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Combined Analysis of Net Groundwater Recharge Using Water Budget and Climate Change Scenarios

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Abstract: Estimating the groundwater recharge rate is essential in all groundwater-related fields, including groundwater development, use, management, modeling, and contamination analysis. In this study, we proposed a combined method of water budget and climate change scenario for estimating the net groundwater recharge rate in the Nakdong River watershed (NRW), South Korea. For the climate change scenario method, the representative concentration pathway (RCP) 4.5 and 8.5 climate scenarios were adopted. First, using the water budget method from 2009 to 2018, the net groundwater recharge rate (NGRR) of 12.15–18.10% relative to annual precipitation (AP) was obtained, subtracting direct runoff (DR) of 21.18–25.32% relative to AP, evapotranspiration (EP) of 40.53–52.29% relative to AP, and baseflow of 12.42–17.84% relative to AP, from the AP (865–1494 mm). The average annual NGRR of the NRW was 200 mm (15.59%). Second, the mean NGRRs from 2009 to 2100 under the RCP 4.5 and RCP 8.5 scenarios were anticipated as 8.73% and 7.63%, respectively. The similarity between the water budget and climate change scenarios was confirmed using data from 2009 and 2018. According to the simple climate change scenario, it is predicted that annual precipitation will increase over the years while the groundwater level and net groundwater recharge rate will decrease. Nonetheless, the estimated NGRR by the water budget method in this study possesses uncertainty due to using potential ET instead of actual ET which should be estimated by considering soil water content.

Keywords: net groundwater recharge rate; water budget; simple climate change scenario; Nakdong river watershed; precipitation

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Citation: Yun, S.-M.; Jeon, H.-T.; Cheong, J.-Y.; Kim, J.; Hamm, S.-Y. Combined Analysis of Net Groundwater Recharge Using Water Budget and Climate Change Scenarios. *Water* **2023**, *15*, 571. https://doi.org/10.3390/w15030571

Academic Editors: Bommanna Krishnappan and Chin H Wu

Received: 14 November 2022
Revised: 20 January 2023
Accepted: 28 January 2023
Published: 1 February 2023

1. Introduction

Groundwater originates mainly from rainfall and is recharged in aquifers. Watershed groundwater recharge is important for its development, use, conservation, and management. Moreover, it is critical for accurately estimating the groundwater recharge rate, which local and federal governments use for relevant policymaking. The groundwater recharge rate is one of the most challenging factors in assessing the quantitative evaluation of groundwater resources [1]. The groundwater recharge rate is calculated using methods, such as baseflow separation, water budget, water table fluctuation (WTF), groundwater modeling, climate change scenarios, and artificial intelligence. The net groundwater recharge rate (NGRR) using the water budget method is the amount of precipitation and groundwater inflow from other basins, excluding direct runoff, evapotranspiration, baseflow, pumping quantity, groundwater outflow into other basins, and coastal groundwater discharge [2,3]. The WTF method, a physical estimation method, estimates the water table rise in the phreatic aquifer and the groundwater recharge rate due to rainfall [4]. The hybrid water table fluctuation method (hybrid-WTF) combines the WTF method and the model of water content in unsaturated zones by considering the delay time of water reaching the water table from the land surface, as well as baseflow and groundwater level drops simultaneously in the condition of a permeable unsaturated zone and the underlying aquifer [5].

Moon et al. [6] estimated the groundwater recharge rate of four major river basins in South Korea using an improved WTF method based on groundwater level. In the rainy season (June–September) of 2005 in the uppermost watershed, Choi et al. [7] estimated average groundwater recharge rates of 24.75%, 13.4%, and 14.0%, respectively, using the WTF method, chloride mass balance method, and baseflow separation methods with chloride tracers. Chung et al. [8] calculated the groundwater recharge in the Mihocheon stream basin in South Korea using the SWAT-MODFLOW model [9], which is a surface water-groundwater integration model. In the Gangcheon Stream basin in Gyeonggi Province, South Korea, Noh et al. [10] calculated average groundwater recharge rates of 17.81% and 18.13%, respectively, using the hybrid-WTF method [5] and groundwater modeling. Bae [11] calculated the groundwater recharge rate using the natural resources conservation service curve number (NRCS-CN) and baseflow separation methods in five sub-watersheds and obtained a 30 mm/yr higher groundwater recharge rate using the baseflow separation and NRCS-CN methods. Lee and Bae [12] examined the variability in groundwater recharge rates due to urbanization and land cover changes. Viji et al. [13] calculated CN, including the antecedent moisture condition (AMC), for the Kundapallam watershed in India, considering land use and hydrological soil grouping (HSG). Ling et al. [14] proposed an improved soil conservation service (SCS)-CN method using nonparametric statistical analysis of rainfall and runoff data from the Wangjiaqiao watershed in China. Shi et al. [15] proposed the SCS-CN method by considering topographic slope, soil moisture, and storm duration factors, and applied the method to the Loess Plateau watershed in China.

Groundwater recharge rates are anticipated to change due to future climate change. Dripps and Bradbury [16] evaluated groundwater resources according to climate change by applying an improved soil water balance (SWB) model by considering soil moisture content, land cover, topography, climate data, and geographic information. Holman [17] analyzed the climate and socioeconomic impacts, uncertainty, and vulnerability of the groundwater recharge rate. Schindler et al. [18] investigated groundwater level variability according to soil type. They proposed a management plan for agricultural groundwater use in northeastern and central Germany, utilizing soil data at 368 monitoring points from 1951 to 2000 as well as using climate change scenarios from 2001 to 2055. Patricia et al. [19] proposed a standardized anomaly index for evaluating the impact of drought on a watershed scale in the Philippines, based on the spatiotemporal characteristics of groundwater level change. Jang et al. [20] estimated the groundwater level change from 2000 to 2012 in four major river basins in South Korea. Using climate change scenarios, they then predicted the groundwater level change from 2000 to 2100. Lee et al. [21,22] proposed coupled model development between groundwater recharge rate and climate change in river watersheds in Korea and calculated groundwater rate by using Visual HELP3. By using climate change scenarios for the Korean Peninsula and a geographic information system (GIS), Lee and Lee [23] estimated the groundwater recharge rates of 27.37% (1970 to 2000), 27.43% (2001 to 2030), 26.06% (2031 to 2050), and 27.88% (2051 to 2100) in the NRW. Lee and Lee [24] revealed the groundwater recharge mechanism in the Wonju and Uiwang areas through a time-series analysis of groundwater levels and rainfall. Kim et al. [25] conducted a time series analysis of the groundwater levels and precipitation on Geumjeongsan Mountain in Busan City. They suggested that the groundwater recharge rate of the bedrock aquifer is governed by fracture zones more than the direct rainfall effect.

The objective of this study is to estimate the net groundwater recharge rate (NGRR) from 2009 until 2100 by using a combined analysis of the water budget method and the climate change scenarios of representative concentration pathways (RCP) 4.5 and 8.5. Using data of 2009–2018, baseflow was calculated using streamflow data at the estuary of the

NRW, and the groundwater recharge rate was estimated based on the water balance. The long-term groundwater recharge until 2100 was predicted using precipitation from the RCP 4.5 and RCP 8.5.

2. Study Area

The Nakdong River watershed (NRW) consists of eight sub-basins in the upstream area (Andong Dam, Imha Dam, Mainstream I, Naeseongcheon, Yeonggang, Byeongseongcheon, Ssanggyecheon, and Wicheon Basin), seven sub-basins in the midstream region (Mainstream II, Gamcheon, Mainstream III, Geumho River upstream, Geumho River downstream, Main stream IV, Hoecheon Basin), six subbasins in the downstream western region (Hwanggang, Mainstream V, Namgang upstream, Yangcheon, Namgang Dam, and Namgang lower basin), six sub-basins in the downstream eastern region (Main stream VI, Miryanggang, Mulgeum, Yangsancheon, and Hagueon, Seobun) Nakdong River basin). The Nakdong River, which originates in Taebaek City, Gangwon Province, passes through Yeongnam Province and, flows into the South Sea through Busan Metropolitan City, with the longest length (510 km) and the second largest area (23,647 km^2) in South Korea.

A total of 122 wells under the National Groundwater Monitoring Network (NGMN) are distributed in the NRW (Figure 1). The surface elevation of the wells was the highest at 735.6 m (ND-3-SS well) and the lowest at 1.4 m (ND-3YN well). The highest groundwater level was 735.1 m, average mean sea level (amsl) (ND-3-SS well), and the lowest was −6.8 m amsl (ND-4-DC well), with an average groundwater level of 98.6 m amsl (Table 1). The highest groundwater temperature was 20.6 °C (ND-3-DGB well) and the lowest was 11.0 °C (ND-1-NA well), with the average groundwater temperature of all the wells being 15.0 °C. In addition, the average groundwater electrical conductivity (EC) of all the wells was 536 µS/cm, with the highest reading of 11,694.6 µS/cm (ND-4-DC well near the coast of the South Sea) and the lowest reading of 83.9 µS/cm (ND-4-USDC well).

Table 1. Well information statistics in the Nakdong River watershed for 2009–2018.

	Surface Elevation (m)	**Well Depth (m)**	**Groundwater Level (m, amsl)**	**Temp. (°C)**	**EC (µS/cm)**
Max	735.6	168.0	735.1	20.6	11,695
Min	1.4	40.0	−6.8	11.0	83.9
Arithmetic mean	105.6	79.7	98.6	15.0	536
Median	78.9	70.0	72.4	15.0	320
Standard deviation	105.4	19.8	104.6	1.2	1083
Range	734.2	128.0	741.9	9.6	11,611

Based on the precipitation distribution map of the NRW, prepared from precipitation data from 30 meteorological stations (Figure 2) from 1996 to 2019, the mean annual precipitation in the NRW was 1277 mm. The precipitation data of the 30 meteorological stations corresponded with the nearest monitoring well. The highest precipitation of 1989 mm/yr was observed in the ND-4-SH well, and the lowest precipitation of 917 mm/yr was observed in the ND-2-PC well. The precipitation in each well was used to calculate the net groundwater recharge.

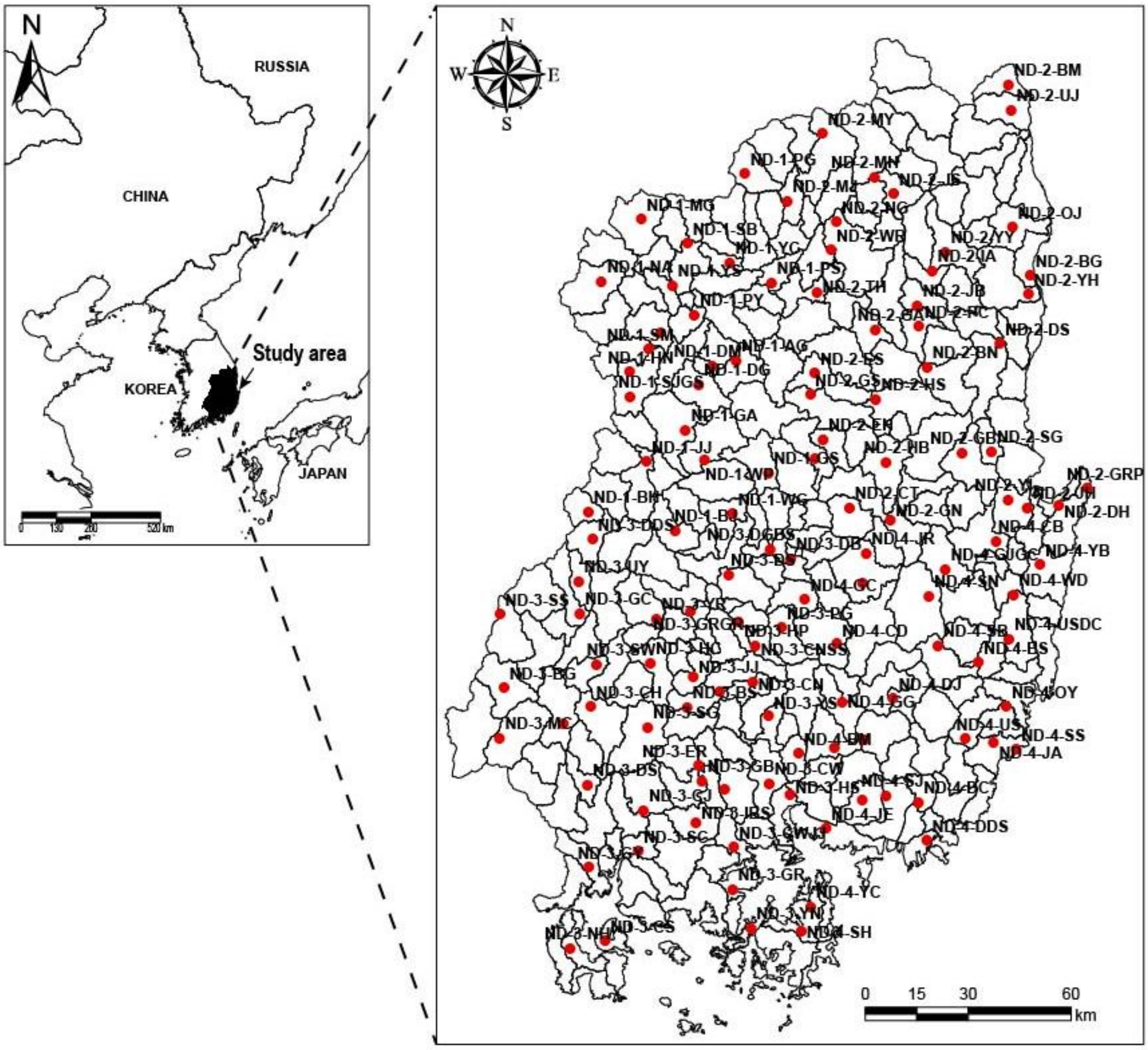

Figure 1. Location of the wells of the national groundwater monitoring network and the standard subwatersheds in the Nakdong River watershed.

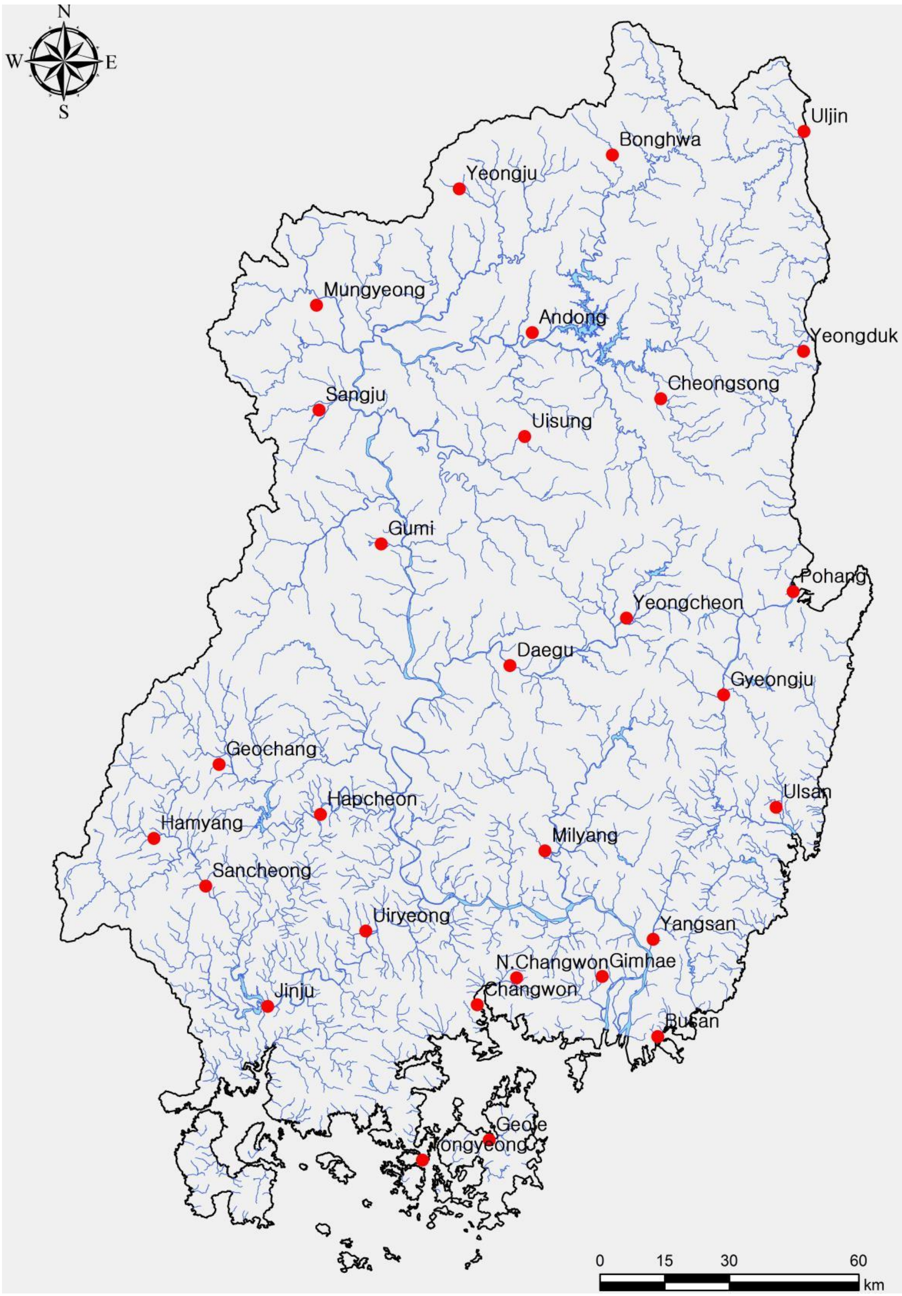

Figure 2. Location of the weather monitoring stations in the Nakdong River watershed [26].

3. Methods

3.1. Method of Water Budget

In the hydrological cycle, the net groundwater recharge rate (*NGRR*) is the water that reaches the saturation zone through the unsaturated zone, and is calculated as the amount excluding direct runoff (*DR*), baseflow (*BF*), the outflow (*OU*) from the aquifer to the sea, the inflow (*RN*) of other geological layers, evapotranspiration (*ET*), as well as pumping (*DO*), if it occurs, from precipitation (*P*) [2,3]:

$$NGRR = P - DR - ET - BF - DO - OU + RN \quad (1)$$

Direct runoff (DR) is the amount that flows through the land surface and enters streams. If there is no RN and DO with no consideration of OU, then Equation (1) is transformed into:

$$NGRR = P - DR - ET - BF \tag{2}$$

Direct runoff (DR) is inversely proportional to the amount of infiltration and directly proportional to the water content in the soil layers. When there is no DR data, the DR is generally calculated using the SCS-CN method [27,28]. The SCS-CN method, DR should be greater than 0, and P should be greater than 0.2:

$$DR = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3}$$

where S is governed by the antecedent soil moisture condition (AMC) and depends on the runoff curve number (CN), which is inversely proportional to DR. The AMC values are determined by 5 or 3-day accumulated antecedent precipitation.

Evapotranspiration (ET) has been estimated in several ways [29–34]. Actual evapotranspiration (AET) is a fraction of potential evapotranspiration (PET) that is assumed as ET in the saturated condition of the soil. In this study, the PET (ET_0, mm/d) as an approximation of the AET was estimated by using the Penman–Monteith equation that is widely used in the world [35] and that considers atmospheric temperature, humidity, wind speed, and radiation. Additionally, Yang et al. [36] estimated the ratio of AET over PET to be 0.96 in the coastal area of Busan City belonging to the NRW.

Baseflow (BF), the water provided by riverside aquifers, is estimated by hydrograph separation [37,38] and the recession of BF is influenced by topography, watershed shape, soil, geological media, etc. The volume of BF discharged from riverside aquifers is given by Meyboom [37]:

$$V_{tp} = \frac{Q_0 t_1}{2.3026} \tag{4}$$

Finally, the baseflow (BF) during seasons adjacent to A and B is expressed by:

$$BF = \frac{2(Q_B - Q_A)t_1}{2.3026} \tag{5}$$

where Q_A is the baseflow at the critical time of recession after the hydrograph peak in season A and Q_B is the baseflow at the critical time of recession after the hydrograph peak in season B. Time t_1 is the time taken for the baseflow recession to decline by one log cycle.

3.2. Method of Climate Change Scenarios

Climate change scenarios calculate future climate factors, such as temperature, precipitation, wind, and humidity, by applying changes in radiative forcing caused by anthropogenic causes (greenhouse gases, aerosols, and land use changes) to the Earth system model. There are six climate change scenarios, A1 (A1FI, A1T, and A1BI), A2, B1, and B2 depending on the projected carbon dioxide emissions [39]. The IPCC (2007) determined the greenhouse gas concentration based on the amount of radiation exerted on the atmosphere by human activities according to the RCP. The Korea Meteorological Administration (KMA) predicted future climate change up to 2100 according to the RCP scenario after simulating past climates for natural and anthropogenic forcing from 1860 to 2005. The KMA developed a climate change scenario for the Korean Peninsula (www.climate.go.kr, accessed on 13 November 2022) using meteorological data (averaged from 2001 to 2010) obtained from the Automated Surface Observing System (ASOS) and the Automatic Weather System (AWS). The 1-km climate change scenario for South Korea was obtained by applying a 12.5-km resolution climate change scenario to the PRISM based downscaling estimation model (PRIDE). The calculated 1-km grid data is converted into administrative district-level data using GIS techniques. This 1-km climate change scenario can reflect the effects of complex topography in South Korea, which cannot be realized in the global climate model.

In this study, using the climate change scenarios of RCP 4.5 and RCP 8.5, $NGRR_i$ is calculated by Jang et al. [20]:

$$NGRR_i = P_i \cdot f \tag{6}$$

where recharge ratio f is determined by:

$$f = \Delta H_i \cdot S_y / P_i \tag{7}$$

where S_y is the specific yield. ΔH_i is the groundwater level difference between H_{imax} (the highest monthly groundwater level in the ith year) and H_{imin} (the lowest groundwater level in the ith year) for each year between 2009 and 2018. The values of f are computed by using Equation (7) with ΔH_i and P_i at each point in the historical period of 2009–2018. Finally, the mean f value of all the wells for the period of 2009–2018 is applied to each well with corresponding precipitation for the period of 2019–2100. P_i is annual precipitation of the ith year.

4. Results

4.1. Net Groundwater Recharge Rate by the Water Budget

The net groundwater recharge rate (*NGRR*) by the water budget was calculated for 264 standard sub-watersheds (Figure 1). For the determination of direct runoff (*DR*) by the SCS-CN method, the SCS-CN values were obtained using the land cover map and soil map of the NRW. The 21 land cover types were discovered in the study area, including forest 67.17% (broadleaf forest 30.58%, coniferous forest 25.39%, mixed forest 11.20%), residential areas 1.01%, industrial areas 1.32%, commercial areas 1.17%, cultural and sports areas 0.02%, transportation areas 0.95%, public facilities areas 0.01%, rice paddy fields 7.57%, farm fields 11.04%, greenhouse cultivation areas 2.39%, orchard 0.43%, other cultivation areas 0.21%, natural grasslands 1.51%, artificial grasslands 0.58%, inland wetlands 0.01%, coastal wetlands 0.01%, natural bare fields 1.05%, and artificial bare fields 0.44%. Drainage grades were divided into A (55.38%), B (20.58%), C (3.03%), and D (21.01%). The *S* values were calculated using the SCS-CN values, considering the area corresponding to each drainage class. Finally, annual *DR* values from 2009 to 2018 were calculated as 183.21 mm (21.18%) to 372.25 mm (25.32%) by using Equation (3). The average annual DR for the ten years is 308.28 mm, which is 24.14% of the average annual precipitation of 1277 mm (Table 2).

Table 2. Estimated *NGRR*, *DR*, ET_0, and *BF* of the Nakdong River watershed, with the ratios (%) to the annual average precipitation (*P*) during 2009–2018.

Year	*P*, mm	*DR*, mm (%)	ET_0, mm (%)	*BF*, mm (%)	*NGRR*, mm (%)
2009	1191	274.91 (23.08)	567.52 (47.65)	196.95 (16.54)	151.62 (12.73)
2010	1345	315.14 (23.43)	590.48 (43.90)	239.94 (17.84)	199.44 (14.83)
2011	1494	372.25 (24.92)	605.59 (40.53)	254.81 (17.06)	261.35 (17.49)
2012	1464	367.67 (25.11)	602.13 (41.13)	254.37 (17.38)	239.83 (16.38)
2013	1072	254.72 (23.76)	547.28 (51.05)	133.09 (12.42)	136.91 (12.77)
2014	1363	345.11 (25.32)	592.25 (43.45)	189.08 (13.87)	236.56 (17.36)
2015	1025	238.26 (23.24)	506.74 (49.44)	155.47 (15.17)	124.53 (12.15)
2016	1465	363.33 (24.80)	604.17 (41.24)	236.25 (16.13)	261.25 (17.83)
2017	865	183.21 (21.18)	452.27 (52.29)	122.64 (14.18)	106.88 (12.36)
2018	1482	368.18 (24.84)	604.89 (40.82)	240.64 (16.24)	268.29 (18.10)

Annual ET_0 was calculated using the Penman-Monteith method, by using the daily average temperature (14.5–15.7 °C), daily maximum temperature (32.5–37.3 °C), daily minimum temperature (−12.8–−6.0 °C), solar radiation (5.99–7.70 h), atmospheric pressure (100.7 to 100.9 kPa), daily average water vapor pressure (1.23 to 1.27 kPa), and daily average wind speed (3.1–3.4 m/s) from 2009 to 2018 (Table 3). Precipitation, temperature, and solar radiation amounts were obtained from 30 meteorological stations in the NRW. Due to the difficulty in directly measuring or calculating longwave radiation [40], 30% of the radiation energy was applied as the net radiation value according to the latitude effect provided by FAO. The annual *PET* from 2009 to 2018 ranged from 452.27 mm (40.53%) to 605.59 mm (52.29%), and the annual average ET for the ten years was 567.33 mm, which corresponded to 44.43% of the 10-year average annual precipitation (1277 mm).

Table 3. Factors for the estimation of ET_0.

	Average Daily Temp. (°C)	Daily Max. Temp. (°C)	Daily Min. Temp. (°C)	Solar Radiation (h)	Atmospheric Pressure (kPa)	Average Daily Water Vapor Pressure (kPa)	Average Daily Wind Speed (m/s)
2009	15.2	32.5	−7.6	5.99	100.7	1.25	3.4
2010	14.9	34.1	−8.1	6.25	100.8	1.26	3.3
2011	14.6	33	−12.8	6.37	100.9	1.23	3.3
2012	14.5	34.5	−9.9	7.12	100.7	1.27	3.3
2013	15.3	35	−10.7	7.7	100.7	1.24	3.4
2014	15.1	32.9	−6	6.89	100.8	1.25	3.2
2015	15.4	33.5	−7.8	7.04	100.8	1.24	3.1
2016	15.7	37.3	−10.2	6.99	100.8	1.26	3.1
2017	15.2	36.2	−7.7	7.55	100.8	1.25	3.2
2018	15.1	36.4	−9.9	7.41	100.8	1.24	3.2

The streamflow rates of peak and re-peak (2763–21,657 m^3/d), numbered from 1 to 10, with a time interval of 1.6–3.2 months between two peaks at the estuary of the NRW (Figure 3), were used for the calculation of the *BF* values. Using Equation (5), from 2009 to 2018, the *BF* values of the NRW were between 122.64 mm (12.42%) and 254.81 mm (17.84%), and the 10-year average *BF* value was 202.32 mm, which was 15.84% of the 10-year annual average precipitation (Table 2).

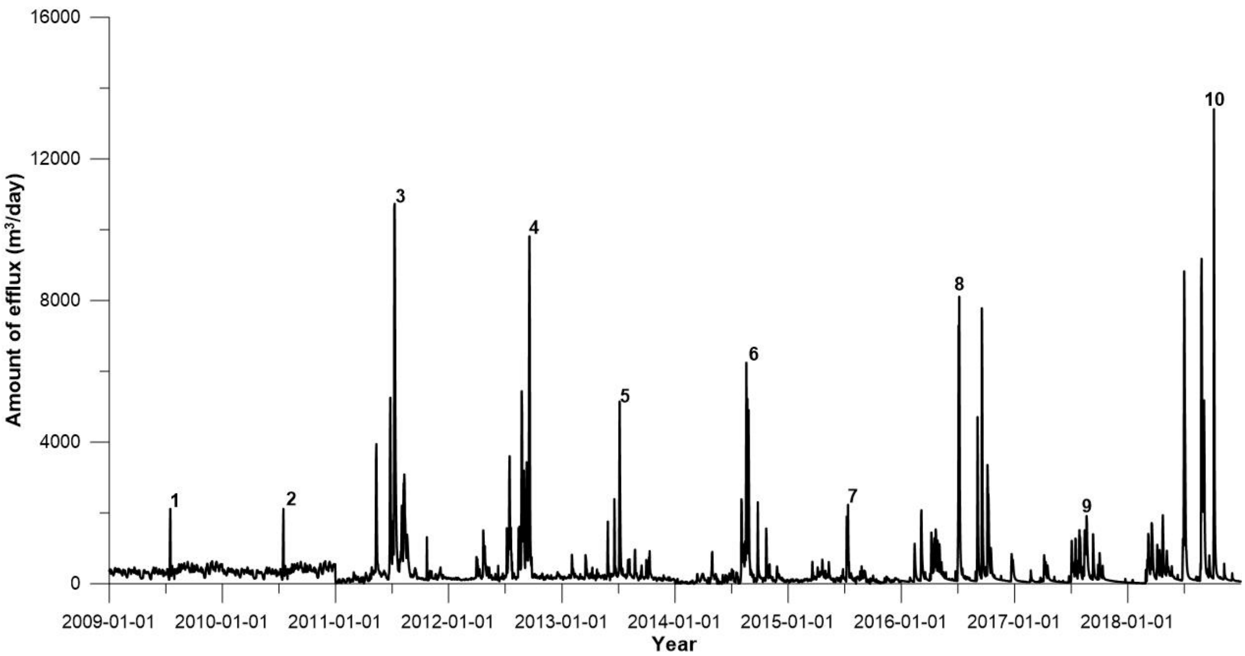

Figure 3. Streamflow in the Nakdong River watershed from 2009 until 2018. The numbers indicate the peaks for estimating baseflow.

From 2009 to 2018 in the NRW, the *NGRR* values were estimated to range from 12.15% to 18.10%. The average of the *NGRR* values in the NRW from 2009 to 2018 is 200 mm

(15.66%) when *DR* of 308 mm (24.12%), *PET* of 567 mm (44.40%), and *BF* of 202 mm (15.82%) are subtracted from the average *AP* (1277 mm).

4.2. Net Groundwater Recharge Rate under the Climate Change Scenarios

Before the RCP 4.5 and RCP 8.5 climate change scenarios, the recharge ratio (f), using the observed 2009–2018 data, was calculated by multiplying ΔH_i and specific yield (S_y) in Equation (7). The S_y value was determined to be 0.12 as a result of matching *NGRR* values with the *NGRR* values by the water budget method. In contrast, the mean S_y value of the NRW was reported to be 0.0134 by Moon et al. [41]. Next, the *NGRR* values from 2019 to 2100 were computed using the predicted precipitation data and f values in Equation (6), based on RCP 4.5 and RCP 8.5 climate change scenarios with a resolution of 1 km. Based on the RCP 4.5 and RCP 8.5 climate change scenarios, Figure 4 and Table 4 show mean AP (mm/yr) for the periods of 2009–2018, 2019–2039, 2040–2059, 2060–2079, and 2080–2100. The AP of the RCP 4.5 displays an increasing tendency from 2040 to 2079 and then a decreasing tendency from 2080 to 2100, while the AP of the RCP 8.5 displays an increasing tendency from 2019 until 2100.

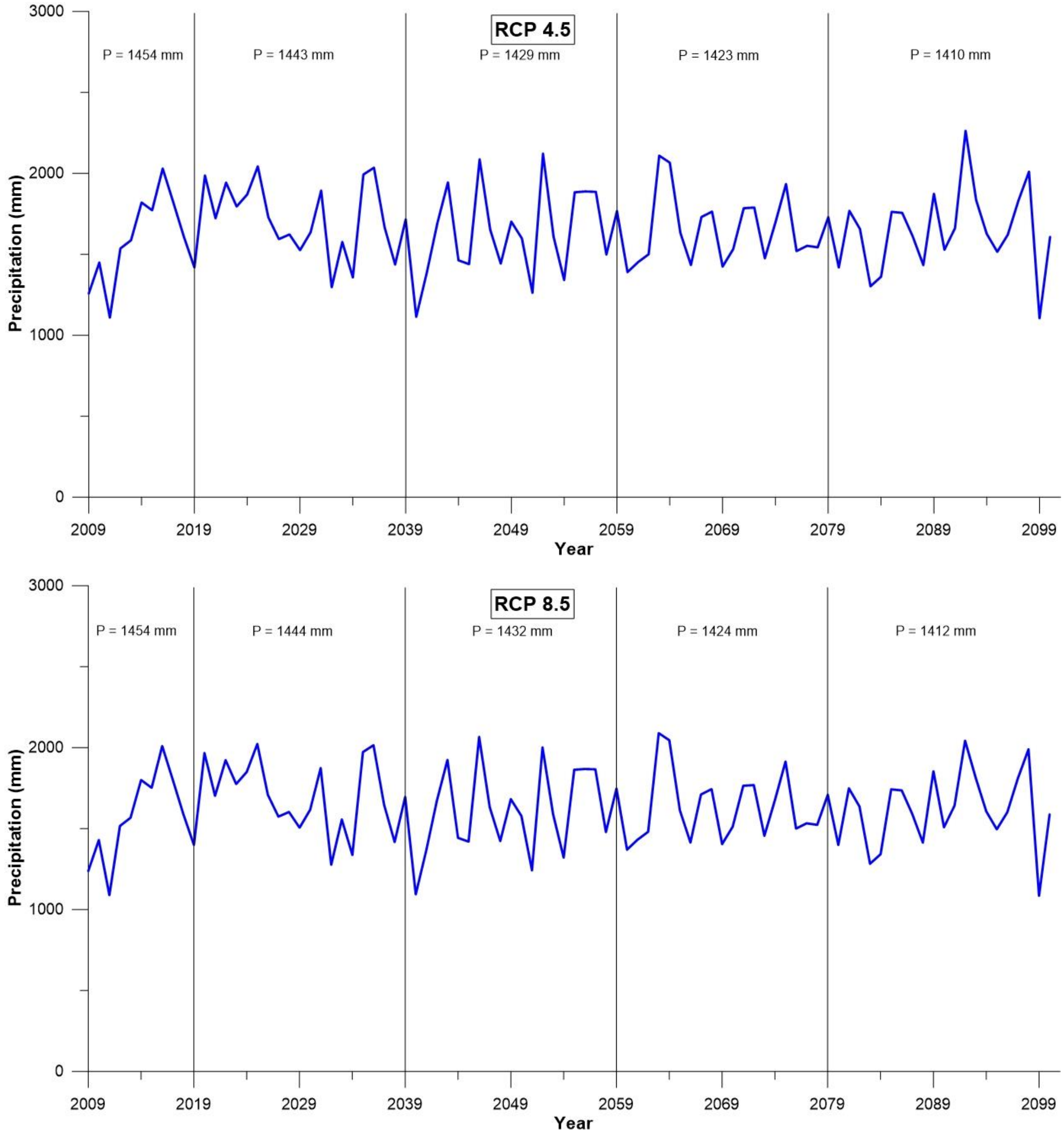

Figure 4. Predicted precipitation of 2009 to 2100 by the RCP 4.5 and 8.5 climate scenarios in the Nakdong River watershed.

Table 4. Estimated *NGRR* (%), annual precipitation (*P*, mm), recharge ratio (*f*), and specific yield (S_y) in the Nakdong River watershed for the periods of 2009–2018, 2019–2039, 2040–2059, 2060–2079, and 2080–2100 by the RCP 4.5 and RCP 8.5 climate change scenarios.

Period	RCP 4.5			RCP 8.5		
(Starting Year–Ending Year)	*P*	S_y	*NGRR*	*P*	S_y	*NGRR*
2009–2018	1455.1	0.12	13.73	1445.2	0.12	14.43
2019–2039	1312.6	0.12	7.74	1387.4	0.12	6.31
2040–2059	1493.1	0.12	7.81	1424.7	0.12	5.78
2060–2079	1538.5	0.12	7.30	1474.8	0.12	5.72
2080–2100	1414.4	0.12	7.05	1585.0	0.12	5.90

According to the climate change scenarios of RCP 4.5 and RCP 8.5, it is predicted that the decline rate of the groundwater level by RCP 4.5 and RCP 8.5 will be 0.023 m/yr and 0.024 m/yr, respectively, reaching a decline of 2.3 m and 2.4 m in 2100, respectively. In general, the decrease in groundwater level over a long period can be attributed to climate change and various man-made effects of groundwater pumping, irrigation, land-use change, etc. [4]. In this study, it is judged that the groundwater level decline with the annual precipitation decrease in the long term is caused by a decrease in infiltration rate into the subsurface as well as an increase in precipitation and an increase in direct runoff during the wet season relative to smaller precipitation in the dry season [20]. Moreover, a temperature increase of 3.5–4.0 °C until 2100 on the Korean peninsula [42] will increase the *ET* rate [43]. On the other side, urbanization can decrease *ET* rates by increasing runoff [44]. The *NGRR* values will be decreased to 7.05% based on the RCP 4.5 and to 5.90% based on the RCP 8.5 climate change scenarios in the period of 2080–2100 (Table 4), with a slightly decreasing tendency (Figure 5). The mean *NGRR* from 2009 to 2100 was estimated to be 8.73% in the RCP 4.5 scenario and 7.63% in the RCP 8.5 scenario, being similar to each other. Precipitation in summer for the periods of 2009–2019, 2020–2039, 2040–2059, 2060–2079, and 2080–2100 by using the RCP 4.5 and 8.5 climate change scenarios is intensified when going to 2100 (Table 5; Figure 6).

Table 5. Maximum, minimum, and mean precipitation (mm/mon) based on the RCP 4.5 and RCP 8.5 climate change scenarios for the periods of 2009–2018, 2019–2039, 2040–2059, 2060–2079, and 2080–2100.

Period	RCP 4.5					RCP 8.5				
(Starting Year–Ending Year)	Max		Min		Mean	Max		Min		Mean
2009–2018	520.2	August 2014	1.9	November 2017	107.6	520.2	August 2014	1.9	November 2017	107.6
2019–2039	502.3	July 2020	5.7	December 2020	109.9	580.8	July 2031	4.9	November 2035	115.9
2040–2059	702.7	July 2052	4.8	February 2042	124.4	657.0	July 2040	5.8	December 2058	118.7
2060–2079	824.1	July 2077	6.6	February 2079	128.2	549.1	July 2061	3.5	April 2072	122.9
2080–2100	980.3	July 2100	4.8	February 2098	117.9	790.2	July 2092	4.5	December 2089	132.1

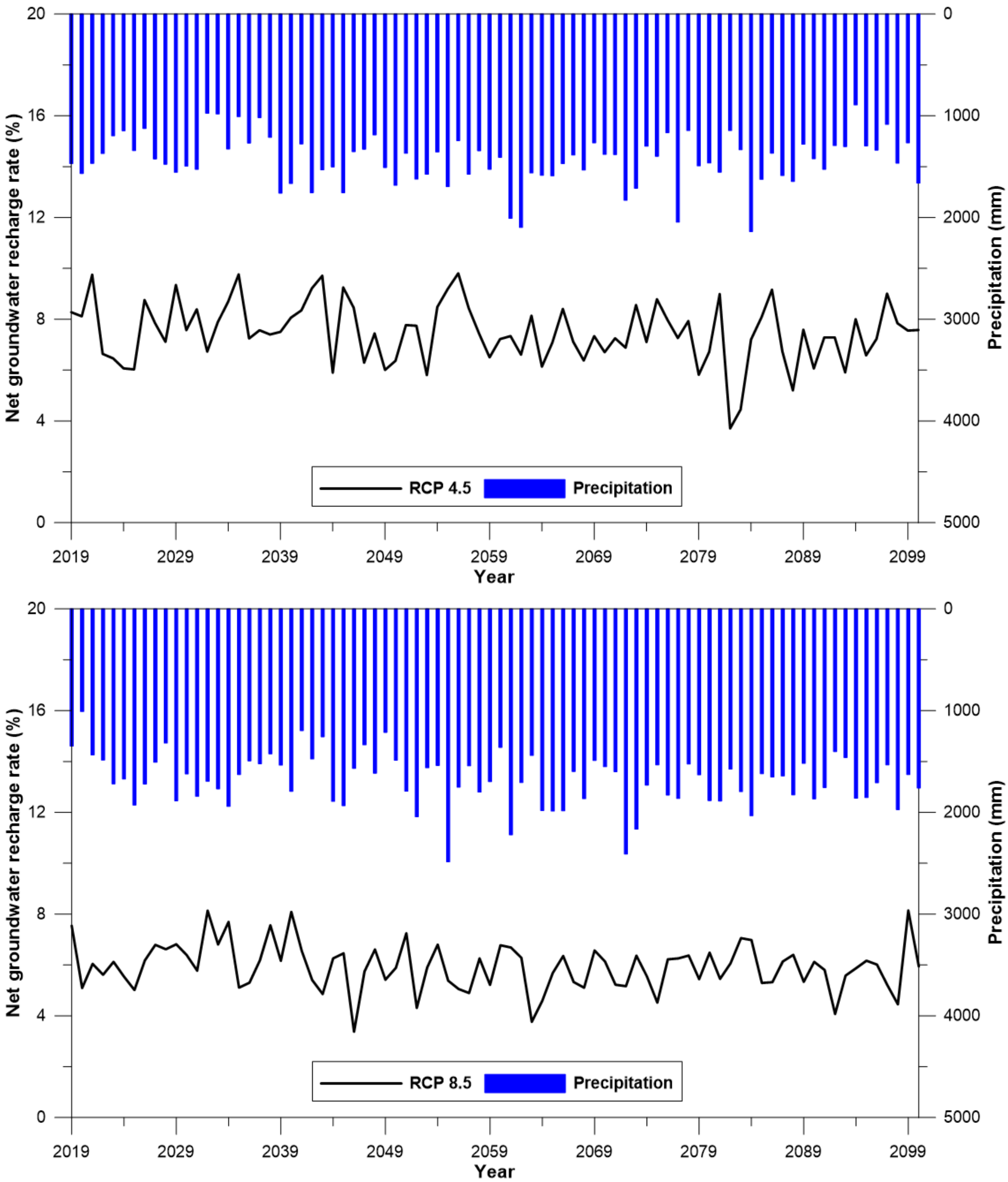

Figure 5. Predicted net groundwater recharge rate in the Nakdong River watershed for 2019–2100.

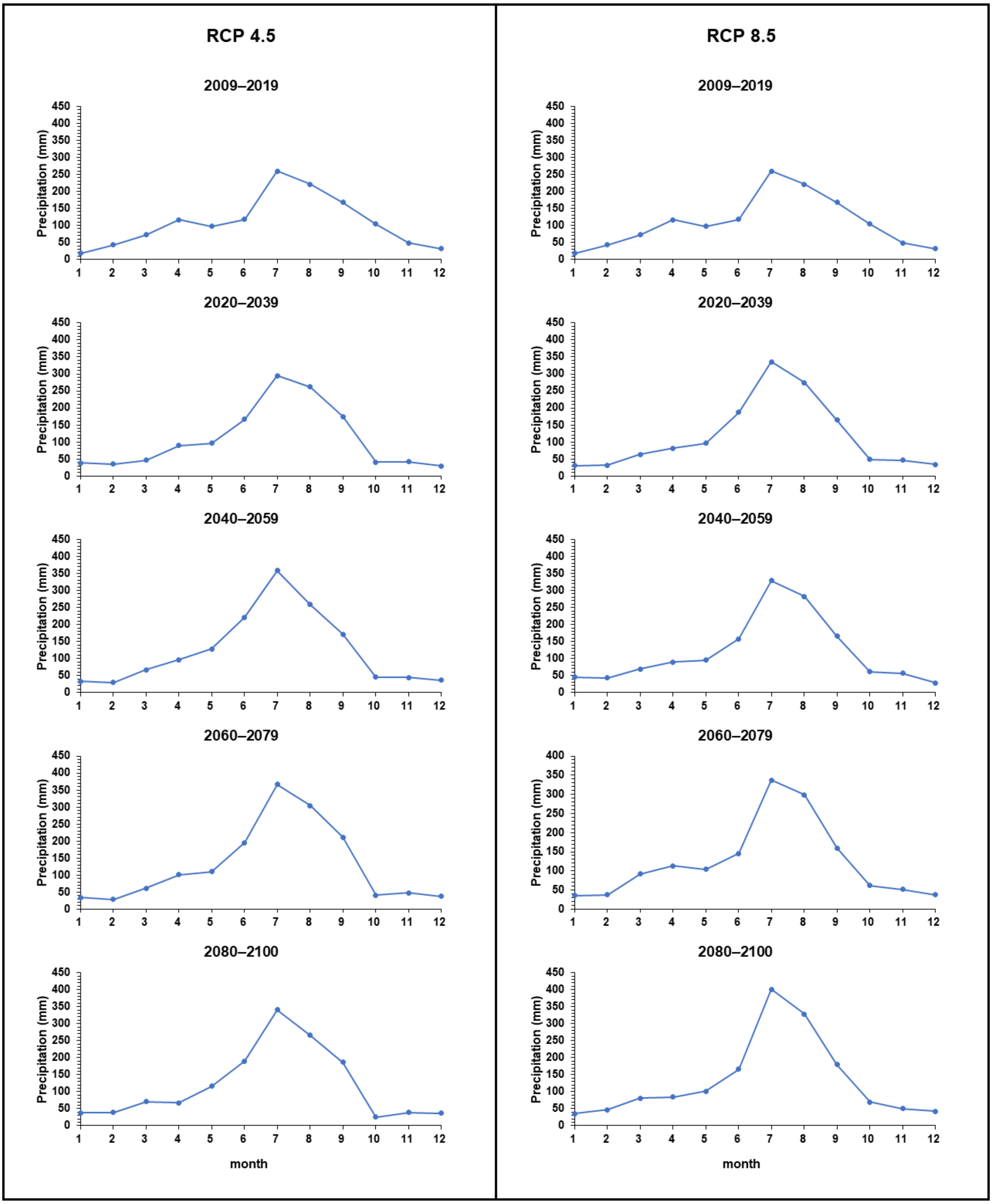

Figure 6. Seasonal trend of precipitation for the periods of 2009–2019, 2020–2039, 2040–2059, 2060–2079, and 2080–2100 using the RCP 4.5 and 8.5 climate change scenarios.

5. Discussion

Thus far, there has been no case of calculating the *NGRR* based on the long-term water budget method and simple climate change scenarios for the total area of the NRW, except in this study. Moon et al. [6] estimated the groundwater recharge rate in the NRW using the WTF method and obtained 6.1%, which is much smaller than the 15.54% of the *NGRR* according to the water budget method in this study. In this study, the observed streamflow rate was compared with the baseflow and calculated direct runoff by the SCS-CN method, showing good matching such that the observed streamflow rate of 323.59–622.42 mm/yr and the baseflow plus the calculated direct runoff of 321.89–617.99 mm/yr from 2009 to 2018 resulted in slightly greater values of the observed streamflow rate than those of the calculated direct runoff and baseflow (Figure 7).

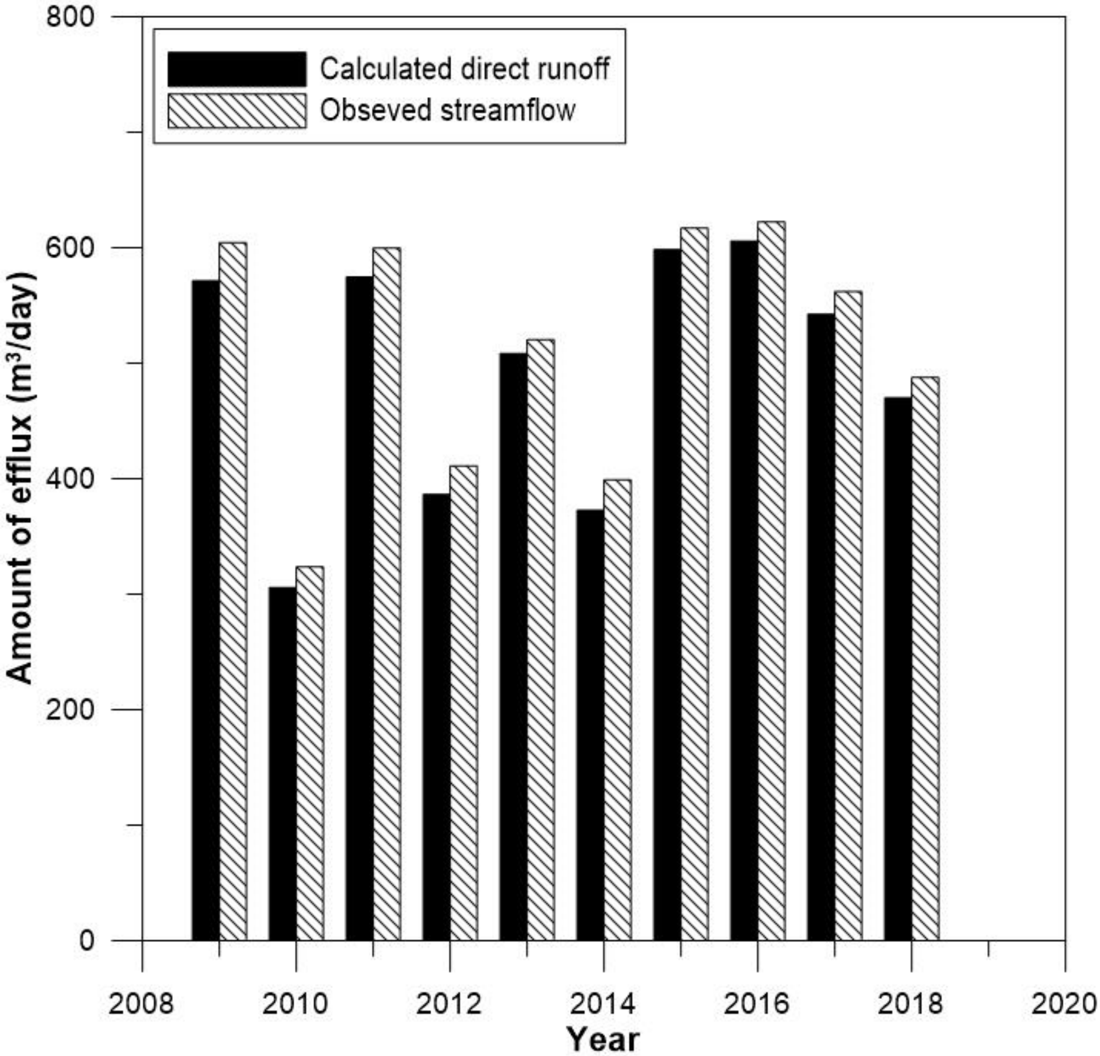

Figure 7. The observed streamflow and calculated direct runoff during 2009–2018.

The *NGRR* (200 mm, 15.66% of the AP) of the NRW in this study was compared with the average annual groundwater recharge rate (196 mm, 14.9% of the AP) in the Yanggok-ri subwatershed in the Geum River watershed from 2001 to 2018 [45]. Hence, the *NGRR* of the NRW is slightly greater than that of the Yanggok-ri subwatershed in the Geum River watershed, owing to the differences in the hydrogeological and climatic conditions. In addition, the NGRR of the NRW of 12.42–17.84% during 2009–2018 showed a much smaller variation than that of 3.6–28.2% in the Yanggok-ri subwatershed of the Geum River watershed during 2001–2018. In addition, the larger the watershed, the smaller the change in the *NGRR*. In this study, the mean of the *NGRR*s from 2009 to 2100 was 8.73% and 7.63%, respectively, using the RCP 4.5 and RCP 8.5 scenarios. In contrast, the *NGRR* of 26.7 mm to 432.5 mm (average 174.6 mm) in the Yanggok-ri subwatershed of the Geum

River watershed from 2019 to 2100 corresponds to 2.8–45.1% of the precipitation in 2100, based on the climate change scenario RCP 8.5 [38].

Looking at the change in the *NGRR* in the period of 2080–2100, the *NGRR* predicted by the climate change scenarios of the RCP 4.5 and RCP 8.5 is predicted to decrease from 13.73% to 7.05% and 14.43% to 5.90%, respectively. The *NGRR*s by the RCP 4.5 and RCP 8.5 scenarios are almost the same during 2009–2018, with a slight difference from the *NGRR* by the water budget analysis (Figure 8). Therefore, it is judged that the estimated values of *NGRR* in the climate change scenarios RCP 4.5 and RCP 8.5 are reasonable. Figure 9A shows the spatial distribution of the average *NGRR*s in the water budget analysis during 2009–2018. The *NGRR* showed high values in the eastern and southern regions but exhibited relatively low values in the inland areas, closely resembling precipitation distribution. In addition, the *NGRR* in the upstream area of the NRW was relatively smaller than that in the downstream area. On the other side, in Figure 9B, the *NGRR* distribution in 2080–2100 using the RCP 4.5 scenario shows overall higher values in the eastern region than those in the inland and southern areas, displaying a different spatial distribution of the *NGRR* from that using the water budget analysis in the period of 2009–2018 and showing smaller *NGRR*s than those by the water budget analysis.

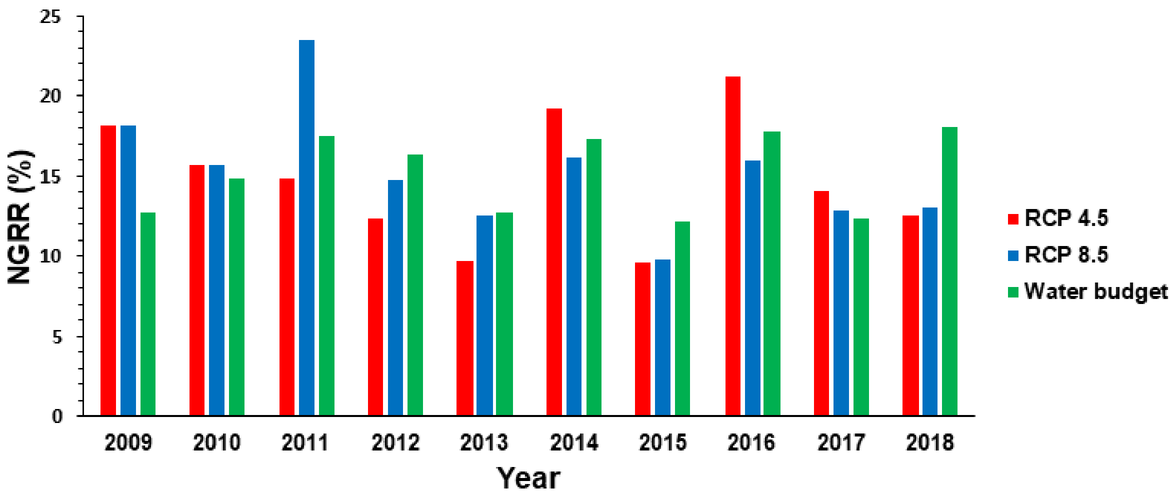

Figure 8. The NGRR (%) relative to the corresponding year from the water budget analysis and RCP 4.5 and 8.5 scenarios from 2009 until 2018.

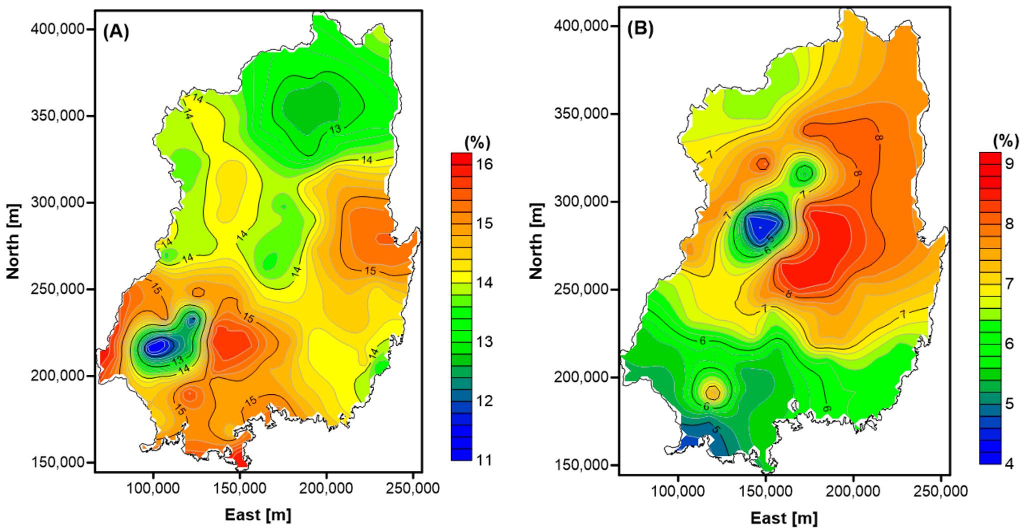

Figure 9. Distribution map of the average NGRRs in the Nakdong River watershed by (**A**) the water budget analysis of the period 2009–2018 and (**B**) the RCP 4.5 scenario in 2080–2100.

The estimated *NGRR* by the water budget analysis in this study possesses uncertainty due to using *PET* instead of *AET*, which can be estimated by considering soil water content [36,46,47]. A future study needs to reveal a more accurate *NGRR* in the NRW which was not possible due to insufficient data on soil water content. For the climate change scenarios, there is uncertainty about the specific yield (S_y), which is an average value (0.12) of the NRW since S_y is spatially different depending on geological formations in the NRW. Finally, the water budget analysis and the climate change scenarios also imply uncertainty due to not considering the effect of land cover change.

6. Conclusions

In this study, the change in the *NGRR* of the NRW was estimated using the water budget method and the climate change scenarios of RCP 4.5 and RCP 8.5. By using the water budget method and precipitation data from 2009 to 2018, direct runoff, evapotranspiration, and baseflow were estimated prior to determining the *NGRR*. The *DR* in the NRW by the SCS-CN method was calculated to be 183.21 mm (21.18%) to 372.25 mm (25.32%). The *PET* obtained by the Penman–Monteith method ranged from 452.27 mm (40.53%) to 605.59 mm (52.29%). The baseflow in the NRW using the baseflow separation method was 122.64 mm (12.42%) to 254.81 mm (17.84%).

The mean annual *NGRR* was determined to be 200 mm (15.66%) by subtracting the mean annual *DR* of 308 mm (24.12%), the mean annual *PET* of 567 mm (44.40%), and the mean annual *BF* of 202 mm (15.82%) from the mean annual precipitation of 1277 mm in the NRW for ten years (2009–2018), with an increasing trend in the *NGRR* over the ten years. The regional distribution of the *NGRR* showed high values in the eastern and southern regions but exhibited relatively low values in the inland areas, closely resembling precipitation distribution. In addition, the *NGRR* in the upstream area of the NRW was relatively smaller than that in the downstream area.

Under a decreased tendency of precipitation and the constant recharge ratio of the NRW, the mean *NGRR* for the entire NRW over the long term until 2100 is predicted to decrease from 13.73 to 7.05% based on the RCP 4.5 and from 14.43 to 5.90% based on the RCP 8.5. The *NGRR* distribution in 2080–2100 using the RCP 4.5 scenario shows overall high values in the eastern region and lower values in the inland and southern areas, similar to the spatial distribution of the *NGRR*, which displays a different spatial distribution of the *NGRR* from that using the water budget analysis in the period of 2009–2018, with smaller *NGRR* values than those by the water budget analysis.

The accuracy of the prediction of the *NGRR* according to the climate change scenarios RCP 4.5 and RCP 8.5 was verified by comparing the 2009 to 2018 water budget analysis and climate change scenarios. However, the robustness of the estimation of the *NGRR* is constrained by the uncertainty of the *PET*, the specific yield, and the land cover change. Therefore, it is judged that the estimated *NGRR* based on the climate change scenarios RCP 4.5 and RCP 8.5 was reasonable. The *NGRR* of the NRW presented in this study will be useful in the long-term development and management of groundwater resources in watersheds worldwide as well as in the NRW. Future research will focus on factors such as change in runoff, baseflow, and evapotranspiration over a long period.

Author Contributions: Conceptualization, S.-M.Y., H.-T.J. and S.-Y.H.; methodology, H.-T.J., J.-Y.C., S.-Y.H. and J.K.; software, S.-M.Y., H.-T.J. and J.-Y.C.; validation J.K. and S.-Y.H.; writing, original draft preparation, S.-M.Y., H.-T.J. and S.-Y.H.; writing, review and editing, J.-Y.C. and S.-Y.H.; visualization, S.-M.Y.; supervision, S.-Y.H.; project administration, S.-Y.H.; funding acquisition, S.-Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science and ICT (2020R1A2B5B02002198).

Data Availability Statement: Data is unavailable due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

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