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Hydro-Economic Water Allocation Model for Water Supply Risk Analysis: A Case Study of Namhan River Basin, South Korea

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Abstract: Rational water resource management is used to ensure a stable supply of water by predicting the supply of and demand for future water resources. However, rational water allocation will become more difficult in the future owing to the effects of climate change, causing water shortages and disputes. In this study, an advanced hydro-economic water allocation and management model (WAMM) was introduced by improving the optimization scheme employed in conventional models and incorporating the economic value of water. By relying upon economic valuation, the WAMM can support water allocation efforts that focus not only on the stability but also on the economic benefits of water supply. The water supply risk was evaluated following the different objective functions and optimization methods provided by the WAMM using a case study of the Namhan River basin in South Korea under a climate change scenario over the next 30 years. The water shortages and associated economic damage were compared, and the superior ability of WAMM to mitigate future water shortages using economic valuation and full-step linear programming (FSLP) optimization was demonstrated. It is expected that the WAMM can be applied to help resolve water shortages and disputes among river basin units under severe drought conditions.

Keywords: climate change; hydro-economic water allocation; optimal water allocation; risk analysis; water supply

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1. Introduction

Water resources are essential for human life and should be stably secured and rationally allocated. According to the World Bank [1], water resource management (WRM) refers to a series of processes, including planning, developing, and managing water resources, related to both water quantity and quality, and across all water uses by consumers. UNESCO [2] reported that global water consumption is expected to increase gradually because of population growth and lifestyle changes, while conflicts over water are expected to intensify owing to climate change (e.g., during times of frequent drought and limited water supply in some areas). According to Adetoro et al. [3], many studies have been conducted worldwide to mediate water disputes from social and engineering perspectives. Such studies include various types of water allocation models presented as a part of engineering solutions to these disputes. The primary objective of a water allocation model is to present the most efficient supply plan for limited water resources according to the priorities or water rights of various water demand sectors. These demand sectors account for municipal, agricultural, and industrial water usage. The allocation results may differ in terms of fairness, economic feasibility, or social importance. The utilization of water allocation models has evolved with their complexity, from early models allocating water resources based on quantitative efficiency to hydro-economic models seeking to maximize socio-economic benefits.

Major studies related to the development and utilization of water allocation models include the introduction of one of the earliest models, MITSIM (Massachusetts Institute of Technology River Basin Simulation Model), by Strzepek and Lenton [4]. Subsequently, Strzepek [5] improved the water allocation simulation function and used it to evaluate the stability of agricultural water supply in the Swedish South-Western Skane Basin. Shafer and Labadie [6] developed the MODSIM (Modified SIMYLD) model, another typical early water allocation model. Later, optimal water allocation models equipped with optimization modules based on linear programming or quadratic programming were developed to maximize water allocation efficiency. Such models include the AQUATOOL, developed by Andreu et al. [7], and the water evaluation and planning system (WEAP), initiated by Raskin et al. [8] and further developed by Yates et al. [9], to provide enhanced user-friendliness. In terms of quantitative water management, the AQUARIUS model developed by Diaz et al. [10] is considered a representative optimal water allocation model for the maximization of water supply reliability and minimization of water shortages. Notably, the WEAP model was incorporated into the Korea-water evaluation and planning system (K-WEAP) model to strengthen its applicability in Korea and has been utilized in various nationwide water management plans [11]. In addition, the Riverware model developed by Zagona et al. [12] further enhanced the optimal water allocation model using an optimization system based on a prioritized set of objectives implemented by linear pre-emptive goal programming. The California value integrated network (CALVIN) model developed by Howitt et al. [13] is a critically important, globally well-known, hydro-economically integrated model that considers not only the water requirements in its optimal solution but also the economic value of water resources based on data collected over 50 years in California, USA. The CALVIN water allocation model has been mainly used to inform water supply plans that minimize water supply costs and maximize the associated economic benefits. Newlin et al. [14] and Pulido-Velazquez et al. [15] presented various possibilities for utilizing the CALVIN model to establish state-wide water resources plans in southern California.

The environmental functions of water resources were divided into regulation, habitat, production, and information by Costanza et al. [16] and de Groot et al. [17]. As reported by UNSD (United Nations Statistics Division) [18], the economic valuation of water resource services is challenging; therefore, numerous researchers have attempted to define their economic value based on measurable variables such as changes in quantity (e.g., supply and regulation), quality (e.g., treatment and generation), ecological services (e.g., refugia and pollination), and cultural features (e.g., recreation). However, since the economic value of water resources mainly depends on national and regional policies and environments, their value may be quantified based on the conditions in the area of interest and period. For instance, many different water resource valuation studies have been conducted in South Korea. Hwang et al. [19] calculated the potential value of groundwater for drought preparation using the contingent valuation method (CVM). Park et al. [20] evaluated the economic value of rainfall in the spring season in terms of dam reservoir water resource utilization during droughts. Moreover, a study by K-water [21] employed various methods to quantitively evaluate the overall value of South Korea's water resources. The K-water study calculated the municipal water supply benefit (based on the willingness to pay, and investigated using the CVM), the industrial water supply benefit (based on the value of the marginal product (VMP) and estimated using the production function of major industrial sectors), and the agricultural water supply benefit (based on a farm crop budget analysis). Lim and Lee [22] presented the agricultural water supply benefit based on the estimated VMP of rice crops in South Korea. Since 2011, the Korea Environment Institute (KEI) has organized, classified, and presented various valuation cases for water resources using the environmental valuation information system (EVIS) [23].

Climate change represents an environmental factor that has a direct impact on the security of water resources. Numerous climate change scenarios have been created globally using various general circulation models (GCMs) to predict rainfall, temperature, and humidity. Using data from these models, multiple studies have predicted the damage arising from potential water shortages due to climate change. Krol et al. [24] developed and applied a model to explain the relationship between climate change and water use, focusing on agriculture in northeast Brazil. Ray et al. [25] and Ashofteh et al. [26] analyzed the water supply risk by applying long-term climate change scenarios to water supply networks. Liu et al. [27] and Basupi and Kapelan [28] compared water shortages under different climate change conditions and suggested a plan for utilizing decision-making tools and a framework to establish an optimal water supply strategy.

Here, a new hydro-economic water allocation model was examined, the water allocation and management model (WAMM), developed by Jeong et al. [29]. Equipped with an advanced optimization module, the WAMM provides enhanced functionality compared with conventional models and incorporates the economic value of water to optimize water allocation. In this case study, the WAMM was applied to the Namhan River basin in South Korea for long-term (30-year) water allocation planning using a future climate change scenario; the water allocation results obtained according to various water supply objectives and optimization methods were compared.

The remainder of this paper is structured as follows. Section 2 introduces and provides details of the WAMM, including the improved optimization algorithm and calculation of the economic value of water resources. It also introduces the process used to establish the climate change scenarios. Section 3 introduces the case study river basin and summarizes the economic value of the water resources in the study area, as well as the relevant climate change scenarios. Section 4 quantitatively compares and analyzes the simulation results of the WAMM according to the type of optimization method and objective function applied. Finally, Section 5 presents the conclusions and plausible future studies.

2. Materials and Methods

A water allocation model is an engineering support tool that can facilitate the rational establishment of a water supply and demand plan within a given river basin. Figure 1 illustrates a simplified river basin in which municipal, industrial, agricultural water demands, and the maintenance flow rate are collected from the mainstream. The water flows in the river and the water storage in reservoirs are controlled by dams. The flow rate of the river and the water available in reservoirs can be estimated based on the water resources available within the relevant basin. Then, the actual available supply that can be supplied to demand sites is determined based on river maintenance flow and restricted water storage capacity in reservoirs. A water allocation plan becomes important when the available water supply does not meet the demand and needs to be determined by considering the importance, water rights, and economic feasibility of each demand site.

The WAMM was developed based on components and input data similar to those of the K-WEAP model that is currently utilized to generate water allocation plans in South Korea. It is equipped with a graphical user interface (GUI) for user convenience, and the water supply system components and input data are provided through a dedicated input module in the form of an Excel spreadsheet. Figure 2a shows the datasheet of the input module and user-interface screens in the WAMM. The WAMM manages water allocation simulations as an individual project that includes all the specifications of system components, operational information, and simulation results needed for establishing a water supply plan. Figure 2b illustrates the control panel for the water allocation strategies and results analysis screens. Notably, the WAMM also provides an advanced optimization module that enables users to select optimization methods and objective functions to apply. The structure of the improved linear programming-based optimization module contained within the WAMM, as well as the development of a water allocation strategy that considers both the reliability and economic benefits of the water supply are described in detail in the next section.

2.1. Full-Step Linear Programming (FSLP) in the WAMM

It was relatively simple to establish a water supply plan in the past. However, as the number and complexity of the factors that must be considered have increased, the importance of water allocation plans and the role of related models have gradually increased as well. As discussed in Section 1, the majority of conventional water allocation models rely on optimal water allocation based on linear programming (LP), such as the AQUATOOL [7] and WEAP [8] models, or quadratic programming (QP), such as the AQUARIUS [10] model. As a mathematical optimization method providing a global optimal solution, LP is still widely used, despite only being applicable to problems with objectives and constraints that can be formulated as linear functions.

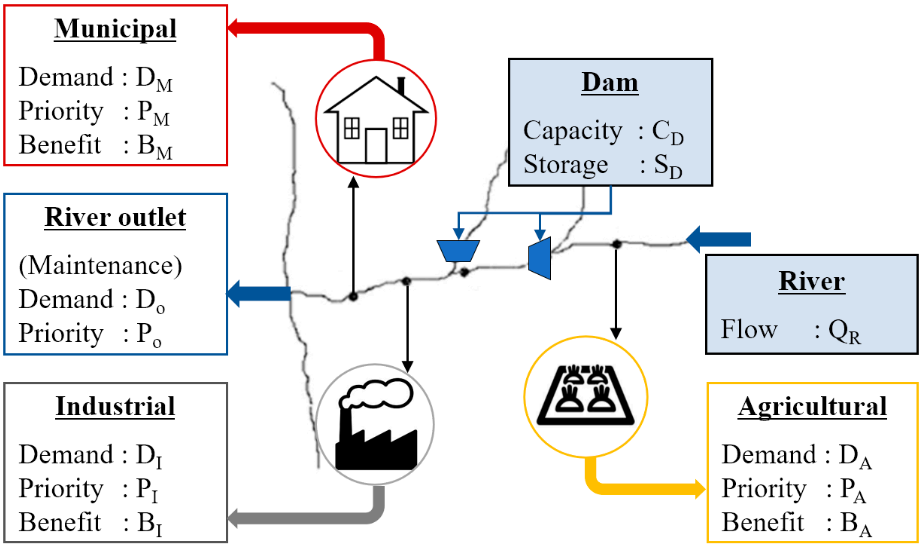
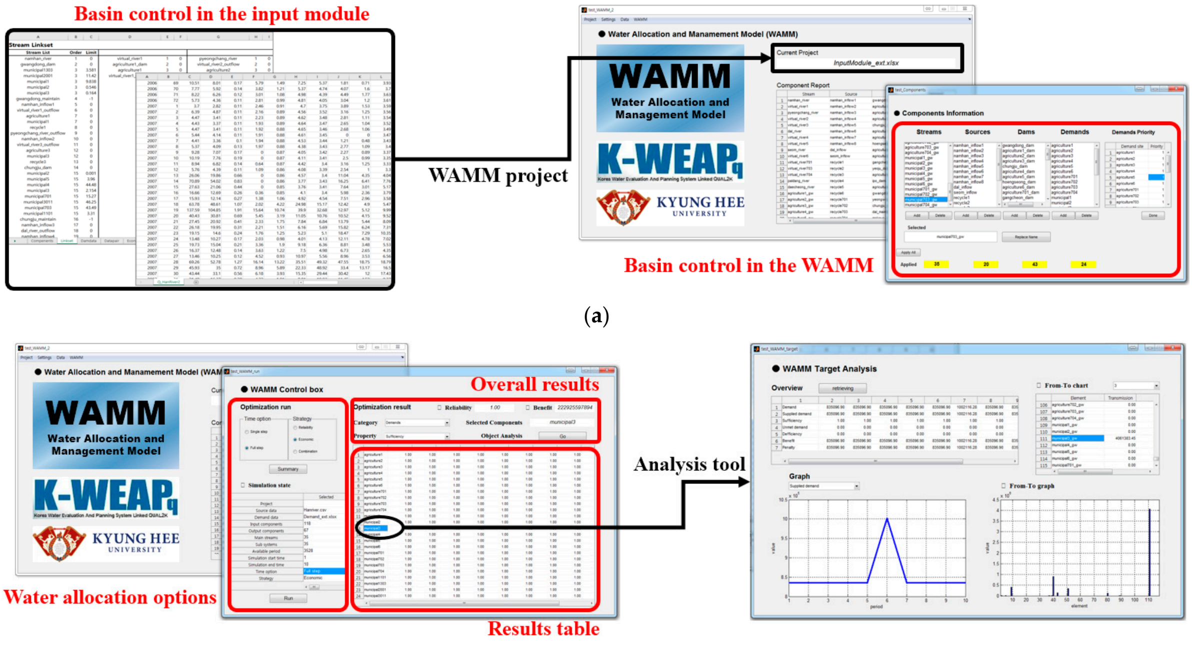


Figure 1. Scheme of water allocation in a river basin.



(a)

(b)

Figure 2. Graphical user interface (GUI) of the water allocation and management model (WAMM). (**a**) Project management window; (**b**) allocation management and results window.

In optimization problems such as water resource planning and allocation, the minimization of costs and maximization of benefits, or the maximization of target performance, are used as objective functions. In the previously described K-WEAP model, the maximization of water reliability (defined as the ratio of water supply to water demand) is used as an objective function. In the K-WEAP model and the WAMM, a function setting the water supply priority for each demand site is provided to reflect the importance of water use. This can be simply expressed as an objective function that maximizes the reliability of water supply based on a set of weighted values as follows:

$$Maximize: \ Reliability = \sum_{i=1}^{N_d} W_i \frac{S_i}{D_i}, \qquad \text{subject to}: \ S_i \le D_i \tag{1}$$

where N_d is the number of demand sites in the basin, W_i is the weight according to the priority of demand site i, S_i is the water supplied to demand site i (m^3), and D_i is the water demand of demand site i (m^3).

For the hydro-economic water allocation model, which allocates water by taking into account the economic value of supplied water, optimization to maximize benefits can be performed by setting the economic value as an objective function. In this study, the economic objective function can be formulated to maximize the benefits of the water supply by weighting the water resources in terms of the economic value of the unit water supply as follows:

$$Maximize: \ Benefit = \sum_{i=1}^{N_d} V_i \, S_i, \qquad \text{subject to}: \ S_i \le D_i \tag{2}$$

where V_i is the economic benefit in Korean Won (KRW) of the supplied water to the demand site i (KRW/m^3). Note that 1000 KRW can be approximated as 1 US dollar.

To establish a rational water supply plan, various socio-economic impacts must be considered using different types of objective functions. Here, two objective functions were constructed and implemented to facilitate optimal water allocation in the WAMM: (1) the reliability (stability) of the water supply (Equations (1)) and (2) the economic benefits of the water supply (Equation (2)).

Traditional water allocation models typically utilize single-step linear programming (SSLP) to optimize the water allocation for each simulation time step. As indicated in Figure 3a, a separate optimization is sequentially performed along the simulation time period, in which the allocation results (e.g., individual supply from source to demand and reservoir storage) of the previous time step are provided as initial values in the subsequent simulation time step. However, this sequential approach has a drawback as the decisions made in the earlier time step cannot be modified, resulting in a potential water shortage in subsequent time steps. Therefore, the WAMM uses full-step linear programming (FSLP) to optimize the entire simulation period at once, mitigating such limitations. As shown in Figure 3b, water allocations over the entire simulation periods were determined simultaneously through a single optimization run. This made it possible to allocate water such that the shortage occurring over the entire simulation period was minimized, realizing water allocations that actively and flexibly responded to changing environments.

For this flexible response, the reliability and benefits of the water supply were calculated for the entire simulation period and not the unit simulation period. Hence, the modified forms of the objective functions for FSLP are as follows:

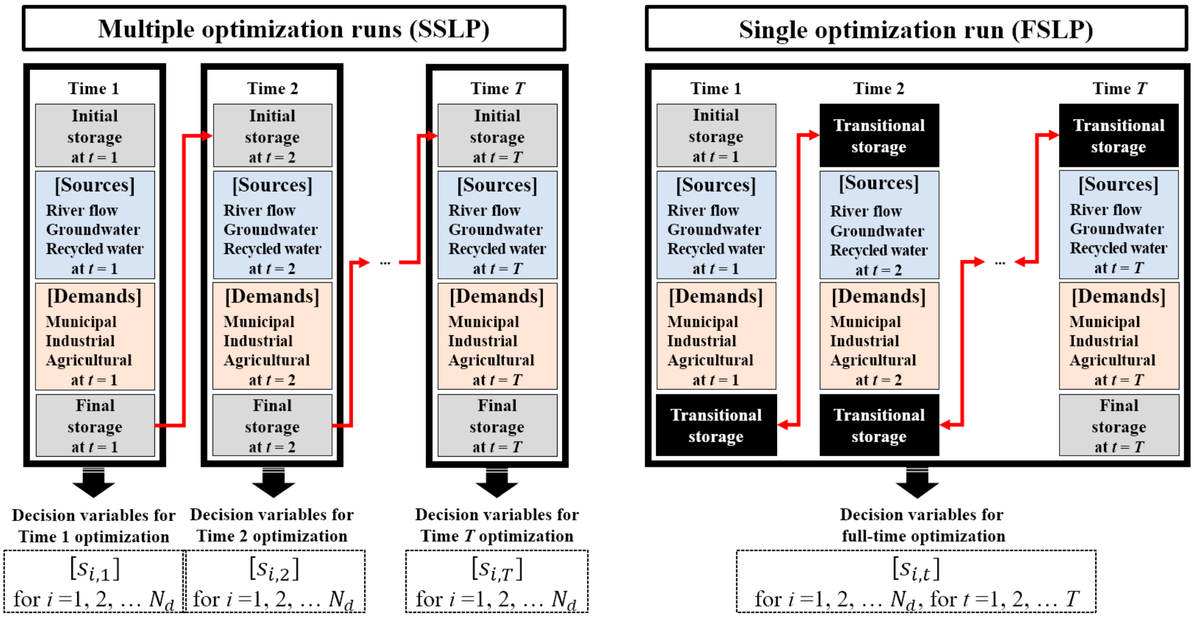
$$Maximize: \ Reliability = \sum_{t=1}^{T} \sum_{i=1}^{N_d} W_i \frac{S_{i,t}}{D_{i,\,t}}, \qquad \text{subject to}: \ S_{i,t} \le D_{i,\,t} \tag{3}$$

$$Maximize: \ Benefit = \sum_{t=1}^{T} \sum_{i=1}^{N_d} V_i \, S_{i,t}, \qquad \text{subject to}: \ S_{i,t} \le D_{i,\,t} \tag{4}$$

where T is the total number of simulation periods in which water is allocated, $S_{i,t}$ is the water supplied to demand site i at simulation time t (m^3), and $D_{i,t}$ is the water demand of demand site i at simulation time t (m^3).

2.2. Economic Valuation of Water Resources in the WAMM

The value of a resource can be defined as the monetary value of the benefit or loss arising from its presence or absence, or a change in its state. In particular, water resources have the characteristics of public goods and behave differently from goods in the general market economy, making it difficult to devise an effective valuation method. Accordingly, the WAMM employed the results of previous studies that evaluated and applied the economic value of water resources for economic analysis as follows.



(**a**) (**b**)

Figure 3. Comparison of long-term water allocation optimization. (**a**) Single-step linear programming (SSLP) optimization framework and (**b**) full-step linear programming (FSLP) optimization framework.

To estimate the economic value of municipal water, K-water [21] calculates the benefit of municipal water supplied to the user by estimating the user's willingness to pay (WTP) for unit demand. The WTP indicates how much value the consumer places on a particular product. In this study, the water supply benefit of municipal water was calculated using the measured WTP and the estimated demand function from the K-water study [21]. Here, the demand function defines the relationship between price and demand to represent the change in the quantity of a product the consumer intends to purchase according to the price of the product. In general, when other supply conditions are the same, the curve of the demand function gradually decreases with increasing price.

To estimate the economic value of municipal water in Korea, the reduction in water consumption corresponding to an increase in water price was first investigated based on the maximum WTP for municipal water demand using a consumer survey. Then, the final supply benefit function was derived by calculating the market demand function reflecting the individual responses in the form of the WTP. In this study, the dependent variable of the supply benefit function is the WTP for municipal water (i.e., the value of unit municipal water). The average monthly water demand per person, average monthly income per person, and the number of persons for each household were selected as explanatory variables. Hence, the linear municipal water supply benefit function can be expressed as

$$P_M = \alpha_0 + \alpha_1 Q + \alpha_2 I + \alpha_3 F + \epsilon \tag{5}$$

where P_M is the value of unit municipal water per person, measured as the WTP (KRW/m^3 /person); Q is the average monthly demand for municipal water per person (m^3/month

/person); I is the average monthly income per person (KRW/month/person); F is the number of persons per household; α_0, α_1, α_2, and α_3 are the coefficients of the regression equation; and ϵ is the error variable of the regression equation.

After excluding the income variable from Equation (5) through a t-test, K-water [21] derived the supply benefit function for municipal water by performing a regression analysis based on the historical data and yielded:

$$P_M = 516.336 - 2.716Q + 65.137F \tag{6}$$

To estimate the economic value of industrial water in Korea, K-water [21] calculated the marginal product output according to the industrial water supply for a given production function. The production function is a mathematical representation of the relationship between input sources and output values of industrial products. K-water [21] expressed this function using the Cobb–Douglas production function estimation method with the production value as a dependent variable, while the input labor, manufacturing cost, amount of tangible fixed assets at year-end, and water supply were taken as explanatory variables, as follows:

$$\ln P_I = \ln \beta_0 + \beta_1 \ln L + \beta_2 \ln W_I + \beta_3 \ln M_I + \beta_4 \ln K \tag{7}$$

where P_I is the production value of industrial products (KRW); L is the number of workers (person); W_I is the industrial water supply quantity (m^3); M_I is the unit manufacturing cost (KRW/unit product); K is the balance of tangible assets at the end of the year (KRW/year); and β_0, β_1, β_2, and β_3 are the coefficients of the regression equation.

A regression analysis of the average technical statistics for all industrial sectors surveyed by the National Water Resources Plan 2011–2020 of South Korea [30] resulted in the following industrial water production function:

$$\ln P_I = 2.02 + 0.73 \ln L + 0.05 \ln W_I + 0.27 \ln M_I + 0.05 \ln K \tag{8}$$

Thus, the value of unit industrial water (KRW/m^3) can be calculated by dividing the calculated production value of industrial products determined using Equation (8) with the quantity of industrial water supplied.

To estimate the economic value of agricultural water in Korea, Lim and Lee [22] calculated its economic benefits based on a production function correlating the agricultural water input with the annual rice production. This process was the same as that used to analyze the VMP of industrial water. Lim and Lee [22] expressed the economic value of agricultural water using the Cobb–Douglas production function estimation method based on the production value of rice as a dependent variable and the total agricultural water supply, agricultural management cost, irrigated farmland area, and drought year correction coefficient as explanatory variables as follows:

$$\ln P_A = \ln \gamma_0 + \gamma_1 \ln A + \gamma_2 \ln W_A + \gamma_3 \ln M_A + \gamma_4 D \tag{9}$$

where P_A is the production value of rice (KRW); A is the area of irrigated farmland (1000 ha); W_A is the agricultural water supply quantity (million m^3); M_A is the agricultural management cost (KRW); D is the drought year correction coefficient; and γ_0, γ_1, γ_2, and γ_3 are the coefficients of the regression equation.

A regression analysis of the total amount of rice production and agricultural infrastructure status in South Korea over 35 years was then applied to obtain the agricultural water production function:

$$\ln P_A = 2.97 + 0.10 \ln A + 0.28 \ln W_A + 0.36 \ln M_A + 0.18D \tag{10}$$

Thus, the value of unit agricultural water (KRW/m^3) can be calculated by dividing the calculated production value of rice determined using Equation (10) with the quantity of agricultural water supplied.

The economic value of various water uses, determined according to the methods described above, can be used to quantify the direct benefit generated from the water supply for each sector. Therefore, in the event of a water supply shortage, the potential economic damage in each demand sector can be calculated and water can be allocated accordingly to minimize overall economic loss (or to maximize overall economic benefit).

2.3. Climate Change Scenarios

2.3.1. Changes in Water Supply

Cho et al. [31] analyzed 52 GCMs (including the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios) and evaluated their fitness for application in South Korea through the climate change adaptation for water resources (CCAW) research project of South Korea. Seventeen GCMs were evaluated as having better availability based on their standardized skill scores and were divided into wet, average, and dry scenarios. In the present research, the RCP 8.5 climate change scenario was selected. This scenario is generated from the Hadley Center Global Environment Model version 2 Atmosphere Ocean (HadGEM2-AO) [32] and is the most suitable scenario for representing typical climate change in the study area [31].

Meteorological information, such as daily precipitation and temperature for the next 30 years, were provided from the model, and the river basin flow was estimated using rainfall-runoff models, such as the Hydrological Simulation Program-FORTRAN (HSPF) [33], Soil and Water Assessment Tool (SWAT) [34], and Precipitation-Runoff Modeling System (PRMS) [35], based on meteorological information in South Korea [36]. Lee et al. [36] applied the three rainfall-runoff models to the four biggest river basins in South Korea and reported that the PRMS model is the most suitable for the Han River basin. Therefore, using the pentad (5-day) averaged flow rate resulting from the PRMS model, the river basin flow according to climate change in the case study basin was estimated and applied as input to the WAMM. Note that the river basin flow represents the available water resources in the study basin.

2.3.2. Changes in Water Demand

Agricultural demand, municipal/industrial (combined) demand, and river maintenance flow are considered water demand sectors in the WAMM. Based on the water demand in 2015, in this study, the changes in population and farmland over the next 30 years were applied, as suggested by the Korea Statistical Yearbook [37], as well as the population projections by province [38], to the water demand change scenario. Based on farmland area statistics in the study area in 2015–2020, farmland area was extrapolated from 2015 to 2045, with a gradual decrease of 15%. Conversely, according to national population projections by province [38], the population in the study area is expected to increase by 12.8% from 2015 to 2036, then decrease by 2.2% from 2036 to 2045. Furthermore, three long-term water demand projections (low demand, average demand, and high demand) were suggested by the National Water Resources Plan 2011–2020 of South Korea (MLTM, Ministry of Land, Transport and Maritime Affairs) [30] to account for the uncertainty of water supply conditions. According to the high demand projection [30], municipal, industrial, and agricultural water demands are expected to increase by 0.66%, 11.07%, and 4.85%, respectively. In the present study, among the three demand projections, the high demand condition was adopted with farmland area and population trends for the estimation of municipal, industrial, and agricultural water demands, for use as WAMM inputs.

3. Case Study

3.1. Application Area (Namhan River Basin, South Korea)

Figure 4 shows the case study area, the Namhan River basin in South Korea, in which approximately 1.5 million people live (investigated in the year 2018), including seven rural sub-basins, to which WAMM performance was applied and analyzed under the climate change scenarios. The total length and area of the river basin are 375 km and 12,407 km^2 (2447, 1773, 2483, 1614, 524, 1491, and 2072 km^2 for the 1001 to 1007 sub-basins). In this case study, water was allocated to meet the requirements in June when water shortage has been frequently observed in the study area. The water allocation period was limited to June (frequent drought month) and evaluated using a pentad (5-day) simulation time step over the next 30 years (with 2015 as the base year); that is, June was divided into six time intervals for every simulation year. Thus, each simulation was conducted independently for each year.

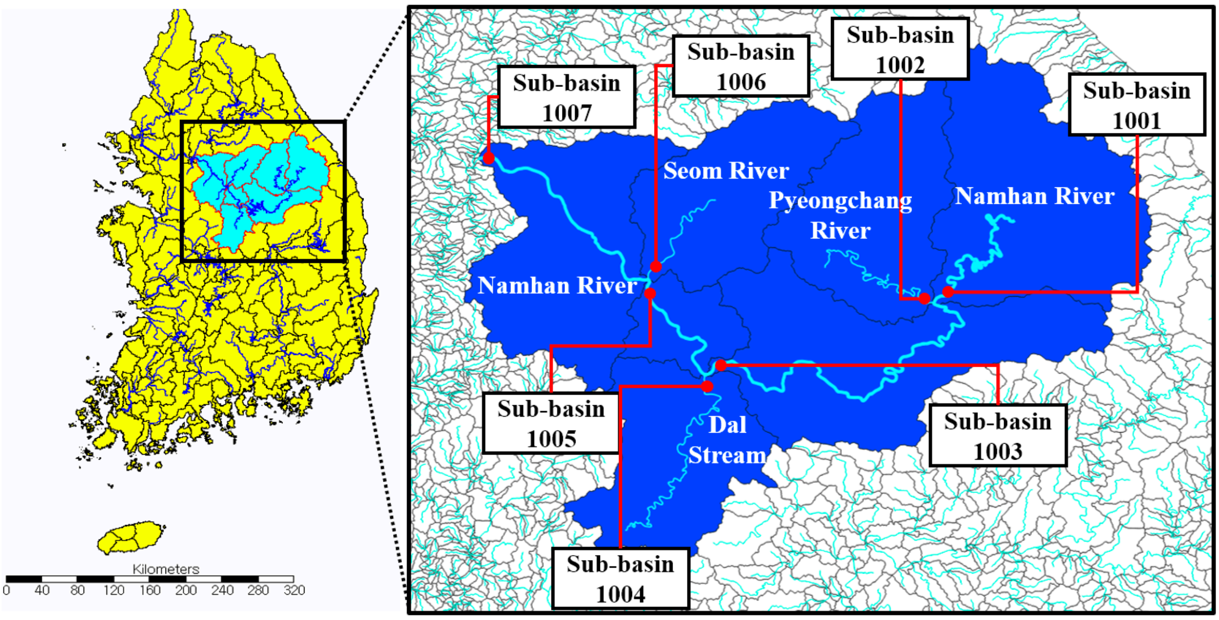


Figure 4. Case study area with seven sub-basins of the Namhan River basin, South Korea.

River flow, groundwater, and dam and agricultural reservoirs were considered water supply sources in the case study basin, while agricultural, municipal/industrial (combined), and river maintenance flow were considered demand sites. The amount of reclaimed water, an additional water supply source, was dynamically determined based on the allocated water at each of the municipal/industrial demand sites with specific reclamation rates. In South Korea, according to the MLTM [30], 65% of the demand supplied to municipal and industrial sites is generally discharged into the river downstream of the demand sites. In the case of agricultural demand, 35% of the demand contributes to water resources gradually; therefore, the net demand (i.e., 65% of the total demand) was applied as the actual agricultural demand without the water reclamation process.

A schematic of the water supply system in the Namhan River basin is shown in Figure 5. The base demands of the municipal/industrial and agricultural demand sites in June 2015 are summarized in Table 1. In total, 29 demand sites, including 10 agricultural sites, 14 municipal/industrial sites, and 5 river maintenance flow gauges, with identical priorities for reliability-based water allocation, use water in the case study basin. The Namhan River is the main stream draining the basin and it has three branches: the Pyeongchang River, Dal Stream, and Seom River. The water flow is controlled by the Gwangdong Dam on the Pyeongchang River before it joins the Namhan River and then by the Chungju Dam on the Namhan River. Next, the Dal stream joins the Namhan River, followed by the

Seom River. The Hoengseong Dam is located upstream on the Seom River and controls its flow. After the joining of the Seom River, three large weirs—the Gangcheon Weir, Yeoju Weir, and Ipo Weir—control the flow of the mainstream of the Namhan River downstream. In addition, agricultural water is supplied by several agricultural reservoirs distributed throughout the basin. Consequently, it is possible to store and supply water in the case study basin through a total of six main water storage facilities (i.e., three dam reservoirs and three weir pools) and 10 agricultural reservoirs in addition to the river flow.

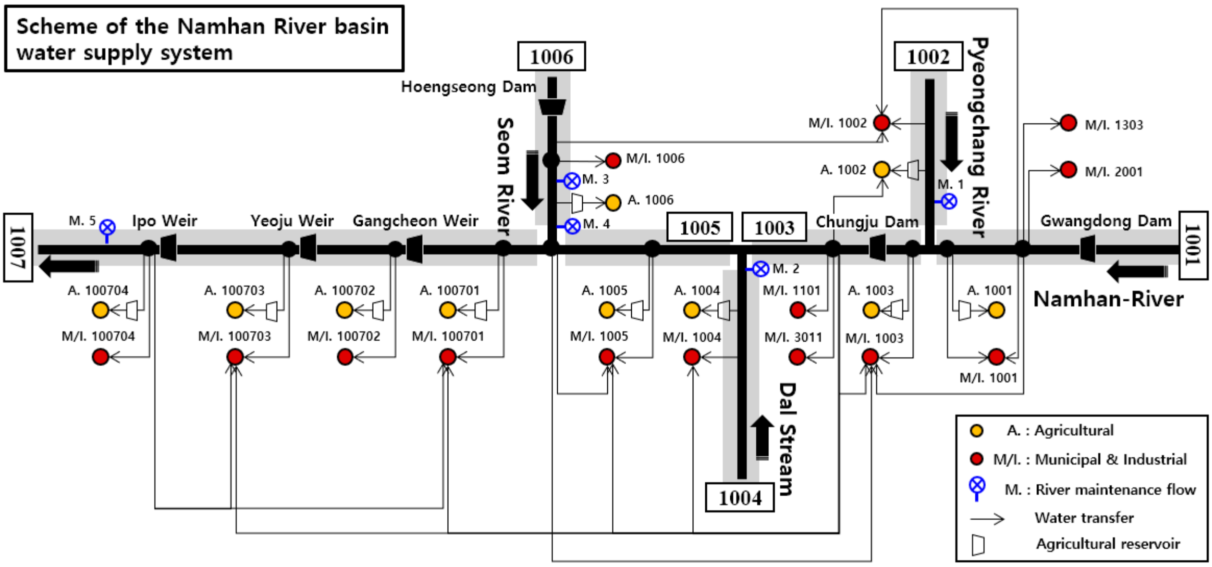


Figure 5. Schematic of the Namhan River basin water supply network.

Table 1. Average water demand at individual sites in the Namhan River basin (in June 2015).

Sub-Basin	Demand Sites	Water Demand (1000 m^3)	Sub-Basin	Demand Sites	Water Demand (1000 m^3)
External transmission	M/I. 1303	245	1005	A. 1005	11,280
	M/I. 2001	780		M/I. 1005	615
	M/I. 1101	225	1006	A. 1006	18,559
	M/I. 3011	3170		M/I. 1006	6095
1001	A. 1001	3900	1007	A. 100701	7649
	M/I. 1001	3090		M/I. 100701	2820
1002	A. 1002	7361		A. 100702	3318
	M/I. 1002	955		M/I. 100702	1960
1003	A. 1003	11,227		A. 100703	49,057
	M/I. 1003	4175		M/I. 100703	6880
1004	A. 1004	28,585		A. 100704	4584
	M/I. 1004	4815		M/I. 100704	2875

Note: A: agricultural water demand; M/I: municipal and industrial water demand.

Every municipal/industrial and agricultural demand site has access to separate groundwater sources nearby. In the WAMM, the recharge of groundwater is not simulated, but only initial groundwater storage is set and supplied to demand sites. However, in the target season (June), little groundwater use was recorded, and so the effect of groundwater supply was not specified in the present case study. Furthermore, Figure 5 shows five flow gauges (M.1 to M.5) for river maintenance flow over the entire river basin, which have flow requirements of 7.73, 5.03, 23.1, 7.57, and 32.5 m^3/s, based on maintenance demand in MLTM [30]. The river maintenance flow requires the minimum flow rates for eco-environmental preservation and induces the discharge of reservoirs and release downstream without actual water consumption.

3.2. Economic Value of Water Resources in the Namhan River Basin

The economic values of municipal, industrial, and agricultural water supply in Namhan River basin were estimated and provided to the WAMM. The economic value of municipal water was estimated to be 1283 KRW/m^3 by substituting the municipal water use status reported in the National Water Resources Plan 2011–2020 of South Korea (MLTM) [30] in the municipal water supply benefit function (Equation (6)). The economic values of industrial and agricultural water were estimated to be 5583 KRW/m^3 and 384 KRW/m^3, respectively, by applying the data used to derive the respective production functions in previous studies (Equations (8) and (10) suggested in [21,22]). Here, the economic value of river maintenance flow was not considered. As the WAMM considers the demand sites of both municipal and industrial water together, their economic value (Table 2) was applied by considering the proportions of municipal and industrial water use at each demand site.

Table 2. Economic valuation of water supply to municipal/industrial water demand sites.

Demand Site	**Municipal Water Demand Ratio (%)**	**Industrial Water Demand Ratio (%)**	**Economic Value of Supply (KRW/m^3)**
M/I. 1001	38	62	3949
M/I. 1002	92	8	1627
M/I. 1003	69	31	2616
M/I. 1004	80	20	2143
M/I. 1005	63	37	2874
M/I. 1006	92	8	1627
M/I. 100701	61	39	2960
M/I. 100702	61	39	2960
M/I. 100703	61	39	2960
M/I. 100704	61	39	2960
M/I. 1101	100	0	1283
M/I. 1303	100	0	1283
M/I. 2001	100	0	1283
M/I. 3011	100	0	1283

3.3. Application of Climate Change Scenario in the Namhan River Basin

3.3.1. River Basin Flow Projection

The predicted precipitation and maximum temperatures in the seven sub-basins in June for the next 30 years are illustrated in Figure 6. Using the PRMS rainfall-runoff simulation, the river basin flow in June for each sub-basin was estimated for the next 30 years (independent year-by-year simulation; Figure 7). It should be noted that the initial storage in the reservoirs at the beginning of June for the next 30 years is fixed as the base value of the standard year of 2015. Sub-basin flows generally change following consistent trends across the years but deviate considerably between wet and drought years. The total river basin flow of the entire Namhan River basin in June exhibits an average of 405 million m^3/month, a maximum of 1455 million m^3/month (2018), and a minimum of 29 million m^3/month (2036) over the next 30 years. Based on comparisons of predicted and gauged rainfall in 2015–2018, the climate change scenarios represent relatively wet conditions in the 1001–1004 sub-basins, and dry conditions in the 1005–1007 sub-basins.

3.3.2. Water Demand Projection

The water demand in June was predicted for each demand site over the next 30 years (Figure 8) based on the water demand change scenario of the Namhan River basin. The agricultural water demand in June was predicted to gradually decrease over the next 30 years from a maximum of 170 million m^3/month in 2015 to a minimum of 144 million m^3/month in 2045 owing to a decrease in the farmland area. On the other hand, the demand for municipal and industrial water in June was predicted to increase from a minimum of 52 million m^3/month in 2015 to a maximum of 57 million m^3/month in 2045, and the annual deviation was predicted to be relatively small.

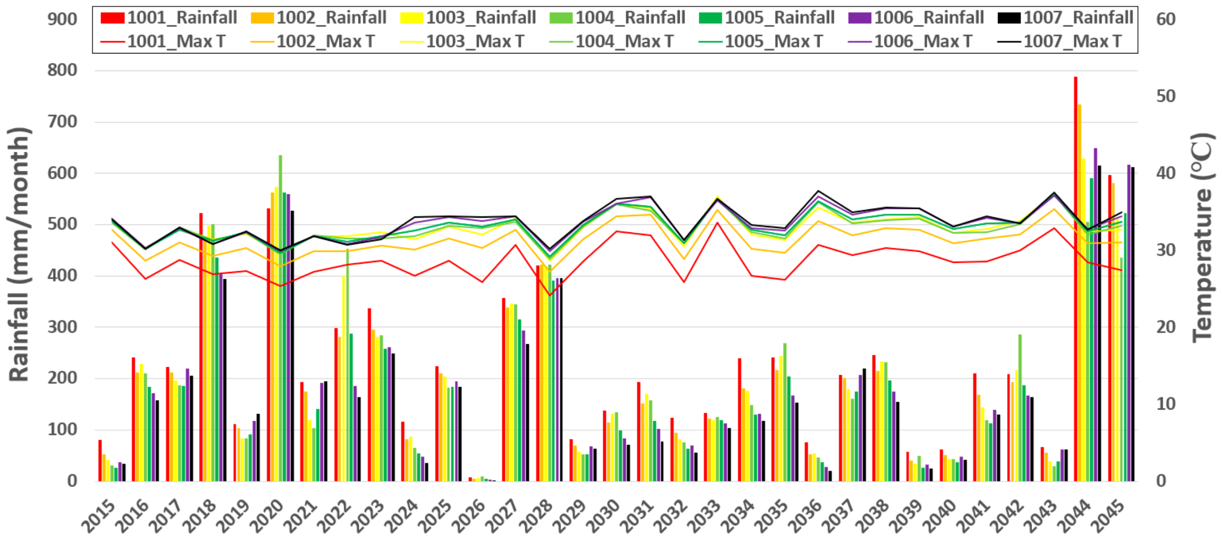


Figure 6. Rainfall and temperature predictions in the Namhan River sub-basins (in June).

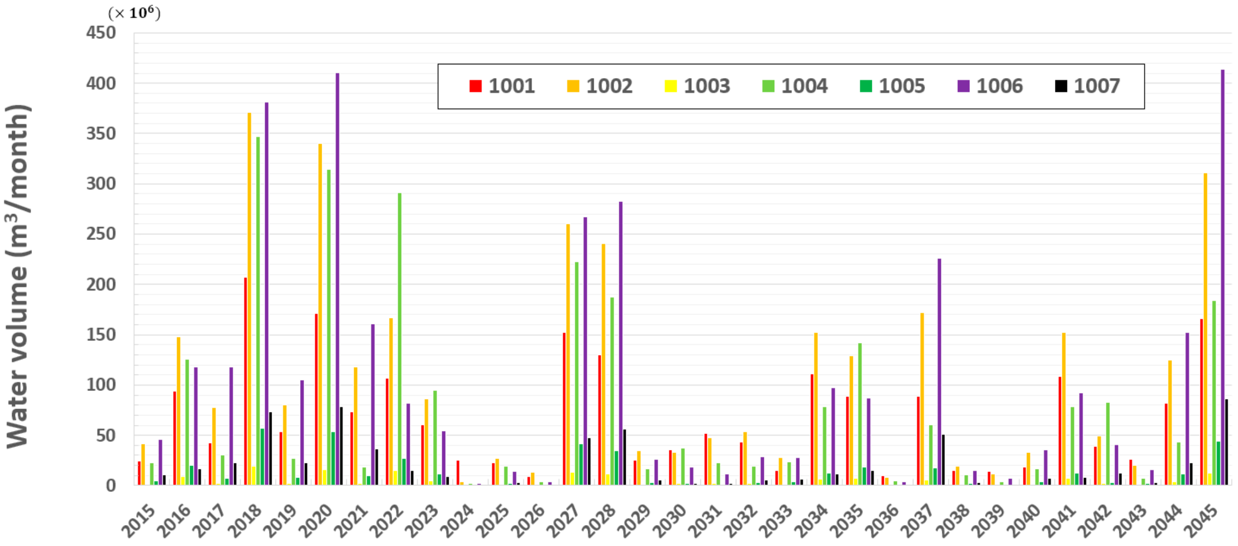
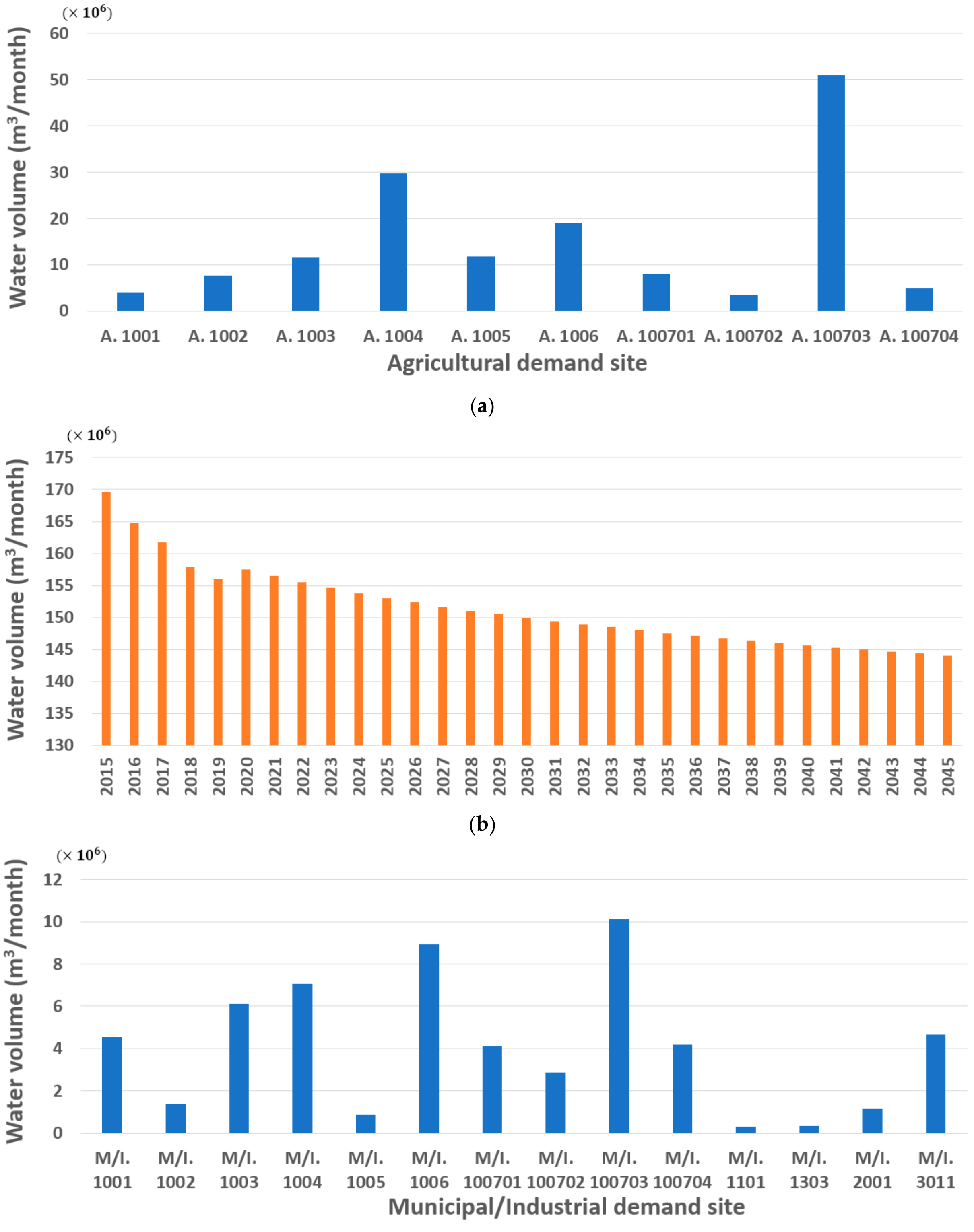


Figure 7. Runoff predictions in the Namhan River sub-basins (in June).

The estimated river basin flow and water demand for the next 30 years were preliminarily compared for the entire Namhan River basin (Figure 9). The total river basin flow shows significant annual variation compared with the water demand. As the river basin flow in June was sometimes remarkably lower than the demand during the 30-year simulation period, the predictions show that water shortage events will occur throughout the basin. However, these results do not include water resources that can be utilized from reservoirs (e.g., dams, weirs, and agricultural reservoirs) in the basin. Thus, actual water shortages are likely to primarily occur in the most notable drought years, including 2024–2026, 2036, and 2038–2039, which are predicted to have insufficient river flow.

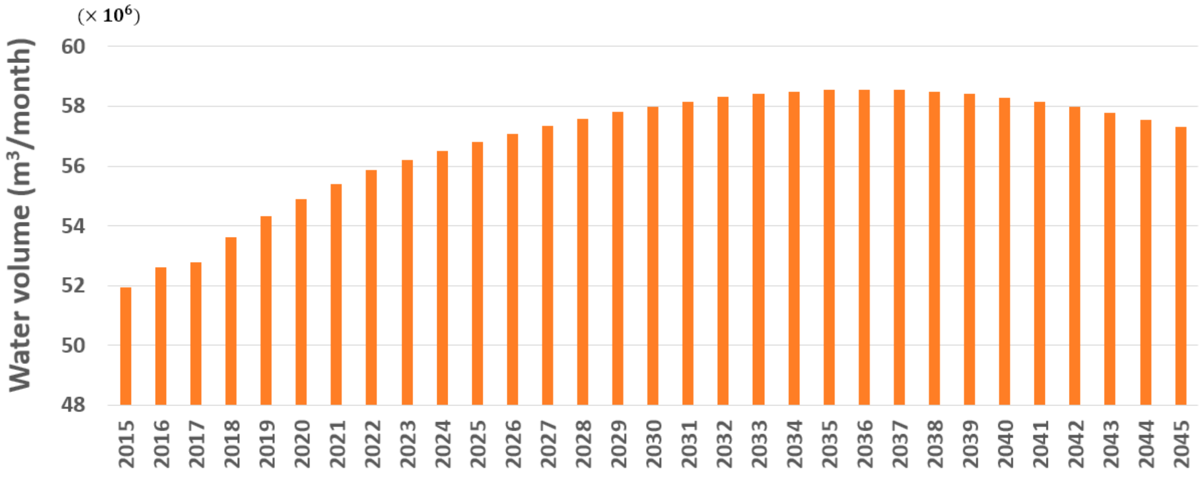


(**a**)

(**b**)

(**c**)

Figure 8. *Cont.*



(**d**)

Figure 8. Water demand prediction in the Namhan River basin (in June). (**a**) Agricultural water demand of each demand site (30-year average); (**b**) total agricultural water demand changes over 30 years; (**c**) municipal/industrial water demand of each demand site (30-year average); and (**d**) total municipal/industrial water demand changes over 30 years.

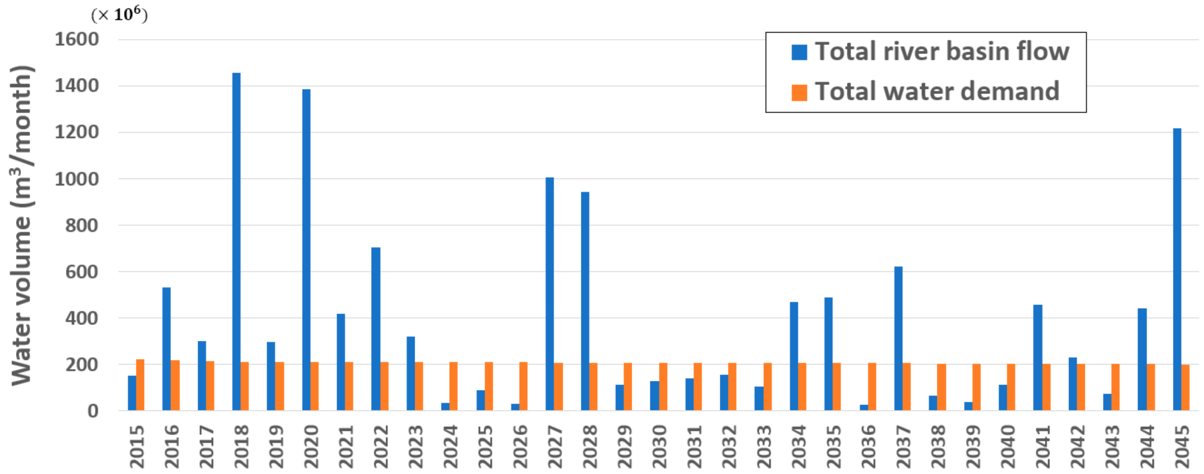


Figure 9. Comparison of predicted river flow and water demand in the Namhan River basin.

4. Application Results

Optimal water allocation under the applied climate change scenario was simulated using the WAMM for the Namhan River basin over the next 30 years. By applying two optimization methods (SSLP and FSLP) and two objective functions (supply reliability and economic benefit), the allocation results were compared to demonstrate the relative effectiveness of the allocation methods embedded in the WAMM.

4.1. Water Allocation Using SSLP

4.1.1. Reliability-Based Water Allocation Using SSLP

First, optimal water allocation was conducted to maximize the water supply reliability as the objective function using the SSLP method (Figure 10). According to the WAMM, water shortages with an average, maximum, and minimum values of 9.7 million m^3/month, 32.3 million m^3/month (2024), and 0.7 million m^3/month (2016), respectively, will occur in the case study area in June over the next 30 years. These water shortages correspond to average, maximum, and minimum economic losses of 5.0 billion KRW/month, 16.9 billion KRW/month (2024), and 0.9 billion KRW/month (2016), respectively.

(**a**)

(**b**)

Figure 10. Water allocation simulation results obtained using reliability-based single-step linear programming (SSLP). (**a**) Water shortage and (**b**) economic damage.

Within the simulation period (30 years), water shortages occur every year at demand site M/I. 3011, where the increasing demand cannot be met owing to the restriction of the transmission capacity. In addition, agricultural sites such as A. 1002, A. 1004, and A. 1006 also incur severe water shortages during drought years. These water shortages are particularly significant in 2024, 2026, and 2036 when the shortages exceed approximately 30 million m^3/month. As shown in Figure 10, agricultural water shortages are dominant (accounting for approximately 86% of the shortages occurring in the basin over 30 years) compared with municipal and industrial water shortages (14%). However, this larger proportion of shortages account for only approximately 63% of the economic damage, while the economic damage in the municipal and industrial sectors is approximately 37%. This result is related to the different economic values of water according to its use.

4.1.2. Economy-Based Water Allocation Using SSLP

The results of the reliability-based water allocation analysis confirm that the trends of water shortage and economic loss in the basin do not necessarily match because the economic value of water is different according to its use. Here, the allocation of water to maximize economic benefit while using the SSLP method is considered.

The results of the water allocation simulation yielded the distribution of water shortages and economic damages in June (Figure 11). The overall water shortage and economic damage are lower than those based on the reliability-based SSLP water allocation. There are two reasons for the lower water shortage. First, the increase in supply to the municipal and industrial water demand sites results in increased production and use of reclaimed water. Second, the river maintenance flow is utilized for supplying demand sectors because the economic value of the maintenance flow is not considered in the economy-based SSLP under drought conditions.

(**a**)

(**b**)

Figure 11. Water allocation simulation results obtained using economy-based single-step linear programming (SSLP). (**a**) Water shortage and (**b**) economic damage.

The water shortage pattern at site M/I. 3011 for the economy-based water allocation observed in Figure 11 is the same as that observed for the reliability-based water allocation in Figure 10. However, the municipal and industrial water shortages in 2024 and 2026 were resolved to a great extent by using the economy-based water allocation; that is, most of the municipal and industrial water shortage events were resolved, except for cases in which the capacity of the supply conduit pipe was limited. In summary, when using economy-based water allocation, the average, maximum, and minimum water shortages in June will be 6.7 million m^3/month, 21.5 million m^3/month (2036), and 0.7 million m^3/month (2016), respectively, which is equivalent to average, maximum, and minimum economic damages of 3.8 billion KRW/month, 10.6 billion KRW/month (2024), and 0.9 billion KRW/month (2016), respectively. Compared with the reliability-based SSLP water allocation results (Section 4.1.1), the economy-based SSLP water allocation method reduces maximum the water shortage and economic damage by approximately 10.8 million m^3/month and 6.2 billion KRW/month, respectively, and the average water shortage and economic damage over 30 years by 3.0 million m^3/month and 1.2 billion KRW/month, respectively.

Notably, the severity of economic damage due to water shortage does not seem to be directly related to the severity of water shortages. The most severe water shortage will occur in 2036, but the most severe economic loss will occur in 2024. In other words, water shortage-induced damage and economic damage exhibit different patterns.

4.2. Water Allocation Using FSLP

4.2.1. Reliability-Based Water Allocation Using FSLP

Next, FSLP-based water allocation was performed (i.e., allocating water over the entire simulation period) and the results were compared with those of the conventional SSLP.

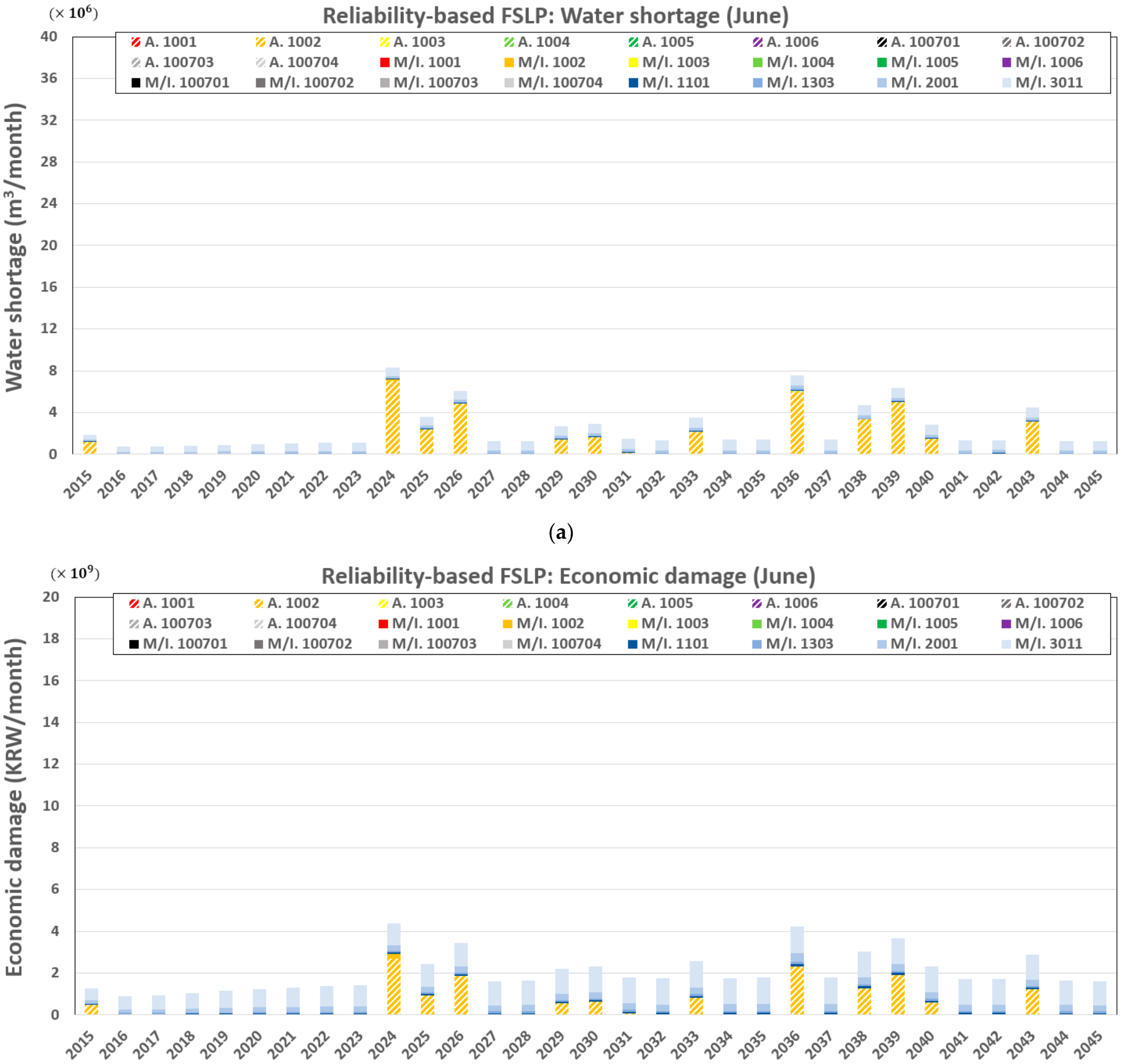
The reliability-based FSLP water allocation simulation provided water shortage and economic loss results for June (Figure 12). As expected, the results of the FSLP water allocation demonstrated a significant reduction in the overall water shortage compared to the results of the SSLP. This reduction is the effect of utilizing storage facilities when simultaneously considering the entire simulation period (all six time steps of June). In particular, in SSLP, regardless of the water shortage occurring in other time steps, the remaining water in the current time step is discharged as is or stored mainly in downstream storage facilities. In FSLP, when water shortage is expected in future time steps, the remaining water in the current time step is secured in an appropriate storage facility where possible, improving allocation results through more flexible preparation for expected water shortage events.

Analyses of the simulation results in Figure 12 reveals that, for reliability-based FSLP water allocation, the average, maximum, and minimum water shortage in June is 2.5 million m^3/month, 8.3 million m^3/month (2024), and 0.7 million m^3/month (2016), respectively; the average, maximum, and minimum economic damage is 2.03 billion KRW/month, 4.38 billion KRW/month (2024), and 0.9 billion KRW/month (2016), respectively. Compared to the reliability-based SSLP water allocation (Section 4.1.1), the FSLP-based allocation considerably increases water allocation efficiency by reducing the maximum water shortage and economic damage by approximately 24.0 million m^3/month and 12.5 billion KRW/month, respectively, and the average water shortage and economic damage over 30 years by 7.2 million m^3/month and 3.0 billion KRW/month, respectively.

4.2.2. Economy-Based Water Allocation Using FSLP

Lastly, economy-based FSLP water allocation was performed and the results of water shortage and economic damage are shown in Figure 13. Compared to the economy-based SSLP (Section 4.1.2), which maximizes economic benefits with the conventional SSLP method, the FSLP reduced the maximum water shortage and economic damage by approximately 13.2 million m^3/month and 6.3 billion KRW/month, respectively, and the average water shortage and economic damage over 30 years by 4.2 million m^3/month and 1.8 billion KRW/month, respectively.

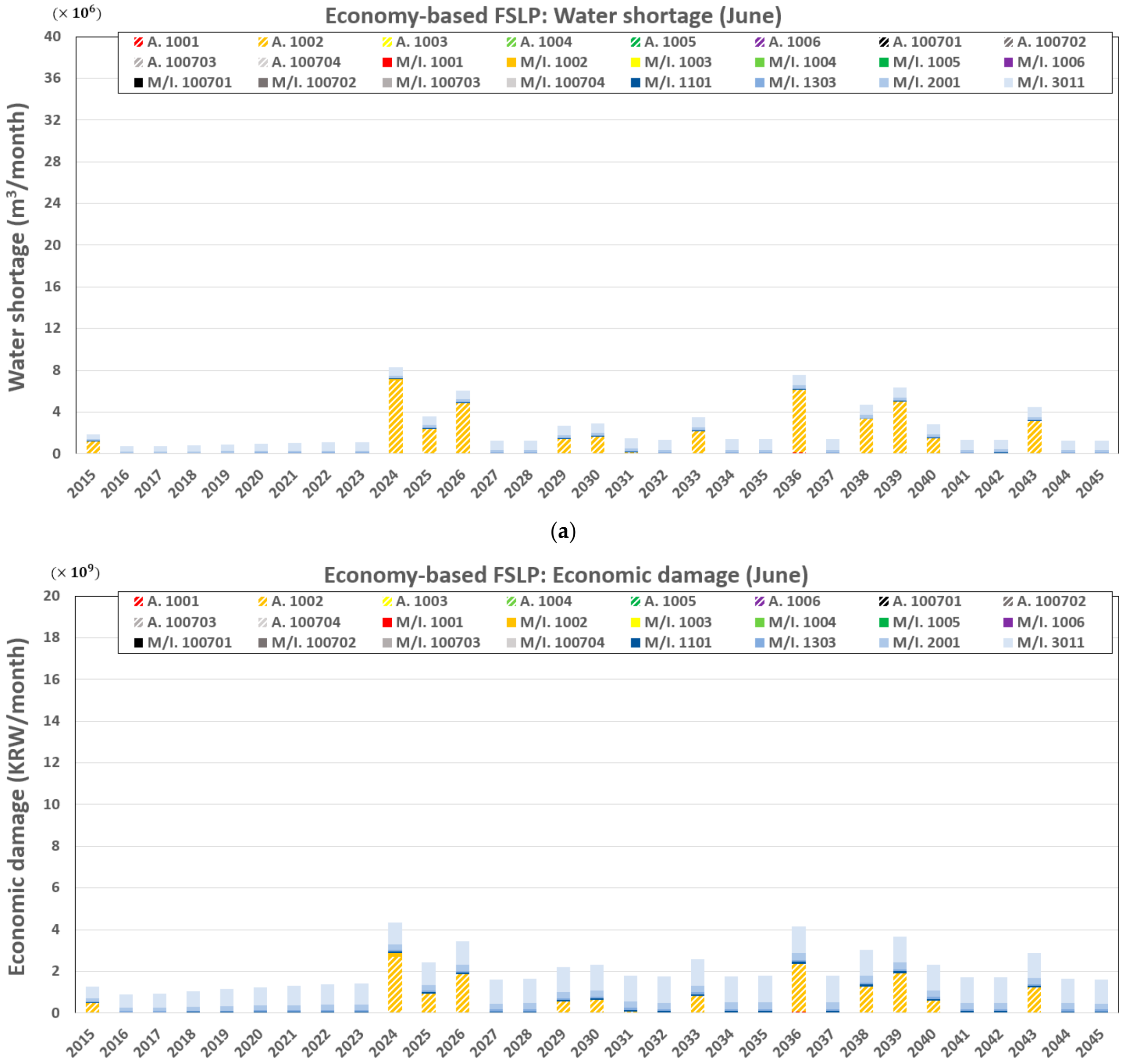
The results of a comparison between the reliability-based FSLP (Section 4.2.1) and economy-based FSLP are as follows. As the reliability-based allocation already maximizes the quantitative efficiency of water supply, the total water shortage was the same throughout the simulation period for both approaches. However, using the economy-based FSLP, the economic damage was slightly reduced by supplying water preferentially to demand sites M/I. 1001 and M/I. 100701–M/I.100704, which have larger proportions of industrial, water rather than supplying demand sites M/I. 1002 and M/I. 1006, in which the proportion of municipal water is higher than industrial water. In summary, the water shortages resulting from the economy-based FSLP water allocation were the same as those resulting from the reliability-based FSLP, but with slightly lower average, maximum, and minimum economic damages of 2.02 billion KRW/month, 4.36 billion KRW/month (2024), and 0.9 billion KRW/month (2016), respectively.



(**a**)

(**b**)

Figure 12. Water allocation simulation results obtained using reliability-based full-step linear programming (FSLP). (**a**) Water shortage and (**b**) economic damage.



(**a**)

(**b**)

Figure 13. Water allocation simulation results obtained using economy-based full-step linear programming (FSLP). (**a**) Water shortage and (**b**) economic damage.

5. Discussion

Conventional water allocation models such as MODSIM [6] and WEAP [8] were developed decades ago but many studies are still widely applying them to water resource management by combining them with optimization schemes and various objective functions. Chou et al. [39] conducted a representative case study in optimizing water resources operation by combining existing models and advanced optimization algorithms. In this study, water allocation results using the reliability-based SSLP of the WAMM represent the conventional approach of WEAP [8]; however, the results using FSLP or economy-based allocation offer an alternative decision for better water resources management. The results, which are based on assumptions such as climate change and water demand scenarios, reveal both water shortage risks and associated economic considerations. Moreover, water supply efficiency according to the objectives and optimization methods of water allocation can be comparatively analyzed.

Table 3 provides a comparative analysis of the four water allocation simulation results evaluated in this study. In terms of the objective function, the economy-based water allocation approach reduced both water shortage and economic damage compared with the reliability-based allocation approach. In terms of the optimization method, the FSLP significantly reduced water shortages compared with the SSLP. Therefore, a water allocation method that considers the economic value of water resources using an FSLP optimization method capable of simultaneously considering the entire simulation period is the most effective approach for the case study basin. Finally, the 30-year average water supply reliability of the reliability-based SSLP water allocation (i.e., the conventional method) was 95%, which improved to 97% when using the economy-based SSLP water allocation and to 99% when using FSLP water allocation.

Table 3. Comparison of full-step linear programming (FSLP) and single-step linear programming (SSLP) water allocation results.

Water Allocation Method	Total Reliability	Average		Maximum		Minimum	
		Water Shortage (10^6 m^3/Month)	Economic Damage (10^9 KRW/Month)	Water Shortage (10^6 m^3/Month)	Economic Damage (10^9 KRW/Month)	Water Shortage (10^6 m^3/Month)	Economic Damage (10^9 KRW/Month)
Reliability-based SSLP	0.95	9.7	5.0	32.3	16.9	0.7	0.9
Economy-based SSLP	0.97	6.7	3.8	21.5	10.6	0.7	0.9
Reliability-based FSLP	0.99	2.5	2.03	8.3	4.38	0.7	0.9
Economy-based FSLP	0.99	2.5	2.02	8.3	4.36	0.7	0.9

6. Conclusions

In this study, a new hydro-economic water allocation and management model, WAMM, was tested by improving the optimization algorithm of conventional water allocation models and considering the economic value of water resources. The WAMM was applied for water allocation simulation considering the impact of climate change and water demand scenarios on the Namhan River basin in South Korea over the next 30 years. A climate change-influenced water supply scenario was constructed based on the precipitation and maximum temperature predictions of the RCP 8.5 climate change scenario derived from HadGEM2-AO GCM. Also, a demand scenario was built based on a demand forecast obtained according to the changes in population and farmland and accounted for the uncertainty of conditions. To evaluate the two objective functions (reliability and economic benefit) and the two optimization methods (SSLP and FSLP) within the WAMM, water supply from the basin over the next 30 years was allocated to four different cases and the allocation results were comparatively analyzed. The results can be summarized as follows.

1. The results of the reliability-based SSLP allocation show that, according to the considered climate change scenario, the water shortage in June over the next 30 years will be an average and maximum of 9.7 million m^3/month and 32.3 million m^3/month (2024), respectively, corresponding to average and maximum economic damages of 5.0 billion KRW/month and 16.9 billion KRW/month (2024), respectively.
2. The results of the economy-based SSLP allocation show a lower total water shortage because water allocation focused on municipal and industrial sectors and the use of reclaimed water increased; moreover, the priority of river maintenance flow demand was lowered. Over the next 30 years, average and maximum water shortages in June of 6.7 million m^3/month and 21.5 million m^3/month (2036), respectively, were obtained, corresponding to average and maximum economic damages of 3.8 billion KRW/month and 10.6 billion KRW/month (2024), respectively. Therefore, compared to the reliability-based SSLP method, in which the objective function of water allocation is simply based on the supply quantity, water allocation considering the economic value of the water reduces both the water shortage and economic loss to a certain degree.
3. The results of the reliability-based FSLP allocation confirm that the total water shortage was considerably reduced by flexibly utilizing storage facilities to respond to water shortages that are predicted to develop throughout the entire simulation period. The average and maximum water shortages in June were found to be 2.5 million m^3/month and 8.3 million m^3/month (2024), respectively, corresponding to aver-

age and maximum economic damages of 2.03 billion KRW/month and 4.38 billion KRW/month (2024), respectively.

4. Economy-based FSLP allocation indicates the same quantity of water shortage as the reliability-based FSLP allocation but preferentially supplies water to municipal/industrial demand sites that comprise a high proportion of industrial water demand. This difference resulted in average and maximum economic damages of 2.02 billion KRW/month and 4.36 billion KRW/month (2024), respectively, over the 30-year period, which are slightly less than the corresponding values obtained using the reliability-based FSLP.

The WAMM has a few important limitations to take note of when applying climate change scenarios to each sub-basin; primarily, the scenarios and economic value of water are somewhat roughly aggregated. However, the water shortage-induced economic damage due to climate change was still successfully minimized and quantified using the model. In future work, the WAMM will be modified to more comprehensively consider water sources such as the conjunctive use of surface water, groundwater, and reclaimed water. Furthermore, more precise climate change scenarios and water valuations would also contribute to specified water resources management. Once effectively derived and demonstrated, the WAMM is expected to offer a robust decision-making tool to resolve water shortages and disputes among river basin units.

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