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Uncertainty and Sensitivity Analysis of the Effective Implementation of Water Quality Improvement Programs for Citarum River, West Java, Indonesia

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Abstract: Pollution of rivers is a challenge for many countries. In the Citarum watershed, Indonesia, where pollution has been an emerging issue nationwide, many programs and policies have been set up. However, implementation of all the planned programs and the significance of their contributions toward water quality improvement of the Citarum River have not been analyzed. In this paper, we present original research on evaluating water quality programs planned to achieve outputs by using uncertainty and sensitivity analysis for a river. The essential inputs included: (1) key parameters, (2) priority planned programs, and (3) interrelationships between programs, parameters, and the level of successfulness of water quality control programs. The first and second inputs were prepared simultaneously using Principal Component Analysis (PCA) and Analytical Hierarchy Process (AHP). The latter was obtained using the Delphi method to obtain the related stakeholders' opinions. Finally, we explore Monte Carlo simulation to analyze parameter uncertainty and sensitivity contributing to the program's effectiveness. By implementing all the water quality control programs, the results showed that cadmium, BOD, and fecal coliform were the most affected parameters. In addition, the most effective programs to improve the pollution index were domestic waste, farming, solid waste, and water resource programs. If those programs were implemented collectively, the probability of reducing the pollution index was within a range 2.01–36.22% from the base case.

Keywords: PCA; AHP; Delphi method; Monte Carlo simulation; Citarum

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1. Introduction

Water pollution is a global concern, as it is a challenge for many countries with rapidly growing economies and populations [1,2]. The deterioration of rivers in developing countries is mainly due to inadequate waste management policies or infrastructure [3]. On the island of Java, Indonesia, particularly in the western part, pollutants entering the catchment and its rivers come from various activities, primarily urban population and industrial [4]. Such a condition has brought negative externalities to downstream water users, resulting in an increased threat to public health and affecting the general welfare of the population [5].

The Citarum River plays a pivotal role in many sectors of West Java province, Indonesia, and its surroundings. Pollution of the Citarum River has been an emerging nationwide issue for years. To handle this, the Government of Indonesia issued Presidential Regulation No. 15/2018 concerning the Acceleration of Pollution and Damage Control in the Citarum River Watershed [6]. One of the mandates stated is to implement the government regulation action plan, consisting of twelve pollution control programs by the related stakeholders.

However, implementation of all the planned programs and the significance of their contributions toward water quality improvement of the Citarum River have not been analyzed. Additionally, evaluating the planned programs mentioned above is essential for proper water quality management.

This study explores uncertainty and sensitivity analysis to evaluate the effectiveness of water quality programs planned to achieve outputs for a river. We employed three methods to obtain inputs of uncertainty and sensitivity analysis: Principal Component Analysis (PCA), Analytic Hierarchy Process (AHP), and the Delphi method. The first two were simultaneously employed to assess the present water quality's key parameters and determine priority planned programs. Then, the relationships between the planned programs and key parameters were defined using the Delphi method. PCA was used to identify key parameters having a great impact on rivers [7,8] or evaluation of spatial and temporal variations in water quality [9]. Meanwhile, many researchers have successfully applied AHP to determine the relative weights of available alternatives [4], for instance, the use of AHP for the water environmental-carrying capacity of a city in the Huaihe River Basin [10], the evaluation of urban river landscape design for Weihe River in China [11], and the development of a river water quality index for West Java, Indonesia [4]. All the inputs are then connected and used to perform uncertainty and sensitivity analysis.

In general, uncertainty and sensitivity analysis can be carried out by analytical and the probabilistic methods. The Delta method is a widely used analytical method compared to other analytical methods, such as Rosenblueth's point estimation method and Harr's point estimation method [12]. Additionally, Monte Carlo simulation is one of the most popular probabilistic methods, which generates outputs from the range of input variables of a model, and then combines these outputs to show the effect of the input variability on the output [12,13].

In this study, Monte Carlo simulation was used to perform uncertainty and sensitivity analysis, which has been widely applied and is a suitable method for modeling [14]. For instance, it has been successfully used to identify the uncertainty and sensitivity of the Environmental Sustainability Index—ESI [15], West Java Water Sustainability Index—WJWSI [13], and performed for projecting uncertainty ranges [16]. It has also been used for uncertainty and sensitivity analysis of water quality parameters or pollutants in a river [17–19]. Monte Carlo simulation defines parameter model uncertainty through repeated iterations using the values of parameters, which are randomly selected within the identified probability distribution.

The principal objective of this study was to identify the most effective program to improve water quality in the Citarum River by performing models of water quality changes after the planned programs were conducted. If the most influencing programs are known, then the decision-makers can set pollution control programs in a more accurate, focused, and effective manner. This research contributes to scholarship on river water quality management by applying an integrated PCA, AHP, and Delphi method to obtain essential inputs for uncertainty and sensitivity analysis using Monte Carlo simulation, namely, (1) key parameters, (2) priority planned programs, and (3) interrelationships between programs and parameters and the level of successfulness of water quality control programs. Therefore, using these integrated methods to generate essential inputs of uncertainty and sensitivity analysis, a similar study with regard to water quality programs improvements can be replicated for other rivers nationwide or worldwide.

The following section introduces the study area and methodology used. In Section 3, we present the results. We discuss the results in Section 4, and the conclusions are presented in Section 5.

2. Material and Methods

2.1. Study Area Description

The Citarum River extends 297 km from its upstream catchment at Situ Cisanti, located at Mount Wayang, Bandung, and flows into the North Coast of Java Island, Muara

Gembong, Bekasi Regency, across thirteen cities. It serves as a raw source of drinking water and has been utilized as the irrigation water source for rice fields and the catchment and hydropower plants for Java and Bali [20,21]. Along the stream are three large reservoirs: Cirata, Saguling, and Jatiluhur Reservoir. The Citarum watershed covers fifteen subwatersheds and is divided into four segments, as illustrated in Figure 1. WJEA conducts regular monitoring on the Citarum River at seven sampling locations, as seen in Figure 1, including (1) Wangisagara, (2) Koyod, (3) Cisirung WWTP, (4) Nanjung, (5) Jatluhur Reservoir Outlet, (6) Walahar Dam, and (7) Tunggak Jati.

Up to now, 15 agencies have monitored 356 monitoring points, resulting in a fragmented database that is difficult to use by policy-makers [22]. Several parameters were measured high and exceeded the effluent standard, such as nitrite, nitrate, BOD, COD, cyanide, chlorine, sulfide, and E. coli. Heavy metals were also high in the river segment, namely, cadmium, hexavalent chromium, zinc, mercury, lead, and copper [23].

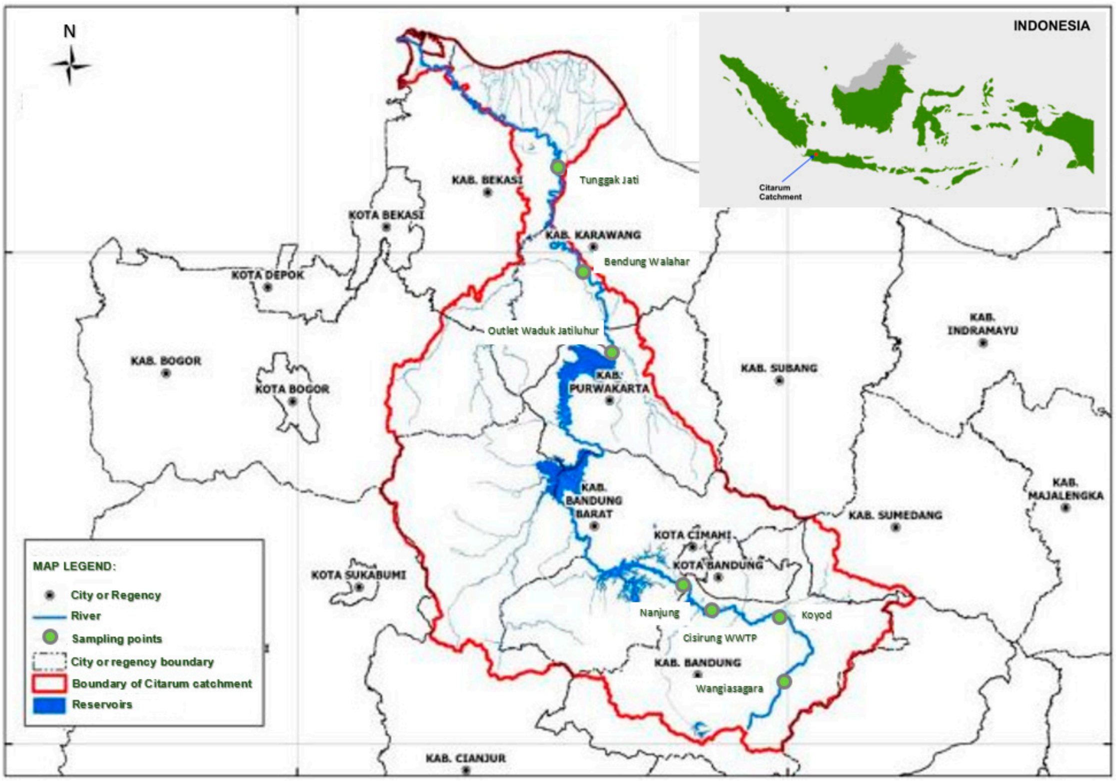


Figure 1. Citarum River monitoring locations, adapted from [24].

In alleviating pollution and damage to the restoration of the Citarum watershed, it is necessary to take accelerated and strategic measures in an integrated manner for control and law enforcement, which will integrate multistakeholders and the government. The President of the Republic of Indonesia stipulated Presidential Decree Number 15 of 2018 concerning the acceleration of pollution control measures to avoid severe impacts on the Citarum watershed [6]. The presidential decree led to the formation of twelve pollution control programs within the Citarum Watershed Management Action Plan, which was compiled by the pollution and damage control task force. For this study, we focused on eight major control programs: (1) Critical land management; (2) Industrial waste management; (3) Livestock waste management; (4) Domestic wastewater treatment plant planning and design; (5) Municipal solid waste management; (6) Open space utilization control; (7) Integrated water resources management, and (8) Water quality monitoring management.

2.2. Methodology

Uncertainty and sensitivity analysis aims to identify changes in water quality parameters implemented in the planned programs as defined in the pollution index. The expected output is to obtain the most effective program for water quality improvement. Meanwhile, the inputs being used were the level of confidence concerning the success of the planned programs, existing water quality parameters, and the relationship between key water quality parameters and the planned programs. Water quality as an uncertainty factor is caused by several monitoring sites (7 points) and the frequency of water quality monitoring (5 times a year), resulting in different results with large variation. In addition, we also considered the planned programs' implementation as an uncertain factor due to the various issues related to the success of the implemention. Therefore, identification of parameters, locations, and the planned programs are required.

Figure 2 presents the steps used for the uncertainty and sensitivity analysis in the study.

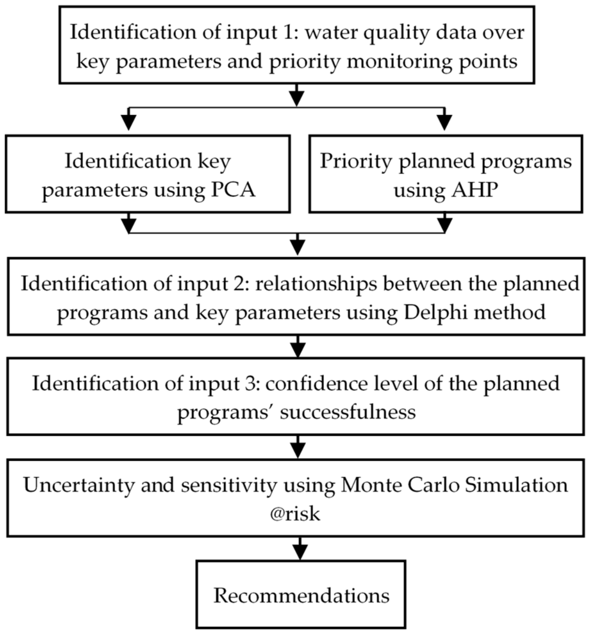


Figure 2. Steps used for uncertainty and sensitivity analysis in the study.

We selected critical parameters to focus on water quality data, input, and factors in a water quality model. The selected statistical method used was PCA. This method is a part of the multivariate analysis, which can provide a unique solution so that a very large number of variables can be reduced [25]. Mathematically, PCA starts from the covariance matrix, describing the dispersion of the measured variables, to obtain the variance of the Pearson product–moment correlation (eigenvalues) and a list of loading coefficients (eigenvectors) [9]. Linear combinations of the original variables and eigenvectors result in new uncorrelated variables, which are performed through varimax rotation, referred to as principal components (PCs) [7,9,26]. The equation used in performing PCA can be expressed as:

$$Z_{ij} = A_{i1}X_{1j} + A_{i2}X_{2j} + A_{i3}X_{3j} + \ldots + A_{im}X_{mj} \quad (1)$$

where Z = component score; A = component loading; x = measured value of variables; i = component number; j = sample number; and m = total number of variables.

In PCA, the original data matrix was standardized, followed by measurements of sampling adequacy and sphericity by the Kaiser–Meyer–Olkin (KMO) and Bartlett's tests; the eigenvectors corresponding to the eigenvalues were used to transform the normalized data into the principal component, and finally, the number of principal components was determined by the cumulative contribution of the variance [7]. We can find the application of PCA in many areas, such as data microarray [27]. Water monitoring variables have been reduced into three components, representing (a) domestic, (b) industry, and (c) animal husbandry and fishery.

The study also focused on monitoring points of the most prioritized subwatershed to serve as input for authorities to conduct monitoring programs. For this sake, AHP was used to identify the priority level of control programs in certain prioritized segments and subwatersheds across the Citarum, along with priority water quality monitoring points conducted by WJEA. According to Saaty [28], AHP is generally a method used to support the decision-making process using varied criteria by comparing weights among those factors or criteria [29]. A few recent studies have also used it to identify weights, as found in [1,30–33]. AHP has advantages, i.e., readily understandable and easily implemented [34], provides a better focus on decision-making criteria [35,36], and integrates the diverse judgments and preferences [37–39]. Just as with any research tool, disadvantages exist in AHP, such as unclear guidance on structuring the problem [40], different competing preference point scales and aggregation methods to be used [36], and it is almost impossible to perform completely consistent pairwise comparisons if there are more than nine criteria [41]. However, compared to other available methods, AHP is the most commonly used to determine the weights of alternatives [41,42]. We used AHP since the advantages outweigh the disadvantages; hence, AHP was an attractive tool that can be used to establish weights.

Steps used for establishing the weights are structuring a hierarchy, constructing pairwise comparison matrices, calculating weight (i.e., the priority eigenvector), evaluating the consistency, and aggregating individual weights to group weights, as presented in Figure 3.

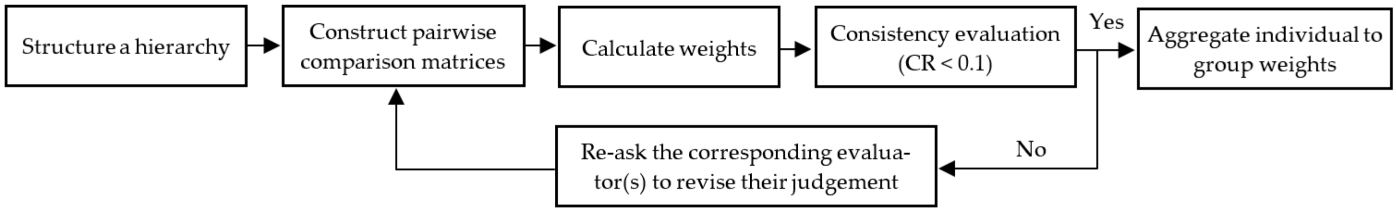


Figure 3. Main steps used in AHP.

The principal eigenvector, the consistency index, and the consistency ratio of AHP can be estimated by solving Equations (2)–(4):

$$Aw = \lambda_{Max} w \quad (2)$$

$$CI = (\lambda_{Max} - N)/(N - 1) \quad (3)$$

$$CR = CI/RI \quad (4)$$

where A = matrix A; w = principal eigenvector; λ_{Max} = largest eigenvalue of the matrix A and corresponding eigenvector w; CI = consistency index; N = dimension of the matrix; CR = consistency ratio, and RI = random index value.

To analyze associations between the planned programs and related parameters, we needed an assessment for level linkages among the planned associated programs and parameters. The study used the Delphi method to collect the values of those linkages. The Delphi is one of the methods to obtain a panel of expert judgments; without any necessity, they gather at the same time and place [43]. It has been widely applied in many areas, one of which has been used to define selected parameters of the water quality index [44] and has advantages in identifying and making a decision based on respondents' questionnaires [45]. We selected the Delphi method from many group decision-making methods since it ensures that inputs from all related stakeholders can be processed appropriately [45], providing sufficient time for experts to give their opinions and reducing variances in judgments [46]. The Delphi method has been applied in several fields to develop, identify, model, and validate data [47], defining parameters for the water quality index [44].

This study obtained the relationships between the planned programs and key parameters from extensive literature and expert judgments using questionnaires. The related stakeholders who participated in this study were selected from universities, environmental consultants, the government, and the community. Additionally, in-depth interviews were also conducted to gather the convergence of the respondents' final opinions. The application of the Delphi method consists of a few steps, including identification of the related stakeholders, questionnaire design and distribution, collection of completed questionnaires, and result analysis [45]. The method used was proportional to the level of relationships for each program, so we obtained their contribution values. The results of those assessments provided different range values. These differences led to uncertainty and were then analyzed using the same approach as the previous uncertainty.

In the uncertainty and sensitivity analysis of the study, a model was made to present relationships between sources of pollutants and levels of pollution in the Citarum River, to define increasing or decreasing parameter concentration related to the planned pollution control programs applied to the Citarum River. The model inputs were the confidence level of the twelve pollution control programs' success, existing data of key water quality parameters, and the relationship between key water quality parameters and the planned programs. The output from these simulation models was the Citarum River pollution level stated in the pollution index. Figure 4 presents framework for the Monte Carlo simulation used in this study.

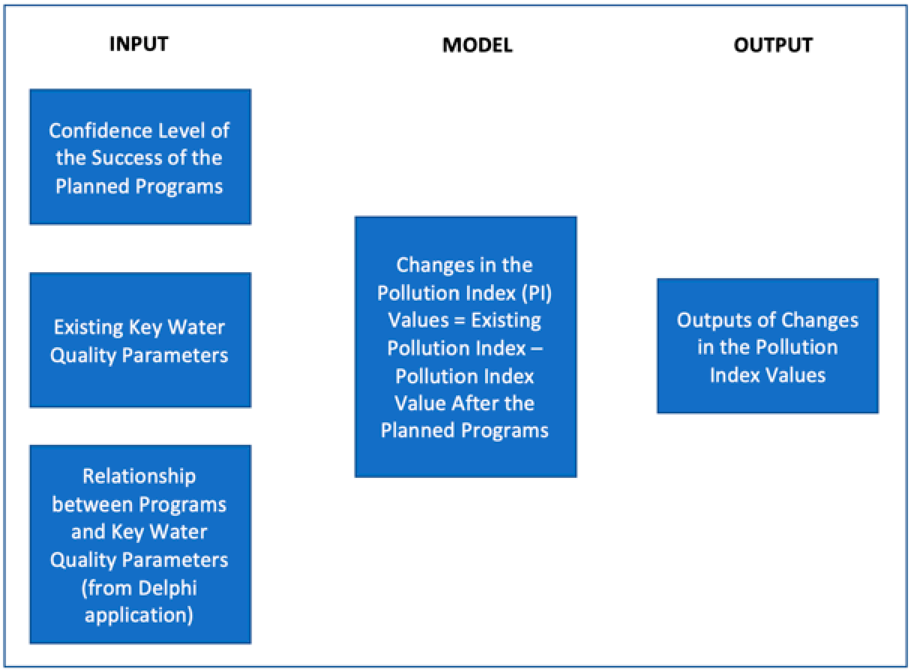


Figure 4. Framework for the Monte Carlo simulation.

The simulations were statistical correlations resulting in equations. In this analysis, it would be identified sources of pollutants and influence significance to output variables. Five thousand uncertainty and sensitivity analysis simulations were carried out to obtain representative data. These analyses can define the level of water quality index confidences modeled [13].

3. Results

3.1. Identification of Key Parameters

For the Citarum River, key monitored parameters likely affected by the implementation of control programs were unclear. Using PCA, we selected the key parameters to focus on the water quality data, known as essential inputs and factors in the overall Citarum water quality model. Key parameters were identified by statistical analysis using thirty-three water quality parameters measured by the WJEA. Based on the interpretation of factors, key parameters for the domestic, industrial, and livestock sectors were obtained for each monitoring point, shown in Table 1. Determination of key pollutants was carried out at each monitoring point (seven locations), as identified in Figure 1.

Table 1. Summary of the selected key parameters.

Location [a]	Industry	Domestic	Livestock
1	Pb	COD	Fecal Coliform
2	Pb	Fecal Coliform	Nitrate
3	Cd	BOD	Fecal Coliform
4	Fe	Fecal Coliform	Nitrate
5	Mn	BOD	Fecal Coliform
6	Pb	Fecal Coliform	Nitrite
7	Mn	BOD	Fecal Coliform

Note: [a] see Figure 1.

The results of PCA analysis for all monitoring points reduced the initial water quality parameters from thirty-two to only three key parameters. To meet the requirements of the PCA method, we ensured that the test results were valid because they passed through testing all requirements and seven stages of the PCA method [43], namely, (1) Kaiser–Meyer–Olkin testing, (2) community testing, (3) total variance testing, (4) scree plot testing, (5) component matrix testing, (6) rotated component matrix testing, and (7) factor interpretation. Based on the analysis of each stage, all monitoring points produce different key parameter results. This is because the characteristics at each point are also different.

3.2. Determination of Prioritized Points in the Citarum Watershed

We selected the water quality data for this research from a monitoring location in the most prioritized subwatershed of the Citarum. In this study, we identified priority levels of subwatersheds and segments within the Citarum watershed. Therefore, at this stage, the aim was to make a priority arrangement of (1) segments, (2) subwatersheds from priority segments, and (3) monitoring points on the Citarum River. The method used in determining the priority arrangement was scoring and weighting, based on criteria that affect the water quality of the Citarum. The weighting process was done using AHP, a globally well-known framework for identifying the weighting criteria. Questionnaires circulated to experts were collected and then analyzed, which took about one month to complete. The results for each factor's scoring and weighting are shown in Table 2. In this study, three evaluators were dismissed since they provided inconsistent judgments. Even though additional time was given to revise their judgments, they did not respond nor return their answers. Therefore, only seven out of the initially selected ten stakeholders were used for further analysis to obtain the weights of levels for the subwatersheds and segments. This value met the consistency ratio below 10% [8]. The consistency value for each evaluator can be seen in Table A1 of the Appendix A. After determining the weight of each aspect, scoring was done subsequently.

Table 2. The weighting of segment selection.

Criteria	Weight	Priority	Parameter	Score [a]
Water quality status	0.23	2	Consistency Vector Mean	5.084
Pollution loading	0.30	1	Consistency Index (CI)	0.021
Land use	0.17	4	Consistency Ratio (CR)	1.89%
Population	0.20	3	Result	Consistent
Land area	0.10	5		

Note: [a] score was calculated using the AHP method.

Based on the scoring and weighting process, we found that the priority for Citarum River management was in segment 1, the Cisangkuy subwatershed, specifically at the monitoring point of location 3 (Cisirung WWTPs). Therefore, the next stage was to focus on this monitoring point. The overall order of priority on the Citarum River management is shown in Table 3, as follows:

Table 3. Order of priority for the Citarum River management plan.

No.	Segment	No.	Subwatershed
A-1	I	B-1 B-2 B-3 B-4 B-5 B-6 B-7	Cisangkuy Cikapundung Cihaur Citarik Cirasea Ciwidey Cikeruh
A-2	IV	B-8 B-9 B-10	Citarum Hilir Cibeet Cikao
A-3	II	B-11 B-12 B-13	Cisokan Cimeta Ciminyak
A-4	III	B-13 B-14	Jatiluhur Cikundul

3.3. Association between Program and Parameters

Out of the twelve pollution control programs, those directly related to water quality pollution were selected. The association between programs and parameters was one of the inputs in the model, expressed by the level of confidence of the experts or stakeholders on the effect of implementing the pollution control program on the key parameters. The value of the association between each control program with key parameters was obtained by taking opinions from experts. The linkage values were collected using the Delphi method through a few steps: identifying stakeholders, designing questionnaires, distributing and collecting questionnaires, and analyzing results. The overall process of this Delphi method needed one month to be completed.

The output at this stage was the confidence distribution frequency and the range as input in the model. Respondents consisted of the academic sector, community groups, and the government sector. Twenty-six respondents were willing to participate in this questionnaire. Respondents comprised 50% of the academic sector, 12% of community groups, and 38% of the government. All selected respondents have strong links to environmental management, water quality management, and the Citarum River. Respondents were asked to rate the relationship on a scale of 1–5, representing a 0–100% value. All the results of the Delphi questionnaire were then used as input for the uncertainty and sensitivity analysis.

3.4. Confidence Level in a Successful Program Implementation

The level of confidence in the program's success was one of the model's inputs, expressed by the percentage of successful program implementation achievements from 2019 to 2020, namely, the success rate of program implementation in one year. The achievement of the pollution control program implementation would affect the effect of the successful implementation of the program on the parameters: the higher the program implementation achievement, the greater the value of program implementation's influence on water quality. All existing value data were obtained from each Citarum River pollution control working group and the West Java Planning Agency in the form of a Carryover Target Program Achievement document dated 14 July 2020. All data obtained represent the pollution control program's success in the entire Citarum River watershed. Table 4 presents the calculation of the confidence level of the pollution control program's success.

Table 4. Confidence level in the pollution control program's success.

Program	Confidence Level
Critical Land Handling	0.04%
Industrial Waste Handling	34.20%
Livestock Waste Handling	35.00%
Domestic Waste Handling	3.52%
Waste Management	45.81%
Spatial Arrangement	0.00%
Water Quality Monitoring	17.65%
Water Resources Management	50.00%

3.5. Uncertainty and Sensitivity Analysis

In this stage, we created a model to identify quality changes in the key parameters after implementing the pollution control program. This stage aimed to determine the relationship between input and output to identify the influential input. The output was (1) the pollution control program that most affects each key parameter, (2) the key parameters most affected by the implementation of the entire pollution control program, and (3) the pollution control program that affects the key parameter's pollution index, and the probability range of the pollution index reduction in percentage.

The inputs used were (1) key parameters of water quality, which are Cd, BOD, and fecal coli with the location focus on monitoring point 3, Cisirung WWTPs; (2) the association of eight pollution control programs with three key parameters; (3) the confidence level in the pollution control program's successfulness. These inputs were used to identify the water quality concentration related to the pollution control program. Based on all the specified inputs, we implemented Monte Carlo simulation by using @Risk Software in the next stage. The output of this simulation model was the pollution index. The simulation of uncertainty analysis was taken from as many as 5000 runs so that the simulation produced representative data, as presented in Figure 5a–f.

Uncertainty analysis in this simulation was intended to test the uncertainty of the input, which had the highest sensitivity to the output. The step taken to perform uncertainty analysis was determining the distribution pattern of the inputs. The distribution pattern for the three water quality parameters, Cd, BOD, and fecal coli, was exponential, Kumaraswamy, and gamma, respectively. In addition, there were distribution patterns for 24 program and parameter linkages. After knowing the distribution pattern, simulation of the output was carried out 5000 times. In the Monte Carlo simulation, the value of the three inputs is one by one to simulate the pollution index so that the pollution index was obtained after the simulation. The output used in the analysis was the output of decreasing the total pollution index from all pollution control programs and all key parameters, which covers all inputs used.

We used the Monte Carlo simulation to ensure that we were able to calculate all inputs based on their distribution pattern, which is one of the advantages of this method. The simulation calculated the pollution index based on the association between input and output equations to determine which input uncertainty affects the output sensitivity. The association between the determined input and output equations was linear. The simulation of pollution index was calculated based on the existing pollution index with the added influence factor, program linkage, and program success. Because the association was linear, the input with the highest uncertainty was the variable that most affected the sensitivity of the output.

The analysis used the output from 5000 simulations and applied the features of the Risk software by analyzing the tornado and spider graphs, according to Figure 3. The entire graph has the same analysis result. The highest value indicates the input with the highest uncertainty and affects the most output sensitivity. Based on the results of visual analysis, the input that had the most influence on the output was the existing water quality data of key parameters, namely, the specifics for Cd, BOD, and fecal coli (Figure 5a,b). Similarly, how those parameters (Cd, BOD, and fecal coli) affect the value of the pollution index can also be explained by the regression values between each of the three parameters and their respective pollution index, as shown in Figure 5c,d. In addition, Figure 5e,f show the superiority of Cd, BOD, and fecal coli parameters when their correlation coefficients and contributions to variance are compared.

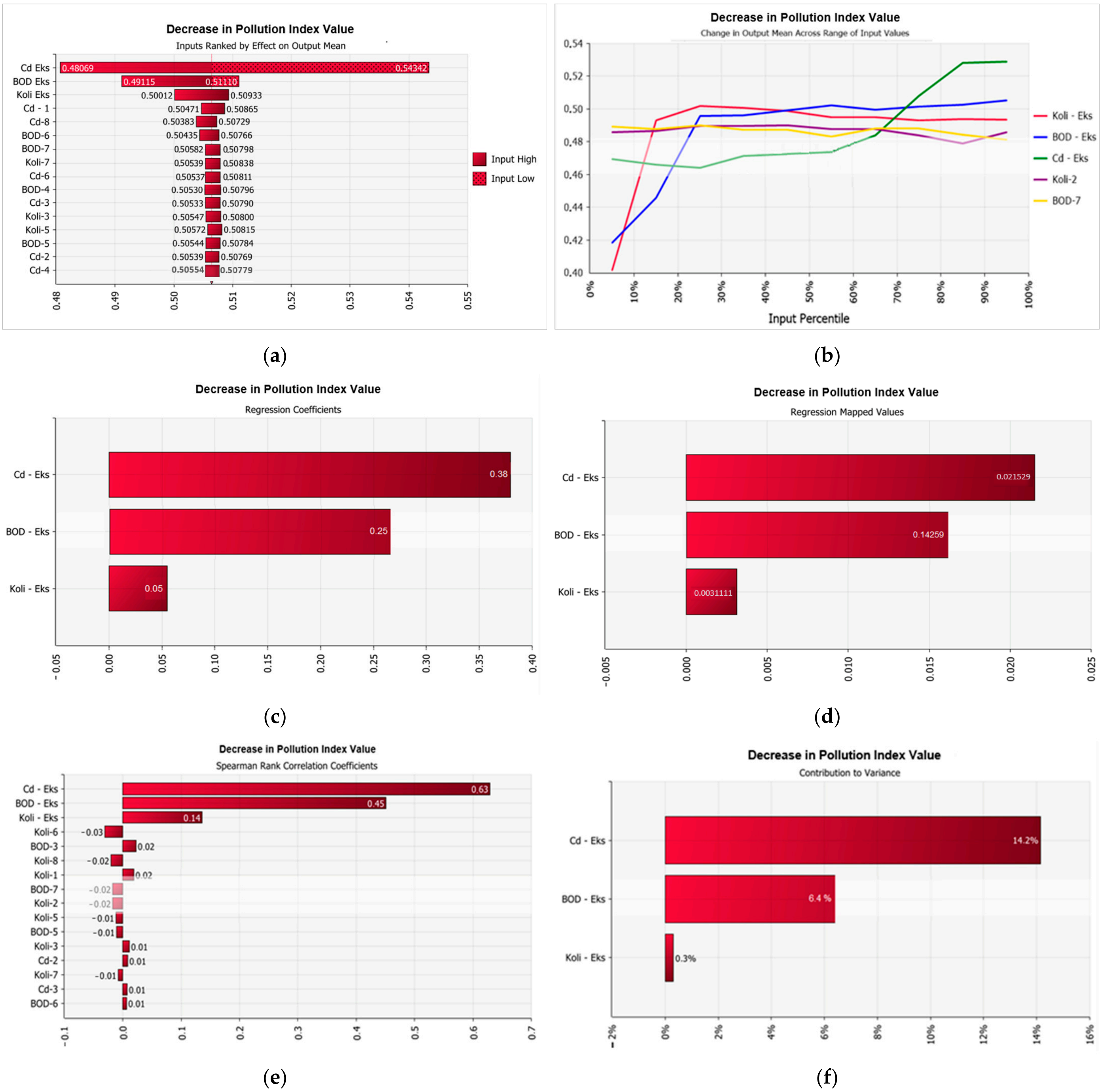
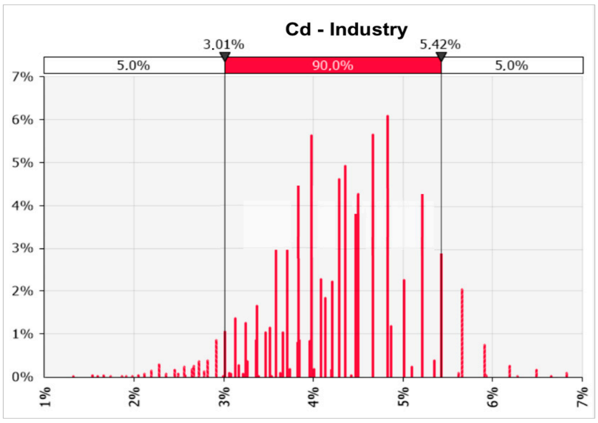


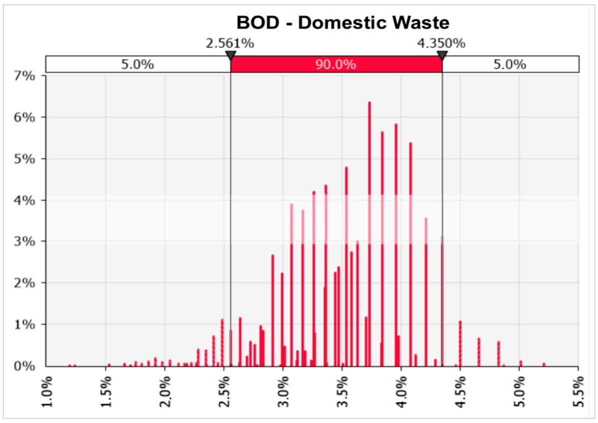
Figure 5. Uncertainty input: (**a**) tornado—change in output statistic; (**b**) spider—change in output statistic; (**c**) tornado—change in regression coefficient; (**d**) tornado—regression mapped values; (**e**) tornado—correlation coefficient; (**f**) tornado—contribution to variance.

3.5.1. The Pollution Control Program That Most Affects Each Key Parameter

This analysis aimed to see the sensitivity of the planned programs to water quality parameters. The program success value in this analysis was the average of all successes or was considered constant for each parameter. The sequence of programs that had the most effect on each parameter is shown in Figure 6 and Table 5.



(**a**)



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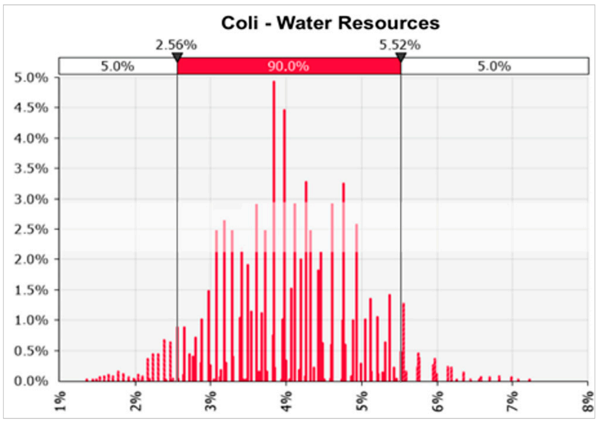


(**c**)

Figure 6. Simulations of the relationship between the pollution programs to each key parameter: (**a**). *Cadmium* with Industrial Waste Treatment Program; (**b**). *Biochemical Oxygen Demand* with Domestic Waste Treatment Program; (**c**). *Fecal Coli* with Water Resource Improvement Program.

Table 5. Programs that most affect the parameters.

Cd	BOD	Fecal Coli
Industrial Waste Handling	Domestic Waste Handling	Water Resources Management
Water Resources Management	Livestock Waste Handling	Domestic Waste Handling
Water Quality Monitoring	Waste Management	Livestock Waste Handling
Waste Management	Industrial Waste Handling	Water Quality Monitoring
Spatial Arrangement	Spatial Arrangement	Waste Management
Critical Land Handling	Water Quality Monitoring	Spatial Arrangement
Domestic Waste Handling	Water Resources Management	Critical Land Handling
Livestock Waste Handling	Critical Land Handling	Industrial Waste Handling

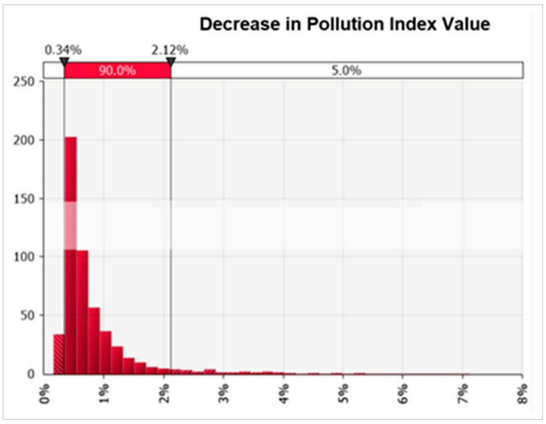
Figure 6a shows that with the 90% confidence level, the Cd parameter might change in the range 3.01–5.42% from its original value when the Industrial Waste program was applied. Figure 6b,c provide similar information for the other two key parameters related to their respective programs: BOD with the Domestic Treatment program and fecal coli with the Water Resource program. For the BOD parameter, based on the Monte Carlo simulation with the confidence level of 90%, as shown in Figure 5b, the Domestic Treatment program might change the BOD value within the range 2.56–4.35% from its original value. With the same confidence level, the value of original fecal coli value might be affected by the Water Resource program, within the range 2.56–5.52%.

3.5.2. The Key Parameters Most Affected by All Pollution Control Programs

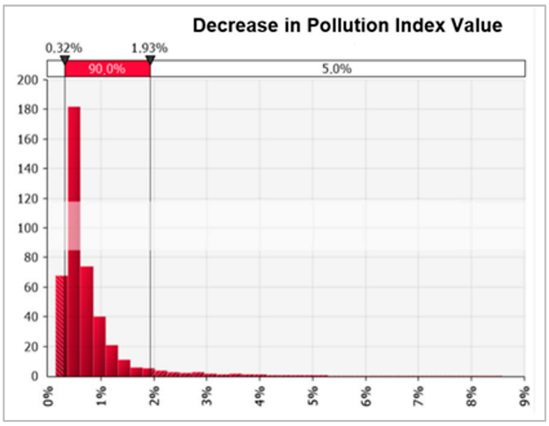
If all programs were implemented, the sensitivity for the Cd parameter was in the range 4.9–48.46% (minimum to maximum). The value for BOD was 5.34–41.3%, while that calculated for fecal coli was 4.8–46.53%. Based on the average value, with the implementation of all programs, it is shown that Cd was the most influential key parameter.

3.5.3. The Pollution Control Program That Most Affects the Key Parameter's Pollution Index

At this stage, we examined the sensitivity of each program to all water quality parameters. We identified sensitivity by investigating the effect of each program on the pollution index for the Cd, BOD, and fecal coli parameters, as presented in Figure 7. The implementation of the most effective program was domestic waste management with an average of 0.8%, followed by livestock waste management (an average of 0.7621%), waste management, and water resources management.



(a)



(b)

Figure 7. Percentage of reduction in pollution index in the program: (**a**) domestic waste handling; (**b**) livestock waste handling.

4. Discussion

Our results show that key parameters of water quality will be affected differently by different water management programs. For the Cadmium (Cd) key parameter, this research indicates that its value is affected the most by Industrial Waste Handling, Water Resource Management, and Water Quality Monitoring. The Cd key parameter is affected the most by the Industrial Waste Handling because the main Cd pollution source is mostly industry, as pointed out by Roosmini et al. [48], Wardhani et al. [49], and Wulandari et al. [50]. Hundreds of industries use the Citarum River as their main wastewater discharge [51–53]. Cadmium is utilized by many industries, such as metals, paints, and steel [48,50]. In the Citarum cases, Cadmium has settled into sediments and potentially causes damage to plants and other living organisms. One of the critical consequences of Cadmium content in the Citarum River is that raw water for various water treatment plants in West Java is taken from the Citarum River. Shara et al. [54] found that the Cadmium level in the Citarum River already exceeded the threshold, which is potentially reaching customers of water companies in many areas of West Java.

It is also worth noted that compared to other key parameters, Cd is the parameter with the highest sensitivity value. This means, in this study, that Cd is the parameter that affects the value of the pollution index the most. Any changes in the value of Cd will have considerable changes in the value of the pollution index of the Citarum River, as the results of both statistical inputs and expert judgments, as explained in the previous subsection. Therefore, in the future, there should be emphasis on how to control and manage the leaching of Cadmium to the Citarum River.

As for BOD, as another example of how a key parameter is affected by different water management programs (see Figure 6), results show that its values are affected most significantly by the Domestic Waste Handling program. This is relevant to various research and literature indicating a strong relationship between BOD and domestic activities, which highlights a considerable increase in BOD in the river as domestic activities intensify [55–58]. In many subwatersheds of the Citarum, domestic pollution contributes to the increase in the BOD parameter above its maximum pollution load [55,56]. Thus, as indicated by this study, in the future, priorities should be given by local and national authorities to programs with a strong emphasis on reducing river pollution caused by household activities.

The other notable parameter is the fecal coli, which is mostly affected by the Water Resource programs undertaken by the provincial government of West Java, as also shown by previous studies, which include land-use management [59,60], law enforcement [61,62], and relocation of slum areas located on river banks [63,64]. Thus, in the future, such programs should be further encouraged and extended to ensure their impacts on the reduction in fecal coli levels in the Citarum River.

As indicated earlier, the sensitivity analysis in this study shows that the most effective program undertaken by the different institutions for the Citarum River is the domestic waste management program (Figure 7), which includes the programs such as wastewater treatment plants [60,65,66], education for mothers living close to the river [67–69], and encouraging community groups to raise social awareness on preventing river pollution [70–72].

Concerning the adopted method used in this study, the weighting process was done using AHP, a globally well-known framework for identifying the weighting criteria. However, we understood that AHP has drawbacks, as mentioned in the methodology section. The use of the original AHP might be the limitation of the study. Therefore, other better methods for determining weights, as they are proven in other areas, should be considered for use in future research. For example, in the transportation sector, recently, there have been main extensions of AHP proposed by some scholars. The fuzzy AHP–linear assignment model has been applied to eliminate untrustworthy responses of the participants and avoid subjectivity in responses [73]. Interval AHP has been performed to attain a consensual preference ranking [74]. A hybrid approach, the fuzzy AHP–interval AHP considers specific group interests of decision-makers [75]. An integrated gray AHP and the Multiobjective Optimization by Ratio Analysis (MOORA) model decreases the subjectivity of the decision-makers [76]. Integration of the AHP–Best Worst Method (BWM) reduces time consumption [77]. Application of the Pareto optimality test in AHP has been proposed to obtain optimality of the eigenvectors while determining weights for alternatives or criteria [78].

Further, along with its merits, for future use of similar methods, in particular methods related to expert judgments as was used in this study, the selection of experts for AHP and Delphi method should be carefully undertaken. The experts to be selected should be representing different expert groups, such as academicians, governmental institutions, the community, and other related groups. In addition, it is important to note that such expert judgment exercises might be time-consuming, both for the respondents (the evaluators) and the researchers. Respondents may spend a significant amount of time giving their judgment when managing a large number of pairwise comparison matrices [41]. To reduce this issue, for at least 5×5 pairwise comparison matrices or more, it is suggested to integrate the BWM model in AHP [77] or decompose the complex problem into simpler and more logical judgments of the attributes [79].

5. Conclusions

This research examined the effective implementation of water quality improvement programs for the Citarum River, West Java, Indonesia, by using uncertainty and sensitivity analysis. Our research shows that industry, domestic, and animal husbandry parameters for each monitoring point were Cd, BOD, and fecal coli. Furthermore, we identified that the most significant key parameter influencing outputs was only Cd. This study also showed that the most influencing programs for pollution control in the Citarum were the planned programs related to the treatment of domestic wastewater. Using Monte Carlo simulation, we projected that there will be a range of increasing probability percentage in pollution index: a minimum of 2%, an average of 5.7%, and a maximum of 36.2%, if all the planned programs stated in the Action Plan were appropriately implemented in the Citarum watershed. This research offers a new approach to help policy-makers prioritize the measures to manage river water quality by considering three essential inputs: (1) key parameters, (2) priority planned programs, and (3) interrelationships between programs, parameters, and the level of successfulness of water quality control programs. Thus, a similar study can be replicated elsewhere.

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Appendix A

Table A1. Consistency ratio value for each evaluator.

Evaluator	1	2	3	4	5	6	7	8	9	10
Consistency Ratio	0.02	**0.18**	**0.31**	0.04	0.02	0.00	0.02	0.01	**0.26**	0.02

Consistency ratio values greater than 0.10 are inconsistent and are in bold.

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