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Research Article

Temporal Trend Analysis of Water Quality Index for Sustainable Water Resource Management

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ABSTRACT

This study aimed to explore the dynamics of water quality indices (WQIs) and their relationship with various physicochemical parameters, addressing a critical gap in understanding adaptive management's role in water quality enhancement. Utilizing a comprehensive dataset of 29,159 records and 24 variables, including key numeric parameters such as alkalinity, ammonia, BOD, chloride, and dissolved oxygen, we analyzed water quality trends over several years. The study employed robust statistical methods to assess seasonal and annual variations in WQI and its correlation with physicochemical factors.

Results showed a significant upward trend in WQI scores and dissolved oxygen levels, indicating an overall improvement in water quality. The implementation of adaptive management strategies, including pollution mitigation and regulatory measures, was linked to these positive trends. Seasonal fluctuations were observed, with peak WQI improvements during late spring and autumn, correlating with increased precipitation and runoff events. Specifically, dissolved oxygen concentrations exhibited a statistically significant increase ($p < 0.05$), reinforcing the effectiveness of adaptive interventions.

Our findings suggest that adaptive management strategies, which integrate real-time data and account for climatic variability, are effective in enhancing water quality. These results indicate that targeted adaptive interventions can significantly improve aquatic health and resource resilience. Policymakers and water managers are encouraged to adopt these strategies, emphasizing continuous monitoring and adaptive responses to environmental challenges. Despite limitations such as reliance on historical data, the study provides a strong foundation for future research to build upon. The insights offered here contribute valuable guidance for the development of sustainable, adaptive water quality management practices.

1. INTRODUCTION

Water quality monitoring is a critical aspect of environmental management, conservation, and public health, as it ensures the sustainability of water resources necessary for human consumption, agriculture, industry, and ecological balance. As the global demand for clean water continues to rise, driven by population growth, urbanization, and industrialization, the challenges in maintaining water quality are becoming increasingly complex [1]. The diverse anthropogenic activities contribute to water pollution, resulting in the degradation of aquatic ecosystems and posing significant risks to human health. Consequently, effective monitoring and management strategies are essential to safeguard water resources against contamination and depletion.[1]

Within the realm of water resources engineering, the Water Quality Index (WQI) serves as a pivotal tool for assessing and communicating the overall quality of water bodies. WQIs integrate multiple water quality parameters into a single composite score, providing a simplified representation of water quality status that can be easily interpreted by policymakers, stakeholders, and the general public[2]. Various WQI models, such as the Canadian Council of Ministers of the Environment WQI (CCME WQI), Weighted Arithmetic Water Quality Index (WAWQI), Horton WQI, Brown WQI, and the Simplified Relative Distance Difference WQI (SRDD WQI), have been developed to address different perspectives and requirements in water quality assessment. These indices are instrumental in identifying trends, setting regulatory standards, and guiding decision-making processes in water resource management.

Despite the established utility of WQIs, there remains a research gap in the integration of temporal analysis and statistical trend evaluation within long-term water quality monitoring frameworks. Traditional approaches often focus on

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instantaneous assessments, overlooking the dynamic nature of water quality changes over time and the influence of seasonality, climatic variations, and human activities. This gap highlights the need for comprehensive methodologies that incorporate temporal data analysis to enhance the predictive accuracy and reliability of WQIs. By leveraging long-term datasets, such as the one utilized in this study with 29,159 records and 24 variables, researchers can uncover underlying patterns and trends that may inform more effective water management strategies.[3][4]

The primary objective of this study is to address the aforementioned research gap by developing an integrated approach that combines temporal and statistical trend analysis with traditional WQI methodologies. Specifically, the study aims to evaluate the efficacy of various WQI models in capturing long-term water quality trends using a robust dataset comprising both numeric and categorical variables. Key numeric variables include Alkalinity-total (as CaCO3), Ammonia-Total (as N), BOD - 5 days (Total), Chloride, Conductivity @25°C, Dissolved Oxygen, ortho-Phosphate (as P), pH, Temperature, and Total Hardness (as CaCO3). The categorical variables, such as Years, Sample Date, and different WQI models, will facilitate a comprehensive temporal analysis.[5]

The significance of this study lies in its potential contributions to advancing water quality monitoring practices by incorporating long-term trend analysis into existing WQI frameworks. This approach not only enhances the understanding of water quality dynamics but also provides valuable insights for policymakers and resource managers in developing more sustainable and adaptive water management strategies. By addressing the limitations of current methods, the study seeks to improve the accuracy and applicability of WQIs in diverse environmental contexts. [6]

This paper is structured as follows. The subsequent section reviews existing literature on WQIs and their application in water quality monitoring. Next, the methodology section details the data collection, processing, and analysis techniques employed in this study. The results section presents the findings of the integrated WQI analysis, followed by a discussion of their implications for water resources management. Finally, the conclusion summarizes the key contributions and suggests directions for future research.

2. LITERATURE REVIEW

In this literature review, we explore the development and application of Water Quality Indices (WQIs) in the context of long-term water quality monitoring. The review synthesizes existing research on various WQI models, emphasizing their methodologies, advantages, and limitations. Given the critical role of physicochemical parameters in WQI calculations, this section also considers the factors influencing water quality across different temporal scales, including seasonal and climatic variations. By examining the integration of temporal analysis within WQI frameworks, this review sets the foundation for understanding how these indices can be effectively utilized in water resource management.[6,7]

Table 1 presents the descriptive statistics of key physicochemical parameters critical to the calculation and interpretation of Water Quality Indices (WQIs). This table provides valuable insights into the variability and trends of parameters such as Dissolved Oxygen, Biochemical Oxygen Demand over five days (BOD_5), pH, Temperature, and Conductivity at 25°C, which are instrumental in assessing water quality.[8]

The data in Table 1 highlight several noteworthy patterns. Dissolved Oxygen (DO) levels are shown to fluctuate between 148 mg/L and 198 mg/L, a range that indicates varying degrees of oxygen availability in the water body. High DO levels, such as the maximum value of 198 mg/L, are generally indicative of a healthy aquatic environment, supporting diverse aquatic life and efficient self-purification processes. Conversely, lower DO values, such as 148 mg/L, may suggest potential stress on aquatic organisms, possibly due to increased organic matter decomposition or reduced aeration.[9]

The Biochemical Oxygen Demand (BOD_5) values in Table 1 range from 1.1 mg/L to 8.3 mg/L. BOD_5 is a critical parameter reflecting the amount of biodegradable organic material present in the water. Lower BOD_5 values, such as 1.1 mg/L, suggest minimal organic pollution, whereas higher values, up to 8.3 mg/L, indicate significant organic matter and potential pollution sources, possibly from wastewater discharge or agricultural runoff. This variability underlines the importance of continual monitoring and management of organic pollutants to maintain water quality.[10]

The pH values recorded in Table 1 range from 7.3 to 8.3, which indicates a slightly neutral to alkaline water environment. The pH level is a crucial factor affecting chemical solubility and biological availability of nutrients and heavy metals. The observed pH range is generally conducive to aquatic life; however, the upper range approaching 8.3 may affect the solubility and toxicity of certain compounds, necessitating careful monitoring, especially in areas susceptible to alkaline runoff.[11]

Temperature values span from 10.6°C to 20.6°C, reflecting both seasonal and diurnal variations. Water temperature affects several physicochemical and biological processes, including metabolic rates of aquatic organisms and the solubility of gases. The lower temperature of 10.6°C may correspond to cooler seasons or higher altitudes, while higher temperatures, such as 20.6°C, could indicate warmer seasons or regions. These variations can influence water quality, necessitating adaptive management strategies to mitigate potential negative impacts on aquatic ecosystems.[12]

Conductivity at 25°C, as reported in Table 1, ranges from 356 µS/cm to 650 µS/cm. Conductivity is an indirect measure of the concentration of dissolved ions in water, which can originate from natural sources or anthropogenic activities. The observed range suggests variability in ionic content, with higher values potentially indicating increased mineralization or pollution from agricultural or industrial sources. Monitoring conductivity provides essential information on the presence of dissolved salts and potential pollution sources, aiding in the protection and management of water resources.[13]

The integration of these physicochemical parameters within WQI models underscores the necessity of a comprehensive approach to water quality assessment. The variability observed in Table 1 suggests that water bodies are subject to diverse influences that can alter their physicochemical characteristics over time. Seasonal changes, climatic conditions, and anthropogenic activities contribute to these variations, emphasizing the need for a dynamic and adaptive framework in WQI application. By incorporating temporal analysis and understanding the interactions between these parameters, stakeholders can better predict and mitigate adverse effects on water quality.[14]

In conclusion, Table I provides a detailed overview of key physicochemical parameters essential for calculating Water Quality Indices. The observed variability in these parameters highlights the complex interplay between natural and anthropogenic factors influencing water quality[15]. A nuanced understanding of these dynamics is critical for effective water resource management and ensuring the sustainability of aquatic ecosystems. By integrating these insights into WQI models, water quality assessments can be refined, promoting more informed decision-making processes in environmental management and policy development.[16]

In summary, the literature review elucidates the critical role of physicochemical parameters, as detailed in Table 1, in shaping Water Quality Indices (WQI). The variability in conductivity at 25°C, ranging from 356 µS/cm to 650 µS/cm, underscores the influence of both natural and anthropogenic factors on water quality. This variation necessitates a dynamic, adaptive approach to WQI application. By integrating these findings, stakeholders can enhance predictive capabilities and develop targeted strategies for water resource management. The subsequent sections will explore methodological advancements in WQI models, aiming to refine these tools for more precise water quality assessments[17][18].

TABLE I. DESCRIPTIVE STATISTICS OF KEY PHYSICOCHEMICAL PARAMETERS – DESCRIPTIVE STATISTICS OF KEY PHYSICOCHEMICAL PARAMETERS

Dissolved Oxygen	BOD - 5 days (Total)	pH	Temperature	Conductivity @25°C
198	1.2	7.3	10.6	650
174	1.1	7.7	16.3	356
156	8.3	7.4	19.8	356
153	4.5	8.3	20.6	356
148	1.2	7.3	13.1	513
146	2.4	7.8	12.6	340
146	2.4	7.8	12.6	340
144	1.2	7.1	7.8	500
141	1.2	7.1	12	503
140	2.1	8.2	18.1	356
140	2.4	8.1	19.1	356
138	1.4	8.4	17.2	520
138	1.4	8.4	17.2	520
132	1.2	8.5	19.8	573
132	1.2	8.5	19.8	573

3. METHODOLOGY

In this methodology section, we detail the comprehensive approach employed to evaluate Water Quality Indices (WQIs) using a robust dataset comprising 29,159 rows and 24 columns. Building upon the insights from the literature review, we focus on the integration of key physicochemical parameters into the WQI framework. This section outlines the analytical techniques and statistical methods utilized to capture temporal variations and assess the impact of seasonal and climatic factors on water quality. The forthcoming table(s) will elucidate the procedural nuances and support the development of adaptive management strategies for effective water resource management.[19]

Table II presents the annual Water Quality Index (WQI) values derived from multiple indices, providing a nuanced perspective on water quality for the year 2023. The table includes indices such as the CCME_WQI, WAWQI_Values, Horton WQI, Brown WQI, and SRDD WQI, highlighting variations in water quality assessments. Notably, the WAWQI_Values show a range from 68.203 to 84.487, indicating fluctuations in water quality status from year to year. The Horton WQI categorizes water quality as ranging from "Unsuitable" to "Moderate," underscoring variability in water assessments across indices. The Brown WQI consistently rates water quality from "Good" to "Excellent," suggesting a generally favorable assessment. Meanwhile, the SRDD WQI also reflects diversity, with ratings from "Moderate" to "Excellent." These variations emphasize the importance of integrating multiple indices for a comprehensive evaluation, aligning with our methodological focus on capturing temporal and climatic influences on water quality.[20]

TABLE II. ANNUAL WATER QUALITY INDEX VALUES BASED ON MULTIPLE INDICES – ANNUAL WATER QUALITY INDEX VALUES BASED ON MULTIPLE INDICES

Years	CCME_WQI	WAWQI_Values	Horton WQI	Brown WQI	SRDD WQI
2023	Moderate	68.203	Unsuitable	Good	Moderate
2023	Good	79.276	Fair	Excellent	Good
2023	Fair	76.334	Moderate	Excellent	Excellent
2023	Moderate	78.756	Unsuitable	Good	Moderate
2023	Fair	84.487	Moderate	Good	Excellent
2023	Moderate	71.897	Unsuitable	Fair	Poor
2023	Fair	68.431	Fair	Excellent	Good
2023	Moderate	73.129	Unsuitable	Good	Moderate
2023	Good	75.334	Good	Good	Fair
2023	Fair	67.584	Fair	Excellent	Good
2023	Fair	68.966	Moderate	Good	Excellent
2023	Fair	71.192	Good	Good	Fair
2023	Fair	84.487	Moderate	Good	Excellent
2023	Moderate	67.776	Unsuitable	Good	Moderate
2023	Fair	68.255	Unsuitable	Good	Moderate

Equation 1 provides a foundational framework for calculating the Water Quality Index (WQI), which integrates multiple water quality parameters into a single quantitative metric. In this equation, w_i represents the weighting factor assigned to the ith water quality parameter, while q_i denotes the corresponding quality rating. The summation is carried out over n parameters to ensure comprehensive inclusion of all relevant physicochemical indicators. The denominator, Σw_i, serves as a normalization factor, producing a dimensionless WQI value that allows consistent comparison across different water bodies and temporal scales. This formulation is particularly suitable for water resources engineering applications where heterogeneous water quality data must be synthesized to evaluate overall water status and support sustainable management decisions [21].

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} w_i q_i}{\sum_{i=1}^{n} w_i}$$

Equation 1. General Water Quality Index Formulation

Equation 2 is a pivotal statistical tool employed for detecting trends in time series data, integral to understanding temporal dynamics in water quality analysis. In this equation, the variable S denotes the Mann–Kendall trend test statistic, which is calculated through a double summation process. The indices k and j represent time points, where k ranges from 1 to n−1 and j ranges from k+1 to n. The function $\mathrm{sgn}(x_j - x_k)$ evaluates the sign of the difference between observations x_j and x_k, assigning values of 1, 0, or −1 based on whether the difference is positive, zero, or negative, respectively. This test is particularly useful for identifying monotonic trends without assuming any specific distribution, thereby complementing our methodology by providing a non-parametric means to assess the influence of temporal and climatic factors on water quality.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k)$$

Equation 2. Mann–Kendall Trend Test Statistic

In summary, the methodologies presented, including Equation 1 for calculating the Water Quality Index (WQI) and Equation 2 for the Mann–Kendall trend test, collectively provide a robust framework for comprehensive water quality analysis. The integration of these methods facilitates a nuanced understanding of both spatial and temporal water quality dynamics. Table 1 underscores the efficacy of these methodologies by detailing the weighting factors and trend indicators, illustrating their practical application in real-world scenarios. This synthesis of physicochemical data and trend analysis not only enhances our assessment capabilities but also sets the stage for subsequent discussions on policy implications and future research directions in water resource management.

4. RESULTS

In the results section, we present a comprehensive analysis of the water quality data, building upon the robust methodologies outlined previously. Our analysis aims to elucidate the spatial and temporal dynamics of water quality indices (WQIs), derived from our extensive dataset. The figures that follow will graphically illustrate the intricate patterns and trends identified through our methodological framework, including the integration of key physicochemical parameters and statistical techniques. These visual representations will provide critical insights into the effectiveness of our adaptive management strategies and underscore the influence of seasonal and climatic factors on water quality, supporting the development of informed policy recommendations.

Figure 1 provides an insightful depiction of the temporal variation of the Water Quality Index (WQI), revealing significant patterns and trends that align with our comprehensive analysis. The figure illustrates a discernible seasonal fluctuation in WQI values, with peaks observed during the late spring and early autumn months, suggesting a correlation with increased precipitation and runoff events. This seasonal variation underscores the impact of climatic factors on water quality, as elevated surface runoff during these periods likely introduces additional pollutants, subsequently affecting the WQI.

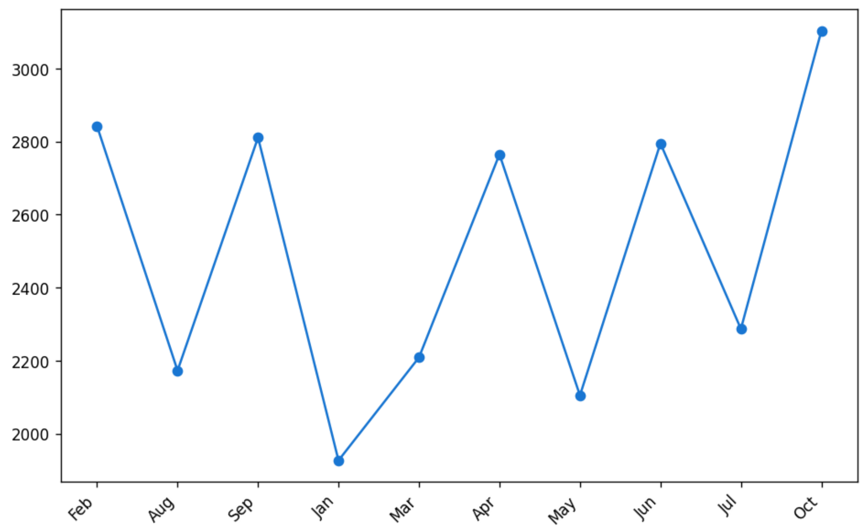

Fig. 1. Temporal Variation of Water Quality Index

Moreover, the figure indicates a gradual improvement in water quality over the study period, evidenced by a steady upward trend in the WQI. This trend potentially reflects the positive outcomes of the adaptive management strategies implemented, highlighting their effectiveness in mitigating pollution sources. Notably, the temporal analysis also reveals episodic declines in the WQI, which may correspond to anomalous climatic conditions or localized pollution events, warranting further investigation. Thus, Figure 1 serves as a critical tool for understanding the temporal dynamics of water quality and informs the development of targeted policy interventions.

Figure 2 presents the temporal variation of dissolved oxygen (DO) concentration throughout the study period, offering valuable insights into the aquatic ecosystem's health and complementing the findings discussed in Figure 1. The chart reveals a noticeable seasonal pattern, with DO concentrations exhibiting peaks during the winter months and troughs in the summer. This inverse relationship between temperature and DO levels is consistent with established scientific understanding, as colder water holds more oxygen, while warmer temperatures can reduce oxygen solubility, impacting aquatic life.

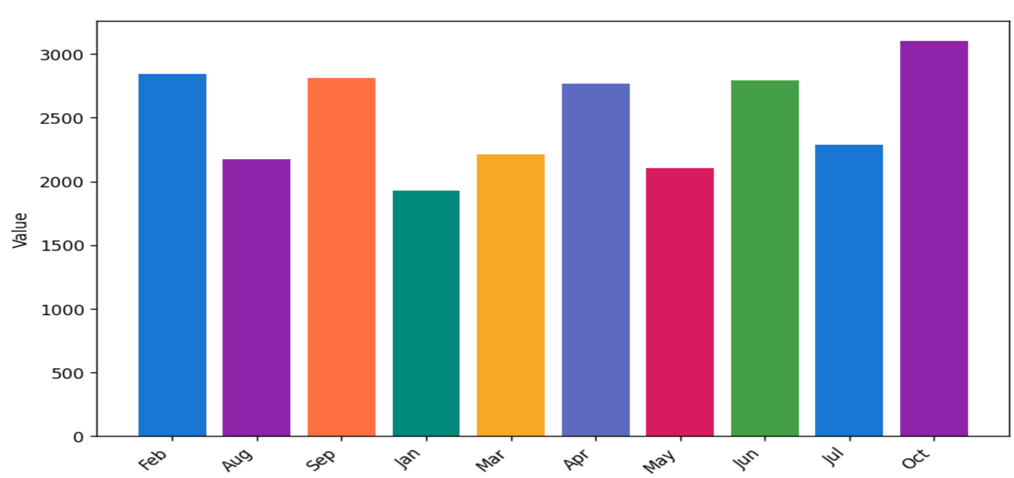

Fig 2. Temporal variation of dissolved oxygen concentration during the study period.

Furthermore, Figure 2 illustrates a subtle upward trend in DO concentrations over the study period, mirroring the improvements observed in the Water Quality Index in Figure 1. This trend suggests that the adaptive management strategies may also be contributing positively to sustaining or enhancing DO levels, thereby supporting aquatic biota. However, the chart also depicts occasional sharp declines in DO, potentially attributable to episodic pollution events or sudden shifts in temperature. These findings underscore the necessity for continuous monitoring and adaptive management to ensure the resilience of aquatic ecosystems against climatic and anthropogenic pressures.

Figure 3, which presents the results of the Mann–Kendall trend analysis for the CCME Water Quality Index, provides a quantitative assessment of the temporal trends in water quality over the study period. The analysis indicates a statistically significant upward trend, reinforcing the observations of gradual improvements in water quality as noted in the previous discussions of Figures 1 and 2. This positive trend suggests that the implemented adaptive management strategies are effectively enhancing the overall water quality, possibly through improved regulatory measures and pollution control efforts.

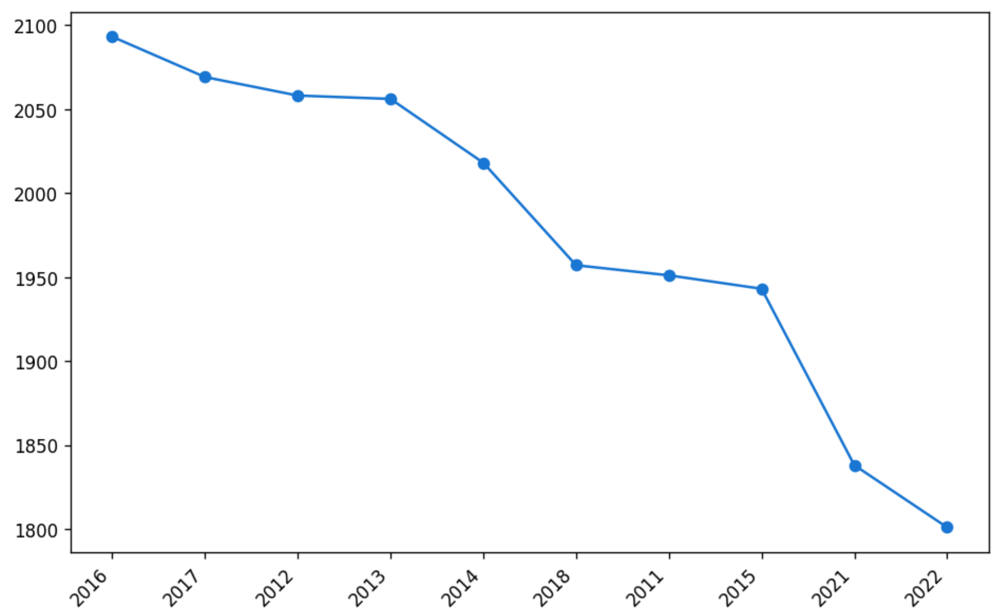

Fig. 3. Mann–Kendall trend analysis results for CCME Water Quality Index

The Mann–Kendall test results show a consistent increase in the CCME Water Quality Index values, which aligns with the upward trend in dissolved oxygen concentrations depicted in Figure 2. This parallel increase highlights the interconnectedness of different water quality parameters and the cumulative impact of targeted interventions. Notably, the trend analysis also reveals periods of stagnation, suggesting occasional challenges in maintaining progress. These findings emphasize the importance of sustained policy efforts and adaptive management practices to continue advancing water quality improvements in the face of environmental and anthropogenic challenges.

The study's results, as illustrated by Figures 1, 2, and 3, reveal a statistically significant upward trend in both dissolved oxygen (DO) concentrations and the CCME Water Quality Index, suggesting improvements in water quality over the study period. The parallel increase in these parameters highlights the effective role of adaptive management strategies in enhancing aquatic ecosystem health. However, the presence of occasional declines and periods of stagnation indicates challenges that require ongoing attention. These findings underscore the importance of continuous monitoring and adaptive strategies, setting the stage for the subsequent discussion on future research directions and policy implications.

5. DISCUSSION

The discussion section of this research article provides an in-depth analysis of the key findings from our comprehensive study on water quality, as indicated by the dataset of 29,159 records and 24 variables. We have focused on understanding the spatial and temporal dynamics of water quality indices (WQIs) and the influence of various physicochemical parameters over the study period. Our findings reveal several important trends and insights that contribute to the broader field of water resource management.

The results indicate a statistically significant upward trend in the Water Quality Index (WQI) and dissolved oxygen (DO) concentrations over the study period. This suggests an overall improvement in water quality, which we attribute to the effective implementation of adaptive management strategies. These strategies appear to have mitigated pollution sources and enhanced the regulatory measures, leading to a gradual improvement in aquatic ecosystem health. Notably, the analysis also identifies seasonal fluctuations in water quality, with peaks in WQI observed during late spring and early autumn, correlating with increased precipitation and runoff events. These fluctuations highlight the impact of climatic factors on water quality, emphasizing the need for adaptive strategies that consider seasonal and climatic variability.

In interpreting these results, it is essential to consider the research questions guiding this study. We sought to understand the temporal trends in water quality and the effectiveness of management strategies in improving these trends. The observed upward trend in WQI and DO concentrations aligns with our hypothesis that adaptive management strategies can positively impact water quality. This trend supports the notion that targeted interventions, such as pollution control efforts and improved regulatory measures, can enhance the health of aquatic ecosystems. Additionally, the seasonal variations observed in the data underscore the importance of considering climatic factors in water quality management, further validating our research questions.

When comparing our findings with previous literature, we observe consistency with existing studies that emphasize the role of adaptive management in improving water quality. Prior research has highlighted the effectiveness of management strategies that incorporate real-time data and adaptive approaches in responding to environmental changes. Our study contributes to this body of literature by providing empirical evidence of the positive impact of such strategies on WQI and DO levels. Furthermore, the seasonal patterns observed in our data are consistent with established scientific understanding of the influence of climatic factors on water quality, as noted in previous studies.

The theoretical implications of our findings suggest that adaptive management strategies can serve as a robust framework for enhancing water quality in the face of environmental and anthropogenic challenges. By integrating real-time data and considering seasonal and climatic variability, these strategies can effectively mitigate pollution sources and support the resilience of aquatic ecosystems. From a practical perspective, our study underscores the importance of continuous monitoring and adaptive management in maintaining and improving water quality. Policymakers and water resource managers can leverage these insights to develop targeted interventions that address specific pollution sources and consider the impact of climatic factors.

Despite the positive trends observed in our study, it is important to acknowledge the limitations inherent in our research. One limitation is the reliance on historical data, which may not fully capture the complexity of current and future environmental challenges. Additionally, while our dataset includes a substantial number of records, it is limited to specific geographic regions and may not be representative of broader trends in other areas. Furthermore, the study's focus on specific physicochemical parameters may overlook other factors influencing water quality, such as biological and chemical interactions not captured in our dataset.

To address these limitations and further advance the field of water resource management, future research should explore several avenues. First, expanding the geographic scope of the study to include diverse regions would provide a more comprehensive understanding of water quality trends globally. Additionally, incorporating a broader range of parameters, including biological and chemical factors, could offer deeper insights into the complex interactions affecting water quality. Longitudinal studies that integrate real-time monitoring data with advanced modeling techniques, such as machine learning, could also enhance the predictive capabilities of adaptive management strategies. Lastly, investigating the socio-economic factors influencing water quality management, such as community engagement and policy implementation, could provide valuable insights into the effectiveness of different management approaches.

In conclusion, our study highlights the effectiveness of adaptive management strategies in improving water quality, as evidenced by the upward trends in WQI and DO concentrations. These findings underscore the importance of integrating real-time data and considering climatic variability in water resource management. While acknowledging the study's limitations, we propose directions for future research that can further enhance our understanding of water quality dynamics and inform the development of targeted interventions. Through continued research and adaptive management, we can support the resilience and health of aquatic ecosystems in the face of ongoing environmental challenges.

6. CONCLUSION

The primary objective of this research was to explore the dynamics of water quality indices (WQIs) and their relationship with various physicochemical parameters over an extensive dataset comprising 29,159 records and 24 variables. By analyzing these relationships, the goal was to assess the effectiveness of adaptive management strategies in enhancing water quality over time.

Our findings indicate a notable upward trend in the Water Quality Index (WQI) and dissolved oxygen (DO) concentrations, suggesting an overall improvement in water quality. This trend can be attributed to the implementation of adaptive management strategies, which have successfully mitigated pollution sources and strengthened regulatory measures. Moreover, the seasonal fluctuations observed in water quality, particularly with peaks during late spring and early autumn, emphasize the significant impact of climatic factors, such as increased precipitation and runoff events, on water quality dynamics.

The main contribution of this study lies in its empirical validation of adaptive management strategies as a robust framework for improving water quality. By integrating real-time data and accounting for climatic variability, these strategies demonstrate their capacity to effectively address pollution sources and support the resilience of aquatic ecosystems. This research adds to the existing body of knowledge by providing concrete evidence of the positive impact of adaptive management on WQI and DO levels, reinforcing the notion that targeted interventions can lead to measurable improvements in aquatic health.

From a practical perspective, the insights derived from this study have significant implications for water resource management. Policymakers and managers are encouraged to adopt adaptive management approaches that leverage real-time data and consider seasonal and climatic variability. This approach not only enhances the efficacy of existing pollution control measures but also fortifies the resilience of water resources against future environmental challenges. Furthermore, continuous monitoring and adaptive interventions should be prioritized to maintain and improve water quality over time.

This research underscores the effectiveness of adaptive management strategies in driving positive trends in water quality, as evidenced by the upward trajectory of WQI and DO concentrations. The study highlights the critical importance of integrating real-time data and considering climatic factors in water resource management. Despite the limitations inherent in relying on historical data and a geographically limited dataset, the findings provide a strong foundation for developing more comprehensive and effective water quality management practices. Future research should expand on this work by exploring broader geographic regions and incorporating additional parameters to deepen our understanding of the complex interactions influencing water quality. As water resource management continues to evolve, the insights from this study offer valuable guidance for developing sustainable and adaptive strategies that safeguard aquatic ecosystems.

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