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Temporal And Seasonal Assessment of Turbidity and Chlorophyll-A In River Ganga Using Sentinel-2 Satellite Imagery and Google Earth Engine

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Abstract – The River Ganga, one of India's most significant rivers, plays a major role in domestic, agricultural, industrial, ecological, and religious activities in Northern India. However, over the past few decades, its water quality has significantly declined due to increasing urbanization, industrial discharge, untreated sewage, and agricultural runoff. This study performs a temporal and seasonal assessment of turbidity and chlorophyll-a between 2019 and 2024 using Sentinel-2 satellite imagery and Google Earth Engine (GEE). The research covers the entire stretch of the Ganga from Uttarakhand to West Bengal and analyzes four seasons (pre-monsoon, monsoon, post-monsoon, and winter). Sentinel-2 imagery was processed using cloud-based geospatial analysis techniques. Results show that turbidity increases during the monsoon due to sediment transport, while chlorophyll-a is found to be higher in urban areas like Kanpur and Varanasi due to nutrient enrichment. This study proves that remote sensing techniques are an effective and cost-effective tool for large-scale river management.

Keywords – River Ganga, Turbidity, Chlorophyll-a, Sentinel-2 Imagery, Google Earth Engine, Seasonal Variation, Water Quality Assessment, Remote Sensing, Satellite Monitoring, Environmental Analysis.

I. INTRODUCTION

Water quality monitoring has become an essential and important part of environmental management and sustainable water resource planning today. Rivers are not only freshwater resources that support ecosystems but are also the foundation of agriculture, industries, fisheries, transportation, and human civilization.

In a developing country like India, rapid industrialization and urbanization have created a serious and widespread problem of water pollution, which poses a major threat to future generations. The Ganga, considered India's holiest river and the center of faith for millions, is losing its ecological health today due to sewage disposal, industrial discharge, agricultural runoff, and religious waste dumping. The deterioration of ecological health not only affects aquatic biodiversity but also has serious adverse effects on human health.

Monitoring river water through conventional methods is quite expensive, time-consuming, and spatially limited, as it requires frequent field sampling and lab testing, which is difficult for large geographical areas. In recent years, remote sensing technology has emerged as a better and more effective alternative that facilitates large-scale water quality monitoring. Satellite imagery provides continuous spatial coverage and allows for the temporal analysis of long-term environmental changes. The Sentinel-2 satellite mission, developed by the European Space Agency (ESA), is highly useful and accurate for inland water quality analysis due to its high-resolution multispectral imagery. Its visible and near-infrared bands specifically help in tracking turbidity, suspended sediments, and chlorophyll-a concentrations.

Google Earth Engine (GEE) is a cloud-based geospatial analysis platform capable of processing large satellite datasets very efficiently. When we combine Sentinel-2 and Google Earth Engine, it gives us the ability to monitor river water quality at low cost and very rapidly. The objective of this study is to understand the changes in turbidity and chlorophyll-a in the Ganga River during 2019 to 2024. This study not only identifies polluted stretches but also deeply analyzes the impact of seasonal variability.

Water quality monitoring has become one of the most important aspects of environmental management and sustainable river basin planning in modern times. Rivers are not only sources of freshwater, but they also support agriculture, industries, fisheries, transportation, biodiversity, and human civilization. In India, the rapid increase in urbanization, industrialization, population growth, and agricultural activities has resulted in severe degradation of river water quality. Among all Indian rivers, the River Ganga holds immense ecological, cultural, religious, and economic importance. Millions of people depend on the river directly or indirectly for drinking water, irrigation, domestic use, and livelihood. However, increasing untreated sewage discharge, industrial effluents, religious waste dumping, and agricultural runoff have significantly deteriorated the river's ecological health over the past few decades.

Conventional methods of water quality monitoring mainly rely on field sampling and laboratory analysis. Although these methods provide accurate results at specific locations, they are expensive, time-consuming, and spatially limited. Monitoring a large river system like the Ganga through manual sampling alone becomes very difficult because of its long geographical stretch and seasonal variability. To overcome these limitations, remote sensing and geospatial technologies have emerged as highly effective tools for large-scale environmental monitoring. Satellite imagery provides continuous spatial coverage and allows researchers to analyze temporal variations over long periods of time.

In this study, Sentinel-2 multispectral satellite imagery and Google Earth Engine (GEE) were used to assess temporal and seasonal variations in turbidity and chlorophyll-a concentrations in the Ganga River from 2019 to 2024.

Sentinel-2 imagery offers high spatial and spectral resolution, making it suitable for inland water quality monitoring. Google Earth Engine provides a cloud-based platform capable of processing large satellite datasets efficiently and rapidly. The main objective of this study is to identify seasonal trends, pollution hotspots, and long-term changes in water quality parameters across the entire stretch of the Ganga River from Uttarakhand to West Bengal. The study also demonstrates the effectiveness of remote sensing techniques as a cost-effective and scalable solution for river health assessment and environmental management

II. STUDY AREA

The River Ganga originates from Gaumukh near the Gangotri Glacier in Uttarakhand and flows through several states of India, covering a distance of approximately 2525 km before finally falling into the Bay of Bengal. It is India's largest and most important river system, supporting nearly 40% of the country's population economically and culturally. Several large and prominent cities are located in this basin, such as Haridwar, Kanpur, Prayagraj, Varanasi, Patna, and Kolkata.

In the upstream Himalayan region, such as Rishikesh and Haridwar, the slope is steep and the water level remains fairly clean and pollution-free due to minimal human activities. Conversely, as the river reaches the middle and downstream stretches, the impact of urbanization and industrialization becomes clearly visible. In industrial hubs like Kanpur and Varanasi, the direct discharge of domestic sewage and industrial effluent severely affects the river's water quality. The climatic conditions of the basin are also quite diverse, ranging from the mountainous climate of Uttarakhand to the humid subtropical climate of Eastern India. Monsoon rainfall is a major driver in this entire system as it controls river flow, sediment transport, and the dilution of pollutants. Additionally, large tributaries like the Yamuna, Gomti, Ghaghara, and Gandak also bring large volumes of water and pollutants, which impact the overall health of the Ganga.

Study Area

The River Ganga originates from the Gangotri Glacier near Gaumukh in Uttarakhand and flows for approximately 2525 km before finally discharging into the Bay of Bengal. It is one of the largest river systems in India and supports nearly 40% of the country's population directly or indirectly. The river basin includes several important cities such as Haridwar, Kanpur, Prayagraj, Varanasi, Patna, and Kolkata. These cities contribute significantly to the economic and social development of the region but also act as major sources of pollution entering the river.

The upstream Himalayan region, particularly areas such as Rishikesh and Haridwar, generally experiences cleaner water conditions because of steep slopes, high flow velocity, and relatively lower anthropogenic activities. In contrast, the middle and downstream sections of the river face severe pollution stress due to increasing urbanization, industrial discharge, domestic sewage inflow, and agricultural runoff. Industrial hubs such as Kanpur and Varanasi contribute large amounts of untreated wastewater and effluents, which negatively impact the river's ecological balance.

The climatic conditions across the Ganga basin vary significantly, ranging from mountainous conditions in Uttarakhand to humid subtropical climates in eastern India. Seasonal rainfall during the monsoon plays a major role in controlling river discharge, sediment transport, dilution capacity, and pollutant concentration. Tributaries such as the Yamuna, Gomti, Ghaghara, and Gandak also influence the overall water quality of the river by contributing additional water, sediments, and pollutants. Due to these diverse environmental and anthropogenic conditions, the Ganga River basin provides an ideal case study for understanding temporal and seasonal variations in water quality parameters such as turbidity and chlorophyll-a.

III. SENTINEL-2 DATA AND GOOGLE EARTH ENGINE

Sentinel-2 is a multispectral Earth observation mission launched by the European Space Agency under the Copernicus Programme. This mission includes two satellites (Sentinel-2A and Sentinel-2B) that capture high-resolution images of every part of the Earth every 5 days. This imagery consists of 13 spectral bands with spatial resolutions of 10m, 20m, and 60m. This high spatial resolution and spectral sensitivity make it an excellent tool for inland waters and river health monitoring. This study used Sentinel-2 Level-2A surface reflectance data, which is obtained after atmospheric correction Google Earth Engine (GEE) has made this research easy and fast because it is a cloud-based platform. The biggest advantage of GEE is that we do not need high-end local computers; we can process large datasets directly on Google's servers. Cloud masking techniques were used to remove the influence of clouds to obtain accurate results. Seasonal median composites were prepared to get a clear picture of each season (winter, monsoon, etc.). With the help of GEE, we analyzed data from the last five years (2019-2024), which would have been nearly impossible using manual methods. This technology significantly reduced computational time and provided us with a comprehensive visual and analytical perspective of the entire stretch.

Sentinel-2 Data and Google Earth Engine

This study utilized Sentinel-2 Level-2A surface reflectance imagery provided by the European Space Agency under the Copernicus Programme. Sentinel-2 consists of two satellites, Sentinel-2A and Sentinel-2B, which together provide high-resolution multispectral imagery every five days. The imagery contains 13 spectral bands with spatial resolutions of 10 m, 20 m, and 60 m, making it highly effective for monitoring inland water bodies and river systems. The visible and near-infrared spectral bands are particularly useful for estimating turbidity, suspended sediments, and chlorophyll-a concentration in water bodies.

Google Earth Engine (GEE) was used as the primary platform for image processing and analysis. GEE is a cloud-based geospatial processing system that enables rapid analysis of large satellite datasets without requiring high-performance local computing systems. In this study, cloud masking techniques were applied to remove cloud-contaminated pixels and improve the accuracy of analysis.

Seasonal median composites were generated for winter, pre-monsoon, monsoon, and post-monsoon periods to observe temporal variability in water quality parameters. The integration of Sentinel-2 imagery and GEE significantly reduced computational complexity and processing time while allowing large-scale monitoring of the entire Ganga River stretch from 2019 to 2024. This combination provided an efficient, cost-effective, and reliable approach for identifying pollution hotspots and understanding seasonal trends in river water quality.

IV. RESULTS AND DISCUSSION

The results of spatial distribution show that turbidity levels always remain low in the upstream Himalayan regions (Rishikesh/Haridwar), reflecting the clean environment and low human intervention there. However, as we move downstream, especially after Kanpur, turbidity levels increase rapidly. The primary reason for this is industrial waste and urban drainage, which increase the number of solids in the water. During the monsoon, soil erosion increases due to rain and runoff, causing turbidity to reach its peak level across the entire river.

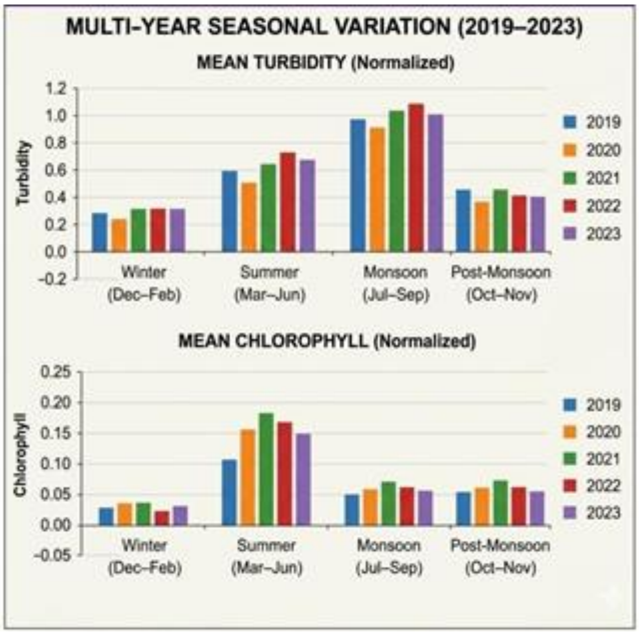

Fig.1 Multi-year seasonal Variations from 2019-2023

The first graph, "Multi-Year Seasonal Variations from 2019–2023," represents the spatial and temporal distribution of turbidity and chlorophyll-a levels in different stretches of the Ganga River over multiple years. The graph clearly indicates that turbidity levels remain comparatively low in the upstream Himalayan regions such as Rishikesh and Haridwar. This is mainly due to cleaner environmental conditions, lower population density, limited industrial activities, and faster river flow velocity in mountainous areas. The reduced human intervention in these regions helps maintain better water quality and lower suspended sediment concentrations.

As the river moves downstream towards densely populated urban and industrial regions such as Kanpur, Prayagraj, Varanasi, Patna, and Kolkata, turbidity levels increase significantly. The graph highlights that middle and downstream stretches experience higher sediment concentration and suspended solids due to untreated sewage discharge, industrial waste, urban runoff, and agricultural activities. These anthropogenic activities continuously deteriorate water quality and increase river pollution levels.

The graph also demonstrates strong seasonal variation in turbidity. During the monsoon season, turbidity reaches its maximum level throughout the river stretch. Heavy rainfall during the monsoon increases surface runoff, soil erosion, and sediment transport into the river channel. Large amounts of suspended particles enter the river from agricultural lands, urban drainage systems, and tributaries, causing a sharp rise in turbidity values. In contrast, turbidity decreases during winter and pre-monsoon seasons because river flow becomes relatively stable and sediment inflow reduces considerably.

The chlorophyll-a trends shown in the graph indicate increased algal growth in polluted urban stretches. Chlorophyll-a concentration is comparatively lower in upstream areas but increases significantly near industrial and urban centers. The primary reason behind this rise is nutrient enrichment caused by excessive nitrogen and phosphorus entering the river through domestic sewage and industrial discharge. Such nutrient-rich conditions promote eutrophication and algal bloom formation. Seasonal analysis further reveals that post-monsoon and winter periods are highly favorable for chlorophyll-a growth because reduced river flow and sufficient sunlight create stable environmental conditions for algae development.

Overall, the graph clearly illustrates the relationship between seasonal hydrological conditions, anthropogenic pollution, and water quality degradation in the Ganga River. It effectively identifies pollution hotspots and highlights the severe impact of urbanization and industrialization on river health.

Significant changes were also observed in chlorophyll-a concentration. In urban stretches where sewage discharge is high, algal growth increases due to an excess of nutrients (Nitrogen and Phosphorus), which can be seen as high levels of chlorophyll-a. Conditions of eutrophication are often found in Kanpur, Varanasi, and Kolkata. Seasonal analysis revealed that post-monsoon and winter seasons are most favorable for chlorophyll-a growth because the water flow is slightly lower and there is sufficient sunlight.

These results clearly indicate that anthropogenic activities, such as untreated sewage discharge and industrial discharge, are severely degrading the water quality of the Ganga in middle and downstream regions. Remote sensing data has helped in accurately identifying these pollution hotspots, which might not have been achieved with such clarity through ground-level sampling.

The average values derived from satellite data (2019–2024) are given in the table below. These values show how turbidity increases during the monsoon season and chlorophyll-a increases during the post-monsoon season.
The results obtained from Sentinel-2 imagery and Google Earth Engine analysis clearly indicate strong spatial and seasonal variations in the water quality of the River Ganga. The upstream Himalayan regions maintain relatively better water quality because of lower population density and limited industrial activity. However, the middle and downstream stretches show severe deterioration due to increasing anthropogenic pressure.

Table 1. Seasonal Variation in Turbidity and Chlorophyll-a Levels in the Ganga River (2019–2024 Satellite Data)

Season	Avg Turbidity (NTU)	Chlorophyll-a (mg/m³)	Dominant Factors
Pre-Monsoon	12.5 - 25.0	4.2 - 7.5	Pollution/Low Flow
Monsoon	45.0 - 85.0	2.1 - 4.0	Sediment/Runoff
Post-Monsoon	15.0 - 30.0	6.5 - 12.0	Nutrient Loading
Winter	8.0 - 18.0	5.8 - 10.5	Algal Growth

According to Table 1, turbidity reaches its peak during the monsoon season (45–85 NTU) because soil and sediments are carried into the river along with rainwater. In contrast, chlorophyll-a (6.5–12.0 mg/m³) is higher during the post-monsoon and winter seasons because stagnant water and nutrients promote algal growth.

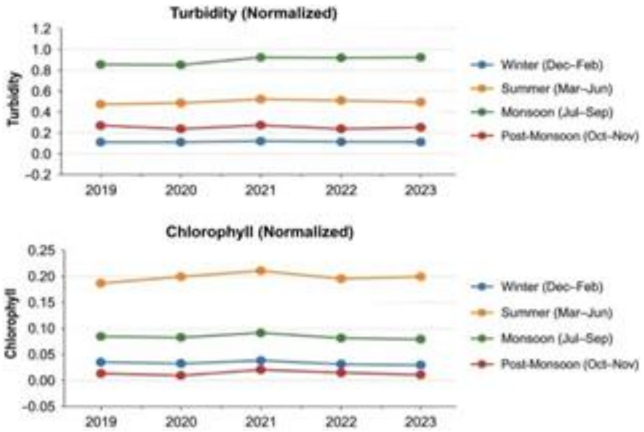

Fig.2 Seasonal Trends from 2019-2023

The second graph, "Seasonal Trends from 2019–2023," provides a comparative understanding of seasonal fluctuations in turbidity and chlorophyll-a concentration over the study period. The graph reveals distinct seasonal behavior for both parameters, which is primarily controlled by climatic conditions, rainfall intensity, river discharge, and human activities within the basin.

The graph indicates that turbidity values are highest during the monsoon season. During this period, intense rainfall causes heavy surface runoff and soil erosion, transporting large amounts of sediments and suspended particles into the river. Tributaries and urban drainage channels further contribute sediment loads, resulting in extremely high turbidity conditions. In some polluted stretches, turbidity values range between 45–85 NTU during monsoon months. This high turbidity reduces light penetration into water, affecting aquatic ecosystems and reducing photosynthetic activity.

In contrast, turbidity levels decline considerably during post-monsoon and winter seasons due to reduced rainfall and lower sediment inflow. River flow stabilizes during these seasons, allowing suspended particles to settle gradually. Cleaner upstream stretches continue to exhibit lower turbidity throughout the year compared to urban downstream sections.

The graph also demonstrates that chlorophyll-a concentration shows an opposite seasonal trend compared to turbidity. Chlorophyll-a levels are comparatively lower during the monsoon season because strong river flow and turbulent conditions reduce algal stability and growth. However, during post-monsoon and winter seasons, chlorophyll-a concentration increases significantly, especially in polluted urban regions. Reduced water velocity, stable hydrological conditions, and increased nutrient availability create favorable conditions for algal blooms. In many downstream stretches, chlorophyll-a concentration ranges between 6.5–12.0 mg/m^3 during these seasons.

The graph strongly reflects the influence of seasonal environmental conditions on river water quality. It highlights how monsoon-driven sediment transport controls turbidity, while nutrient accumulation and stable water conditions regulate chlorophyll-a concentration. These observations emphasize the need for season-specific management strategies for pollution control and river restoration in the Ganga basin.

The study identified major pollution hotspots near urban and industrial cities such as Kanpur, Varanasi, and Kolkata, where turbidity and chlorophyll-a concentrations are consistently high. The high turbidity observed during monsoon seasons is mainly associated with sediment transport, runoff, and erosion processes. Meanwhile, increased chlorophyll-a concentration during post-monsoon and winter seasons indicates nutrient enrichment and eutrophication caused by sewage discharge and industrial waste. The use of remote sensing technology enabled accurate identification of pollution-prone areas and provided continuous large-scale monitoring capability. Unlike conventional field-based methods, satellite-based monitoring offers faster data acquisition, better spatial coverage, and long-term environmental assessment. The results also demonstrate that seasonal variability plays a significant role in controlling river water quality dynamics. Therefore, pollution management strategies should consider both spatial and temporal variations while implementing river conservation programs.

V. CONCLUSION

This study demonstrates the power of Sentinel-2 satellite imagery and Google Earth Engine. We have successfully analyzed the temporal and seasonal patterns of the Ganga River from 2019 to 2024. The conclusion is that monsoon is the main period for turbidity, while the winter season is responsible for chlorophyll-a and algal blooms. Upstream stretches are still in better condition, but middle and downstream stretches need immediate attention and pollution control management. Remote sensing technology has provided a cost-effective and scalable solution. Using this data, the government and environmental agencies can better implement projects like 'Namami Gange'. Future research can make these predictions even more accurate by using field-based validation and machine learning models.

This study successfully demonstrated the application of Sentinel-2 satellite imagery and Google Earth Engine for temporal and seasonal assessment of turbidity and chlorophyll-a concentration in the River Ganga between 2019 and 2024. The analysis revealed that turbidity reaches maximum levels during the monsoon season due to increased rainfall, runoff, and sediment transport, whereas chlorophyll-a concentration becomes higher during post-monsoon and winter seasons because of stable flow conditions and nutrient enrichment.

The study further highlighted that upstream regions such as Haridwar and Rishikesh still maintain comparatively cleaner environmental conditions, while middle and downstream urban stretches are severely affected by sewage discharge, industrial effluents, and anthropogenic activities. Major polluted zones identified in this research include Kanpur, Varanasi, Patna, and Kolkata.

Remote sensing and cloud-based geospatial analysis proved to be highly effective, economical, and scalable techniques for large-scale river monitoring. The integration of Sentinel-2 imagery with Google Earth Engine significantly reduced processing complexity and enabled long-term environmental analysis over a large geographical region. The findings of this research can support government agencies and river management authorities in implementing effective pollution control and river restoration programs such as Namami Gange Programme.

Future studies can improve the accuracy of water quality estimation by integrating field-based validation, machine learning algorithms, and advanced geospatial modeling techniques. Continuous monitoring and sustainable management strategies are essential for restoring the ecological health of the Ganga River and ensuring safe water resources for future generations.

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