

ABSTRACT

Nutrient and sediment pollution remains a major environmental challenge across the southeastern United States, where land use changes, climatic variability, and complex watershed characteristics influence contaminant generation and transport. Understanding these interactions is essential for improving water-quality predictions and developing effective watershed management strategies under changing environmental conditions. This dissertation advances regional water-quality modeling through an integrated assessment of nutrient and sediment dynamics, future climate and land use changes, and machine-learning approaches. The research focuses on total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) across approximately 628,000 km² and 8,321 subwatersheds in the southeastern United States.

The first study refines the SPAtially Referenced Regression On Watershed attributes (SPARROW) modeling framework by incorporating detailed land use and land cover characteristics, surficial geology, and improved source-to-stream delivery representations. The refined RSPARROW model explicitly accounts for agricultural sources and the influence of forest and wetland cover on contaminant transport. Model calibration and evaluation demonstrated improvements in regional Kling–Gupta efficiency (KGE) from 0.82 to 0.87 for TN, 0.58 to 0.70 for TP, and 0.72 to 0.80 for SS, accompanied by reductions in predictive uncertainty of 18.9%, 23.2%, and 31.5%, respectively.

Building on the refined modeling framework, the second study investigates the individual and combined effects of climate and land use changes on future nutrient and sediment loads and in-stream concentrations. Nineteen scenarios were evaluated through 2100, revealing projected load increases of approximately 15–50% under climate change alone and 5–30% under land use change alone. Combined changes produced the largest increases, particularly for SS (50–120%). However,

projected increases in nutrient loads did not necessarily correspond to higher in-stream concentrations, highlighting the importance of distinguishing changes in contaminant mass transport from concentration-based water-quality responses.

The third study evaluates the integration of RSPARROW-informed machine learning to improve nutrient and sediment load prediction and assess spatial generalizability. Random Forest models were developed using watershed source and transport characteristics, with 38 additional hydroclimatic predictors representing storm events, antecedent conditions, soil moisture, climate variability, and streamflow dynamics. Hydroclimatic regionalization was investigated across four watershed groups to compare full-region and subregional modeling approaches. The analysis examines the predictive contributions of additional environmental information and the effectiveness of regionalization for estimating loads at withheld monitoring locations, highlighting the importance of spatial validation and the limitations of increasing model complexity.

Overall, this dissertation advances regional water-quality modeling by improving the representation of contaminant sources and transport processes, quantifying the implications of future climate and land use changes, and evaluating the potential of physically informed machine learning for watershed-scale prediction. The findings provide a scientific foundation for more reliable water-quality assessments, targeted pollution mitigation, and sustainable watershed management under evolving environmental conditions.