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An Analysis of Eutrophication Pattern in Phewa Lake Using Remote Sensing Technique

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Abstract

Eutrophication has emerged as a critical environmental issue for freshwater ecosystems, particularly in regions experiencing rapid urbanization and tourism growth. Phewa Lake, situated in Pokhara, Nepal, faces increasing ecological stress from untreated sewage discharge, stormwater runoff, and seasonal tourist influx. This study investigates the spatial and temporal patterns of eutrophication in Phewa Lake using Sentinel-2 satellite imagery from 2017 to 2024. Two spectral indices were employed; Normalized Difference Chlorophyll Index (NDCI) to evaluate chlorophyll-a concentration and Normalized Difference Water Index (NDWI) to evaluate turbidity and surface water conditions. Twenty-four cloud-free images representing pre-monsoon, monsoon, and post-monsoon periods were analyzed in ArcGIS and correlated with rainfall and tourism data to identify major eutrophication drivers. The results indicate elevated NDCI values during pre-monsoon and post-monsoon seasons, corresponding with higher anthropogenic activity and reduced water levels, while increased NDWI values during the monsoon season reflect dilution effects and improved water clarity. These findings demonstrate that eutrophication in Phewa Lake is primarily governed by human-induced factors and natural hydrological variations. The integration of remote sensing and GIS techniques offers a reliable, non-invasive, and cost-effective approach for long-term lake monitoring. This study underscores the need for sustainable wastewater management, stricter regulation of tourism-related pollution, and incorporation of satellite-based monitoring into freshwater management and policy frameworks for Phewa Lake and similar ecosystems.

Keywords

Eutrophication, Remote Sensing, Sentinel-2, NDCI, NDWI

1. Introduction

Phewa Lake, located in the Pokhara Valley of Kaski District, Nepal, is the country’s second-largest freshwater lake. It is an essential ecological and socio-economic asset, supporting biodiversity, agriculture, fisheries, domestic use, and tourism [1]. The lake provides habitat for a wide range of aquatic and semi-aquatic species and plays a crucial role in maintaining the ecological balance of the Pokhara Valley. In addition, it serves as an important freshwater resource for surrounding communities, particularly during dry seasons when alternative water sources are limited. The lake’s cultural importance, exemplified by the Tal Barahi Temple on its central island, and its tourism-driven economy contribute significantly to local livelihoods and regional development [2]. Religious tourism, recreational boating, and lakeside hospitality services attract both domestic and international visitors throughout the year, reinforcing the lake's role as a focal point of socio-cultural activities in Pokhara. Beyond its ecological and cultural roles, Phewa Lake is pivotal to the region's economy. Tourism, centred on the lake, contributes significantly to Pokhara's economic development by generating employment opportunities and fostering businesses such as hotels, restaurants, and recreational services.

However, rapid urbanization and unregulated tourism have intensified anthropogenic pressures, primarily through the discharge of untreated sewage and solid waste into the lake via multiple inflow channels [1]. The absence of adequate wastewater treatment infrastructure and effective regulatory enforcement has further aggravated the direct discharge of pollutants into the lake system. This pollution has accelerated eutrophication, characterized by nutrient enrichment that stimulates algal blooms, reduces water clarity, depletes dissolved oxygen, and endangers aquatic biodiversity [3], [4]. These processes negatively affect ecosystem health, fisheries productivity, and the aesthetic value of the lake, thereby threatening its long-term sustainability.

Major contributing factors include sewage discharge, agricultural runoff, sediment disturbance from tourism, urban stormwater, deforestation, and climatic variability. The interaction of these factors leads to complex seasonal and spatial variations in nutrient concentration and water quality, making eutrophication a persistent management challenge. Understanding these dynamics is crucial for effective management. Remote sensing technologies, particularly Sentinel-2 multispectral data, provide advanced means to monitor water quality parameters such as chlorophyll-a concentration, turbidity, and algal bloom extent [5]. These technologies enable repeated observations over large areas, overcoming many of the limitations associated with conventional field-based monitoring.

This study applies Sentinel-2 imagery and spectral indices Normalized Difference Chlorophyll Index (NDCI) and Normalized Difference Water Index (NDWI) to analyze the eutrophication patterns of Phewa Lake from 2017 to 2024. The selected indices are particularly suitable for detecting chlorophyll-a concentration and surface water characteristics in turbid inland water bodies. The primary problem addressed is nutrient pollution from untreated sewage, which exacerbates eutrophication and degrades water quality [6]. Traditional in-situ monitoring methods are limited in spatial and temporal coverage; hence, remote sensing offers a cost-effective and comprehensive alternative.

The study aims to identify eutrophication patterns using remote sensing, assess chlorophyll-a and turbidity variations, and examine the influence of tourism and rainfall on water quality. By integrating satellite-derived indices with ancillary socio-environmental data, the study seeks to establish a clearer link between human activities, hydrological conditions, and water quality dynamics. Findings from this research contribute to sustainable lake management by correlating water quality trends with anthropogenic and climatic drivers, supporting evidence-based environmental policies. The study's scope covers the period from 2017 to 2024, focusing on seasonal and inter-annual changes, though limitations such as cloud interference, atmospheric correction errors, and localized data gaps are acknowledged. Overall, this research demonstrates the utility of remote sensing as a non-invasive, efficient, and scalable approach for monitoring eutrophication in freshwater ecosystems and guiding sustainable management of Phewa Lake.

2. Methodology

2.1 Study Site

The study was conducted in Phewa Lake, located in Pokhara Metropolitan City, Gandaki Province, Nepal (28.2096°N, 83.9856°E), at an elevation of approximately 742 meters above sea level which is shown in Figure 1. Phewa Lake is the second-largest freshwater lake in Nepal, covering an area of about 5.23 km² and draining a catchment of nearly 110 km². The lake is primarily fed by Harpan Khola, which serves as the main inflow channel transporting surface runoff, sediments, and nutrients from the surrounding watershed, and it drains into the Seti Gandaki River through Pardi Khola. The hydrological regime of the lake is strongly influenced by seasonal rainfall, particularly during the monsoon period, resulting in significant variations in water level, inflow intensity, and nutrient loading throughout the year. The watershed surrounding Phewa Lake is characterized by mixed deciduous and subtropical forest cover along with expanding agricultural and urban land uses. In recent years, the lake has experienced increasing anthropogenic stress due to rapid urbanization, unplanned settlements, population growth, and intensive shoreline development. The proliferation of hotels, restaurants, recreational facilities, and residential buildings along the lakeshore has contributed to increased wastewater discharge, stormwater runoff, and solid waste inflow into the lake, often without adequate treatment. These pressures are further intensified during peak tourism seasons, leading to elevated nutrient input and deterioration of water quality conditions.

Phewa Lake's natural beauty, combined with its cultural and religious significance, makes it one of Nepal's most important tourism destinations. Cultural landmarks such as the Tal Barahi Temple located on an island within the lake, the World Peace Pagoda overlooking the basin, and the scenic backdrop of the Annapurna Himalayan range enhance its socio-economic value. While tourism plays a crucial role in supporting local livelihoods and regional development, the concentration of tourism-related activities has increased the vulnerability of the lake to eutrophication. The combined effects of hydrological sensitivity, intensive human activity, untreated sewage discharge, and fluctuating tourism pressure render Phewa Lake an ideal site for studying eutrophication dynamics and their driving forces using remote sensing techniques.

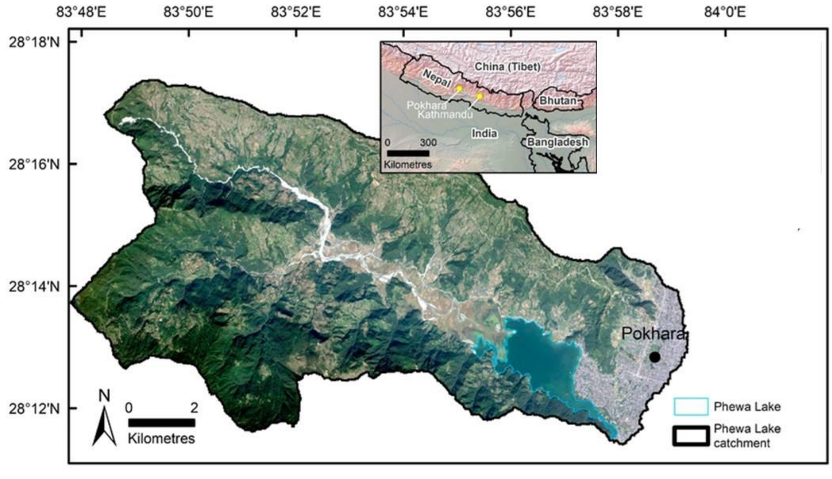

Figure 1: Study Area Map Showing Phewa Lake

2.2 Data Collection

The data collection framework integrates multi-temporal remote sensing datasets with relevant ancillary information to systematically analyze the spatial and temporal dynamics of eutrophication in Phewa Lake over an extended period. This integrated approach enables the simultaneous assessment of water quality indicators derived from satellite imagery alongside external environmental and anthropogenic variables, providing a holistic understanding of lake processes. By combining high-resolution multispectral satellite data with supporting datasets such as tourism records and precipitation information, the framework captures both short-term seasonal variability and long-term inter-annual trends in eutrophication. This methodology ensures comprehensive spatial coverage across the entire lake surface as well as consistent temporal representation of key hydrological and anthropogenic phases, thereby enhancing the reliability and robustness of water quality assessment and trend analysis for Phewa Lake.

a) Remote Sensing Technique

Sentinel-2 satellite imagery, renowned for its high-resolution multispectral capabilities, is utilized to extract critical water quality indicators such as chlorophyll-a concentration, turbidity, and the occurrence of algal blooms. Sentinel-2 multispectral satellite imagery, obtained from the Copernicus Open Access Hub, was used to derive water quality parameters including chlorophyll-a concentration and turbidity. Images from 2017 to 2024 were analyzed, representing pre-monsoon (March–May), monsoon (June–August), and post-monsoon (October–November) periods. For each season, one cloud-free image was selected, yielding a total of 24 images across the eight-year study period as shown in Table 1. This seasonal selection captures the influence of rainfall and tourism patterns on eutrophication levels.

Table 1: Satellite Image Data Selection by Date

Year	Season	Month	Selected Date	Reason for Selection
2017	Pre-monsoon	April	2017-04-11	Early monsoon
	Monsoon	September	2017-09-13	Monsoon period
	Post-monsoon	November	2017-11-12	High tourism, clear skies
2018	Pre-monsoon	March	2018-03-07	Start of pre-monsoon
	Monsoon	September	2018-09-18	Mid-monsoon period
	Post-monsoon	November	2018-11-27	High tourism, clear conditions
2019	Pre-monsoon	March	2019-03-27	End of pre-monsoon
	Monsoon	June	2019-06-20	Early monsoon
	Post-monsoon	November	2019-11-22	Post-tourism season
2020	Pre-monsoon	March	2020-03-16	Mid pre-monsoon
	Monsoon	September	2020-09-27	Late monsoon
	Post-monsoon	October	2020-10-22	Early tourism season
2021	Pre-monsoon	March	2021-03-06	Pre-monsoon sampling
	Monsoon	September	2021-09-12	Late monsoon
	Post-monsoon	November	2021-11-11	Tourism peak

2022	Pre-monsoon	March	2022-03-06	Early pre-monsoon
	Monsoon	August	2022-08-13	Mid-monsoon
	Post-monsoon	November	2022-11-01	Peak tourism
2023	Pre-monsoon	March	2023-03-11	Dry season
	Monsoon	September	2023-09-27	Late monsoon
	Post-monsoon	November	2023-11-16	Tourism peak
2024	Pre-monsoon	March	2024-03-05	Early pre-monsoon
	Monsoon	September	2024-09-11	Mid-monsoon
	Post-monsoon	November	2024-11-05	High tourism

b) Tourism Status

Tourism records for Pokhara (2017–2024) were collected from the Nepal Tourism Statistics published by the Department of Tourism. Since approximately 60% of Nepal's tourists visit Pokhara, these data serve as a proxy for estimating seasonal anthropogenic pressure on Phewa Lake. A linear regression model was applied to predict tourist arrivals for 2024 based on prior trends, accounting for seasonal variations and the post-pandemic recovery period as shown in Table 2. The results revealed strong seasonality, with peaks during October–November and distinct declines in 2020–2021 due to COVID-19 restrictions.

Table 2: Tourism Trend in Pokhara (2017-2024)

Year	March	April	May	July	August	September	October	November	Total (9 months)
2017	63,775	53,155	37,664	25,344	44,267	41,180	67,495	59,882	392,762
2018	74,812	59,190	41,295	43,969	52,607	55,124	78,447	88,715	494,159
2019	76,411	65,639	46,997	42,550	56,849	55,562	80,458	78,181	502,647
2020	25,666	8	19	118	160	350	1,215	1,174	28,710
2021	9,152	13,639	919	1,856	3,656	5,944	14,003	15,681	64,850
2022	25,291	36,953	32,456	26,677	24,782	34,988	53,149	43,592	277,888
2023	59,656	59,264	46,622	34,636	40,292	54,607	70,384	65,178	430,639
2024	44,287	38,080	27,249	23,171	29,450	32,776	48,307	46,620	289,940

c) Precipitation Pattern

Historical monthly rainfall data (2017–2024) for Pokhara were retrieved from the ERA5 reanalysis dataset via the Copernicus Climate Data Store (CDS) as shown in Table 3. Rainfall influences nutrient loading and dilution dynamics in the lake. During monsoon months, heavy precipitation contributes to nutrient inflow and surface runoff, while in dry seasons, reduced rainfall exacerbates pollutant concentrations. The dataset facilitated the correlation of rainfall variability with NDCI and NDWI fluctuations to evaluate the hydrological impact on eutrophication.

Table 3: Precipitation Data of Pokhara (mm/hr)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	15	20	35	60	120	300	600	550	400	150	50	20
2018	10	25	40	70	130	320	610	560	410	160	55	25
2019	12	22	38	65	125	310	605	555	405	155	52	22
2020	14	24	36	68	128	315	608	558	408	158	54	23
2021	13	23	37	66	126	312	606	556	406	156	53	21
2022	11	21	39	69	129	318	609	559	409	159	56	24
2023	16	26	41	72	132	325	612	561	412	161	57	26
2024	17	27	42	73	133	327	613	562	413	162	58	27

Integration of Sentinel-2, tourism, and rainfall datasets enabled both spatial and temporal analyses. Spatial mapping identified nutrient hotspots and their proximity to pollution sources, while temporal trends revealed seasonal variations and long-term eutrophication progression. This integrated framework provides a foundation for sustainable management strategies and policy development.

2.3 Data Analysis Techniques

The principle of remote sensing for water quality assessment relies on analyzing spectral reflectance patterns corresponding to optically active parameters such as chlorophyll-a and turbidity [7]. Sentinel-2's 13-band Multi Spectral Instrument (MSI) provides data across visible, near-infrared (NIR), and shortwave infrared (SWIR) ranges with resolutions of 10 m, 20 m, and 60 m, suitable for aquatic analysis. Key spectral bands used include:

- Band 3 (Green, 10 m)
- Band 4 (Red, 10 m)
- Band 5 (Red Edge, 20 m)
- Band 8 (NIR, 10 m)

Optically active parameters influence light scattering and absorption in the water column [8], [9]. While parameters like pH and dissolved oxygen lack strong optical signatures, they can be inferred indirectly by correlating them with optically active indicators [10], [11]. The study adopts a systematic approach combining remote sensing, GIS, and statistical analysis to evaluate these interactions. Software tools including ArcGIS, Google Earth, and Microsoft Excel were used for image processing, mapping, and quantitative data analysis.

Data analysis involved multi-source integration to quantify and interpret spatial-temporal trends in water quality and eutrophication. Two indices were applied for quantitative analysis of water quality:

a) Normalized Difference Chlorophyll Index (NDCI): The NDCI uses the red and red-edge spectral bands to detect chlorophyll-a concentration in water. It is specifically designed to assess the presence and abundance of chlorophyll in aquatic environments. This makes it particularly suitable for analyzing eutrophication patterns and water quality. The NDCI is calculated using the following formula which is given by [12].

$$NDCI = \frac{(B5 - B4)}{(B5 + B4)} \tag{1}$$

Values greater than 0.4 signify eutrophic conditions with high chlorophyll-a concentration.

b) Normalized Difference Water Index (NDWI): NDWI is used to monitor changes in water content and assess turbidity. It is particularly effective in identifying water bodies and their characteristics. According to McFeeters [13] this index is calculated using the formula,

$$NDWI = \frac{(B3 - B8)}{(B3 + B8)} \tag{2}$$

Higher NDWI values indicate clearer water with better reflectance, while lower values suggest increased turbidity.

3. Results and Discussion

3.1 Overview

This section presents the analytical outcomes derived from Sentinel-2 satellite imagery and ancillary data to examine eutrophication patterns in Phewa Lake from 2017 to 2024. The discussion interprets these findings in light of seasonal variability, anthropogenic stress, and hydrological influences. The results are based on Normalized Difference Chlorophyll Index (NDCI) and Normalized Difference Water Index (NDWI) analyses, raster computations in ArcGIS, and statistical correlations with rainfall and tourism datasets. Together, they provide a comprehensive understanding of eutrophication dynamics and their environmental implications for Phewa Lake.

3.2 Raster-Based Index Computation

Raster calculation in ArcGIS is a powerful tool for performing cell-by-cell arithmetic or logical operations on raster datasets. It is commonly used for spatial analysis tasks such as land cover classification, environmental modelling, and hydrological studies. Raster analysis in ArcGIS was applied to perform cell-by-cell operations on multispectral data and derive NDCI and NDWI rasters. The resulting maps reveal the spatial distribution of chlorophyll-a concentration and surface water characteristics during different seasons. Spatial variations across years show distinct eutrophication patterns, with higher NDCI values (in Figure 2 and Figure 3) observed in the near-shore zones and reduced NDWI (in Figure 4 and Figure 5) in dry months, signifying increased nutrient accumulation and reduced water clarity. These raster outputs provided the foundation for subsequent temporal trend and correlation analyses.

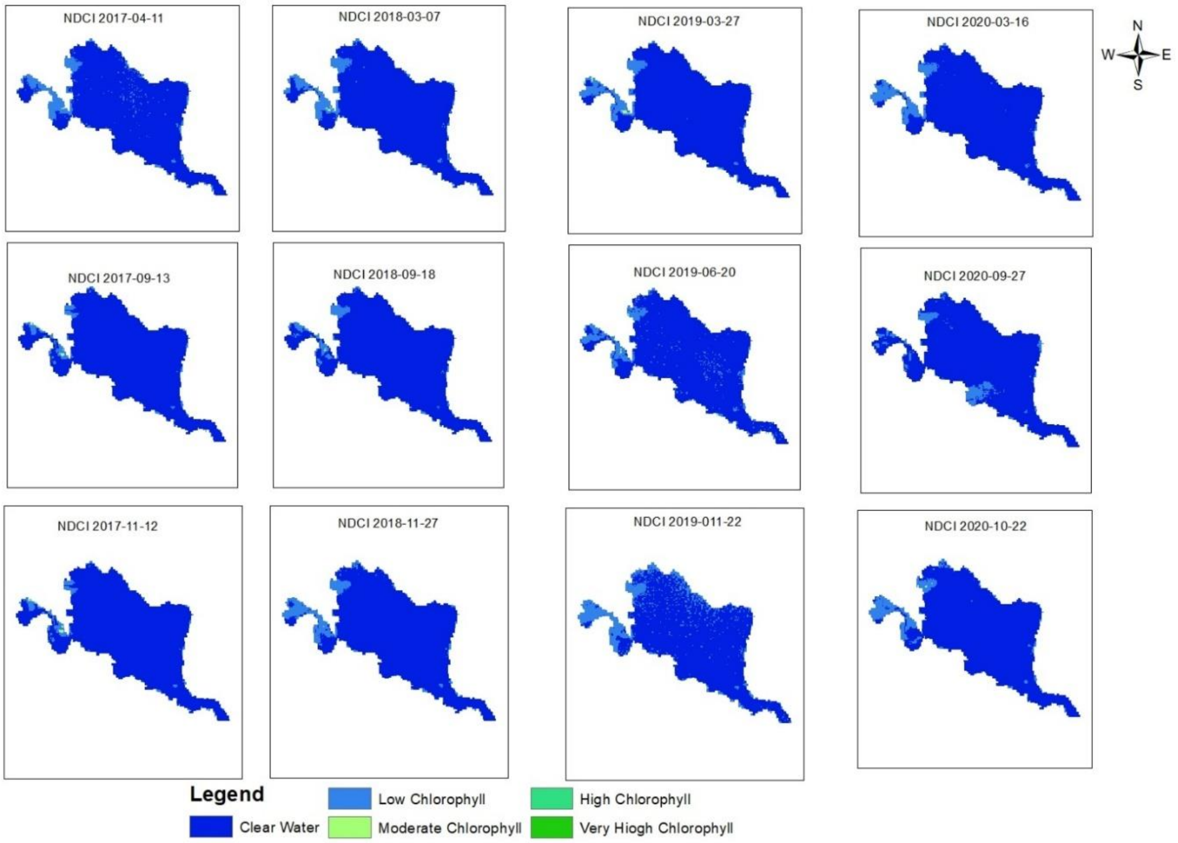

Figure 2: Raster Calculation of the study area to determine NDCI in Phewa Lake From 2017-2020

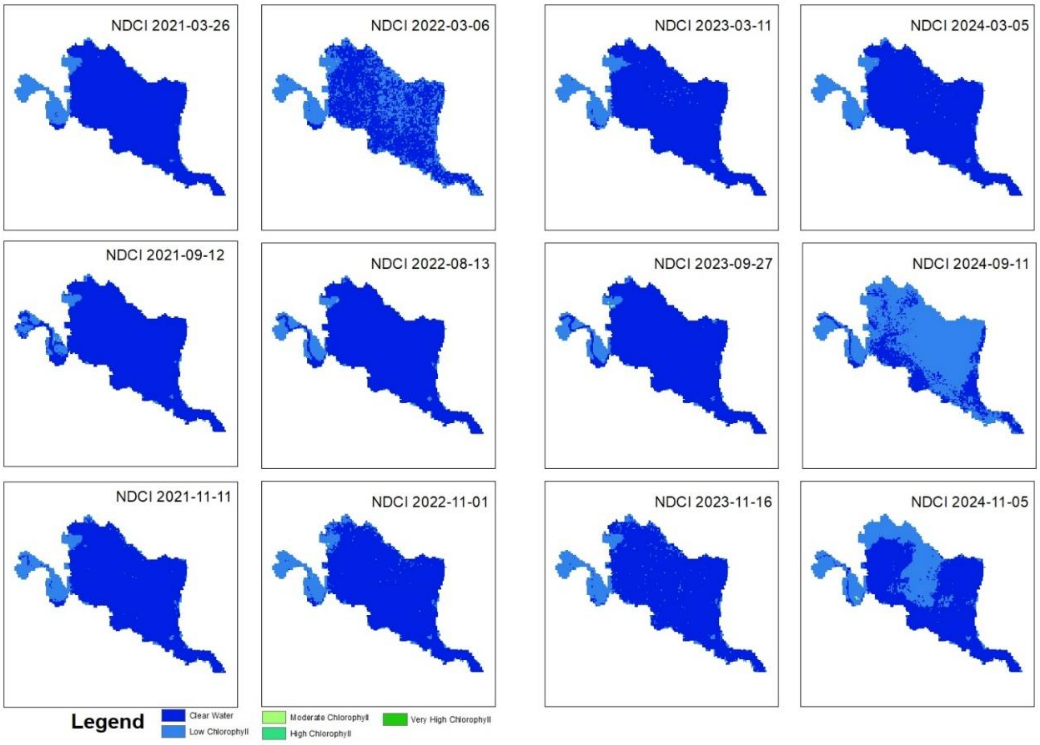

Figure 3: Raster Calculation of the study area to determine NDCI in Phewa Lake From 2021-2024

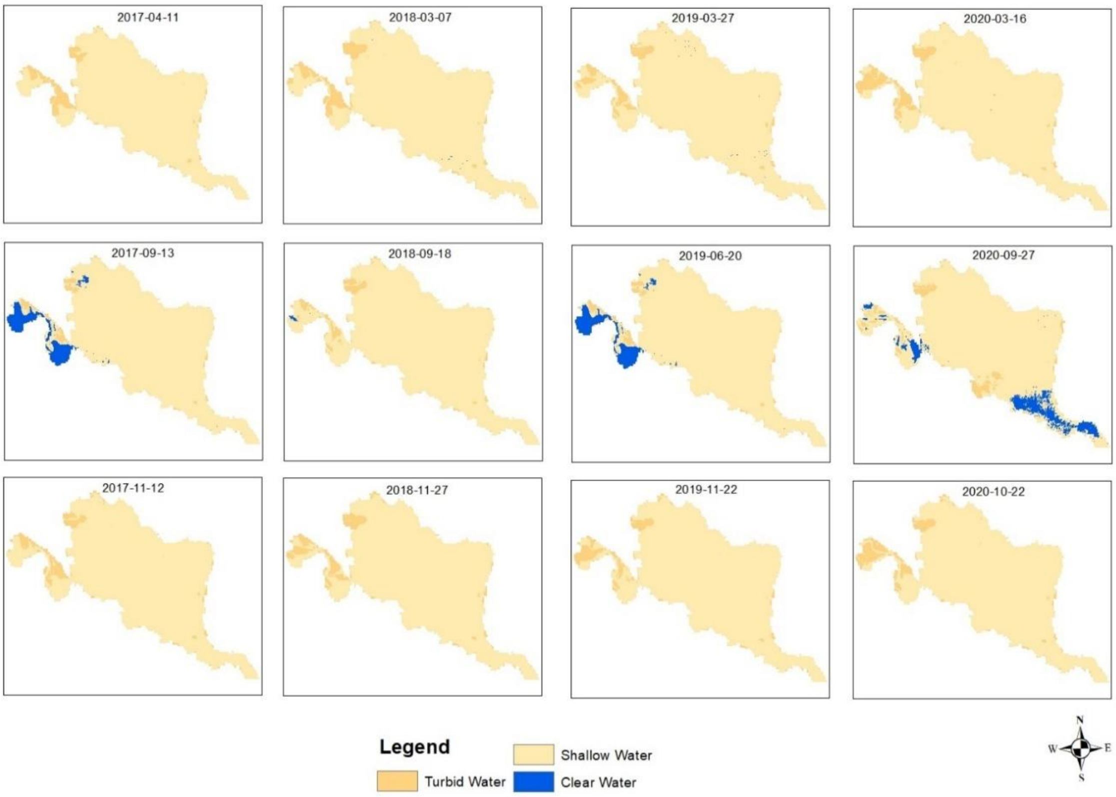

Figure 4: Raster Calculation of the study area to determine NDWI in Phewa Lake From 2017-2020

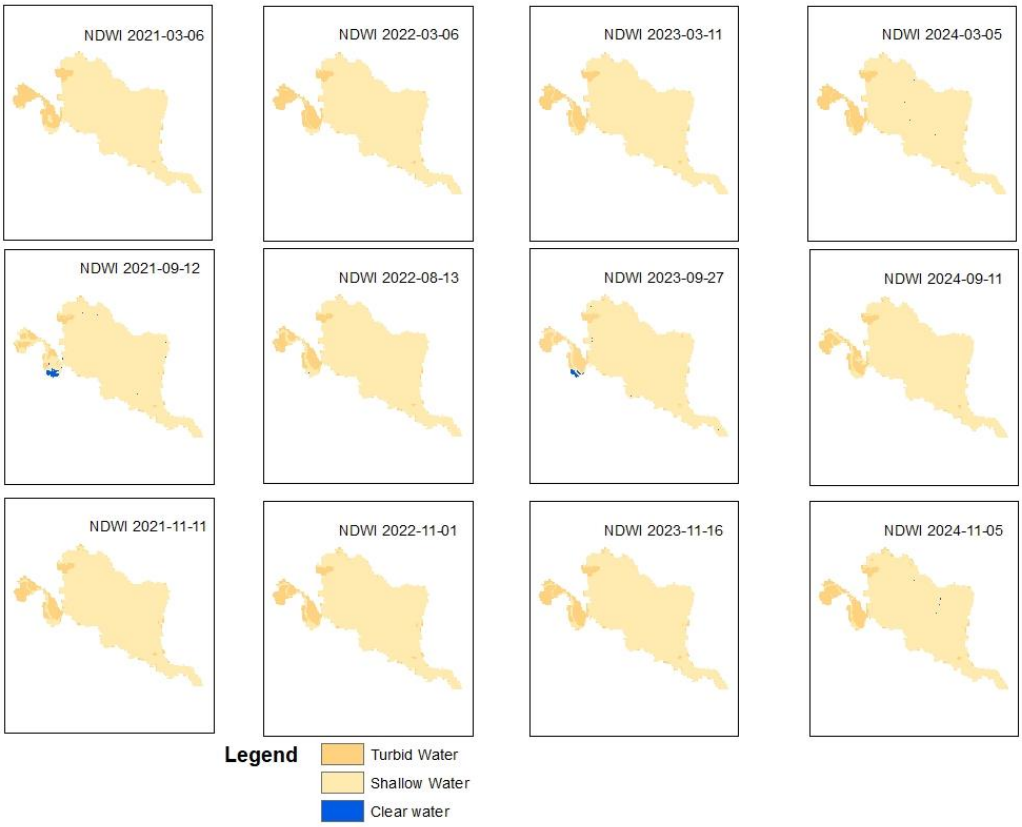

Figure 5: Raster Calculation of the study area to determine NDWI in Phewa Lake From 2021-2024

3.3 NDCI Dynamics (2017–2024)

The Normalized Difference Chlorophyll Index (NDCI) effectively captured the temporal variability in chlorophyll-a concentration, serving as an indicator of eutrophication intensity. Statistical summaries and trend graphs indicate pronounced seasonal and inter-annual fluctuations. From 2017 to 2019, NDCI values remained moderate, suggesting stable eutrophic conditions, with a notable peak in April 2019 (0.32) representing a major algal bloom, possibly linked to high tourist influx and limited dilution. In 2020, NDCI values dropped sharply across all metrics, corresponding to the COVID-19 lockdown and reduced anthropogenic load. This temporary recovery period highlights the dominant influence of human activities on nutrient dynamics. Post-2021, mean and maximum NDCI values steadily increased, demonstrating renewed eutrophic stress as tourism and urban activity resumed. By 2024, the upward trend in mean NDCI confirms a long-term intensification of eutrophication. Minimum NDCI values also exhibited greater fluctuation after 2020, indicating increased spatial heterogeneity in water quality and the weakening of the lake's self-purification capacity. These results collectively reveal that Phewa Lake's trophic condition has transitioned from moderate to increasingly eutrophic over the eight-year period, with human-driven nutrient inputs serving as the primary catalyst.

3.4 NDWI Trends and Water Clarity

The Normalized Difference Water Index (NDWI) results complement NDCI by depicting changes in water extent and turbidity. Maximum NDWI values approached 1.0 during monsoon months (e.g., September 2017, 2020, 2023), reflecting increased water inflow and improved clarity due to rainfall-induced dilution. Mean NDWI values revealed significant seasonal oscillations, with higher averages during monsoon and sharp declines in dry months such as March 2024 (0.05). The persistence of low or negative NDWI values (−0.3 to −0.55) across several dry-season observations points to recurring turbidity and sediment accumulation in shallow zones. Overall, NDWI trends indicate that Phewa Lake experiences strong hydrological seasonality: rainfall replenishes and flushes the system during monsoon, whereas prolonged dry periods allow nutrient buildup and sediment deposition. The comparison between pre-monsoon and post-monsoon NDWI patterns confirms reduced dilution capacity and increasing vulnerability to eutrophication during low-flow months.

3.5 Relationship Between NDCI, NDWI, Rainfall, and Tourism

The correlation analysis integrates biophysical indices with external variables to identify key eutrophication drivers. Figure 6 illustrates the relationships among NDCI, NDWI, rainfall, and tourist arrivals from 2017 to 2024. Rainfall exhibits a negative correlation with NDCI ($r = -0.45$) and a positive correlation with NDWI ($r = +0.81$)**,** confirming its moderating influence on nutrient concentration and water quality. During monsoon periods (> 500 mm/month rainfall), NDCI values declined while NDWI rose, reflecting improved water clarity and dilution effects. Conversely, low rainfall months corresponded with high NDCI, indicating intensified eutrophication due to limited flushing. Tourism displayed a positive correlation with NDCI ($r = +0.09$) and a negative correlation with NDWI ($r = -0.13$)**,** emphasizing anthropogenic stress as a critical factor. Peaks in tourist arrivals during pre- and post-monsoon seasons (April and October) coincided with high NDCI and reduced NDWI, evidencing nutrient enrichment from increased wastewater discharge and surface runoff from hospitality facilities. The drastic reduction in 2020 tourist activity corresponded with improved water quality, reinforcing the direct impact of human presence on eutrophication levels. A strong inverse relationship between NDCI and NDWI (r = −0.76) highlights the balance between algal biomass and water volume: as water clarity and extent increase, chlorophyll-a concentration decreases. These dynamic underscores the seasonal interplay between natural and anthropogenic drivers in shaping Phewa Lake's ecological condition.

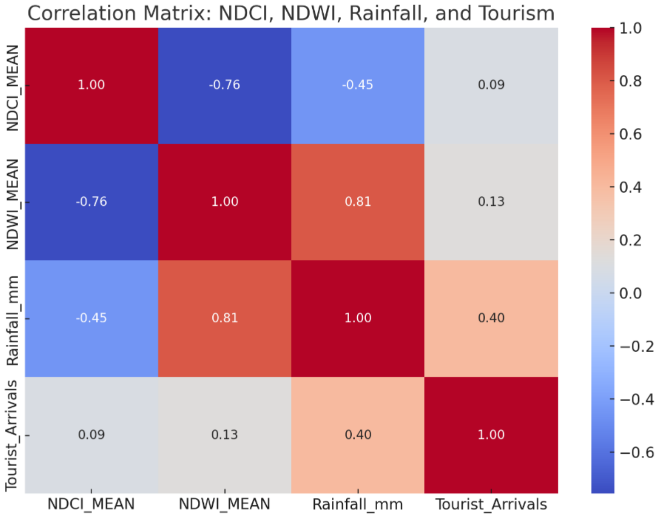

Figure 6: Correlation Matrix between NDCI, NDWI, Rainfall and Tourism

3.6 Interpretation and Implications

The combined trends reveal that Phewa Lake's eutrophication is primarily governed by human-induced nutrient loading modulated by seasonal rainfall cycles**.** High NDCI + Low NDWI combinations dominate during dry, high-tourism periods, indicating elevated eutrophic risk, whereas the reverse occurs during monsoon dilution. The study demonstrates the value of integrating remote sensing and GIS for continuous water quality monitoring and supports the hypothesis that anthropogenic inputs, rather than natural variability, are the predominant cause of eutrophication in Phewa Lake. Management implications include strengthening wastewater treatment infrastructure**,** implementing seasonal tourism regulations**,** and adopting catchment-based runoff control**.** Incorporating satellite-based monitoring into regional management frameworks can provide early-warning indicators and long-term data continuity for decision-making.

4. Conclusions

This study investigated the eutrophication dynamics of Phewa Lake, Nepal, using an eight-year time series (2017–2024) of Sentinel-2 satellite imagery. The Normalized Difference Chlorophyll Index (NDCI) and the Normalized Difference Water Index (NDWI) were employed to assess chlorophyll-a concentrations and turbidity levels, respectively. These indices were analyzed seasonally and temporally in conjunction with monthly rainfall and tourism data to understand the anthropogenic and climatic drivers of eutrophication.

- Eutrophication in Phewa Lake has increased significantly over time, particularly during pre-monsoon and post-monsoon seasons when tourist activity and nutrient input are highest.

- NDCI trends showed elevated chlorophyll-a concentrations during dry seasons, confirming the presence of algal blooms and nutrient enrichment due to anthropogenic stress.
- NDWI trends indicated improved water quality and turbidity reduction during the monsoon season, owing to rainfall-induced dilution and flushing.
- The year 2020, marked by COVID-19 lockdowns, showed the lowest NDCI values and improved NDWI, clearly demonstrating the lake's ability to recover in the absence of human interference.
- Correlation analysis revealed a negative relationship between rainfall and NDCI (i.e., more rainfall results in less eutrophication) and a positive relationship between rainfall and NDWI (i.e., improved water clarity with more rainfall).
- Tourism showed a moderate impact on NDCI during dry months, when limited rainfall reduces the lake's self-purification capacity, amplifying the effects of wastewater inflow.
- Remote sensing (Sentinel-2 data and GIS analysis) proved to be an effective, scalable, and non-invasive tool for long-term monitoring of lake water quality and eutrophication dynamics as well as an early waning tool for identifying periods of elevated eutrophication risk.
- The findings emphasize the need for improved wastewater management, regulated tourism practices, and catchment-level planning to mitigate nutrient loading and ensure the long-term ecological sustainability of Phewa Lake.

Conflicts of Interest Statement

The Authors declare that they have no financial interests or personal relationships that could have influenced the research presented in this paper.

Data Availability Statement

The data supporting the findings of this study are presented in the manuscript. Additional data will be provided upon request.

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