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Analyzing Priority Management for Water Quality Improvement Strategies with Regional Characteristics

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Abstract: As the management areas for NPS pollution continue to increase, it is essential to conduct a situation analysis considering the regional characteristics and the scope of pollution reduction. In this study, the focus is on differentiating regional (urban, agricultural) characteristics to enhance water quality and reduce pollution loads in the increasing management areas for NPSs. Furthermore, priority management areas are identified based on urgency and vulnerability, and management strategies are proposed. The assessment involved evaluating both streamflow and water quality (T-P) using long-term monitoring data and watershed models (SWAT and HSPF) that take into account regional characteristics. The results indicated notable regional improvements, with T-P pollution reductions ranging from 20.7% to 26.8% and T-P concentration reductions ranging from 16.4% to 24.7% compared to baseline conditions in unmanaged areas. Based on these research findings, it is anticipated that the efficient and effective management of NPS pollution can be implemented on a regional basis. Moreover, the results of this study will not only contribute to the establishment of pollution standards, but also significantly impact the evaluation and proposal of management objectives, thereby making a substantial contribution to national water quality policies.

Keywords: water quality; priority management; NPS pollution; watershed model

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1. Introduction

Climate change variability has recently increased, exacerbated by industrialization, urban population concentration, and rapid urban expansion [1–5]. Furthermore, distortions in the water cycle and pollution discharge rates in regions affected by heavy rainfall have sharply increased [6]. This escalation is attributed to changes in rainfall patterns due to climate change, resulting in the increased runoff of NPS pollutants. In this situation, the water quality pollution caused by nonpoint sources (NPSs) in urban and rural areas continues to increase. According to reports from the Environmental Protection Agency (EPA), NPS pollution accounts for approximately 30% of all pollution sources, and its contribution varies depending on the land use in the watershed [7]. To deal with these challenges, various countries such as the United States, China, and South Korea are conducting extensive research [8–13].

In particular, South Korea began designating NPS pollution management areas in 2007, and by 2023, the number of these areas had increased significantly to 27, and research on the impact of NPS pollution on water quality has been steadily increasing [14]. Given the substantial and increasing contribution to pollution made by NPSs, they have a considerable adverse impact on river water quality in South Korea [15–17]. In urban areas, pollution loads are increasing due to industrialization and population concentration, while in rural areas, pollution loads are increasing due to nitrogen and phosphorus in fertilizers [18]. According to the third integrated plan for managing NPS pollutants, as announced by the Ministry of Environment in South Korea, it is expected that by 2030, there will be an increase of approximately 15.3% compared to 2018. In this context, managing the discharge of NPS pollutants due to rainfall events is influenced by land use conditions, highlighting the need for the development of efficient and effective strategies for watershed management [19–24]. However, NPS pollution is widely distributed over large areas and is discharged indiscriminately, making it challenging to characterize and quantify their emissions on a regional scale, both in urban and agricultural settings [25–27]. Furthermore, quantitative techniques for NPS pollutants typically require long-term monitoring, which is often impractical due to management costs, the time consumed, and human resource constraints [28]. To address these challenges, researchers are employing various watershed models to study NPS pollution reduction [29]. While numerous empirical monitoring studies have been conducted to make such assessments [30], the Soil and Water Assessment Tool (SWAT) [31] and physical-based models, including the Annualized Agricultural NPS (AGNPS) [32], Water Erosion Prediction Project (WEPP) [33], and Hydrological Simulation Program-Fortran (HSPF) [34], are widely utilized. Lee et al. [35] utilized the SWAT to assess the effectiveness of Best Management Practices (BMPs) such as vegetation mats with infiltration rolls and roll-type vegetation channels. The simulation results indicated a 55% reduction in soil erosion for the vegetation mat with infiltration rolls and a 59% reduction for roll-type vegetation channels. In research carried out by Qiu et al. [36], the SWAT was employed to reduce and assess the NPS pollution loads using the applicability of BMP optimization. Bai et al. [37] assessed NPS pollution loads under changing environmental conditions using HSPF and found it to be highly applicable to the basin under study. Wang et al. [38] investigated the uncertainties of input parameters in watershed modeling based on HSPF, providing valuable insights for improving the accuracy of estimations. SWAT and HSPF are widely used models for reducing NPS pollution, primarily due to their capabilities in addressing a variety of hydrological, hydraulic, and water quality processes, as well as effectively modeling various sources of pollution [39].

However, although these physical-based models employ different mechanisms and equations for the same BMPs [40], in previous studies, analyses of streamflow and water quality were conducted using a single model across various research sites. This preference is attributed to the cost of measured data and the variability in hydro-meteorological and geographical conditions. Since each model has its strengths and weaknesses, it is essential to select a model that considers regional characteristics for the long-term prediction of streamflow and water quality. Furthermore, in presenting management strategies, it is necessary to maximize efficiency in reducing pollution loads by prioritizing areas for NPS pollution management, thus saving monitoring time and maximizing cost-effectiveness. In this context, South Korea faces the challenge of managing NPS pollution areas to improve water quality and reduce the pollution load, which incurs significant monitoring costs annually. Moreover, as new NPS pollution management areas in South Korea are designated, the same process, from analyzing regional characteristics to selecting models and making predictions, needs to be repeated. As the number of such management areas continues to expand, there arises a need for a comprehensive situational analysis that takes into account pollution sources and the potential scope for pollution reduction.

Therefore, the objective of this study is to utilize quantified monitoring data and apply it to models to systematically evaluate water quality improvement and the reduction in NPS pollution. (1) To quantify NPS pollution loads and evaluate long-term changes in streamflow and water quality, it is essential to utilize models that consider regional characteristics (urban, agricultural). Subsequently, after assessing the watershed-scale NPS pollution and its various factors, considering urgency and vulnerability, an analysis of management areas should be conducted. NPS pollution prioritization should be determined, identifying critical areas that require immediate attention. (2) Watershed models, with a focus on the identified priority management areas, will be used to conduct diverse evaluations aimed at proposing strategies for water quality improvement and NPS pollutant reduction within the region. The aim is to contribute to institutional improvements and provide data for watershed-integrated management systems.

2. Methods

2.1. Description of Site and Model Input Data

This research focuses on the study areas designated as NPS pollution management regions in South Korea, aligning with government policy initiatives. The investigation identifies five distinct regional characteristics (Figure 1). Currently, in the five study areas, policies are underway to improve water quality and reduce total phosphorus (T-P) pollution within the context of NPS pollution.

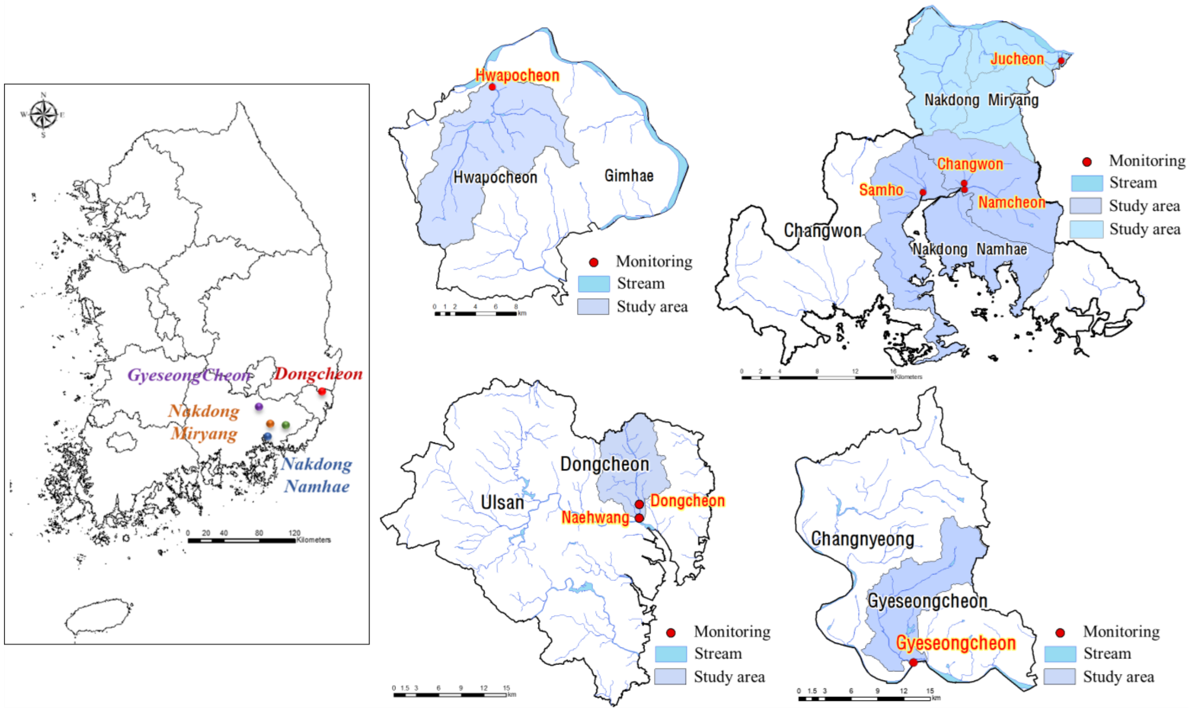

Figure 1. Location and monitoring site of the five study areas (NPS pollution management areas).

As shown in Table 1, within the five study areas, land use characteristics predominantly center on urban and agricultural land use, with forests being the exception. Dongcheon, representing a mere 8.4% of Ulsan's total land use area, accommodates 22.6% of the city's population. It exhibits a relatively high impervious area percentage (21.9%) in Dongcheon compared to Ulsan's impervious area percentage (14.6%). The topographical variations within Dongcheon encompass slopes ranging from 3.3% to 41.2%. The study area in Hwapocheon, located in Gimhae City, accounts for 88.8% of the livestock population (815,000 livestock units) compared to the total livestock population in Gimhae (918,000 livestock units). Moreover, Hwapocheon's agricultural land extends over an area of 30.824 km^2, constituting 22.8% of the watershed area in Gimhae City. Sub-basins within this region exhibit variable slopes ranging from 2.77% to 20.41%. The Gyesungcheon region within Changnyeong County is notable for hosting 43.2% of the country's total livestock population (1,508,000 livestock units). Its agricultural area spans 29.039 km^2, accounting for 27.8% of the total agricultural area in Gyesungcheon (104.324 km^2). The average slope in the sub-basins varies from 16.4% to 51.7%. Changwon City is geographically divided into two regions: Nakdong Miryang and Nakdong Namhae. Notably, Nakdong Miryang's agricultural area (63.781 km^2) represents roughly 38.6% of the total area (165.380 km^2), while Nakdong Namhae's land area accounts for about 6.9% (18.927 km^2). The average slope in the Nakdong Miryang management area varies from 0.7% to 21.1% based on the sub-basin, and the average slope in the Nakdong Namhae ranges from 1.9% to 17.0% based on the sub-basin.

Table 1. Land use characteristics in the five study areas.

Study Area	Total Area (km^2)	Agriculture	Forest	Urban	Etc.
Dongcheon	89.477	16.155 (18.0%)	43.743 (48.9%)	19.585 (21.9%)	9.994 (11.2%)
Hwapocheon	134.850	30.824 (22.8%)	65.775 (48.8%)	24.519 (18.2%)	13.732 (10.2%)
Gyesungcheon	104.324	29.039 (27.8%)	55.236 (52.9%)	2.457 (2.4%)	17.592 (16.9%)
Nakdong Miryang	165.380	63.781 (38.6%)	59.279 (35.8%)	14.770 (8.9%)	27.550 (16.7%)
Nakdong Namhae	272.629	18.927 (6.9%)	149.564 (54.9%)	83.868 (30.8%)	20.27 (7.4%)

This study simulated streamflow and water quality considering the characteristics of the five study areas by utilizing input data for the model, including river network, soil map, land use map, climatic data, and digital elevation model (DEM). The topographic data, which are the input data for the model, were constructed using the digital elevation model (DEM) of 30 m × 30 m resolution provided by the National Geographic Information Institute, Republic of Korea. The reconnaissance soil map (1:25,000) provided by the Rural Development Administration (RDA), Republic of Korea, was used as a base soil map. The climatic data used in the model are daily radiation (MJ/m), daily precipitation (mm), daily mean relative humidity (%), daily mean wind velocity (m/s), and daily maximum/minimum temperature (°C) obtained from the Korea Meteorological Administration (KMA). River network data were obtained from the Water Environment Information System in the form of Korea Reach Files (KRF), and land use data were sourced from the Environmental Spatial Information Service. Table 2 presents the distribution of annual average precipitation in the five study areas. Precipitation data from the Korean Meteorological Administration for the years 2012 to 2021 were used to create this dataset. Despite being in the same year, precipitation is distributed diversely due to the different geographical locations, as illustrated in Table 2. The annual average highest precipitation is 1985.7 mm in the Nakdong Miryang region, while the annual average lowest precipitation is 671.4 mm in the Dongcheon area. Therefore, considering the significant variability in precipitation across the research target areas, it is necessary to implement NPS pollution management strategies that take into account the unique characteristics of each region.

Table 2. The pattern of annual precipitation in the five study areas from 2012 to 2021.

	Precipitation(mm)				
Year	**Dongcheon**	**Hwapocheon**	**Gyesungcheon**	**NakdongMiryang**	**NakdongNamhae**
2012	1458.1	1432.2	1621.4	1828.5	1559.4
2013	858.3	1057.2	1092.3	1114.9	1110.6
2014	1398.7	1634.8	1767.4	1549.4	1525.8
2015	1044.6	1034.6	1236.0	1101.1	1110.7
2016	1693.9	1634.0	1978.8	1985.7	1892.9
2017	671.4	755.8	720.2	945.7	879.3
2018	1416.1	1469.7	1589.2	1654.9	1507.3
2019	1450.1	1494.0	1536.1	1675.3	1675.3
2020	1557.9	1702.5	1892.5	1798.6	1798.6
2021	1337.0	1552.6	1708.2	1555.8	1710.6
Average	1288.6	1376.7	1514.2	1521.0	1477.1
Max.	1693.9	1702.5	1978.8	1985.7	1892.9
Min.	671.4	755.8	720.2	945.7	879.3

2.2. Description of SWAT and HSPF

It is possible to apply management measures to the five study areas with one model and analyze the effects of load reduction and water quality improvement. However, using an appropriate model that considers regional characteristics is efficient and effective not only in simulating streamflow and water quality predictions, but also in estimating NPS pollution load. In particular, South Korea has a large proportion of mountainous terrain and has topographical characteristics such as highly developed agricultural areas with steep slopes. As a result, NPS pollution problems occur during rainfall in rural areas with steep slopes and slope lengths.

The SWAT has the advantage of improving water quality and reducing pollution load by applying BMP on a field basis for each Hydrologic Response Unit (HRU), considering the steep slope and slope characteristics [41,42]. On the other hand, in the case of HSPF, it is difficult to consider soil characteristics, and applying BMP on a field basis is relatively more difficult than the SWAT, so it is not efficient in rural areas [43,44]. In the case of HSPF, various management studies are being widely conducted to improve water quality management due to the increase in impervious area ratio in urban areas during rainfall [45–48]. A description of each model and regional application studies in this study is provided in the following subsections.

2.2.1. SWAT

SWAT, a watershed model, is widely utilized as a semi-distributed watershed model. The HRUs employed in SWAT models integrate information on land use, soil types, and topographic features, such as slope, to calculate various processes including runoff, soil erosion, sediment transport, nutrient movement, and other pollutant transport phenomena within each sub-basin. Based on water balance equations, the model simulates hydrological processes like surface runoff, peak flows, groundwater dynamics, and evapotranspiration. Rainfall-induced soil erosion is determined using the Modified Universal Soil Loss Equation (MUSLE). The SWAT can simulate the transport of various substances, such as sediments, nutrients in different forms, and heavy metals, primarily in conjunction with hydrological processes [49]. The model integrates numerous empirical equations to represent critical parameters or pollutant behaviors. However, the successful implementation of SWAT requires extensive parameter data and a substantial amount of measured data for these parameters to facilitate model development and calibration [50–52]. Moreover, SWAT finds extensive applications in simulating water quantity and quality assessments and evaluating the impacts of BMPs and climate change. Lee et al. [53] reported evaluating the reduction effect of NPS pollution by applying BMPs to small agricultural watersheds in South Korea using the SWAT. Four BMP scenarios including the application of a riparian buffer system, a vegetation filter strip, and the fertilizing control amount for crops were analyzed. Lee et al. [54] evaluated streamflow and sediment on agricultural farmland using the SWAT and the effect of rice straw mat on sediment yield at a watershed. The research results showed that rice straw mats reduce average daily sediment yield by 46.3% during the rainy season. The SWAT has been widely applied in various applications in South Korea.

2.2.2. HSPF

HSPF is a continuous, distributed watershed-scale modeling tool developed by the EPA. It is now an integral part of Better Assessment Science Integrating Point and Non-point Sources (BASINS), a comprehensive watershed assessment system with a GIS framework for data processing and evaluation, incorporating various tools and models [55]. HSPF's versatility in representing hydrologic, hydraulic, and water quality processes, as well as different pollution sources has contributed to its widespread use in urban areas. Gong et al. [56] analyzed pollutant discharge resulting from changes in impervious land in urban areas using HSPF. The simulation considered scenarios with increased impervious land area and the constant number of point source loads before and after development. The results showed a higher NPS pollutant load after development, emphasizing the need for measures to control NPS pollution during development. Lee et al. [47] reported on the setting of scenarios based on riparian buffer areas using HSPF, indicating the effectiveness of BMPs in reducing and managing NPS pollution, including Biochemical Oxygen Demand (BOD) and T-P. HSPF excels in simulating areas with different land uses at a sub-day time step, similar to the SWAT model. Its simulation algorithms combine physically based and empirical approaches. However, like the SWAT, HSPF demands substantial measured data for calibration and validation. The model's flexible modular design and robust simulation capabilities make it a crucial tool for water resource management in watersheds [57,58]. While there are numerous NPS pollution models available, each model has its specific scope of application.

2.3. Model Application and Evaluation

Under the methodology put forth by Moriasi et al. [59], we evaluated the suitability of the model by utilizing the coefficient of determination (R^2) and the Nash–Sutcliffe Efficiency (NSE) metrics for both streamflow and water quality (Table 3).

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)\left(Y_i^{sim} - \overline{Y}^{sim}\right)\right)^2}{\left(\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2 \sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y}^{sim}\right)\right)^2} \quad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2} \quad (2)$$

where Y_i^{obs} is the observed data, $\overline{Y}^{obs}$ is the mean of the actual value, Y_i^{sim} is the estimated value of t, $\overline{Y}^{obs}$ is the mean of the estimated value, and n is the total number of times. r is the variation coefficient ratio between the simulated (CV^{sim}) and the observed (CV^{obs}) streamflow, in which σ^{sim} and σ^{obs} represent the standard deviations of both measured and simulated data, respectively. β is the ratio between the simulated mean (μ^{sim}) and the observed mean (μ^{obs}) streamflow and r is the correlation between the measured and simulated values.

Table 3. Model calibration and validation criteria.

Output Response		Very Good	Good	Satisfactory	Not Satisfactory
NSE	Streamflow	>0.80	0.80 ≥ NSE > 0.70	0.70 ≥ NSE > 0.50	0.50≥
	T-P	>0.80	0.80 ≥ NSE > 0.70	0.70 ≥ NSE > 0.45	0.45≥
R^2	Streamflow	>0.85	0.85 ≥ R^2 > 0.75	0.75 ≥ R^2 > 0.60	0.60≥
	T-P	>0.80	0.80 ≥ R^2 > 0.65	0.65 ≥ R^2 > 0.40	0.40≥

In the South Korean policy, the third integrated measure for the NPS pollutant management plan (2021~2025) by the Ministry of Environment, the T-P of NPS pollution was set as the priority management and reduction target. The streamflow data (2010~2021) were obtained from the Water Management Information System (WAMIS), while the observed T-P data (2012~2021) were acquired from the Water Environment Information System (WEIS). These data were utilized for the calibration and validation of the model.

This study calibrated the SWAT and HSPF for streamflow observed from a monitoring station (Dongcheon, Hwapocheon, Gyeseongcheon, Jucheon, Samho, Changwon, Namcheon) in the five study areas and attempted to improve streamflow predictions using models. In the case of Dongcheon (study area), it was divided into Dongcheon (streamflow monitoring) and Naehwang (T-P monitoring) because it was difficult to secure data from the same monitoring location. Unlike the other four study areas, the simulation period of the Dongcheon area was different due to missing values in the streamflow data.

Detailed information regarding monitoring locations, corresponding calibration and validation periods, and the number of monitoring data for the five study areas are delineated in Table 4. Furthermore, the models used for each specific region (urban, agricultural) were delineated and are presented in the table separately.

Table 4. Dataset for model (SWAT and HSPF) simulation.

Study Area	Main Outlet (Monitoring)	Number of Monitoring (Streamflow, T-P)	Period (Year)
Dongcheon	Dongcheon	Streamflow (3639)	Calibration 2010~2013 Validation 2014~2019
	Naehwang	T-P (120)	Calibration 2012~2016 Validation 2017~2021
Hwapocheon	Hwapocheon	Streamflow (374), T-P (377)	Calibration 2012~2016 Validation 2017~2021
Gyeseongcheon	Gyeseongcheon	Streamflow (371), T-P (377)	Calibration 2012~2016 Validation 2017~2021
Nakdong Miryang	Jucheon	Streamflow (374), T-P (374)	Calibration 2012~2016 Validation 2017~2021
Nakdong Namhae	Samho, Changwon, Namcheon	Streamflow (183), T-P (183)	Calibration 2012~2016 Validation 2017~2021

2.4. Approach for Selecting Areas for NPS Pollution Management

To address water quality pollution concerns resulting from rainfall events and to analyze water quality improvements due to NPS pollution control strategies, various factors influencing NPS pollution were systematically considered. Based on the prioritization of these factors, we identified areas for focused pollution management. These considerations are specific to urban and agricultural areas, taking into account watershed-specific water quality (T-P), impervious surface ratios, population density, the distribution of agricultural land, slope, and livestock populations.

(1) The assessment of watershed-specific water quality (T-P) was executed based on model-generated data encompassing T-P concentrations during precipitation events. (2) High impervious surface ratios were calculated for watersheds where urbanization is known to exacerbate water quality issues. (3) Areas characterized by elevated population density were earmarked for urban regions, given the well-established relationship between population growth and the exacerbation of NPS pollution. (4) Given the pronounced influence of substantial soil and livestock waste runoff in agriculturally driven regions, due consideration is accorded to the extent of agricultural land area. (5) Watersheds with steeper slopes were singled out for prioritized attention, owing to the heightened susceptibility to water quality deterioration in response to intense precipitation events. (6) In agricultural regions, specific emphasis was placed on watersheds with substantial livestock populations, as a significant correlation exists between livestock numbers and T-P discharges.

2.5. Strategies for Improving Water Quality and Reducing NPS Pollution

In this study, we focused on T-P as the water quality within the context of the third Comprehensive Plan for NPS Pollution Management, a policy initiative in progress in South Korea. We have applied various scenarios to analyze the impact of reducing T-P on water quality. In this study, three different scenarios (Scenario 1 to 3) were set to reduce the T-P pollution, taking into account land use and regional characteristics (urban and agricultural areas) (Table 5). Scenarios 1 and 2 were presented within the current feasible limits while considering the region's budget/economic feasibility. Furthermore, Scenario 3 was formulated to optimize the efficacy of NPS pollution reduction. To reduce NPS pollution during precipitation events, a thorough analysis of management measures was conducted, focusing on areas characterized by high urgency and vulnerability. In urban areas, strategies encompassed the application of Low Impact Development (LID) techniques to impervious areas. This entailed the operation of road vacuum cleaning vehicles within the management area and the installation of NPS pollution reduction facilities. In agricultural areas, scenario analysis was carried out with an emphasis on ownership areas with a substantial distribution of agricultural area. Measures included the implementation of NPS pollution reduction facilities such as the application of rice straw mats in field artificial wetlands, and riparian buffer zones. Furthermore, strategies such as managing water flow for paddy fields and reducing fertilizer usage were integrated into the scenario analysis.

Table 5. Suggestion comprehensive management plan for reducing NPS pollution.

Study Area	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
Dongcheon	NPS pollution control facilities (4 Priority management area)	NPS pollution control facilities (4 Priority management area)	NPS pollution control facilities (10 Priority management area)
	-	Applying LID to 30% of impervious area	Applying LID to 30% of impervious area
	-	Combined Sewer Overflows (CSOs)	Combined Sewer Overflows (CSOs)
	-	Road vacuum cleaning 50% within the management area	Road vacuum cleaning 50% within the management area
Hwapocheon	Reducing fertilizer usage by 30%	Reducing fertilizer usage by 30%	Reducing fertilizer usage by 30%
	Road vacuum cleaning within the management area	Road vacuum cleaning within the management area	Road vacuum cleaning within the management area
	-	Livestock rainwater reduction facility (3 Priority management area)	Livestock rainwater reduction facility (3 Priority management area)
	-	-	NPS pollution control facilities (3 Priority management area)
Gyesungcheon	Application of 30% rice straw mat in the field	Application of 30% rice straw mat in the field	Application of 50% rice straw mat in the field
	Managing water flow for 30% of paddy fields	Managing water flow for 30% of paddy fields	Managing water flow for 50% of paddy fields
	-	Application of two NPS pollution control facilities (3 Priority management area)	Application of two NPS pollution control facilities (3 Priority management area)
Nakdong Namhae	Application of two NPS pollution control facilities (3 Priority management area)	Application of two NPS pollution control Facilities (3 Priority management area)	Application of two NPS pollution control facilities (3 Priority management area)
	Buffer storage facility	Buffer storage facility	Buffer storage facility
	Applying LID to 5% of impervious area	Applying LID to 5% of impervious area	Applying LID to 5% of impervious area
	Road vacuum cleaning 20% within the management area	Road vacuum cleaning 30% within the management area	Road vacuum cleaning 40% within the management area
Nakdong Miryang	Managing water flow For paddy fields	Managing water flow For paddy fields	Managing water flow For paddy fields
	Reducing fertilizer usage by 40%	Reducing fertilizer usage by 50%	Reducing fertilizer usage by 50%
	30% reduction in livestock load	40% reduction in livestock load	50% reduction in livestock load

3. Results

3.1. Simulation Result Accuracy Analysis

It is necessary to accurately predict streamflow and T-P in gauged watersheds to estimate reducing NPS pollution according to certain scenarios. In this study, we referenced the performance evaluation criteria (NSE, R^2) for recommended statistical performance measures for watershed models presented by Moriasi et al. [59]. This means that the evaluation criteria for the calibration and validation of the model are consistent with those presented in Table 3. Streamflow is closely related to the influx of pollutants into rivers, so accurate streamflow correction is necessary for the adjustment of water quality parameters. Therefore, model calibration and validation were conducted in the order of streamflow, T-P, focusing on parameters that significantly influence changes in each category (Table 6). The streamflow calibration and validation R^2 results are as follows: Dongcheon watershed 0.84 (good), 0.67 (satisfactory); Hwapocheon 0.93 (very good), 0.77 (good); Gyeseongcheon 0.93 (very good), 0.84 (good); Nakdong Miryang 0.75 (satisfactory), 0.80 (good); Nakdong Namhae 0.64 (satisfactory)~0.85 (good), 0.65 (satisfactory)~0.81 (good). Additionally, the NSE results for the five study areas range from 0.52 (satisfactory) to 0.89 (very good). Therefore, based on Moriasi et al.'s [59] evaluation criteria, it can be concluded that the simulated values reflect the observed values well. For T-P, a water quality parameter, the results ranged from satisfactory to very good across the five study areas, indicating that the 10-year long-term simulated values reflect the observed values well. Although the NSE and R^2 simulation results are satisfactory, some values are calculated slightly lower, below 0.50. This is believed to be due to the scarcity of water quality data despite model calibration and validation to consider watershed characteristics. In other words, although 10 years of long-term monitoring data were used, the analysis resulted in limitations due to the inadequacy of T-P data, which is observed at 8-day intervals, unlike streamflow data, to fully reflect the characteristics of the river.

Table 6. The results evaluation indices for streamflow and T-P simulation during the calibration and validation.

Study Area (Using Model)	Main Outlet (Monitoring Data)	Model Evaluation (SWAT, HSPF)		NSE	R^2
Dongcheon (HSPF)	Dongcheon	Streamflow	Calibration	0.77 (Good)	0.84 (Good)
			Validation	0.52 (Satisfactory)	0.67 (Satisfactory)
	Naehwang	T-P	Calibration	0.62 (Good)	0.70 (Good)
			Validation	0.55 (Good)	0.65 (Satisfactory)
Hwapocheon (SWAT)	Hwapocheon	Streamflow	Calibration	0.89 (Very Good)	0.93 (Very Good)
			Validation	0.74 (Good)	0.77 (Good)
		T-P	Calibration	0.94 (Very Good)	0.74 (Good)
			Validation	0.95 (Very Good)	0.75 (Good)
Gyeseongcheon (SWAT)	Gyeseongcheon	Streamflow	Calibration	0.70 (Satisfactory)	0.93 (Very Good)
			Validation	0.69 (Satisfactory)	0.84 (Good)
		T-P	Calibration	0.46 (Satisfactory)	0.51 (Satisfactory)
			Validation	0.68 (Very Good)	0.82 (Very Good)
Nakdong Miryang (SWAT)	Jucheon	Streamflow	Calibration	0.71 (Good)	0.75 (Satisfactory)
			Validation	0.80 (Good)	0.80 (Good)
		T-P	Calibration	0.46 (Satisfactory)	0.46 (Satisfactory)
			Validation	0.61 (Good)	0.69 (Good)
Nakdong Namhae (HSPF)	Samho	Streamflow	Calibration	0.81 (Very Good)	0.85 (Good)
			Validation	0.62 (Satisfactory)	0.65 (Satisfactory)
		T-P	Calibration	0.78 (Very Good)	0.86 (Very Good)
			Validation	0.83 (Very Good)	0.86 (Very Good)
	Changwon	Streamflow	Calibration	0.79 (Good)	0.82 (Good)
			Validation	0.81 (Very Good)	0.81 (Good)
		T-P	Calibration	0.66 (Very Good)	0.68 (Good)
			Validation	0.46 (Satisfactory)	0.51 (Satisfactory)
	Namcheon	Streamflow	Calibration	0.59 (Satisfactory)	0.64 (Satisfactory)
			Validation	0.57 (Satisfactory)	0.68 (Satisfactory)
		T-P	Calibration	0.71 (Very Good)	0.77 (Good)
			Validation	0.82 (Very Good)	0.88 (Very Good)

3.2. Identification of Priority Areas for NPS Pollution Management

To improve water quality in the five study areas, we prioritized the sub-basins based on local conditions such as watershed area, economic feasibility, placement of NPS pollution control facilities, and government funding.

Figure 2 presents the final ranking results and locations of NPS priority management areas for each study area. The results of calculating the ranking of factors related to NPS considering the regional characteristics of urban and agricultural areas in the five study areas are as follows.

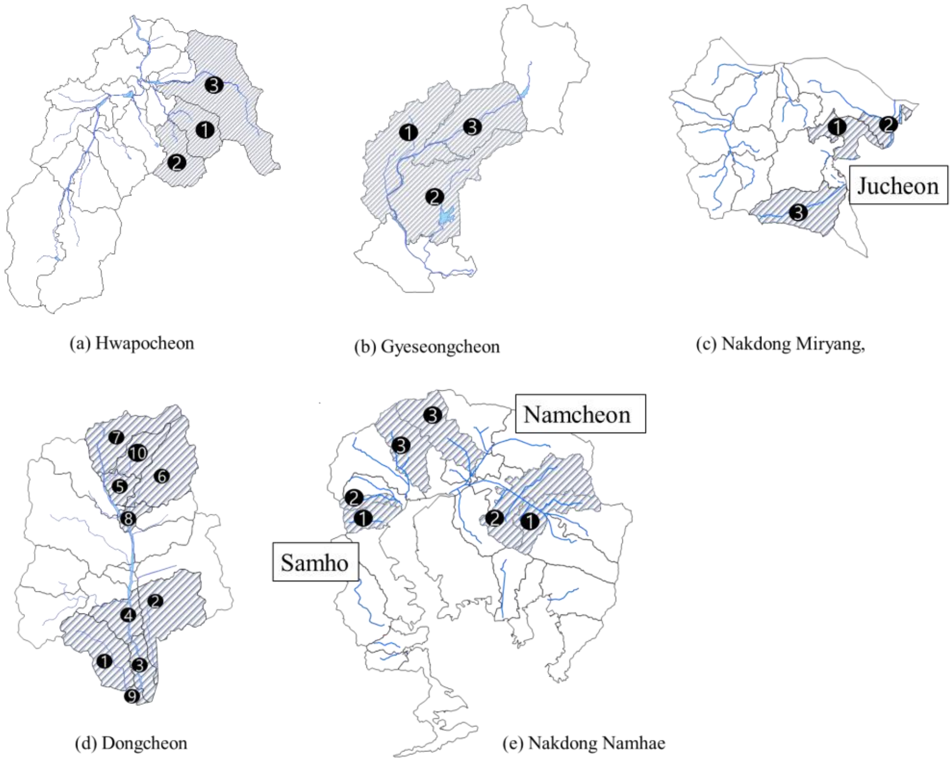

Figure 2. Analysis results of NPS priority areas within the study areas (priority order number).

The Hwapocheon region was divided into 23 sub-basins, characterized by agricultural areas. Table 7 lists the top three sub-basins in this region that require intensive management for NPS pollution. Although sub-basin 15 ranked seventh in terms of rainfall T-P concentration, it was calculated to have the second-highest T-P pollutant load per unit area at 6.11 kg/day/km^2. Additionally, its slope of 17.21% was 6.2 times higher than the lowest average slope within the sub-basins.

Table 7. Ranking results of Hwapocheon priority management for NPS pollution.

Final	(1)		(2)		(3)		(4)		(5)		Sub-Basin
Ranking	Result	Ranking	Result	Ranking	Result	Ranking	Result	Ranking	Result	Ranking	Number
1	0.215	7	0.871	12	17.21	2	7719	6	6.11	2	15
2	0.202	12	1.229	8	10.81	8	30,508	1	4.57	5	14
3	0.138	23	2.292	4	15.65	4	16,678	2	1.84	10	17

Note: (1) Average T-P concentration during rainfall (mg/L). (2) Agricultural area (km^2). (3) Slope (%). (4) Livestock density per unit sub-basin area (total number/km^2). (5) T-P pollutant load per sub-basin area (kg/day/km^2).

Gyesungcheon, representing agricultural areas with livestock farming influence on NPS pollution, is divided into five sub-basins. The calculation of priority management areas resulted in 37,247 total number/km^2. Moreover, the T-P pollutant load per unit area was 316.15 kg/day/km^2, and the rainfall T-P concentration was 0.304 mg/L. The analysis suggests that the areas of interest are more closely associated with livestock density and NPS pollution than other factors such as slope and agricultural area. We calculated the priority by sub-basin in Dongcheon considering the characteristics of urban areas. Among the sub-basins, the one with the highest pollutant load was determined to be 7.22 kg/day/km^2, with an impervious area ratio of 59.2%, a rainfall T-P concentration of 0.093 mg/L, and a high population density of 8616 individuals/km^2. Table 8 presents the top 10 priority sub-basins out of the 20 sub-basins analyzed.

Table 8. Ranking results of Gyesungcheon priority management for NPS pollution.

Final Ranking	(1) Result	(1) Ranking	(2) Result	(2) Ranking	(3) Result	(3) Ranking	(4) Result	(4) Ranking	(5) Result	(5) Ranking	Sub-Basin Number
1	0.304	1	6.36	3	23.3	3	37,247	1	316.15	1	3
2	0.282	2	9.34	1	16.4	5	757	3	164.51	2	4
3	0.259	3	3.17	4	33.2	2	15,620	2	77.77	4	2

Note: (1) Average T-P concentration during rainfall (mg/L). (2) Agricultural area (km^2). (3) Slope (%). (4) Livestock density per unit sub-basin area (total number/km^2). (5) T-P pollutant load per sub-basin area (kg/day/km^2).

We calculated the priority by sub-basin in Dongcheon considering the characteristics of urban areas. Among the sub-basins, the one with the highest pollutant load was determined to be 7.22 kg/day/km^2, with an impervious area ratio of 59.2%, a rainfall T-P concentration of 0.093 mg/L, and a high population density of 8616 individuals/km^2. Table 9 presents the top 10 priority sub-basins out of the 20 sub-basins analyzed.

Table 9. Ranking results of Dongcheon priority management for NPS pollution.

Final Ranking	(1) Result	(1) Ranking	(2) Result	(2) Ranking	(3) Result	(3) Ranking	(4) Result	(4) Ranking	Sub-Basin Number
1	0.093	1	59.2	1	8067	2	7.22	1	19
2	0.07	10	41.5	2	2768	9	5.57	2	21
3	0.065	11	37.1	4	6032	4	3.08	7	18
4	0.072	8	30.7	7	5032	5	2.6	8	17
5	0.078	7	24.2	9	6793	3	1.38	14	4
6	0.019	20	33.4	6	5019	6	4.87	4	5
7	0.084	3	12.2	12	2414	13	2.59	9	2
8	0.071	9	40.7	3	2573	11	0.72	18	7
9	0.064	12	22.3	11	8616	1	0.49	19	20
10	0.027	17	36.6	5	2657	10	1.48	13	3

Note: (1) Average T-P concentration during rainfall (mg/L). (2) Impervious area ratio (%). (3) Population density per unit sub-basin area (individuals/km^2). (4) T-P pollutant load per sub-basin area (kg/day/km^2).

The Nakdong Miryang and Nakdong Namhae in Changwon were distinguished, with Nakdong Miryang characterized as an agricultural area. The determination of priority management areas for the sub-basins is shown in Table 10. Notably, among these areas, the presence of monitoring stations is evident in the mainstream, encompassing six sub-basins. Sub-basin 5, with the highest average T-P concentration during rainfall at 0.099 mg/L, exhibits characteristics such as a higher impervious surface ratio (14.6%), elevated population density per unit sub-basin area (742 individuals/km^2), and substantial T-P pollutant load per sub-basin area (0.543 kg/day/km^2). Moreover, the livestock density per unit sub-basin area stands at 4269.10 individuals per km^2. Consequently, sub-basin 5 emerges as a priority area for management, primarily due to its leading position across factors associated with NPS pollution.

Table 10. Ranking results of Nakdong Miryang priority management for NPS pollution.

Name	Final Ranking	(1)		(2)		(3)		(4)		(5)		Sub-Basin Number
		Result	Ranking	Result	Ranking	Result	Ranking	Result	Ranking	Result	Ranking	
Sincheon	1	0.052	1	9.1	1	837	1	0.343	3	208.2	1	1
	2	0.045	5	7.6	2	705	2	0.322	4	175.3	2	3
	3	0.04	6	7.3	3	687	3	0.457	1	170.9	3	5
Miryang	1	0.079	3	7.9	1	136	1	0.525	1	1471.8	1	3
	2	0.102	1	7.4	2	122	2	0.48	2	1321.8	2	2
	3	0.08	2	5.1	3	90	3	0.39	3	977.2	3	1
Jucheon	1	0.099	1	14.6	1	742	1	0.543	1	4269.1	1	5
	2	0.054	4	8.9	2	445	2	0.294	5	2558.9	2	3
	3	0.088	2	5.6	4	322	4	0.521	2	1853.0	4	6
	4	0.046	6	6.8	3	374	3	0.213	6	2148.2	3	2
	5	0.067	3	5.4	5	279	5	0.415	4	1604.4	5	1
	6	0.048	5	3.3	6	181	6	0.508	3	1043.0	6	4

Note: (1) Average T-P concentration during rainfall (mg/L). (2) Impervious area ratio (%). (3) Population density per unit sub-basin area (individuals/km^2). (4) T-P pollutant load per sub-basin area (kg/day/km^2). (5) Livestock density per unit sub-basin area (total number/km^2).

The Nakdong Namhae is characterized by urban areas, with the Samho watershed and Namcheon watershed divided into 11 sub-basins each. Table 11 presents the top 3 sub-basins within the 11 sub-basins that require NPS pollution reduction. In the case of Samho, it ranked fourth in terms of rainfall T-P concentration among the 11 sub-basins. However, sub-basin 6 within Samho, with the highest impervious area ratio, population density, and T-P pollutant load per unit area, was identified as the highest priority area for NPS pollution control. In Namcheon, sub-basin 3, with consistently high rankings in factors related to NPS pollution, was designated as a priority area. Thus, by designating priority areas for NPS pollution in the five study areas under investigation, we can assess the effectiveness of region-specific water quality (T-P) improvement through various measures, such as road vacuum cleaning within the management study area, livestock rainwater reduction facilities, and the application of rice straw mats in the fields.

Table 11. Ranking results of Nakdong Namhae priority management for NPS pollution.

Name	Final Ranking	(1)		(2)		(3)		(4)		Sub-Basin Number
		Result	Ranking	Result	Ranking	Result	Ranking	Result	Ranking	
Samho	1	0.159	4	29.5	1	6423	1	0.413	1	6
	2	4.509	1	25.7	2	5125	2	0.333	3	2
	3	0.17	3	21.2	3	5008	3	0.351	2	5
Namcheon	1	2.962	4	44.7	4	5573	4	3.99	4	3
	2	2.768	6	36.7	5	5004	5	6.935	1	4
	3	6.883	1	30.4	6	4047	8	4.717	3	8
Yanggog	1	0.116	2	19.3	2	2770	1	0.338	1	1
	2	0.044	5	22.1	1	2298	2	0.246	4	3
	3	0.371	1	11.2	6	2005	4	0.271	2	5

Note: (1) Average T-P concentration during rainfall (mg/L). (2) Impervious area ratio (%). (3) Population density per unit sub-basin area (individuals/km^2). (4) T-P pollutant load per sub-basin area (kg/day/km^2).

3.3. NPS Pollution Reduction Results by Scenario

Using the model and 10-year streamflow data, Flow Duration Curves (FDC) were constructed, and NPS pollutant management streamflow ranges were set from 5% to 40%.

As shown in Table 12, considering the agricultural areas of the Nakdong Miryang, Hwapocheon, and Gyesungcheon watersheds, management measures tailored to the regional characteristics were evaluated for pollutant load reduction and water quality improvement. These measures include livestock rainwater reduction facilities, NPS pollution control facilities in priority management areas, a reduction in fertilizer usage, the management of water flow for paddy fields, and the use of rice straw mats in fields.

Table 12. T-P pollution reduction results by region according to various management plans.

Management Plan		Default	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
Gyesungcheon	Average T-P pollution load (kg/d)	36.2	33.1	30.4	28.7
	Reduction of NPS pollution (%)	-	8.6%	16.0%	20.7%
Hwapocheon	Average T-P pollution load (kg/d)	79.8	67.8	67.2	58.4
	Reduction of NPS pollution (%)	-	15.0%	15.8%	26.8%
Dongcheon	Average T-P pollution load (kg/d)	29.0	26.0	25.2	22.7
	Reduction of NPS pollution (%)	-	10.3%	13.1%	21.7%
Nakdong Namhae	Average T-P pollution load (kg/d)	6.0	5.2	5.0	4.7
	Reduction of NPS pollution (%)	-	13.3%	16.7%	21.7%
Nakdong Miryang	Average T-P pollution load (kg/d)	21.2	18.0	16.7	16.4
	Reduction of NPS pollution (%)	-	15.1%	21.2%	22.6%

In urban areas such as Dongcheon and Nakdong Namhae, the analyzed NPS management plan included applying LID in impervious areas, road vacuum cleaning, addressing combined sewer overflows, and implementing NPS pollution control facilities in priority management areas. When Scenario 3 was applied within the management streamflow range, T-P load reduction was observed compared to the default (current T-P values), with reductions of 20.7% in Gyesungcheon, 26.8% in Hwapocheon, 21.7% in Dongcheon, 21.7% in Nakdong Namhae, and 22.6% in Nakdong Miryang. Applying the proposed management measures by region reduced the T-P load by over 20% in all areas (Table 12). Hwapocheon exhibited the most substantial reduction in NPS pollutants among the five study areas. For Hwapocheon, the anticipated reduction effects were as follows: 15.0% for Scenario 1, 15.8% for Scenario 2, and 26.8% for Scenario 3 based on activities targeting NPS pollutant reduction, such as reducing fertilizer usage, livestock rainwater reduction facilities, and NPS pollution control facilities.

In Scenario 3, the higher efficiency in reducing pollution compared to Scenario 2 can be ascribed to multiple factors. This is because the priority management area constitutes approximately 27% (36.236 km^2) of the total watershed area (134.850 km^2), representing a significant proportion. As indicated in Table 7, compared to other sub-basins within Hwapocheon, the priority management area stands out for its steep slopes, concentrated livestock density, and higher T-P discharge. Taking these considerations into account, Scenario 3 includes nonpoint source (NPS) reduction facilities such as vegetated swales, constructed wetlands, and infiltration trenches. The reduction efficiencies are specified as 51%, 60%, and 73%, respectively. Therefore, based on an overall investigation of watershed characteristics and the implementation of NPS pollution control measures, this study demonstrates that Scenario 3 leads to a significant reduction in pollution loads.

An analysis of the average water quality (T-P) improvement effects by region revealed results of 22.2% for Hwapocheon, 16.4% for Nakdong Namhae, 20.2% for Changnyeong, 24.7% for Nakdong Miryang, and 20.5% for Dongcheon, compared to Scenario 3 (Figure 3). Among these regions, Nakdong Miryang demonstrated the most significant water quality improvement, with positive improvements from Scenario 1 to Scenario 3 of 15.7%, 23.6%, and 24.7%, respectively. The region with the second-highest water quality management effect was Hwapocheon. In the case of Namcheon Namhae, the water quality improvement effects were found to be lower compared to other regions. One of the reasons is that the land use distribution ratio in urban areas in the Namcheon Namhae is 30.8%, which is the highest ratio compared to other regions. Urban areas have a greater impact on surface runoff than agricultural areas, and in this study, management measures related to water quality as well as streamflow (applying LID in impervious areas, road vacuum cleaning the management area, application of NPS pollution control facilities, etc.) were proposed to suit the characteristics of urban areas. As a result, although the relative water quality improvement effect was less significant compared to other study areas, it is considered that the reduction in pollution loads is higher due to the influence of streamflow.

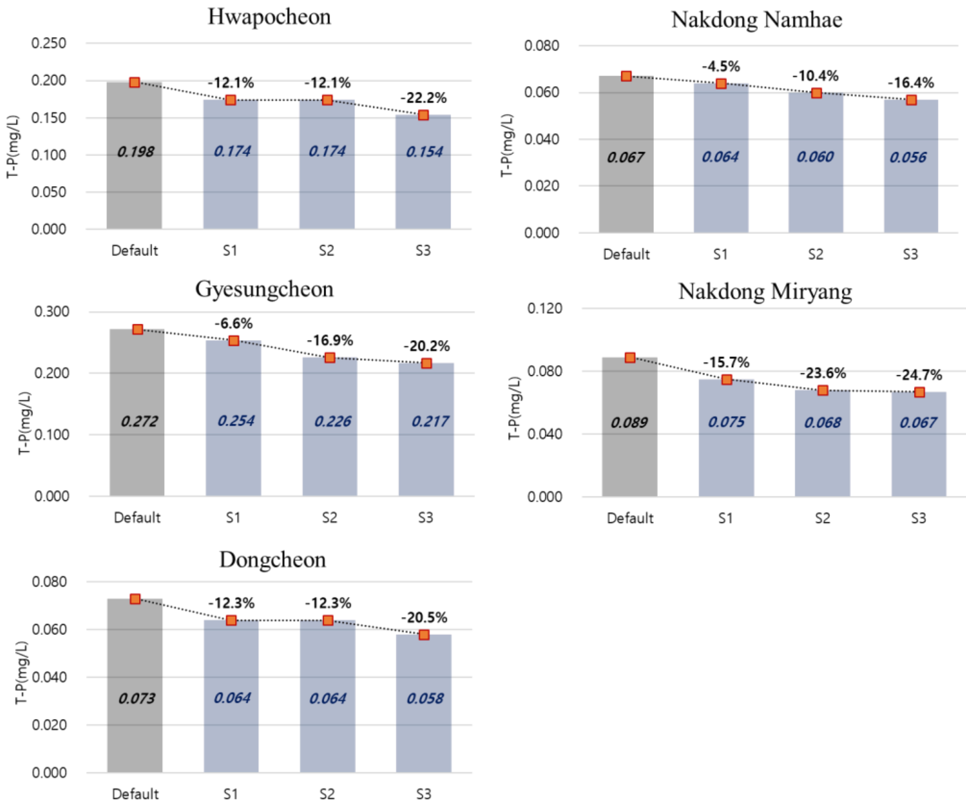

Figure 3. Results of regional T-P improvement effect based on various management methods.

The results of applying management measures from Scenario 1 to Scenario 3, as presented in Figure 3, show an overall reduction in pollutant loads and an improvement in water quality in the five study areas. When comparing the management measures of Scenario 1 and Scenario 2, it was observed that the pollutant loads decreased in the Hwapocheon and Dongcheon watersheds; however, the water quality did not show any significant improvement. This suggests that the proposed management measures are more influenced by streamflow variability rather than water quality (T-P) fluctuations. Therefore, for water quality (T-P) improvement in the Hwapocheon watershed, it is suggested that applying NPS control facilities would be more efficient than implementing livestock rainwater reduction facilities. Furthermore, in the Dongcheon watershed, installing NPS pollution reduction facilities in priority management areas for NPS pollution is an effective management measure for water quality improvement. In the Nakdong Miryang region, unlike the other four study areas, the results of Scenario 3 show a reduction in pollutant loads by 1.4% and a slight improvement in water quality by 1.1% compared to Scenario 2. Through these results, it is suggested that applying Scenario 2 instead of Scenario 3 could propose an effect of more than 20% reduction in pollutant loads and improvement in water quality.

4. Discussion

This study selects regional priorities for NPS pollution management and proposes a concentrated reduction and management plan. Utilizing non-structural management approaches such as fertilizer inhibition and road cleaning can effectively improve water quality in regions considering cost-effectiveness, environmental factors, ease of maintenance, and safety. This approach is expected to yield cost-saving benefits and save time by avoiding indiscriminate management measures within the constraints of our government's limited budget.

Compared to previous studies, this study focuses on analyzing NPS pollution reduction by considering various regional characteristics and utilizing long-term monitoring data, rather than proposing a pollution reduction and management plan for a particular region (testbed). It not only conducts long-term monitoring and analysis to improve water quality and reduce pollution loads in various regions, but also presents comprehensive analysis scenarios. During scenario setup, as it is impractical to install NPS pollution control facilities in every watershed of the study area, concentrating management efforts on selected areas, as proposed in this study, before evaluating water quality and pollution loads would be more efficient. This means that the application of NPS pollution control is expected to be a better approach than proposing limited management measures for specific regions.

Consequently, the study results contribute to making the water quality management and protection decisions made by policymakers more efficient based on the information. Moreover, it is anticipated that this study's analytical procedures and results can serve as a manual for NPS pollution management practitioners and be utilized as fundamental data for policy formulation.

5. Conclusions

Despite ongoing efforts in South Korea to manage and improve water quality in areas affected by NPS pollution, there are still limitations in effectively managing NPS pollution. This study highlighted the necessity of systematically expanding NPS pollution reduction facilities in various managed areas and effectively managing NPS pollution across different regions.

In this study, an analysis was conducted on five study areas (Dongcheon, Gyesungcheon, Hwapocheon, Nakdong Namhae, and Nakdong Miryang) designated as NPS pollution management areas by national policies. The evaluation primarily focused on analyzing regional characteristics by applying SWAT and HSPF approaches using long-term monitoring data spanning approximately 10 years. To identify areas requiring immediate attention in NPS management, vulnerability and urgency were assessed. The prioritization based on regions (urban and agricultural areas) and the application of management plan scenarios has resulted in a reduction of over 20% in pollution loads. Water quality has also shown a similar improvement trend in the five study areas. Scenario 3 proposed in this study was considered an effective approach to improve T-P pollutant loads, considering NPS reduction and urgency. As these results consider various characteristics of NPS pollution, they are not limited to specific regions. As the reduction scenarios proposed are tailored to the conditions of urban and agricultural areas, they may apply to other regions. In a situation where NPS pollution management areas are increasing not only in South Korea, but globally, there is an expectation that the utilization and applicability of NPS pollution-related data will be significant by predicting the reduction in NPS pollution loads and water quality improvement. Future research aims to complement the economic feasibility and reduction efficiency by considering the installation and maintenance costs of reduction facilities within the study area in conjunction with the findings of this study.

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