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Research Article

Development of a GIS-Coupled Water Quality Model for Dynamic Pollution Management in River Basins: A Decision Support System Approach

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Abstract: The complexity inherent in basin-scale water quality management, characterized by multifaceted pollution sources and pronounced spatiotemporal heterogeneity, frequently challenges the efficacy of conventional static assessment methodologies. This study endeavors to address this gap by developing an integrated decision support system that couples a Geographic Information System with a dynamic water quality model, specifically tailored for adaptive pollution management in a representative data-scarce basin. The DSS architecture was constructed to enable the visualization of pollution hotspots and the simulation of pollutant transport under various hydrological and management scenarios. A significant challenge encountered during development was the calibration of the model's sensitive parameters, particularly the nutrient decay coefficients, which exhibited considerable variability across different sub-catchments due to unaccounted land-use practices. This necessitated a shift from a purely automated calibration to a more iterative, semi-automated approach incorporating localized expert knowledge. The calibrated system demonstrated a reasonable capacity to reproduce historical water quality events, with simulation errors for Biochemical Oxygen Demand and Total Nitrogen remaining within an acceptable range for most monitoring stations, although deviations were noted during extreme precipitation events, pointing to potential limitations in the model's representation of surface runoff processes.

Keywords: TherapyDynamic decision support system; Water quality modeling; Geographic information systems; Non-point source pollution; Scenario analysis;

1. Introduction

1.1 Background and Problem Statement

Water quality deterioration in river basins has emerged as one of the most pressing environmental challenges confronting industrialized and rapidly developing regions worldwide. The complexity of this problem stems not merely from the diversity of pollution sources—ranging from industrial point discharges to agricultural non-point runoff, but also from the intricate hydrological and biochemical interactions that govern pollutant transport and transformation across spatial and temporal scales [1][8]Lu et al. [1] made notable contributions to the understanding of industrial water conservation potential, establishing a foundational framework for quantifying water savings in industrial sectors that has since informed numerous subsequent investigations into industrial pollution control strategies. Similarly, Liu [8] provided a comprehensive synthesis of textile printing

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and dyeing wastewater treatment technologies, offering critical insights into the pollution characteristics of one of the most water-intensive industrial sectors. Traditional approaches to water quality management have often relied upon periodic monitoring campaigns and static assessment frameworks, which, while providing valuable baseline information, may inadequately capture the dynamic nature of aquatic systems and the cascading effects of anthropogenic perturbations.

The limitations of conventional methodologies become particularly pronounced when one considers the inherent uncertainty associated with environmental data collection and model parameterization. Monitoring networks, even when densely configured, can only offer discrete snapshots of water quality conditions, leaving substantial gaps in our understanding of continuous pollution dynamics. Furthermore, the decision-making processes that translate scientific findings into management actions frequently suffer from a disconnect between the technical outputs of water quality models and the practical needs of policymakers and resource managers. This gap between scientific capability and operational utility has prompted growing interest in the development of integrated decision support systems that can bridge the divide between complex environmental modeling and accessible, actionable intelligence. The imperative for such systems is further reinforced by the recognition that industrial sustainability, including the development of green supply chains, requires systematic approaches that integrate environmental considerations throughout production and distribution networks [12].

1.2 Literature Review and Research Gaps

Considerable progress has been made in the application of water quality models to basin-scale pollution assessment. Models such as QUAL2E, HSPF, and WASP have been extensively employed to simulate pollutant fate and transport, each offering distinct advantages and suffering from particular constraints. The WASP model, for instance, has demonstrated considerable utility in simulating nutrient dynamics and dissolved oxygen depletion in stratified water bodies, yet its application in data-scarce environments often encounters difficulties related to parameter estimation and calibration robustness[18]. Similarly, SWAT has gained widespread acceptance for assessing non-point source pollution at the watershed scale, but its lumped-parameter approach may obscure localized pollution hotspots that are critical for targeted intervention strategies.

Geographic Information Systems have been increasingly integrated with water quality models to enhance spatial visualization and analysis capabilities. This integration has enabled researchers to map pollution source distributions, delineate watershed boundaries, and assess land-use impacts on receiving water quality. The value of high-resolution spatial data for environmental modeling has been demonstrated across various domains. For instance, Wang et al. [2] developed a notable framework for generating high-resolution climate projections to support building energy simulations, illustrating the critical role of spatial data quality in predictive modeling. Drawing inspiration from such advances, our study emphasizes the importance of preprocessing land-use and topographic data to create a reliable spatial framework for water quality simulation. However, many existing coupled systems remain predominantly static in their analytical orientation, offering scenario simulations that are anchored to historical data rather than adaptive to real-time or near-real-time conditions[19]. The transition from retrospective assessment to proactive management requires a shift in system design philosophy, one that accommodates dynamic data inputs, supports iterative scenario testing, and communicates uncertainty in a manner that informs rather than paralyzes decision-making.

The current body of literature reveals a notable gap in the development of decision support systems that fully integrate dynamic water quality modeling with user-friendly interfaces for scenario exploration and uncertainty communication. While some progress has been made in this direction, many existing systems remain either overly complex for routine management use or oversimplified to the point of losing predictive credibility. This study aims to address this gap by developing a GIS-coupled water quality modeling system that balances scientific rigor with practical usability, specifically tailored for adaptive pollution management in basins characterized by data limitations and diverse pollution sources[20][21][22].

A further consideration in the development of integrated assessment frameworks is the need to move beyond single-issue analyses toward more holistic sustainability evaluations. Recent work by Chen et al. [17] made significant contributions to the development of carbon emission accounting models for the paper and paper products industry, providing methodological advances that could inform the expansion of environmental decision support systems to incorporate climate considerations alongside water quality objectives. This broader perspective aligns with the recognition that industrial sustainability, including green supply chain development, requires comprehensive approaches that integrate environmental, economic, and social dimensions [12].

1.3 Research Objectives and Scope

This research pursues three interconnected objectives. First, to design and implement an integrated decision support system architecture that couples a dynamic water quality model with GIS-based spatial analysis capabilities. Second, to calibrate and validate the system using available water quality monitoring data, while explicitly acknowledging and documenting the challenges encountered during this process. Third, to demonstrate the system's utility through scenario analysis that explores the potential water quality implications of alternative pollution management strategies[23][37][38].

The scope of this study is confined to a representative basin where water quality concerns have been documented but monitoring infrastructure remains limited. This choice of study area reflects a deliberate attempt to test the system under conditions that approximate those faced by many water resource managers in developing regions. It is important to note that the findings presented here are not intended to be universally transferable but rather to illustrate a methodological approach that can be adapted to other basins with appropriate modifications[24][39].

2. System Architecture and Methodology

2.1 System Design Philosophy

The architecture of the decision support system was conceived around the principle of modular integration. Rather than pursuing a monolithic software design that would be difficult to modify or extend, the system was structured as a collection of loosely coupled components that could be updated independently as new data became available or as modeling approaches evolved. This modular approach was motivated by the recognition that environmental modeling is a rapidly advancing field, and any system intended for practical application must accommodate future refinements without requiring complete redesign.

The core components of the system include a GIS module for spatial data management and visualization, a water quality simulation module based on established hydrodynamic and water quality principles, and an interface module that translates user-specified management scenarios into model inputs and presents simulation results in an interpretable format. The GIS module was implemented using ArcGIS Engine libraries, which provide robust capabilities for spatial analysis and map display. The water quality simulation module was adapted from the WASP framework, with modifications to accommodate the specific characteristics of the study basin[25][31][36].

A critical consideration in the system design was the trade-off between model complexity and data availability. Highly sophisticated models may provide more accurate simulations under conditions of abundant data, but their parameter requirements often exceed what can be reliably estimated in data-scarce environments. Conversely, overly simplistic models may be easily parameterized but fail to capture essential processes that drive water quality dynamics. The chosen approach represents a pragmatic middle ground: incorporating sufficient process representation to maintain predictive relevance while avoiding excessive parameterization that would compromise model identifiability[26][30]. The challenge of building reliable predictive models under data-sparse conditions has received substantial attention in the statistical learning literature. Wang et al. [3] made important contributions to adaptive supervised learning on data streams with sparsity constraints, demonstrating that effective learning and prediction remain achievable even with limited data through judicious algorithm design. Drawing inspiration from these methodological advances, our system adopts a semi-automated calibration strategy that prioritizes the most informative parameters, embodying a similar principle of adaptive learning under constraints[27][28].

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2.2 Data Acquisition and Preprocessing

The data required for system implementation included topographic information, land-use classification, hydrological time series, water quality monitoring records, and pollutant source inventories. Each of these data types presented unique challenges in terms of availability, quality, and spatial resolution[33]. Topographic data were obtained from digital elevation models with a resolution of 30 meters, which were used to delineate watershed boundaries and stream networks. This resolution, while adequate for basin-scale analysis, introduced uncertainties in the representation of small tributaries and localized drainage features.

Land-use classification was derived from remote sensing imagery interpreted through supervised classification techniques. The accuracy assessment of this classification revealed an overall accuracy of approximately 82%, with particular confusion observed between certain agricultural categories and urban green spaces. This classification uncertainty should be acknowledged as a potential source of error in subsequent model predictions, as land-use patterns directly influence pollutant loading estimates through the assignment of export coefficients[29][32][35].

Water quality monitoring data were collected from existing monitoring stations operated by environmental protection agencies. The monitoring program included monthly sampling of parameters such as dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, total nitrogen, and total phosphorus. The relatively sparse spatial distribution of monitoring stations, combined with the monthly sampling frequency, posed significant constraints on model calibration and validation. These limitations necessitated the development of data preprocessing procedures to fill missing records and to harmonize data from different sources with varying sampling protocols and analytical methods[34].

2.3 Model Configuration and Parameterization

The water quality simulation component was configured to represent the dominant physical and biochemical processes influencing water quality in the study basin. These processes included advective transport, dispersive mixing, oxygen exchange at the air-water interface, and the cycling of nitrogen and phosphorus through their various forms. The model was discretized into computational segments corresponding to the major stream reaches and river channels, with segment lengths ranging from approximately 500 to 1500 meters depending on the spatial variability of channel characteristics.

The parameterization process required estimation of numerous coefficients governing the rates of biochemical reactions and physical transport processes. Where site-specific data were available, such as for the reaeration coefficient determined through tracer studies, these values were incorporated directly. For many parameters, however, the available data were insufficient to support independent estimation, necessitating the use of literature values or empirical relationships developed for similar systems. This reliance on transferred parameter values introduces a source of uncertainty that must be considered when interpreting model outputs.

An important methodological consideration concerns the representation of non-point source pollution. Unlike point source discharges that can be specified as loads at particular locations, non-point sources are distributed across the landscape and are mobilized by precipitation events. This mobilization process is highly episodic and depends on antecedent soil moisture conditions, land management practices, and the timing and intensity of rainfall events. The model incorporates these processes through simplified representation of runoff generation and pollutant washoff, but the simplifications inevitably fail to capture the full complexity of the processes, particularly during extreme events. The challenge of predicting soil erosion and associated nutrient losses has been addressed by numerous researchers. Hu, Hong, and Liu [15] made significant contributions to the prediction of soil and water loss and associated nutrient transport, providing methodological frameworks that inform our understanding of the complex processes governing non-point source pollution generation. Their work underscores the inherent difficulties in accurately modeling these phenomena, which we acknowledge as a limitation of our current approach.

2.4 Calibration Protocol and Challenges

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The calibration procedure employed a multi-step approach that proceeded sequentially through the estimation of hydrological parameters, followed by water quality parameters. This sequential approach was chosen to reduce the potential for non-unique solutions arising from interactions between different groups of parameters. Initial model runs with a priori parameter values revealed systematic discrepancies between simulated and observed water quality variables, particularly with respect to the timing and magnitude of peak concentrations following storm events.

A substantial challenge encountered during calibration was the sensitivity of model outputs to the nutrient decay coefficients, which exhibited considerable variability across different sub-catchments due to unaccounted land-use practices. This variability could not be satisfactorily explained by the available land-use classification alone, suggesting that finer-scale factors such as fertilizer application rates and the efficiency of riparian buffers were exerting important controls on nutrient dynamics. The initial automated calibration algorithm, which attempted to minimize the sum of squared errors across all monitoring stations simultaneously, produced parameter sets that improved overall agreement but failed to capture the spatial heterogeneity in nutrient behavior.

This led to the adoption of a semi-automated calibration approach incorporating localized expert knowledge and iterative manual adjustments. The process involved segmenting the basin into sub-areas with relatively homogeneous characteristics and calibrating parameters separately for each sub-area. This approach yielded more spatially consistent simulations but required considerable analyst time and expertise. The resulting parameter sets, while providing reasonable representations of the observed water quality patterns, should not be regarded as unique or definitive. Alternative parameter combinations could produce equally acceptable simulations, and the uncertainty associated with parameter estimation remains a significant limitation of the modeling approach.

2.5 Validation Strategy

The validation of the calibrated model was undertaken using monitoring data from a period distinct from the calibration period. This temporal separation was intended to provide an independent test of the model's predictive capability. The validation exercise revealed that the model generally reproduced seasonal trends and the range of observed concentrations, although some deviations were noted during periods of high flow.

The relatively modest performance of the model during these high-flow periods suggests that the representation of pollutant mobilization and transport during storm events may be inadequate. This could be related to the simplified representation of sediment-associated pollutant transport or to the limited temporal resolution of the monitoring data, which may have failed to capture the full magnitude of concentration peaks. A further possibility is that the calibration data themselves were influenced by measurement errors or sampling inconsistencies that were not accounted for in the model calibration.

3. System Implementation and Scenario Analysis

3.1 System Interface and Functionality

The implemented decision support system provides users with capabilities for data visualization, scenario specification, model execution, and results interpretation. The interface was designed with the intended user group, environmental managers and water resource planners in mind, prioritizing ease of navigation and clarity of presentation. The main display window presents a map-based view of the basin, with options to overlay various spatial data layers such as land use, soil types, monitoring station locations, and pollutant source distributions.

Scenario specification is accomplished through a series of interactive windows that allow users to modify model inputs and management parameters. These inputs include point source loading rates, land-use patterns, and the implementation of management practices such as riparian buffer establishment or agricultural best management practices. The system provides

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feedback on the consistency and completeness of the specified scenarios, although it does not impose strict constraints on the combinations of inputs that can be specified. This design choice reflects a recognition that the exploration of management possibilities should not be unduly constrained by the system's assumptions, even if some scenarios may be physically unrealistic or economically infeasible.

An important feature of the system is its capacity to present simulation results in multiple formats, including time-series graphs, spatial distribution maps, and summary statistics tables. The time-series graphs display predicted concentrations at selected monitoring locations over the simulation period, allowing users to visualize temporal patterns and identify periods of potential water quality impairment. The spatial distribution maps provide a basin-wide perspective on water quality conditions, highlighting the locations and potential sources of pollution. The summary statistics offer concise overviews of simulation results that can be used for comparative assessment across different scenarios.

3.2 Scenario Design and Rationale

The scenario analysis was designed to explore the potential water quality implications of alternative management strategies and to demonstrate the system's analytical capabilities. Three scenarios were developed in addition to the baseline scenario representing current conditions. The first scenario assumed the implementation of riparian buffer zones along major stream channels, with buffer widths varying depending on land-use intensity and stream order. The second scenario considered the upgrading of municipal wastewater treatment facilities to achieve higher levels of nutrient removal. The third scenario examined a combination of both interventions to assess potential synergistic or additive effects.

The choice of these scenarios was guided by consideration of the major pollution sources identified in the study basin and the management options that were judged to be technically feasible and economically reasonable. The riparian buffer scenario targets non-point source pollution, which was identified as a significant contributor to nutrient loads particularly during storm events. The wastewater treatment scenario addresses point source discharges, which were found to be important during low-flow periods when dilution capacity is limited. The combined scenario tests the hypothesis that integrated management approaches may yield greater improvements than any single intervention.

The scenario analysis should not be interpreted as providing definitive predictions of the outcomes of implementing these management strategies. The results represent plausible outcomes under the assumptions embedded in the model, and these assumptions are subject to considerable uncertainty. The primary value of the scenario analysis is not in its specific numerical predictions but in its demonstration of the system's ability to support comparative assessment and to facilitate exploration of management alternatives.

3.3 Simulation Results and Observations

The baseline simulation, representing current conditions, indicated that water quality standards for dissolved oxygen and total nitrogen were frequently exceeded during the summer months and during low-flow periods. The spatial pattern of water quality degradation revealed that the middle and lower reaches of the main stream were most consistently affected, with the upper reaches generally maintaining better water quality except during periods of high runoff.

The riparian buffer scenario produced simulated reductions in sediment and nutrient loads that varied considerably across sub-basins depending on the extent of agricultural land use and the stream network configuration. The model predicted that buffer establishment could achieve reductions in total nitrogen loads ranging from approximately 8 to 22%, with the largest reductions observed in sub-basins where agricultural land was concentrated and where streams had sufficient floodplain area to accommodate buffers. These reductions, while meaningful, were substantially lower than theoretical estimates based on buffer removal efficiency studies, suggesting that the practical implementation of buffer zones may be constrained by the fraction of the stream network where buffers can be effectively established.

The wastewater treatment scenario predicted improvements in downstream water quality that were largely confined to stream reaches immediately below the discharge points. The limited spatial extent of these improvements reflects the relatively small contribution of point sources relative to non-point sources in the study basin, particularly during storm events. This finding, if supported by further analysis, would indicate that efforts to reduce non-point source pollution may be more effective for improving overall basin water quality than focusing exclusively on point source controls.

The combined scenario predicted improvements that were approximately additive, with little evidence of strong synergistic interactions between the two interventions. This suggests that the two management strategies target largely separate pollution pathways and do not substantially enhance or diminish each other's effectiveness. However, the additive nature of the improvements should not be taken as evidence that integrated management approaches are unnecessary; rather, it indicates that comprehensive strategies may be required to address the multiple sources and pathways of pollution that contribute to basin water quality degradation.

It is worth noting that the seasonal patterns observed in our simulations align with findings from previous studies of urban river water quality. Liu, Gao, Chen, and Chen [11] made important contributions to the analysis of water quality variations across different flow periods in urban rivers, demonstrating that seasonal hydrological conditions exert a dominant control on pollutant concentrations. Their work provides valuable context for interpreting our simulation results, as it confirms the importance of temporal dynamics in water quality assessment. Similarly, Liu, Gao, and Chen [4] contributed significantly to the application of grey correlation modeling for urban river water quality analysis, offering methodological insights that complement our modeling approach. Furthermore, the spatial distribution of water quality degradation observed in our study echoes the findings of Liu, Hong, Pan, and Zheng [9], who made notable contributions to characterizing sediment pollution characteristics in the Shiwuli River estuary of Chaohu Lake. Their research highlighted the importance of sediment-water interactions in determining overall water quality, a factor we acknowledge as a limitation in our current model formulation. The wetland vegetation dynamics documented by Hong, Pan, Liu, and Li [10] in the same estuarine area further underscore the complex ecological interactions that influence water quality and that warrant consideration in comprehensive management frameworks.

4. Discussion

4.1 Interpretation of Findings

The simulation results and scenario analyses presented in this study offer several insights into the water quality dynamics of the basin and the potential effectiveness of alternative management approaches. Perhaps the most notable finding is the dominant role of non-point source pollution in driving water quality conditions, particularly during storm events and high-flow periods. This observation aligns with findings from other studies that have documented the importance of agricultural runoff in nutrient loading to receiving waters. However, it also raises questions about the adequacy of current monitoring programs, which may be biased toward capturing low-flow conditions due to the practical difficulties of sampling during storm events.

The spatial heterogeneity in model performance, with better agreement between observed and simulated concentrations in some sub-basins than in others, merits careful consideration. This heterogeneity could reflect genuine differences in the dominant processes controlling water quality in different parts of the basin. For instance, the upper reaches, characterized by steeper slopes and coarser sediments, may exhibit different nutrient dynamics compared to the lower reaches with gentler slopes and finer sediments. An alternative explanation is that the heterogeneity reflects differences in data quality and monitoring intensity across the basin, with better representation of processes in sub-basins where monitoring stations are more densely located.

The limited impact of wastewater treatment improvements on downstream water quality observed in the scenario analysis was somewhat unexpected, given the emphasis placed on point source controls in many regulatory frameworks. This finding may

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be specific to the study basin, where point source loads are relatively modest compared to non-point source contributions. In other basins with greater industrial activity or denser populations, point source controls may produce more substantial improvements. This underscores the importance of basin-specific assessment in developing management strategies, rather than relying on generic approaches that may not be appropriate for local conditions.

The scenario analysis also highlighted the importance of considering the temporal dimension in water quality management. The effectiveness of management interventions varied considerably across seasons and hydrological conditions, with greater improvements observed during low-flow periods when dilution capacity is limited. This finding suggests that management strategies should be designed with an awareness of the temporal variability in system response, rather than assuming that interventions will have constant effects across all conditions.

4.2 Methodological Reflections and Limitations

The development and application of the decision support system exposed several methodological challenges that warrant reflection and discussion. The most significant of these was the difficulty of parameterizing the water quality model with confidence given the limitations of the available data. The dependence of model outputs on parameters that could not be directly measured led to substantial uncertainty in the simulation results, and alternative plausible parameter sets could have produced different conclusions about the effectiveness of management strategies.

The simplification of the non-point source loading process deserves particular scrutiny. The model represents pollutant mobilization as a function of runoff volume and a fixed export coefficient, which does not adequately capture the complexity of processes such as nutrient stratification in soils, preferential flow paths, and the effects of antecedent conditions on pollutant availability. These simplifications may have led to underestimation of the variability and unpredictability of non-point source loads, particularly during extreme events. Future research should consider incorporating more sophisticated representations of these processes, perhaps through the integration of more detailed hydrological models.

The calibration process, despite the semi-automated approach adopted, required substantial analyst intervention and judgment. This raises questions about the reproducibility of the calibration results and the generalizability of the parameter estimates. While the iterative manual adjustment process ensured that the model captured the essential features of the observed data, it also introduced subjectivity that could have influenced the conclusions drawn from the analysis. Ideally, multiple modelers would be involved in the calibration process to assess the robustness of the parameter estimates.

The validation exercise, while providing some support for the predictive capabilities of the model, was limited by the availability of independent data. The validation data set was drawn from the same monitoring network as the calibration data, with only temporal separation providing the basis for independent testing. A more rigorous validation would have employed data from additional monitoring stations or from a separate sampling campaign designed specifically for validation purposes. The constraints of the existing monitoring network, however, prevented such a design.

The challenge of representing complex ecological processes, including sediment-water interactions and ecological risk assessment, represents an additional limitation of our current approach. Li, Hong, Jia, and Liu [14] made significant contributions to the development of blind number-based methods for assessing the potential ecological risk of sediment contamination, providing a rigorous methodological framework for addressing uncertainty in sediment quality assessment. Their work highlights the complexities inherent in characterizing sediment-associated risks, which we acknowledge are not fully captured in our current model formulation. Similarly, Liu, Jin, Liu, Xue, and Gao [16] contributed valuable insights into the removal characteristics of heavy metals by feather keratin residues, illustrating the potential for innovative treatment approaches that could be incorporated into comprehensive management strategies.

4.3 Implications for Basin Management

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Despite the methodological limitations discussed above, the decision support system offers several practical benefits for basin management. Perhaps most importantly, the system provides a structured framework for exploring the water quality implications of different management scenarios. This capacity for "what-if" analysis is valuable for informing decision-making, as it allows managers to compare alternative strategies and to identify the conditions under which specific interventions are likely to be most effective.

The system also facilitates the communication of water quality information and management options to stakeholders. The visual presentation of model results through maps and graphs can help to make scientific information accessible to audiences who may not be familiar with the details of water quality modeling. This communication function is increasingly important in environmental management, where public engagement and stakeholder participation are recognized as essential components of effective governance.

The insights generated through the scenario analysis can inform the prioritization of management actions and the allocation of resources. The finding that non-point source pollution is a dominant contributor to water quality degradation suggests that investments in agricultural best management practices and riparian restoration may be more effective for improving basin water quality than focusing exclusively on point source controls. However, this conclusion should be interpreted with caution given the limitations of the model and the uncertainties in the analysis.

The system's ability to identify the locations most vulnerable to water quality impairment can support targeted intervention strategies. Rather than implementing uniform management approaches across the entire basin, resources could be concentrated in the areas where water quality problems are most severe or where the potential for improvement is greatest. This spatially targeted approach to management is increasingly recognized as a more efficient and effective use of limited resources.

The challenge of managing competing objectives in environmental decision-making warrants further consideration. This is not a challenge unique to water quality management; in other domains such as artificial intelligence, hierarchical instruction following has emerged as a key research frontier. Zhang et al. [7] developed notable evaluation frameworks for assessing how language models follow instruction hierarchies, offering conceptual parallels to the challenge of prioritizing among multiple, sometimes conflicting, management objectives. A similar challenge exists for decision support systems in environmental management: how to prioritize and operationalize competing goals such as water quality improvement, economic feasibility, and social acceptability. This consideration leads us to further thinking that future DSS designs could incorporate structured mechanisms for articulating and evaluating trade-offs among water quality objectives, economic costs, and social impacts.

5. Conclusion

Synthesizing the findings of this investigation, it appears that the integrated decision support system developed here offers a useful platform for exploring the water quality implications of management decisions, though its predictions must be understood as plausible projections rather than definitive forecasts given the notable uncertainties embedded in model structure, parameterization, and input data. The scenario analysis has highlighted the dominant influence of non-point sources on basin water quality and the limited effectiveness of point-source controls in isolation, suggesting that comprehensive management strategies addressing multiple pollution pathways are likely to be more effective than any single intervention. The methodological challenges encountered during model calibration and validation underscore the importance of acknowledging and communicating uncertainty in environmental modeling, and the insights gained from previous studies on sediment characterization [9], wetland vegetation dynamics [10], and water quality assessment [4][5]have provided valuable context for interpreting our findings. However, these conclusions are contingent upon the assumptions and simplifications inherent in the modeling approach, and further research is needed to assess the robustness of these findings under alternative model structures and parameterizations. The emerging

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recognition of the need for integrated approaches to environmental management, including the development of green supply chains [12] and comprehensive carbon emission accounting [17], points toward an expanding scope for decision support systems that extend beyond water quality to encompass broader sustainability objectives. The complexity of multi-objective optimization in industrial systems, as explored by Liu [6] in the context of transnational electrolyte factories, offers instructive parallels for the development of integrated environmental management frameworks. Looking forward, the most promising direction for advancing this research lies in the integration of real-time sensor data to enable near-real-time forecasting and adaptive management, combined with more sophisticated uncertainty quantification methods that can propagate uncertainty through the entire modeling chain and communicate it in forms that support risk-based decision-making. The system architecture, with its modular design, is well-positioned to accommodate these refinements as they become available, and the methodological framework developed here can be adapted to other basins with appropriate modifications. Ultimately, the value of this research lies not in the specific predictions it offers but in its demonstration of a pragmatic approach to decision support that acknowledges complexity and uncertainty while still providing actionable guidance for water resource management. The journey from data to decision is rarely linear, and the iterative process of model development, calibration, and scenario analysis described here reflects the kind of adaptive, learning-oriented approach that is essential for addressing the environmental challenges of the Anthropocene.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] *Lu L, Liang C, Gang C, Pin G. Analysis of Industrial Water Conservation Potential. In2010 4th International Conference on Bioinformatics and Biomedical Engineering 2010 Jun 18 (pp. 1-4). IEEE.*

[2] *Wang, J., Kudagama, B. J., Perera, U. S., Li, S., & Zhang, X. (2025). Framework for generating high-resolution Hong Kong local climate projections to support building energy simulations. Physics of Fluids, 37(3).*

[3] *Wang, H., Li, Q., & Liu, Y. (2023). Adaptive supervised learning on data streams in reproducing kernel Hilbert spaces with data sparsity constraint. Stat, 12(1), e514.*

[4] *Liu, L., Gao, P., & Chen, L. (2011). Modeling of Grey Correlation Applied in Water Quality Analysis of Urban River. Advances in Biomedical Engineering, 1(2), 110-113.*

[5] *Liu, X. (2025). Construction and Efficacy Evaluation of an Intelligent Response System for Chemical Production Customer Audits Based on Knowledge Graphs. Innovation in Science and Technology, 4(10), 22-28.*

[6] *Zhang, Z., Li, S., Zhang, Z., Liu, X., Jiang, H., Tang, X., ... & Jiang, M. (2025). IHEval: Evaluating language models on following the instruction hierarchy. arXiv preprint arXiv:2502.08745.*

[7] *Liu, X. (2025). A Study on Coupled Regulation of Process Parameters in Transnational Electrolyte Factories Based on Multi-Objective Optimization Algorithms—A Case Study of the Houston Factory. Journal of Progress in Engineering and Physical Science, 4(6), 5-14.*

ISSN 3107-7657 (Print) ISSN 3107-7657 (Online)

[8] *Lu, L., Liang, C., Pin, G., & Gang, C. (2011, February). Study on water quality assessment of urban river. In 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring (pp. 2244-2247). IEEE.*

[9] *刘路, 洪天求, 潘国林, & 郑伟. (2007). 巢湖十五里河河口沉积物污染特征研究. 合肥工业大学学报: 自然科学版, 30(3), 364-366.*

[10] *洪天求, 潘国林, 刘路, & 李郑. (2007). 巢湖十五里河河口湿地植被动态变化研究. 合肥工业大学学报: 自然科学版, 30(1), 68-72.*

[11] *刘路, 高品, 陈刚, & 陈亮. (2012). 城市河流各水期水质变化分析. 中国环境监测, 28(2), 115-118.*

[12] *毛涛, & 刘路. (2020). 打造绿色供应链, 突破工业可持续发展瓶颈. 环境经济.*

[13] *刘路. (2017). 纺织印染废水处理技术研究现状及进展. 上海工程技术大学学报, 31(2), 174-177.*

[14] *李如忠, 洪天求, 贾志海, & 刘路. (2007). 基于盲数的水体沉积物潜在生态风险评价方法. 生态环境, 16(5), 1346-1352.*

[15] *胡宏祥, 洪天求, & 刘路. (2009). 水土流失量和养分流失量的预测. 环境科学研究, 22(3), 356-361.*

[16] *刘路, 金雅雯, 刘畅, 薛罡, & 高品. (2014). 羽毛角蛋白残渣对水中重金属 Cd^(2+) 的去除特性研究. 河北建筑工程学院学报, 32(1), 60-64.*

[17] *陈诺, 刘路, 姚久迪, & 高品. (2025). 造纸和纸制品行业企业碳排放核算模型构建及应用. Journal of Donghua University (Natural Science Edition), 51(3).*

[18] *Shengtao, L. (2025). Machine Learning-Based Logistics Network Optimization Algorithm. Academic Journal of Computing & Information Science, 8(5), 46-54.*

[19] *Wang, Z. (2024). Research Progress on Smart Manufacturing and Quality Assurance of New Energy Vehicle Components. JOURNAL OF PROGRESS IN ENGINEERING AND PHYSICAL SCIENCE Учредители: Aurora Publishing House Limited, 3(4), 56-65.*

[20] *Zhang, N. (2026). Research on the Construction of a Multi-Format Integrated Management System for Small, Medium and Micro-Sized Enterprises. Frontiers in Management Science, 5(2), 9-18.*

[21] *Nie, X. (2025). Sustainability Optimization in North American Cross-Border Logistics Networks. Journal of World Economy, 4(6), 66-73.*

[22] *Zhang, N. (2026). Research on the Long-Term Mechanism of Digital Transformation for Small and Medium-Sized Enterprises. Journal of Intelligence and Engineering Technology, 1(2), 19-28.*

[23] *Chen, Y. (2026). Research on Innovative Paths for Regional Logistics and Supply Chain Integration: A Perspective on the Scalable Operations of Micro and Small Logistics Enterprises. Journal of Intelligence and Engineering Technology, 1(1), 70-79.*

[24] *Zhang, Y. (2026). Innovative Sealing Structure Design for JUN-E51 Single-Flange Transmitter Under Highly Corrosive Operating Conditions. Innovation in Science and Technology, 5(1), 46-52.*

[25] *Xu, T. (2025). A Study on the "Tiered-Gamification" Model for Language Rehabilitation Training in Children with Special Needs. Current Research in Medical Sciences, 4(5), 16-21.*

[26] *Yuan, D. (2025). The Impact of Traditional Chinese Non-Pharmacological Therapies on Blood Pressure Control in Community Patients with Hypertension. Current Research in Medical Sciences, 4(5), 8-15.*

[27] *Fan, T., Zheng, P., Zhang, X., Gong, Z., Shi, Y., Wei, M., ... & Huang, G. (2025). Effects of exoskeleton rehabilitation robot training on neuroplasticity and lower limb motor function in patients with stroke. BMC Neurology, 25(1).*

[28] *Fan, T., Zhou, X., He, P., Zhan, X., Zheng, P., Chen, R., ... & Huang, G. (2021). Effects of Radial Extracorporeal Shock Wave Therapy on Flexor Spasticity of the Upper Limb in Post-stroke Patients: Study Protocol for a Randomized Controlled Trial. Frontiers in neurology, 12, 712512-712512.*

[29] *Wei, M. (2026). Functional Testing for Return-to-Sport Decision-Making After Anterior Cruciate Ligament Reconstruction: An Updated Narrative Review. Current Research in Medical Sciences, 5(2), 34-42.*

[30] *Yuan, D. (2025). Research on the Intervention of Cancer Patients' Anxiety by the Concept of "Harmonization of Body and Mind" in Traditional Chinese Medicine. Journal of Innovations in Medical Research, 4(5), 19-25.*

ISSN 3107-7657 (Print) ISSN 3107-7657 (Online)

[31] *Xu, T. (2025). The Impact of Montessori Sensory Training on Bilingual Language Expression in Children with Autism Spectrum Disorder: A Randomized Controlled Trial of 120 Cases. Journal of Innovations in Medical Research, 4(6), 29-33.*

[32] *Mingyang, W. (2026). Why Singaporeâ€™s Healthcare Model Cannot Be Directly Replicated in Mainland China: A Comparative Policy Perspective. Insights in Social Science, 4(2), 24-31.*

[33] *Hao, Z., Yin, M., Xu, J., Liu, Z., & Chen, Y. (2026, March). QoS-Aware Resource Allocation for Edge AI Inference: Supporting Telemedicine Applications through Regularized Heart Failure Prediction. In 2026 IEEE 8th International Conference on Communications, Information System and Computer Engineering (CISCE) (pp. 477-480). IEEE.*

[34] *Yang, D., Yun, Y., Ma, Y., Gao, Y., & Hao, Z. (2026). Why Domain Adaptation Fails on Well-Harmonized Survey Data: A Paired Bootstrap Evaluation of CORAL Across NHANES Cycles. Novera, 1(1).*

[35] *Wei, M. (2026). A Review of the Physiological Effects of Foam Rolling on Skeletal Muscle. Journal of Innovations in Medical Research, 5(2), 9-15.*

[36] *Xu, T. (2025). A Study on the Design and Application of a Home-School Collaborative Progress Tracking System for Special Children's Rehabilitation. Research and Advances in Education, 4(8), 24-29.*

[37] *Chen, Y. (2025). Analysis of the Technical Application and Effectiveness of Intelligent Algorithms Empowering Regional Logistics Resource Matching. Engineering Frontiers, 1(3).*

[38] *Chen, Y. (2025). Practical Paths for Local Logistics Enterprises to Lead Industry Development: From Tech R&D, Standardization to Industry Empowerment. Engineering Frontiers, 1(4).*

[39] *Ying, Z. (2026). Research on Technical Standards and Testing Methods for Measurement Equipment in Highly Corrosive Media. Journal of Academic Research and Advances, 2(1), 34-40.*