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Improving Water Quality in the Citarum River through Economic Policy Approaches

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Abstract: This study examines the upper basin of the Citarum River in West Java, Indonesia, to analyze the optimal environmental policy and issues affecting the balance between economic activities and water environment conservation, for example, controlling water quality while maximizing economic activities in the region. The quantitative results derived using model simulation analysis clarifies the study's issues. An integrated model linking two sub-models describing socio-economic activities and the dynamics of water pollutants was simulated. The model incorporates government subsidies for sewerage system maintenance and septic tank installation as economic policy variables for water quality control. Further, the optimal amount of these subsidies and changes in local economic activities according to water pollution load constraints are derived in a time-series structure for each region from 2015 to 2030. The gross regional product (GRP) maximization problem is solved under the inflow constraints of total nitrogen, total phosphorus, and chemical oxygen demand into the river. The results showed that the most favorable balance between water environment conservation and local economic activities can be achieved by setting the inflow constraint for 2030 at +3% of the 2015 level and the maximum annual cost of the measures at 10 times the current environmental budget of the West Java Province.

Keywords: Citarum River; domestic wastewater; regional economy; extended input-output analysis; environmental policy

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1. Introduction

1.1. Research Background

There is often a trade-off between economic growth and environmental pollution. Zaidi et al. [1] analyzed the factors that affect CO_2 emissions in Asia-Pacific Economic Cooperation countries and showed that economic growth is a factor that increases CO_2 emissions. Chen et al. [2] analyzed the causal relationship between PM2.5 concentration and energy consumption, energy intensity, economic growth, and urbanization using panel data and econometric methods. They found that economic growth is an important variable that affects the increase in PM2.5. Zhang et al. [3] conducted various statistical tests to investigate the causal relationship between economic growth and COD/NH_3-N emissions. They found an inverse U-shaped curvilinear relationship between economic growth and COD/NH_3-N emissions. Against this background, there is a need for an economic policy that balances the environment and the economy.

Numerous studies explore economic instruments that balance the environment and the economy. Guo et al. [4] analyzed the correlation between environmental regulations, technological innovation, and green growth. They found that environmental regulations have a significant positive impact on technological innovation and technological innovation has a significant positive impact on green growth.

Regarding the trade-off between water quality in public water bodies and economic activities in those watersheds, which is the subject of this study, Yang et al.'s [5] study on the Liao River in China, for example, showed that introducing subsidy policies for livelihood measures and production value adjustment can help achieve both economic growth and water quality improvement with changes in industrial structure. In Hirose's [6] study on the Kasumigaura basin in Ibaraki Prefecture, Japan, a linear programming model was developed to reduce the total amount of pollutant loadings entering Kasumigaura while maintaining the level of socio-economic activity within the basin; further, a 10-year optimization simulation was conducted. The results showed that a 12% reduction was optimal considering the cost of countermeasures and the basin's gross regional product (GRP). Mizunoya et al. [7] also conducted a numerical simulation analysis to improve the water quality of a lake in Kasumigaura and evaluated the advantages and disadvantages of introducing new technologies, such as a new type of septic tank. The study showed that the introduction of the new technology would reduce pollution and increase social welfare compared with the current situation. Additionally, Mizunoya et al. [8] evaluated the impact of municipal mergers in the Kasumigaura basin on the environment and environmental policy and showed that the budget required improvements to the water environment, which can be achieved to a certain extent by improving administrative efficiency through mergers. Nozaki [9] conducted a simulation analysis for the simultaneous reduction of environmental load in the water and air spheres for the Tokyo metropolitan government. The researcher showed that a reduction in environmental load is feasible through the simultaneous combination of sewage policy, solar power generation policy, biomass power generation policy, and subsidy policy for any resulting reduction of productive capital. While there are many studies that have quantitatively analyzed how to balance the environment and economics of watersheds and their effects on various rivers and lakes around the world, there are few studies that have been conducted on public watersheds in developing countries.

This study focuses on the Citarum River in Indonesia, which in recent years has been known as one of the most polluted rivers in the world. Some of the main measures that are currently being implemented are the cleaning of the river by the Indonesian military and the strengthening of the crackdown on factories that violate water quality standards. These measures have had some temporary effects, such as clearing the garbage dumped illegally in the Citarum River and increasing the incentives to improve water quality by collecting fines from the offending factories. However, these measures will not lead to long-term improvements in water quality unless they continue to be implemented. Therefore, other methods need to be considered.

1.2. Research Objectives

Kerstens et al.'s [10] research is an example of a study on the Citarum River. This study showed that the cost–benefit ratio is highest when only domestic measures (sewerage systems for urban areas and septic tanks for rural areas) are implemented according to the urban scale, but industrial wastewater measures and the introduction of advanced treatment are also necessary to achieve the target water quality. However, it is unclear whether the method that was most effective for the Citarum River is one that will lead to long-term improvement in water quality. In this study, the impact of introducing measures for domestic generation sources of water pollutants in the upper Citarum River basin was assessed by simulation analysis using an extended input–output model. Through the simulation using the constructed model, we quantitatively clarify the following: the optimal budget allocation to each policy, changes in each water pollutant discharge (total nitrogen, total phosphorus, and COD, important indicators of eutrophication), and changes in local economic activities owing to the implementation of each policy. Through these analyses, we aim to propose an economic approach to improve both the water quality of the Citarum River and the growth of the local economy. The extended input–output analysis adopted in this study applies input–output analysis, which uses input–output tables to analyze complex economic effects and environmental issues, making it possible to ascertain the domino effects of environmental policy implementation on the industry.

2. Materials and Methods

2.1. Overview of the Study Area

In this study, the area of the upper basin of the Citarum River in West Java, Indonesia (78% of Bandung Province and the entire area of Bandung City and Cimahi City), which is enclosed by the bold line in Figure 1, was chosen as the study area. The total study area is 1586 km^2, which is 4.48% of the total area of the West Java Province (35,378 km^2). In 2015, 5.82 million people were living in the area, which is 12.5% of the total population of the West Java Province. The GRP, which represents the economic scale of the region, was 144 trillion rupiah as of 2015; the GRP per capita was 24.72 million rupiah/person, which is less than one-tenth of the GRP per capita of 4.225 million yen/person in Japan, one of the most economically developed countries in the same Asian region.

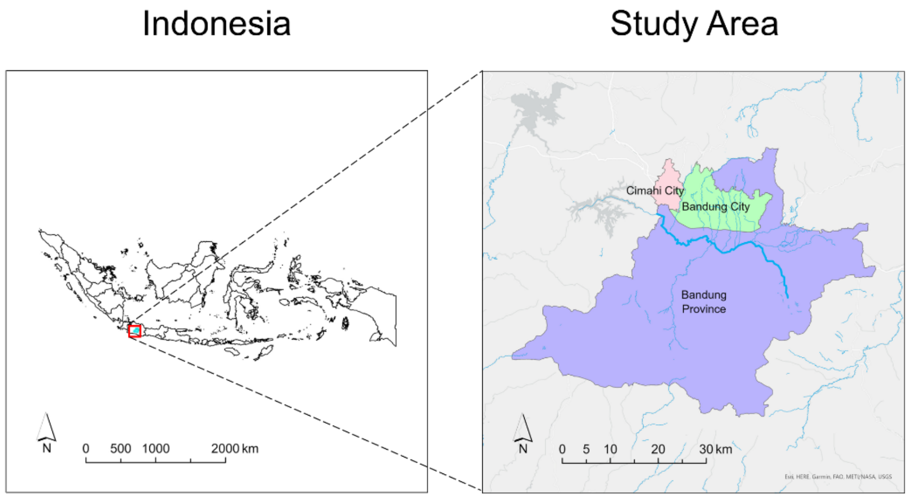

Figure 1. Study area. Source: Prepared by the authors using ArcGIS.

The deterioration of the water quality is a serious problem in this river. The second of Indonesia's four levels of water quality standards, Class II, sets a water quality standard of 0.25 (mg/L) for total phosphorus and 25 (mg/L) for chemical oxygen demand (COD). (Total nitrogen is not set) [11]. In contrast, water quality measurements in 2013 in Nanjing, approximately 70 km from the headwaters of the Citarum River, showed total nitrogen at 2.37 (mg/L), total phosphorus at 0.31 (mg/L), and chemical oxygen demand (COD) at 113 (mg/L) [12]. It shows that both total phosphorus and chemical oxygen demand (COD) exceeded the water quality standards (Class II). Particularly, the COD value was four times higher than the water quality standard value, indicating the severity of water pollution. The main reason for this water pollution is the extremely high influx of water pollutants from the household and industrial sectors. Particularly, there are still inadequate sewage treatment systems, and many factories do not treat wastewater properly and do not comply with effluent standards, which are major issues. In response to this situation, the Indonesian government launched a plan to clean the Citarum River in 2018. The ultimate goal of this plan is to achieve a Water Quality Index (WQI) $\geq$ 80 [13]. The WQI, an overall index that assesses water quality on a 100-point scale, can be calculated by summing the product of the rating score of a water quality parameter and the weighting of that parameter. While there are many ways to choose the parameters, in Indonesia, seven parameters are used: total suspended solids, dissolved oxygen, biochemical oxygen demand, COD, total phosphate, and fecal coil. Considering that the 2018 WQI in Indonesia was 33.43 and the 2019 WQI was 40.20 [13], water quality needs to be significantly improved for Indonesia to achieve its stated goals.

2.2. Simulation Conditions

The real economic growth rate of West Java has been stable and high at 6.5%, 6.5%, 6.3%, 5.1%, and 5.1% from 2011 to 2015, respectively, and the GRP per capita (FY2015) is less than one-tenth of that of Japan; therefore, it is not desirable to set restrictions on economic activities to reduce the water pollution load at this stage. However, it is possible to set numerical targets to reduce water pollutant inflows and implement policies to achieve them.

In this study, we considered that it would be appropriate to derive a policy that maximizes economic activity while constraining water pollutant inflows rather than minimizing water pollutant inflows by restricting economic activity. Therefore, a simulation was conducted to maximize the total value of the GRP for the simulation period, accounting for the social discount rate under the constraint of water pollutant inflows. Here, GRP is an economic indicator for the entire study area, expressed as the sum of the gross value added by each industry, and the objective function is defined by the following equation:

$$max \sum_{t=1} \frac{1}{(1+\rho)^{t-1}} GRP(t), \tag{1}$$

where ρ is the social discount rate (=0.08) and $GRP(t)$ is the gross regional product.

In addition to the constraint on the amount of water pollutants discharged, this study sets an upper limit on the annual cost of the government's countermeasures. The simulation was conducted as an optimization problem to maximize the above objective function under these conditions. The simulation was conducted for a period of 16 years, from 2015 to 2030, using the input coefficient calculated using the latest 2010 version of the Indonesian input–output table. The sources of water pollutants were classified into three categories: household, non-point, and industry. The target area, domestic wastewater treatment facilities as household generation sources, and land use as non-point sources were classified into three, three, and five categories, respectively, as shown in Table 1. Regarding the classification of industries, we divided them into five sectors: "agriculture," "livestock," "fishery," "manufacturing," and "other industries." The simulation calculations were conducted using the mathematical software LINGO 8.1.1.20 (LINDO SYSTEMS Inc. Chicago, IL, USA).

Table 1. Classifications in the model.

No.		Area Division		Source of Water Pollutants		
	Water Pollutants (Index in the Model: *P*)	City or Regency (Index in the Model: *j*)	Percentage of Area That belongs to the Watershed	Household Domestic Wastewater Treatment Facility (Index in the Model: *k*)	Non-Point Land Use (Index in the Model: *l*)	Industry Sector (Index in the Model: *m*)
1	Total nitrogen	Bandung Regency	78%	Sewerage system	Forest	Agriculture
2	Total phosphorus	Bandung City	100%	Septic tank	Agricultural land	Livestock
3	COD	Cimahi City	100%	Untreated	Urban area	Fishery
4					Pasture	Manufacturing
5					Others	Other industries

Note. COD: chemical oxygen demand.

2.3. Policies to Be Introduced

The main cause of water pollution in the Citarum River is the very high inflow of water pollutants from the domestic and industrial sectors. Among them, the discharge of water pollutants from domestic wastewater accounts for a very large proportion; the results of the authors' simulation of the current situation in the next section show that 84% of total nitrogen, 88% of total phosphorus, and 88% of COD are discharged from the domestic sector. The main reason for this is the high percentage of the population with untreated domestic wastewater owing to inadequate sewage treatment systems. Particularly, the sewerage usage rate in the target area was only 11.2% (2015), which urgently needs improvement. In addition to the sewerage system, it is also important to increase the installation rate of septic tanks. A septic tank is a decentralized treatment system that treats only manure through the action of microorganisms and is commonly used in Indonesia. Although the treatment capacity of this system is lower than that of a sewerage system, it has an advantage in that it is easy to introduce in both urban and rural areas; therefore, its use must be expanded. Based on these issues, this study considers the introduction of policies to control the inflow of water pollutants from the domestic sector. The two specific policies are a subsidy policy for sewerage system maintenance (for Bandung City and Cimahi City) and a subsidy policy for septic tank installation (for all areas); these policies could be implemented by the West Java Province government, the local government to which the study area belongs.

2.4. Setting up the Simulation Case

The simulation was conducted using the five cases listed in Table 2. The five cases were divided into two main categories: Case 0, in which no livelihood measures were introduced, and Case 1, in which livelihood measures were introduced. Case 1 was further divided into four cases (Cases 1-1 to 1-4) to analyze the difference in the effect of policy implementation depending on the maximum cost of the measures. In Case 1-1, the maximum annual cost is the same as the actual environmental budget of West Java Province (11.365 billion rupiah, which is 0.85 million per year in US dollars). In Cases 1-2 and 1-3, the maximum annual cost of the measures is set to 5 and 10 times the budget in Case 1-1, respectively. No budget constraint is set in Case 1-4. For each of the above cases, we increased the inflow constraint in 1% increments from the minimum inflow constraint value to obtain a viable solution. Further, we simulated the case where the inflow constraint value in 2030 was +25% compared with 2015. The obtained solutions were compared and analyzed to find a policy that can balance economic activities and reduce water pollutant inflows in the upper Citarum River basin.

Table 2. Setting conditions for each simulation case.

Case	Measures for Household	Maximum Budget (Million Rupiah/Year)	Note
Case 0	—	—	—
Case 1-1	Introduced	11,365	Actual value
Case 1-2	Introduced	56,825	Actual value ×5
Case 1-3	Introduced	113,650	Actual value ×10
Case 1-4	Introduced	No budget constraint	—

2.5. Formulation of the Model

For the formulation of the simulation model, we referred to the studies of Hirose [6], Mizunoya et al. [8], Nozaki [9], and Yamagishi [14]. The simulation model developed in this study consists of two sub-models: the water pollutant flow balance model and the socio-economic model, and an objective function, as mentioned in Section 2.2. The water pollutant flow balance model describes the pathways through which water pollutants are generated from social activities in each area of the watershed flow into the river. The socio-economic model describes the socio-economic structure of the basin, including the production activities of each industry and the consumption by the final demand sector, the relationship between the socio-economic activities and the pollutants emitted by them, and the activities of the government to control pollutant emissions. Two policies to improve water quality, subsidized sewerage system installation and subsidized septic tank installation, were incorporated into the model to provide an optimal hybrid of policy instruments.

In the model, the exogenous variables (*ex*) were calculated based on existing data, and the endogenous variables (*en*) were determined by the structure of the model.

2.5.1. Water Pollutant Flow Balance Model

1. Water pollutant loads flowing into the Citarum River

Water pollutants generated by socio-economic activities in the study area can be divided into three categories according to their sources: household, non-point, and industry.

$$Q^P(t) = \sum_j QZ_j^P(t) + \sum_j QL_j^P(t) + \sum_j QX_j^P(t), \tag{2}$$

where $Q^p(t)$ is the total load of pollutant p in the river at time period t (*en*), $QZ_j^p(t)$ is the pollutant p from households in area j at time period t (*en*), $QL_j^p(t)$ is the pollutant p emitted by non-point sources in area j at time period t (*en*), and $QX_j^p(t)$ is pollutant p emitted by industrial sources in area j at time period t (*en*).

2. Load of water pollutants from household sources:

$$QZ_j^P(t) = \sum_k E_k^P Z_{jk}(t), \tag{3}$$

where E_k^p is the emission coefficient of pollutant p from household wastewater treatment system k (*ex*) and $Z_{jk}(t)$ is the population using household wastewater treatment system k in area j at time period t (*en*).

3. Load of water pollutants from non-point sources:

$$QL_j^P(t) = \sum_l G_l^P L_{jl}(t), \tag{4}$$

where G_l^P is the coefficient of pollutant p emitted through land use l (*ex*) and $L_{jl}(t)$ is the area of land use l in area j at time period t (*en*).

4. Load of water pollutants from industrial activities:

$$QX_j^P(t) = \sum_m P_m^P x_{jm}(t), \tag{5}$$

where P_m^P is the coefficient of pollutant p emitted by industry m (*ex*) and $x_{jm}(t)$ is the production of industry m in area j at time period t (*en*).

2.5.2. Socio-Economic Model

1. Household generation sources:

a. Population of each area

The population of each area changes at a constant rate.

$$Z_j(t+1) = Z_j(t) + \Delta Z_j, \tag{6}$$

where $Z_j(t)$ is the population in area j at time period t (*en*) and ΔZ_j is the population change in area j (*ex*).

b. Population using each domestic wastewater treatment facility

The sum of the populations using all domestic wastewater treatment facilities is equal to the population of each area. The number of people using each wastewater treatment facility changes depending on population growth, policy, and budget expenditures by the government to promote the use of other treatment facilities.

$$Z_j(t) = \sum_k Z_{jk}(t), \tag{7}$$

$$Z_{jk}(t+1) = Z_{jk}(t) + \Delta Z_{jk}(t), \tag{8}$$

where $\Delta Z_j(t)$ is the change in the number of people using domestic wastewater facilities k in area j at time period t (*en*).

c. Population using the sewerage system

The increase in the population using sewerage depends on the amount of construction investment. The number of people using the sewerage system per construction investment is assumed to be 0.866 people per million rupiah [15].

$$\Delta Z_{j1}(t) \le \Gamma i_j^{SW}(t), \tag{9}$$

where Γ is the reciprocal of the necessary per capita construction investment using the sewerage system in area j (0.866 person/million rupiah) (*ex*) and $i_j^{SW}(t)$ is the construction investment in area j for the sewerage system (k = 2) at time period t (*en*).

d. Construction investment for the sewerage system

The total investment amount for the construction of a sewerage system in area j is determined by the construction investment from the West Java Province government and subsidies provided by the central government. The subsidy rate from the central government is set at 0.477, referring to the fact that ((national budget) + (donors))/(total projected allocations) = 0.477 [16] for sewerage system investment in Indonesia during 2010–2014.

$$i_j^{SW}(t) = \frac{1}{1 - M_1} s_{j1}(t), \tag{10}$$

where M_1 is the subsidy rate from the central government (*ex*) and $s_{j1}(t)$ is the construction investment from the West Java Province government to area j at time period t *(en)*.

e. Maintenance cost of the sewerage system

The sewerage system maintenance costs were covered by users. The per capita sewerage usage fee is uniformly set at 219,000 rupiah/year [15].

$$mc_j(t) = N_1 Z_{j1}(t). \tag{11}$$

where $mc_j(t)$ is the total maintenance cost of the sewerage system in area j at time period t (*en*) and N_1 is the charge per capita of the sewerage system in area j (*ex*).

f. Subsidization for the installation of septic tanks

The West Java Province government provides subsidies to installers of septic tanks. The amount of subsidy per person for the installation of septic tanks is 2 million rupiah (we assumed a subsidy amount based on the price of septic tanks [17] and the number of household members in Indonesia [18,19]).

$$\delta \Delta Z_{j2}(t) = s_{j2}(t), \tag{12}$$

where δ is the installation cost per capita of septic tanks and $s_{j2}(t)$ is the amount of the subsidy from the West Java Province government for the installation of septic tanks in area j at time period t (*en*).

2. Non-point generation sources:

a. Land use

The total area of land use in each area was equal to the gross area of each area.

$$L_j = \sum_k L_{jl}(t), \tag{13}$$

where L_j is the gross area of area j (*ex*) and $L_{jl}(t)$ is the area of land use l in area j (*ex*).

b. Change in land use

Each land use area is assumed to have a constant annual change.

$$L_{jl}(t+1) = L_{jl}(t) \pm \Delta L_{jl}, \tag{14}$$

where ΔL_{jl} is the amount of change in land use l in area j (*ex*).

3. Industrial generation sources:

a. Production function and curtailment

The production in each industry is determined not only by supply and demand but also by working capital.

$$x^P_{jm}(t+1) \le \alpha_m k^P_{jm}(t), \tag{15}$$

where α_m is the working capital–output ratio in industry m *(ex)* and $k^P_{jm}(t)$ is the working capital of industry m in area j *(en).*

b. Accumulation of the working capital

The amount of capital stock in each industry is determined by the accumulation of net investment in each period.

$$k^P_{jm}(t+1) = k^P_{jm}(t) + \Delta k^P_{jm}(t) - d_m k^P_{jm}(t), \tag{16}$$

where d_m is the depreciation rate of industry m (*ex*).

4. The cost of the Citarum River water quality improvement measures:

The West Java Province government budgets the cost of measures to reduce the pollution load in the Citarum River. Here, budget constraints are set for the countermeasure cost according to the scenario.

$$y(t) = \sum_j s_{j1}(t) + \sum_j s_{j2}(t), \tag{17}$$

$$y(t) \le \overline{y}, \tag{18}$$

where $y(t)$ is the cost of the Citarum River water quality improvement measures (*en*) and $\overline{y}$ is the budget constraint (*ex*).

5. Flow balance in commodity markets:

The total product of each industry is determined by the balance between supply and demand.

$$\boldsymbol{x}(t) \ge Ax(t) + C(t) + B\, i^P(t) + B^{SW} i^{SW}(t) + B^{SP}(\delta \Delta Z_2(t)) + e(t), \tag{19}$$

where $\boldsymbol{x}(t)$ is the production value column vector by industry in the entire target region at time period t (*en*), A is the input–output coefficient matrix (*ex*), $C(t)$ is the column vector of consumption at time period t (*en*), B is the capital formation coefficient matrix (*ex*), $i^P(t)$ is the production investment column vector in the entire target region at time period t (*en*), B^{SW} is a production inducement matrix for each industry owing to sewerage system construction (*ex*), $i^{SW}(t)$ is the total sewerage construction investment amount in the entire target area at time period t (*en*), B^{SP} is a production inducement matrix for each industry owing to the installation of septic tanks (*ex*), $\Delta Z_2(t)$ is the increase in the number of people using a septic tank in the entire target region at time period t (*en*), and $e(t)$ is the net export column vector at time period t (*en*).

2.5.3. Social Cost

In this study, the social costs incurred owing to water pollution in the river were also included in the analysis. Here, the social cost was calculated by adding the amount of water pollutants flowing into the Citarum River and the social cost per kg of each water pollutant.

$$SC(t) = \sum_P \mu^P Q^P(t), \tag{20}$$

where $SC(t)$ is the total social cost incurred owing to water pollution in the river (*en*) (unit: million rupiah) and μ^P is the social cost per kg of water pollutant P (*ex*) (unit: million rupiah/kg).

2.5.4. Constraints on the Inflow of Water Pollutants

We set constraints on the amount of total nitrogen, total phosphorus, and COD flowing into the Citarum River in 2030.

$$Q^p(2030) \leq \overline{Q^p}(2030), \tag{21}$$

where $\overline{Q^p}(t)$ is the restriction on the amount of water pollutant P flowing into the Citarum River by 2030 (*ex*).

Additionally, the following equation was used to set the constraints so that the amount of each water pollutant flowing into the river would increase or decrease year by year. When the emission constraint in 2030 is +x% of the 2015 level,

$$Q^p(t+1) \leq Q^p(t)\sqrt[15]{\frac{100+x}{100}}. \tag{22}$$

3. Results

3.1. Analysis of the Current Situation and Setting of the Simulation Criteria

Before conducting the simulation, we calculated the discharge pollution load and GRP from the 2015 data; these are summarized in Tables 3 and 4, respectively. Table 3 shows that for all water pollutants, the largest amount is discharged from domestic sources, accounting for 84% of total nitrogen, 88% of total phosphorus, and 88% of COD. Among them, the amount of discharge from untreated domestic wastewater accounts for more than 40% of any water pollutant; therefore, the introduction of domestic generation source control measures examined in this study is considered to be appropriate. Table 4 also shows that the GRP composition of manufacturing and other industries is high in the study area, with the former accounting for 25.7% and the latter 71.3%. This suggests that the economy of the study area has a structure that is easily influenced by changes in the output of manufacturing and other industries. These were used as the criteria for conducting the simulations.

Table 3. Water pollutant discharge by sector in 2015.

	Source	Value	Unit	Emission Pollutant Load (Ton/Year)		
				Total Nitrogen	Total Phosphorus	COD
Household						
	Sewerage system	654,850	Person	658	288	1873
	Septic tank	2,439,051	Person	7718	1438	34,880
	Untreated	2,730,542	Person	10,166	1694	65,081
	Total	5,824,443	Person	18,543	3421	101,834
Land use						
	Forest	158.18	km^2	84	5	103
	Agricultural land	1045.77	km^2	982	74	1377
	Urban area	249.27	km^2	241	22	1340
	Pasture	40.45	km^2	25	2	33
	Others	92.28	km^2	78	5	131
	Total	1585.95	km^2	1410	109	2985
Industry						
	Livestock	714,222	10^6 rupiah	216	78	617
	Fishery	612,834	10^6 rupiah	211	50	513
	Manufacturing	85,744,280	10^6 rupiah	1785	248	9455
	Others	193,964,798	10^6 rupiah	0	0	0
	Total	285,204,308	10^6 rupiah	2212	376	10,585
Total inflow amount				22,164	3906	115,405

Source: Agaton et al. [20], S. M. Kerstens et al. [10], Statistics of Jawa Barat [18,21], and Yang [22]. Note. COD: chemical oxygen demand.

Table 4. Gross regional product in 2015.

Industry	Added Value (Million Rupiah)
Agriculture	3,427,281
Livestock	488,785
Fishery	517,826
Manufacturing	36,921,487
Others	102,615,137
Total = gross regional product (GRP)	143,970,516

Source: Compiled by the authors from Statistics Indonesia [23] and Statistics of Jawa Barat [21]. Note. GRP: gross regional product.

3.2. Simulation Results

Figure 2 shows the relationship between the inflow constraints in 2030 (compared with 2015) and the objective function in each case obtained from the simulation. The minimum inflow constraint values for which feasible solutions were obtained for Cases 0 to 1-4 are +21%, +15%, +7%, +1%, and −1%, respectively. Based on this result, the simultaneous reduction of total nitrogen, total phosphorus, and COD by 2% or more compared with 2015 cannot be achieved by 2030 only by measures for domestic generation sources. However, comparing the results of imposing the same inflow constraints between cases, it can be seen that the implementation of measures for domestic generation sources has the effect of boosting basin economic activity (that is, the objective function). Table 5 shows the value obtained by dividing the increment of the objective function owing to the increase in the countermeasure budget by the increase in the countermeasure budget (value converted to the present value). From an economic point of view, this can be regarded as the social benefit rate that the implementation of measures for domestic generation sources brings to the region. Table 5 shows that the objective function increases by more than four times the countermeasure cost increment among all comparable cases. Additionally, in the most cost-effective condition, the increment of the objective function is 1800 times greater than the increment in the policy budget. Figures 3–5 show the changes in total nitrogen, phosphorus, and COD inflows at the minimum inflow constraint values for which a feasible solution was obtained in each case. The outline of this is summarized in Table 6. From Cases 0 to 1-3, the amount of total phosphorus is not smaller than the value in 2015 in any scenario. This result indicates that the most important focus for technological development in this river basin is the development of phosphorus removal technology. The phosphorus removal rate of the Indonesian sewerage system used in this study is 29% [10], which is lower than the phosphorus removal rate of 50% of the combined treatment septic tank in Japan [24]. Additionally, the phosphorus removal rate of septic tanks in Indonesia is 5%, which is only one-third of the 15% phosphorus removal rate of Japan's single-treatment septic tanks [24]. This result reiterates the limitations of this technology and the possibility of improving the phosphorus removal capacity. Mizunoya et al. [7], who studied Kasumigaura in Japan, found that total nitrogen is the pollutant that should be focused on the most for pollution reduction in the basin. This indicates that there are different pollutants that should be focused on depending on the economic activities and available pollution reduction technologies in a country or watershed.

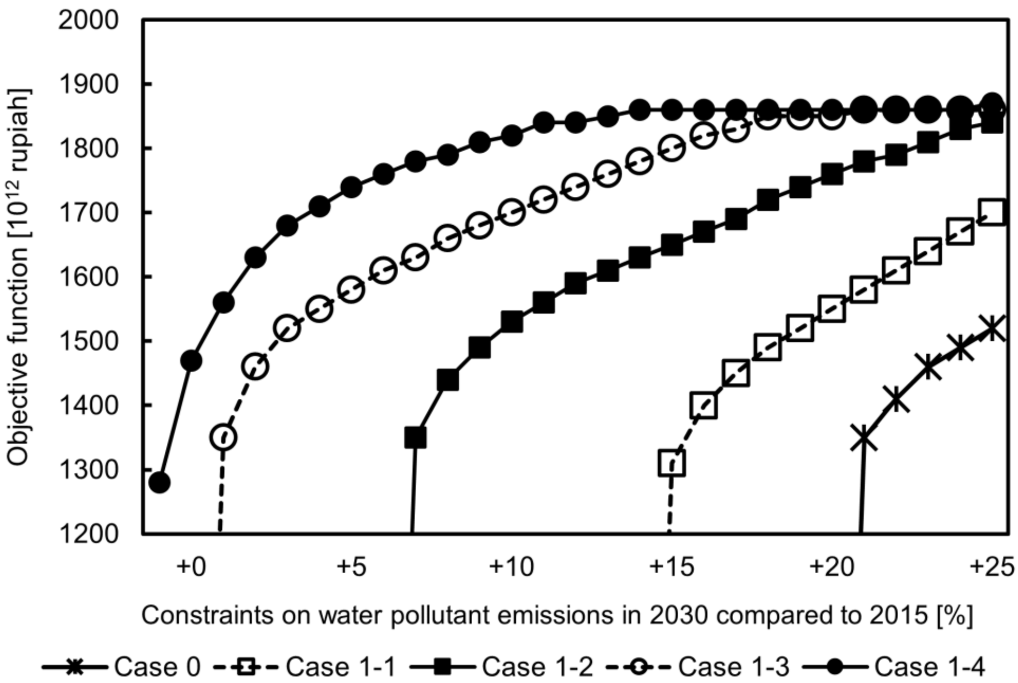

Figure 2. Relationship between inflow constraints and the objective function.

Table 5. Increment of the objective function in proportion to the increment of the policy budget (Million rupiah).

	Constraints on Water Pollutant Inflows in 2030 Compared with 2015 Values				
Changes in the Cases	**+5%**	**+10%**	**+15%**	**+20%**	**+25%**
Case 0 → Case 1-1	—	—	—	—	1800.0
Case 1-1 → Case 1-2	—	—	790.7	488.4	333.3
Case 1-2 → Case 1-3	—	326.9	300.0	176.5	37.7
Case 1-3 → Case 1-4	69.3	9.3	25.3	4.3	4.4

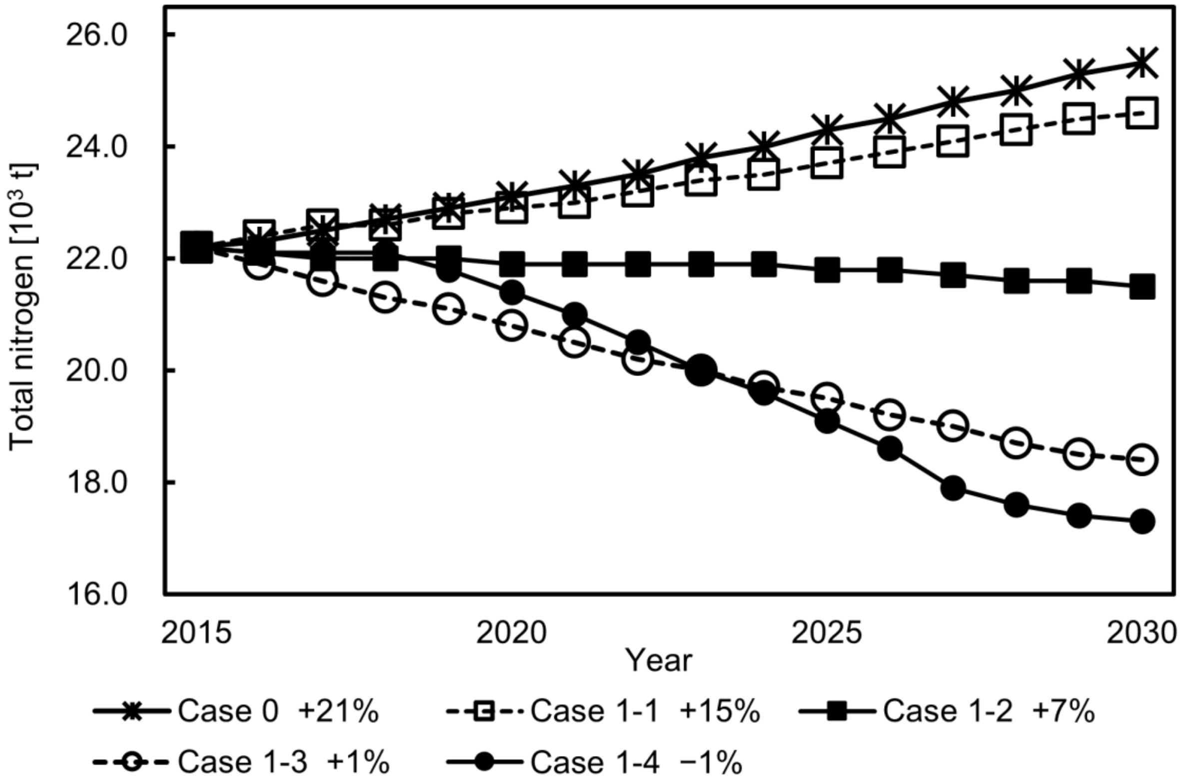

Figure 3. Changes in total nitrogen inflow.

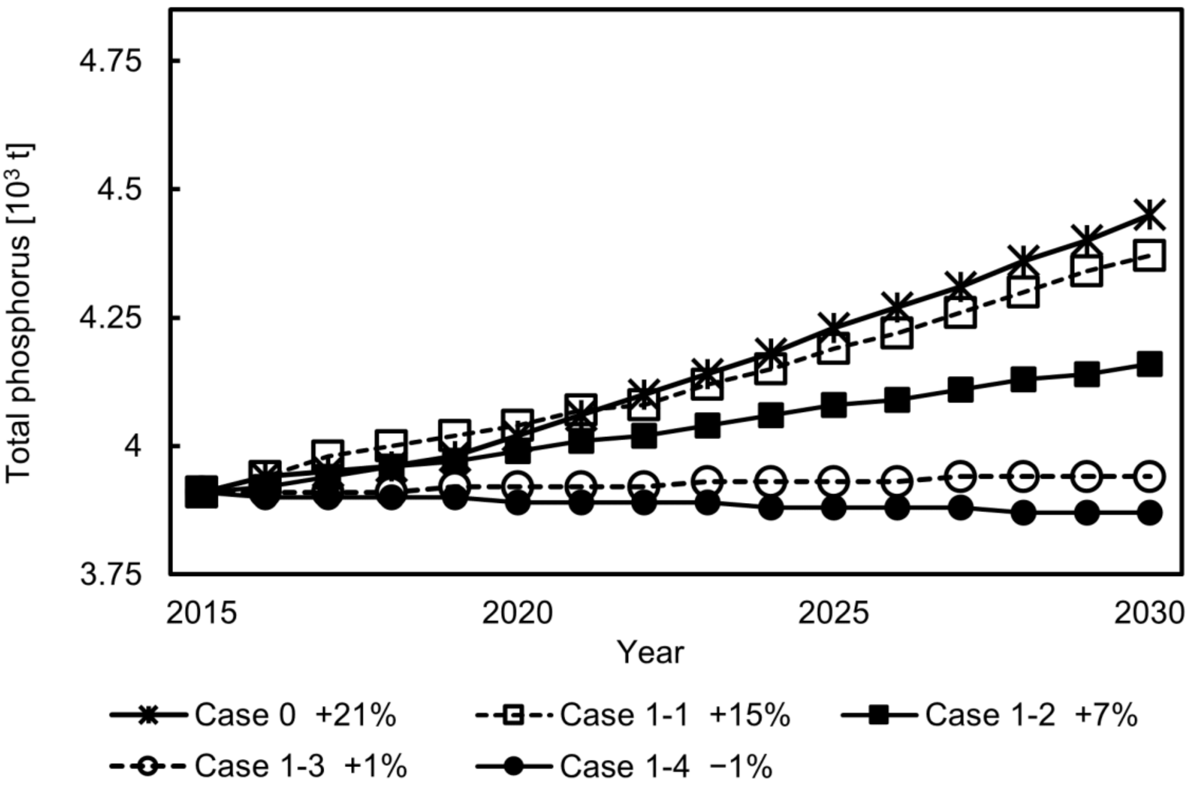

Figure 4. Changes in total phosphorus inflow.

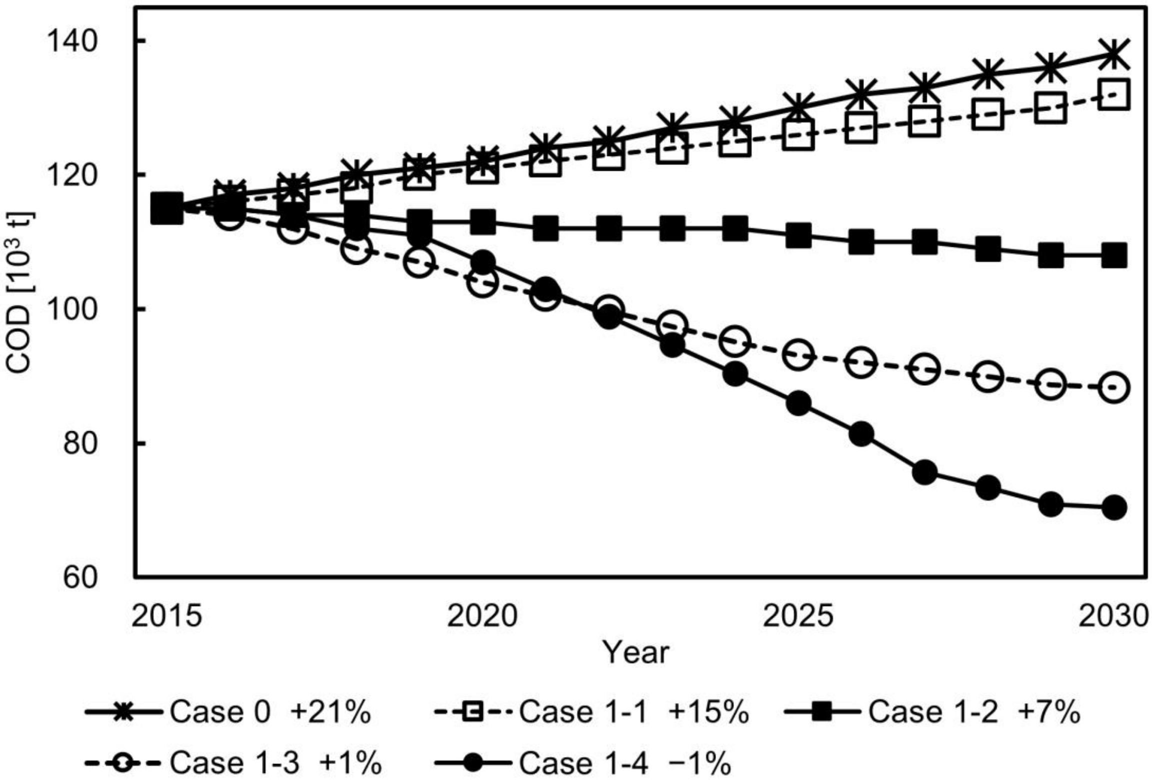

Figure 5. Changes in chemical oxygen demand inflow. Note. COD: chemical oxygen demand.

Table 6. Amount of each water pollutant that will be inflowed in 2030 (compared with 2015).

Case	Inflows in 2030 (Compared with 2015)	Total Nitrogen (%)	Total Phosphorus (%)	COD (%)
Case 0	+21%	+15	+14	+20
Case 1-1	+15%	+11	+12	+15
Case 1-2	+7%	−3	+6	−6
Case 1-3	+1%	−17	+1	−23
Case 1-4	−1%	−22	−1	−39

Note. COD: chemical oxygen demand.

Table 6 shows that the total nitrogen and COD inflows in 2030 compared with 2015 are +15% and +20%, +11% and +15%, −3% and −6%, −17% and −23%, and −22% and −39%, respectively, in order, from Cases 0 to 1-4. Based on these values, the inflow reduction of any water pollutant cannot be achieved not only in Case 0 but also in Case 1-1 with the current policy budget amount as the budget constraint. This result suggests that the current policy budget is not sufficient to reduce the inflow of water pollutants. If the policy budget is increased to five times the current level (Case 1-2), both total nitrogen and COD inflows can be reduced, but the reduction rates are still small, −3% and −6%, respectively. Meanwhile, if the policy budget is increased to 10 times the current level (Case 1-3), both total nitrogen and COD inflows can be reduced by more than 15%. Even in Case 1-4, without a budget constraint, the reduction of total phosphorus emissions is found to be difficult. Figure 6 shows the population composition by domestic wastewater treatment facility for the entire target area in 2030 in each case obtained from the simulation. From this figure, it can be seen that as the budget increases, the sewer-using population increases, and the population with untreated domestic wastewater decreases. Particularly, Case 1-3 shows that it is possible to increase the sewer-using population by 2.66 million people from 2015 to 2030 and to decrease the population with untreated domestic wastewater by 890,000 people. However, the budget amount of Case 1-3 (113.65 billion rupiah/year) is also insufficient to reduce the population with untreated domestic wastewater to zero, and a further budget increase is necessary. Case 1-4, which had no budget constraint, is able to reduce the population with untreated domestic wastewater to zero in 2030; however, the cumulative cost of implementing this measure is 3.16 times higher than Case 1-3 (5.39 trillion rupiah), which is considered difficult to achieve under the current circumstances.

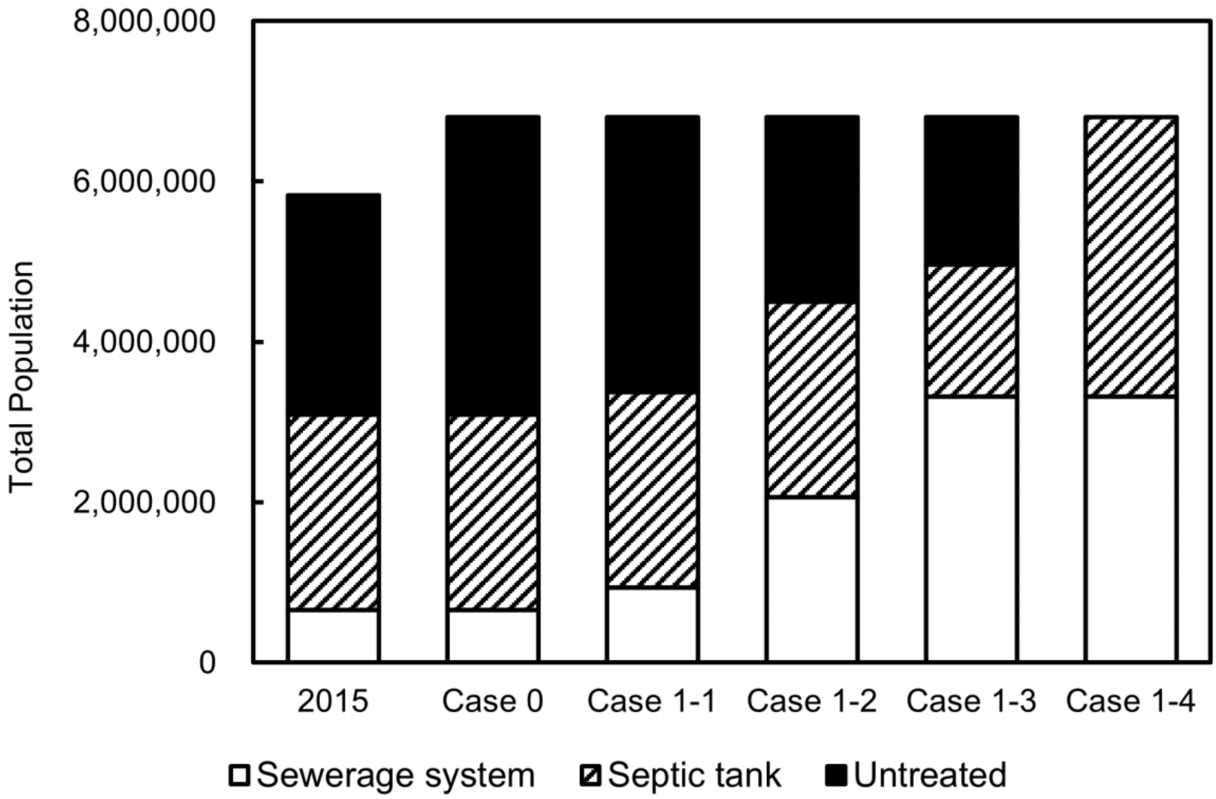

Figure 6. Population by domestic wastewater treatment facility.

3.3. Estimation of Social Costs in Each Case

Table 7 shows the estimation results of the social costs associated with total nitrogen, total phosphorus, and COD inflow in each case. The explanation of the terms in Table 7 is as follows: "Benefit" is the present value of the reduction in social costs. To estimate the social cost, we used 11,640 CNY per ton for COD, referring to K. Tang [25], and 0.075 USD per ton and 55.43 USD per ton for total nitrogen and total phosphorus, respectively, referring to H. Sandhu [26]. If water pollutant inflow can be reduced by introducing policies and increasing the budget, social costs will also be reduced, and the value obtained by converting this reduction into the present value will be used as a benefit. "Cost" is the sum of the annual budgeted amount in the simulation, converted to the present value. It should be noted that the budget limits given exogenously in the simulations did not necessarily match the budget amounts derived. "B/C" indicates the cost–benefit ratio (benefit divided by cost). When the cost–benefit ratio of a policy is greater than one, it can be considered that implementing the policy does not cause any harm. "Budget ceiling" indicates the value obtained by dividing the annual budget's upper limit in each case by the actual environmental policy budget of West Java. In other words, when this value is X, the upper limit of the annual budget is X times the actual environmental policy budget of West Java. "Inflows in 2030 (compared with 2015)" is the change in the inflows of substances that could not be reduced most when comparing the inflows of each water pollutant in 2030 with those in 2015 in terms of the percentage. This is the value used as the "simultaneous reduction rate" in this study.

Table 7. Benefit and cost.

Budget Ceiling (Times)	Inflows in 2030 (Compared with 2015)	Benefit (10^{12} Rupiah)	Cost (10^{12} Rupiah)	B/C	Objective Function (10^{12} Rupiah)
×	+21%	—	—	—	(1348)
1	+15%	0.56	0.11	5.17	(1310)
1.5	+13%	0.72	0.16	4.62	(1377)
2	+11%	1.14	0.21	5.43	(1319)
2.5	+11%	1.27	0.26	4.84	(1402)
3	+10%	1.66	0.32	5.15	(1367)
3.5	+9%	2.06	0.37	5.60	(1338)
4	+8%	2.47	0.42	5.88	(1300)
4.5	+8%	2.57	0.47	5.45	(1385)
5	+7%	2.98	0.54	5.55	(1348)
5.5	+6%	3.39	0.58	5.87	(1310)
6	+5%	3.51	0.63	5.57	(1394)
6.5	+5%	3.94	0.68	5.76	(1357)
7	+4%	4.29	0.74	5.84	(1319)
7.5	+4%	4.41	0.79	5.60	(1394)
8	+4%	4.80	0.84	5.71	(1348)
8.5	+2%	5.18	0.89	5.81	(1291)
9	+2%	5.31	0.95	5.61	(1377)
9.5	+1%	5.39	1.00	5.40	(1310)
10	+1%	5.60	1.05	5.33	(1348)
No budget constraint	−1%	6.36	3.83	1.66	(1281)

Note. B/C: cost–benefit ratio.

The cost–benefit ratio exceeds four in all cases except the case with no budget limit (Case 1-4). As mentioned in the previous section, the highest priority of the policies for changing the domestic wastewater treatment system was the shift from untreated domestic wastewater to sewerage use. The high efficiency of this policy in reducing water pollutants is considered to be the reason the cost–benefit ratio exceeds 4 in each case where the annual budget ceiling is equal to or 5 or 10 times the actual environmental budget of the West Java Province. Conversely, in the case with no upper budget limit, the cost–benefit ratio is as low as 1.66. In this case, because the budget can be used as much as possible, the economic ripple effect of the policy introduction is large (e.g., in the +15% scenario, the difference between the objective functions of Cases 1-1 and 1-4 is 550 trillion rupiah from Figure 2). However, the efficiency of reducing water pollutants is poor, and in other cases, the policy judged to be low priority could be implemented. In such a case, the cost–benefit ratio is considered to decrease. In all cases, the value of the benefit is less than 1% of the objective function. Based on this result, the social cost of water pollution does not account for a high proportion of the local economy. Furthermore, as the objective functions vary widely, the change in the target reduction rate has a greater effect on the objective function than the reduction in social costs. The results shown in Table 7 are all for the minimum inflow case for each budget amount, and we expected the difference in the objective function to be close to zero before running the simulation. However, owing to the limitations of the simulation and other factors, slight differences in conditions resulted in variations in the objective function. This result suggests that when the inflow constraint is relaxed by 1%, the objective function will increase more than the incremental social cost, which reflects the current situation in which the environment is sacrificed for the sake of the local economy.

4. Discussion

4.1. Discussion of Main Results

First, we discuss the effects of the implementation of domestic source measures on the objective function. The effect of increasing the objective function occurred because, as the upper limit of the annual countermeasure cost increased, it became less necessary to reduce the amount of water pollution by adjusting the production value. Table 3 shows that, in the study area, more than 80% of all water pollution was from domestic generation sources, which strongly indicates the possibility of reducing water pollution by introducing domestic measures. However, there is a limit to the extent of reduction by adjusting the production value, and whether the amount of emissions can be reduced depends largely on the degree of the introduction of domestic water generation source measures. Sewerage systems and septic tanks are not only effective in reducing water pollutants but they can also be expected to have economic ripple effects on various industries in the process of manufacturing and operating these facilities. This is why the difference in the upper limit of the annual countermeasure cost has more influence than the amount of the countermeasure and depending on the conditions; it can have the effect of increasing the objective function more than 100 times.

Second, we consider the change in the amount of water pollutants emitted owing to the change in the upper limit of the annual countermeasure cost. In the simulation with an increased budget, the sewerage system installation subsidy policy was prioritized over the septic tank installation subsidy policy, and the former targeted the urban cities of Bandung and Cimahi; this resulted in an increase in the population using the sewerage system in Bandung and Cimahi. As a result, the population composition by domestic wastewater treatment changed, and the water pollutant discharge per capita decreased. Based on the discussion in the previous section, the reduction of water pollutant inflow is highly dependent on the degree of the introduction of domestic source control measures, and thus, the reduction of emissions from domestic generation sources leads to a significant reduction in the inflow of water pollution. Therefore, the amount of water pollutant inflow reduced as the upper limit of the annual countermeasure cost increased. Changes in the population using domestic wastewater treatment facilities were made in the following order of priority: first, conversion from untreated domestic wastewater to sewerage system use, from septic tank use to sewerage system use, and from untreated domestic wastewater to septic tank use. The main reason for this is the cost-effectiveness of the oxidizing pond sewerage system, which is commonly used in Indonesia [15]. Although the treatment capacity of the oxidizing pond sewerage system is lower than that of the activated sludge system, it is naturally higher than that of the septic tank; thus, it is reasonable that the policy of subsidizing sewerage system development was given higher priority.

In the above discussion, it is considered to be an important result that the objective function boosting effect is more than 100 times compared with the cumulative maximum measure cost of 1.82 trillion rupiah depending on the conditions; total nitrogen and COD can be reduced by more than 15%, and the population with untreated domestic wastewater can be reduced by 900,000 people, while the population using the sewerage system can be increased by 2.66 million people. This led to the conclusion that Case 1-3 is the optimal case, where the annual cost of measures is 10 times the current level.

4.2. Determination of the Optimal Inflow Rate Target

Figure 7 shows the change in the basin GRP in Case 1-3, which was selected as the best case in this study. The years in which economic growth stops are 2015, 2018, 2020, 2020, and 2021, in that order, from +1% to +5% of the 2015 inflow constraint in 2030; economic growth stops earlier for the +1% and +2% inflow constraints than for the other constraint scenarios. Additionally, since the GRP in 2030 also drops significantly, the scenarios with inflow constraint values of +1% and +2% are economically burdensome. Meanwhile, all the changes in the GRP between the +3% and +5% scenarios are continuous, and there are no sudden changes associated with the increase or decrease of inflow constraints. Figures 8–10 show the changes in the total inflow of total nitrogen, total phosphorus, and COD from the inflow constraint values of +1% to +5%, and Table 8 summarizes the results. The changes in the inflow of total nitrogen, total phosphorus, and COD are all continuous between the inflow constraint value of +1% and +5%, and the inflow does not change significantly as the inflow constraint value increases or decreases. Additionally, the reduction of total phosphorus inflow is difficult and still remains a barrier to simultaneous reduction.

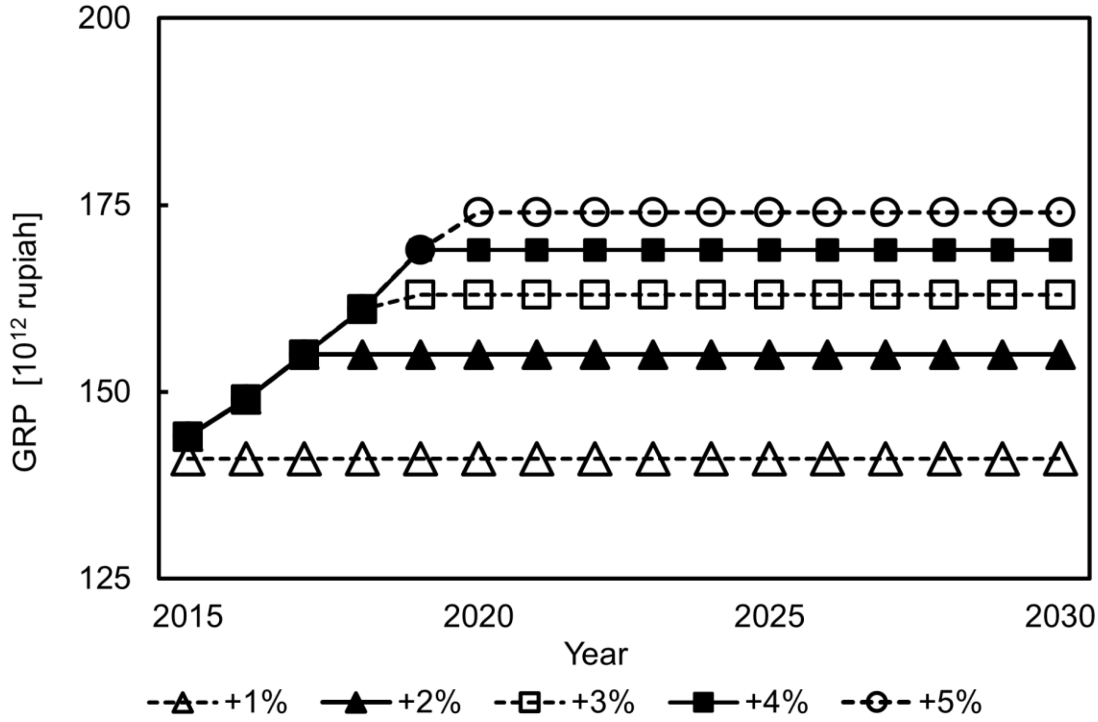

Figure 7. Changes in watershed gross regional product in Case 1-3. Note. GRP: gross regional product.

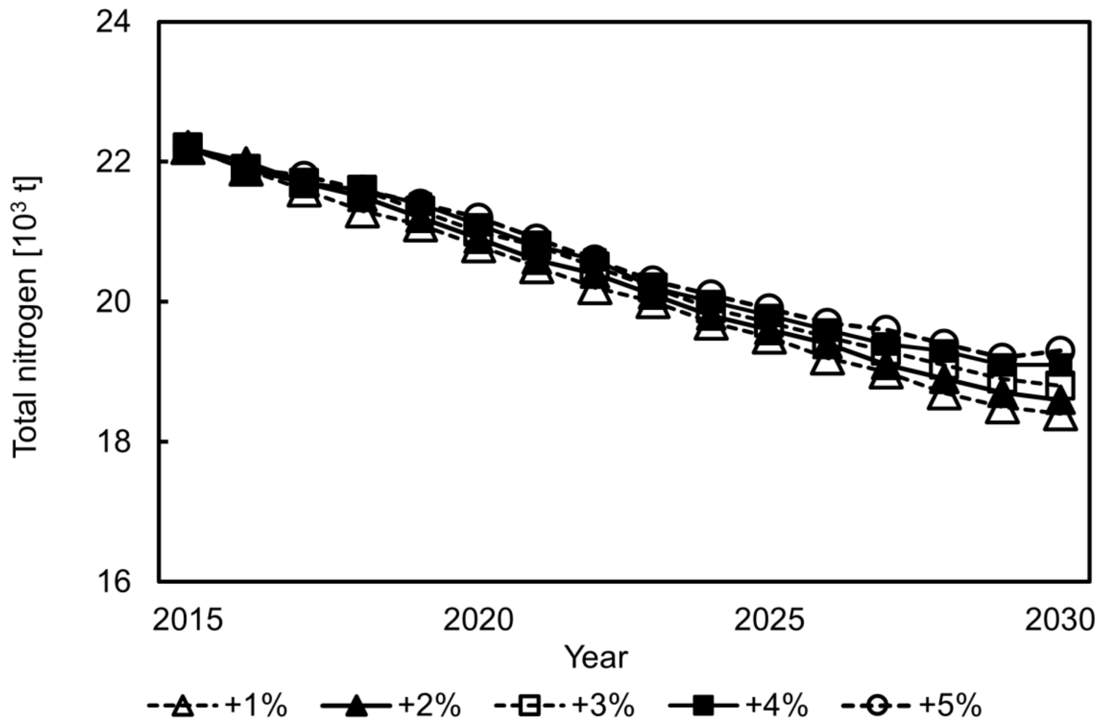

Figure 8. Changes in total nitrogen inflow (Case 1-3).

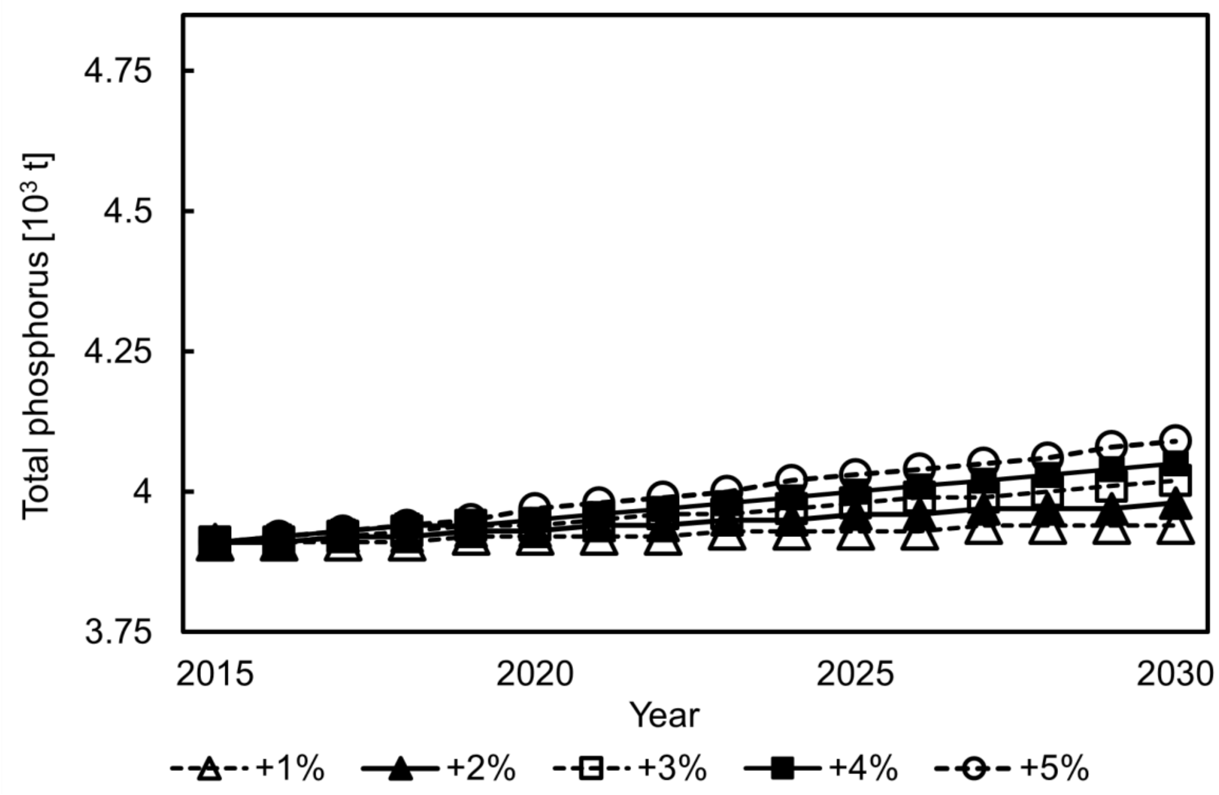

Figure 9. Changes in total phosphorus inflow (Case 1-3).

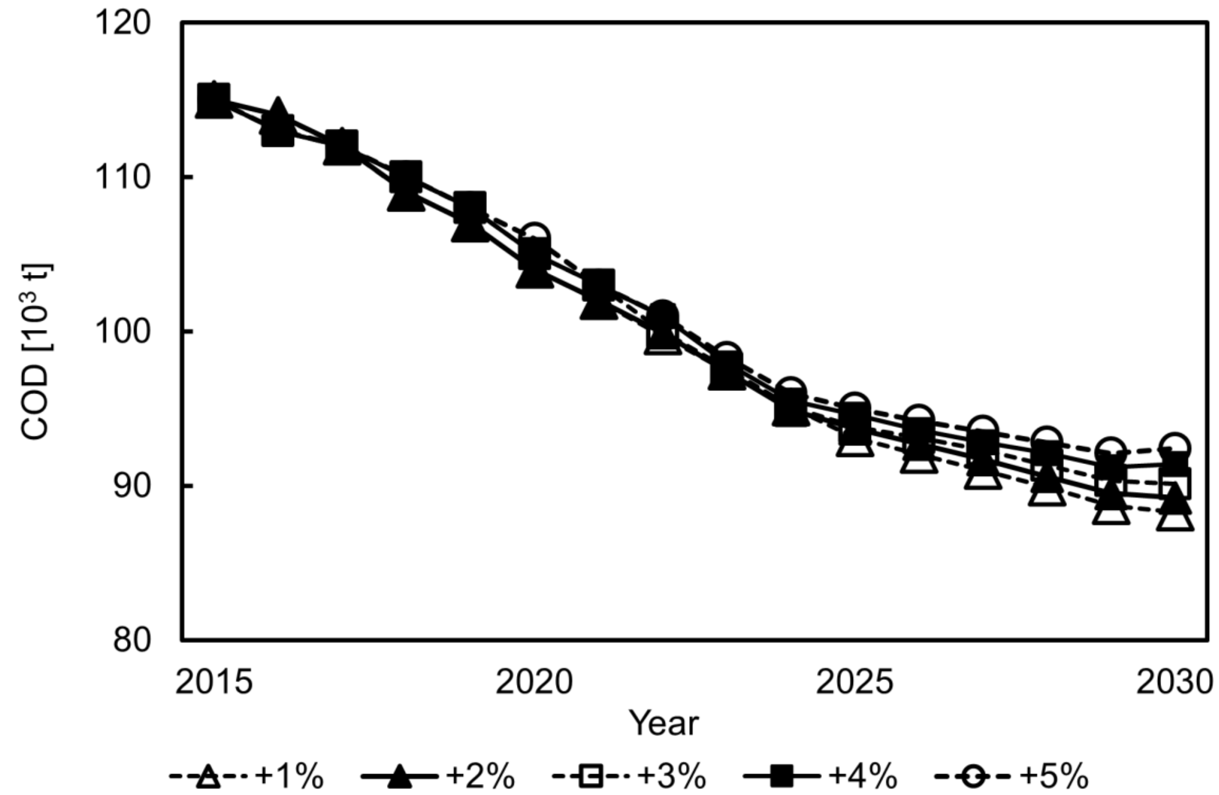

Figure 10. Changes in chemical oxygen demand inflow (Case 1-3). Note. COD: chemical oxygen demand.

Table 8. Comparison of water pollutant inflows in 2030 with inflows in 2015.

Inflows in 2030 (Compared with 2015)	Total Nitrogen (%)	Total Phosphorus (%)	COD (%)
+1%	−17	+1	−23
+2%	−16	+2	−22
+3%	−15	+3	−22
+4%	−14	+4	−21
+5%	−13	+5	−20

Note. COD: chemical oxygen demand.

Figure 11 shows the population by domestic wastewater treatment in 2030 in each scenario with an inflow constraint value of +1% to +5%. The population using sewerage systems in 2030, for the scenario with the inflow constraint value of +1%, is 3.32 million, 3.32 million, 3.32 million, 3.32 million, and 3.31 million, respectively, and the population with untreated domestic wastewater in 2030 is the inflow. From the scenario with the constraint value of +1%, the numbers are 1.84 million, 1.84 million, 1.84 million, 1.89 million, and 1.89 million, respectively. The results show that there is no significant difference in the population using each type of domestic wastewater treatment facility under any of the inflow constraint values. Further, the results indicate that the population using sewerage systems will increase by 2.66 million between 2015 and 2030, and the population with untreated domestic wastewater will decrease by more than 840,000. However, in the scenarios with inflow constraint values of +4% and +5%, the number of people using septic tanks is more than 40,000 less than that in the scenarios with +1% to +3%, and the number of people without domestic wastewater treatment increases by that amount.

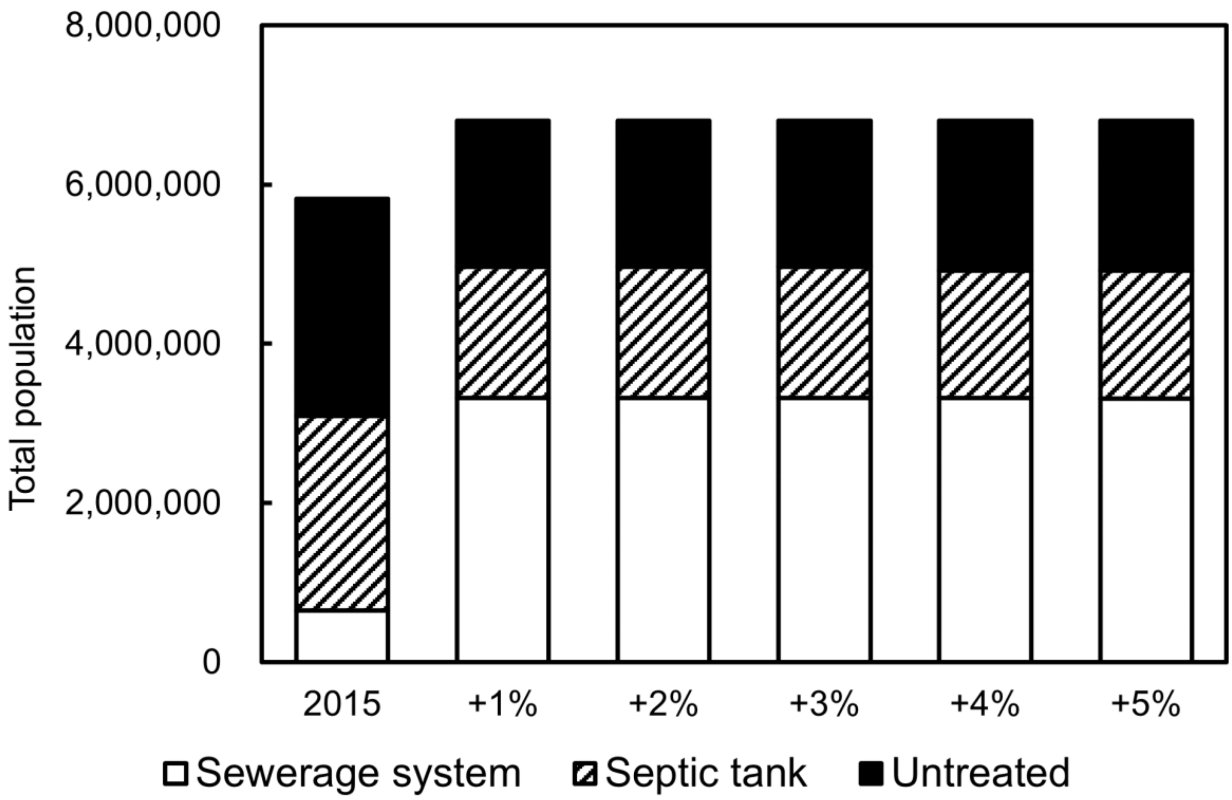

Figure 11. Population by domestic wastewater treatment facility (Case 1-3).

Figure 12 shows the budget allocation in a scenario with an inflow constraint of +1% to +5%. Budget expenditures for the sewerage system installation subsidy policies in Bandon and Cimahi are 1.24 trillion and 0.37 trillion rupiah, 1.24 trillion and 0.37 trillion rupiah, 1.24 trillion and 0.37 trillion rupiah, 1.24 trillion and 0.37 trillion rupiah, and 1.24 trillion and 0.37 trillion rupiah. Additionally, the budget expenditure for the septic tank installation policy in Bandon Province is 0.10 trillion, 0.10 trillion, 0.10 trillion, 0.10 trillion, and 0.10 trillion rupiah, respectively, in that order, from the scenario with the inflow constraint value of +1%. The results show that there is no significant difference in the budget allocation for any of the inflow constraint values and that more than 90% of the budget should be allocated to the subsidized sewerage system installation policy in Bandung and Cimahi. However, in each scenario with inflow constraint values of +4% and +5%, the budget amount for the septic tank installation policy in Bandung Province is reduced compared with the case of each scenario of +1% to +3%. We now discuss these results.

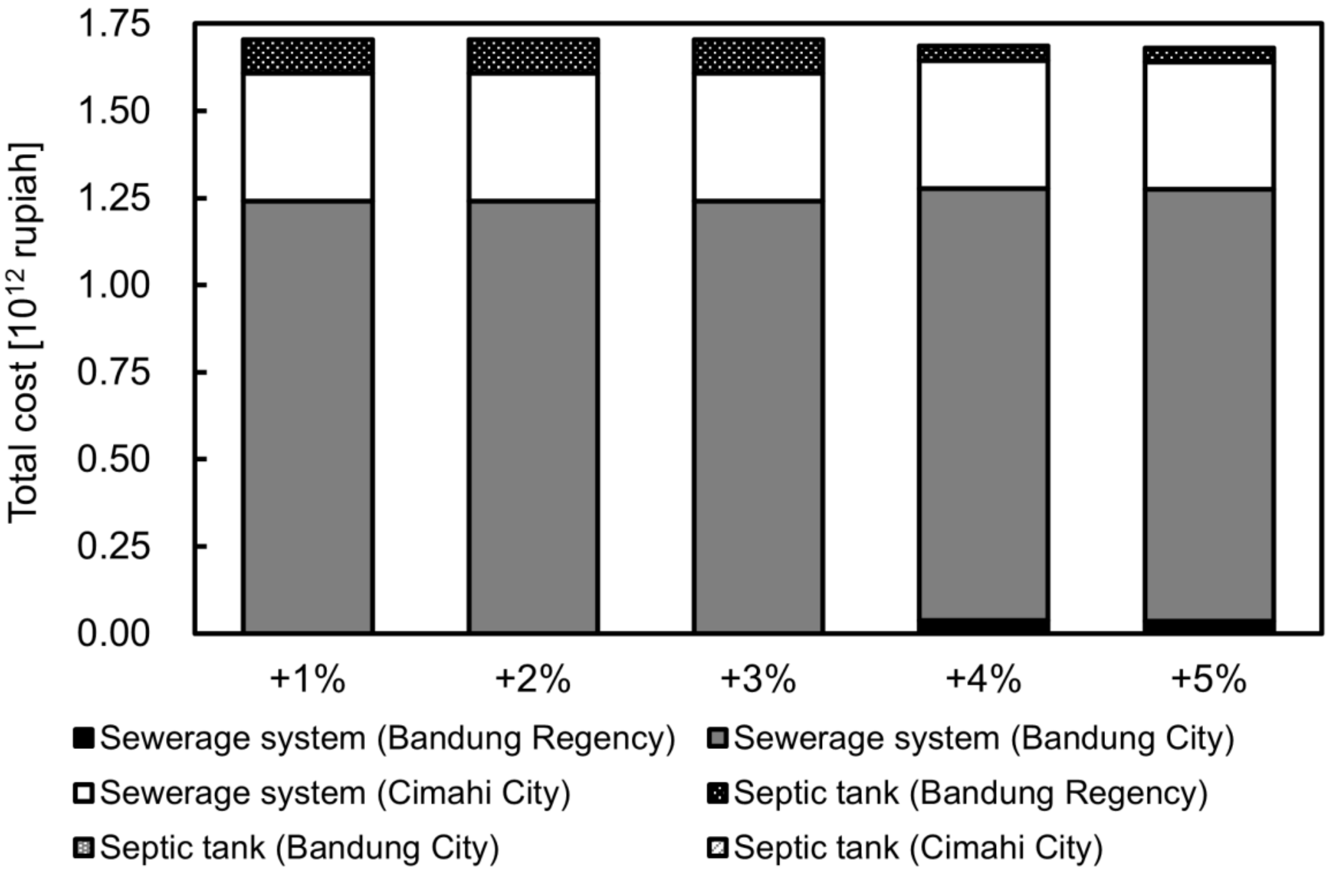

Figure 12. Budget allocation for measures of the Citarum River (Case 1-3).

First, we discuss the consistency of the GRP trends with the actual values. At this point, it is necessary to consider that economic growth stagnated worldwide in 2020 owing to the impact of the spread of COVID-19. Indonesia is one of the countries affected by this, and the GDP growth rate in 2020 was −2.07%, the first negative growth in 22 years since 1998, immediately after the Asian currency crisis [27]. Although the outlook for 2021 and beyond is uncertain at the time of writing this paper, it means that the economic growth rate was positive until 2019, just before the impact of the spread of the new coronavirus infection, and that economic growth stopped in 2020. Therefore, the scenarios with inflow constraint values of +3% and +4% can be said to be consistent with the real world.

Next, we consider why the changes in total nitrogen, total phosphorus, and COD inflows were all continuous and the change in polluted inflow as the inflow constraint value increased or decreased was small. Figures 11 and 12 show that there is no significant difference in the population using domestic wastewater treatment facilities and budget allocation for any inflow constraint value. Meanwhile, the GRP in 2030 decreased by 2.9%, 3.6%, 4.9%, and 9.0% when the inflow constraint was tightened from +5% to +4%,

+4% to +3%, +3% to +2%, and +2% to +1%, respectively. At this time, there was no significant change in the inflow of water pollutants from the domestic generation source in the scenario with an inflow constraint of +1% to +5%, while there was a significant change in the inflow of water pollutants from the industrial generation source in the scenario with an inflow constraint of +1% to +5%. Based on the above, it can be said that in the scenario with an inflow constraint value of +5%, the reduction of pollution owing to measures for domestic sources has already reached its limit, and inflow reduction by production value adjustment must be carried out, thereby achieving the inflow constraint of total nitrogen, total phosphorus, and COD in the subsequent scenarios.

We will now discuss why the reduction of total phosphorus was a barrier to simultaneous reductions. This was because the reduction in total phosphorus owing to the sewerage system and the septic tank, which we assumed were introduced, were not very high, with total phosphorus removal rates of 29% and 5%, respectively; therefore, there was a limit to the reduction in total phosphorus. To reduce all water pollutants by the same percentage (simultaneous reduction), it is necessary to consider policies that introduce more advanced purification technologies in addition to the policies considered in this study, such as the introduction of advanced treatments that remove phosphorus and nitrogen.

Finally, we discuss the reason the population with untreated domestic wastewater was larger in the scenarios with inflow constraint values of +4% and +5% than in the scenarios with +1% to +3%. The most probable reason for this is the reduction in the budget for the septic tank installation subsidy policy in Bandung Province. In this simulation, the sewerage subsidy policy for Bandon Province was not derived, and the population other than the septic tank users was classified as untreated, so the decrease in the budget amount directly led to an increase in the population with untreated domestic wastewater.

The above discussion shows that the scenarios with inflow constraints of +1% and +2% stop economic growth faster, and the decline in the objective function is larger than that in the scenario with an inflow constraint of +3% and above. Further, the scenario with an inflow constraint of +4% and above increases the population with untreated domestic wastewater in Bandung compared with the scenario with an inflow constraint of +3% and below. This is an important result. From these results, we can conclude that the optimal inflow constraint value in Case 1-3, which is selected as the optimal case in this study, is +3%.

5. Conclusions

5.1. Summary

In this study, we examined regional environmental policies for the simultaneous reduction of water pollutants in the upper Citarum River basin in West Java, Indonesia. An inflow constraint value was set for each water pollutant inflow in 2030 compared with 2015, and a simulation was conducted to maximize the basin GRP in the target area.

As a result, we found that the best balance between the environment and the economy is achieved when the upper limit of the annual countermeasure cost was set to 10 times the current environmental policy budget of West Java and the inflow constraint value in 2030 was set to +3% compared with 2015. In this scenario, the total value of the objective function was 1519 trillion rupiah.

The optimal cumulative budget allocation for each policy was 1.24 trillion and 0.37 trillion rupiah (93 million and 28 million in USD) for the subsidy policy for sewerage system installation in Bandung City and Cimahi City, respectively, and 0.10 trillion rupiah (7.5 million in USD) for the subsidy policy for septic tank installation in Bandung Province. In this case, the water pollutant inflow to the Citarum River in 2030 (compared with 2015) was −15% for total nitrogen, +3% for total phosphorus, and −22% for COD. Although the reduction in total phosphorus was not achieved, it was found that total nitrogen and COD could be reduced by more than 15%.

For the method that was found to be optimal in this study to be considered feasible in reality, the first prerequisite is that the annual cost of the measures should be capped at 10 times the amount of the environmental budget of West Java Province, and this is the first barrier to its realization. However, considering that the total policy budget for 2015 in West Java is 28.6 trillion rupiah, the magnitude of the upward effect of the objective function, and the calculation result of social costs, this scenario can never become a reality. For social costs in particular, it was shown that the benefit (reduction in social costs) is 0.56 trillion rupiah for a cost of 0.11 trillion rupiah when the amount is the same as that of the environmental budget of West Java Province, while the benefit is 5.33 trillion rupiah for a cost of 1.05 trillion rupiah in the case of a 10-fold increase. This result suggests that increasing the environmental budget for water pollution prevention can significantly reduce future environmental remediation costs and can be expected to serve as a basis for encouraging the realization of the budget increase. Additionally, it was shown that if the inflow constraint value for 2030 is set to 103% compared with 2015, the GRP growth rate after 2020 would be 0%. Although Indonesia's GDP growth rate fell to −2.07% in 2020 owing to the spread of the new coronavirus infection, stable economic growth can be expected after the country mitigates the coronavirus shock, considering the GDP transition until 2019. Therefore, it is necessary to consider where to balance environmental problems and economic growth based on the actual situation. However, the method proposed in this study has the potential to mitigate the trade-off between the environment and the economy in the sense that it reduces total nitrogen and COD by more than 15% while increasing the basin GRP by 13%. This could be an option for improving water quality in the Citarum River using economic methods.

5.2. Limitation of the Study

The first issue that future studies should address is the reduction of total phosphorus. Considering that it is difficult to reduce the inflow of total phosphorus only by the domestic wastewater generation source measures introduced in this study and that it is a barrier to simultaneous reduction, it is necessary to consider other measures such as the introduction of advanced treatment to remove phosphorus and nitrogen.

Another major issue is the reduction in the population with untreated domestic wastewater. Case 1-3, which increased the maximum annual cost by 10 times, was judged to be the best case, but Case 1-4, which increased the annual cost by more than three times, was necessary to reduce the number of people with untreated domestic wastewater to zero. In this study, Case 1-4 was considered unfeasible. However, if future studies can identify a case that is more optimal than Case 1-3 by conducting a cost–benefit analysis that considers social costs, a more accurate proposal for increasing the cost of countermeasures can be made.

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