

## Article

# Impact Assessment of Climate Change on the Near and the Far Future Streamflow in the Bocheongcheon Basin of Geumgang River, South Korea

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**Abstract:** Highly concentrated precipitation during the rainy season poses challenges to the South Korean water resources management in efficiently storing and redistributing water resources. Under the new climate regime, water resources management is likely to become more challenging with regards to water-related disaster risk and deterioration of water quality. To alleviate such issues by adjusting management plans, this study examined the impact of climate change on the streamflow in the Bocheongcheon basin of the Geumgang river. A globally accepted hydrologic model, the HEC-HMS model, was chosen for the simulation. By the calibration and the validation processes, the model performance was evaluated to range between “satisfactory” and “very good”. The calibrated model was then used to simulate the future streamflow over six decades from 2041 to 2100 under RCP4.5 and RCP8.5. The results indicated significant increase in the future streamflow of the study site in all months and seasons over the simulation period. Intensification of seasonal differences and fluctuations was projected under RCP 8.5, implying a challenge for water resources managers to secure stable sources of clean water and to prevent water-related disasters. The analysis of the simulation results was applied to suggest possible local adaptive water resources management policy.

**Keywords:** hydrologic modeling; climate change impact assessment; water resource management



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## 1. Introduction

South Korea demonstrates a strong seasonality: 55.3% of its average annual rainfall (723.2 mm of 1307.7 mm) in the 30 year period between 1981 and 2010 was concentrated in the summer season, from June to August [1,2]. To cope with such seasonality, water resources in Korea are generally stored in reservoirs created behind dams during the rainy season and used during the dry season. However, if the reservoirs are insufficiently filled due to below average precipitation in a given rainy season, water shortages or droughts may occur in the following year [3]. In contrast, if precipitation increases compared to the average or if the rainy season is prolonged, serious flooding may occur in the downstream regions.

Such difficulties in domestic water resource management resulting from the seasonality are projected to be exacerbated under the changing climate [4–10]. Notably, increase in the annual rainfall (+54.28 mm/10 years) was observed in the 30 year period from 1981 to 2010 in South Korea, attributed especially to the summer rainy season accompanied by torrential rain [1]. According to the Korea Meteorological Administration, the summer rainy season in 2020 started on June 24 and ended on August 16, which was the longest rainy season on record since 1973 [11]. During this period, multiple extreme events of torrential rains (87 and 79 mm per hour in Busan and Daejeon metropolitan cities, respectively) were observed under the influence of the typhoon “rose”. According to the National Assembly Budget Office, 88.4% of the annual damage cost from natural disasters in South Korea is

attributed to typhoons and heavy rains, as those observed in 2020. Thus, the mitigation of damage against such water-related natural disasters is the main target of national disaster reduction policies [12].

Several studies highlighted the insufficient and unsustainable nature of establishing future water resource management plans and disaster reduction policies based on the recorded hydrologic conditions of the recent past [13,14]. Instead, to predict the likelihood and the magnitude of natural disasters along with the impact of climate change on the availability of water resources, researchers should primarily conduct simulations of streamflow, which is likely to increase due to continuous or extreme rainfall in the future [15–20].

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is a commonly used watershed model to simulate streamflow or rainfall runoff processes. The HEC-HMS was used in several studies in various regions with different climatic and geographic conditions [21–26]. It was evaluated to be spatially and temporally accurate in predicting the watershed responses in event-based and continuous simulation as well as in simulating various scenarios in flood forecasting [27,28] and watershed management [29–31].

The objective of this study was to simulate and detect trends in the changes in future streamflow over the six decades from 2041 to 2100 under RCP4.5 and RCP8.5, using the HEC-HMS model. The model performance was proven effective by calibration and validation processes using two statistical measures of *NSE* and  $R^2$ . Simulations were run over a 60 year period to consider the cumulative effect of continuous rainfall in simulation results rather than a single rainfall event and to reflect changes in trend over a long period. With further analysis of the results from the simulations, sustainable adaptive management strategies are suggested to cope with climate change impacts. Among various climate change responses such as introducing dam operation rules, increasing the storage, diversifying water resources by water recycling, and improving water transportability from water-rich to water-poor regions [32–34], site-specific measures that are more in line with the simulation results are suggested for water resources managers of the Bocheongcheon basin of the Geumgang river.

## 2. Materials and Methods

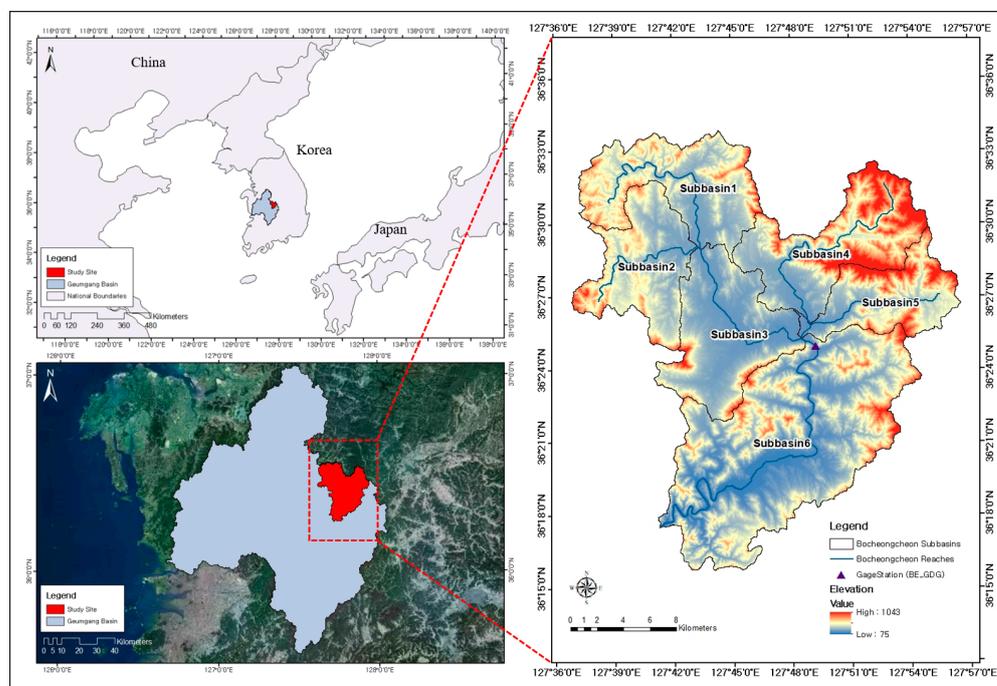
### 2.1. Study Area

The Bocheongcheon Basin, the target site for this study, is one of the 14 mid-sized sub-basins of the Geumgang River watershed, which is one of the four major rivers in Korea (Figure 1). The area of the Bocheongcheon basin is approximately 553.6 km<sup>2</sup>, accounting for approximately 5.6% of the total area of the Geumgang River watershed (9914 km<sup>2</sup>). The Gidaeyo gage station, which is located within the basin, recorded the average outflow of 11.31 m<sup>3</sup>/s and the maximum outflow of 308 m<sup>3</sup>/s in 2020. The basin spreads over four administrative districts: Boeun-gun, Okcheon-gun, Yeongdong-gun, and Sangju-si. Okcheon-gun was one of the most affected areas during the long rainy season in the summer of 2020, and the magnitude of damage caused by climate change is forecasted to worsen in the future [11].

This study site is also important because Daecheong Lake, located downstream of the sub-basin, constantly experiences problems with water quality due to excessive pollutants flowing in from the upstream region. As the deteriorating water quality was identified as a persisting issue to be tackled to secure a drinking water source for the nearby population [35,36], there is need for simulations of rainfall runoff in the Bocheongcheon Basin.

The simulation results of future streamflow in the Bocheongcheon Basin can serve as essential information guiding decision makers in establishing adaptive measures against the aforementioned water-related disasters and water quality issues in the nearby regions, especially the downstream sub-basins. Many past studies suggested management methods based on the simulations of the downstream regions near Daecheong Lake, where larger populations reside [16,37,38]. However, without considering the hydrologic cycle in the

upstream regions, such management methods have failed to prevent those issues from reoccurring. This study aims to suggest alternative measures by analyzing the simulation results of Bocheongcheon in comparison to those of other studies that focused on the downstream regions.



**Figure 1.** Location of the Bocheongcheon Basin of Geumgang, South Korea.

## 2.2. HEC-HMS Model

The HEC-HMS model was developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) to simulate the complete hydrological processes of dendritic watershed systems. It provides supplementary analysis tools for model optimization and forecasting streamflow in addition to the traditional hydrologic analysis procedures, such as event infiltration, unit hydrographs, and hydrologic routing [39].

The HEC-HMS model represents a watershed with a combination of primary hydrologic elements. A sub-basin is an individual physical watershed with an outflow hydrograph at its outlet. A reach derives the outflow at the downstream end from the inflow at the upstream end. A junction is where the inflow hydrographs are combined to derive a single outflow hydrograph. A sink has inflow but no outflow. These elements are connected through the basin model, which calculates the precipitation–runoff response based on meteorological data from the meteorological model. Finally, the control specification model defines the time period and the interval of each simulation run. Each model run combined the three models (the basin model, the meteorological model, and the control specification model) to obtain the results.

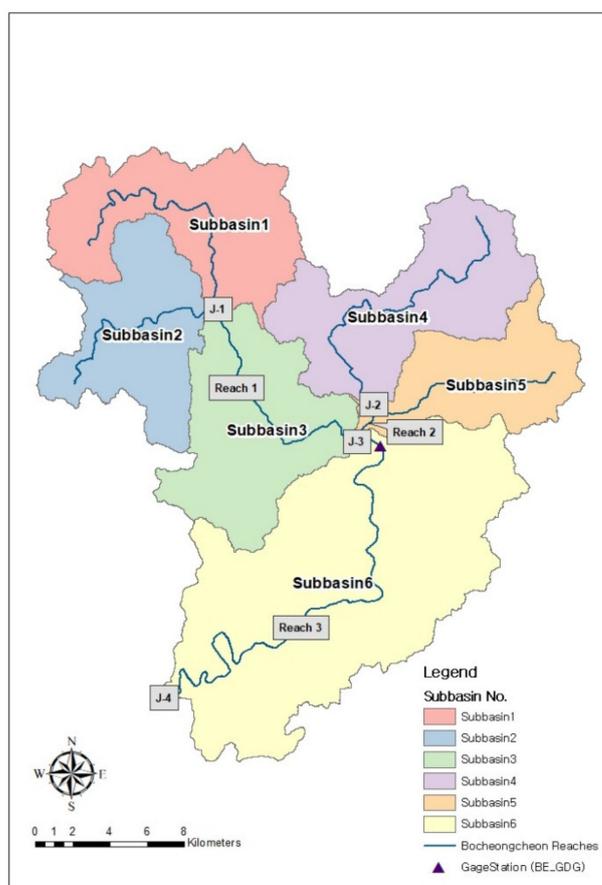
In this study, the HEC-HMS Version 4.5 was used, as it provides an optimization tool. Using the optimization tool, it is possible to derive a combination of optimal parameters for any target element upstream of the observed flow location when the observed precipitation and the discharge data are available. Seven different objective functions are available to estimate the goodness-of-fit between simulated and observed discharges [39]. This optimization tool can help researchers to overcome the issue of limited data availability.

The HEC-HMS model was chosen for use in this study over many other available hydrologic models, such as PRMS (Precipitation-Runoff Modeling System), SWAT (Soil & Water Assessment Tool), ReFH (Revitalised Flood Hydrograph), and SLURP (Semi-distributed Land Use-based Runoff Processes), because of the above-mentioned functions as

well as high modeling accuracy and easy-to-use GUI. The model suitability for simulation of rainfall runoff was confirmed by many existing studies [21,23,24,29].

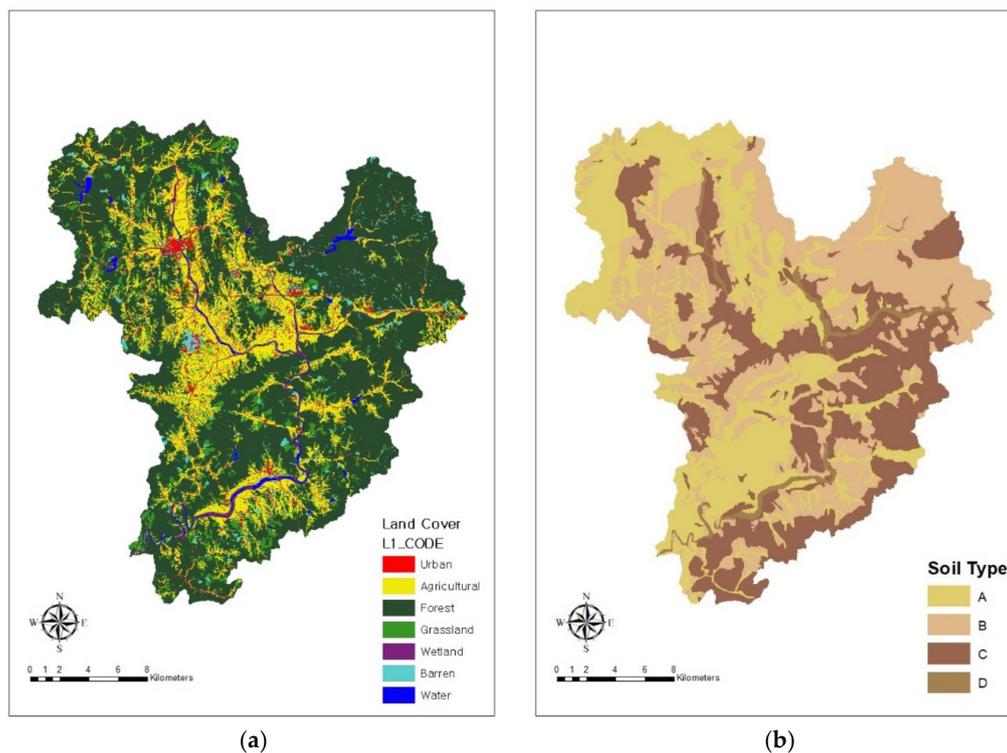
### 2.3. Model Application

For the initial setup of the HEC-HMS model for the rainfall runoff simulation, the basin model was constructed by dividing the mid-sized Bocheongcheon Basin into six smaller sub-basins based on a digital elevation model (DEM) and connecting four conjunction points with three reaches, as shown in Figure 2. For the constructed basin, appropriate methods were selected for loss, direct runoff, and routing models, and the parameter values were calculated accordingly.



**Figure 2.** Schematic diagram of the HEC-HMS model structure.

For the loss model to calculate the actual infiltration, we selected the Soil Conservation Service Curve Number (SCS-CN) method, which calculates the loss rate in the event of rainfall by determining the discharge based on soil cover, land use conditions, and preceding precipitation [40]. Using the 2019 Level 3 land cover map provided by the Ministry of Environment and the soil type map provided by the National Institute of Agricultural Sciences of South Korea (Figure 3), we calculated the area-weighted average SCS-CN and the percentage of impervious area for each sub-basin.



**Figure 3.** Physical characteristics of the Bocheongcheon Basin: (a) Level 1 land cover map (reclassified from Level 3 land cover map); and (b) soil type map.

In the direct runoff model, the effective rainfall calculated in the loss model was converted into the actual surface runoff [39]. This is the most important factor in flood hydrology analysis and is used for the transformation. For the calculation of direct runoff for each sub-basin, we adopted the Clark unit hydrograph method, which is widely used in Korea [41]. It utilizes a time–area curve built into the program to develop a translation hydrograph resulting from the precipitation. It is an objective method that synthesizes a unit hydrograph based on only two parameters: the time of concentration ( $T_c$ ) and the storage coefficient ( $K_c$ ). Among the various equations used to calculate the two parameters for each sub-basin, we used equations 1 and 2 developed by the Seokyeong University using the domestic hydrological observation data to represent the runoff characteristics of river basins in South Korea [42].

$$T_c = 0.339A^{0.282} \frac{L^{0.318}}{H^{0.078}} \quad (1)$$

$$K_c = 1.075 \frac{L^{0.472}}{A^{0.188}} T_c^{0.655} \quad (2)$$

where  $T_c$  is the maximum travel time in the sub-basin (h),  $A$  is the sub-basin area ( $\text{km}^2$ ),  $L$  is the length of the flow path (km),  $H$  is the difference in altitude or the difference between the elevation of the inflow point and that of the outflow point (m), and  $K_c$  is the storage coefficient.

The Muskingum method was used to compute the outflow hydrograph from the inflow hydrograph. This method was used to determine the extent to which the magnitude of the peak flow was reduced and the time delay while passing through a section of the river. For this, Muskingum  $K$  and  $X$  are the required parameters. Muskingum  $K$  ( $Km$ ) is defined as the travel time through the reach, and Muskingum  $X$  is the weighting between the inflow and the outflow influence [39].

The values of all parameters for each element were calculated by the aforementioned methods using the ArcGIS 10.5 program and later calibrated based on the daily observed discharge at the Boeun-gun Gidaeyo station for two years from 1 January 2007 to 31 December 2008 provided by the Korean Water Resources Management Information System.

For calibration, the conventional manual trial-and-error and HEC-HMS semi-automatic optimization methods were employed in parallel to achieve the optimal combination of parameters to derive values closest to those observed for outflow at the target conjunction point. Despite its time-consuming and labor-intensive nature, the trial-and-error method allows researchers to follow the physical meaning of the parameters defined in the models such that they remain within the realistic range [18]. Conversely, the semi-automatic optimization method built in the HEC-HMS model allows its model parameters to be calibrated on a series of single-flood events and selects the best-performing model parameter based on predefined algorithms [41]. With the goal of minimizing weaknesses and maximizing advantages of each method, a combined strategy of the two methods was adopted and applied to find the best possible set of parameters. Specifically,  $Km$  and  $X$  for the two reaches and SCS-CN,  $Tc$ , and  $Kc$  for all sub-basins were calibrated starting from the upstream to the downstream sub-basins.

Inserting the optimized parameters as the model input, we simulated the daily outflow at junction 3 for the year 2017 and validated it by comparing the results with the observed data. The discharge data of junction 3 was used for calibration and validation processes instead of the discharge data of junction 4. Although junction 4 is the point of final outflow of the sub-basin, it was evaluated to be less suitable due to the absence of a gage station nearby. However, the Boeun-gun Gidaeyo gage station near junction 3 could provide more precise data needed for the process. To evaluate the model accuracy, we considered Equations (3) and (4), which represent the Nash–Sutcliffe efficiency ( $NSE$ ) [43] and the coefficient of determination ( $R^2$ ), respectively.

$$NSE = 1 - \left[ \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O)^2} \right] \quad (3)$$

$$R^2 = \left[ \frac{\sum_{i=1}^n (O_i - O)(S_i - S)}{\sqrt{\sum_{i=1}^n (O_i - O)^2} \sqrt{\sum_{i=1}^n (S_i - S)^2}} \right]^2 \quad (4)$$

where  $O$  is the observed value, and  $S$  is the simulated value.

The two equations were chosen as many studies evaluated them as appropriate statistical performance measures for hydrological modeling [8,42,43].  $R^2$  is a standard regression method used to describe the degree of collinearity between observed and simulated data.  $NSE$  was evaluated to be good for use, especially with continuous long-term simulations and the determination of how well the model simulates trends for the concerned output response. This study adopted the evaluation criteria (Table 1) previously recommended for the two statistical performance measures for use in watershed- and field-scale hydrological modeling [44].

**Table 1.** Performance evaluation criteria for Nash–Sutcliffe efficiency (NSE) and coefficient of determination ( $R^2$ ) for the modeling of flow <sup>1</sup>.

Measure	Performance Evaluation Criteria			
	Not Satisfactory	Satisfactory	Good	Very Good
NSE	$NSE \leq 0.50$	$0.50 < NSE \leq 0.70$	$0.70 < NSE \leq 0.80$	$0.80 < NSE \leq 1$
$R^2$	$R^2 \leq 0.60$	$0.60 < R^2 \leq 0.75$	$0.75 < R^2 \leq 0.85$	$0.85 < R^2 \leq 1$

<sup>1</sup> Includes all streamflow, surface runoff, and baseflow, as appropriate.

As the final step of the study, rainfall runoff was simulated for the 60 year period from 2041 to 2100 using the daily precipitation data of the MME5s to predict the impact of climate change on the future rainfall runoff. We selected MME5s (Multi-Model Ensembles version 5) among various global and regional climate models (GCMs and RCMs), as it was suggested that the findings based on one GCM or RCM provide only a small subset of possible outcomes, indicating the necessity to use an ensemble of GCMs and/or RCMs [5]. To reduce the uncertainty of each RCM and enhance the final confidence level, MME5s was created by an ensemble of five RCMs: HadGEM3-RA (the Hadley Centre Global Environment Model version 3 for the Region of Asia), RegCM4 (the Regional Climate Model system version 4), SNURCM (the Seoul National University Regional Climate Model), GRIMs (the Global/Regional Integrated Model System), and WRF (the Weather Research and Forecasting Model). It has a fine spatial resolution of 1 km and is widely used in various studies targeting South Korea [45].

This study employed climate data created under the two RCP scenarios, RCP4.5 and RCP8.5, to compare the results based on different assumptions of greenhouse gases emitted in future years. RCP8.5 is generally considered to be the basis for the worst-case high emission scenario, whereas RCP4.5 is considered to be an intermediate mitigation scenario [46]. The difference in the simulation results of the two scenarios may serve to advocate global and national emission reduction goals.

### 3. Results

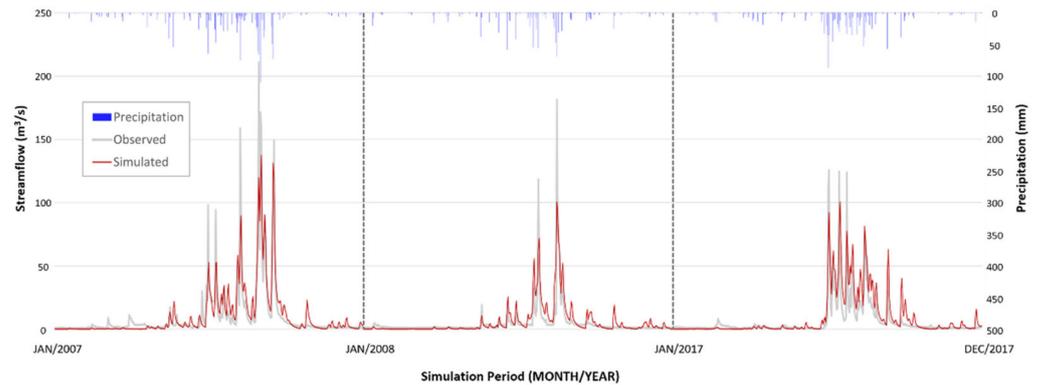
#### 3.1. Model Calibration and Validation

For calibration, we tested all objective functions of the models and found that the functions of the “sum of squared residuals” and the “mean of squared residuals” performed most efficiently in terms of the parameter optimization, judged based on NSE. Conversely, the available functions of the “peak-weighted RMSE” or the “percent error in peak discharge” did not perform well in this study. A reason for this could be that the evaluation of the optimization result was based on the discharge volume, not the peak discharge. Considering simulations for shorter time periods, the functions based on a statistic of peak discharge may be more appropriate for use. The results of the parameterization are presented in Table 2.

**Table 2.** Final calibrated model parameters.

Element	Model Parameters				
	SCS-CN	K	Tc	Muskingum K	Muskingum X
Sub-basin 1	42.406	2203	1694	-	-
Sub-basin 2	26.716	0974	1694	-	-
Sub-basin 3	17.071	0567	1098	-	-
Sub-basin 4	23.113	0391	0058	-	-
Sub-basin 5	38.149	-	-	-	-
Sub-basin 6	43.339	7078	4125	-	-
Reach 1	-	-	-	149.490	0014
Reach 2	-	-	-	27.327	0014

The combination of optimized parameters was used as the input for the calibrated model and was further validated using the observed data of 365 days in 2017. Figure 4 shows the results for calibration and validation periods in the form of hydrographs. As presented in Table 3, the *NSE* and the  $R^2$  values were 0.825 and 0.822 for 2007, 0.728 and 0.715 for 2008, and 0.614 and 0.723 for 2017, respectively. These values range from “satisfactory” to “very good” according to the performance evaluation criteria presented in Table 1, indicating high model accuracy. Figure 5 shows the line of best fit between the observed and the simulated streamflow of calibration (2007–2008) and validation (2017) periods.

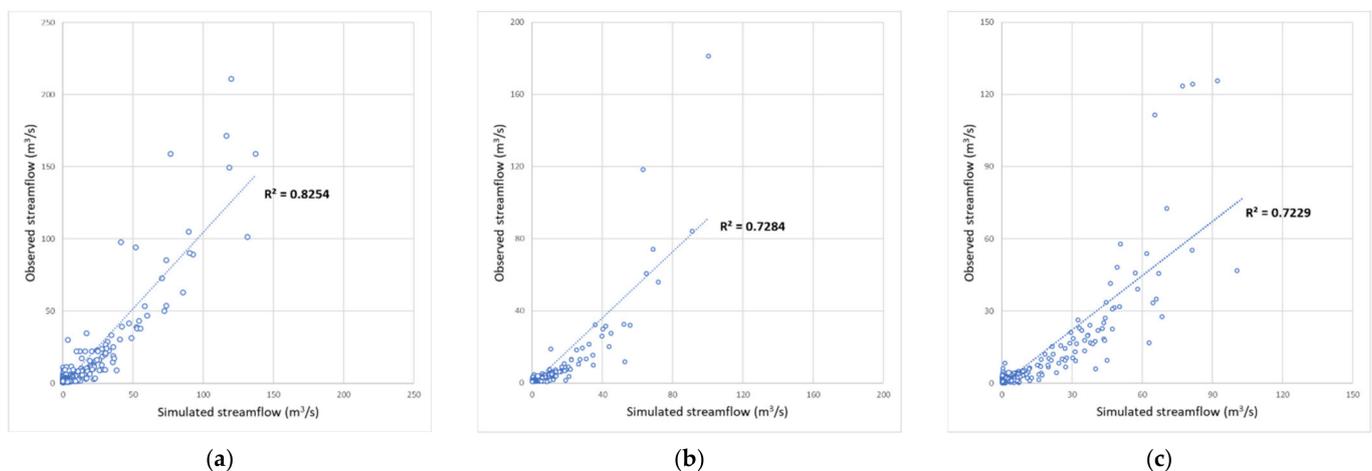


**Figure 4.** Observed and simulated hydrographs for calibration (2007–2008) and validation (2017) periods.

**Table 3.** Calibration and validation results.

	Period	Total Outflow <sup>1</sup>		Statistical Measure	
		Observed	Simulated	$R^2$	NSE
Calibration	2007	3730.18	3939.00	0822	0825
	2008	1731.00	2167.10	0715	0728
Validation	2017	2385.30	3389.60	0723	0614

<sup>1</sup> Refers to the sum of daily outflow ( $m^3/s$ ) over the year from junction 3.



**Figure 5.** Observed and simulated hydrographs for the calibration and validation periods of (a) 2007; (b) 2008; and (c) 2017.

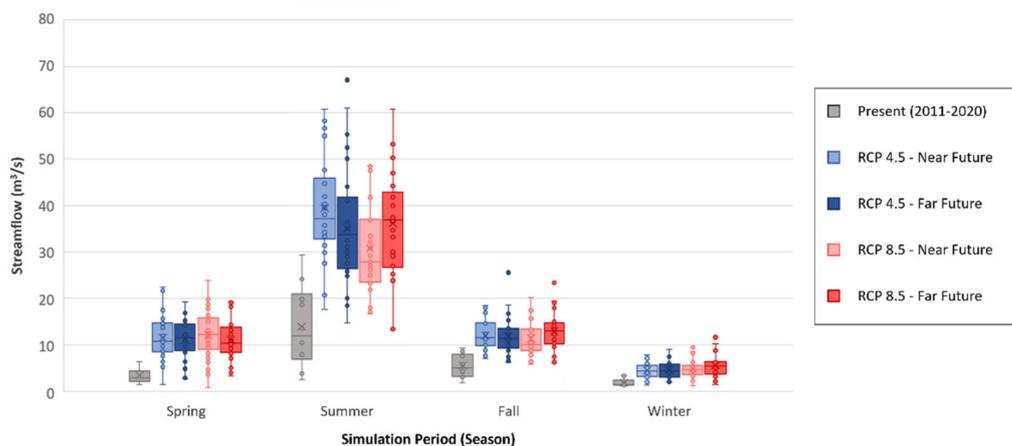
### 3.2. Simulation for Future Streamflow

After calibration and validation of the model, which confirmed its performance accuracy, the impact of climate change on the future discharge was assessed. In this study, we simulated the streamflow for the 60 year period between 2041 and 2100 to detect continual changes in trends over time. This was not achievable in previous studies that simulated streamflow for individual years in the future. The simulation results showed that the total annual runoff is projected to gradually decrease and approach the baseline (2011–2020) in the long run under RCP4.5, whereas it continues to increase over time under RCP8.5. These opposing trends are clearly shown in Figure 6.



**Figure 6.** Change in total annual streamflow (m<sup>3</sup>/s) under RCP4.5 and RCP8.5.

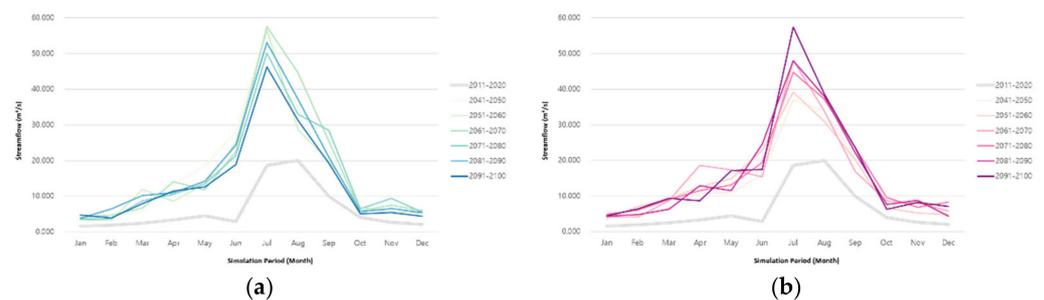
As discussed earlier, rainfall is heavily concentrated in the summer season in South Korea; thus, it is important to analyze the seasonal changes in the streamflow. To do so, the simulation results of the daily streamflow for the near future (2041–2070) and the far future (2071–2100) periods were further divided into four seasons: spring (March–May), summer (June–August), fall (September–November), and winter (December–February). As shown in Figure 7, we found that the seasonal streamflow is expected to increase in all four seasons, and the gap between dry and rainy seasons is expected to increase. However, there is a considerable difference in the magnitude of the seasonality between the two RCP scenarios. Under RCP4.5, the seasonality is expected to gradually alleviate in the far future period compared to the near future period. However, under RCP8.5, the seasonality is projected to worsen in the far future period in comparison to the near future period.



**Figure 7.** Seasonal streamflow under RCP4.5 and RCP8.5 for near (2041–2070) and far (2071–2100) future periods.

The results were further analyzed by subdividing them into six decades and calculating the monthly average, as shown in Figure 8 and presented in Table 4. In the baseline period of 2011–2020, the highest monthly average streamflow was observed in August,

which was attributed to the concentrated precipitation in this month. However, this was projected to change, as the highest monthly streamflow was simulated to occur in July in all six decades under both RCP4.5 and RCP8.5. However, distinct trends were observed when comparing the two scenarios. Under RCP4.5, the high July streamflow and its consequent differences from other months are expected to decrease over time. Monthly fluctuations within each season are also expected to decrease in the far future, showing smoother lines compared to earlier decades. In contrast, under RCP8.5, the average streamflow in July increased over time, while that of October tended to decrease. This implies that the difference between the two seasons is likely to worsen. Monthly fluctuations within the dry seasons are expected to increase in the future.



**Figure 8.** Projected monthly average streamflow under (a) RCP4.5 and (b) RCP8.5 by decade.

**Table 4.** Differences in average streamflow between July and October by decade.

Scenario	Period	Monthly Average Streamflow (m <sup>3</sup> /s)			
		July	October	Difference (July–October)	Change over Decades <sup>1</sup>
RCP4.5	2041–2050	57.412	6901	50.511	
	2051–2060	56.510	6772	49.738	−0773
	2061–2070	57.590	5910	51.680	+1942
	2071–2080	50.151	6380	43.772	−7909
	2081–2090	53.128	5579	47.549	+3777
	2091–2100	46.287	5076	41.211	−6338
RCP8.5	2041–2050	37.073	6830	30.244	
	2051–2060	39.190	6626	32.564	+2321
	2061–2070	48.131	8658	39.473	+6909
	2071–2080	44.736	9620	35.116	−4357
	2081–2090	48.015	7601	40.415	+5298
	2091–2100	57.444	6231	51.213	+10.798

<sup>1</sup> Refers to the change in the difference between July and October compared to the previous decade.

## 4. Discussion

### 4.1. Findings of Site-Specific Trend of Future Streamflow

Projections of the near and the far future streamflow in the Bocheongcheon basin in this study shed a light on the site-specific trend, distinct from other previous studies conducted over South Korea. Before discussing the implications of the simulation results for water resources management policy, major findings are reviewed in this chapter.

Bae et al. detected a decreasing trend in spring streamflow and an increasing trend in summer streamflow in South Korea for the period between 1968 and 2001 and warned that these trends are likely to continue in the future [5]. If these trends were to severely worsen, it would suggest increased risk of droughts in the spring and floods in the summer. However, the results of our study found that these trends do not apply to the Bocheongcheon basin, as its streamflow is projected to increase in all months and seasons over the six decades in the future (2041–2100). Our simulation results suggest that the water resources managers

of the basin should focus on potential threats that are more likely to result from increasing streamflow.

Jung et al. spatially analyzed future hydrologic elements and projected decreases in dry season flow in the southern regions of the country in contrast to slight increases in the northern regions. It was forecasted that these spatial distributions will become more distinct in the far future period of the 2080s [8]. However, such projections could not aid the water resources managers of the Bocheongcheon Basin of Geumgang River, as the basin is located in the central region. As the pattern of streamflow varies by regions, we suggest that future streamflow be simulated at a basin level if the purpose of hydrologic modeling is to serve as evidence for local adaptive measures.

#### *4.2. Implications for Water Resources Management*

In Korea, there have been numerous studies which suggested water resources management measures against stream depletion and water pollution of rivers and lakes, which are worsening due to the recently increased occurrences of serious drought [47–49]. However, as there are concerns about the widening variation in rainfall by region, which may impair regional water supply stability and riverine ecosystem health, it is essential to prepare a scientific basis for regional or local water resources management at a smaller basin level.

The results of this study can serve as such scientific evidence guiding decision makers, as the Bocheongcheon basin is projected to have increased streamflow in all months and seasons over the six decades (2041–2100) in the future. The projected increase in the overall streamflow, especially the summer season flow, does not directly bring advantages with enhanced amounts of water resources but rather indicates increased flood risk in the region during the wet season. The local decision-makers involved in water resources management must develop more robust adaptive plans for multiple threats following the increased flood risk. In this chapter, two major goals for management policy are suggested for the study site based on the simulation results:

1. The simulation results suggest the need for adaptive measures against an aggravating threat in deterioration of water quality due to increased inflow of pollutants into rivers carried by increased surface runoff. Especially for the Bocheongcheon basin, an area subject to intensive management of agricultural non-point pollutants, appropriate best management practices (BMPs) must be carefully selected and placed to secure quality water near agricultural land [50–52]. The effect of BMPs can be enhanced when coupled with maintenance of soil loss reduction infrastructure in high-altitude arable lands, which were identified as major sources of agricultural non-point pollutants in South Korea [53]. For the urban areas in the basin, reinforcement of early rainwater treatments by LID (low impact development) application should be considered to allow for more natural purification [54,55].
2. As the future summer streamflow is projected to significantly increase in the study site under climate change, local water resources managers should consider increasing the security degree of dams and other river infrastructures. According to the Third National Climate Change Adaptation Plan, “strengthening site-specific flood response” is promoted as the main task of sustainable flood management under the changing climate [53]. Measures to expand sewage pipes and to place more storage facilities and pumping stations are being considered in urban areas that are identified to experience an increase in rainfall runoff exceeding the installed capacity. Therefore, the projected future rainfall runoff in this study can be considered when newly setting design standards for dams and reservoirs. To expand reservoir capacity in the region, improved use of near-by agricultural reservoirs can also be a possible strategy, as there are approximately 300 of them in Boeun-gun, Okcheon-gun, and Yeongdong-gun of the study site [56].

In addition to the explored implications for water resources management policy, the simulation results of the study are valuable, as they firmly endorse the national initiatives for reduction of greenhouse gas emissions. Intensification of seasonal differences and fluctuations was projected under RCP 8.5 comparative to RCP 4.5, which suggests more difficulty caused for water resources managers to secure stable source of clean water and to prevent water-related disasters. This finding strongly indicates the need to reduce greenhouse gas emissions more assertively. Similarly, the nationally announced goal of achieving carbon neutrality by 2050 by harnessing green innovations and advanced digital technologies [57] is strongly supported by this study.

## 5. Conclusions

In this study, future rainfall runoff was simulated using the HEC-HMS model in the Bocheongcheon Basin of the Geumgang River to help establish efficient future water resources management measures. For the simulation, parameter values for loss, transform, and routing methods were individually calculated based on the land cover and the soil map of the target site and were applied to the model. Calibration of the model was conducted by combining the trial-and-error and the built-in optimization methods, resulting in an efficient simulation of discharge at junction 3 for the period of 2007 and 2008. When compared to the observed streamflow, the simulated streamflow showed high NSE and  $R^2$  values of 0.825 and 0.822 for 2007 and 0.728 and 0.715 for 2008, respectively. Using the calibrated parameters, we simulated the streamflow for 2017, which also showed fine NSE and  $R^2$  values of 0.614 and 0.723, respectively.

After confirming the model performance, the streamflow for the 60 year period (2041–2100) under RCP4.5 and RCP8.5 was simulated. The results revealed distinct changing trends in the streamflow in different time periods depending on the scenario. This indicated potential threats that may arise under the current water resources management policy. The future water resources management policy should be based on the change in streamflow controlled by the changing intensity and the frequency of rainfall during the wet and the dry seasons under the new climate regime. As such, the results derived in this study are meaningful, as they simulate the impact of climate change on the streamflow over an extensive period of 60 years instead of simulating the streamflow over a single year. Based on the 60 year simulation results, policy measures against increased threats of deteriorating water quality and increasing flood risk were suggested.

However, we would like to highlight a few factors that should be further considered when applying the findings of this study to future water resources management policy. The results of this study are affected to an extent by uncertainties resulting from hydrologic modeling and climate change scenarios. In future studies, these uncertainties should be quantified for more precise impact assessment of climate change on water resources. To reduce uncertainty caused by using a single hydrologic model, researchers can consider multi-model simulation.

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