

Modelling Urban River Pollution Dynamics and Sources Using QUAL2Kw: Implications for Water Quality Management in the Cikapundung River

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Abstract:

Rapidly growing cities face increasing pressure from domestic and industrial activities, leading to significant water quality degradation. The Cikapundung River in Bandung, Indonesia, has experienced declining water quality due to intensified anthropogenic influences. This study aims to model pollution dynamics, quantify pollutant loads from multiple sources, and evaluate their implications for river water quality management. A combination of field measurements, secondary data, and the QUAL2Kw model was employed to simulate the spatial variation of key parameters, including biochemical oxygen demand, chemical oxygen demand, dissolved oxygen, and ammonia. Pollution loads from both point and non-point sources were estimated, and the model was calibrated and validated using observed data. Simulations were further conducted to assess the potential effectiveness of different pollution control strategies. The results reveal significant spatial variability in water quality along the river, with pollutant concentrations increasing downstream, primarily driven by untreated wastewater. Model outputs indicate that several river segments exceed permissible water quality standards, particularly for BOD and COD, reflecting high organic pollution loads. Scenario analysis demonstrates that reducing domestic wastewater inputs and improving waste treatment infrastructure could substantially enhance water quality conditions. This study highlights the critical role of integrated water quality modeling in understanding urban river pollution.

Keywords: Urban river pollution, water quality modeling, pollution dynamics, water quality management.

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1. INTRODUCTION

Urban rivers constitute a vital element of urban ecosystems, playing a significant role in sustaining human well-being and supporting economic development (Francis, 2012). They provide essential water resources for domestic consumption, agriculture, and industrial activities, while also delivering a wide range of ecosystem services that enhance environmental quality and urban livability (Marselina et al., 2022). Despite these benefits, the rapid expansion of urban areas, coupled with increasing population pressures, has placed considerable strain on river systems. This challenge is particularly pronounced in low- and middle-income countries, where urban growth often outpaces the development of adequate wastewater management infrastructure (UNESCO, 2017). Consequently, many urban rivers have become primary receivers of untreated or insufficiently treated wastewater from domestic, industrial, and surface runoff sources, leading to progressive deterioration of water quality and ecological degradation (Alcamo, 2001).

In these regions, the problem of urban river pollution is further intensified by structural and institutional limitations. Inadequate sanitation facilities, weak enforcement of environmental regulations, and the close spatial interaction between residential settlements and industrial activities contribute to the direct discharge of pollutants into river systems (Marselina, Putri, et al., 2025). As a result, rivers are subjected to high organic and nutrient loads, typically indicated by elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammonia concentrations, alongside reduced dissolved oxygen (DO) levels (Marselina, *et al.*, 2025). These conditions disrupt aquatic ecosystems, threaten biodiversity, and pose serious risks to human health. Additionally, deteriorating water quality increases the cost and complexity of water treatment for downstream users, thereby amplifying socio-economic burdens (Chapra, 2008; Paul & Meyer, 2001; WHO, 2017; Amalia, *et al* 2021).

Indonesia, as one of the rapidly urbanizing low- and middle-income countries, faces challenges similar to those observed globally in managing urban river water quality (Asian Development Bank [ADB], 2020). Rivers flowing through major urban centers have experienced significant environmental degradation due to continuous discharges of domestic wastewater and industrial effluents (UNEP, 2016; World Bank, 2019; Asdak, 2010). Among these, the Citarum River Basin has gained international attention because of its severe pollution levels and is often cited as one of the most polluted river systems worldwide (Department, 2019). Within this basin, tributaries play a crucial role in influencing overall water quality (Ministry of Industry Republic of Indonesia, 2019).

The Cikapundung River, which flows through Bandung City, represents a key tributary that contributes substantially to the pollution dynamics of the Citarum system. However, compared to the main river, it has received relatively limited scientific investigation (ADB, 2016; BBWS Citarum, 2018). Beyond conventional indicators of organic pollution such as BOD and COD, ammonia nitrogen (NH₃-N) is recognized as a critical parameter in assessing water quality in urban rivers (Andara et al, 2014). This is

particularly relevant in contexts where domestic wastewater is discharged with minimal or no treatment (Metcalf & Eddy, 2014; Cha.pra, 2008). Ammonia is primarily derived from sewage and livestock waste, and its presence in elevated concentrations significantly contributes to oxygen depletion through nitrification processes (Rasmikayati et al, 2017).

Furthermore, ammonia can exert toxic effects on aquatic organisms, thereby compromising ecological integrity (Camargo & Alonso, 2006; Metcalf & Eddy, 2014). Empirical studies conducted in Indonesian urban rivers, including the Cikapundung River, have reported elevated ammonia concentrations, reflecting ongoing nutrient enrichment and persistent domestic wastewater pollution (Fitriana et al., 2024; Fitriana et al., 2025). These findings underscore the importance of incorporating ammonia as a key parameter in water quality assessment and modeling to better understand biogeochemical processes and inform effective management strategies (Marselina et al., 2025).

The vulnerability of the Cikapundung River to pollution is closely linked to its geographical and socio-economic context. Flowing through densely populated and industrialized areas of Bandung City, the river is exposed to multiple pollution sources, including domestic sewage and industrial discharges (BBWS Citarum, 2018; BPLHD Jawa Barat, 2017; ADB, 2016). Previous studies have consistently reported declining water quality in the river, characterized by elevated BOD and COD levels, reduced dissolved oxygen concentrations, and increased nutrient loads, particularly ammonia (Yustiani & Sutjiningsih, 2019; Yustiani & Wicaksono, 2021; Fitriana et al., 2024). Such conditions not only threaten the ecological health of the river but also undermine ongoing efforts to improve water quality in the downstream sections of the Citarum River Basin (Aswan, 2017).

To address these complex challenges, water quality modeling has emerged as an essential tool for river management and decision-making. These models enable the simulation of pollutant transport and transformation processes, as well as the evaluation of different management scenarios. One widely used model is QUAL2K, developed by the United States Environmental Protection Agency, which is capable of simulating steady-state water quality conditions under varying pollutant loads and hydraulic characteristics (Chapra et al., 2008). In Indonesia, the application of QUAL2K in various river systems, including the Citarum River, has demonstrated its effectiveness in estimating pollution loads and assessing the potential impacts of pollution control strategies (Hartono et al., 2021; Fitriana et al., 2024).

Despite the growing application of water quality models, a significant research gap remains in the context of the Cikapundung River. Existing studies have largely focused on domestic wastewater as the primary source of pollution, while the contribution of industrial effluents particularly from small- and medium-scale industries has often been inadequately addressed or oversimplified (ADB, 2016; BBWS Citarum, 2018). Moreover,

there is a lack of comprehensive scenario-based analyses using calibrated models to evaluate the effectiveness of different pollution reduction strategies. This limitation hinders the development of targeted and evidence-based management interventions for improving river water quality (Chapra, 2008; World Bank, 2019).

Therefore, this study aims to bridge this gap by applying the QUAL2K water quality model to the Cikapundung River, with a particular emphasis on the combined impacts of domestic and industrial wastewater discharges (Jayanti et al., 2023). By integrating field measurements, secondary data, and model calibration, the research evaluates current water quality conditions and simulates alternative pollution management scenarios. These scenarios include reductions in domestic wastewater loads, improved regulation of industrial discharges, and integrated approaches addressing both sources simultaneously.

The model outputs are analyzed based on key water quality parameters, including BOD, COD, dissolved oxygen, and ammonia.

2. METHODOLOGY

2.1 Research workflow

This study adopted a quantitative, model-based environmental assessment approach to evaluate the water quality of the Cikapundung River under existing conditions and alternative pollution management scenarios. The research followed a systematic workflow comprising problem identification, literature review, data collection, data processing, water quality modeling, calibration and validation, scenario simulation, and results interpretation. The study began with problem identification and a comprehensive literature review to establish the research scope and theoretical foundation.

This stage focused on urban river pollution, pollutant transport processes, and water quality modeling, and supported the selection of the QUAL2Kw model as the primary analytical tool. The workflow ensured the integration of field measurements and secondary data into a consistent modeling framework for both diagnostic and predictive analysis.

2.2 Study area

The study was conducted in the Cikapundung River, an urban river system located in the Bandung Metropolitan Area, West Java, Indonesia. The river originates from the northern highlands of Lembang–Maribaya and flows through the urban core of Bandung before discharging into the Citarum River in the Bojongsoang area. The river system exhibits distinct longitudinal characteristics. The upstream section is relatively less disturbed, with forested land cover and low population density.

In contrast, the midstream section is highly urbanized, receiving substantial inputs from domestic wastewater, urban runoff, and small-scale industrial activities. The downstream section represents a pollution accumulation zone influenced by both upstream and local pollutant sources. To capture spatial variations in water quality, four

sampling stations were selected to represent upstream, midstream, and downstream conditions. This stratified spatial arrangement enabled a comprehensive assessment of pollution dynamics along the river.

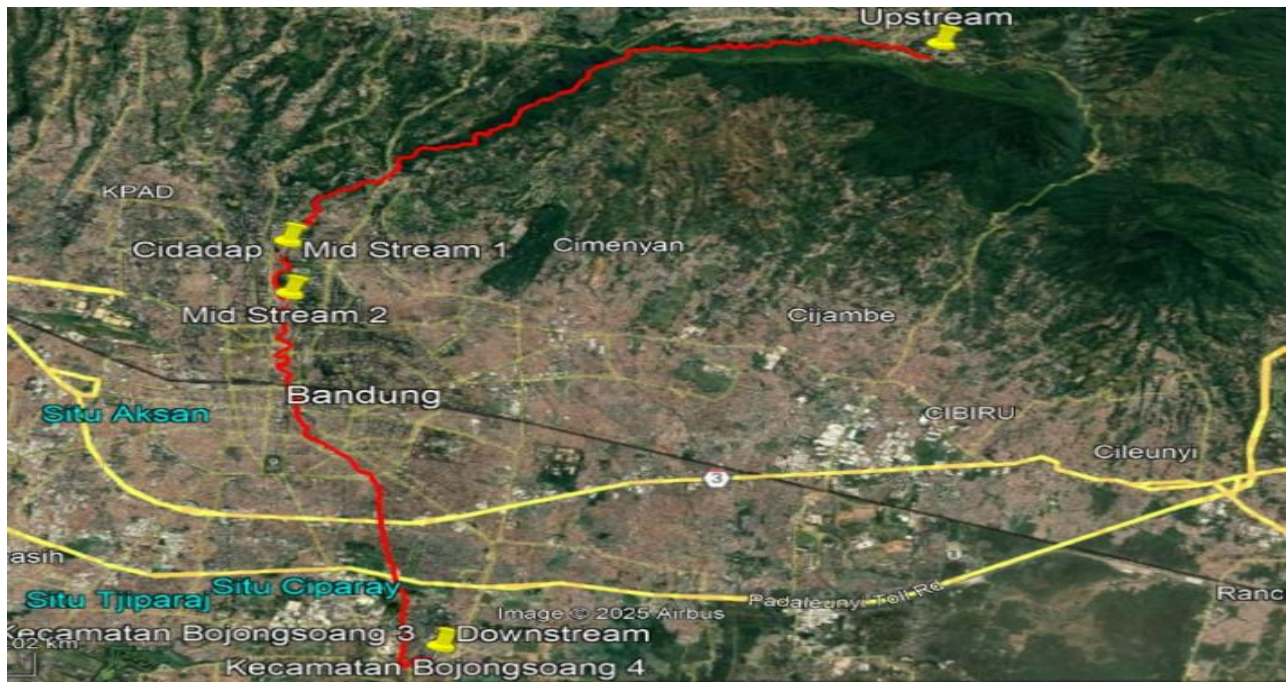


Figure1: Study area and sampling locations along the Cikapundung River

Source: Google Earth

2.3 Data collection and analysis

Primary data were collected through field measurements and laboratory analyses. Hydrological and physical parameters measured in situ included river discharge, flow velocity, water depth, channel geometry, river slope, travel time, and temperature. Physico-chemical water quality parameters analyzed included dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia nitrogen ($\text{NH}_3\text{-N}$), pH, and temperature. These parameters were selected due to their relevance in assessing organic pollution and overall river health.

Secondary data were obtained from relevant government agencies and institutions to complement field measurements. These included watershed boundary data, land use information, population and livestock statistics, industrial wastewater discharge data, and meteorological variables such as rainfall, temperature, humidity, and wind speed. These datasets were essential for estimating pollutant loads from point and non-point sources and for defining boundary and environmental conditions required for modeling.

Laboratory analyses were conducted in accordance with standard methods, including APHA, AWWA, WEF (2017), and SNI protocols. BOD was analyzed using the 5-day incubation method, COD using the closed reflux titrimetric method, and ammonia using the phenate method with spectrophotometric measurement. All samples were preserved, transported, and analyzed within the recommended holding times to ensure data quality and reliability. All collected data were processed and prepared prior to modeling. This involved data screening, unit standardization, and temporal alignment to ensure consistency with model requirements. Pollutant loads from point and non-point sources were calculated and formatted for input into the model.

Water quality modeling was performed using the QUAL2Kw model to simulate the longitudinal variation of water quality parameters under steady-state conditions. The model incorporated key physical and biochemical processes, including advection, dispersion, reaeration, organic matter decomposition, and nitrification. In addition, model calibration was conducted by adjusting kinetic and stoichiometric parameters to achieve agreement between simulated and observed water quality data. Model validation was subsequently performed using independent datasets and statistical evaluation to assess accuracy, and scenario simulations were carried out to evaluate the effectiveness of different pollution control strategies. These included reductions in pollutant loads from point sources, non-point sources, and combined interventions.

The simulation results were analyzed to identify spatial pollution patterns, critical pollution sources, and the potential effectiveness of management interventions. The findings were interpreted in relation to environmental standards and used to support recommendations for sustainable water quality management of the Cikapundung River and reliability of the model predictions.

3. RESULTS AND DISCUSSION

3.1 WATER QUALITY OF THE CIKAPUNDUNG RIVER BASED ON SELECTED PARAMETERS

3.1.1 Dissolved Oxygen (DO)

Observed dissolved oxygen (DO) concentrations along the Cikapundung River ranged from 6.75 mg/L in the upstream reach to 4.4 mg/L in the downstream reach, remaining above the Class II standard (≥ 4 mg/L) at all monitoring stations. Despite compliance, a clear longitudinal decline in DO was observed. This decreasing trend is causally linked to increasing oxygen demand as the river flows through urbanized areas. Elevated organic matter inputs and ammonia concentrations stimulate biochemical oxidation and nitrification processes, both of which consume dissolved oxygen. Although atmospheric reaeration partially compensates for oxygen depletion, the downstream DO levels approach the regulatory threshold, indicating reduced resilience. This suggests that any additional pollutant loading particularly organic or nitrogenous waste could result in oxygen depletion and subsequent ecological stress.

3.1.2 Biochemical Oxygen Demand (BOD)

BOD concentrations exhibited significant spatial variability, with an extremely high value recorded in the upstream reach (21.781 mg/L), far exceeding the Class II standard (≤ 3 mg/L). This indicates substantial input of biodegradable organic matter, likely originating from untreated domestic wastewater, livestock waste, and direct sewage discharges near the headwaters. In contrast, BOD₅ levels decreased sharply in the midstream sections (2.967 mg/L and 0.453 mg/L), falling within permissible limits.

This reduction reflects the influence of natural self-purification processes, including microbial degradation, dilution, and sedimentation. However, the downstream concentration increased again (3.570 mg/L), exceeding the standard and indicating renewed organic pollution inputs. This spatial pattern demonstrates a cause–effect relationship where pollution inputs in the upstream and downstream sections drive elevated BOD₅ levels, while midstream reductions are governed by in-stream attenuation processes. It further indicates that pollution sources are distributed along the river continuum rather than localized.

3.1.3 Chemical Oxygen Demand (COD)

COD concentrations exceeded the Class II standard (≤ 25 mg/L) in the upstream (76.77 mg/L) and downstream (45.64 mg/L) reaches, while midstream values showed partial compliance but remained elevated in some sections. The high upstream COD indicates the presence of both biodegradable and non-biodegradable organic pollutants, such as detergents, household chemicals, and small-scale industrial discharges. Unlike BOD, COD does not decrease proportionally in the midstream sections, suggesting that persistent organic compounds are less responsive to natural degradation processes. The downstream increase in COD reflects the cumulative effect of upstream pollutant transport combined with additional local inputs. This highlights a key causal mechanism: while biodegradable organic matter is reduced through biological processes, non-biodegradable substances accumulate along the river, contributing to sustained high COD levels.

3.1.4 Ammonia Nitrogen (NH₃–N)

Ammonia nitrogen concentrations exceeded the Class II standard (≤ 0.2 mg/L) at all monitoring locations, ranging from 0.222 mg/L to 0.485 mg/L. The highest concentrations were observed in the upstream and downstream sections, indicating continuous inputs of nitrogen-rich waste.

The persistence of elevated ammonia levels, even in midstream areas, suggests limited nitrification efficiency, likely constrained by high organic loads and insufficient hydraulic retention time. Since nitrification is an oxygen-dependent process, the observed decline in DO further limits ammonia conversion to nitrate. This establishes a direct causal relationship where high organic pollution reduces DO availability, which in turn

inhibits nitrification, resulting in sustained ammonia concentrations. Consequently, ammonia pollution poses a chronic risk to aquatic ecosystems and contributes indirectly to oxygen depletion.

3.2 CALIBRATION OF WATER QUALITY MODEL OF THE CIKAPUNDUNG RIVER USING QUAL2Kw

3.2.1 QUAL2Kw Model Calibration and Validation Results

The QUAL2Kw model was calibrated and validated to ensure that simulated water quality parameters accurately represent observed field conditions. Calibration and validation are essential steps to establish the reliability of the model before it is used for scenario simulation and policy evaluation.

3.2.3 Calibration Results

Model calibration was performed by iteratively adjusting selected kinetic and stoichiometric parameters within QUAL2Kw until simulated concentrations of key water quality variables closely matched observed field data. The calibration focused on dissolved oxygen (DO), biochemical oxygen demand (BOD₅), and ammonia nitrogen (NH₃-N), as these parameters are most sensitive to changes in organic and nutrient loading.

Key parameters adjusted during calibration included the reaeration coefficient, CBOD degradation rates, and nitrification rate constants. Calibration results indicate that the model successfully reproduces the spatial trends observed in the field, particularly the decline in DO and increase in BOD₅ and NH₃-N from upstream to downstream sections. Graphical comparison between observed and simulated values shows good agreement across most sampling locations, with minor deviations in highly polluted downstream segments. These deviations are expected due to the simplified steady-state assumptions and uncertainties in pollutant load estimation.

3.2.4 Model Validation and Performance

Model validation was conducted by comparing simulated results against an independent subset of observed data not used during the calibration process. Model performance was evaluated using the Normalized Root Mean Square Error (NRMSE) as a quantitative indicator of goodness-of-fit.

The calculated NRMSE values for DO, BOD₅, and NH₃-N are below the acceptance threshold of 0.5, indicating satisfactory model performance. This confirms that the calibrated QUAL2Kw model can represent the key water quality dynamics of the Cikapundung River and is suitable for simulating pollution management scenarios.

3.2.5 Water Quality Simulation under Existing Conditions

The QUAL2Kw simulation results for slow-reacting carbonaceous biochemical oxygen demand (CBODs) along the Cikapundung River show a noticeable variation in concentration along the modeled river reach. At the upstream section of the river (approximately 31–32 km from the downstream boundary), the CBODs concentration begins at around 21–22 mg/L. moving downstream toward the midstream section (approximately 24–15 km), and the CBODs concentration gradually decreases to approximately 12–13 mg/L. This reduction indicates the occurrence of natural self-purification processes, including microbial degradation of organic matter, dilution, and settling processes within the river system.

However, a significant increase in CBODs concentration is observed further downstream. Starting at approximately 15 km upstream, the CBODs value increases sharply, reaching around 30 mg/L at approximately 6 km upstream and remaining relatively constant until the downstream boundary. This increase suggests the presence of additional organic load inputs in the downstream section of the river, which may originate from anthropogenic activities such as domestic wastewater discharge, urban runoff, or other point and non-point pollution sources entering the river system.

Overall, the modeled CBODs profile indicates that while the upstream and midstream sections demonstrate some capacity for organic matter attenuation, the downstream section experiences increased organic loading, resulting in higher CBODs concentrations. This condition may potentially influence the oxygen balance of the river system, as higher CBOD levels can increase oxygen consumption during microbial decomposition processes.

These results highlight the importance of controlling organic pollutant discharges in the lower reaches of the river to prevent further deterioration of water quality and to maintain the ecological function of the Cikapundung River.

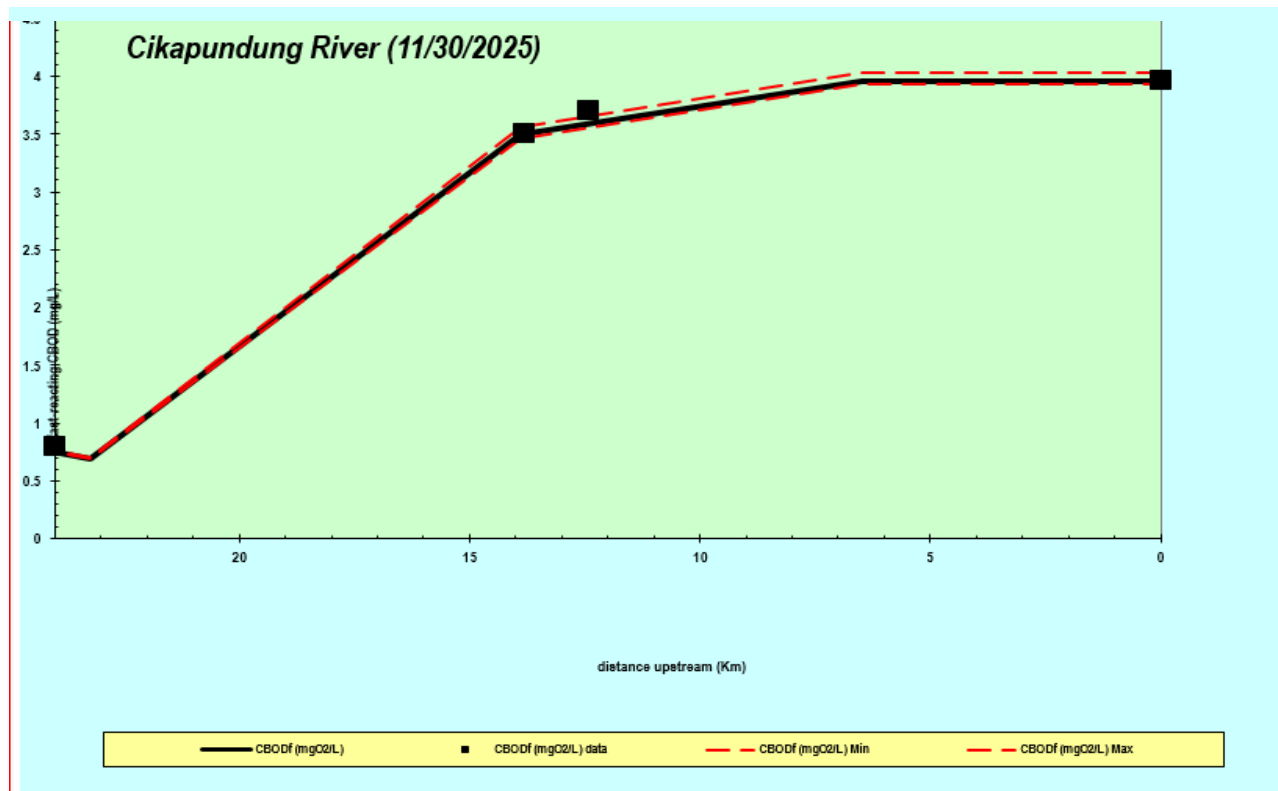


Figure 2: QUAL2Kw simulation results for slow-reacting carbonaceous biochemical oxygen demand (CBODs)

In addition, the QUAL2Kw simulation results for ammonia (NH_4) along the Cikapundung River show spatial variations in concentration along the modeled river reach. At the upstream section of the river (approximately 31–32 km from the downstream boundary), the ammonia concentration begins at a very low level, close to 0 $\mu\text{g/L}$, indicating minimal ammonia input from the headwater source.

Moving downstream toward the midstream section (around 24 km upstream), the ammonia concentration increases significantly, reaching approximately 1.2–1.3 $\mu\text{g/L}$. This increase suggests the presence of external nitrogen inputs, which may originate from domestic wastewater, urban runoff, or other anthropogenic sources entering the river system.

Further downstream (between 24 km and 15 km upstream), the ammonia concentration shows a slight gradual decrease, indicating that biogeochemical processes such as nitrification and dilution may be occurring within this section of the river. These processes convert ammonia into nitrate while simultaneously reducing ammonia concentrations in the water column.

In the lower reach of the river (approximately 15 km to 6 km upstream), the ammonia concentration continues to decline, reaching about 0.8 $\mu\text{g/L}$ near the downstream boundary. After this point, the ammonia concentration remains relatively

stable, indicating that the river system has begun to reach a new equilibrium condition between pollutant inputs and natural attenuation processes.

Overall, the modeled ammonia profile suggests that while ammonia inputs occur in the midstream section, the river still demonstrates a moderate capacity for nitrogen transformation and dilution, which helps reduce ammonia concentrations toward the downstream segment. This behavior reflects the influence of biological processes, hydraulic dilution, and water quality dynamics within the Cikapundung River system.

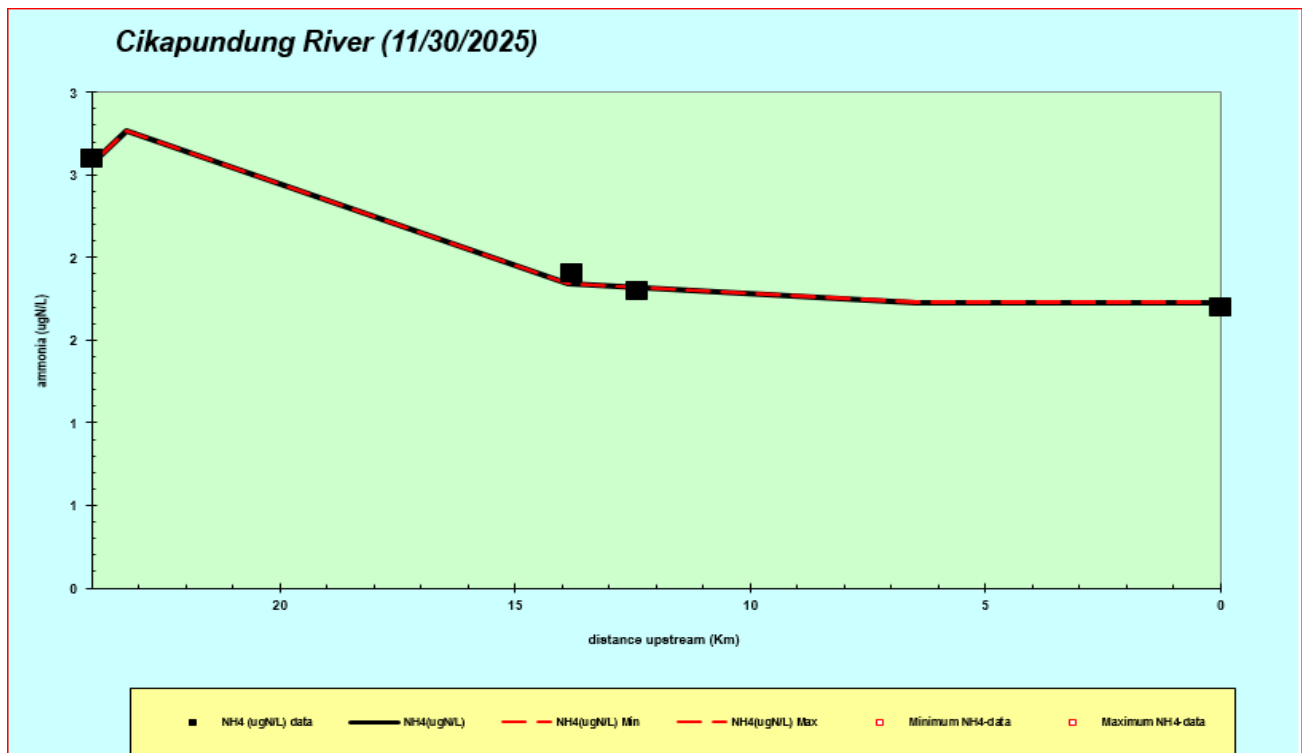


Figure 3: QUAL2Kw simulation results for Ammonia (NH₄) along the Cikapundung River

4. CONCLUSION AND RECOMMENDATIONS

The evaluation of water quality in the Cikapundung River reveals pronounced spatial variability in key parameters, including BOD, COD, ammonia (NH₃-N), and dissolved oxygen, reflecting the cumulative influence of anthropogenic activities along the river continuum. The results demonstrate a clear longitudinal pattern in which pollutants are introduced in the upstream areas, partially attenuated through natural self-purification processes in the midstream reaches, and subsequently accumulate in the downstream sections. High BOD and COD concentrations in the upstream indicate significant organic

and chemical pollution inputs, primarily from domestic wastewater, agricultural activities, and localized discharges.

In the midstream sections, reductions in BOD suggest effective biodegradation and dilution processes; however, the persistence of elevated COD highlights the presence of non-biodegradable pollutants that are resistant to natural attenuation. This divergence between BOD and COD confirms that low biodegradable organic matter does not necessarily indicate good water quality, particularly in urban environments where chemically stable contaminants dominate. Downstream conditions are characterized by increasing concentrations of BOD, COD, and ammonia, driven by cumulative pollutant loading, reduced flow velocity, and diminished self-purification capacity, thereby posing risks to ecological integrity and water usability.

Furthermore, the analysis of pollution sources indicates that both point and non-point sources contribute significantly to river degradation. Domestic wastewater is identified as the dominant source of BOD and ammonia, while industrial activities contribute substantially to elevated COD levels. This highlights the multi-source and cumulative nature of pollution within the watershed, necessitating integrated management strategies. The application of the QUAL2Kw model successfully simulated the spatial behavior of water quality parameters and effectively represented key processes such as organic matter decomposition, nitrification, reaeration, and pollutant transport. Scenario analysis further demonstrated that targeted reductions in point source pollution are effective in lowering COD concentrations, while non-point source control plays a critical role in improving BOD, ammonia, and dissolved oxygen levels. The most significant improvements in overall water quality are achieved through a combined management approach, underscoring the importance of coordinated interventions across different pollution sources and river segment.

4.1 Recommendations

Based on the findings of this study, it is recommended that water quality management in the Cikapundung River adopt a more integrated, spatially targeted, and data-driven approach to effectively address the identified challenges. First, there is a need to strengthen continuous and systematic water quality monitoring programs by incorporating key parameters such as BOD, COD, and ammonia, with increased sampling frequency to capture temporal variability and ensure alignment with national water quality standards. In addition, river management strategies should be spatially differentiated according to the distinct characteristics of each river segment, including conservation and protection measures in the upstream areas, improved domestic wastewater management in the midstream urban zones, and stricter regulation and enforcement of industrial effluent standards in the downstream sections.

Given the significant contribution of untreated domestic wastewater and inadequately controlled industrial discharges, it is further recommended to expand both centralized and decentralized wastewater treatment infrastructure, alongside the implementation of community-based sanitation programs and pollution load allocation

mechanisms to ensure equitable and effective control of pollution sources. Moreover, the integration of advanced tools such as Geographic Information Systems (GIS) is essential to enhance spatial analysis, monitoring efficiency, and informed decision-making. Finally, the application of the QUAL2Kw model should be strengthened as a decision-support tool in river management, with future efforts directed toward incorporating dynamic modeling approaches to account for seasonal variability, as well as regular calibration and validation using updated field data to maintain model accuracy and reliability.

4.2 Limitations and Future Research

This study provides important insights into the spatial dynamics of water quality in the Cikapundung River; however, several limitations should be acknowledged. First, the analysis is based on a steady-state modeling approach (QUAL2Kw), which assumes constant flow and pollutant loading conditions. As a result, the model does not fully capture temporal variability, particularly seasonal fluctuations in river discharge, rainfall, and pollutant inputs that are characteristic of tropical urban watersheds. Second, the study relies on limited temporal sampling, which may not adequately represent short-term variations in water quality driven by storm events, peak discharge conditions, or intermittent pollution discharges.

Third, although both point and non-point pollution sources were considered, uncertainties remain in the estimation of pollutant loads, especially for diffuse sources such as urban runoff, agricultural activities, and informal wastewater discharges. These uncertainties may influence the accuracy of model inputs and simulation outputs. Additionally, the study focuses primarily on conventional physico-chemical parameters (DO, BOD, COD, and $\text{NH}_3\text{-N}$), while other important indicators such as heavy metals, pathogens, and emerging contaminants were not included, limiting a more comprehensive assessment of water quality and ecological risk.

Furthermore, the spatial resolution of the study is constrained by the number of sampling stations, which, although representative, may not fully capture micro-scale variability along the river, particularly in highly heterogeneous urban environments. Data availability from secondary sources also posed limitations in terms of consistency, resolution, and completeness, which may affect the robustness of pollution load estimation and model calibration.

Future research should therefore focus on incorporating dynamic (time-variable) modeling approaches to better represent seasonal and event-based variations in water quality. Increasing the frequency and spatial density of sampling would improve the reliability of both empirical analysis and model calibration. There is also a need to integrate additional water quality parameters, including microbiological indicators, heavy metals, and emerging pollutants, to provide a more holistic assessment of river health.

Moreover, future studies should enhance the quantification of non-point source pollution through advanced techniques such as remote sensing, GIS-based modeling, and watershed-scale hydrological simulations. The integration of real-time monitoring systems and sensor-based data collection is also recommended to support adaptive river management. Finally, coupling water quality models with socio-economic and policy analysis would provide a more comprehensive framework for designing effective and sustainable river management strategies in rapidly urbanizing regions.

Ethics Statement

This study did not involve human participants, human tissues, personal data, or animals. The research was based on river water sampling, laboratory analysis of water quality parameters, and secondary data obtained from relevant sources. Therefore, ethical approval and informed consent were not required for this study.

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