

Oleksii Nazarenko
Bachelor's degree candidate in specialty E4 «Earth Sciences»,
Educational Program "Water and Land Resource Management"
Academic supervisors:
Illia Tsyhanenko-Dziubenko
PhD (Ecology)
Head of the Earth Sciences Department
Sviatoslav Kurylo
Associate Professor, PhD (Hydrology),
Associate Professor of the Earth Sciences Department
Zhytomyr Polytechnic State University

MATHEMATICAL MODELING OF HYDROECOLOGICAL STATUS OF SMALL RIVERS UNDER ENVIRONMENTAL CHALLENGES: EXPERIENCE FROM THE HNYLOPIAT RIVER

Relevance. The escalating environmental pressures on small river systems worldwide necessitate advanced mathematical modeling approaches for effective water quality management. The research addresses the critical need for sustainable water quality management in urban aquatic ecosystems, aligning with UN Sustainable Development Goals 6, 14, and 17 for clean water, aquatic life protection, and collaborative partnerships.

Practical Significance. The practical significance extends beyond academic research, providing water resource managers with science-based tools for proactive decision-making, enabling early warning systems for ecological threats, and supporting evidence-based policy development for sustainable urban water management. The developed automated river hydroecological status forecasting system transforms complex mathematical models into practical management tools, allowing real-time monitoring and prediction of water quality conditions that support evidence-based decision-making for sustainable urban water resource management. This comprehensive mathematical modeling approach provides water resource managers with powerful tools for understanding, predicting, and managing the hydroecological status of small river systems under increasing environmental pressures, contributing to sustainable water quality management aligned with international environmental standards and development goals.

Objective. The research introduces a novel integrated approach combining multiple mathematical models to assess and predict hydroecological status under various environmental scenarios. The scientific novelty lies in the simultaneous application of Streeter-Phelps, QUAL2K, and WASP models for comprehensive dissolved oxygen dynamics analysis, coupled with advanced temperature stratification modeling

The Hnylopiat River, located in the Zhytomyr and Vinnytsia oblasts, represents an ideal case study as a small river system experiencing typical environmental pressures found across Ukraine and Eastern Europe. This river basin demonstrates the characteristic challenges of anthropogenic impacts on small river ecosystems, making it representative for broader regional applications. The research methodology encompasses three primary mathematical modeling approaches that provide comprehensive analysis of dissolved oxygen dynamics and water quality parameters.

The Streeter-Phelps model serves as the foundation, describing the fundamental relationship between dissolved oxygen concentration and biochemical oxygen demand using differential equations for organic matter decomposition and oxygen deficit dynamics. The analytical solution process derives exponential decay functions enabling precise prediction of water quality conditions under various loading scenarios. The QUAL2K model provides advanced analysis of seasonal variations in biochemical oxygen demand concentrations along the river continuum, with distinct patterns for winter, spring, summer, and autumn conditions across the 45-kilometer river stretch. The WASP model incorporates multi-dimensional modeling with 2D longitudinal variations in dissolved oxygen across seasonal cycles and 3D full hydrodynamics capturing complex three-dimensional flow patterns and their impact on water quality distribution.

The implementation results demonstrate the models' effectiveness in capturing seasonal and spatial variations in water quality. Dissolved oxygen concentration analysis reveals clear seasonal patterns, with winter months typically exhibiting higher oxygen levels due to increased solubility at lower temperatures. Conversely, BOD concentrations display corresponding inverse patterns, with higher biological oxygen demand during warmer months. Distance-based analysis reveals how pollution loads impact water quality downstream from discharge points, providing crucial information for identifying critical management zones along the river continuum.

The CE-QUAL-W2 temperature stratification model reveals how thermal dynamics affect dissolved oxygen distribution throughout the water column, while comprehensive uncertainty analysis and multi-dimensional modeling approaches quantify model sensitivity to parameter variations, providing confidence intervals for predictions and identifying critical parameters requiring precise calibration for reliable forecasting. Comprehensive comparative analysis across all three modeling approaches ensures model reliability and accuracy, demonstrating how Streeter-Phelps, QUAL2K, and WASP models predict dissolved oxygen and BOD concentrations along the river continuum.

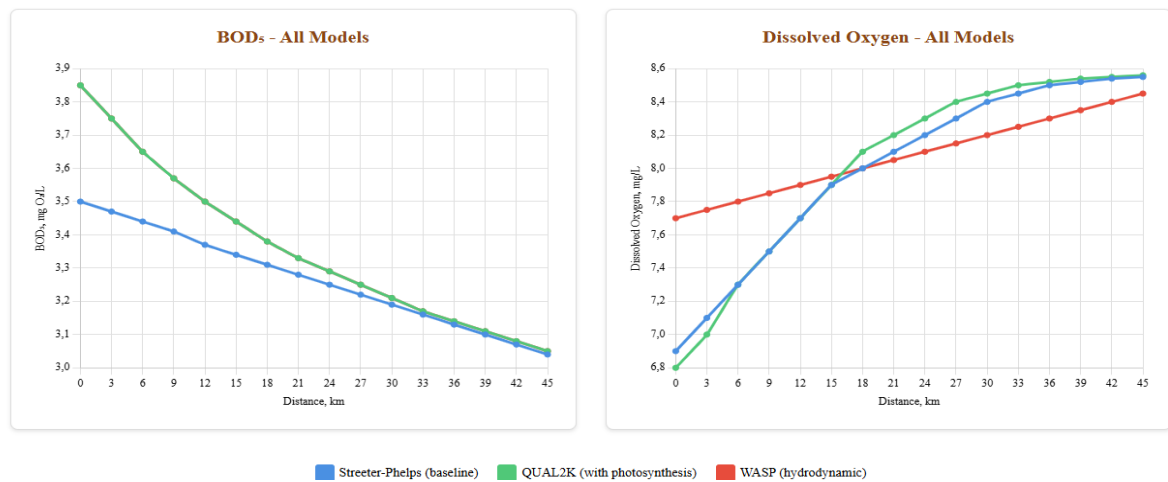


Fig. 1. Comparative analysis of BOD5 and dissolved oxygen dynamics along the Hnylopiat River

Scenario-based management analysis compares improvement versus degradation pathways under different management interventions. Improvement scenarios include baseline conditions, treatment upgrades achieving 60% efficiency, full reconstruction reaching 80% efficiency, and nature-based solutions. Degradation scenarios examine no action, increased pollution, and climate change impacts, enabling proactive planning and demonstrating quantitative benefits of various management strategies. Based on comprehensive modeling results, integrated management recommendations span industrial measures including upgrading wastewater treatment facilities to 95% efficiency and implementing closed-loop water systems, nature-based solutions emphasizing riparian buffer zones and bioengineering structures, regulatory measures proposing increased penalties and economic incentives, social initiatives focusing on public education and community monitoring, automated monitoring programs with remote sensing capabilities, and financing strategies including EU funding opportunities and public-private partnerships.

Conclusions. The research demonstrates four primary achievements that significantly advance the field of hydroecological modeling for small river systems. Multi-model integration significantly enhances prediction accuracy compared to single-model approaches, with the simultaneous application of Streeter-Phelps, QUAL2K, and WASP models providing significantly more reliable predictions of dissolved oxygen dynamics and water quality parameters, enabling comprehensive assessment of complex hydroecological processes in small river systems. The developed algorithmic framework successfully transforms complex mathematical models into practical management tools, allowing real-time monitoring and prediction of water quality conditions that support evidence-based decision-making for sustainable urban water resource management. Comparative scenario modeling demonstrates that integrated management strategies combining industrial upgrades, nature-based solutions, and regulatory measures can achieve substantial improvements in river water quality, with treatment efficiency upgrades showing the most significant impact on dissolved oxygen recovery. The comprehensive uncertainty and sensitivity analysis framework provides quantified confidence intervals for model predictions, identifying critical parameters requiring precise calibration and ensuring that management recommendations are based on robust scientific evidence suitable for policy implementation.

References

1. Kapelista I., Kireitseva H., Tsyhanenko-Dziubenko I., Khomenko S., Vovk V. Review of Innovative Approaches for Sustainable Use of Ukraine's Natural Resources. *Grassroots Journal of Natural Resources*. 2024. Vol. 7, No. 3. P. 378-395.
2. Tsyhanenko-Dziubenko I., Kireitseva H., Shomko O., Gandziura V., Khamdosh I. Analytical assessment of heavy metals polyelement distribution in urbanized hydroecosystem components: spatial differentiation and migration patterns. *Journal Environmental Problems*. 2025. Vol. 10, No. 2. P. 135-144.
3. Tsyhanenko-Dziubenko I., Kireitseva H., Demchuk L., Vovk V. Hydrochemical Determination of the Teteriv River and the Kamianka River Eutrophication Potential. *17th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment*. 2023. Vol. № 1. P. 1-4.
4. Kireitseva H., Tsyhanenko-Dziubenko I., Khomenko S., Palii O. Integral assessment of the effectiveness of water resource management in communities for sustainable development. *Ecological Safety and Balanced Use of Resources*. 2025. Vol. 16, No. 1. P. 27-38.