forms [%] over the years 1990–2018 (Corine CLC).

Land Use/Land Cover	1990	2000	2006	2012	2018
The Mahomet River					
Urban and Built-Up	1.15%	1.15%	2.56%	2.59%	2.59%
Mixed Cover	48.55%	48.17%	46.24%	45.76%	45.76%
Pasture	2.39%	2.39%	3.51%	3.51%	3.51%
Complex Cultivation Patterns	3.44%	3.44%	1.49%	1.50%	1.50%
Land principally occupied by agriculture, with significant areas of natural vegetation	11.57%	11.98%	9.84%	10.17%	10.17%
Broad-leaved Forest	15.33%	15.33%	6.27%	6.27%	6.27%
Evergreen Needleleaf Forest	11.99%	12.18%	12.47%	12.46%	12.54%
Mixed Forest	4.02%	3.99%	15.07%	15.18%	15.33%
Deciduous Broadleaf Forest	1.37%	1.17%	2.35%	2.36%	2.13%
Water Bodies	0.20%	0.20%	0.20%	0.20%	0.20%
The Kamionka River					
Urban and Built-Up	1.04%	1.05%	3.35%	3.35%	3.35%
Mixed Cover	59.34%	59.36%	60.44%	59.89%	59.89%
Pasture	6.42%	6.42%	4.57%	3.95%	3.95%
Complex Cultivation Patterns	5.72%	5.72%	3.27%	3.36%	3.36%
Land principally occupied by agriculture, with significant areas of natural vegetation	12.78%	12.78%	12.62%	12.71%	12.71%
Broad-leaved Forest	2.17%	2.17%	1.66%	1.76%	1.76%
Evergreen Needleleaf Forest	9.22%	11.45%	7.76%	7.86%	8.19%
Mixed Forest	0.00%	0.00%	4.27%	4.27%	4.59%
Deciduous Broadleaf Forest	3.19%	0.92%	1.92%	2.73%	2.08%
Water Bodies	0.12%	0.12%	0.12%	0.12%	0.12%

2.2.2. Satellite Images

The satellite data used in this study comprised solely the Sentinel-2 mission, which is part of the Copernicus program conducted by the European Space Agency (ESA). The Sentinel-2 mission consists of two satellites, Sentinel-2A and Sentinel-2B, that provide global coverage of the Earth's surface in high spectral, spatial, and temporal resolution (Table A1) [25]. These satellites deliver images in 13 spectral channels, enabling detailed analysis of land cover and monitoring of environmental changes. Spectral channels in the visible and near-infrared range (B4, B5, and B6), crucial for identifying surface water phytoplankton, were further used to calculate chlorophyll-a concentration indices.

2.3. Methodology

2.3.1. Analytical Methods of In Situ Data

Statistical analyses were conducted using the Statistica 13.3 software, employing a nonparametric Wilcoxon paired *t*-test to determine the significance of differences between the compared pairs of results. The charts depict the average values of the examined water quality parameters. The bars encompass the median and quartiles 25–75, along with the range between the maximum and minimum values. The water quality research included both field measurements (measuring DO and transparency), while the remaining quality parameters were determined based on samples collected and analyzed in the laboratory (Table 3). During the first series of bioremediation treatments in 2013–2014, water parameter measurements were performed 4 times (07.2013; 08.2013; 11.2013; 05.2014). A water parameter analysis was conducted four times each year during the second series of bioremediation treatments in 2016–2017 (months-05.2016; 07.2016; 10.2016; 11.2016; 04.2017; 05.2017; 07.2017; 10.2017; 11.2017; 04.2018).

Table 3. The applied measurement methods in the study of selected water quality parameters.

The Measured Parameters	Unit	Methods/Tools
Dissolved oxygen 2014–2018	mg O_2/dm^3	By portable Multi-Function Meter CX-401 with oxygen galvanic oxygen sensors COG-1 (made by Elmetron, Zabrze, Poland)
Transparency	cm	Secchi disc methods
Chlorophyll-a	mg/dm^3	Spectrophotometric method (PN-86/C-05560/02) [26]
pH	-	PN-EN ISO 10523:2012 [27]
Chemical Oxygen Demand (COD)	mg O_2/dm^3	PN-ISO 15705:2005 [28]
Biochemical Oxygen Demand (BOD_5)	mg O_2/dm^3	PN-EN 1899-2:2002 [29]
Total phosphorus	mg/dm^3	PN-EN ISO 15681-2:2019-02 [30]
Total nitrogen	mg/dm^3	PN-EN 11905-1:2001 [31]
Suspended matter (SM)	mg/dm^3	PN-EN 872:2007 [32]

2.3.2. NDR Modeling

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software component (NDR—Nutrients Delivery Ratio) was used in the modeling of the distribution of nutrients in the area of both catchments [33]. The NDR computational model is spatially explicit, applying maps (Geographical Information System) as information sources and delivering maps as the final output. The NDR maps the Phosphate (Ptot) and Nitrate (Ntot) sources from the catchment area and their transport into the river bed. The Nutrient Delivery Ratio (NDR) is a model that is used to assess the impact of human activities on water quality. This model calculates the amount of nutrients that enter surface waters from agricultural areas, forests, urban areas, and other surfaces [34–36].

This mathematical model uses a simple material balance approach to describe the nutrient transport load through a defined area (in the studied watershed/subwatershed).

The magnitude of the load in the model is presented in kg of analyzed nutrients per 1 standard pixel (kg·px^{-1}). The nutrient loads across the landscape are determined based on land cover classification (LULC) maps [37,38]. The results of the NDR can be interpreted as a measure of the risk of water pollution by nutrients in any given area. These results are typically presented on a map, allowing for the quick comparison of different areas and the identification of the highest-risk contamination areas [39,40]. It is also important to note that the results of the NDR model are only a prediction and actual nutrient concentrations in water may be differently related to actual water conditions and external factors, such as rainfall or agricultural practices [40–44].

2.3.3. Satellite Data Processing and Analysis

Satellite data from the Sentinel-2 mission for the years 2015–2019 were used in this analysis. These data were made available and processed using Google Earth Engine (GEE), a platform for processing large geospatial datasets. This platform enabled the efficient management of satellite data, image processing, and real-time trend analysis, which was crucial for the implementation of this study. The use of GEE significantly accelerated the analysis process, allowing for the processing of a large amount of data without the need for local computational infrastructure. Images at the 1C processing level, recorded before 2016, were subjected to atmospheric correction (Figure 2).

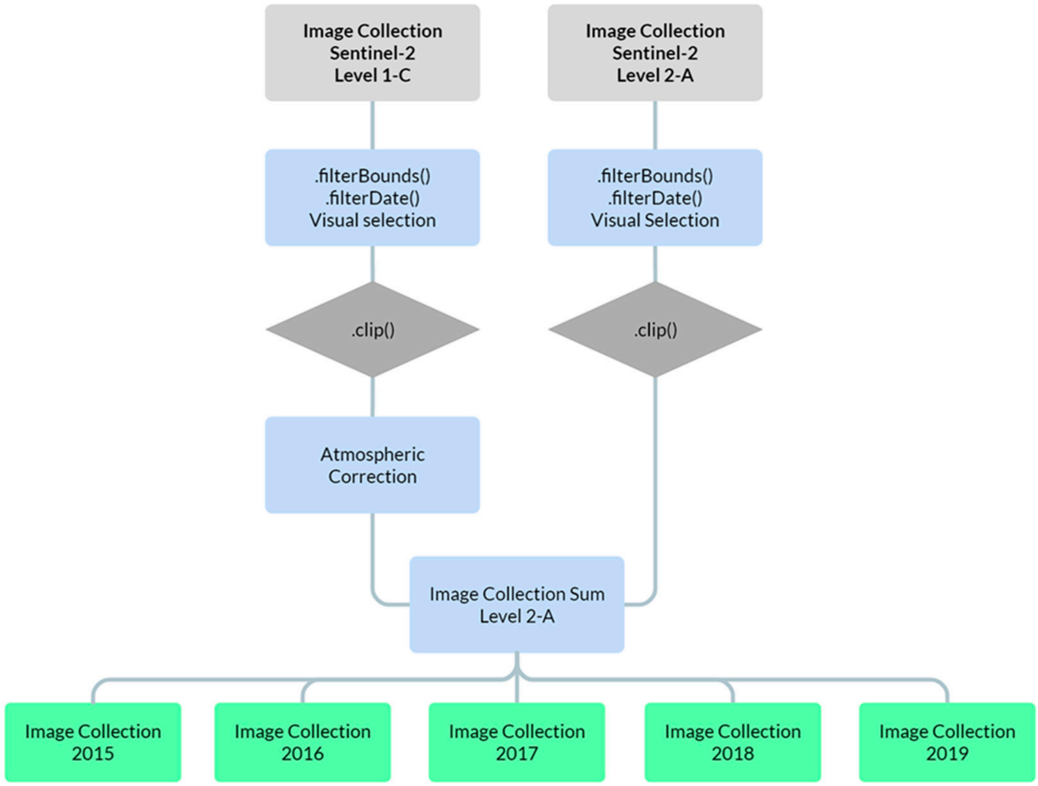

Figure 2. The flowchart of the process for harmonizing Sentinel-2 images to the processing level required for analyzing chlorophyll concentrations in water.

In the obtained satellite image collections, cloud-covered areas were eliminated using cloud masking algorithms. Subsequently, water bodies were extracted using the Water Index (NDWI—Normalized Difference Water Index). For these areas, the Maximum Chlorophyll Index (MCI) was calculated, which enables the detection and quantification of algal blooms, especially at high concentrations of chlorophyll-a. The MCI, designed to identify maximum chlorophyll absorption occurring near a wavelength of 675 nm, is often used to monitor algal blooms in water bodies [45]. The MCI is calculated using the Formula (1):

$$MCI = B5 - B4 - ((\lambda_{B5} - \lambda_{B4}) \times (B6 - B4)/(\lambda_{B6} - \lambda_{B4})), \quad (1)$$

where

- B4, B5, and B6 represent the spectral reflectance in a given spectral channel,
- Λ_{B4} = 0.665 nm, λ_{B5} = 0.705 nm, and λ_{B6} = 0.740 nm represent the central wavelengths of the corresponding bands of Sentinel-2.

Based on the calculated indices, an intuitive color palette was developed, in which the chlorophyll concentration is visualized using a color gradient from dark blue (lowest chlorophyll concentrations), through red, and to purple (highest chlorophyll concentrations). This color palette was designed to facilitate the precise and easy comparison of indices over different periods. The visualization of the MCI allowed for the spatial representation of phytoplankton biomass distribution from May to October in the years 2015–2019. As part of the monitoring of the water quality of the Siemiatycze reservoir, a series of analyses of MCI visualizations were conducted to assess the variability of chlorophyll-a concentration, a water eutrophication indicator.

3. Results and Discussion

3.1. Analytical Methods of In Situ Data Elaboration

Monitoring of Physical and Chemical Parameters and Water Quality

The research results indicate a significant variation in the values of analyzed pollutant parameters. Organic pollutants expressed as a whole as the COD and readily biodegradable fractions (BOD5) differed both between the collection points and delivered variable values for the period between 2013 and 2014 (Figures 3 and 4) (Tables A2 and A3). These differences result from the activity of microorganisms in different temperatures and the nature of the pollutants introduced from various sources into the reservoirs [14,46]. A relatively low BOD5/COD ratio was observed. Before starting the microbiological treatment, BOD5 values were between 9 to 33% of COD. The COD reduction was on average 23.6%, but the range of variation was from 4 to 63% between sampling points. BOD5 reduction was significantly higher on average, around 70% with a spread of results in the range of 37.5–90%. Only one point did not exhibit change, which may be attributed to meteorologic random events in this region during the sampling process or excess inputs from pollution sources. Easily biodegradable organic compounds are the main source of carbon for microorganisms in biopreparations introduced into lake waters [6,15,47]. Dobrzyński et al. [16], along with other researchers [8,14], also observed similar results. The low BOD5/COD ratio confirms the disparity in the reduction degree of both types of organic pollutants (Figures 3 and 4). Dondajewska el at. also documented the positive influence of microorganisms from EM biopreparations on the mineralization of organic matter and the development of phytoplankton biodiversity [9].

Nutrients are another group of pollutants responsible for lake water hypertrophy and the intensive eutrophication process of all reservoirs in Siemiatycze [7,48]. Reservoir II was characterized by significantly higher concentrations of total nitrogen compared with the other sites. Higher levels of total phosphorus in the waters of Reservoirs III and I indicate an increase in the intensity of eutrophication processes in these reservoirs compared with Reservoir II (Figure 3). During the purification period, an average decrease in total nitrogen by approximately 20% was observed, as well as total phosphorus by about 29%. Except for the two sampling points 7 and 8, the variation in total nitrogen concentrations was relatively unchanged (Figure 3). The nature of phosphorus variability from the sampling points of all samples was much more diverse (Figure 3).

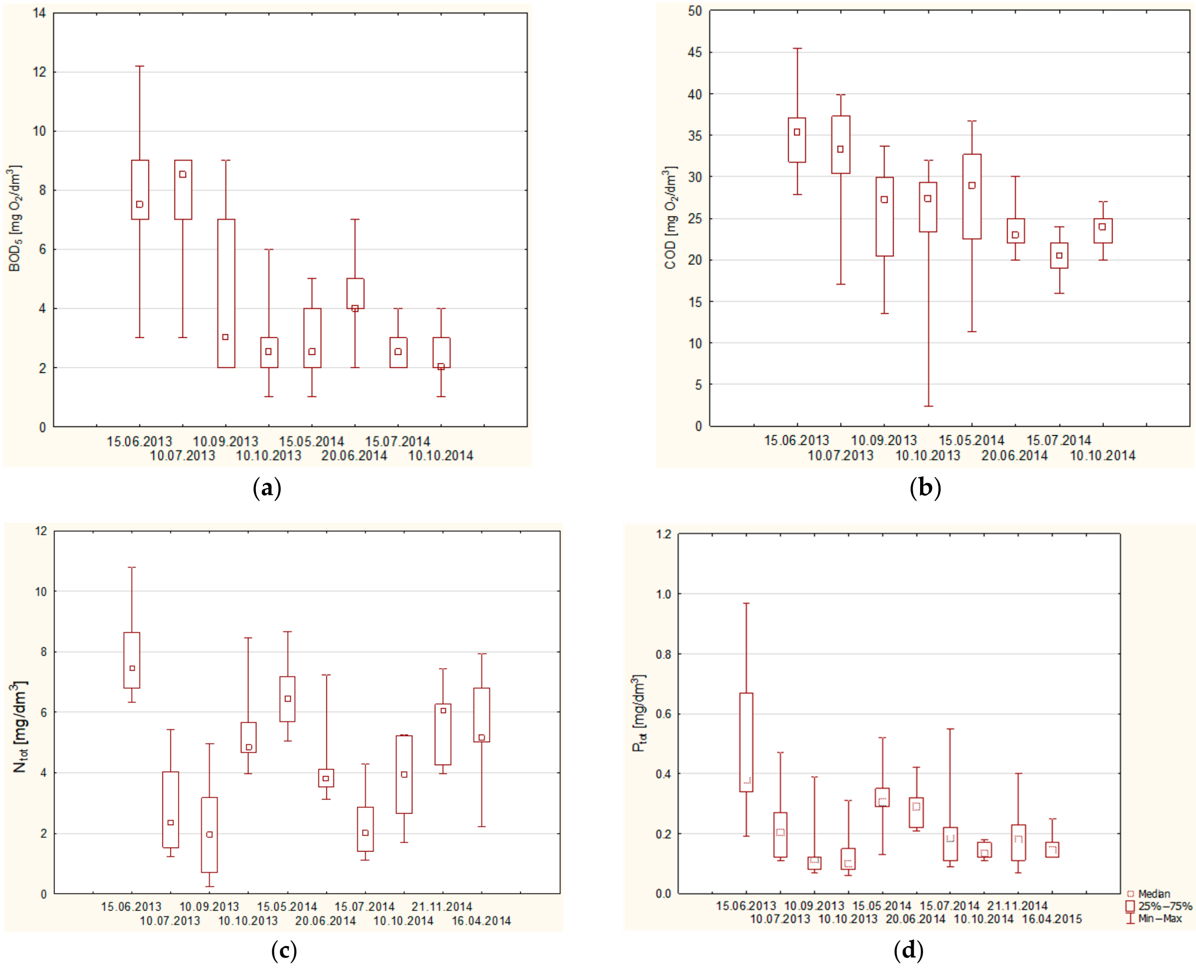

Figure 3. The changes (AVG ± SD) in water parameters in the Siemiatycze reservoirs: (**a**) BOD5; (**b**) COD; (**c**) N_{tot}; (**d**) P_{tot}.

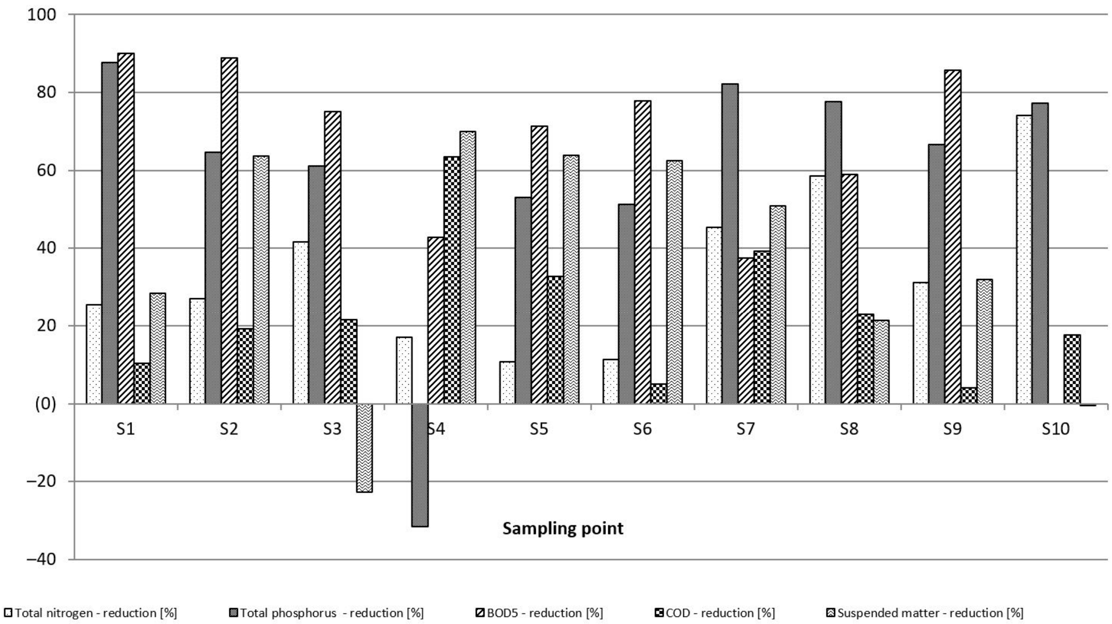

Figure 4. The percentage of reduction in the studied chemical parameters in water samples of Siemiatycze Reservoirs I, II, and III between 2016 and 2017.

The average reduction in both nutrient types in the range of 20–30% improved water transparency and other biological parameters in the aquatic environment (Figure 3) (Tables A4 and A5). Ganesh, in 2008, advocated for the application of EMs in small- and mid-sized water bodies, reporting a decrease in nutrient concentrations observed in select reservoirs in Hungary and India [49]. Dondajewska et al. only recorded minor changes in nutrient levels in a rehabilitated reservoir in Konin, with statistically insignificant results [9].

The level of the suspension also significantly decreased at most sampling points (Figure 5). In the following growing season, statistical differences were observed in suspended matter decline in all the reservoirs' (SM) levels (Table A6).

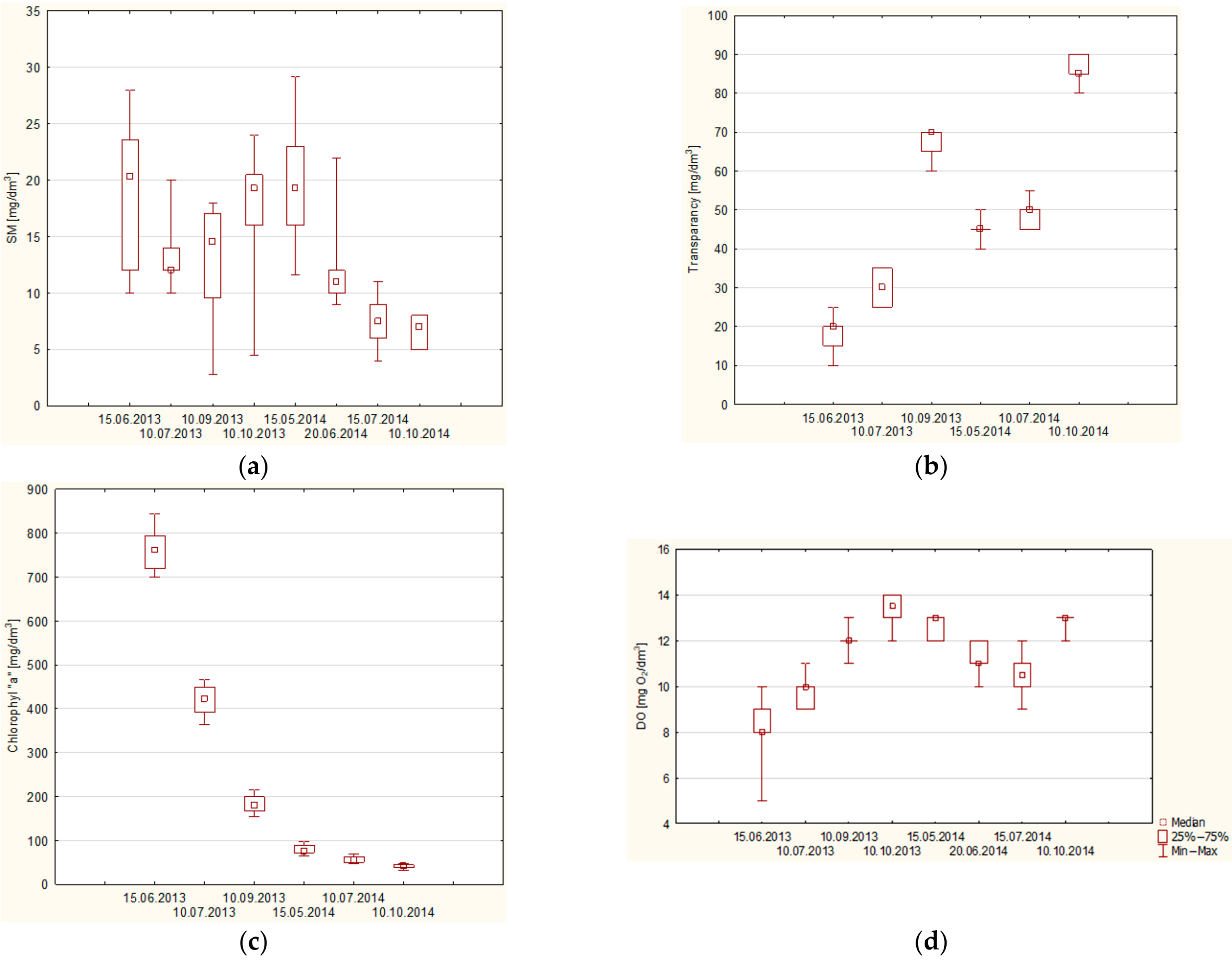

Figure 5. The changes (AVG ± SD) in water parameters in the Siemiatycze reservoirs: (**a**) SM; (**b**) transparency; (**c**) chlorophyll-a; (**d**) DO.

Water transparency in the reservoir was primarily influenced by the planktonic algae biomass, as noted in the initial chlorophyll levels before the bioremediation process (Figure 5). Following the remediation procedures, a gradual increase in transparency was observed, which persisted throughout the subsequent season (Figure 5). These differences were statistically significant (Table A8). As expected, with increased water transparency, a notable reduction in chlorophyll was observed (Figure 5) (Table A8). A similar effect of EM application on the development of chlorophyll-a values was observed during laboratory tests conducted on water samples taken from the lake Beytepe [50]. Suspended solids remained at a similar level during the early rehabilitation phase (Figure 5), yet statistically significant differences were noted in analogous months during the subsequent season (Table A8). Jóźwiakowski et al. observed similar dependencies in 2009 using liquid EMs produced by SCD Probiotics Technology in a small reservoir fed by municipal wastewater (constructed wetlands) [51].

The increase in dissolved oxygen levels in the water reservoirs also indicates a significant improvement in the examined quality parameters, maintaining favorable conditions for the development of biodiversity in aquatic ecosystems (Figure 5). The revitalization processes carried out in the period 2013–2014 brought visible effects on water quality improvement for treated reservoirs. Despite the immediate success of EM treatments, further efforts are required to eliminate pollution sources in the surface waters of the Kamionka and Mahomet rivers valleys, as these will reduce the treatment's efficacy. However, the persistence of the effect is still maintained due to the existence of "beneficial" consortia of microorganisms introduced from biopreparation in the lake's water and sediments. The use of EMs is a successful example of bio-based treatments used to rebalance the ecology of aquatic ecosystems and the capability of water to self-purify [52,53]. Biopreparation-based lake water treatments are unpopular due to society's prejudice against microorganisms. Moreover, few companies offer microbiological lake reclamation methods [47–49,54–57], mostly due to the lack of qualified technicians who hold sufficient knowledge and experience in the preparation of microbiological "cocktails" suitable for the nature of pollutants and specificities of degraded water environments [14,58]. Therefore, mechanical and chemical methods of lake reclamation are still the most widely used water treatment practices [54,56], despite being costly and severely invasive in already debilitated ecosystems [59].

3.2. Land Cover

The land use structure in the period of 1990–2018 exhibited slight changes in both the Kamionka and Mahomet basins. Urbanized areas represented just above 1% in both catchments in the 1990s, and subsequently increased by 2018, reaching 2.6% in the Mahomet catchment and 3.3% in the Kamionka catchment (Table 1). Mixed cover represented more than 48% of the Mahomet catchment and 59% of the Kamionka catchment, observing a decrease of approximately 3% in the Mahomet catchment, while no significant changes were noted for the Kamionka catchment for the 2018 survey (Table 1). Being the most abundant land cover and due to the buffer characteristics of root systems, the loss of mixed cover has the greatest impact on the surface runoff of nutrients and pollutants into both rivers and reservoirs in Siemiatycze.

Pasture areas in the Kamionka catchment were reduced by approximately half (from 6.4% to 3.9%) in the same period, while in the Mahomet catchment, a slight increase of over 1% in this type of land use was recorded (from 2.3% to 3.5%) (Table 1). Due to their small share of the total area, they do not have a significant impact on the nutrient balance in the reservoirs. Agricultural land use underwent a significant reduction by 2018 in both catchments, including both complex cultivation patterns and land predominantly occupied by agriculture, with significant areas of natural vegetation. However, they still represent over 11% of the Mahomet catchment and 16% of the Kamionka catchment (Table 1), which, due to the specificity of agricultural practices and fertilizer use, can significantly affect the increase in nutrient runoff into both rivers.

Forest areas constitute more than 36% of the Mahomet catchment and 16.6% of the Kamionka catchment (Table 1), and they have a positive impact on the reduction in nutrients (with an increased retention time for P_{tot} and N_{tot}) in the soil [48,60,61]. No further changes should be expected from 2018 to 2023, as this is a period of significant economic development stagnation, in line with the global crisis trend observed throughout the EU.

3.3. NDR Modeling

The analysis of surface and subsurface P and N for the Kamionka and Mahomet basins for the period 1990 to 2012 brings evidence to the effects of reservoir nutrient retention in the system (Figure 3). The evolution of land use partially explains the widespread retention of nutrients originating in upstream agricultural areas throughout the basin (1990); these systems contribute to the downstream accumulation of nutrients in recent years (2012)

(Figure 4). The widespread upstream sources were maintained throughout the study period, however downstream growing retention is notably contributing to water quality degradation. The climate also plays an important role in nutrient usage, mainly in lentic reservoirs and lakes where during the winter frozen conditions, microorganisms are unable to process excess nutrient loads; however, when the thawing of ice happens, lentic systems mix due to temperature variation, which renders nutrients' wider availability, leading to microorganism growth and the commonly observed algal blooms [62]. Shallow reservoirs with increased sedimentation may observe several algal blooms throughout the warmer seasons as the thermocline depth increases [63]. The need to remove excess nutrients from the reservoirs is mandatory as it implies eutrophication, and loss of ecosystem services [64]. To effectively mitigate eutrophication and reduce the associated risks, strategic nutrient removal or utilization during the natural cycling of lentic systems, particularly in the spring and fall seasons, is highly recommended. By carefully managing the nutrient dynamics in these reservoirs, it is possible to optimize the efficiency of nutrient processing and minimize the risk of eutrophication.

In addition to excess nutrient inputs, it is crucial to consider other contributing factors that can exacerbate the eutrophication process. Discharges of untreated sewage and the illegal release of pollutants from dispersed point sources pose significant threats to the water quality of reservoirs II and III. These activities introduce additional nutrients and contaminants into the aquatic systems, further intensifying the eutrophication process and compromising the overall health of the ecosystem [65]. To address these challenges effectively, it is essential to implement comprehensive management strategies that encompass nutrient removal techniques, stringent monitoring of discharges, and the implementation of pollution control measures. Collaborative efforts among regulatory bodies, local communities, and stakeholders are crucial in implementing sustainable practices and ensuring the long-term health and sustainability of reservoir ecosystems [66]. By proactively managing nutrient inputs and addressing other pollution sources, it is possible to mitigate eutrophication risks and safeguard the ecosystem services provided by reservoirs. This includes the preservation of water quality, the maintenance of biodiversity, and the provision of essential ecosystem functions that support human well-being and sustainable development.

3.4. Satellite Analysis Results

In 2013–2014, quality parameters were determined using field survey methods and analytical laboratory techniques due to the sole availability of satellite images from the OLI sensor (Landsat 8 satellite) with a poor spatial resolution (30 m). In the following period of 2015, a secondary deterioration of quality parameters was observed, which prompted the authorities of the city of Siemiatycze to carry out analogous bioremediation treatments using allochthonous biopreparations. However, the technological development of systems that allow the acquisition of increasingly accurate geodata from satellite images progressed rapidly [67]. Starting in 2015, changes in water transparency were imaged using remote sensing analyses of Sentinel-2 images with a satisfactory resolution (10 m). Remote sensing methods enable the effective assessment of qualitative changes in water, even in the absence of analytical data. The analysis of satellite data from the Sentinel-2 mission for the Siemiatycze reservoir in the years 2015–2019 allowed for a detailed examination of the seasonal variability of chlorophyll-a concentrations, an important indicator of the trophic state and eutrophication of surface waters. In 2015, the Siemiatycze reservoir was characterized by moderate to high chlorophyll-a concentrations, with the highest concentrations in central areas during the summer months (Figure 6). This indicated intense phytoplankton activity, especially in July and August, likely due to favorable temperature conditions and nutrient availability. In 2016, an increase in chlorophyll-a concentrations was observed in June, lasting until September, but not reaching the levels of the previous year, with a noticeable decline in October reflecting the seasonal change in temperature and biological activity (Figure 6). The summer of 2017 brought a further increase in concentrations, peaking in July and then gradually decreasing, indicating the end of the vegetative season with very low chlorophyll-a concentrations in October (Figure 6). The reduction in chlorophyll-a concentrations, observed in 2016 and 2017 (compared to 2015), corresponded with water test results, where reductions in total phosphorus and total nitrogen concentrations were noticeable (Figure 4). In 2018, intense algal blooms were observed in July, with high chlorophyll-a concentrations persisting until early August, followed by a decline in subsequent months, suggesting changes in environmental conditions limiting algal growth (Figure 7). In 2019, the spring months were characterized by low chlorophyll-a concentrations, which sharply increased in June, peaking in July, and a clear decline was observed from August to September, confirmed by a further limitation of phytoplankton activity in October, closing the observed seasonal cycle (Figure 7). The analysis of processed spectral data products from Sentinel-2 indicates a clear seasonality in the dynamics of chlorophyll-a concentrations, consistent with expectations for the life cycle of phytoplankton. Furthermore, the observed fluctuations may be linked to local anthropogenic factors, such as the influx of nutrients from agricultural areas. These results highlight the importance of continuous water quality monitoring using remote sensing techniques, supported by local in situ measurements and ecosystem process modeling. Integrating these data will allow for a deeper understanding of the dynamics of chlorophyll-a concentrations and the identification of potential long-term trends, which is crucial for protecting aquatic ecosystems from the effects of eutrophication. Such monitoring can contribute to effective water resource management and the implementation of actions aimed at reducing processes that promote the eutrophication of water bodies.

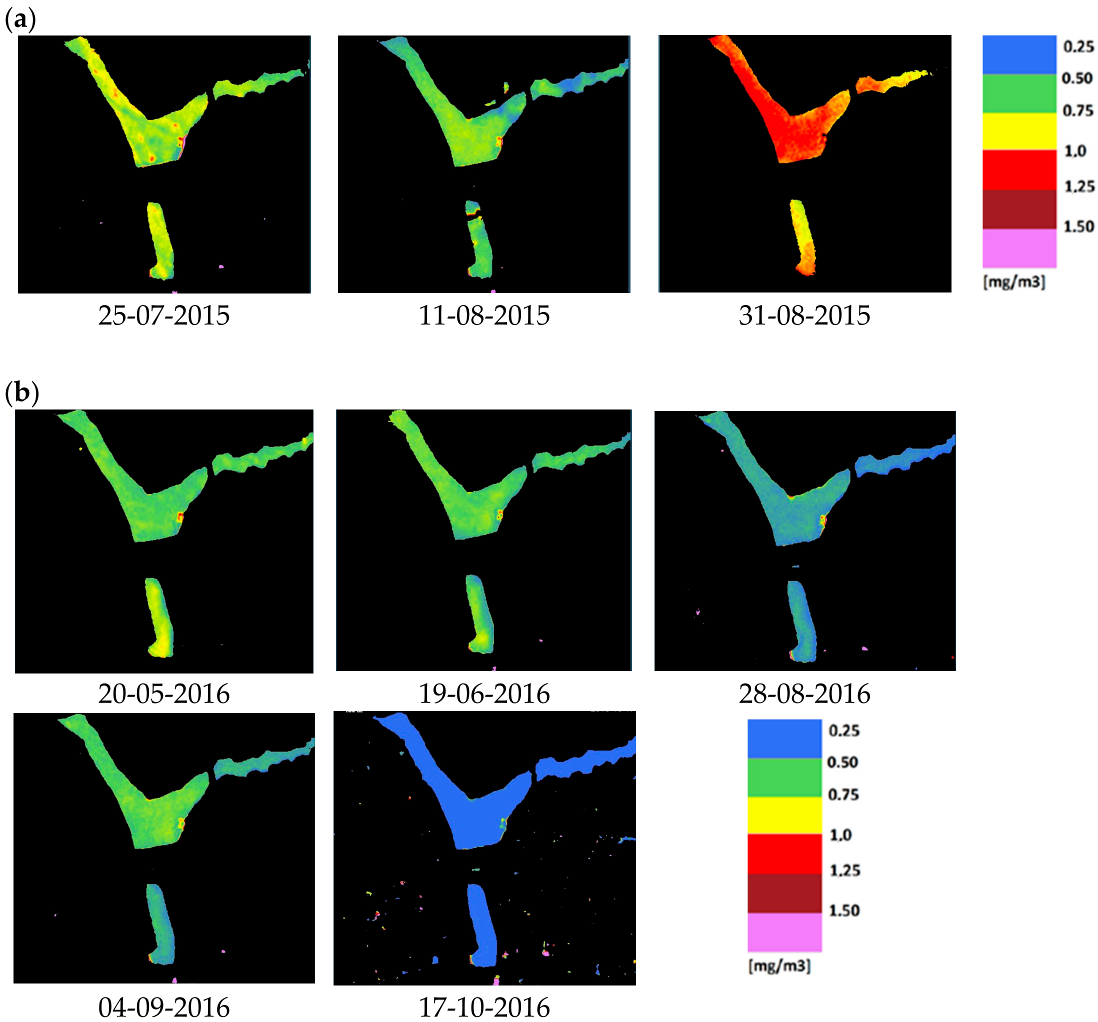

Figure 6. *Cont.*

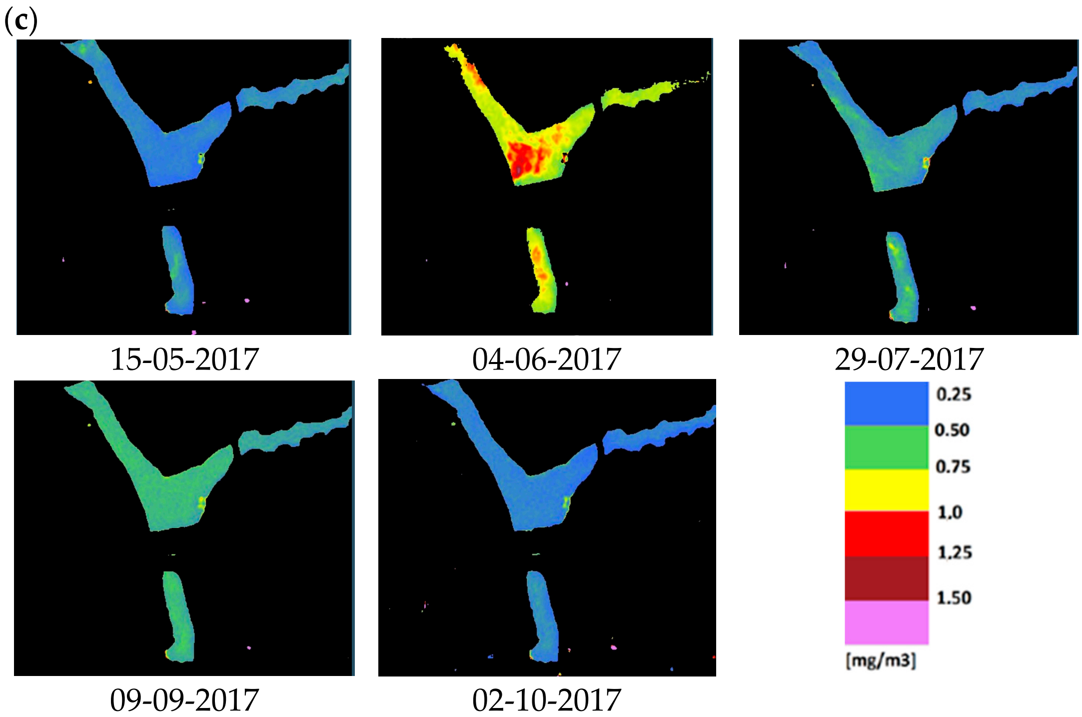

Figure 6. The spatial distribution of chlorophyll-a concentrations in the Siemiatycze reservoir from July to August (**a**) year 2015; (**b**) and from May to October year 2016, (**c**) year 2017.

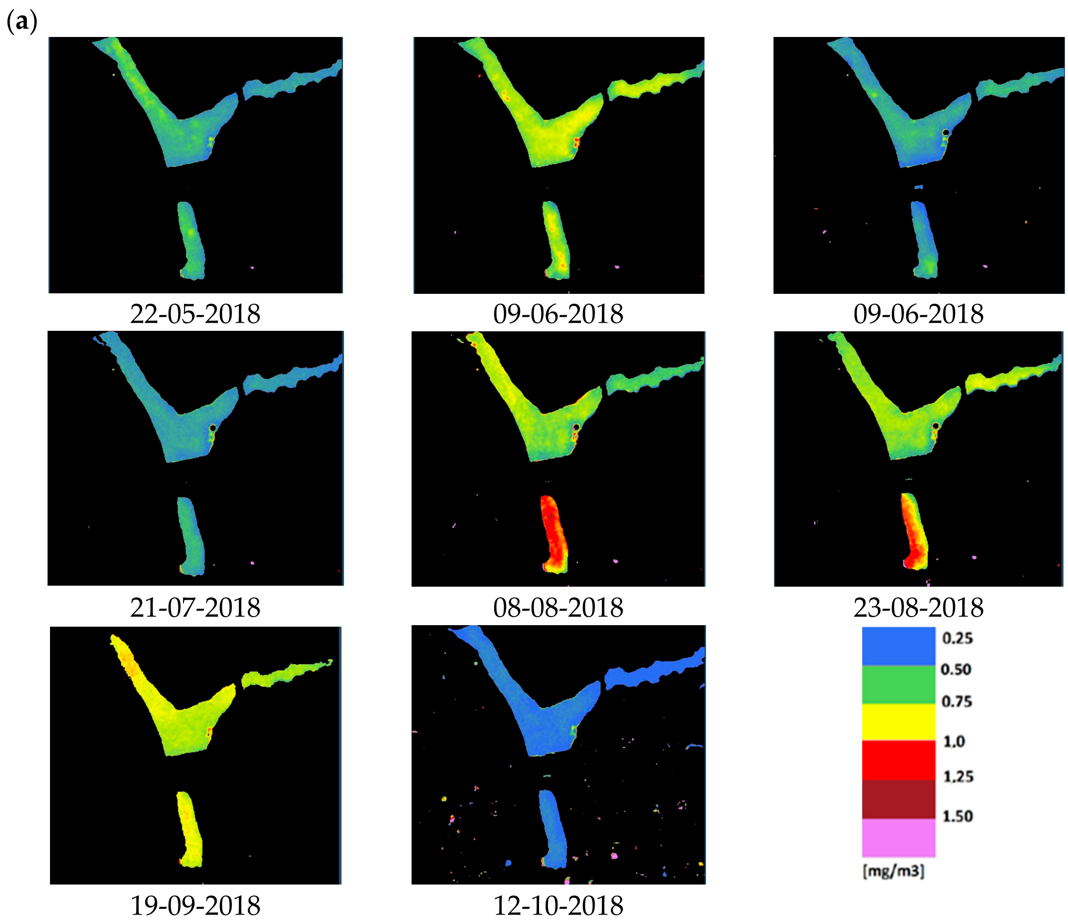

Figure 7. *Cont.*

(**b**)

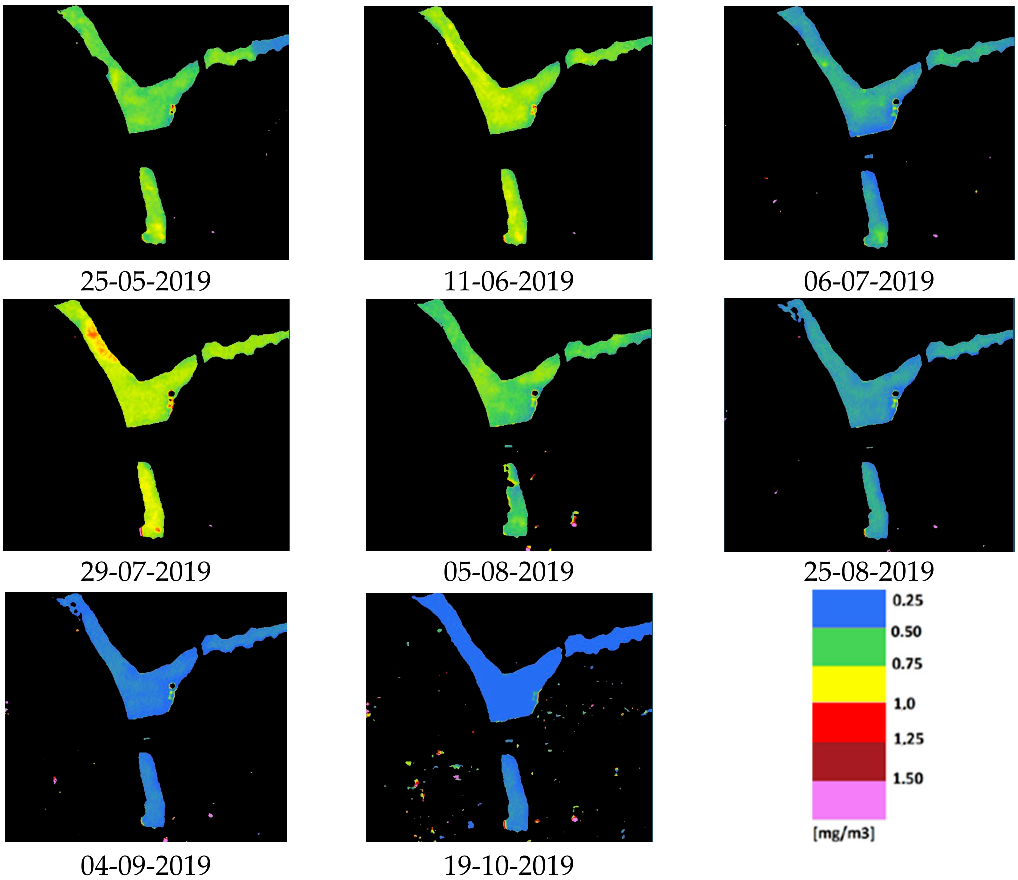

Figure 7. The spatial distribution of chlorophyll-a concentrations in the Siemiatycze reservoir from May to October, (**a**) year 2018; (**b**) year 2019.

In our study, we carefully analyzed all available satellite images from all periods (from spring to autumn) to obtain the most comprehensive view of the changes occurring in the Siemiatycze reservoirs. However, for clarity in presenting the results, the figures (Figures 6 and 7) only include selected images representing specific months, from May to October. This approach was taken to highlight the seasonal variability in chlorophyll-a concentrations, from spring to autumn. The choice of these periods allowed us to illustrate key trends and changes in the dynamics of the water reservoir's ecosystem across different seasons.

4. Conclusions

This paper's sections offer technical methodologies and efficient procedures that, when combined, can contribute towards a comprehensive reservoir rehabilitation. The analysis of the water quality at the Siemiatycze lakes indicates that until 2013, a successive deterioration in the water quality parameters occurred. Based on the conducted research and observations, the following conclusions can be drawn:

1. An improvement in the studied water quality parameters was observed after microbiological remediation processes were carried out in 2013–2014. Additionally, an odor reduction was noted. The results of the analysis carried out and the observations made indicate a possible, strong influence of the conducted reclamation processes on the environmental and recreational values and services of the reservoirs.
2. The effect of improved water quality persisted until 2015, but in subsequent seasons, a gradual recurrence of water blooms resulting from the intensive eutrophication of the reservoir was observed. Therefore, reclamation treatments with biopreparations

were applied once more in 2016–2017. Sudden improvements in water quality were again observed after the treatments. The reduction in reservoir algal blooms appears to be a direct consequence of the use of biopreparations.

3. Remote sensing evaluation methods based on satellite images have proven to be highly effective in assessing the effects of reclamation processes. Remote sensing studies using Sentinel-2 satellite images indicated the successive occurrences of water blooms in the reservoirs from 2015 onward, as well as an improvement in water quality (reduction in algal blooms) after microbiological reclamation treatment.
4. The performed analyses indicate that the microbiological reclamation method represents an interesting and effective (non-invasive to aquatic ecosystems) biotechnology for cleaning polluted water reservoirs or parts thereof, such as bathing areas. However, it takes considerable time to achieve the effects of reclamation.
5. Reducing the inflow of pollutants into the reservoir and biological enclosure of the littoral zone can also contribute to accelerating and maintaining the treatment effect.

Author Contributions: Conceptualization, R.M., Z.K., E.G., L.S. and M.J.; methodology, R.M., Z.K. and E.G.; software, R.M., Z.K. and E.G.; validation, R.M., E.G., L.S. and M.J.; formal analysis, R.M. and E.G.; investigation, R.M. and E.G.; resources, R.M. and E.G.; data curation, R.M. and E.G.; writing—original draft preparation, R.M., E.G. and M.J.; writing—review and editing, R.M., Z.K., E.G., L.S. and M.J.; visualization, R.M., Z.K. and E.G.; supervision, R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. The spectral and spatial characteristics of the sensors of Sentinel-2 [25].

Spatial Resolution (m)	Band Number	Sentinel-2A Central Wavelength (nm)	Sentinel-2A Bandwidth (nm)	Sentinel-2B Central Wavelength (nm)	Sentinel-2B Bandwidth (nm)
10	2	492.4	66	492.1	66
	3	559.8	36	559.0	36
	4	664.6	31	664.9	31
	8	832.8	106	832.9	106
20	5	704.1	15	703.8	16
	6	740.5	15	739.1	15
	7	782.8	20	779.7	20
	8a	864.7	21	864.0	22
	11	1613.7	91	1610.4	94
	12	2202.4	175	2185.7	185
60	1	442.7	21	442.2	21
	9	945.1	20	943.2	21
	10	1373.5	31	1376.9	30

Table A2. The statistical differences for changes in the water BOD5 before and after reclamation, in the next measurement periods 2013–2014 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	8	13	0.700140042	0.48384036
10.07.2013 and 10.09.2013	9	3	2.31016062	0.0208798948
10.09.2013 and 10.10.2013	7	0	2.36643191	0.0179610673
10.10.2013 and 15.05.2014	9	20.5	0.236939551	0.812703838
15.05.2014 and 20.06.2014	10	9	1.88569461	0.0593370109
20.06.2014 and 15.07.2014	10	4	2.3953418	0.0166054475
15.07.2014 and 10.10.2014	6	7.5	0.628970902	0.529368555

Table A3. The tatistical differences for changes in the water COD before and after reclamation, in the next measurement periods 2013–2014 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	10	10	1.78376517	0.0744627595
10.07.2013 and 10.09.2013	10	8	1.98762405	0.0468541307
10.09.2013 and 10.10.2013	10	19	0.866400225	0.38627137
10.10.2013 and 15.05.2014	10	20	0.764470787	0.444587303
15.05.2014 and 20.06.2014	10	12	1.57990629	0.114129316
20.06.2014 and 15.07.2014	10	2	2.59920068	0.0093445408
15.07.2014 and 10.10.2014	9	4.5	2.13245596	0.0329701375

Table A4. The statistical differences for changes in the water N_{tot} before and after reclamation, in the next measurement periods 2013–2014/15 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	10	0	2.80305955	0.0050623364
10.07.2013 and 10.09.2013	10	0	2.80305955	0.0050623364
10.09.2013 and 10.10.2013	10	0	2.80305955	0.0050623364
10.10.2013 and 15.05.2014	10	0	2.80305955	0.0050623364
15.05.2014 and 20.06.2014	10	1	2.70113011	0.00691079318
20.06.2014 and 15.07.2014	10	1	2.70113011	0.00691079318
15.07.2014 and 10.10.2014	10	3	2.49727124	0.0125158163
10.10.2014 and 21.11.2014	10	0	2.80305955	0.0050623364
21.11.2014 and 16.04.2015	10	24	0.356753034	0.721276934

Table A5. The statistical differences for changes in the water P_{tot} before and after reclamation, in the next measurement periods 2013–2014/15 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	10	0	2.80305955	0.0050623364
10.07.2013 and 10.09.2013	10	0	2.80305955	0.0050623364
10.09.2013 and 10.10.2013	10	23	0.458682472	0.646462514
10.10.2013 and 15.05.2014	10	0	2.80305955	0.0050623364
15.05.2014 and 20.06.2014	10	10	1.78376517	0.0744627595
20.06.2014 and 15.07.2014	10	10	1.78376517	0.0744627595
15.07.2014 and 10.10.2014	10	14.5	1.3250827	0.18514467
10.10.2014 and 21.11.2014	9	7	1.83628152	0.0663169473
21.11.2014 and 16.04.2015	10	17.5	1.01929438	0.308064

Table A6. The statistical differences for changes in the water SM before and after reclamation, in the next measurement periods 2013–2014 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	9	4.5	2.13245596	0.0329701375
10.07.2013 and 10.09.2013	10	24.5	0.305788315	0.759766025
10.09.2013 and 10.10.2013	10	8	1.98762405	0.0468541307
10.10.2013 and 15.05.2014	10	17	1.0702591	0.284503505
15.05.2014 and 20.06.2014	10	3.5	2.44630652	0.0144333573
20.06.2014 and 15.07.2014	9	1.5	2.48786529	0.0128517444
15.07.2014 and 10.10.2014	10	12	1.57990629	0.114129316

Table A7. The statistical differences for changes in the water transparency before and after reclamation, in the next measurement periods 2013–2014 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	10	0	2.80305955	0.0050623364
10.07.2013 and 10.09.2013	10	0	2.80305955	0.0050623364
10.09.2013 and 15.05.2013	10	0	2.80305955	0.0050623364
15.05.2014 and 10.07.2014	7	0	2.36643191	0.0179610673
15.07.2014 and 10.10.2014	10	0	2.80305955	0.0050623364

Table A8. The statistical differences for changes in the water chlorophyll-a before and after reclamation, in the next measurement periods 2013–2014 year.

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
15.06.2013 and 10.07.2013	10	0	2.80305955	0.0050623364
10.07.2013 and 10.09.2013	10	0	2.80305955	0.0050623364

Table A8. *Cont.*

Pair of Variables	Wilcoxon Paired *t*-Test			
	N Significant	T	Z	*p*
10.09.2013 and 15.05.2013	10	0	2.80305955	0.0050623364
15.05.2014 and 10.07.2014	10	0	2.80305955	0.0050623364
15.07.2014 and 10.10.2014	10	0	2.80305955	0.0050623364

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