water

Article

Assessment of Water Supply Stability for Drought-Vulnerable Boryeong Multipurpose Dam in South Korea Using Future Dry Climate Change Scenarios

Wonjin Kim [1], Jiwan Lee [1,*], Jinuk Kim [1] and Seongjoon Kim [2]

[1] Graduate School of Civil, Environmental and Plant Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Korea; compmp@konkuk.ac.kr (W.K.); saertt@konkuk.ac.kr (J.K.)
[2] School of Civil and Environmental Engineering, College of Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Korea; kimsj@konkuk.ac.kr
* Correspondence: closer01@konkuk.ac.kr; Tel.: +82-2-444-0186

Received: 4 September 2019; Accepted: 13 November 2019; Published: 15 November 2019

Abstract: This study assessed the water supply stability for Boryeong multipurpose dam by applying future dry climate change scenarios and Soil and Water Assessment Tool (SWAT). CMCC-CM, INM-CM4, and IPSL-CM5A-MR RCP 4.5 and 8.5 scenarios were selected as the future dry conditions using Runs theory and Standardized Precipitation Index (SPI). For historical (1980–1999), present (2000–2019), and future periods (2030s, 2050s, 2070s, and 2090s) of the 6 scenarios, SWAT model was used to simulate the future dam water supply stability. The stability was evaluated in terms of reliability (R_T), resilience (R_S), and vulnerability (V) based on the monthly target storage. The results showed that the future R_T can be decreased to 0.803 in 2050s IPSL-CM5A-MR RCP 8.5 scenario from present 0.955. The future R_S and V showed the minimum value of 0.003 and the biggest value of 3567.6×10^6 m^3 in 2070s IPSL-CM5A-MR RCP 4.5 scenario. The future R_T, R_S, and V showed that the dam has low resilience and is vulnerable to future drought scenarios.

Keywords: climate change; drought; dry scenario; SWAT; water supply; Runs theory; SPI

1. Introduction

Climate change is a major factor affecting watershed hydrological cycle that causes natural disasters such as flood and drought resulting in large-scale damage of human life and economic loss [1]. The exacerbation of seasonal rainfall in a changing climate may have profound effects on water resource systems and many attempts have been exercised to quantify drought. The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report [2] predicted that global average temperature would increase by 4.8 °C in 2100 in the case of business as usual greenhouse gas emissions. Particularly in South Korea, the average temperature is expected to increase up to 6 °C in 2100 compared to the present status. The changes will bring out significant influences on hydrologic behavior and it is necessary to predict and evaluate the effects of seasonal big variation on hydrologic environment and the water resources management [3–5].

Drought can be occurred depending on climatic characteristics and the water supply capacities from meteorological to agricultural, hydrological, and socioeconomic droughts [6]. The impact of climate change and drought are closely interrelated. Climate change is expected to increase the frequency and severity of droughts in some regions [7–9]. During the 20th century, South Korea has suffered severe drought with interval of 6 to 7 years. However, since 2000, the drought has been occurred 12 times and consecutively occurred from 2013 to 2018. Although the government has equipped the dam infrastructures to supply agricultural, municipal, and industrial water demands under the national economic development plan since 1965, the recent meteorological drought is threatening the safe water supply. The present dam operation by the frequent drought phenomena is now our challenge to overcome and should be adjusted by preparing the risk management of drought.

There are many future climate change scenarios of Global Circulation Models (GCMs) and Representative Concentration Pathways (RCPs). The Coupled Model Inter-comparison Project 5 (CMIP5) climate models have been used in South Korea because they consider Asian–Australian monsoon climate factor [10]. Many studies have studied the climate change impact on future dam inflow from watershed [11–15]. Studies of dam water supply satisfying water demands under future dam inflow and release conditions are necessary. The future dam water storage failure potential evaluation is necessary to observe how much the dam water supply is vulnerable to future coming droughts.

The impacts of climate change on water resources management has been studied with global, national, and regional scales [16–18]. The challenge considering dam water supply condition is to evaluate and quantify the water supply performance considering dam water uncertainties. One of the widely used water supply safety measures was introduced by Hashimoto et al. [19] with the 3 measures of reliability, resilience, and vulnerability. In the study, each criterion represents different performance of water supply behavior and they complement each other in understanding water supply safety. The 3 measures have been studied for water resources system design. Hurst [20], Matalas and Fiering [21], Moy et al. [22], and Vogel and Bolognese. [23] studied the parametric rules of measures performance and evaluated the dam water supply safety.

The semi-distributed physically based hydrologic model, Soil and Water Assessment Tool (SWAT) developed by the USDA-ARS (Agricultural Research Service) has been used to evaluate the impact of future climate change on watershed hydrology [24–28]. The SWAT has dam release simulation option using target release. The target release approach was applied in some studies to reflect reservoir operation [29,30].

This study is to evaluate the water supply safety of multipurpose dam applying future climate change conditions with SWAT. To reflect the future dry climate change, the Standardized Precipitation Index (SPI) and Runs theory were applied to determine dry scenarios from CMIP5 RCP 4.5 and 8.5 scenarios. Before future evaluation, the SWAT was calibrated using the observed dam inflow, release, and dam water storage data. The present target release of the dam was used for future dam release pattern. The future dam water supply safety through the 3 measures were estimated under the future potential drought scenarios.

2. Materials and Methods

2.1. Study Area Description

Figure 1 shows the Boryeong Dam located in the mid-west region of South Korea. The dam is 50 m height and has 108.7×10^6 m^3 of effective storage capacity with 163.6 km^2 watershed area. The Korea Water Resources Corporation (K-water) supplies municipal and industrial waters to three cities (Boryeong, Seosan, Dangjin), five counties (Seocheon, Cheongyang, Hongseong, Yesan, and Taean) and two electrical power plants (Dangjin and Seobu).

The dam watershed suffered severe meteorological droughts for 3 years (2015–2017) with average precipitation of 783.8 mm/year, approximately 60% of 40-year (1976–2015) average precipitation (1188 mm/year). The dam storage rate was about 47.5% at the beginning of 2015 but fell below 20% in September 2015 due to the lack of summer rain (June to August) and no autumn typhoon. By the continuing rainfall deficit, the dam storage rate reached 7.5%, the lowest value since the dam operation in 1998. This long period of drought caused the first restriction of municipal water supply from multipurpose dam operated by central government in South Korea. The government solved the suffering problem by installing water transfer pipelines from neighbour watershed stream.

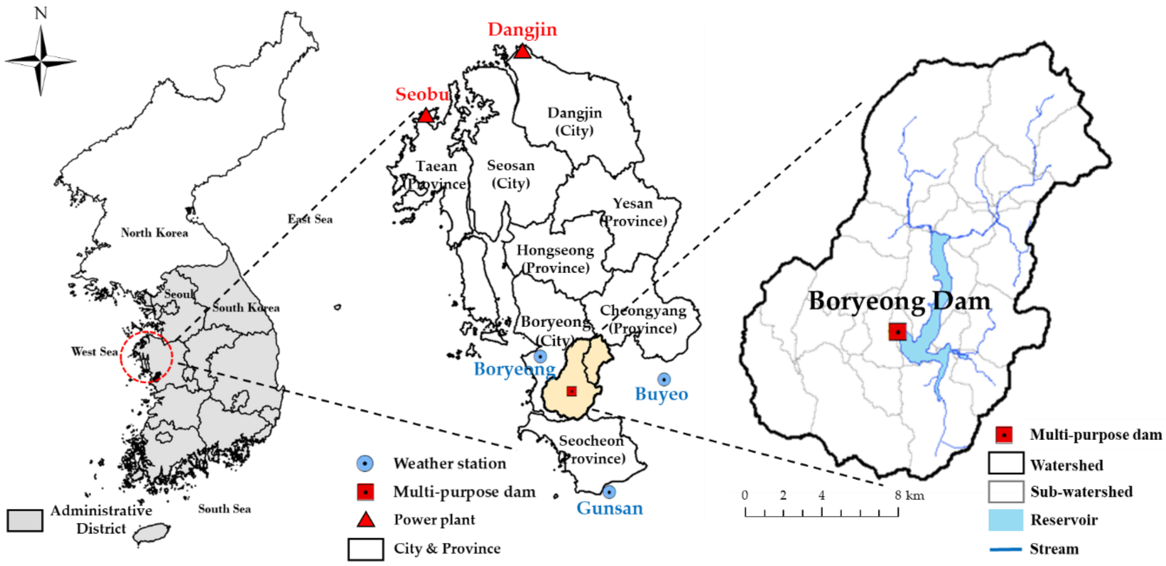


Figure 1. The studied Boryeong Dam watershed.

Figure 2 shows the elevation, soil texture, and land use of the dam watershed. Forest covers 71%, and rice paddy and upland crop areas occupies 12%. Silt loam and loam are the dominant soil types with 62% and 22% respectively.

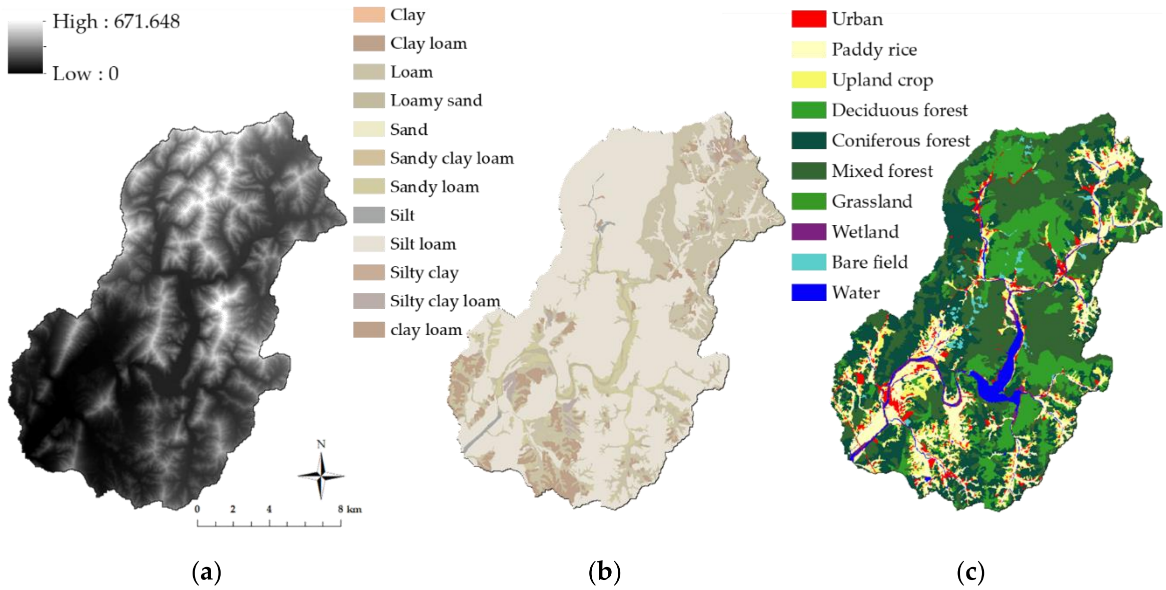


Figure 2. Study area Geographic Information System (GIS) spatial data. (**a**) Elevation; (**b**) Soil; (**c**) Land use.

6 years (2002–2007) of daily weather data including precipitation (mm), maximum and minimum temperatures (°C), wind speed (m/s), relative humidity (%), and solar radiation (MJ/m^2) were collected from 3 weather stations: Boryeong, Gunsan, and Buyeo (Figure 1) for SWAT modelling.

2.2. SWAT Model Description

SWAT is a watershed hydrology and water quality evaluation model developed to quantify the impact of land management practices [14]. The model operates by dividing the watershed into sub-watersheds with each sub-watershed being connected to stream channels. Sub-watersheds are further divided into Hydrological Response Units (HRUs) which are portions of a sub-watershed that possess unique land use, management, and soil attributes [31]. The simulation of the hydrological cycle is based on the water balance equation as follows:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw} \right)_i \quad (1)$$

where SW_t is the final soil water content (mm water); SW_0 is the initial soil water content of day i (mm water); t is the time (days); R_{day} is the amount of precipitation in day i (mm water); Q_{surf} is the amount of surface run-off in day i (mm water); E_a is the amount of evapotranspiration in day i (mm water); W_{seep} is the amount of water entering the vadose zone from the soil profile in day i (mm water); and Q_{gw} is the amount of return flow in day i (mm water).

The water balance for dams or floodgates considers inflow, outflow, precipitation, evapotranspiration, and seepage. The equation is expressed as:

$$V = V_{stored} + V_{flow\ in} - V_{flow\ out} + V_{pcp} - V_{evap} - V_{seep} \quad (2)$$

where V is the water storage in the reservoir at the end of each day; V_{stored} is the volume of water stored in the reservoir at the beginning of a day; $V_{flow\ in}$ and $V_{flow\ out}$ are the volumes of water entering and flowing out of the reservoir throughout a day, respectively; and V_{pcp}, V_{evap}, and V_{seep} are the volumes of precipitation falling into the reservoir, the water removed by evaporation and the water lost by seepage, respectively.

SWAT has four available dam release ($V_{flow\ out}$) options: Daily measured outflow, monthly measured outflow, annual average release, and target release. Among these options, the target release approach was adopted. Although the method is simplistic and cannot account for all decisions, it can realistically simulate major outflows. For the target release approach, the reservoir outflow is calculated as follows:

$$V_{flow\ out} = \frac{V - V_{targ}}{ND_{targ}} \quad (3)$$

where $V_{flow\ out}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the reservoir (m^3 H_2O), V_{targ} is the target reservoir volume for a given day (m^3 H_2O) and ND_{targ} is the number of days required for the reservoir to reach the target storage.

2.3. Selecting Future Dry Scenarios

The selection of a GCM is very important when carrying out studies on watershed hydrology and the related water resource facilities. GCM assessment results are sensitive and carry uncertainty into the study, especially for studies of future drought conditions. To overcome the inability to properly validate a given GCM scenario, this study tried to select the appropriate GCMs for predicting future drought likelihood. The Coupled Model Inter-comparison Project (CMIP) Phase 5 proposed 4 representative concentration pathways (RCP) considering economic growth rate, industrialization and restoration technology. In this study, we adopted the RCP 4.5 and 8.5 scenarios and tested 26 GCMs (Table 1) to select the dry scenarios by applying the SPI and Runs theory.

Table 1. Description of the 26 Coupled Model Inter-comparison Project 5 (CMIP5) Global Circulation Models (GCMs).

Number	GCMS	Grid Cells (km × km)	Reference
1	CMCC-CM	22 × 18	Centro Euro-Mediterraneo per I Cambiamenti Climatici
2 3 4	CCSM4 CESM1-BGC CESM1-CAM5	13 × 15 13 × 15 13 × 15	National Center for Atmospheric Research
5	BCC-CSM1-1-M	15 × 12	Beijing Climate Center, China Meteorological Administration
6	MRI-CGCM3	15 × 12	Meteorological Research Institute
7	CNRM-CM5	12 × 10	Centre National de Recherches Meteorologiques
8	MIROC5	12 × 10	Atmosphere and Ocean Research Institute
9	HadGEM2-AO	9 × 11	Met Office Hadley Centre
10	HadGEM2-CC	9 × 11	Beijing Climate Center, China Meteorological Administration
11	HadGEM2-ES	9 × 11	Meteorological Research Institute
12	INM-CM4	8 × 10	Institute for Numerical Mathematics
13	IPSL-CM5A-MR	7 × 11	Institut Pierre-Simon Laplace
14	CMCC-CMS	9 × 7	Centro Euro-Mediterraneo per I Cambiamenti Climatici
15 16	MPI-ESM-LR MPI-ESM-MR	9 × 7 9 × 7	Max Planck Institute for Meteorology (MPI-M)
17	FGOALS-s2	6 × 9	Institute of Atmospheric Physics, Chinese Academy of Sciences
18	NorESM1-M	7 × 8	Norwegian Climate Centre
19 20	GFDL-ESM2G GFDL-ESM2M	6 × 7 6 × 7	Geophysical Fluid Dynamics Laboratory
21 22	IPSL-CM5A-LR IPSL-CM5B-LR	5 × 8 5 × 8	Institut Pierre-Simon Laplace
23	BCC-CSM1-1	6 × 5	Beijing Climate Center, China Meteorological Administration
24	CanESM2	6 × 5	Canadian Centre for Climate Modeling and Analysis
25 26	MIROC-ESM-CHEM MIROC-ESM	6 × 5 6 × 5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo, and National Institute for Environmental Studies)

The SPI developed by McKee et al. [32] is an indicator of meteorological drought which quantifies the precipitation deficit with multiple time scales from 1 month to 48 months, with categories of near normal (+0.99 ~ −0.99), moderately dry (−1.0 ~ −1.49), severely dry (−1.5 ~ −1.99), and extremely dry (below −2.0). The SPI for drought in South Korea has been studied [33–35], and the results show that SPIs at 3 and 6 months (SPI-3 and SPI-6) are suitable for representing the spring agricultural drought from March to May and the hydrologic drought extending over the next three months. These droughts affect reservoir storage and withdrawals from streamflow, as well as the socioeconomic drought via the limited municipal and industrial water supplies [36]. In this study, SPI-6 was selected to consider the reservoir storage deficit and the resulting limited water supply from the dam.

The Runs theory was proposed to evaluate drought parameters and observe their statistical results in the distribution of water deficits. The parameters are derived below a truncation level, which may be constant or a function of time. In this study, the theory was applied to quantify the degree of water supply failure in future climate scenarios. Three indices (drought severity, duration, and magnitude) were used in the quantification. They represent the different characteristics of water supply failure. The general expression of each index is as follows:

$$M = S/D \tag{4}$$

$$S = \sum_{i-start}^{end} SRS_i \tag{5}$$

$$SRS_i = truncation\ level - criterion_i \tag{6}$$

$$D = final\ day - initial\ day\ (criterion_i < truncation\ level) \tag{7}$$

where M is the magnitude; S is the severity, which is the sum of SRS_i in the study period; D is the duration, which is the number of days of one deficit event where the criterion is continuously smaller than the truncation level; SRS_i is the difference between the *truncation level* and the $criterion_i$; the *truncation level* is the SPI value at which severe drought begins; and the $criterion_i$ is the SPI value of the ith day.

Using 26 GCMs, the future dry scenarios were selected using the following three steps. First, the three parameters (magnitude, duration, and severity) of Runs theory corresponding to each scenario were calculated using the SPI at 6 months. Second, the parameters were transformed into cumulative distribution functions in the 0 to 1 range (because their units are not dimensionally consistent). Third, the parameters were summed and ranked assuming that each parameter had equal weight for affecting dryness.

2.4. Measures of Dam Water Supply Safety

Hashimoto et al. [19] suggested three metrics for evaluating the possible performance of water resource systems: Reliability, resilience, and vulnerability. Reliability describes how likely a system is to fail; resilience refers to how quickly a system recovers from failure; and vulnerability refers to how severe the consequences of failure may be. Furthermore, there are additional methods for evaluating the sustainability of water resources systems.

Reliability is the probability or frequency of success in a system. Time-based and occurrence-based reliability were evaluated in the study. The difference between the two measures is the time-step consideration. Time-based reliability counts the number of days that the system was in a satisfactory state during the study period, and occurrence-based reliability considers the number of years. A general expression for estimating reliability is:

$$R_T = \frac{\sum_{t=1}^{T} Z_t}{T} \tag{8}$$

where R_T is reliability, $t = 1 \ldots, T$ is a simulated time series, and Z_t is a state variable which equals 1 when the system is in a satisfactory state and 0 when the system is in an unsatisfactory state. The system is in an unsatisfactory state when the dam storage is lower than the pre-determined dam water level, otherwise the system is in a satisfactory state.

Resilience describes how quickly the system can recover from an unsatisfactory state within a given time period. If the failure recovery is slow and prolonged, it implies that re-examination of the dam performance should occur so that the system can recover rapidly after failure. The general equation for resilience is:

$$R_s = \frac{\sum_{t=1}^{T-1} W_t}{T - \sum_{t=1}^{T} Z_t} \tag{9}$$

where R_s is resilience, T is the total duration of the study period, and W_t is a transition indicator which has a value of 1 when the system is in an unsatisfactory state in the tth time-step and transitions to a satisfactory state in the t + 1th timestep. Otherwise, W_t is 0.

Vulnerability represents how severe the results of failure are. It is expressed as follows:

$$V = \frac{max\left\{\sum_{t\in J_i} C - X_t,\ i = 1,\ldots,N\right\}}{\sum_{t=1}^{T-1} W_t} \tag{10}$$

where V is vulnerability, X_t is the dam storage at the tth time-step, C is the low water level of the target dam, and $J_i, \ldots, J_N$ are periods of unsatisfactory states.

3. Results and Discussion

3.1. SWAT Calibration and Validation

SWAT was calibrated (2002–2004) and validated (2005–2007) using the daily observed dam inflow and storage data. The hydrological parameters of the SCS curve number, soil evaporation compensation coefficient, maximum canopy storage, delay time for aquifer recharge, and baseflow recession constant were calibrated for dam inflow, hydraulic conductivity of the reservoir bottom, and lake evaporation coefficient for dam storage.

Table 2 shows the summary of the SWAT calibrated parameters. The important parameters were surface runoff CN2, evapotranspiration ESCO, baseflow GW_DELAY, GWQMN, and ALPHA_BF. Seven reservoir parameters (RES_ESA, RES_EVOL, RES_PSA, RES_PVOL, RES_VOL, RES_K, and EVRSV) were calibrated.

Table 3 shows the statistical summary of SWAT calibration and validation results for dam inflow and storage. Figure 3 shows the comparison of 3a observed vs. simulated dam inflow and 3b observed vs. simulated dam storage using observed dam release and 3c observed vs. simulated dam storage by applying SWAT monthly target release respectively. The average Root Mean Square Error (RMSE) of 3a–c were 1.80 m^3/s, 0.67 × 10^6 m^3, and 0.46 × 10^6 m^3, the average Nash–Sutcliffe model Efficiency (NSE) were 0.52, 0.96, and 0.98, the PBIAS were −0.04%, −0.09%, and +0.02% respectively. The error of dam inflow influenced the dam storage simulation. The big error of dam storage was caused by the storm inflow and the error continued to the next storm event.

Table 2. The Soil and Water Assessment Tool (SWAT) calibrated parameters for dam inflow and storage.

Parameters	Definition	Default	Range		Adjusted Value
			UB	LB	
Surface Runoff					
CN2	SCS Curve Number for moisture condition	Given by HRU	0	100	10 (Add)
Evapotranspiration					
CANMX	Maximum canopy storage (mm)	0	0	100	7 (Replace)
ESCO	Soil evaporation compensation coefficient	0.95	0	1	0.95 (Replace)
Groundwater					
GW_DELAY	Delay time for aquifer recharge (days)	31	0	500	100 (Replace)
ALPHA_BF	Baseflow recession constant	0.048	0	1	0.048 (Replace)

Table 2. *Cont.*

Parameters	Definition	Default	Range		Adjusted Value
			UB	LB	
Reservoir					
RES_ESA	Reservoir surface area when the reservoir is filled to the emergency spillway (ha)	-	-	-	690 (Replace)
RES_EVOL	Volume of water needed to fill the reservoir to the emergency spillway (10^4 m^3)	-	-	-	11,335.5 (Replace)
RES_PSA	Reservoir surface area when the reservoir is filled to the principal spillway (ha)	-	-	-	672 (Replace)
RES_PVOL	Volume of water needed to fill the reservoir to the principal spillway (10^4 m^3)	-	-	-	10,693.3 (Replace)
RES_VOL	Initial reservoir volume (10^4 m^3)	-	-	-	8997.8 (Replace)
RES_K	Hydraulic conductivity of the reservoir bottom (mm/h)	0.6	0	1	0.7 (Replace)
EVRSV	Lake evaporation coefficient	0.6	0	1	0.6 (Replace)

UB: Upper Bound, LB: Lower Bound.

Table 3. The statistical summary of SWAT calibration and validation for dam inflow and storage.

Year	Dam Inflow			Dam Storage Using Daily Release Data			Dam Storage by Monthly Target Release		
	RMSE (m^3/s)	NSE	PBIAS (%)	RMSE (10^6 m^3)	NSE	PBIAS (%)	RMSE (10^6 m^3)	NSE	PBIAS (%)
Cal (2002~2004)	+2.08	+0.48	+0.01	+0.54	+0.98	+0.00	+0.63	+0.96	+0.03
Val (2005~2007)	+1.51	+0.57	−0.09	+0.80	+0.94	−0.24	+0.29	+0.99	+0.01
Average	+1.80	+0.52	−0.04	+0.67	+0.96	−0.09	+0.46	+0.98	+0.02

Cal: Calibration Period, Val: Validation Period, RMSE: Root Mean Square Error. NSE: Nash–Sutcliffe model Efficiency.

Figure 4 shows the monthly target release and storage now managed by K-water. This was applied for future dam release. The minimum outflow shows the downstream river maintenance flow rate. The maximum outflow includes the municipal and industrial water supply. The maximum outflows from June to September have much bigger values than other months because of flood control during rainy season in South Korea. The 21.7 m^3/s maximum outflow in July considers the prevention of overbank flooding by dam release.

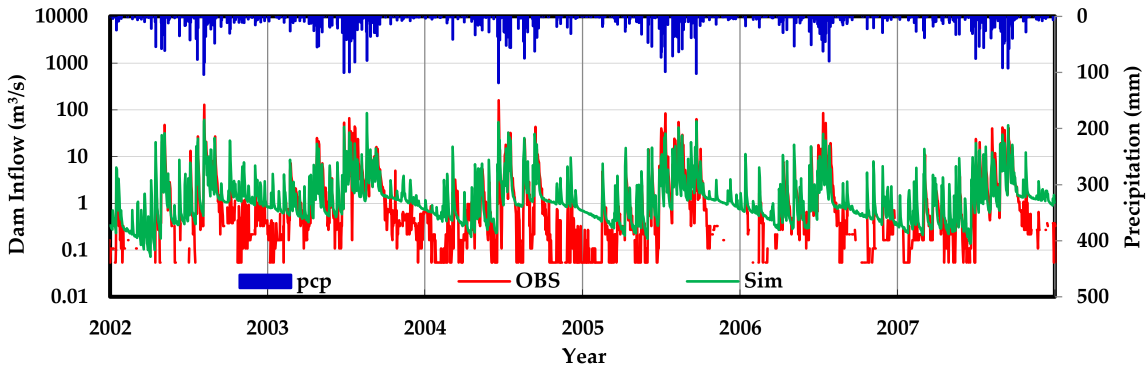
3.2. Selected Future Dry Climate Scenarios

Figure 5 shows the result charts expressing dryness with severity, duration, and magnitude for RCP 4.5 and 8.5 scenarios of 26 CMIP5 GCMs. From left to right direction, the scenarios were ranked from dry to wet. The INM-CM4 and BCC-CSM1-1-M were the driest scenarios in RCP 4.5 and 8.5 scenarios respectively. The three GCMs of CMCC-CM, INM-CM4, and IPSL-CM5A-MR were all included within the top 10 dryness ranking in both RCP 4.5 and 8.5 scenarios. Thus the 6 scenarios for 3 GCMs were selected for the future Boryeong Dam water supply stability evaluation.

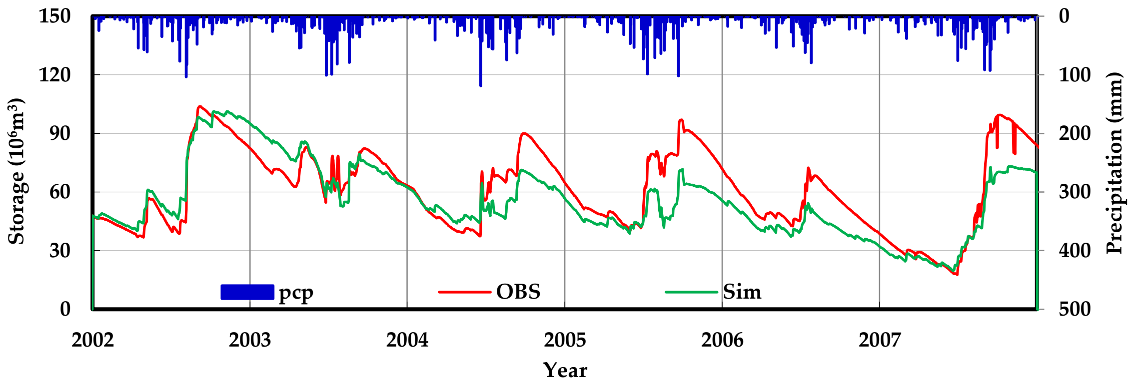
Since the Boryeong Dam was designed to endure drought for 20-year return period, the evaluation periods were divided into 20-year interval from historical period (1980–1999), present period (2000–2019), and future periods (2030s: 2020–2039, 2050s: 2040–2059, 2070s: 2060–2079, and 2090s: 2080–2099). SWAT evaluated the simulation performance of dam inflow for the 6 scenarios. Table 4 shows the statistical summary of dam inflow simulation using each scenario of the historical period. The RMSE are in the range of 2.51 to 3.04 m^3/day and the PBIAS showed the range from −13.26 to +7.27%.

Table 4. The statistical results of dam inflow with the selected climate change scenarios applied.

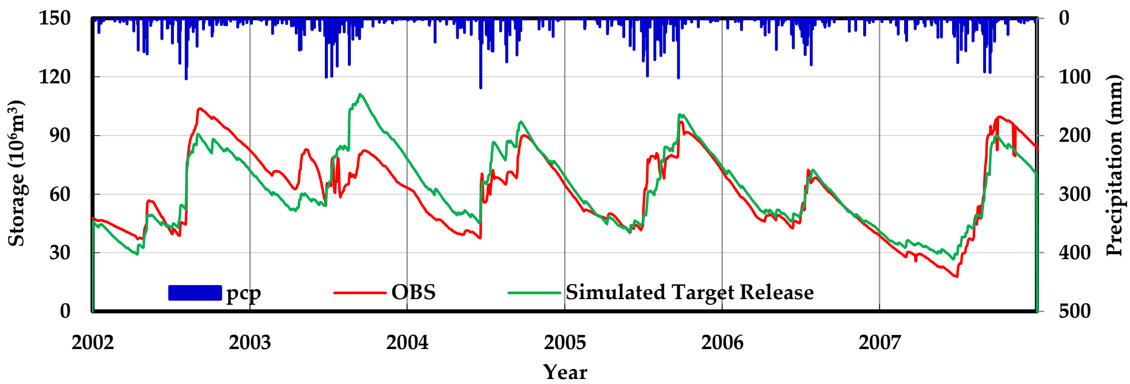
Index	RCP 4.5			RCP 8.5		
	CMCC-CM	INM-CM4	IPSL-CM5A-MR	CMCC-CM	INM-CM4	IPSL-CM5A-MR
RMSE (m^3/day)	2.60	2.73	3.01	2.51	3.04	2.59
PBIAS (%)	−3.05	+3.64	−13.26	+7.27	−0.14	−2.86



(**a**)



(**b**)



(**c**)

Figure 3. Comparison of daily observed and simulated dam inflow (**a**), dam storage using observed release data (**b**), and dam storage estimated by applying the monthly target release (**c**).

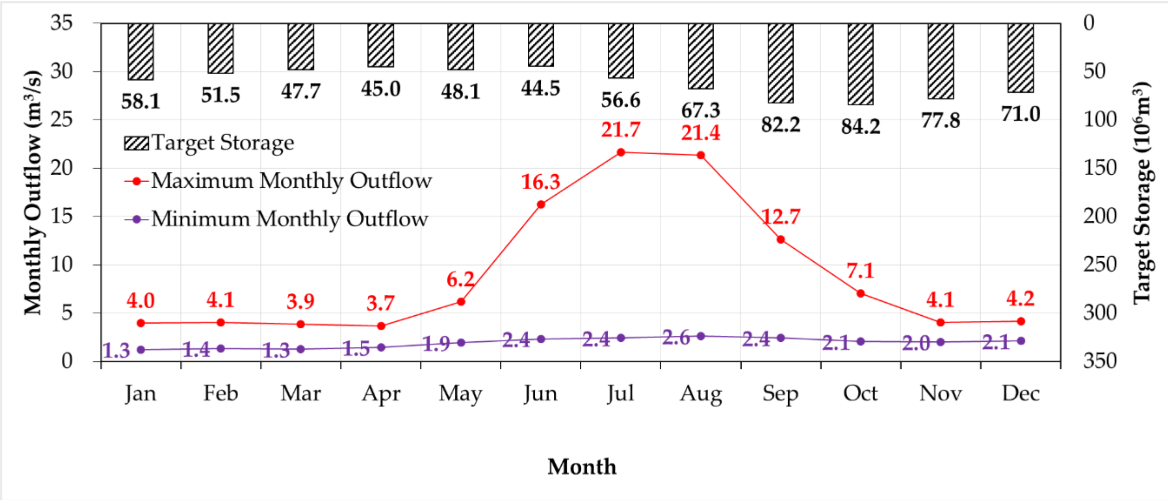
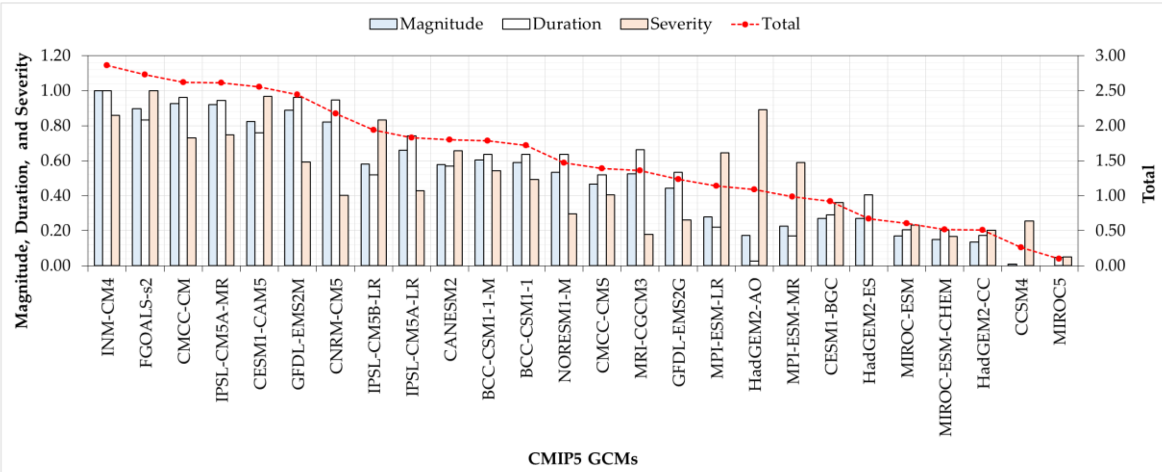
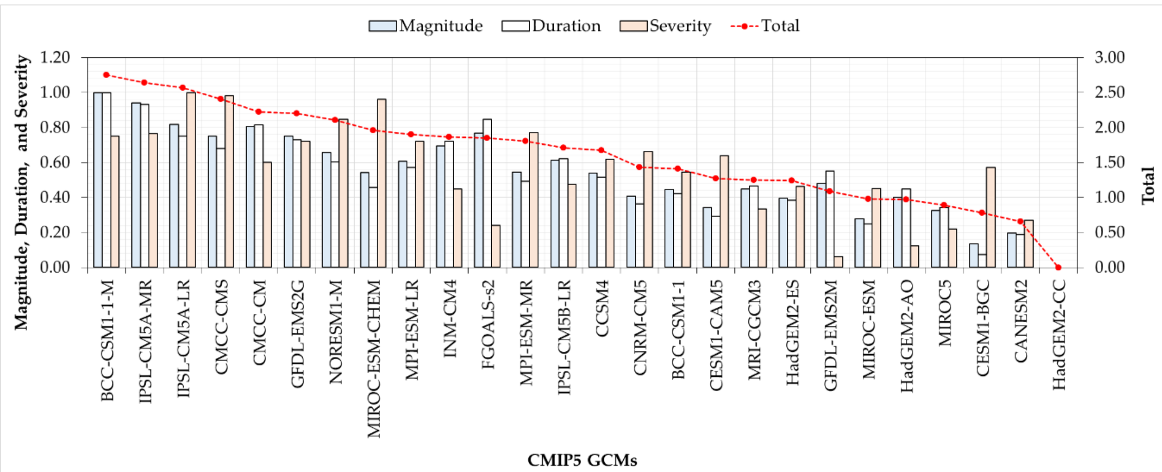


Figure 4. Monthly dam outflows for future target releases.



(**a**)



(**b**)

Figure 5. The dryness ranking of Representative Concentration Pathway (RCP) 4.5 (**a**) and 8.5 (**b**) scenarios for the 26 CMIP5 GCMs (Total = Magnitude + Duration + Severity).

The SPI-6 of present, 2030s, 2050s, 2070s, and 2090s periods for the 6 scenarios was evaluated. Table 5 shows the average value below −1.5 of SPI-6 and the count days for present and future periods.

The INM-CM4 and IPSL-CM5A-MR for both RCP 4.5 and 8.5 scenarios had the overall increase day for SPI-6 below −1.5 from present to future periods. The CMCC-CM scenario had the day increase in 2030s RCP 4.5 and 2070s RCP 8.5 comparing with present days of SPI-6 below −1.5.

Table 5. The average value below −1.5 of SPI-6 and the count days during each period for present and future periods.

Period	RCP 4.5						RCP 8.5					
	CMCC-CM		INM-CM4		IPSL-CM5A-MR		CMCC-CM		INM-CM4		IPSL-CM5A-MR	
	Ave.	Days	Ave.	Days	Ave.	Days	Ave.	Days	Ave.	Days	Ave.	Days
Present	−2.09	602	−1.98	287	−1.93	340	−2.06	576	−1.83	367	−2.00	469
2030s	−2.11	685	−1.86	491	−1.83	592	−1.82	319	−2.18	386	−1.86	460
2050s	−1.73	464	−1.96	587	−2.01	609	−1.77	453	−1.86	696	−1.73	524
2070s	−1.76	314	−2.05	423	−2.01	457	−1.81	664	−1.81	464	−1.87	483
2090s	−1.72	339	−1.95	640	−1.89	396	−1.95	444	−1.70	452	−2.08	633

Present: 2000–2019, 2030s: 2020–2039, 2050s: 2040–2059, 2070s: 2060–2079, 2090s: 2080–2099, Ave.: The average value below −1.5 of SPI-6.

3.3. Evaluation of the Boryeong Dam Water Supply Stability for 6 Future Dry Scenarios

Figure 6 shows the reservoir management standard for the Boryeong Dam with 4 stages of dam storage conditions including attention, caution, alert, and serious. Table 6 lists the dam water supply plan when reservoir storage is under drought conditions. Based on Figure 6, Table 6, and the SWAT simulation results, the reliability (R_T), resilience (R_S), and vulnerability (V) of the Boryeong Dam was evaluated with respect to the likelihood of entering the serious storage condition stage using 6 future scenarios.

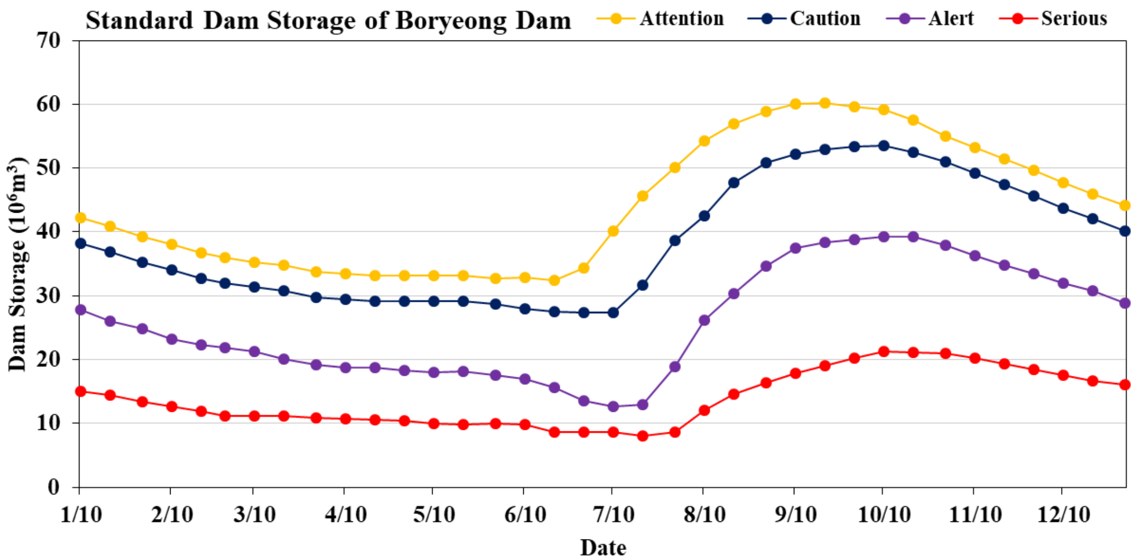


Figure 6. The reservoir management standard for Boryeong Dam with 4 stages dam storage conditions: attention, caution, alert, and serious.

Table 6. The dam water supply plan when reservoir storage is under drought conditions.

Response Plan	Water Supply	Restriction
Attention	Supply 80%–90% of basic plan	Supply actual demand of domestic/industrial water, agricultural water and river maintenance water
Caution	Supply 60%–80% of basic plan	Restriction on river maintenance water supply
Alert	Supply 50%–60% of basic plan	Restriction on river maintenance water and agricultural water supply
Serious	Supply less than 50% of basic plan	Restriction on domestic/industrial water, agricultural water, and river maintenance water supply

Table 7 shows the results of R_T, R_S, and V of each period for the 6 future dry scenarios. As mentioned earlier, the Boryeong Dam was built to endure drought for 20-year return period. This means that the R_T of the dam should be maintained higher than 0.95. As seen in Table 7, the R_T in historical period was above 0.95 for the 6 scenarios. The R_T below 0.95 in the present period showed 2 times in CMCC-CM RCP 4.5 and 8.5 scenarios. The R_T below 0.95 in each period of 2030s, 2050s, 2070s, and 2090s appeared 1, 3, 2, and 2 times respectively. The future R_T had the lowest value of 0.913, 0.887, and 0.803 for 2090s CMCC-CM RCP 8.5, 2030s INM-CM4 RCP 8.5, and 2050s IPSL-CM5A-MR RCP 8.5 scenarios respectively.

Table 7. The evaluation results of the Boryeong Dam water supply safety for 6 future dry scenarios.

	Period	RCP 4.5			RCP 8.5		
		CMCC-CM	INM-CM4	IPSL-CM5A-MR	CMCC-CM	INM-CM4	IPSL-CM5A-MR
Reliability (R_T)	Historical	1.000	1.000	0.964	1.000	1.000	0.964
	Present	0.928	1.000	1.000	0.928	0.997	0.955
	2030s	0.954	0.963	0.990	0.992	0.887	0.949
	2050s	0.924	0.990	0.974	0.997	0.914	0.803
	2070s	0.949	0.920	0.959	0.949	0.903	0.974
	2090s	0.978	0.932	0.993	0.913	0.996	0.959
Resilience (R_S)	Historical	1.000	1.000	0.015	1.000	1.000	0.015
	Present	0.009	1.000	1.000	0.009	0.087	0.006
	2030s	0.015	0.011	0.042	0.082	0.011	0.008
	2050s	0.020	0.081	0.042	0.045	0.014	0.005
	2070s	0.019	0.009	0.003	0.019	0.020	0.005
	2090s	0.025	0.006	0.039	0.017	0.031	0.010
Vulnerability (V) (10^6 m^3)	Historical	0.0	0.0	266.2	0.0	0.0	266.2
	Present	262.8	0.0	0.0	262.8	18.4	1848.0
	2030s	591.8	756.5	39.1	24.1	666.3	1226.4
	2050s	349.4	18.1	16.4	47.8	305.1	794.1
	2070s	467.4	785.5	3567.6	216.1	50.9	1525.5
	2090s	47.2	633.1	51.6	203.4	85.2	977.1

As seen in Table 7, the low R_S below 0.1 appeared 2 and 4 times in historical and present periods respectively. The future R_S showed values below 0.1 for all periods from 2030s to 2090s with the range of 0.015~0.082 in CMCC-CM, 0.006~0.081 in INM-CM4, and 0.003~0.042 in IPSL-CM5A-MR scenarios. Similarly, the V greater than zero in historical and present periods appeared 2 and 4 times for the same scenarios of R_S below 0.1. The future V showed values above zero for all periods from 2030s to 2090s with the range of 24.1~591.8 × 10^6 m^3, 18.1~785.5 × 10^6 m^3, and 16.4~3567.6 × 10^6 m^3 respectively. The future V showed the biggest values of 591.8 and 3567.6 × 10^6 m^3 for 2030s CMCC-CM RCP 4.5 and 2070s IPSL-CM5A-MR RCP 4.5 scenarios respectively while the R_S was the lowest values of 0.015 and 0.003 for the same scenario period.

4. Conclusions

The climate change impacts on water supply safety of Boryeong multipurpose dam was evaluated using future dry scenarios and SWAT. The future dry climate change scenarios were selected using Runs theory with SPI, meteorological drought severity, duration, and magnitude. The 6 future dry scenarios were applied to SWAT using the module of monthly target release from the dam. Using the SWAT results, the reliability (R_T), resilience (R_S), and vulnerability (V) for the entry of serious storage stage of Boryeong Dam were estimated.

Since the dam was designed to endure drought for 20-year return period, the evaluation periods were divided into 20-year interval from historical period (1980–1999), present period (2000–2019), and future periods (2030s: 2020–2039, 2050s: 2040–2059, 2070s: 2060–2079, and 2090s: 2080–2099).

The RCP 4.5 and 8.5 scenarios of 26 CMIP5 GCMs were tested for dryness with severity, duration, and magnitude. Among them, the 3 GCMs of CMCC-CM, INM-CM4, and IPSL-CM5A-MR were selected because both RCP 4.5 and 8.5 scenarios were all included within top 10 future dryness characteristics. The INM-CM4 and IPSL-CM5A-MR for both RCP 4.5 and 8.5 scenarios showed the days increase for SPI-6 below -1.5 from present to future periods.

The SWAT results showed that the future R_T was below 0.95 (threshold value for the 20-year return period drought) 9 times, while the R_T in the historical period was above 0.96. All the values of R_S in the future were less than 0.082, implying very weak resilience. The relationship between R_S and V was observed to be inversely proportional. The V of the 2070s IPSL-CM5A-MR RCP 4.5 scenario showed the largest value of 3567.6×10^6 m^3 while the R_S was the lowest, at 0.003. Overall, the predicted future dam resilience was lower and vulnerability was higher compared to the historical and present periods.

Under the future dry climate conditions, the Boryeong Dam showed unstable water supply fulfillment in many future periods in terms of reliability, resilience, and vulnerability. It is necessary to prepare the future coming droughts by adjusting present monthly target storage and release, dam reinforcement, and water import from neighbor watershed.

In this study, the present monthly target release was used for future dam storage simulation and to evaluate the future reservoir stability. The future water demands were assumed to be unchanged. Thus, further researches are necessary to consider future predicted water demands and apply reservoir operation model to mimic future dam release such as HEC-ResSim (Hydrologic Engineering Center-Reservoir System Simulation) [37].

Author Contributions: Data curation, J.L.; Investigation, J.K.; Supervision, S.K.; Writing—review and editing, W.K.

Funding: This subject is supported by the Korean Ministry of the Environment (MOE) as the "Water Management Research Program (79617)", and this work was supported by the "University Innovation Grant" from the Ministry of Education and the National Research Foundation of Korea.

Acknowledgments: This manuscript was also edited for English language by American Journal Experts (AJE).

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

References

1. Chen, R.S.; Boulding, E.; Schneider, S.H. *Social Science Research and Climate Change*; D. Reidel: Dordrecht, The Netherlands, 1983.
2. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: The Physical Science Basis, IPCC Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.
3. Gleick, P.H. Climate change, hydrology, and water resources. *Rev. Geophys.* **1989**, *27*, 329–344. [CrossRef]
4. Wood, A.W.; Lettenmaier, D.P.; Palmer, R.N. Assessing climate change implications for water resources planning. *Clim. Chang.* **1997**, *37*, 203–228. [CrossRef]

5. Joh, H.-K.; Lee, J.-W.; Park, M.-J.; Shin, H.-J.; Yi, J.-E.; Kim, G.-S.; Srinivasan, R.; Kim, S.-J. Assessing climate change impact on hydrological components of a small forest watershed through SWAT calibration of evapotranspiration and soil moisture. *Trans. ASABE* **2011**, *54*, 1773–1781. [CrossRef]
6. Wilhite, D.A. Drought as a natural hazard: Concepts and definitions. In *Drought*; Wilhite, D.A., Ed.; Drought Mitigation Center Faculty Publications: London, UK, 2000; pp. 3–18.
7. Kelley, C.P.; Mohtadi, S.; Cane, M.A.; Seager, R.; Kushnir, Y. Climate change in the fertile crescent and implications of the recent Syrian drought. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 3241. [CrossRef] [PubMed]
8. Madadgar, S.; Moradkhani, H. Drought analysis under climate change using copula. *J. Hydrol. Eng.* **2013**, *18*, 746–759. [CrossRef]
9. Trenberth, K.E.; Dai, A.; van der Schrier, G.; Jones, P.D.; Barichivich, J.; Briffa, K.R.; Sheffield, J. Global warming and changes in drought. *Nat. Clim. Chang.* **2013**, *4*, 17–22. [CrossRef]
10. Sperber, K.R.; Annamalai, H.; Kang, I.S.; Kitoh, A.; Moise, A.; Turner, A.; Wang, B.; Zhou, T. The Asian summer monsoon: An intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Clim. Dyn.* **2013**, *41*, 2711–2744. [CrossRef]
11. Andersson, L.; Wilk, J.; Todd, M.C.; Hughes, D.A.; Earle, A.; Kniveton, D.; Layberry, R.; Savenije, H.H.G. Impact of climate change and development scenarios on flow patterns in the Okavango River. *J. Hydrol.* **2006**, *331*, 43–57. [CrossRef]
12. Park, J.Y.; Kim, S.J. Potential impacts of climate change on the reliability of water and hydropower supply from a multipurpose dam in South Korea. *JAWRA J. Am. Water Resour. Assoc.* **2014**, *50*, 1273–1288. [CrossRef]
13. Park, J.-Y.; Yu, Y.-S.; Hwang, S.-J.; Kim, C.; Kim, S.-J. SWAT modeling of best management practices for Chungju dam watershed in South Korea under future climate change scenarios. *Paddy Water Environ.* **2014**, *12*, 65–75. [CrossRef]
14. Park, M.J.; Ha, R.; Kim, N.W.; Lim, K.J.; Kim, S.J. Assessment of future climate and vegetation canopy change impacts on hydrological behavior of Chungju dam watershed using SWAT model. *KSCE J. Civ. Eng.* **2014**, *18*, 1185–1196. [CrossRef]
15. Jeong, H.G.; Kim, S.-J.; Ha, R. Assessment of climate change impact on storage behavior of Chungju and the regulation dams using SWAT model. *J. Korea Water Resour. Assoc.* **2013**, *46*, 1235–1247. [CrossRef]
16. Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.; Peng, S.; Li, J.; Zhou, L.; Liu, H.; Ma, Y.; Ding, Y.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [CrossRef] [PubMed]
17. Schewe, J.; Heinke, J.; Gerten, D.; Haddeland, I.; Arnell, N.W.; Clark, D.B.; Dankers, R.; Eisner, S.; Fekete, B.M.; Colón-González, F.J.; et al. Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3245. [CrossRef] [PubMed]
18. Sowers, J.; Vengosh, A.; Weinthal, E. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Clim. Chang.* **2011**, *104*, 599–627. [CrossRef]
19. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [CrossRef]
20. Hurst, H.E. Long-term storage capacity of reservoirs. *Trans. Am. Soc. Civ. Eng.* **1951**, *116*, 770–808.
21. Matalas, N.C.; Fiering, M.B. *Water Resources Systems Planning in Climate, Climate Change, and Water Supply*; National Academy of Sciences: Washington, DC, USA, 1977.
22. Moy, W.-S.; Cohon, J.L.; ReVelle, C.S. A Programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir. *Water Resour. Res.* **1986**, *22*, 489–498. [CrossRef]
23. Vogel, R.M.; Bolognese, R.A. Storage-reliability-resilience-yield relations for over-year water supply systems. *Water Resour. Res.* **1995**, *31*, 645–654. [CrossRef]
24. Arnold, J.G.; Williams, J.R.; Maidment, D.R. Continuous-time water and sediment-routing model for large basins. *J. Hydraul. Eng.* **1995**, *121*, 171–183. [CrossRef]
25. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment part I: Model development1. *JAWRA J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
26. Shi, P.; Chen, C.; Srinivasan, R.; Zhang, X.; Cai, T.; Fang, X.; Qu, S.; Chen, X.; Li, Q. Evaluating the SWAT Model for hydrological modeling in the Xixian watershed and a comparison with the XAJ model. *Water Resour. Manag.* **2011**, *25*, 2595–2612. [CrossRef]
27. Narsimlu, B.; Gosain, A.K.; Chahar, B.R. Assessment of future climate change impacts on water resources of Upper Sind river basin, India using SWAT Model. *Water Resour. Manag.* **2013**, *27*, 3647–3662. [CrossRef]

28. Kim, B.S.; Kim, H.S.; Seoh, B.H.; Kim, N.W. Impact of climate change on water resources in Yongdam Dam Basin, Korea. *Stoch. Environ. Res. Risk Assess.* **2007**, *21*, 457. [CrossRef]
29. Fu, C.; James, A.L.; Yao, H. SWAT-CS: Revision and testing of SWAT for Canadian shield catchments. *J. Hydrol.* **2014**, *511*, 719–735. [CrossRef]
30. Kim, N.W.; Lee, J.E.; Kim, J.T. Assessment of flow regulation effects by dams in the Han River, Korea, on the downstream flow regimes using SWAT. *J. Water Resour. Plan. Manag.* **2012**, *138*, 24–35. [CrossRef]
31. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. *Soil and Water Assessment Tool: Theoretical Documentation Version 2000. USDA-ARS Grassland*; Soil and Water Research Laboratory and Blackland Research Center: Texas, TX, USA, 2001.
32. McKee, T.B.; Doesken, N.J.; Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. In Proceedings of the 8th Conference on Applied Climatology, American Meteorological Society, California, CA, USA, 17–22 January 1993; pp. 179–184.
33. Nam, W.H.; Hayes, M.J.; Svoboda, M.D.; Tadesse, T.; Wilhite, D.A. Drought hazard assessment in the context of climate change for South Korea. *Agric. Water Manag.* **2015**, *160*, 106–117. [CrossRef]
34. Lee, J.H.; Seo, J.W.; Kim, C.J. Analysis on trends, periodicities and frequencies of Korean drought using drought indices. *J. Korea Water Resour. Assoc.* **2012**, *45*, 75–89. [CrossRef]
35. Lee, J.H.; Cho, K.K.; Kim, C.J.; Park, M.J. Analysis on the spatio-temporal distribution of drought using potential drought hazard map. *J. Korea Water Resour. Assoc.* **2012**, *45*, 983–995. [CrossRef]
36. Lee, J.W.; Jang, S.S.; Ahn, S.R.; Park, K.W.; Kim, S.J. Evaluation of the relationship between meteorological, agricultural, and in situ big data droughts. *J. Korean Assoc. Geogr. Inf. Stud.* **2016**, *19*, 64–79. [CrossRef]
37. Klipsch, J.D.; Hurst, M.B. *HEC-ResSim Reservoir System Simulation User's Manual*; Version 3.0.; U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center: Davis, CA, USA, 2007.