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Abstract: The interest in renewable energy to replace fossil fuel is increasing as the problem caused by climate change has become more severe. In this study, small hydropower (SHP) was evaluated as a resource with high development value because of its high energy density compared to other renewable energy sources. SHP may be an attractive and sustainable power generation environmental perspective because of its potential to be found in small rivers and streams. The power generation potential could be estimated based on the discharge in the river basin. Since the river discharge depends on the climate conditions, the hydropower generation potential changes sensitively according to climate variability. Therefore, it is necessary to analyze the SHP potential in consideration of future climate change. In this study, the future prospect of SHP potential is simulated for the period of 2021 to 2100 considering the climate change in three hydropower plants of Deoksong, Hanseok, and Socheon stations, Korea. The results show that SHP potential for the near future (2021 to 2040) shows a tendency to be increased, and the highest increase is 23.4% at the Deoksong SPH plant. Through the result of future prospect, we have shown that hydroelectric power generation capacity or SHP potential will be increased in the future. Therefore, we believe that it is necessary to revitalize the development of SHP to expand the use of renewable energy. In addition, a methodology presented in this study could be used for the future prospect of the SHP potential.

Keywords: climate change scenario; generation potential; hydropower; renewable energy

1. Introduction

With accelerating climate change, leading countries have established long-term plans to reduce greenhouse gas (GHG) emissions and have attempted to implement such plans. To this end, they are implementing energy transition policies according to their own economic interests to ultimately reduce carbon emissions by migrating from fossil energy to renewable energy. In this situation, small hydropower (SHP), which is clean energy that uses water, is a representative renewable energy source that is sustainable even in future climate change because it reduces carbon emissions [1,2]. Thus far, the value of SHP has been relatively underestimated due its initial investment cost being high compared to other energy sources with technical development. However, the development of SHP will gradually be expanded in the future as renewable energy sources are attracting global attention [3,4]. Therefore, reliable data for selecting promising candidate sites for SHP, such as on the estimation of the available power generation potential, are important. However, SHP is sensitive to climate conditions because it generates power using the head of flowing water. In recent years, the occurrence frequency of abnormal climate, such as droughts and floods, has been slowly increasing due to climate change. This change also has a direct impact on the amount of power generated by the operation of SHP plants [5–7].

Many studies have been conducted to estimate the SHP potential under climate change (discussed in the next chapter). Nevertheless, few studies have been conducted on the

estimation of the SHP potential in ungauged basins for the estimation of the available power generation potential under climate change. Therefore, this serial study aims to calculate the future SHP potential in ungauged basins. To this end, calculating the accurate runoff is most important. In the first part of the serial study, Jung et al. (2021) proposed a method of improving the accuracy of discharge data by applying four blending techniques after calculating the discharge using the Kajiyama formula, the modified-TPM model that calculates the runoff using hydro-meteorological data, and the Tank model that calculates the runoff based on the rainfall-runoff process [8]. For the next step, the SHP potential under climate change was predicted based on the results of Jung et al. (2021) on the calculation of the SHP potential in ungauged basins in this study [8].

To analyze the future variability of the SHP potential under climate change, the discharge data until 2100 were calculated using the climate change scenario. Based on the discharge data, the SHP potential was predicted. The background of SHP potential calculation, climate model, and climate change scenario are explained in Section 2, respectively. The SHP potential is estimated under climate change and the variability of SHP potential is analyzed in Section 3. The discussion and conclusions are provided in Section 4. The flowchart of the serial study is shown in Figure 1. Part I shows the flow of the previous study [8], and part II shows the flow of this study.
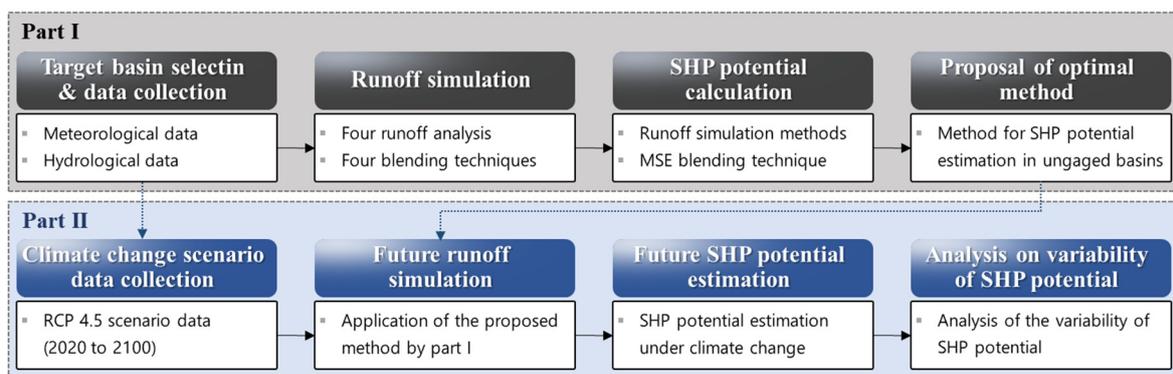

Figure 1. The flowchart of the serial study.

2. Literature Review

Hydropower is a renewable energy source that is the largest source of low-carbon electricity worldwide and sustainable even in future climate change [1,9]. The studies on hydropower have been done by many researchers regarding the benefits, costs, risk, and so on [10–17]. There are also several studies on political and social debates on hydropower such as Iron Gates on the river Danube [18–21]. Hydropower is classified based on the power capacity, and hydropower plants generating the capacity of 10,000 kW or less is defined as small hydropower plant [22].

The SHP potential is the sum of small hydropower resources corresponding to the annual maximum power generation [3]. The energy potential is data for estimating the total amount of energy resources available throughout an area, and the renewable energy potential is applied to the data for establishing the domestic renewable energy distribution plan and the energy basic plan. Currently, the regional distribution characteristics of hydropower and other renewable energy sources are analyzed in detail through the combination of geographic information. The potential of renewable energy resources generally starts from the theoretical potential and forms a stepwise pyramid structure. To calculate the potential, it is necessary to prepare standard coefficients for the number of resources (natural environmental conditions), geographic conditions, technical elements (e.g., energy efficiency, operation rate, and collection rate), environmental performance, and technological progress through long-term data accumulation. Many studies have been conducted on the estimation of the SHP potential [8].

Since the SHP potential is mainly determined by water quantity, discharge is the important factor [23]. Therefore, many studies have used the available discharge for estimating the SHP potential [24–31]. When the discharge data were insufficient or unavailable such as an ungauged basin, the discharge data calculated by the precipitation data or else were used [24,28,29,32–36]. Noyes (1980) and Park and Lee (2008) simulated the discharge by analyzing rainfall data [32,37]. Larentis et al. (2010) and Yu et al. (2017) calculated the discharge values to estimate the potential of hydropower plant candidate sites [24,38]. Several researchers used the hydrological model, soil and water assessment tool (SWAT) model and geographic information system (GIS) to estimate the hydropower potential [33–35]. The method to accurately calculate discharge has also been studied. Park and Lee (2008) suggested the flow-duration characteristics model which estimates the hydropower potential by calculating the discharge using precipitation data, basin area, and runoff coefficient [26,28]. Cheng et al. (2017) and Zlatanović et al. (2014) used the gray model [39] and an open-source software application [40], respectively. Saliha et al. (2011) estimated the discharge values in an ungauged basin by combining a hydrological model and neural network theory [41]. Kim et al. (2018) used a grid-based surface runoff model [42], and Kim et al. (2012) applied the tank model [43].

However, there is no official methodology to calculate the discharge for estimating the hydropower potential, and the results can be different from different methods even with the same precipitation data. To decrease the uncertainty of the discharge results and improve the accuracy of the SHP potential estimation, this serial study was conducted. The discharge was calculated using several runoff formulas and hydrologic models and blending techniques have been proposed to reduce the uncertainty of the results and to increase the usability of the results in the first part of the serial study. A previous study (Jung et al., 2021) confirmed that it is possible to estimate the reliable SHP potential through the application of the discharge simulation and blending technique that uses meteorological data even in ungauged basins without discharge data [8].

In the same manner, it is possible to estimate the SHP potential that considers climate change by collecting the future meteorological data of the target basin from the climate change scenario data. The projection of hydropower productivity of existing power plants is an important issue all over the world these days. Many studies have been conducted on the variability of the SHP potential in consideration of climate change worldwide [44–59]. In previous studies, the most common way to prospect the future hydropower potential under climate change is to use a hydrological model with a climate model to simulate the discharge first, and then calculate the potential. Several studies evaluated the impacts of climate change on hydrology using hydrological models [49,60–64]. Kim et al. (2018) estimated the SHP potential under climate change using a grid-based surface runoff model [44]. Liu et al. (2016) projected impacts of climate change on hydropower potential in China using simulation from eight global hydrological models and five general circulation models (GCMs) [65]. Wang et al. (2019) used the variable infiltration capacity (VIC) hydrological model coupled with five climate models to assess the impact of climate change on river discharge and hydropower potential in the Nanliujiang River basin [66].

Future climate change is forecasted using a climate model. Climate models are computer programs created based on the mathematical equations that are used to quantitatively calculate the atmospheric temperature, air pressure, wind, vapor, clouds, and rainfall, which react to the ground surface and atmosphere due to solar heat [67]. Climate deals with phenomena over a long time scale, such as changes in oceans, glaciers, and ground surface. It can be affected by elements that occur slowly, such as changes in the chemicals in the atmosphere caused by human activities. Today, climate models under development worldwide are evolving into earth system models that combine biogeochemical modules beyond atmosphere–ocean–sea ice coupling. Models with different levels of complexity are being developed for various purposes. In general, an earth system model is constructed in a way that allows the solar energy supplied to the earth to act on the circulation of water, heat, and matter among the atmosphere–ocean–sea ice–land–hydrology areas. Changes

in GHG emissions, aerosols, and ground conditions caused by human activities are also considered a part of the earth system [68].

Many other studies that used the climate change scenario driven by GCM outputs have been performed around the world [69–75], as well as at the national or regional scales [7,44,50,76–84]). Lehner et al. (2005) used three GCMs to evaluate the impacts on hydropower potential in Europe [85]. van Vliet et al. (2016) evaluated changes in the hydropower generated worldwide due to climate change using GCMs under the representative concentration pathways (RCPs) 2.6 and 8.5 [5]. Hamududu and Killingtveit (2012) simulated changes in runoff using 12 different GCMs and estimated the hydropower generated under climate change [45]. Kim et al. (2012) predicted the future runoff by applying the rainfall data for the future target period to the tank model based on the Intergovernmental Panel on Climate Change (IPCC) A1B climate change scenario and researched the variability of the power generated by SHP under climate change [43]. Spalding–Fecher et al. (2016) evaluated the vulnerability of hydropower due to climate change in the Zambezi River basin in South Africa [47]. Chilkoti et al. (2017) evaluated the impact of climate change on hydroelectric power generation using regional climate models (RCMs) [49]. In addition, Fan et al. (2020) analyzed changes in the hydropower generated in China due to climate change using RCP climate change scenarios [50]. Casale et al. (2020) used Poli-Hydro with IPCC climate scenarios until 2100 to assess present and future hydropower potential in the Kabul River [86].

As mentioned above, many studies have been continuously conducted to estimate the SHP potential under climate change for the existing SHP plants [45,49,60–73]. However, few studies have been conducted on the estimation of the SHP potential in ungauged basins for the estimation of the available power generation potential. Therefore, this study aims to calculate the future SHP potential in ungauged basins.

3. Methodology

3.1. SHP Potential Calculation

There are mainly two methods to obtain energy from water: the hydrokinetic and hydrostatic methods. Hydrokinetic energy is the energy generated by the movement of a body of water. The kinetic energy inside the flowing water is directly converted into electricity by turbines. The hydrostatic energy is also produced by moving water. It is produced by storing water in reservoirs to create a pressure head and extracting the potential energy of water [87]. In this study, the hydropower potential from hydrostatic method was considered.

The hydropower potential is classified into the theoretical potential, geographic potential, and technical potential. The theoretical potential was defined as the total energy of the precipitation on the surface of all basins in the Korean Peninsula. The geographic potential was defined as the potential that considered the runoff ratio caused by the geographic characteristics of the basins in the theoretical potential. The technical potential was defined as the potential that considered the system efficiency and operation rate in the geographic potential. The hydropower potential was calculated for each water system and administrative district.

The SHP potential is widely applied not only to the SHP plants already developed but also in such areas as the selection of new suitable sites for SHP from the beginning stage of a policy to the site selection stage. The potential data are also used for the forecast of the future power market, establishment of future energy policies, selection of sites for power plants, development of communities, and construction of distributed power generation systems. As for the calculated potential, the theoretical potential, geographic potential, or technical potential is used depending on the purpose.

The technical potential was calculated and used in this study. Assuming the water quantity used in the water turbine per unit time as Q (m^3/s), the head as H (m), the water density is ρ (kg/m^3), and the efficiency of the water turbine generator is η, the

technical potential becomes P = $\rho \cdot g \cdot Q_d \cdot H_e \cdot \eta$ (kW). The g is gravity acceleration (m/s^2), and Q_d (m^3/s) and H_e (m) indicate design discharge and effective head respectively [8].

3.2. Climate Model and Climate Change Scenario

For the simulation of the future climate of South Korea, Korea Meteorological Administration (KMA) is preparing a global climate change scenario using Coupled Model Intercomparison Project Phase 5 (CIMIP5), a circulation coupled model. It has introduced and used GCM of Hadley Center Global Environment Model-Regional Climate Model (HadGEM3-RA) and HadGEM2-AO from the Hadley Center (UK Met Office), which have a horizontal resolution of 135 km for the atmosphere. The Hadley Center climate model is used for understanding climate change and to provide projections of future climate [88,89].

A climate change scenario can be simply defined as the future carbon dioxide concentration in the atmosphere to be used as the forced condition of a climate change model. In other words, predictable scenarios, such as on whether the carbon dioxide concentration of the earth sharply increases with the current slope, whether the present level is maintained due to reduction efforts, and whether it decreases with resilience, can be determined and used as the same boundary conditions in various models.

Future meteorological variability due to global warming and its impact on climate change are materialized through GCMs and are used as the most general climate change forecast data. GCMs are global atmosphere–ocean circulation models based on complex interactions among various forces, such as solar radiation energy, volcanic eruptions, and greenhouse effects, and various conditions, including the atmosphere, oceans, and ground surface. Such models may vary depending on the time and country, and are classified according to the consideration of oceans, ground surface, and living organisms as well as the dimensions and factors. With the development of technology, climate change models have been developed so that more factors can be considered with higher dimensions and resolution.

The IPCC have been developing future climate change scenarios based on the GHG emission scenarios and evaluating climate change response strategies. In the IPCC fifth assessment report in 2014 (AR5), GHG concentrations were determined based on the radiation to the atmosphere caused by human activities. RCPs were newly presented to indicate that socio-economic scenarios may vary for one representative radiative forcing. In addition, in the Coupled Model Intercomparison Project Phase 5 (CMIP5), a part of the World Climate Research Programme (WCRP) project, GCMs have been developed, compared, and verified using the RCP scenarios with other forcing scenarios since 2009 [90].

As for the future climate change scenarios produced for the Korean Peninsula, KMA has simulated the Korean Peninsula and nearby areas with a resolution of $1° \times 1°$ using HadGEM2-AO, a global climate model. Based on these results, it has simulated the entire Korean Peninsula with a resolution of 12.5×12.5 km using HadGEM3-RA, a regional climate model. As for the RCP scenarios selected in conjunction with climate change response policies, RCP 2.6, 4.5, 6.0, and 8.5 scenarios are presented. This study used the future climate data that applied the RCP 4.5 scenario, which is mainly used for calculating the long-term runoff and considers the substantial realization of GHG reduction policies [91].

3.3. RAPS (Rescaled Adjusted Partial Sums) Method

The RAPS method is a time series analysis method that can detect and quantify trends and fluctuations in values. It is based on visual determination of a subseries from the original time series data. The RAPS values provide insight into the new subseries parts, where occurrences of the data grouping, fluctuations, and similar appearances by using the mean and standard deviation values of the original time series data. The RAPS can be calculated by Equation (1):

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - \overline{Y}}{S_y} \tag{1}$$

where Y_t is the value of the time series, $\overline{Y}$ is the mean value of the time series, S_y is standard deviation of the time series. The plot of the RAPS versus time shows the trends and fluctuations of Y_t [92–94].

4. Estimation and Variability Analysis of SHP Potential under Climate Change

4.1. Target Basin Selectin and Data Collection

4.1.1. Target Basin Selection

In Korea, there 5 large basins, including the Han River basin, then a large basin has medium basins, and a medium has standard basins. In this study, the Deoksong and Hanseok power plants in the Han River basin and Socheon power plant in the Nakdong River basin were selected in the same manner as in a previous study [8]. In the simulation of the runoff to calculate the power generation potential of the target SHP plants, the standard basins where the plants were located were analyzed. Deoksong SHP plant was located in the Jeongseon standard basin, and the nearby rainfall stations were Yeongwol and Daegwanryeong stations under the control of KMA. The discharge data of the Jeongseon streamflow station could be used. Hanseok SHP plant was located in the Saigokcheon junction standard basin, and the nearby rainfall stations were Yeongwol and Yeongju stations under the control of KMA. The discharge data of the Yeongchun streamflow station could be used. Socheon SHP plant was located in the Socheon streamflow station standard basin, and the nearby rainfall stations were Uljin and Bonghwa stations under the control of KMA. The discharge data of the Socheon streamflow station could be used (Figure 2).
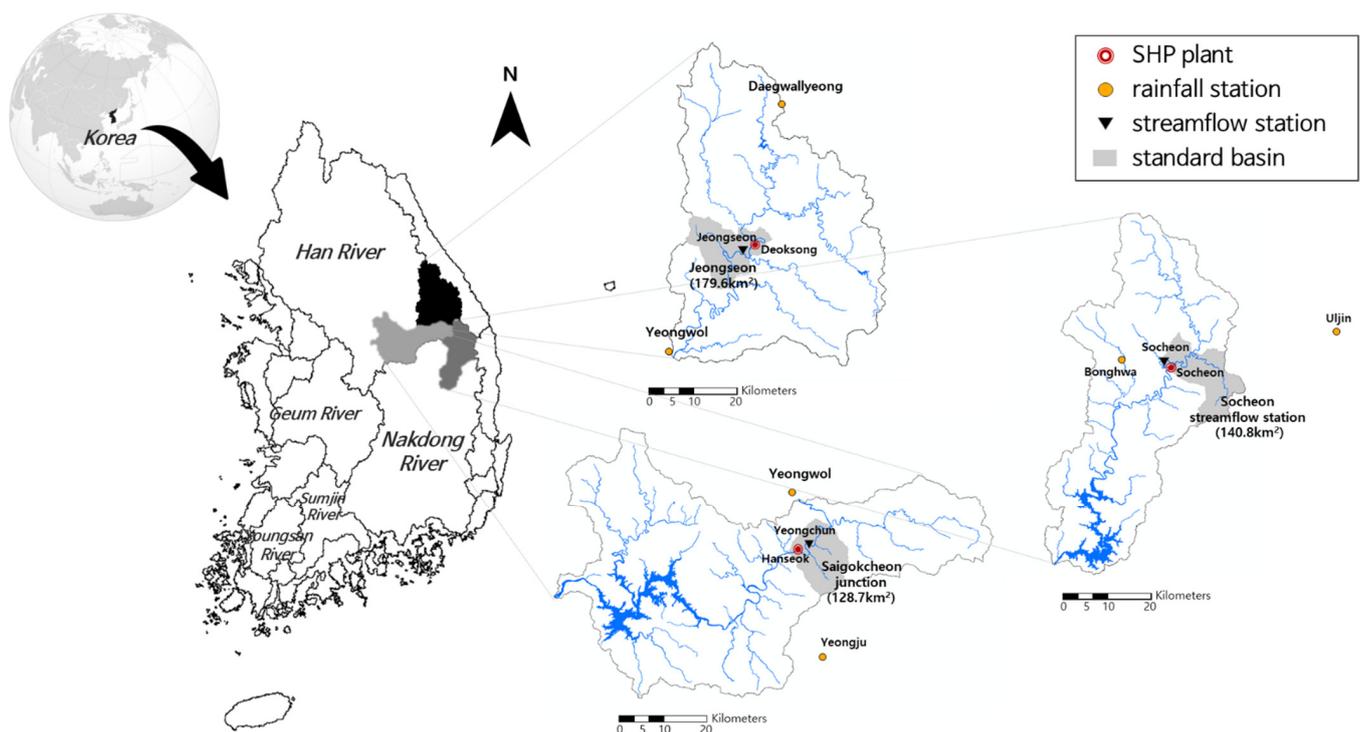

Figure 2. The study basins, basin area, locations of SHP plants, rainfall, and streamflow stations (reprinted from [8]).

Table 1 shows the information on the selected three SHP plants, including the effective head, power generation discharge, and power generation capacity. Tables 2–4 show the general characteristics of each standard basin and the specifications of the nearby rainfall stations.

Table 1. Information on SHP plants of target basins (reprinted from [8]).

SHP Plant	Standard Basin	Commissioned Time	Effective Head [m]	Power Generation Flow Rate [m^3/s]	Installed Power Associated with the Hydropower Plant [kW]
Deoksong	Jeongseon	March 1993	12.5	25.0	2600
Hanseok	Saigokcheon junction	March 1998	3.8	Avg. 3.02/Max. 12.7	2214
Socheon	Socheon streamflow station	August 1985	22.5	12.5	2400

Table 2. General characteristics of basins (Reprinted from [8]).

Standard Basin	Large Basin	Runoff Coefficient (C)	Runoff Curve Number (CN)	Basin Area [km^2]	Cumulative Basin Area [km^2]
Jeongseon	Han River	0.56	58	179.6	1834.7
Saigokcheon junction	Han River	0.56	64	128.7	4898.0
Socheon streamflow station	Nakdong River	0.57	47	140.8	547.2

Table 3. Specifications of rainfall station (reprinted from [8]).

Observation Station	Management Agency	Coordinates (WGS84)		Start of Observation
		Latitude	Longitude	
Yeongwol		37.18	128.46	1 December 1997
Daegwallyeong	Korea Meteorological	37.68	128.72	11 July 1971
Yeongju	Administration	36.87	128.52	28 November 1972
Uljin	(KMA)	36.99	129.41	12 January 1971
Bonghwa		36.94	128.91	1 January 1988

Table 4. Specifications of streamflow station (reprinted from [8]).

Observation Station	Management Agency	Zero of Staff Gauge (EL.m)	Benchmark Elevation (EL.m)	Start of Observation
Jeongseon	Ministry of Environment	296.79	312.42	1 January 1918
Yeongchun	K-water	159.97	177.63	30 August 1985
Socheon	K-water	250.08	262.03	16 July 1978

4.1.2. Climate Change Scenario Data Collection

To analyze the variability of the SHP potential under climate change, future climate data were collected using a climate change model and a scenario. In this study, the model and scenario of the CMIP5 phase were used. In addition, the future climate data that applied the RCP 4.5 scenario, which is mainly used to calculate the long-term runoff, were used. As for the climate change scenario data, daily data on the precipitation, average temperature, relative humidity, and average wind speed were collected in the same way as the observation data, and future climate data from 2021 to 2100 were constructed.

The precipitation of the climate change scenario may exceed the outlier range because it tends to be underestimated compared to the observed precipitation. Therefore, outlier testing and bias correction through quantile mapping are required for the climate change scenario [95]. In this study, the climate change scenario data were also corrected through quantile mapping and outlier testing. The box plot method was used for testing outliers. In addition, when quantile mapping was performed, the monthly parameter values for each point were estimated and the probability distribution of the scenario precipitation data were corrected through that of the precipitation data observed in the past. In addition, the basin average value was calculated by assigning the Thyssen polygon area ratio of each meteorological observation network to the meteorological data by point collected through the climate change scenario as a weight in the same way as the observed meteorological data.

In this study, the entire period from 2021 to 2100 was divided into four periods as follows to analyze future climate change by period according to the climate change scenario data.

Projection Period 1: 2021–2040
Projection Period 2: 2041–2060
Projection Period 3: 2061–2080
Projection Period 4: 2081–2100

When the average value of the future monthly average temperatures was compared with that of the data during the observation period (2008–2017) for the Jeongseon basin, it was found to decrease by 0.5 °C in Project Period I but increase by 0.2, 0.7, and 1.0 °C in Project Periods II, III, and IV, respectively (Figure 3a). In the case of the future monthly precipitation, the average value of the monthly precipitations was expected to increase by 4.6, 6.3, 18.9, and 11.7% in Project Periods I, II, III, and IV, respectively, compared to the present level (Figure 3b).
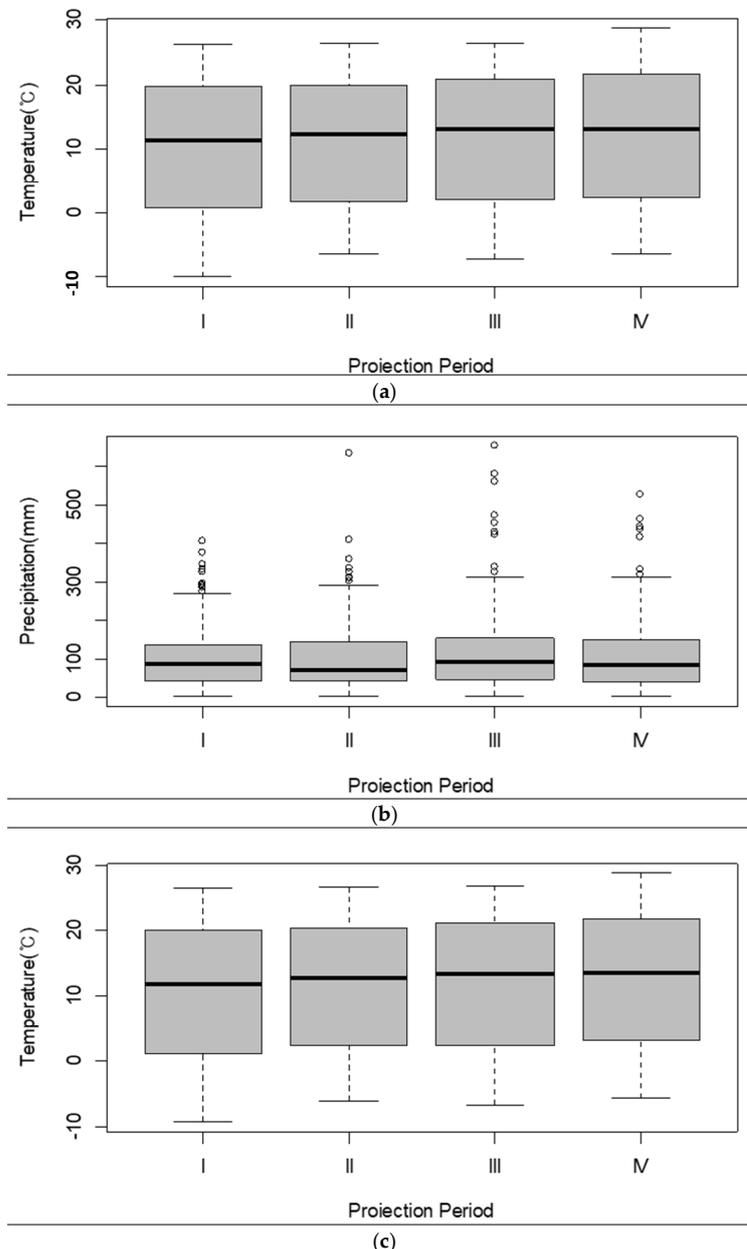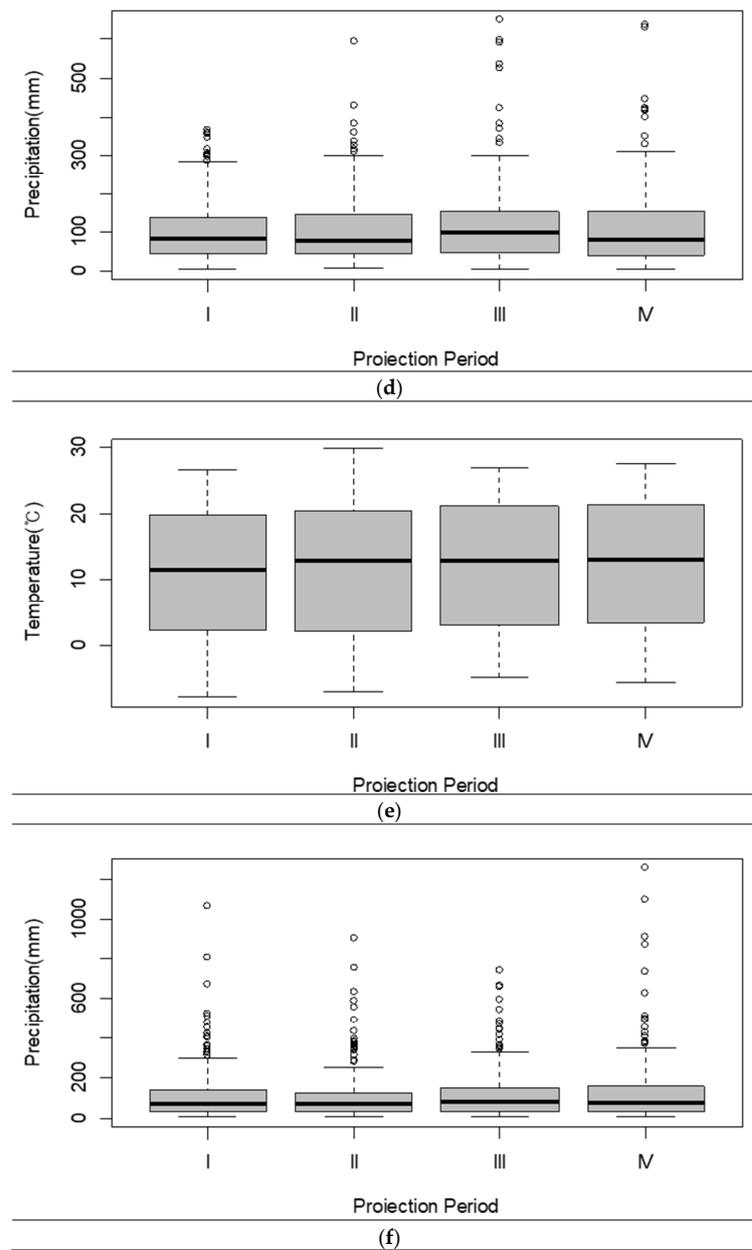

(**a**)

(**b**)

(**c**)

Figure 3. *Cont.*

(d)

(e)

(f)

Figure 3. Changes in future monthly average temperatures and monthly precipitations. (**a**) Monthly average temperature (Jeongseon basin), (**b**) monthly precipitation (Jeongseon basin), (**c**) monthly average temperature (Saigokcheon junction basin), (**d**) monthly precipitation (Saigokcheon junction basin), (**e**) monthly average temperature (Socheon streamflow station basin), (**f**) monthly precipitation (Socheon streamflow station basin).

When the average value of the future monthly average temperatures was compared with that of the data during the observation period (2008–2017) for the Saigokcheon junction basin, it was found to decrease by 0.7 and 0.1 °C in Project Periods I and II but increase by 0.5 and 0.8 °C in Project Periods III and IV (Figure 3c). In the case of the future monthly precipitation, the average value of the monthly precipitations was expected to increase by 5.2%, 6.1%, 19.0%, and 13.7% in Project Periods I, II, III, and IV, respectively, compared to the present level (Figure 3d). When the average value of the future monthly average temperatures was compared with that of the data during the observation period (2008–2017) for the Socheon streamflow station basin, it was found to increase by 1.0, 1.6, 2.1, and 2.3 °C in Project Periods I, II, III, and IV, respectively (Figure 3e). In the case of the future monthly precipitation, the average value of the monthly precipitations was expected

to increase by 27.6%, 22.4%, 35.6%, and 47.2% in Project Periods I, II, III, and IV, respectively, compared to the present level, indicating that the future precipitation will significantly increase compared to the present level (Figure 3f).

4.2. SHP Potential Estimation under Climate Change

In this study, the method proposed by Jung et al. (2021) was applied [8], and the SHP potential was calculated using the climate change scenario data. In other words, the runoff was simulated by applying flow duration characteristics model, Kajiyama formula, and modified-TPM. In addition, the future runoff by basin was simulated by applying the MSE blending technique to the discharge simulation results.

For the future prospect in consideration of climate change, the entire period from 2021 to 2100 was divided into four periods with 20 years. Figures 4–6 show changes in annual average discharge and monthly average discharge by period for the runoff simulation results by SHP plant.

The future runoff forecast results of the Deoksong SHP plant basin show that the runoff tends to increase as the precipitation increases due to future climate change. The correlation coefficients between the monthly precipitation and runoff of each period are 0.94, 0.94, 0.96, and 0.95, respectively. In particular, the annual average runoff was simulated to be largest in Projection Period III, indicating that the meteorological data that considered climate change were reflected well in the simulation because the same pattern as the average precipitation of the Jeongseon basin was observed (Figure 4 and Table 5).
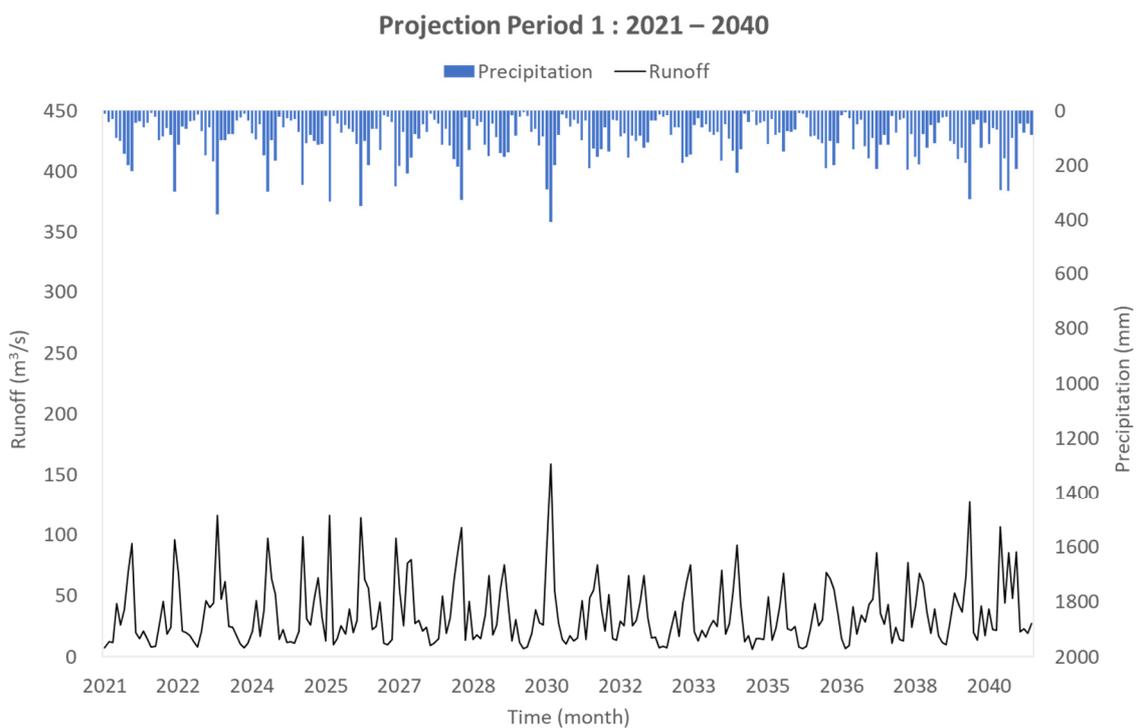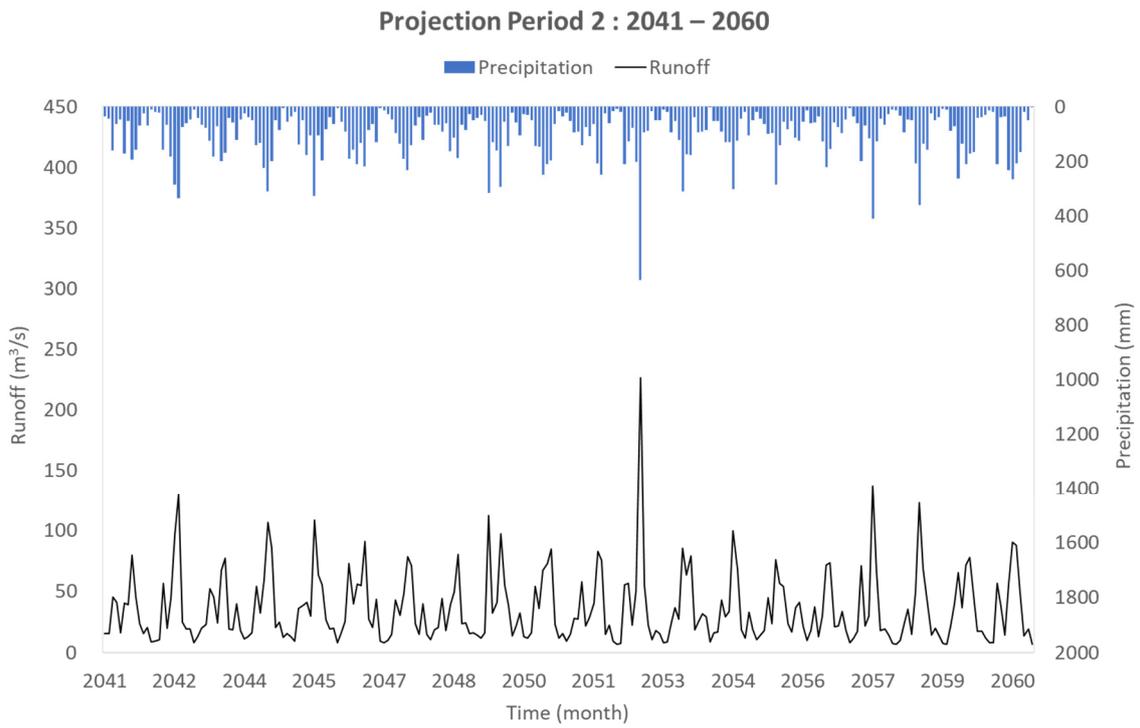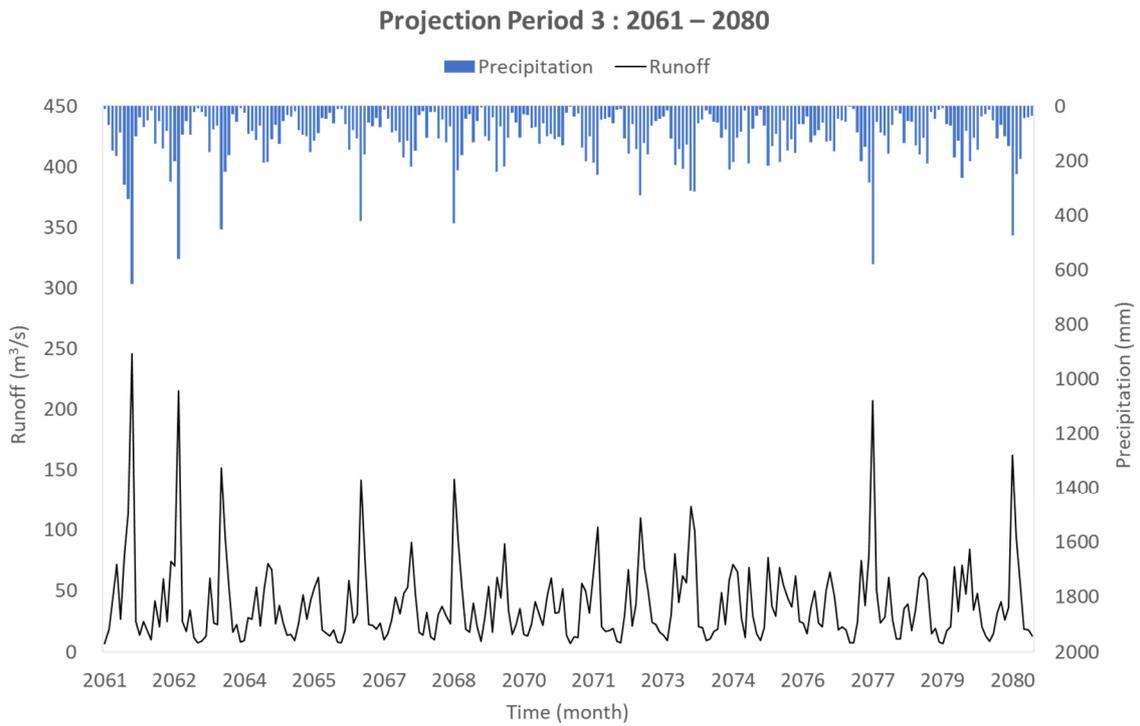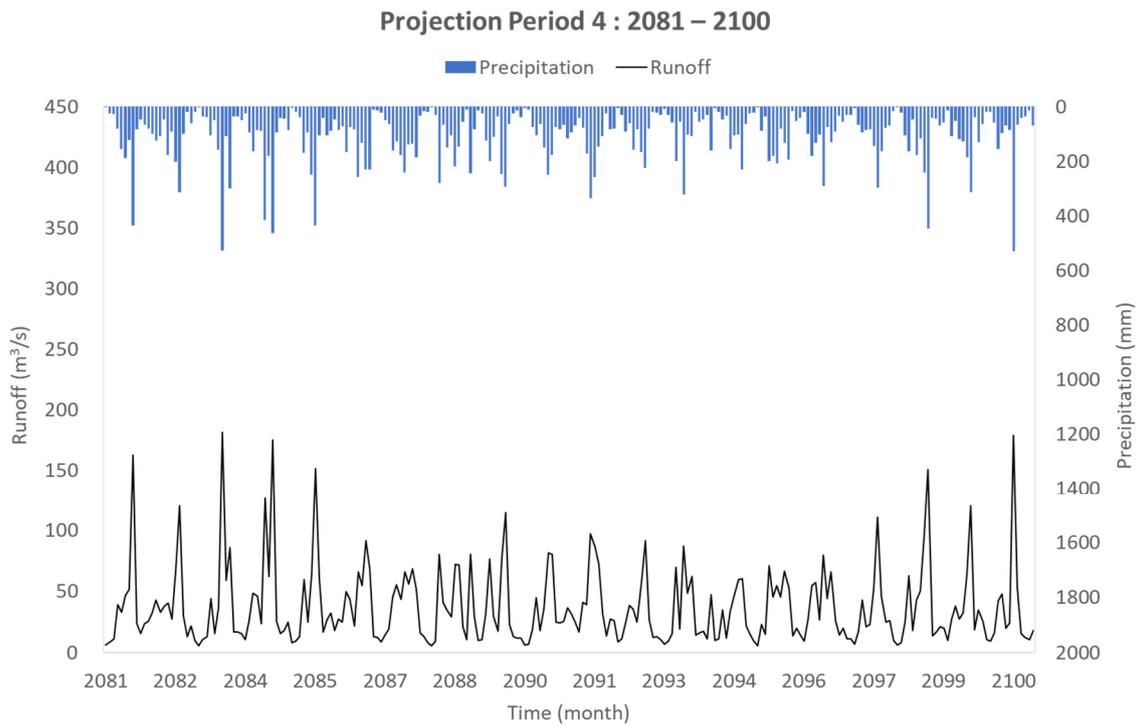

(a)

Figure 4. *Cont.*

Projection Period 2 : 2041 − 2060

(**b**)

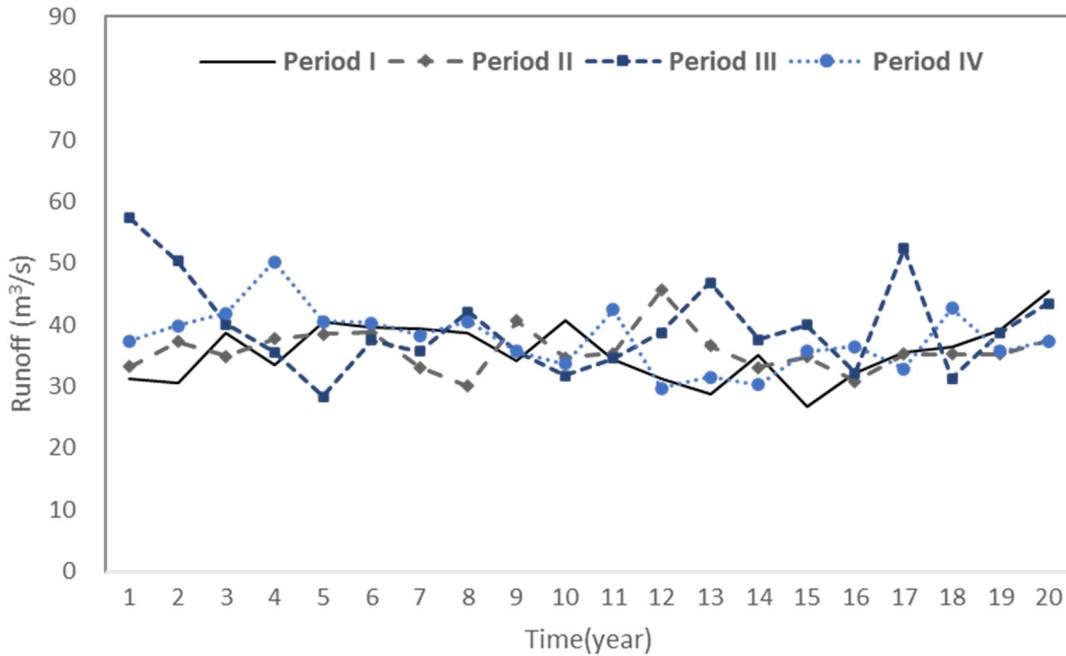**Projection Period 3 : 2061 − 2080**
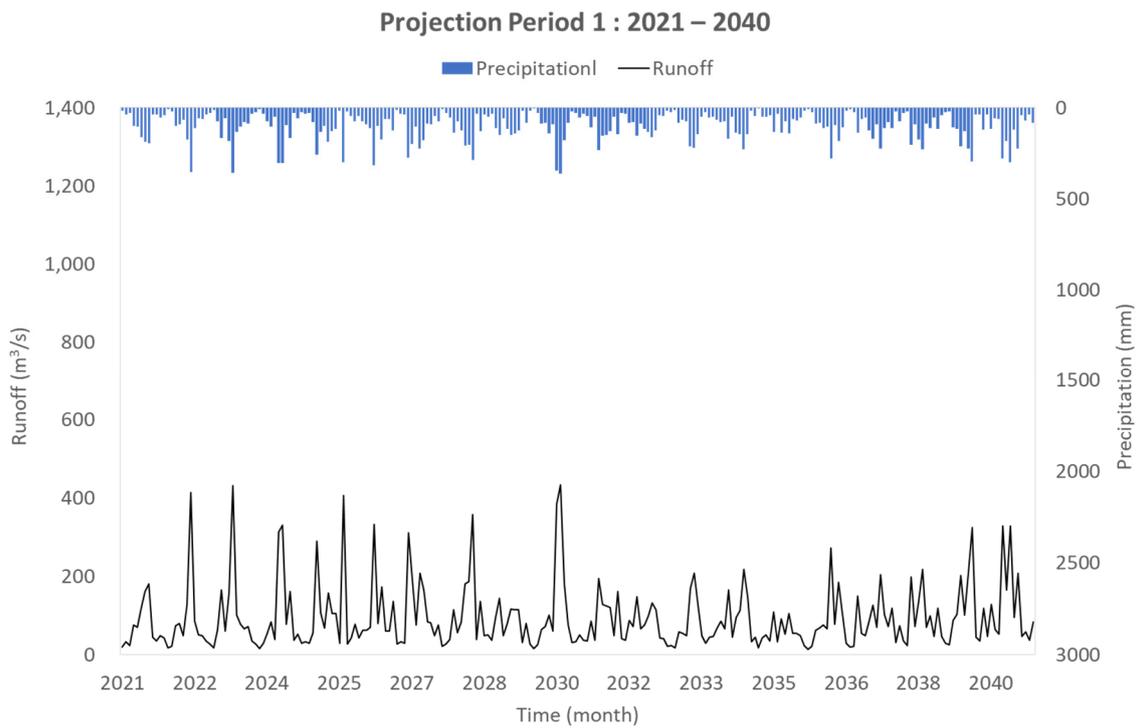

(**c**)

Figure 4. *Cont.*

(d)

(e)

Figure 4. Future discharge simulation results of the Deoksong SHP plant basin. (**a**) Monthly average discharge: Period I (2021–2040), (**b**) monthly average discharge: Period II (2041–2060), (**c**) monthly average discharge: Period III (2061–2080), (**d**) monthly average discharge: Period IV (2081–2100), (**e**) annual average discharge.

Projection Period 1 : 2021 − 2040

(**a**)

Projection Period 2 : 2041 − 2060

(**b**)

Figure 5. *Cont*.

Projection Period 3 : 2061 – 2080

(**c**)

Projection Period 4 : 2081 – 2100
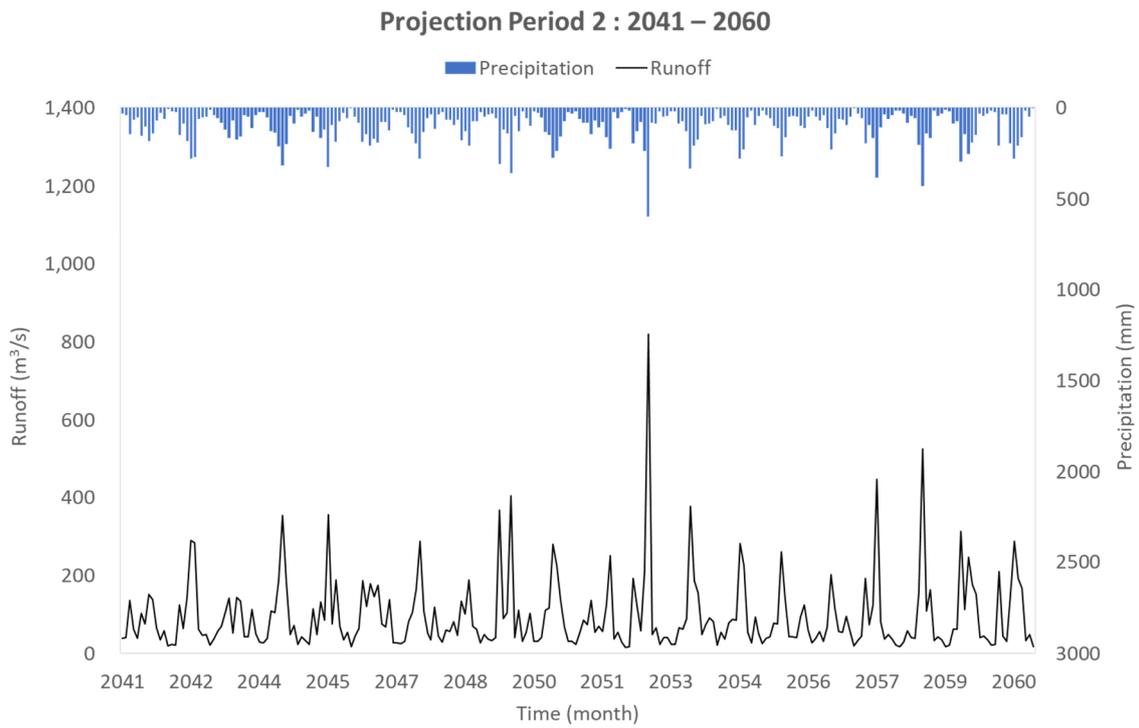

(**d**)

Figure 5. *Cont.*

(**e**)

Figure 5. Future discharge simulation results of the Hanseok SHP plant basin. (**a**) Monthly average discharge: Period I (2021–2040), (**b**) monthly average discharge: Period II (2041–2060), (**c**) monthly average discharge: Period III (2061–2080), (**d**) monthly average discharge: Period IV (2081–2100), (**e**) annual average discharge.
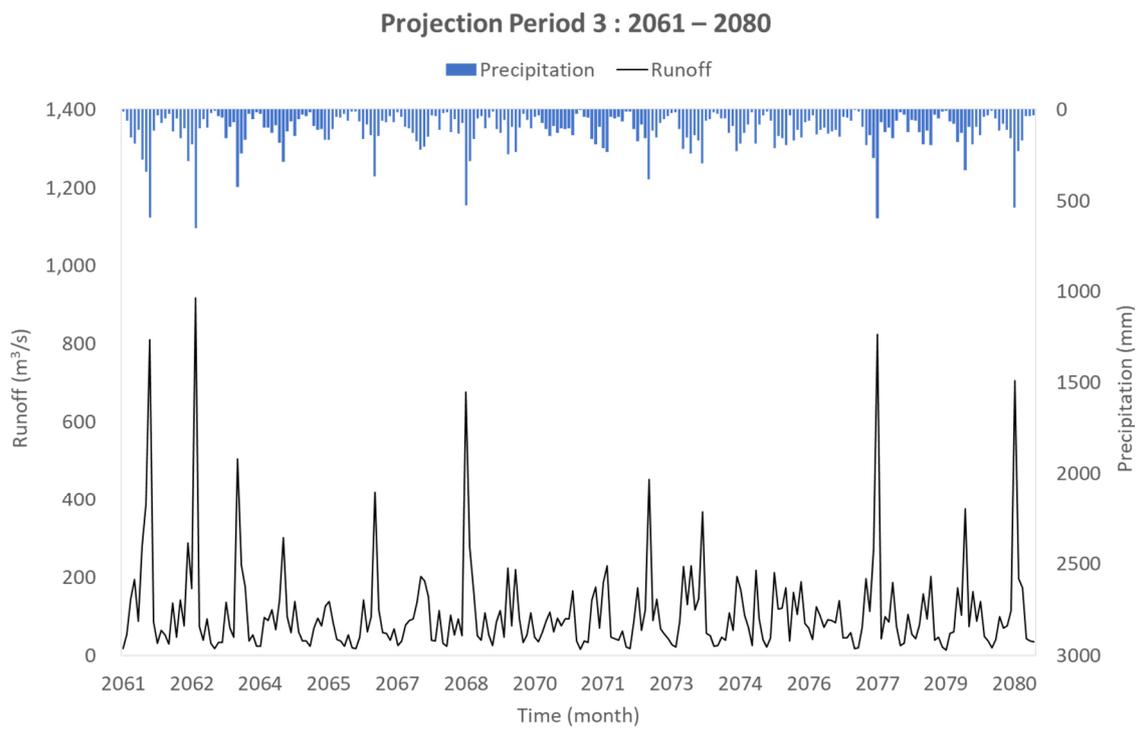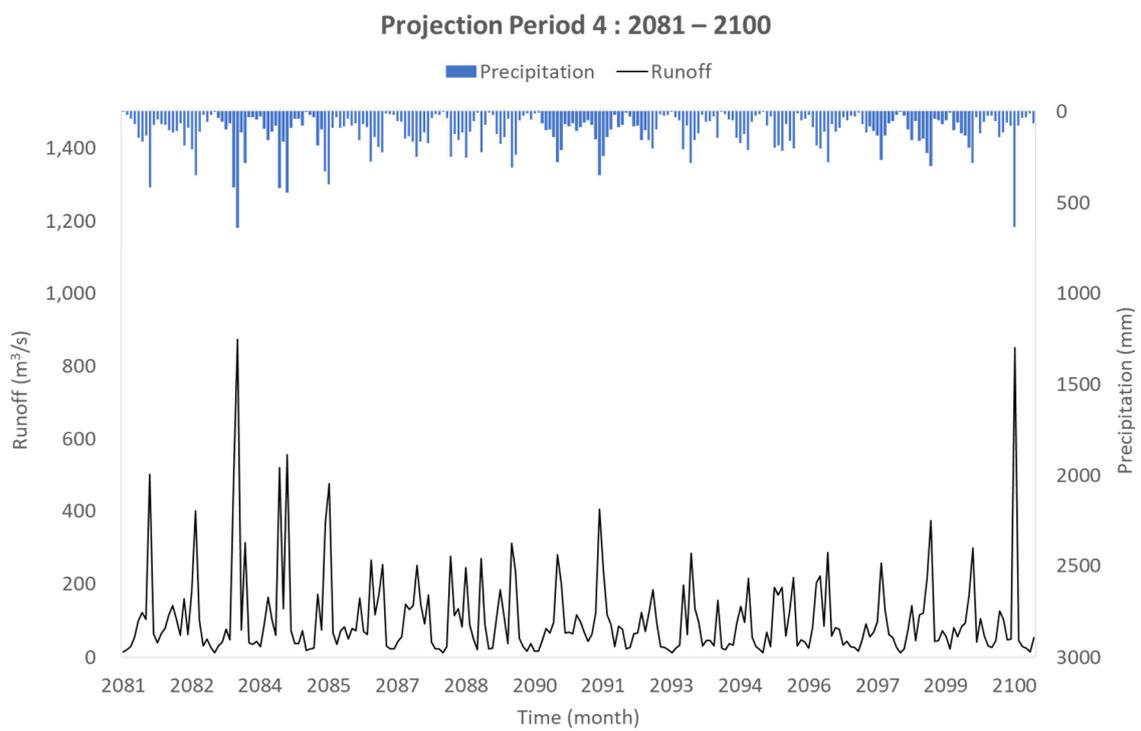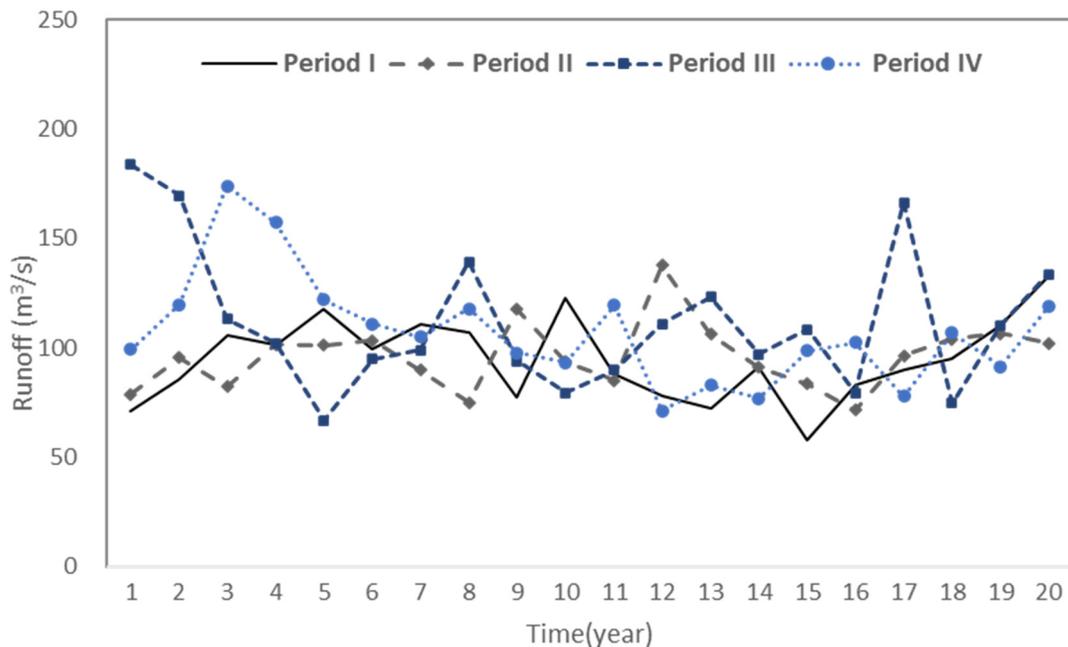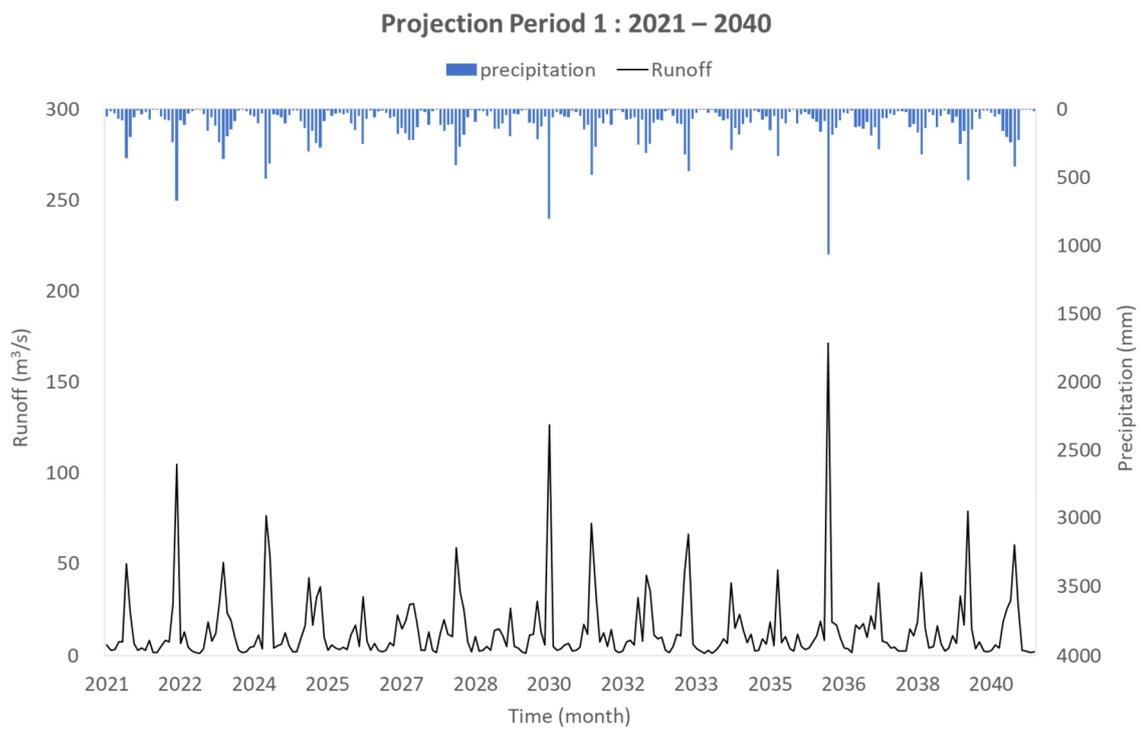
Table 5. Future runoff statistics in the Deoksong SHP plant basin [Unit: m^3/s].

Projection Period	I (2021–2040)	II (2041–2060)	III (2061–2080)	IV (2081–2100)
Mean	35.6	35.9	39.5	37.6
Standard deviation	4.7	3.5	7.5	4.9

The future runoff forecast results of the Hanseok SHP plant basin also showed that the runoff increases as the precipitation increases due to future climate change. The correlation coefficients between the monthly precipitation and runoff of each period are 0.97, 0.97, 0.97, and 0.98, respectively. In addition, the annual average runoff was simulated to be largest in Projection Period III due to the influence of the precipitation change in the Saigokcheon basin (Figure 5 and Table 6).

Table 6. Future runoff statistics in the Hanseok SHP plant basin [Unit: m^3/s].

Projection Period	I (2021–2040)	II (2041–2060)	III (2061–2080)	IV (2081–2100)
Mean	94.9	96.2	111.8	107.2
Standard deviation	19.0	15.4	32.4	25.3

Projection Period 1 : 2021 − 2040

(**a**)

Projection Period 2 : 2041 − 2060

(**b**)

Figure 6. *Cont.*

Projection Period 3 : 2061 − 2080

(**c**)

Projection Period 4 : 2081 − 2100

(**d**)

Figure 6. *Cont.*

(**e**)
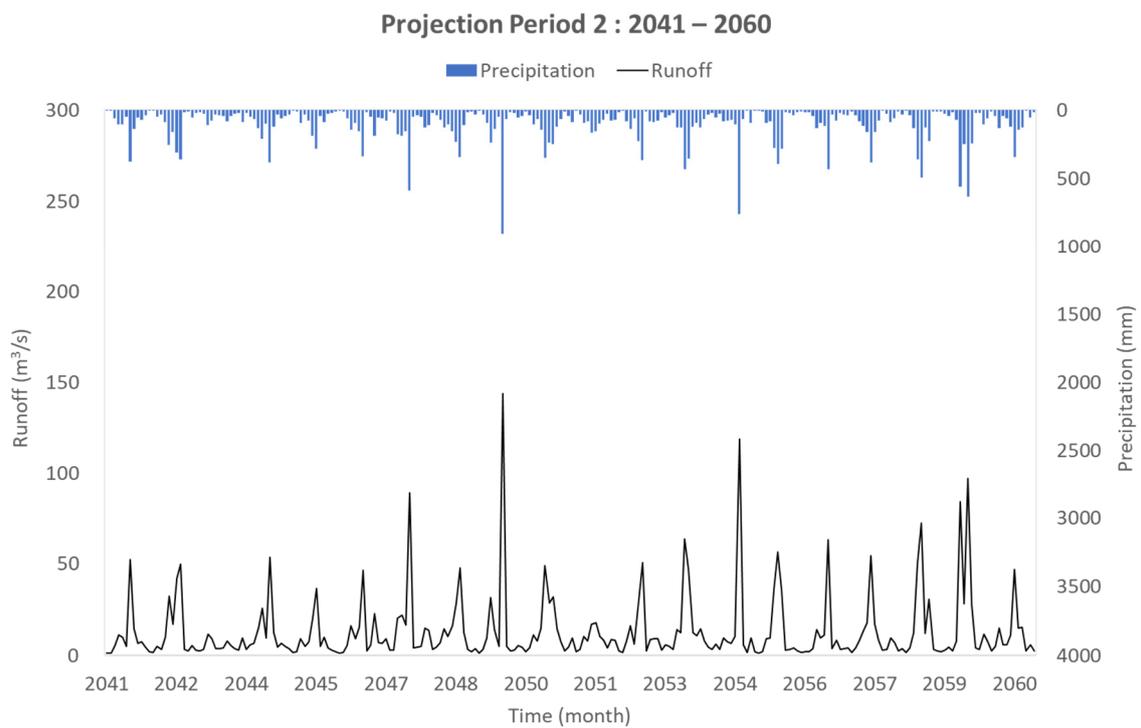
Figure 6. Future discharge simulation results of the Socheon SHP plant basin. (**a**) Monthly average discharge: Period I (2021–2040), (**b**) monthly average discharge: Period II (2041–2060), (**c**) monthly average discharge: Period III (2061–2080), (**d**) monthly average discharge: Period IV (2081–2100), (**e**) annual average discharge.
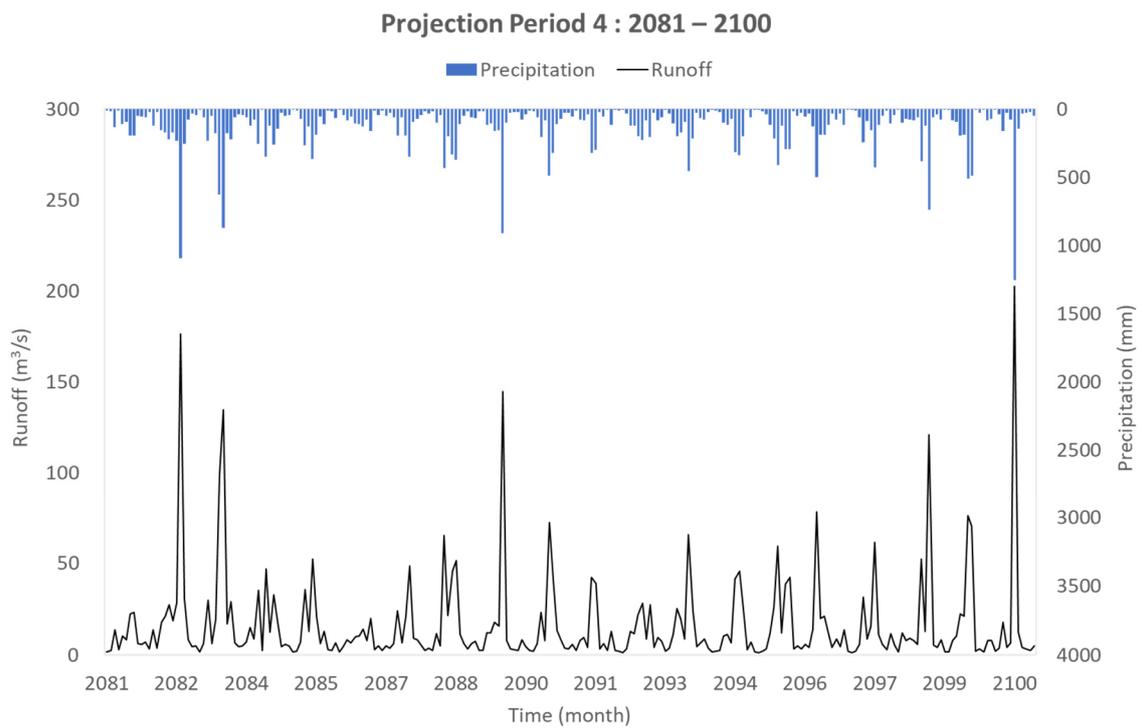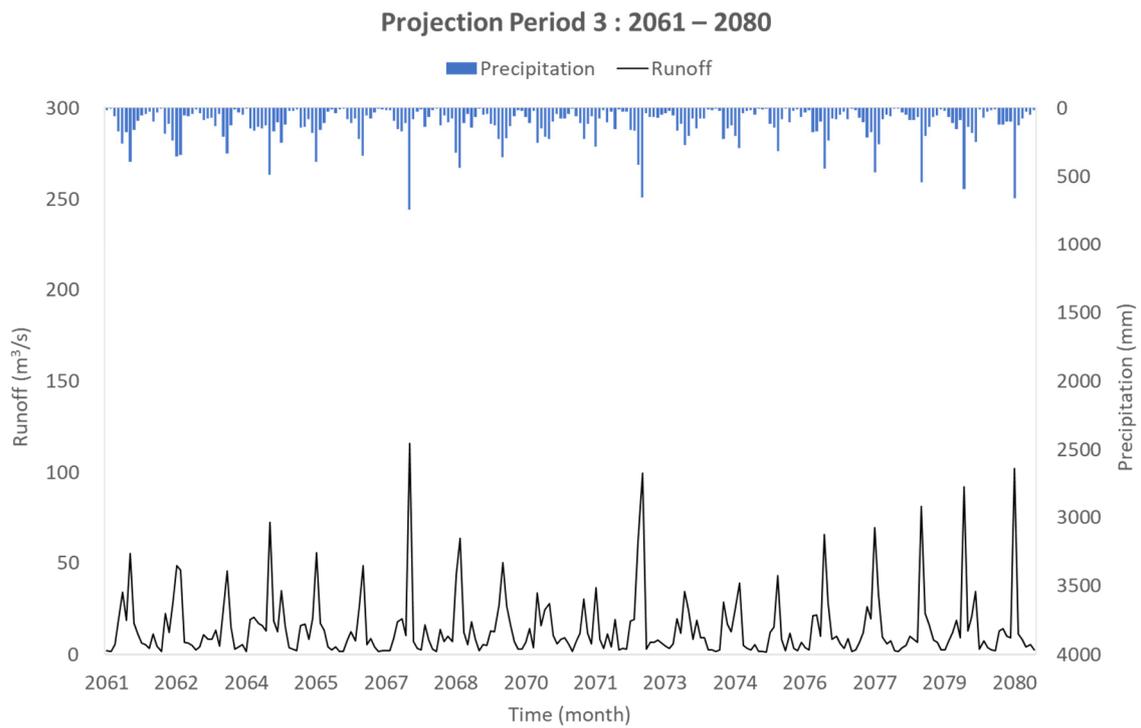
The future runoff forecast results of the Socheon SHP plant basin also showed that the runoff will gradually increase. The correlation coefficient between the monthly precipitation and runoff of each period are all 0.99. In particular, in Projection Period IV, the average value of the monthly average runoff increased to 16.7 and the standard deviation also significantly increased to 26.3. This indicates that the runoff will increase in the same pattern as the increase in precipitation due to the influence of climate change (Figure 6 and Table 7).

Table 7. Future runoff statistics in the Socheon SHP plant basin, [Unit: m^3/s].

Projection Period	I (2021–2040)	II (2041–2060)	III (2061–2080)	IV (2081–2100)
Mean	14.0	13.4	14.8	16.7
Standard deviation	3.5	4.0	3.0	5.9

The time series of runoff were analyzed by applying the RAPS method. The time data series of the RAPS for monthly runoff by period are as shown in Figure 7. The red dotted lines indicate the inflection points where time series could be divided into possible subseries. In Period I, it was shown that the RAPS values of Deoksong and Hanseok increased from 2021 and decreased from 2030–2031 to 2036–2037 (Figure 7a). In Period II, it was shown that the RAPS values of Socheon decreased from 2041 to 2047–2048 and increased until 2060 (Figure 7b). In Period III, it was shown that the RAPS values of Deoksong and Hanseok increased until 2062–2063 and decreased until 2080 (Figure 7c). In Period IV, it was shown that the RAPS values of Deoksong and Hanseok increased until 2085–2086 and decreased from 2091–2092 until 2100, and the RAPS values of Socheon also increased until 2085–2086 and decreased until 2098–2099 (Figure 7d). Deoksong and Hanseok showed almost the same pattern of RAPS values, while RAPS of Socheon had low fluctuation. It can be concluded that this is because both Deoksong and Hanseok are adjacent to each other and are affected by the Yeongwol rainfall station.
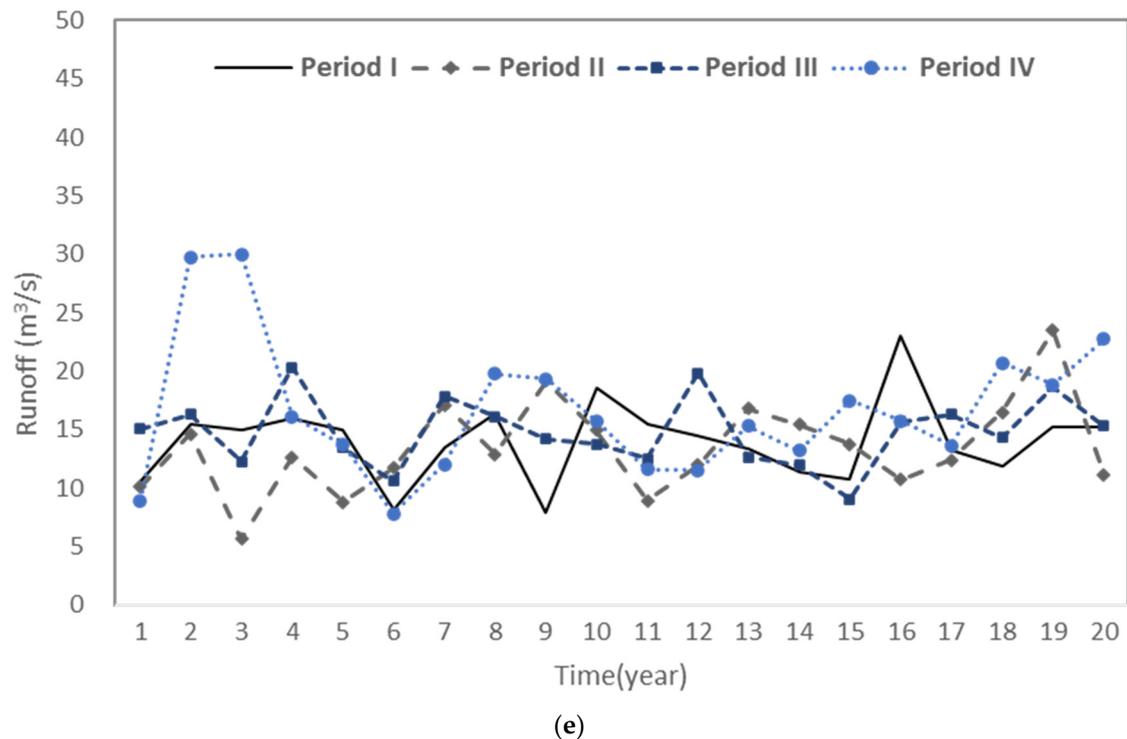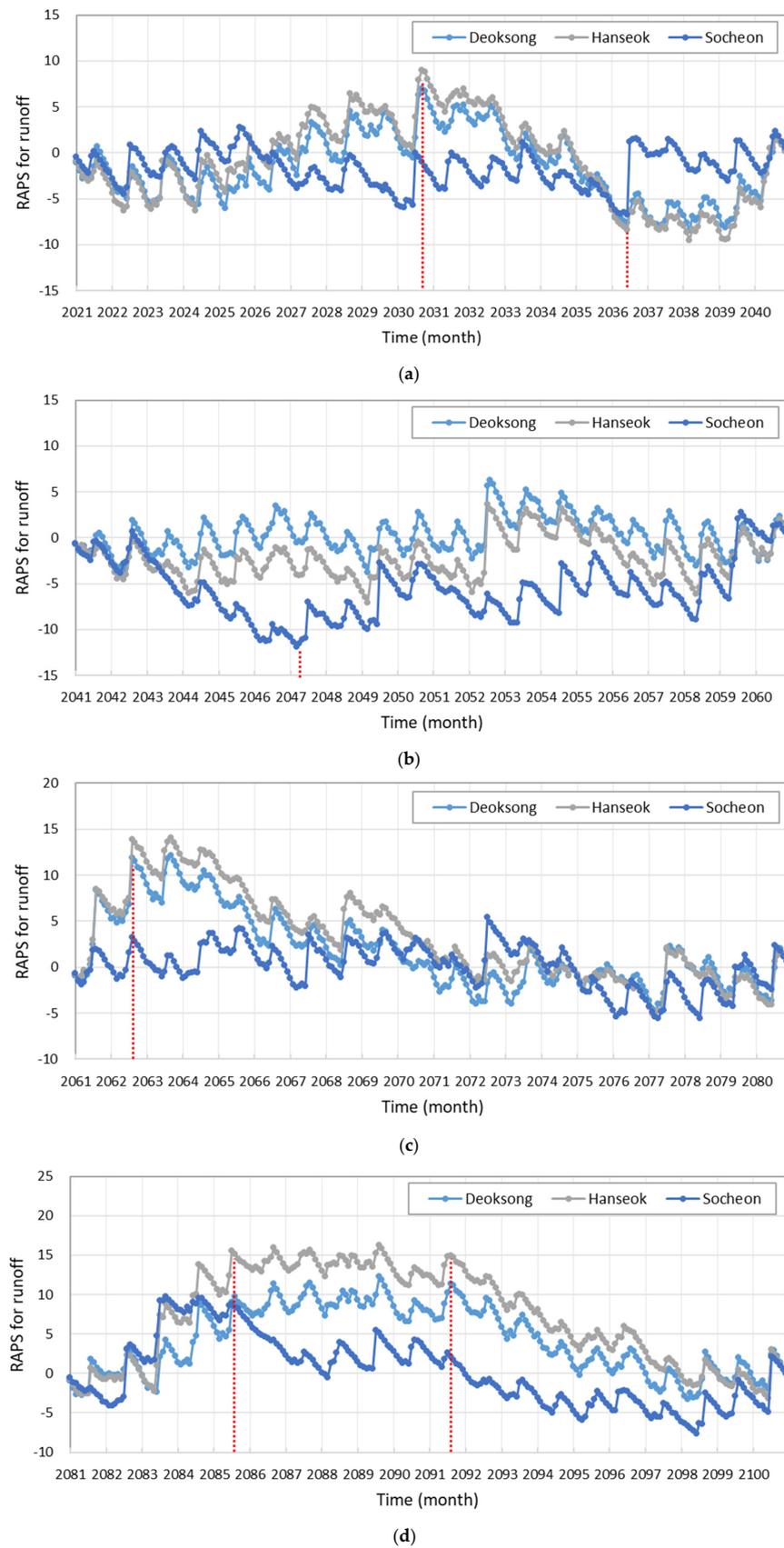
Figure 7. Future discharge simulation results of the Socheon SHP plant basin. (**a**) Monthly average discharge: Period I (2021–2040), (**b**) monthly average discharge: Period II (2041–2060), (**c**) monthly average discharge: Period III (2061–2080), (**d**) monthly average discharge: Period IV (2081–2100).

The future runoff change in each basin under climate change was analyzed. Based on the results, the SHP potential of each plant was calculated. In this instance, the plants were assumed to operate until 2100 for the analysis even though the average lifespan of SHP plants is approximately 50 years. Table 8 shows the results of estimating the annual SHP potential of each SHP plant.

Table 8. Estimated annual SHP potential by SHP plant (2021–2100) [unit: MWh].

Year	Deoksong	Hanseok	Socheon	Year	Deoksong	Hanseok	Socheon
2021	9261	7847	6451	2061	10,361	20,363	8216
2022	9336	9490	6422	2062	10,419	18,722	8369
2023	10,348	11,661	8534	2063	8985	12,529	8201
2024	9305	11,178	7109	2064	10,751	11,293	10,864
2025	9841	12,889	8201	2065	9591	7385	8272
2026	11,140	10,997	6236	2066	9853	10,543	6496
2027	10,409	12,232	9091	2067	10,313	10,937	7929
2028	9442	11,816	9103	2068	10,384	15,513	8779
2029	10,172	8556	6489	2069	10,432	10,388	8365
2030	9532	13,655	7608	2070	10,518	8755	9311
2031	10,001	9708	8220	2071	9328	9961	8553
2032	10,260	8556	8509	2072	10,172	12,288	7441
2033	9196	8021	6151	2073	10,050	13,550	8726
2034	10,231	9997	8044	2074	10,337	10,682	7117
2035	9499	6388	7363	2075	10,931	11,948	6301
2036	9549	9183	8479	2076	10,739	8783	8576
2037	10,686	9870	9207	2077	10,655	18,440	8199
2038	10,629	10,433	8020	2078	9345	8233	7448
2039	10,053	12,253	7541	2079	10,226	12,127	8963
2040	11,443	14,635	7084	2080	10,051	14,859	7752
2041	10,383	8690	6672	2081	9698	11,038	7173
2042	8886	10,567	7027	2082	10,876	13,244	10,213
2043	10,564	9075	5670	2083	8876	19,216	8811
2044	9708	11,263	7978	2084	10,825	17,352	8957
2045	10,635	11,236	6143	2085	9755	13,475	7664
2046	10,263	11,370	7476	2086	10,318	12,181	7083
2047	9546	9944	8663	2087	9953	11,566	7340
2048	10,036	8304	8150	2088	9986	13,062	8604
2049	10,266	12,985	6477	2089	9022	10,848	7649
2050	9141	10,326	8551	2090	10,097	10,358	7426
2051	10,443	9319	8166	2091	11,325	13,143	6817
2052	9250	15,317	7344	2092	9364	7887	8171
2053	10,535	11,731	9354	2093	8506	9095	8321
2054	9753	10,083	6516	2094	9303	8493	6964
2055	10,417	9198	6217	2095	9759	10,829	7762
2056	10,105	7949	6394	2096	10,320	11,258	8694
2057	8827	10,677	7989	2097	9738	8606	7690
2058	9229	11,525	6827	2098	9501	11,779	8284
2059	9473	11,832	7898	2099	10,485	10,178	7260
2060	8941	11,324	7675	2100	9151	13,214	6501

4.3. Analysis of the Variability of SHP Potential under Climate Change

The variability of SHP potential under climate change was analyzed. First, the annual SHP potential forecast results of the Deoksong SHP plant showed that the power generation potential tends to increase during the entire projection period. When the variability was analyzed for each future projection period, the annual potential was expected to increase by 1776, 1580, 1931, and 1603 MWh in Projection Periods I, II, III, and IV, respectively, compared to the present level (Table 9).

Table 9. Analysis of the variability of annual SHP potential by SHP plant [unit: MWh].

SHP Plant	Period			Average Annual Potential	Variation Compared to the Present Level
Deoksong	Present		2008–2017	8241	-
	Future	I	2021–2040	10,017	1776 (↑21.6%)
		II	2041–2060	9820	1580 (↑19.2%)
		III	2061–2080	10,172	1931 (↑23.4%)
		IV	2081–2100	9843	1603 (↑19.4%)
Hanseok	Present		2008–2017	10,645	-
	Future	I	2021–2040	10,468	−176 (↓1.7%)
		II	2041–2060	10,636	−9 (↓0.1%)
		III	2061–2080	12,365	1720 (↑16.2%)
		IV	2081–2100	11,841	1197 (↑11.2%)
Socheon	Present		2008–2017	7208	-
	Future	I	2021–2040	7693	485 (↑6.7%)
		II	2041–2060	7359	151 (↑2.1%)
		III	2061–2080	8194	986 (↑13.7%)
		IV	2081–2100	7869	661 (↑9.2%)

In the case of the Hanseok SHP plant, the annual SHP potential showed a tendency to increase during the projection period. When the average annual potential was estimated for each projection period and compared with that of the current period, the annual potential was expected to slightly decrease by 176 and 9 MWh in Projection Periods I and II, respectively, but increase by 1720 and 1197 MWh in Projection Periods III and IV, respectively, compared to the present level (Table 9).

The annual SHP potential forecast results of the Socheon SHP plant showed that the potential tends to increase noticeably over time. Compared to the present level, the annual potential was expected to increase by 485, 151, 986, and 661 MWh in Projection Periods I, II, III, and IV, respectively (Table 9).

When the annual SHP potential was forecasted during the period from 2012 to 2100 by applying the climate change scenario, it was expected to significantly increase for all three target SHP plants compared to the present level. This appears to be due to the influence of the increase in discharge caused by climate change.

5. Discussion and Conclusions

The IPCC has presented the pathway required to limit the global average temperature rise to within 1.5 °C by 2100. To attain this target and to achieve a net-zero rise by 2050, it is necessary that carbon dioxide emissions are reduced globally by at least 45% compared to 2010 by 2030. All participating countries, including Korea, have submitted their Nationally Determined Contribution (NDC) and agreed to achieve a global average temperature rise below 1.5 °C. SHP generation is clean because it does not generate GHG emissions. The technological development and investment effectiveness of SHP are also competitive in comparison with other renewable energy sources. SHP is becoming increasingly important worldwide as we simultaneously face climate change and resource crises, with the latter represented by high oil prices. Korea has a relatively large amount of precipitation and is composed of mountainous area in most parts of the country; SHP can thus be developed using various methods. Therefore, the accurate determination and projection of SHP potential should be investigated. The market supply should also be expanded through technological development. In this study, the future SHP potential under climate change was predicted using the method proposed in a previous part of this serial study. The SHP potential from 2021 to 2100 was calculated using RCP 4.5 climate change scenario data. Many studies have been conducted on the estimated potential and prospection for SHP, but not for ungauged basins. This serial study suggests a method that can accurately estimate

SHP potential by applying four discharge estimation methods and a blending technique to minimize uncertainty. This method can be applied to ungauged basins and for the future.

It is expected that the potential for SHP generation by the three target SHP plants will be increased considering climate change. Findings of the present study indicate that the SHP potential for the near future (2021–2040) tended to decrease slightly compared to the present potential at the Hanseok SHP plant; however, the overall trend exhibited an increase by a maximum of 21.6%. This escalation appears to be based on the increase in precipitation and discharge under the influence of climate change. Previous studies on SHP potential projection using climate change scenarios demonstrated similar results, with a likely increase in precipitation. Nonetheless, it is difficult to forecast the severity of climate change for the projection periods III and IV (2061–2100). Because of the uncertainty, it is desirable to focus on the SHP potential during the first two periods and assess the tendency of the SHP potential during the last two periods. For future work, the long-term simulation of river dynamics through computational fluid dynamics (CFD) or cellular automata could also improve the forecasting of SHP potential.

The results suggested that the discharge and hydropower potential would increase with climate change. However, the design discharge (the maximum discharge that can contribute to generating energy) was considered for the calculation of the SHP potential in this study. The river discharge exceeding the design discharge did not contribute to the calculation of the potential; thus, only the design discharge amount was calculated. Therefore, if the theoretical potential is calculated considering only the increase in discharge caused by climate change without considering the existing design discharge, greater SHP potential can be used. This indicates that for future SHP plant design, the hydropower generated can be efficiently used if the design discharge is calculated to exceed the discharge increased by climate change.

The validity of the suggested method was assessed in this study by assuming that the gauged basins of the three hydropower plants of Deoksong, Hanseok, and Socheon were ungauged. This method can estimate the SHP potential of ungauged basins based purely on precipitation data, both in domestic (Korean) and overseas regions in the future. However, a limitation of the study was that we did not assess the variation in conditions in SHP plants. We considered discharge to be the most important factor for calculating SHP potential; thus, the plants' lifespan, operation rate, and other conditions that may be altered in the future by climate change were ignored. Therefore, for long-term implementation, relatively minor factors need to be considered. The Sixth Assessment Report (AR6) of the IPCC and the CMIP6 climate change scenario data have also been used to validate many recent studies. Ongoing work may be based on new scenarios from CMIP6 models, and up-to-date scenarios may improve the accuracy of projecting SHP generation potential.

In conclusion, the applicability of the suggested method for estimating SHP potential in an ungauged basin in which no measured discharge data exists was confirmed in this study; subsequently, it was applied to assess future SHP potential. The results of this study are expected to be used as a procedure for calculating the existing SHP potential and for the planning of SHP plants in the future. If the capacity of future facilities is accurately calculated based on the energy potential based on the method applied in this study, it will be possible to minimize the initial loss of facility investment and maintenance costs. The results are also expected to play an important role in supporting decision-making when energy policies are developed in corresponding areas.

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