

Research Article

Application of the QUAL2K Water Quality Model to Assess Pollutant Dispersion in River Sosiani in Western Kenya

Maemba Okori^{*} , Julius Kipkemboi Kollongei 

Department of Agricultural and Biosystems Engineering, University of Eldoret, Eldoret City, Kenya

Abstract

This study applied the QUAL2K water quality model to investigate the pollutant dispersion dynamics in River Sosiani, a vital freshwater source in western Kenya. The river, which historically supported diverse domestic, agricultural and recreational uses for the Eldoret City residents, is currently facing severe degradation due to urbanization and inadequate waste management practices. The model was calibrated and validated using weekly field data collected over six months from designated sampling points. Model performance was evaluated using standard statistical measures, including the R-Squared correlation (R^2), the Nash-Sutcliffe efficiency (NSE), and the ratio of the Root Mean Square Error to the observations' standard deviation (RSR). The results demonstrated good to excellent performance, with R^2 values ranging from 0.82 to 0.95, NSE value above 0.75, and RSR values below 0.5 confirming the model's reliability in simulating the rivers pollutant dispersion dynamics. The simulation results revealed deterioration in water quality from upstream to downstream. Precisely, dissolved oxygen (DO) decreased significantly along the river course, while carbonaceous biochemical oxygen demand (CBOD_f), electrical conductivity (EC), temperature, total phosphate (TP), and nitrate-nitrogen (NO₃-N) concentration all increased. pH remained within the neutral to slightly alkaline range, with some localized shifts downstream, while flow discharge (DS) increased progressively from upstream to downstream. These trends, revealing an increasing pollution load, mainly in urbanized areas, highlight the significant impact of anthropogenic activities on River Sosiani ecological health and underline the urgent need for targeted interventions to mitigate further degradation.

Keywords

QUAL2K Model, River Sosiani, Water Quality Parameters, Pollutant Dispersion, Performance Evaluation, Modelling

1. Introduction

Urban rivers globally are increasingly threatened by pollution due to rapid industrialization, urbanization, and inadequate waste management [1]. This pollution poses significant risk to water quality, aquatic ecosystems, public health and local livelihoods especially in developing countries necessitating effective management strategies. River Sosiani in western part of Kenya exemplifies these challenges as it

traverses through diverse land use activities and densely populated Eldoret city. Originally a vital source of freshwater for Eldoret residents and neighboring towns supporting agricultural, recreational and domestic uses, River Sosiani has been converted to a conduit for untreated agricultural, industrial and municipal effluents [2]. This transformation has rendered the River Sosiani unfit for most utilization, threat-

^{*}Corresponding author: maemba@uoeld.ac.ke (Maemba Okori), emmanuel.okori58@gmail.com (Maemba Okori)

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ening both public health and ecological integrity.

Degradation of River Sosiani reflects common challenge many developing urban centers are struggling with, where efforts to boost economic development have negatively impacted environmental sustainability. The discharge of untreated or partially treated effluents affects the river's natural self-purification capacity, leading to decrease in dissolved oxygen levels, accumulation of toxic substances and eutrophication [3]. Additionally, these pollutants not only undermine the aquatic life but also pose eminent risks to human health through direct contact, consumption of polluted water and bioconcentration of pollutants in the food chain [4].

The existing body of research on River Sosiani has mostly concentrated on empirical water quality monitoring. Studies [2, 5] established significant spatiotemporal variation in parameters such as TSS, turbidity, BOD, DO, temperature, TDS, EC, nitrate and phosphate along the river, attributing parameter spikes to unregulated point source discharges and urban runoff. Further work [6] examined the dispersal of Faecal Coliforms and associated these with waterborne diseases prevalence in downstream populations, underscoring the socio-health implications of riverine pollution. Broadening the scope, another study [7] evaluated health risk associated with heavy metal contamination and discovered that children exposed to lead-contaminated water from the river had higher hazard indices and an increased lifetime cancer risk.

Despite these significant advances, predictive modelling of pollutant dynamics in River Sosiani catchment remain inadequately underdeveloped. Current studies fall short of estimating contaminant fate under various environmental or anthropogenic situations. Furthermore, there is a lack of integration between biological, chemical and hydrological data to determine how pollutants disperse longitudinally. To address these gaps, the present study was formulated with the aim of developing a robust and comprehensive water quality model for River Sosiani using QUAL2K framework. Specifically,

the research models pollutants dispersion dynamics in River Sosiani considering both point and non-point sources and evaluates the model performance. QUAL2K model has been effectively applied in a number of riverine ecosystems globally, however no published study has implemented the model in River Sosiani catchment. The aim of the study was to model the water quality of polluted segment of River Sosiani by the comprehensive application of QUAL2K model and evaluate the performance of the model using statistics based on R^2 , RSR and NSE.

2. Materials and Methods

2.1. Study Area and Sampling Point Description

The study area is located in Uasin Gishu County in the former Rift Valley province in Kenya. The River Sosiani catchment lies between latitude 00°18'00"N, 00°37'00"N and longitude 035°00'00"E, 035°35'00"E within the elevation range of 2,764 m and 2004 m above the seal level (Figure 1). River Sosiani emanates from the Two River Dam in Kipkorgot, a confluence of Endoroto and Ellegerini streams, whose origin is the Kaptagat forest in the highlands of the Keiyo escarpment. River Sosiani and its tributaries traverses through diverse land use area including forests, peri-urban agricultural fields, car wash stations, industrial zones, municipal waste discharge points and informal settlements. The catchment constitutes a sub-basin of the larger River Nzoia, a sub-catchment that empties into Lake Victoria, the largest freshwater lake in Africa and the second largest in the world. Six sampling points were selected based on accessibility and ensuring they accurately reflect the impact of land use types nearby and upstream (Figure 1). The selected sampling points are described in Table 1 below.

Table 1. Sampling points description in River Sosiani catchment.

Sampling point	Location	Description
SP1	Plateau bridge, upstream of River Endoroto	Wetland and minimal anthropogenic activity
SP2	Naiberi bridge, upstream of River Ellegerini	Forest and minimal anthropogenic activity
SP3	Kolol bridge, immediately after the Two Rivers Dam	Livestock farming and agricultural zone
SP4	Annex bridge	Agricultural and carwash zone
SP5	West indies bridge	Urban runoff, industrial effluent hotspot and residential discharge
SP6	Solo bridge in Huruma	Informal settlement, solid waste leachate exposure and municipal effluent discharge zone

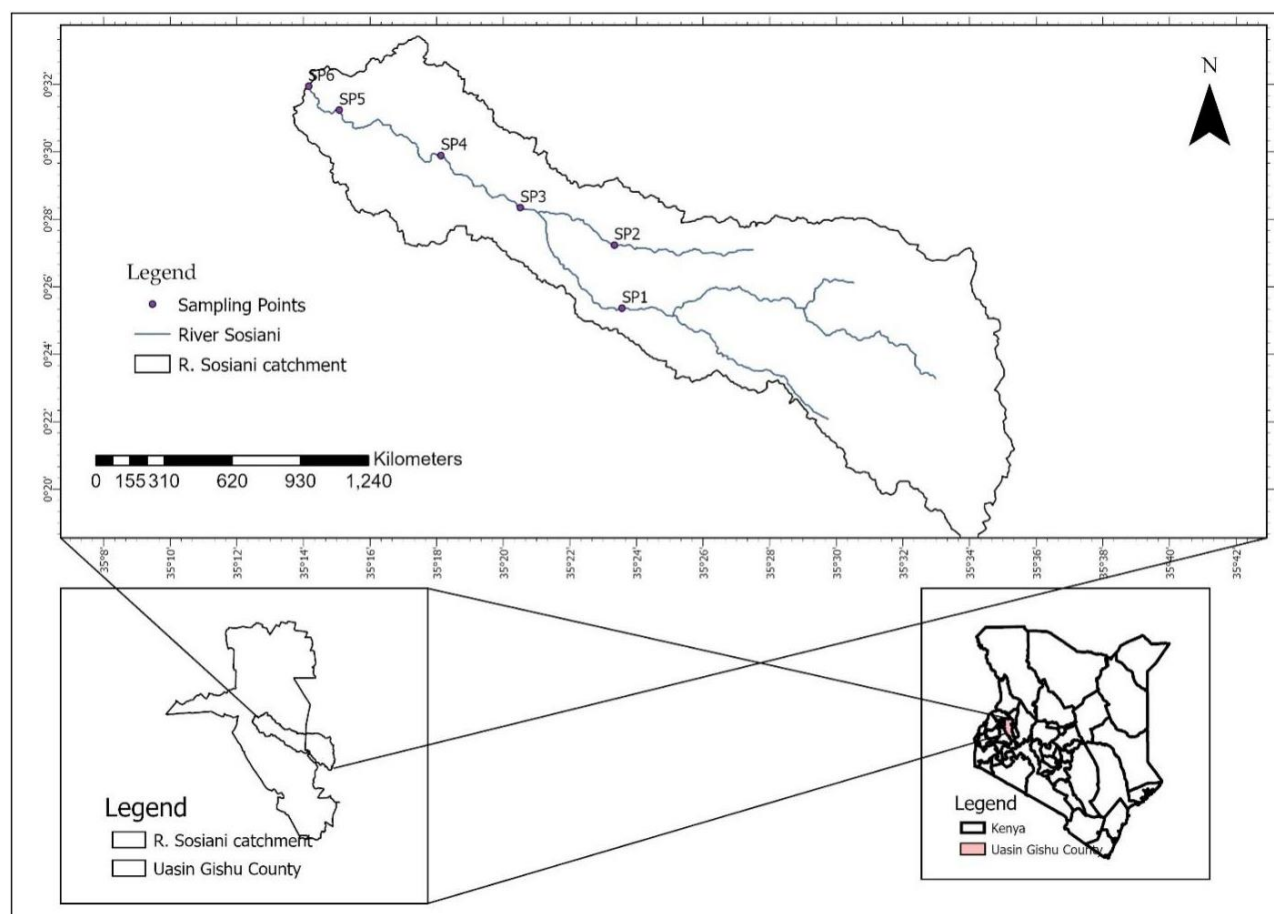


Figure 1. The River Sosiani Catchment and Sampling Points, Uasin Gishu County, Western Kenya [2].

2.2. Data Collection

2.2.1. Water Quality Parameter Sampling and Analysis

Field campaigns were carried out from the 6 sampling points on a weekly basis for a period of 6 months starting from February to July 2023 to capture both dry (Feb-Mar) and wet season (Apr-Jul) data variability. Duplicate grab water samples were collected using clean plastic bottles at 0.5 m depth in the sampling points. In-situ measurements for temperature, EC and pH were performed using Hanna instrument model HI 9811-5 Portable pH/EC/TDS/°C Meters while DO was measured using SX716 model dissolved oxygen meter. Both

the instruments were checked for faults and calibrated before the commencement of data collection with standard reference solutions as per the instrument's manual instructions to ensure accuracy.

Samples for $\text{NO}_3\text{-N}$ and TP were collected in 500 ml plastic bottles while Biochemical Oxygen Demand (BOD_5) samples were collected in duplicate in 500 ml BOD-sampling bottles, labelled based on sampling site and then kept in the ice-cold cooler box before transportation to the laboratory for examination [8]. Standard methods for examination of water quality parameters were applied [9]. These data informed boundary conditions and pollutant loads in QUAL2K simulations, particularly for evaluating pollutant dispersion dynamics.

Table 2. Physicochemical parameters of the water samples in dry and wet seasons.

Sampling point	Season	Parameter							
		DO (mg/L)	CBODf (mg/L)	Temp (°C)	EC ($\mu\text{S}/\text{cm}$)	pH	$\text{NO}_3\text{-N}$ (mg/L)	TP (mg/L)	DS (m^3/s)
SP1	Dry	7.39	1.94	20.49	87.78	7.02	1.25	0.22	0.01
	Wet	9.19	1.30	16.89	32.35	7.10	0.86	0.10	0.62

Sampling point	Season	Parameter							
		DO (mg/L)	CBODf (mg/L)	Temp (°C)	EC (µS/cm)	pH	NO ₃ -N (mg/L)	TP (mg/L)	DS (m ³ /s)
SP2	Dry	7.88	1.72	19.10	76.67	6.91	0.94	0.13	0.04
	Wet	8.91	1.06	17.39	27.65	7.10	0.52	0.06	0.60
SP3	Dry	6.66	2.82	24.07	97.78	7.62	1.26	0.23	0.05
	Wet	8.36	1.8	18.94	31.76	7.16	0.92	0.12	1.89
SP4	Dry	7.07	2.39	21.97	158.89	7.41	1.26	0.24	0.06
	Wet	8.27	1.84	19.44	38.24	7.29	0.93	0.13	1.92
SP5	Dry	5.71	4.99	24.11	198.89	7.67	1.5	0.43	1.09
	Wet	7.53	4.21	20.21	79.41	7.42	1.22	0.22	4.29
SP6	Dry	5.38	5.2	25.78	342.22	8.24	1.75	0.64	1.51
	Wet	7.22	4.43	21.08	115.29	7.72	1.31	0.32	5.07

2.2.2. Geometric and Hydraulic River Data

Data on River Sosiani geometric (e.g., width, depth and slope) was collected using both field survey and remote sensing techniques. Land use data for the watershed was gathered using field surveys and satellite images to assess non-point pollution sources. Stream velocity was estimated using the float object method validated using empirical equations (Manning's equation). To determine river discharge a velocity- area method and correction factor of 0.85 was used in calculation [10]. This data was essential for parameterizing and running the QUAL2K model to simulate pollutant dispersion and water quality dynamics along River Sosiani research area.

2.2.3. Catchment Climate Data

Meteorological input data for the catchment required by QUAL2K model was obtained from Eldoret meteorological department in Kapsoya.

2.3. Modelling Approach: QUAL2K Framework

2.3.1. Overview of QUAL2K

Qual2K model is a one-dimensional steady state water

quality model widely used to predict instream water quality parameters [11]. The water quality parameters include BOD, DO, organic nitrogen, temperature, nitrite, nitrate, ammonia, dissolved phosphorous, organic phosphorous, coliforms, algae as chlorophyll, three conservative constituents' solute and one arbitrary non-conservative constituents' solute in any combination selected by the user. Qual2K is an upgraded version of Qual2E developed by the United States Environmental Protection Agency (US-EPA) [11]. The model is freely available from its website and utilizes Microsoft excel as the graphical user interface.

2.3.2. Model Setup and Configuration

River Sosiani was segmented into 4 reaches, with each reach further divided into 3-5 computational River elements to a total of 18 elements with numbering beginning from mainstem headwater (Figure 2). Lateral inflows were incorporated at relevant reaches using measured flow rates and pollutant concentrations. River Ellegerini (SP2) and other streams downstream and Huruma waste water treatment plant were treated as point sources since they confluences with the main river, for the purpose of modeling using the QUAL2K model. Upstream flow and quality data from SP1 served as the upstream boundary.

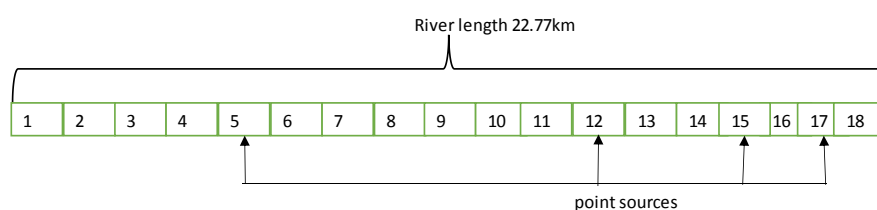


Figure 2. River Sosiani Segmentation.

2.3.3. Model Calibration and Validation

The study performed two model calibration which included water quality and hydraulic parameter calibration using data collected in dry season (February-march 2023). Water discharge (DS) was chosen for hydraulic calibration, while for water quality calibration the selected parameters were, Temperature, EC, DO, CBODf, pH, NO₃-N, and TP. The model was validated by utilizing observed water quality and flow discharge (DS) data collected from different sampling point in River Sosiani during the wet season (April-July 2023). The process was done without changing the calibrated parameters.

2.4. Data Analysis and Visualization

Model output from QUAL2K were exported and processed using R programming language for visualisation. The model performance efficiency for both calibration and validation were evaluated using three measures of fitness namely; R-squared correlation (R^2), ratio of Root Mean Square Error to observations standard deviation (RSR) and Nash-Sutcliffe efficiency

(NSE).

3. Results and Discussion

The results of the parameters simulated by the model in both calibration and validation are shown in Figures 3 and 4 respectively. (OB-observed, SIM- simulated). The results from the graphs show the simulated data (SIM) pattern were comparable to the observed data (OB) at five sampling point along River Sosiani mainstream. The calibration and validation results of the QUAL2K model revealed good agreement between the observed and simulated values, with a few exceptions.

From the results obtained for calibration and validation, the performance of the model was evaluated using R^2 (R-squared correlation), RSR (The RMSE-observations standard deviation ratio) and NSE (The Nash-Sutcliffe efficiency) statistical criteria. The error between the simulated and observed value for all parameters for both calibration and validation are given in Table 3.

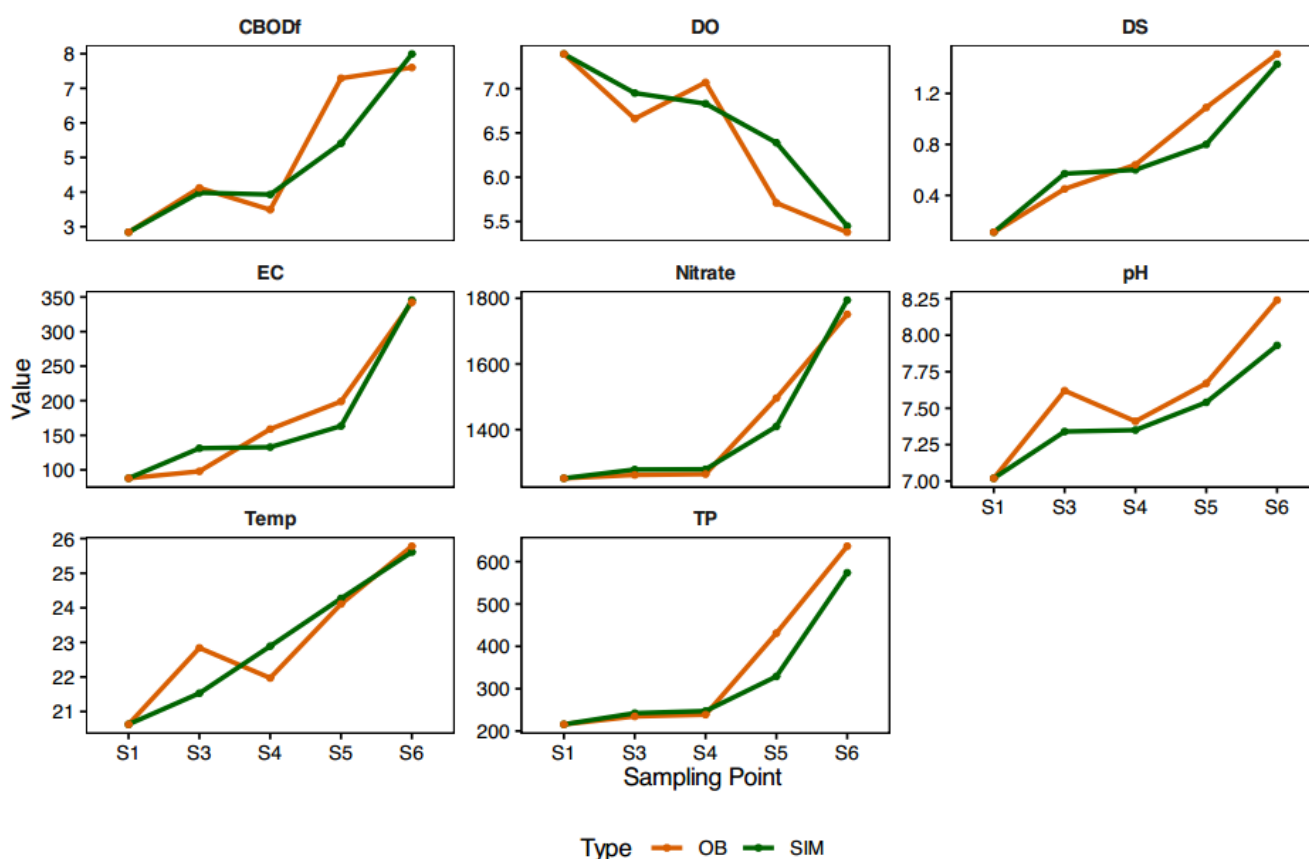


Figure 3. Comparison of observed and simulated data for calibration.

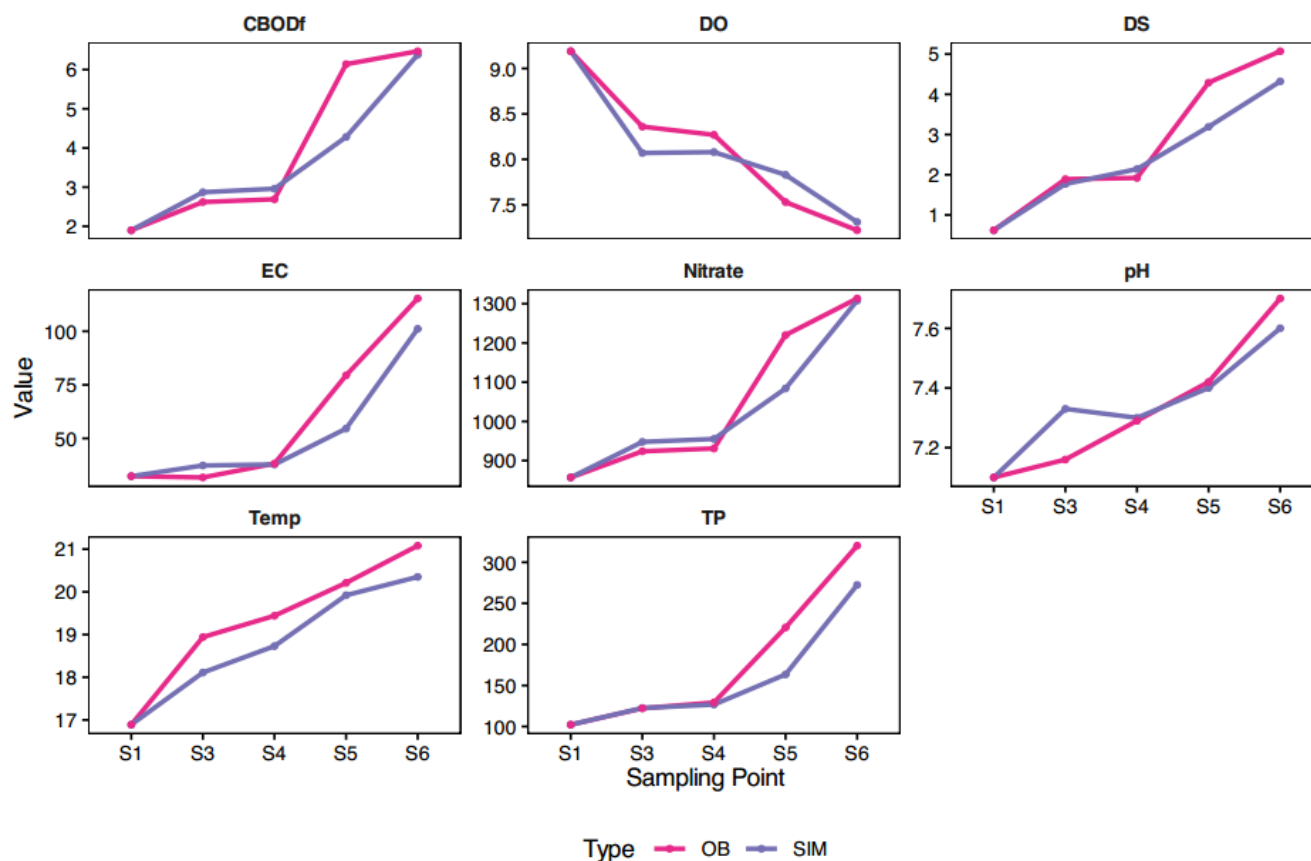


Figure 4. Comparison of observed and simulated data for validation.

Table 3. Statistical errors of parameters for model calibration and validation.

Evaluation Statistics	Modelling Phase	Parameters							
		DS	Temp	EC	DO	CBODf	NO ₃ -N	TP	PH
R ²	Calibration	0.94	0.84	0.93	0.84	0.82	0.95	0.95	0.95
	Validation	0.92	0.96	0.95	0.91	0.84	0.9	0.96	0.86
RSR	Calibration	0.26	0.37	0.24	0.4	0.4	0.2	0.3	0.45
	Validation	0.33	0.38	0.35	0.27	0.39	0.31	0.37	0.37
NSE	Calibration	0.91	0.83	0.93	0.8	0.8	0.95	0.89	0.75
	Validation	0.86	0.82	0.92	0.91	0.81	0.88	0.83	0.83

The model evaluation results demonstrate very good to excellent performance in both calibration and validation. The R² correlation values for all parameters ranged from 0.82 to 0.95, with values for EC, TP, pH, Discharge and NO₃-N exceeding 0.90, regarded as excellent level of model performance [12]. DO and CBODf recorded R² values between 0.75 and 0.90, reflecting very good model performance criteria [12, 13]. Similarly, in validation phase, R² value for Temperature, EC, DO, TP and NO₃-N also exceeded 0.90, reinforcing the model's excellent simulative capacity, while CBODf and pH

maintained a strong correlation of 0.84 and 0.86 respectively, again within a good range. Furthermore the NSE values for all parameters were above 0.75 and the RSR values were below 0.5 in both calibration and validation, indicative of a very good model performance thresholds [13, 14]. Overall, the high R² and NSE values alongside low RSR values indicate that the model provides a very good to excellent fit between observed and simulated data, affirming its reliability and applicability in stream water quality modelling.

The calibration results of the model output Figure 3, show

deterioration of water quality parameters from the headwaters (SP1) to downstream (SP6) area. Acceptable river ecological health often includes DO level at or above 4 mg/l and BOD₅ not exceeding 4 mg/l DO [15]. The DO level along the River Sosiani decreased from the upstream to the downstream. Between SP1 and SP3, consistently high DO levels (>6 mg/l) in River Sosiani suggest moderate self-purification, likely due to minimal anthropogenic activities in the upstream. Conversely, downstream DO levels sharply decline to hypoxic levels (<4.0 mg/L) around SP5 and SP6 due to organic loading from urban runoff, industrial effluents, and sewage, threatening aquatic life. The other water quality parameters increased along River Sosiani from the headwaters to the downstream. CBODf, EC, TP and NO₃-N show low concentration at SP1 reflecting minimal pollution in this section. This can be attributed to minimal upstream pollution sources and the presence of a wetland located upstream of SP1, that acts as a natural purifier by trapping sediments and absorbing agricultural nutrients before they enter this section of the river. They rise notably at SP3 and SP4, where livestock farming, agriculture and carwash activities are prominent indicating organic runoff from farming, animal waste, and detergents. At SP5 and SP6 which receives untreated residential sewage, industrial effluent and urban leachates, a significant spike of CBODf, EC, TP and NO₃-N appear due to high organic loads. High downstream levels of these water quality parameters suggest potential chronic nutrient enrichment and ecological stress posing a risk for downstream eutrophication during low flow in dry season. Temperature increases from upstream to downstream, with lowest at SP1 and SP3 due to wetland shading and riparian trees buffering solar heating. From SP4 to SP6, temperatures sharply increase due to open canopy, urban heat and warm effluents discharge. These warm temperatures, especially at SP5 and SP6, amplify eutrophication risk by favoring cyanobacterial dominance and faster algal turnover. The pH levels remained within the neutral to slightly alkaline range (6.8-8.4). At SP1 and SP3, pH values reflect stable, buffered conditions. However, localized shifts at SP5 and SP6 suggest possible contribution from industrial effluent, detergents and organic decay processes, which alkalize the water downstream. The discharge (DS) shows increasing trend from SP1 to SP6 indicating increasing flow downstream reflecting the cumulative input of water from tributaries, point and diffuse sources along River Sosiani. These findings mirrored with [16, 17] study findings, revealing decline in self-purification of Haraz River and Likas River respectively due to organic matter loading from polluted point sources.

The validation stage Figure 4, exhibits both consistent and distinct difference when compared the calibration stage. These variations can be attributed to increased surface runoff, higher dilution effects and intensified non-point pollution sources typically experienced during wet season. The DO trend during validation mirrored the calibration phase but showed higher overall values across the sampling point. SP5 and SP6, influenced by urban runoff, industrial discharges and

sewerage, exhibited DO depressions, though slightly evaluated compared to the dry season. These could be attributed to dilution effects from increased river flow likely diluting oxygen demanding substances, leading to enhancing DO availability. CBODf, EC, TP and NO₃-N increased from upstream to downstream but concentration levels were lower than the calibration value. SP5 and SP6 still recorded relatively elevated CBODf due to persistent municipal and industrial waste inflows, though lower than in the calibration phase. Lower CBODf levels could be linked to rainfall diluting organic pollutants, while the increased flow likely improved their dispersion and microbial breakdown. EC levels dropped across all the sampling points, reflecting lower dissolved ion concentration from dilution. SP5 and SP6, which showed the highest EC concentration in dry season due to wastewater and solid waste leachate, dropped due to rain-induced dilution. Decline in NO₃-N at SP3, where agriculture dominates could be attributed to rainwater flushing fertilizers before significant leaching into River Sosiani. Similarly, the most significant drop in TP levels were observed at SP5 and SP6, where high concentration during dry season was linked to sewage and waste discharge. Although these point pollution sources remained, the increased water flow during the wet season diluted and reduced the pollutants level. Temperature declined slightly in wet season in all sampling points in comparison to dry season. These could be linked to overcast condition, increased baseflow and rainfall introducing cooler runoff into River Sosiani. The pH remained within near neutral range during wet season where increased inflow regulated extreme pH deviation. Discharge was notably higher in wet season due to rainfall.

4. Conclusion and Recommendation

The study successfully developed and applied water quality model for River Sosiani using QUAL2K framework, achieving the study objective of modelling pollutant dynamics while evaluating the contribution of both point and non-point sources. The model was calibrated and validated using field data from six sampling points (SP1-SP6), reflecting diverse land uses in River Sosiani catchment. The model performance was evaluated using R², RSR and NSE. The results of model performance revealed good fit between observed and simulated data in both calibration and validation. The model output reveal deterioration in water quality from upstream to downstream, characterized by decreased DO and Increased Temperature, CBODf, EC, TP, NO₃-N, pH and DS. These findings highlight the urgent need for proactive interventions to mitigate further deterioration of this vital water resource. It is recommended that management strategies prioritize pollution control at the Huruma WWTP, development and implementation of an integrated watershed management plan, and promotion of community awareness and participation in water quality protection.

Abbreviations

CBODf	Carbonaceous Biochemical Oxygen Demand
DO	Dissolved Oxygen
DS	Flow Discharge
EC	Electrical Conductivity
NSE	The Nash-Sutcliffe efficiency
R ²	R-squared Correlation
RSR	The RMSE-observations Standard Deviation Ratio
TP	Total Phosphate

Author Contributions

Maemba Okori: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Julius Kipkemboi Kollongei: Software, Supervision, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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