Advancing Remote Sensing for Continuous Monitoring and Detection of Water Pollution Incidents

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Abstract: In the face of increasing industrial pollution, there is an urgent need to enhance water quality monitoring around industrial zones. This research explores the development of an advanced remote sensing system designed to continuously monitor water quality and provide early (timely) warning on changes that could signify environmental risks. With increasing incidences of water pollution due to industrial activities, there is a critical need for more dynamic and proactive monitoring approaches. This study investigates the feasibility of integrating remote sensing imagery to establish a comprehensive monitoring system that measures a spectrum of water quality indicators. At the core of the system lies near real-time data acquisition and processing capabilities, enabling the notification about significant changes in water quality. By leveraging remote sensing imagery, this system aims to provide detailed spatial and temporal analyses of water contaminants. This study could revolutionize the way water quality is monitored in sensitive and critical areas, offering a scalable solution to water management challenges and significantly enhancing environmental protection efforts. The results can contribute to the sustainable management of water resources, ensuring compliance with environmental regulations and safeguarding public health and ecosystems.

Keywords: remote sensing; water pollution; monitoring; Google Earth Engine.

1 Introduction

Rapid industrialization across the globe has been instrumental in driving economic growth and shaping modern societies. However, this development comes with a significant environmental cost, primarily due to the emission of pollutants like hazardous chemicals and microorganisms, which degrade the quality of air, soil, and crucially, water. This pollution not only threatens biodiversity but also poses serious public health risks (Adejumoke et al. 2018, Boyd 2020, Ingrao et al. 2023).

Remote sensing technology has emerged as a key tool in addressing these environmental challenges. It offers unprecedented capabilities for the continuous, detailed observation and analysis of water quality, proving essential for the effective management and preservation of water resources. Studies such as those by Karan and Samadder (2016) and Crioni et al. (2023) have demonstrated the utility of remote sensing in evaluating the impacts of industrial activities like coal mining and tailing dam failures on water quality.

Moreover, the advent of platforms like Google Earth Engine (GEE) has significantly enhanced the potential for long-term environmental monitoring. GEE allows researchers to access a vast archive of historical data, enabling them to conduct detailed longitudinal studies that provide deeper insights into trends and changes in water quality over extended periods (Khan et al. 2023).

Building on these foundational studies, this research investigates the possibility of a remote sensing system explicitly tailored for monitoring water pollution resulting from industrial incidents. The primary goal is to enhance the capability of remote sensing data to detect and monitor such events continuously, thereby ensuring more effective management of water resources in the face of ongoing industrial pollution. This approach should facilitate immediate response and help with long-term environmental planning and mitigation strategies.

2 Materials and methods

This research builds on previous work (Ruppen et al. 2023) examining the impacts of tailings spills on water quality, focusing on a case study involving the Catoca diamond mine incident in Angola. This spill significantly impacted the Tshikapa and Kasaï Rivers, extending into the Democratic Republic of the Congo, affecting both human populations and ecological systems over a course of more than 1,400 kilometers until reaching the Congo River. Using Sentinel-2 satellite imagery, the study evaluates the spatial and temporal extent of pollution in the rivers following a significant spill in July 2021.

The objective is to investigate a continuous monitoring using remote sensing data, particularly within the GEE platform that will be used to monitor critical junctures where water bodies intersect—areas particularly vulnerable to pollution. The aim is to provide early warnings for water quality deterioration and continuous monitoring, which could be pivotal for proactive environmental management and public health safety.

Consistent with previous research, this study employs high-resolution Sentinel-2 imagery processed on the GEE platform. This approach ensures accessibility to updated and historical data for comprehensive temporal analysis. Special attention is given to the critical area, the flow point of Lova river, where the spillover from the dam is discharged, into the Tshikapa river. This strategic point is often susceptible to rapid changes in water quality due to accumulated runoff from upstream sources.

Table 1. Indices used in this study.

#	Index	Formula	Reference
1	NDTI	$\frac{NIR - G}{NIR + G}$	Garg et al. (2017)
2	TI	$\frac{R}{G}$	Dasi et al. (2023)
3	NDWI	$\frac{G - NIR}{G + NIR}$	Singh et al. (2015)
4	MNDWI	$\frac{G - SWIR}{G + SWIR}$	Singh et al. (2015)
5	Ch_a	$\frac{RE - R}{RE + R}$	Dasi et al. (2023)
6	FAI	$\frac{R - (B + (NIR - B) * (R - B))}{NIR + G}$	Santecchia et al. (2023)
7	HMRI	$\frac{SWIR - SWIR\ II}{SWIR + SWIR\ II}$	Santecchia et al. (2023)
8	MPI	NDTI + TI + HMRI	Santecchia et al. (2023)

The utilization of spectral indices in remote sensing is a powerful tool for assessing environmental characteristics, particularly water quality. In the analysis of Sentinel-2 imagery within the GEE platform, several indices are computed to monitor and evaluate the status of water bodies effectively (Table 1). The Normalized Difference Turbidity Index (NDTI) and Turbidity Index (TI), detect and quantify suspended particles in water, providing insights into water clarity and potential contamination (Garg et al. 2017, Dasi et al. 2023). The NDWI and Modified NDWI (MNDWI) highlight water features by suppressing vegetation and enhancing water bodies, crucial for delineating and monitoring aquatic environments (Singh et al. 2015). can affect water quality (Dasi et al. 2023). The floating algae index (FAI) is derived to The Chlorophyll-a Index (Ch_a) helps identify the concentration of chlorophyll, a key indicator of algal blooms that assess water moisture content and floating algae concentration, providing additional details on environmental conditions that affect water quality (Xue and Su 2017). Lastly, the Heavy Metal Reflectance Index (HMRI) and a composite Metal Pollution Index (MPI), are designed to detect and monitor heavy metals and overall metal pollution within water bodies (Santecchia et al. 2023).

The outcomes of the spectral indices are then cross compared to investigate whether satellite data could be used to detect water pollution immediately following an incident. Specifically, we analyzed the Sentinel-2 data spanning a full year, from January to December 2021, focusing on capturing the environmental conditions before and after the pollution event at the Catoca diamond mine. Due to cloud cover, images exist from April to November. By comparing the calculated indices for this period with the known timing and impact of the spill, we aimed to determine the effectiveness of remote sensing as a tool for early detection of such events, and continuous monitoring afterwards. This approach allowed us to assess the responsiveness of our indices in real-time scenarios and their potential to inform timely environmental management decisions.

3 Results

In the analysis of the Catoca diamond mine incident using various spectral indices derived from Sentinel-2 imagery, distinct patterns were observed in the response of each index to the pollution event (Figure 1).

NDWI and MNDWI, indices, typically used to assess water content, did not show any significant variation around the date of the incident. This was expected, as these indices are not specifically tailored to detect the type of pollutants released during the tailings dam spill.

The NDTI, TI and MPI, showed elevated values on the date of the incident (end of July, 2021), suggesting an increase in water turbidity, which is consistent with the spill investigated in this study. Interestingly, these indices again showed high values in October, indicating another possible event or residual effects from the initial spill. Ch_a, which

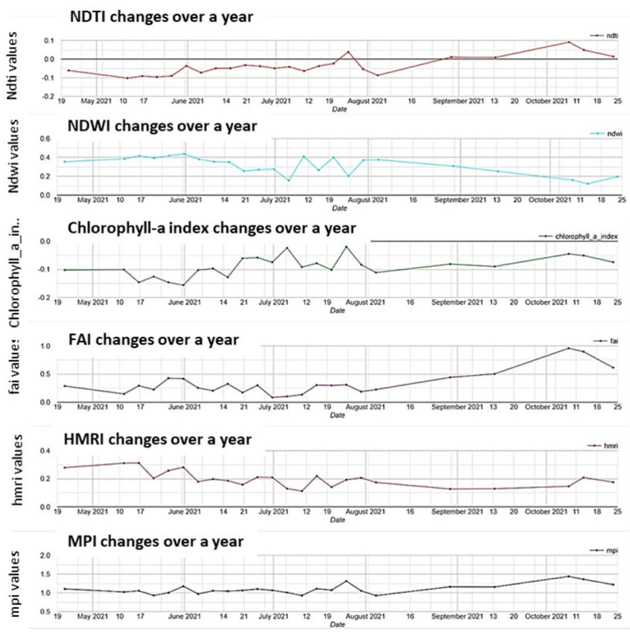

Figure 1. Results of the spectral indices.

is often used to detect algal growth that is potentially indicative of nutrient-rich pollution, registered high values on the incident date. However, similar peaks were observed on other dates, complicating the use of this index alone to pinpoint the specific pollution event.

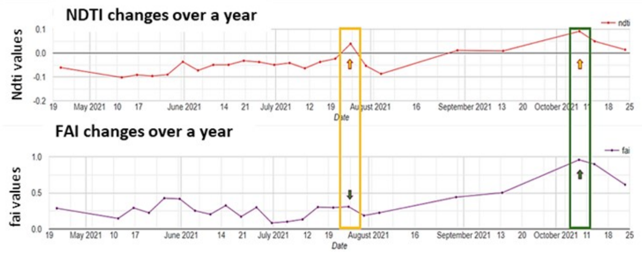

Figure 2. NDTI and FAI emphasizing the incident date and algal blooms.

The FAI did not show elevated values on the day of the incident but did register high readings post-October. This suggests that the index may be more responsive to changes in algal blooms, which could occur as a secondary effect of nutrient influx following the spill.

4 Discussion and Conclusions

The results underscore the complexities of using remote sensing data for environmental monitoring. While certain indices like NDTI and TI can be directly indicative of an incident like a tailings dam spill, others like the Ch_a or FAI may capture broader ecological shifts that require careful interpretation.

The analysis of spectral indices NDTI, TI, and MPI around the incident at the Catoca diamond mine and subsequent months, reveals important insights into the dynamics of water pollution and its detection using remote sensing data.

In October, the situation appeared to evolve. While NDTI and TI remained high, indicating continued elevated turbidity, the FAI also showed exceptionally high values. High FAI is indicative of algal blooms, which often result from nutrient-rich environments that can follow the initial deposit of pollutants such as phosphates or nitrates that fertilize the water (Figure 2).

The differentiation between the sources of turbidity based on the relationship between NDTI, TI, and FAI can be crucial for effective monitoring and remediation efforts. When turbidity indices are high, but FAI is low, this suggests that the water turbidity is likely due to inorganic or non-biological factors such as silt, clay, or heavy metals. This condition would align with incidents like tailings spills.

Conversely, when both turbidity indices and FAI are high, this points towards biological factors compounding the turbidity, particularly algal blooms. In these cases, while initial pollutants may still be present, the ecological response to the nutrient influx is now a significant factor in the water quality issues. Critical environmental data such as the indices reported in this study, can be significantly enhanced with the use of real-time, "living" sensors, such as those based on Bioelectrochemical Systems (BES). BES use live microbial communities to convert biochemical energy locked in organic matter, directly into electricity, and they have a remarkable ability to respond to environmental perturbations with high sensitivity. This renders BES devices excellent biosensors for environmental events, since these can nicely complement observed index measurements from satellites such as Sentinel-2.

This study builds on the work of Ruppen et al. (2023), enhancing their framework by incorporating advanced indices and proposing new tools for continuously monitoring and detecting water pollution incidents. For future work, it is essential to validate these findings across more diverse case studies and integrate them with living biosensor technologies, such as those based on BES, for a more robust, real-time analysis.

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