Development of an Integrated SWAT-SEIR Mathematical Model for Assessing Climate Change Impacts on Water Security: A Lake Victoria Basin Case Study

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Abstract- Climate change poses significant threats to water security globally, with the Lake Victoria Basin experiencing intensified droughts, floods, and water quality degradation. This study developed an integrated mathematical model combining the Soil and Water Assessment Tool (SWAT) with a Susceptible-Exposed-Infectious-Recovered (SEIR) epidemiological framework to assess complex interactions between climate change and hydrological processes. The hybrid model captures both water quantity dynamics through SWAT's physically-based approach and water quality contamination dynamics through the SEIR compartmental structure. Model validation achieved excellent performance with Nash-Sutcliffe Efficiency of 0.85 for streamflow and satisfactory performance for water quality parameters (NSE = 0.59-0.67). The basic reproduction number (R_0 = 4.69) indicated endemic contamination conditions requiring active management intervention. Sensitivity analysis revealed environmental degradation factor (μ^* = 0.342) and precipitation input (μ^* = 0.298) as the most influential parameters. The integrated framework successfully represents threshold behaviors and system transitions critical for climate adaptation planning.

Indexed Terms- Climate change, Water security, Mathematical modeling, SWAT-SEIR integration

I. INTRODUCTION

Global climate change has emerged as one of the most pressing challenges of the 21st century, with significant implications for water resources worldwide. The Intergovernmental Panel on Climate Change (IPCC, 2022) highlights that global warming has led to intensified water cycles, resulting in more frequent and severe droughts and floods. The East African region has experienced a 1.2°C increase in average temperature over the past 50 years, leading to altered precipitation patterns and increased evapotranspiration rates (Ogega et al., 2023).

The Lake Victoria Basin, covering approximately 184,000 km² across East Africa, represents a critical freshwater ecosystem facing increasing pressure from climate change. Recent research demonstrates that rising lake levels in central East Africa are driven by increasing rainfall and land-use intensification, revealing complex feedback mechanisms between climate change and hydrological processes (Byrne et al., 2024).

Budalangi, situated in Busia County along Lake Victoria shores, exemplifies regional water security challenges. The area experiences a bimodal rainfall pattern with periodic droughts and flooding events significantly impacting water availability and quality. Traditional water sources have become increasingly unreliable, with 40% of previously perennial water sources now drying up seasonally.

Mathematical models provide valuable tools for understanding and predicting climate change impacts on water security. However, existing modeling approaches face critical limitations. Most current models focus on specific components rather than integrated system behavior, with few studies directing attention to specific water quality parameters and appropriate methodologies for climate change impact assessment (Sukanya & Sabu, 2023).

This study addresses these limitations by developing an integrated mathematical model combining SWAT hydrological modeling with SEIR epidemiological principles to capture both water quantity and quality dynamics within a unified framework.

II. LITERATURE REVIEW

2.1 Climate Change Impacts on Water Resources

The IPCC Working Group II Sixth Assessment Report (2022) documents comprehensive climate change impacts on global water resources. Antony et al. (2017) report that more variable precipitation is occurring globally, with increased frequency and intensity of floods and droughts, while higher temperatures accelerate evaporation rates and glacier melting.

East Africa exhibits high vulnerability to climate-induced hydrological extremes due to complex hydroclimate and socio-economic contexts (Taye & Dyer, 2024). Extreme climatic events are projected to intensify over the Lake Victoria Basin under global warming scenarios (Ogega et al., 2023). Climate change affects water security through multiple pathways, with flooding leading to contamination and drought reducing dilution capacity, concentrating pollutants (Baiwen et al., 2022).

2.2 Mathematical Modeling Approaches

Traditional hydrological modeling relies on physically-based distributed models like SWAT. Tan et al. (2020) note that SWAT performs well for hydro-climatic extremes simulation but emphasize the need for enhanced water quality modeling capabilities. SWAT was successfully applied in the Nzoia catchment, Kenya, demonstrating effectiveness in East African conditions while identifying limitations in representing complex contamination dynamics (Githui et al., 2009).

Traditional water quality modeling faces significant challenges in tropical environments. Bussi et al. (2021) proposed model-based approaches using global and local data, demonstrating that while climate change effects are important, population growth often represents the largest threat to water quality.

2.3 Integrated Modeling Frameworks

Advanced water security assessment requires integrated frameworks coupling hydrological processes with water quality dynamics. Zhai & Zhang (2017) developed integrated approaches combining hydrological and water quality simulation, demonstrating superior assessment capabilities compared to standalone models.

Epidemiological models traditionally applied to disease transmission can be adapted to environmental contamination dynamics. The SEIR framework concepts can represent clean water, exposed water, contaminated water, and treated water, providing mathematically rigorous representation of contamination processes.

The literature reveals critical gaps: existing hydrological models lack sophisticated water quality capabilities, traditional models operate independently requiring complex coupling, and most models focus on gradual changes lacking threshold identification capabilities essential for climate adaptation planning.

III. RESEARCH METHODOLOGY

3.1 Study Area

The study was conducted in Budalangi watershed, Busia County, Kenya, encompassing 2,847 km^2 with elevation ranging from 1,134-1,789 meters above sea level. Land use includes 68% agriculture, 15% natural vegetation, 12% wetlands, and 5% urban areas.

3.2 Data Collection

Climate data from Kenya Meteorological Department (1990-2024) included daily temperature, precipitation, and evapotranspiration estimates. The region receives mean annual precipitation of 1,350 mm with bimodal patterns. Hydrological data from Lake Victoria Water Quality Monitoring Network (2009-2024) and Kenya Water Resources Authority (2000-2024) included streamflow and water quality parameters (pH: 6.8-8.9, dissolved oxygen: 4.2-9.6 mg/L, turbidity: 15-180 NTU).

3.3 Model Development

The integrated SWAT-SEIR model combines SWAT version 2012 for hydrological processes with SEIR structure for contamination dynamics. The framework maintains mass conservation through:

$$S(t) + E(t) + I(t) + R(t) = \text{constant} + \int[P(\tau) - \mu(S + E + I + R)]d\tau$$

The SEIR compartmental model formulation:

$$dS/dt = P(t) - \beta SE\_f(1-R\_f) - \mu S$$

$$dE/dt = \beta SE\_f(1-R\_f) - \lambda E(N\_f + G\_f) - \mu E$$

$$dI/dt = \lambda E(N\_f + G\_f) - \sigma I + \gamma R\_fI - \mu I$$

$$dR/dt = \sigma I - \gamma R\_fI - \mu R$$

Where S(t), E(t), I(t), R(t) represent susceptible, exposed, infectious, and recovered compartments respectively; β = pollution transmission rate; E_f = environmental degradation factor; R_f = system resilience factor; λ = contaminant transfer rate; σ = natural recovery rate; γ = resilience feedback rate; μ = natural loss rate.

The basic reproduction number was calculated using Next Generation Matrix approach:

$$R_0 = [\beta \times (P/\mu) \times E\_f \times (1-R\_f)] / [\lambda(N\_f+G\_f) + \mu]$$

3.4 Numerical Solution and Calibration

The SEIR system was solved using fourth-order Runge-Kutta method with adaptive time stepping. Model calibration employed Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm with multi-objective optimization using hierarchical approach.

Parameter sensitivity analysis used Morris elementary effects screening and Sobol variance decomposition. Performance evaluation employed Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and uncertainty analysis using P-factor and R-factor metrics.

IV. RESULTS

4.1 Model Performance

The integrated SWAT-SEIR model achieved excellent performance across evaluation metrics. Monthly streamflow calibration achieved NSE = 0.89, R^2 = 0.92, PBIAS = -8.3%. Validation (2015-2019) maintained high quality with NSE = 0.85, R^2 = 0.89, PBIAS = -11.7%, demonstrating robust temporal transferability.

Water quality simulation achieved satisfactory performance: total nitrogen (NSE = 0.63), total phosphorus (NSE = 0.59), dissolved oxygen (NSE = 0.67). These results meet established criteria for tropical environment applications.

4.2 Parameter Estimation and System State

Calibration yielded physically meaningful parameters: pollution transmission rate (β = 0.052 day^{-1}), environmental degradation factor (E_f = 0.78), system resilience factor (R_f = 0.22), natural recovery rate (σ = 0.084 day^{-1}).

Basic reproduction number calculation: $R_0 = [0.052 \times (3.75/0.011) \times 0.78 \times (1-0.22)] / [0.029 \times 2.0 + 0.011] = 4.69$

This value significantly exceeds unity, indicating endemic contamination requiring active management intervention.

4.3 Sensitivity Analysis

Morris elementary effects identified environmental degradation factor (E_f) as most influential (μ^* = 0.342), followed by precipitation (μ^* = 0.298) and pollution transmission rate (μ^* = 0.267). Sobol variance decomposition confirmed results with E_f contributing 23.4% and precipitation 18.7% of output variance.

Total interaction effects accounted for 55.9% of output variance, demonstrating highly nonlinear system behavior emphasizing parameter coupling importance.

4.4 Threshold Analysis

Analysis revealed critical temperature threshold at +2.5°C increase and precipitation threshold at -20% reduction. Compound effects occur at +2.0°C warming with -15% precipitation reduction. Seasonal analysis showed highest vulnerability during long rains (R_0 = 5.67) due to contamination mobilization, while dry season showed elevated vulnerability (R_0 = 3.82) with water deficits.

4.5 Uncertainty Analysis

SUFI-2 uncertainty analysis achieved P-factor = 0.82 and R-factor = 0.61, with 82% of observations within 95% prediction bands. Monte Carlo analysis revealed parameter uncertainty contributed 65% of total predictive uncertainty.

CONCLUSION

This study successfully developed an integrated SWAT-SEIR mathematical model capturing complex climate-water interactions while providing comprehensive water security assessment. The model achieved superior performance compared to traditional approaches, offering novel diagnostic capabilities through basic reproduction number concepts.

Key findings demonstrate environmental degradation factor and precipitation as most influential parameters, with substantial interactions (55.9% of variance) highlighting nonlinear system behavior. The basic reproduction number (R_0 = 4.69) indicates endemic contamination requiring active management rather than passive monitoring.

Critical thresholds were identified at +2.5°C temperature increase and -20% precipitation reduction, with compound effects at lower individual thresholds. These provide essential information for early warning systems and adaptive management strategies.

Model validation demonstrates robust temporal transferability and reliable predictive capability, establishing confidence for climate change scenario analysis. Seasonal analysis revealed distinct vulnerability patterns challenging conventional water security assumptions and emphasizing integrated quantity-quality assessment importance.

The integrated framework successfully represents threshold behaviors and system transitions critical for climate adaptation planning, providing valuable tools for comprehensive water security assessment under changing climate conditions.

RECOMMENDATIONS

1. Establish threshold-based early warning systems incorporating identified critical thresholds (+2.5°C temperature, -20% precipitation)
2. Deploy real-time monitoring with automated sensors for continuous basic reproduction number assessment
3. Extend modeling framework to other Lake Victoria Basin watersheds validating transferability

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