

Implementation of Qual2Kw and MCDA in Formulating Sustainable River Water Quality Standard Compliance Program Policies: A Case Study of the Cileungsi River in Bogor Regency

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ABSTRACT

This study aims to develop an integrative approach between water quality modeling using QUAL2Kw software and the Multi-Criteria Decision Analysis (MCDA) method with PROMETHEE software to support the formulation of policies for sustainable river water quality standards. The study was conducted on the Cileungsi River, West Java, with key parameters of BOD, COD, and TSS. Modeling was carried out in four tiered scenarios representing existing conditions and quality standards targets of classes IV, III, and II, thus providing a basis for designing technical interventions such as reducing point source and non-point source pollutant loads, increasing upstream discharge, and improving upstream water quality. Based on the results of iterations and model observations, six policy criteria (K1–K6) and twelve program alternatives (P1–P12) were obtained to achieve river water quality standards. PROMETHEE analysis was used to determine program priorities based on stakeholder preference weights. The results of the study show that the integration of QUAL2Kw–PROMETHEE is able to provide a more measurable scientific and policy basis, with the main priorities being the development and improvement of IPAL performance, control of non-point sources, and an increase in river base discharge. This approach has the potential to be applied as an evidence-based policy decision-making model in river water quality management in Indonesia.

KEYWORDS Qual2Kw, MCDA (Multi-Criteria Decision Analysis), Water Quality Standards



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INTRODUCTION

River water is a strategic resource that supports the socio-economic life of communities and is also an important indicator of environmental quality. However, river water quality in Indonesia still faces serious pressure from domestic, industrial, agricultural, and land use change activities. The 2020 Environmental Quality Index report shows that the national Water Quality Index (WQI) value is only 53.53 (moderate category), lower than other components such as the air quality index (87.21). West Java Province, which includes the Cileungsi River, is among the regions with a relatively low WQI value (41.50), indicating that water pollution is a critical issue that must be addressed immediately.

This national condition is in line with global trends. The 2024 Environmental Performance Index (EPI) ranks Indonesia relatively low on environmental quality indicators, especially water, compared to many other countries. The report emphasizes that evidence-based water quality management is an urgent need to improve environmental performance and meet Sustainable Development Goals (SDGs), particularly SDG 6: Clean Water and Sanitation.

The Cileungsi River is one of the important sub-watersheds in West Java that faces high pressure from domestic and industrial activities (Effendi & Sudarmadji, 2012; Benham et al., 2012; Cinelli et al., 2014). Previous research shows that the largest contribution to pollutant

load comes from domestic waste (more than 80% of BOD and COD), followed by industrial and agricultural activities. This condition causes water quality in certain segments to not meet class IV quality standards, and to be far from the class II target as mandated by Government Regulation No. 22 of 2021.

Water quality modeling using QUAL2Kw is an effective tool for analyzing river assimilation capacity and projecting the impact of interventions. Several international studies (Ha et al., 2019; Fan et al., 2020) show that QUAL2Kw has advantages in predicting water quality responses to technical scenarios (reduction of point source/non-point source loads, increased upstream discharge, and improved input water quality) with a high level of precision ($R^2 > 0.9$). In the Indonesian context, research by Sukandi et al. (2020) and Arifin & Hadi (2019) confirms that a spatial approach based on pollution load capacity can serve as the basis for formulating more measurable water pollution control policies.

Technical models alone are not sufficient as a basis for policy. Environmental decision-making requires multidimensional considerations, including aspects of cost, effectiveness, social acceptability, and institutional factors (Fatimah et al., 2019; Hidayat et al., 2019; Liyanage & Yamada, 2017). This is where Multi-Criteria Decision Analysis (MCDA) plays an important role. MCDA allows the integration of model simulation results with stakeholder preferences to obtain fairer and more sustainable program priorities (Cinelli et al., 2014).

The implementation of water quality modeling with QUAL2Kw has been widely carried out in Indonesia. QUAL2Kw is used to simulate river water quality and calculate the carrying capacity of water pollutants in rivers. However, no studies have been found that explicitly integrate QUAL2Kw modeling results with MCDA methods to formulate water quality improvement program policies for meeting water quality standards (Grzywna et al., 2024; Anggraini, 2025). This study combines these two approaches in the context of water quality management in the Cileungsi River in Bogor Regency, West Java. Research in Indonesia that integrates water quality modeling results (QUAL2Kw) with MCDA to formulate policies is still very limited. Most studies stop at technical analysis or normative recommendations without a model-based priority selection mechanism. Thus, this study is important to fill the knowledge gap by presenting an integrative approach that links water quality models with policy instruments through MCDA (Thompson et al., 2019; Wilk et al., 2018; Zulkifli et al., 2021).

Based on the background and problems described above, this study aims to develop an integrative approach between water quality modeling using QUAL2Kw software and the Multi-Criteria Decision Analysis (MCDA) method with PROMETHEE software to support the formulation of policies for sustainable river water quality standards compliance, specifically to analyze current water quality conditions and pollution load distribution in the Cileungsi River through QUAL2Kw modeling; develop tiered scenarios representing existing conditions and quality standards targets of classes IV, III, and II to provide a basis for designing technical interventions; formulate policy criteria and program alternatives based on modeling iterations and stakeholder preferences; and determine program priorities using PROMETHEE analysis to achieve sustainable river water quality standards. This research is expected to provide both theoretical and practical benefits. Theoretically, it contributes to the body of knowledge on integrated water quality management by providing an innovative framework that combines quantitative modeling with multi-criteria decision analysis, offering a novel approach that bridges the gap between technical analysis and policy formulation and enriching the literature

on evidence-based environmental decision-making. Practically, the findings offer valuable insights for local and central governments in establishing priority water pollution control programs based on pollution load capacity, balancing technical, economic, social, and institutional aspects, and serving as a reference for policymakers in developing more measurable, efficient, and sustainable water quality management strategies. The QUAL2Kw–PROMETHEE integrative approach also has the potential to be developed for other rivers in Indonesia as a decision support system aligned with evidence-based policy principles in national water quality management, ultimately contributing to the achievement of sustainable development goals, particularly SDG 6: Clean Water and Sanitation.

RESEARCH METHOD

This study was conducted on the Cileungsi River, which is 70.58 km long and covers a river basin area of 26,614.68 ha in Bogor Regency, West Java. Water measurements and sampling were carried out in September 2024. This study was conducted in the Cileungsi Watershed, Bogor Regency, West Java, during the period January–December 2023. The research location was chosen because the Cileungsi River Basin is one of the areas with high pollution load pressure in the upper reaches of the Bekasi River. The approach used was a systems thinking approach, which views the river basin as a single ecosystem with interrelationships between physical, social, and institutional components (Thompson et al., 2019; Webster et al., 2025). This approach allows for an integrated analysis of hydrological dynamics, pollutant load distribution, and pollution load capacity-based policy interventions.

Primary and secondary data were collected through field surveys, river water sampling, and compilation of data on water quality, rainfall, and hydrological characteristics. Sampling was conducted using stratified purposive random sampling to ensure spatial representation between river segments according to variations in pollutant sources. Hydrological analysis and watershed boundaries were analyzed using HEC-HRM software, while spatial mapping of pollutant loads was performed using Geographic Information Systems (GIS). Water quality modeling used QUAL2Kw software, with the main parameters being BOD, COD, and TSS, which have been proven effective for capacity analysis and river water quality scenario simulation (Fan et al., 2020; Ha et al., 2019).

This study is applied research with a mixed-methods approach that integrates QUAL2Kw-based water quality modeling and Multi-Criteria Decision Analysis (MCDA) using the PROMETHEE method. The modeling results are then integrated with MCDA using the PROMETHEE method to determine policy program priorities based on six policy criteria (K1–K6) and twelve program alternatives (P1–P12). The combination of QUAL2Kw–PROMETHEE enables evidence-based policy formulation that considers technical effectiveness, economic efficiency, and social and institutional sustainability (Cinelli et al., 2014; Bousquet et al., 2023). This integrative approach is an innovation in river water quality management in Indonesia, which has so far been limited to technical analysis without the support of a multi-criteria decision framework.

RESULT AND DISCUSSION

Pollution Burden Allocation

Water pollution load allocation is calculated based on a water quality model. The water quality model uses a BOD parameter approach with four model scenario approaches. Scenario 1 (existing) shows actual conditions based on monitoring data, with a recorded BOD pollutant load of 4,480.37 kg/day, distributed across segment 1 (2,566.04 kg/day), segment 2 (1,365.98 kg/day), segment 4 (468.29 kg/day), and segment 3 (78.06 kg/day). Model validation shows excellent results with $R^2 = 0.997$, $r = 0.998$, and $RMSE = 0.052$, indicating a high level of precision. This is in line with Kannel et al. (2007), Ha et al. (2019), and Fan et al. (2020), who stated that $R^2 > 0.9$ and $r > 0.98$ reflect a very strong predictive model. The DTBPA model simulation process is presented in Figure 1.

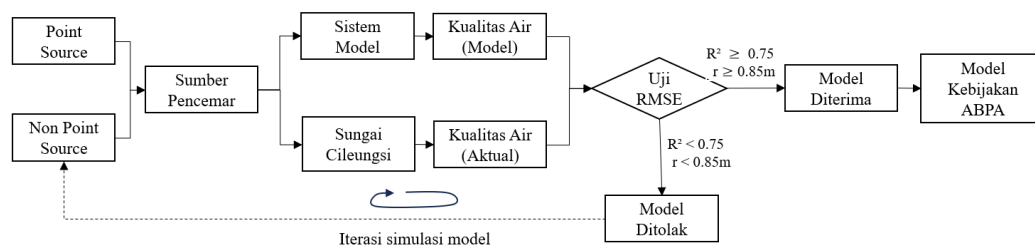


Figure 1. Water quality model simulation process

Source: Research data processing with QUAL2Kw (2025)

Scenario 2 (meeting class IV quality standards) requires a reduction in BOD load to 1,656.66 kg/day, or 36.98% of the existing condition. The segments requiring load reduction are segment 1 (21.16%), segment 2 (9.54%), segment 4 (5.94%), and segment 3 (0.34%). Scenario 3 (Class III quality standards) shows that of the total existing load of 2,823.71 kg/day, only 1,969.88 kg/day can be accommodated, requiring a reduction of 853.83 kg/day (19.06.5%). Segment 2 is the most critical, requiring a reduction of 508.66 kg/day (11.35%) and segment 1: 310.95 kg/day (6.94%). This condition can be achieved with interventions including a 25–30% reduction in PS and NPS loads, as well as an increase in upstream discharge. This strategy aligns with Fatima (2022) and Ickowicz (2017), who emphasize the importance of a spatial approach in water quality control. Scenario 4 (class II quality standard) requires a reduction of 256.60 kg/day (5.77%) from the existing load of 1,969.88 kg/day to 1,711.28 kg/day. The load reduction in all segments is as follows: segment 1 (3.54%), segment 2 (1.01%), segment 3 (0.13%), and segment 4 (1.10%). The intervention was carried out by increasing the headwater discharge to 2 m³/second and reducing NPS by 25%. Studies by Sukandi et al. (2020) and Arifin & Hadi (2019) show that spatial-segmental management and increased discharge can significantly improve water quality. This model provides a strong scientific basis to support water pollution control policies based on carrying capacity. A comparison between the distribution of monitoring concentrations and the models from Scenario 1, Scenario 2, Scenario 3, and Scenario 4 is presented in Figure 2.

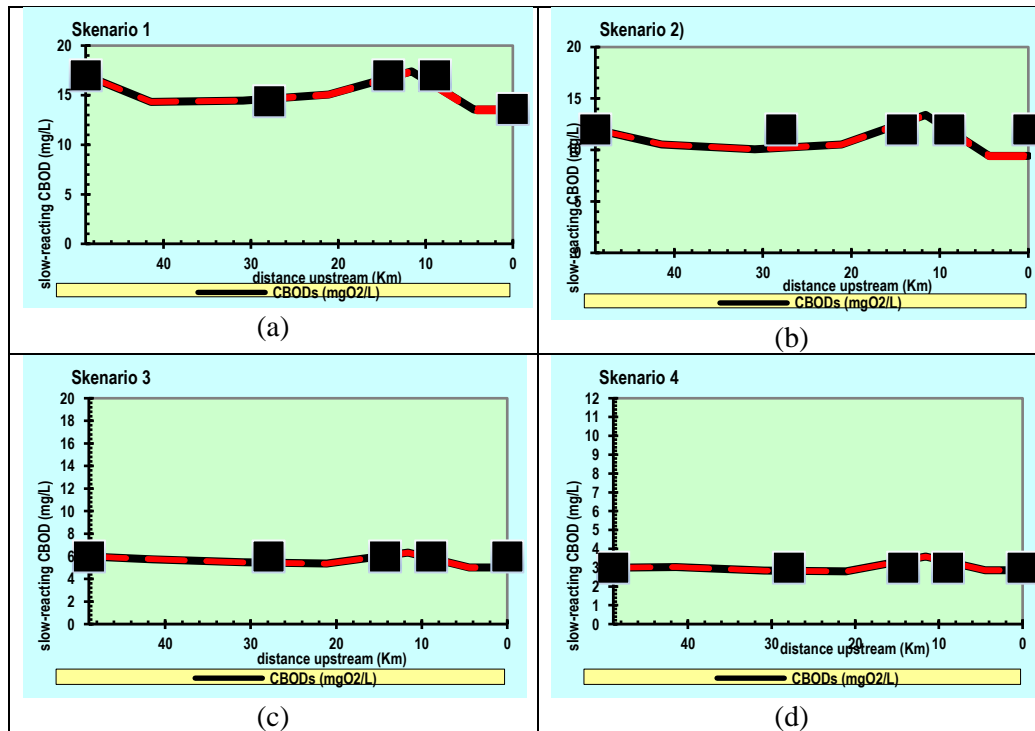


Figure 2. Water quality model: (a) scenario 1, (b) scenario 2, (c) scenario 3, and (d) scenario 4.

Source: Research data processing with QUAL2Kw (2025)

Transformation of Intervention Models into Activity Programs

Based on the modeling results, the water quality of the Cileungsi River can meet Class 2 water quality standards (ultimate goal) with four alternative types of intervention activities, namely (1) reduction of PS and non-PS pollution loads (2) Policies to restrict wastewater discharge into rivers (3) Improvement of water quality upstream and (4) Increasing water availability upstream to maintain flow (flushing) during the dry season. From the 4 intervention criteria, the following types of activity programs are recommended to meet Class II water quality standards: (1) P1:

Obligation to construct a wastewater treatment plant for businesses/activities that do not yet have wastewater treatment facilities, (2) P2: Improvement of wastewater treatment plant performance for businesses/activities that already have wastewater treatment facilities but do not yet meet BMAL requirements, (3) P3: Granting of wastewater discharge permits in segments that have exceeded ABP with compensation, (4) P4: Prohibition of wastewater discharge permits into water bodies in segments that have exceeded ABP, (5) P5: Construction of IPAL for businesses/activities that generate wastewater (agriculture, livestock) carried by runoff, (6) P6: Construction of green infrastructure (wetlands, biopores, porous pavements, PAH, etc.) to reduce runoff, (7) P7: Construction of river embankments so that runoff does not directly enter water bodies but is managed by green infrastructure, (8) P8: Construction of reservoirs, ponds, and reservoirs to increase water reserves that can be used during the dry season, for flushing water bodies, (9) P9: Reforestation of steep slopes (slope > 40%*) to reduce runoff and increase the base flow reserves needed during the dry season, (10) P10: Improving the performance of activities/businesses by striving for “Clean Production” for activities or

businesses that produce wastewater. (11) P11: Increasing community capacity to improve public understanding of the meaning and benefits of river water pollution control.

The implementation of programs and activities to meet class 2 quality standards is important to prevent further environmental damage, which has the potential to cause economic losses due to decreased water productivity, increased water treatment costs, and declining public health. This intervention strengthens the institutional role in supervision, cross-sector collaboration, and regulatory enforcement to ensure sustainable water quality management. PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) analysis was used to determine the priority order of programs (P1–P12) based on six policy criteria (K1–K6) resulting from the integration of the QUAL2Kw model and stakeholder preferences. There were a total of 12 program alternatives and 6 active criteria, all of which were maximized. The criteria weights indicate the relative level of importance to the goal of meeting river water quality standards, ranging from 15.1 to 17.5%. The highest weight is given to K2 (17.5%), followed by K5 (17.2%) and K1 (16.9%), indicating that policy effectiveness and direct contribution to reducing pollutant loads are the most prioritized aspects.

The Phi value (net flow) describes the final position of each program. Based on the simulation results:

- (a) P12 obtained the highest Phi value (0.6419) → becoming the top priority program, followed by P7 (0.5445) and P8 (0.4422).
- (b) Programs with moderate scores include P11 (0.1549), P9 (0.0858), and P10 (0.0825), indicating moderate effectiveness.
- (c) Programs with negative scores such as P4 (0.0352), P2 (−0.1088), P1 (−0.1451), P6 (−0.4514), P3 (−0.5785), and P5 (−0.7033) are categorized as low priority.

The final order of priority based on Phi values can be presented as follows:

P12 > P7 > P8 > P11 > P9 > P10 > P4 > P2 > P1 > P6 > P3 > P5

Substantive Interpretation

Based on these results, programs P12, P7, and P8 occupy the most strategic positions because they meet the best combination of technical, institutional, and sustainability criteria. P12 can be associated with increased river base flow or improved upstream conditions (flushing & conservation). P7 and P8 are related to controlling non-point source loads through green infrastructure and runoff management (reservoirs, dams, green open spaces). Meanwhile, P1–P5, which focus on IPAL obligations, improvements to existing IPAL, and control of small-scale industries, have lower effectiveness when viewed from a multi-criteria preference

perspective—possibly due to limitations in terms of cost, institutional readiness, or spatial impact range. The Phi values are presented in Figure 3.

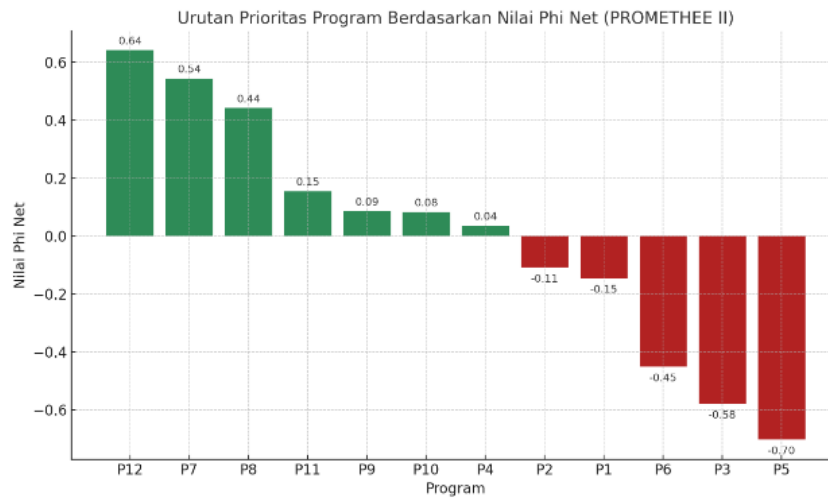


Figure 3. Program Priority Order Based on Net Phi Value

Source: Research data processing with PROMETHEE (2025)

Based on the GAIA (Geometrical Analysis for Interactive Aid) diagram, it shows the distribution of decision alternatives, where the decision vector (π) strongly points to alternatives with high aggregate performance (P12, P7, P8). Sensitivity Analysis (Walking Weights) shows that decision stability is quite high because the differences in weight between criteria are relatively small ($\pm 2\%$), so that small changes in weight do not greatly affect the top three rankings.

The policy implications of the PROMETHEE results indicate the following programs:

1. The upstream discharge and conservation improvement program (P12) should be a top policy priority.
2. Programs based on runoff control and green infrastructure (P7–P8) should be a medium-term strategic support.
3. Industrial and domestic waste control programs (P1–P5) remain important, but need to be strengthened with regulations and incentives to make them economically and institutionally viable.

The results of the PROMETHEE analysis support the concept of a water quality standard fulfillment policy based on a combination of technical and conservative interventions, in line with the QUAL2Kw modeling results which show the importance of simultaneously reducing pollutant loads and increasing upstream discharge.

Based on the GAIA diagram, it shows a visual representation of the relationship between criteria and the position of program alternatives (P1–P12) in a two-dimensional decision space (U–V axis). Each colored vector illustrates the direction and intensity of the criteria group's contribution to the overall result. There are two main groups in this graph: green vectors representing the Green criteria group (K1–K4) and pink vectors representing the K5–K6 group. The direction of the vectors indicates the orientation of the criteria preferences, while the length of the vectors indicates the strength of their contribution to the global decision. Programs P12 and P7 are located in the same direction as the red (Green) vector, indicating that both perform

very well on technical criteria, such as effectiveness in reducing pollutant loads, increasing upstream discharge, and efficiency of intervention outcomes. The position of P8 is between the Green and Pink vectors, indicating a relatively balanced performance between technical effectiveness and institutional policy aspects. Conversely, P9 and P10 are close to the Pink vector, which indicates a dominance of performance in socio-economic and institutional criteria, but their technical contribution to improving water quality is lower, as shown in Figure 4.

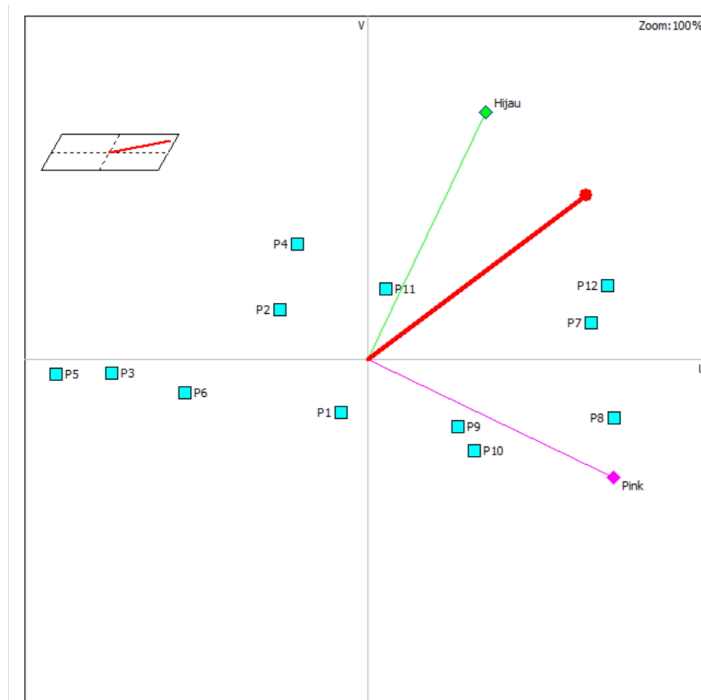


Figure 4. GAIA Diagram

Source: Research data processing with PROMETHEE (2025)

Alternatives P5, P3, and P6 are located far from the decision vector, indicating a position that is less supportive of the overall policy objectives. This condition indicates that the program has limited contribution to significant water quality improvement, or faces constraints in implementation aspects such as high costs and technical readiness. P2 and P4 occupy a middle and relatively neutral position, which means that their performance is moderate across all criteria and can be considered as a complement to medium-term policy strategies.

The decision vector direction (π vector), which in the graph appears to point strongly towards P12 and P7, indicates that the combination of these two programs is most consistent with the ideal policy direction according to the QUAL2Kw–PROMETHEE integration results. These results reinforce the findings from the PROMETHEE II ranking stage, where P12 and P7 occupy the highest Phi Net values. Conceptually, this indicates spatial and preferential consistency in the multi-criteria decision-making system. Similar findings were also reported by Brans and Mareschal (2005), who explained that the orientation of alternatives towards the decision vector reflects the degree of conformity to the dominant preference profile.

CONCLUSION

This study shows that the integration of water quality modeling using QUAL2Kw and PROMETHEE multi-criteria analysis can produce a strong scientific basis for formulating policies to meet river water quality standards. The modeling results show that the water quality of the Cileungsi River can meet Class II water quality standards if a combined intervention is carried out in the form of a 25–30% reduction in point source and non-point source pollutant loads, an increase in upstream base flow of up to ± 2 m³/second, and improvement of upstream water quality. From the integration of the model and stakeholder preferences, six policy criteria (K1–K6) and twelve program alternatives (P1–P12) were obtained, in which programs P12 (increased discharge and upstream conservation), P7 (runoff control infrastructure), and P8 (reservoirs/dams as flushing water storage) are the top priorities with the highest net Phi values and are consistent with the ideal policy direction in the GAIA diagram.

This approach shows that model-based decision-making and multi-actor preferences can strengthen the direction of water pollution control policies to be more measurable, efficient, and sustainable. In practical terms, the results of this study can serve as a reference for local and central governments in establishing priority water pollution control programs based on pollution load capacity, balancing technical, economic, social, and institutional aspects. This QUAL2Kw–PROMETHEE integrative approach also has the potential to be developed for other rivers in Indonesia as a decision support system that is in line with the principles of evidence-based policy in national water quality management.

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