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Sustainability of Groundwater Exploitation Under Climate Change Scenarios in a Mountainous Area of South Korea

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Abstract: The excessive extraction of groundwater is a globally significant issue, as it can lead to the permanent loss of groundwater system sustainability. Sustainable groundwater requires development that appropriately balances the needs of both humans and the environment. In this study, the exploitable groundwater (EGW) of the So-Yang-gang Dam (SYD) Basin was estimated based on simulated groundwater recharge rates using SWAT, and the sustainability of future groundwater development was evaluated under different climate change scenarios. The EGW in each sub-watershed of the SYD was estimated to range from 60 to 240 mm/year, with higher values in the upstream watersheds. A sustainability index (*SI*) was evaluated, ranging from 0.56 to 1.0 across various GCMs. The analysis revealed that uniform EGW across a watershed is overestimated value in sub-watersheds with low recharge rates, potentially accelerating groundwater depletion in those areas. Thus, a flexible EGW estimation approach is essential to balance groundwater conservation with human water demands.

Keywords: exploitable groundwater; sustainable groundwater; climate change; SSP scenarios; groundwater recharge; So-Yang-gang Dam; SWAT

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1. Introduction

Groundwater supplies almost 50% of the world's drinking water and 40% of irrigation water [1–3], serving as a common-pool resource that supports humans and ecosystems [4]. Groundwater development has increased worldwide to achieve industrial development, economic growth, and prosperous human life [5,6]. However, excessive groundwater extraction has led to groundwater depletion [7–9], which may cause additional damage such as seawater intrusion and land subsidence [10,11]. Richey et al. [12] and Famiglietti [13] warned that some of the major large aquifers in Nevada, Kansas, Texas, California, southern China, northern India, and Saudi Arabia have lost sustainability and are facing irreversible situations. Recent studies highlight the need for regulations for groundwater development and usage, as groundwater levels have been declining at an accelerated rate in approximately 30% of aquifers worldwide, including major large-scale aquifers, over the past 40 years [14–16].

Groundwater sustainability is defined as the development and use of groundwater that can be maintained indefinitely without causing unacceptable environmental, economic, or social consequences [17]. To maintain and manage a sustainable groundwater system, it is crucial to interpret how groundwater resources behave under varying climatic and environmental conditions [18]. In South Korea, the goal of groundwater management is to ensure the stable quantity and quality of groundwater by promoting the rational development, utilization, conservation, and management of groundwater as a public resource [19]. Currently, the country defines EGW as the annual recharge amount during a 10-year drought frequency [19]. However, from the perspective of sustainability, it is

necessary to implement appropriate groundwater management strategies that consider climate change.

Future climate change is expected to intensify the frequency and severity of extreme events such as droughts and floods, and as a consequence, groundwater will also be affected by such change. Nourani et al. (2023) [20] reported that climate change and excessive groundwater exploitation will lead to a decline in groundwater levels in the Ardabil Plain of Iran. Kamali and Asghari (2023) [21] emphasized that droughts resulting from climate change will impact groundwater storage, highlighting the need for regulations on groundwater use. As the increased variability in precipitation due to climate change affects groundwater recharge, it is essential to project future groundwater variability using scenarios from multiple climate models.

The SYD watershed, located in the eastern highlands of South Korea, is a forest-dominated region where groundwater dependence is high due to the rapid runoff of rainfall into rivers. In mountainous areas, groundwater with higher geothermal properties than surface water is extensively used for winter agricultural activities. With the increasing cultivation of field crops, including house farming, groundwater use is increasing [22]. Therefore, research on EGW in the SYD watershed is crucial to ensure future groundwater sustainability.

This study aims to estimate proper EGW by sub-watersheds and to evaluate groundwater sustainability under future climate change scenarios. To achieve this, the following steps were carried out: (1) a SWAT model was established and calibrated for the study area; (2) EGW was estimated using three methods, precipitation, recharge, and surface water–groundwater linkage; and (3) future groundwater sustainability was assessed under the AR6 SSP2-4.5 and SSP5-8.5 scenarios using Reliability, Resilience, and Vulnerability measures.

2. Materials and Methods

2.1. Study Area

The study area is the upstream watershed of the SYD, including the Inje region, where the Inbuk and Naerin streams converge and flow into the SYD, which is the largest multipurpose dam in Korea. The latitude and longitude of the study area are between 37°07′ and 37°22′ N and 127°22′ and 127°33′ E, respectively. The watershed's elevation ranges from 71 to 1673 m, and over 90% of the area consists of forests and pastures. Agricultural land and urban areas occupy 5.7% and 0.7% of the total area, respectively, and are located near the rivers. Among the 68 soil series in the watershed, SONGSAN and SAMGAG types, classified as sandy loam, are the most prevalent, accounting for 26.21% and 13.88%, respectively. The unmeasured areas adjacent to North Korea are assumed to have ODAE soil and forest land cover. The average annual temperature in Inje-gun is 10.5 °C, with annual maximum and minimum temperatures of 23.9 °C and −5.3 °C, respectively, resulting in an annual temperature range of 29.1 °C. The annual precipitation is 1196 mm, with summer precipitation amounting to 839.3 mm. The average annual wind speed is 1.8 m/s.

The watershed is a mountainous high-altitude area where the upstream regions are restricted from being developed, being designated as natural environment conservation areas, national park protection zones, and military facility protection zones. Nevertheless, the area's population is slowly increasing, given its close proximity to Seoul, the capital city of South Korea, with an influx of people returning or moving for rural living [23]. The overdevelopment of groundwater in urbanizing Inje-gun could lead to the drying up of upstream rivers. Moreover, a reduction in surface water–groundwater in the study area could affect the storage volume of the SYD, which in turn could impact the water supply in Seoul.

Figure 1 illustrates the study area, with the six-digit numbers representing the sub-watershed codes. The map also shows the locations of four weather stations and three streamflow gauges along with the river network. Gauge 1 represents the observation

station on the Inbuk stream, Gauge 2 is located on the Naerin stream, and Gauge 3 indicates the observation station for the multipurpose SYD.

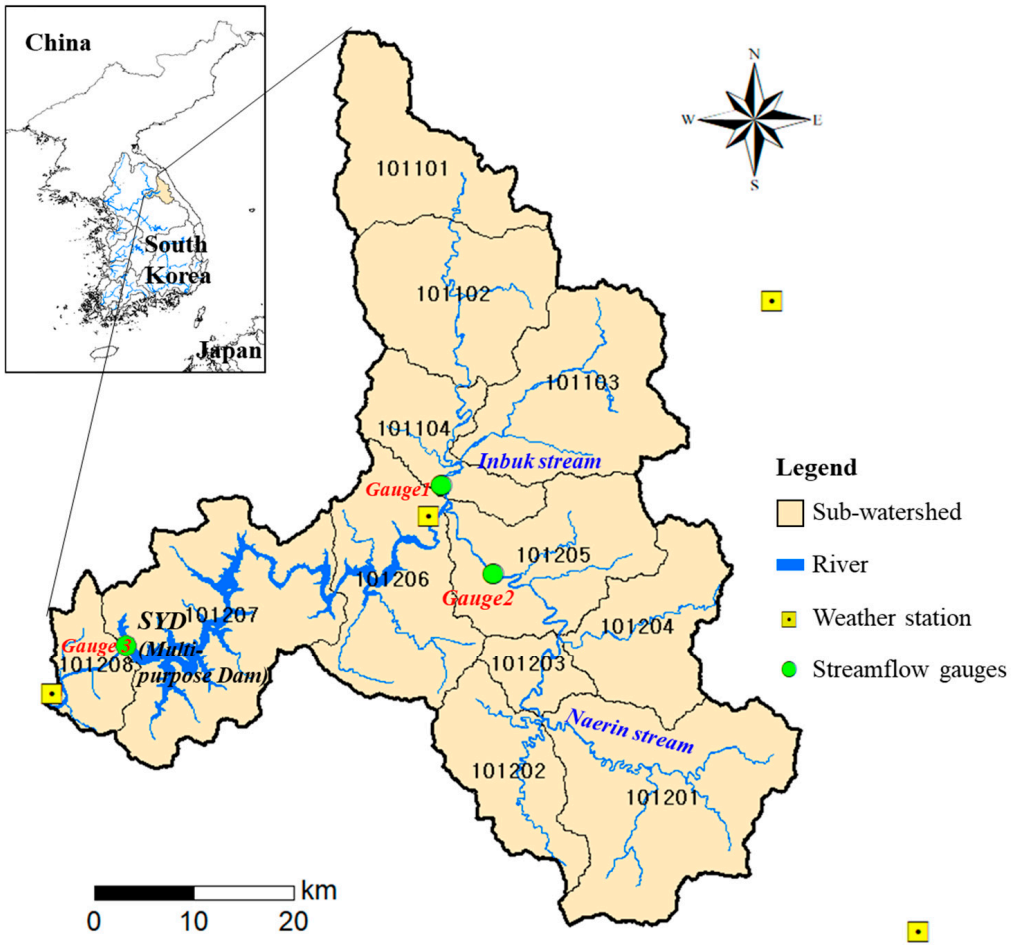

Figure 1. Illustration of the study area.

2.2. Soil and Water Assessment Tool (SWAT)

SWAT is a physically based, semi-distributed model designed for long-term rainfall-runoff simulations. It was developed to simulate runoff, nutrient transport, and agricultural chemical behavior in large, complex watersheds with varying soil types, land use, and land management practices [24]. SWAT utilizes hydrologic response units (HRUs), which are defined by specific soil and land use conditions. For accurate hydrologic cycle simulations, SWAT uses a water balance equation to compute hydrologic components such as precipitation, evapotranspiration, surface runoff, baseflow, and groundwater recharge for each HRU. The water balance equation used by SWAT is expressed as follows:

$$SW_t = SW_0 + \sum_{i=0}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \quad (1)$$

where SW_t represents the final soil moisture content (mm), SW_0 represents the initial soil moisture content (mm) for day i, t represents time (days), R_{day} represents the precipitation amount (mm) on day i, Q_{surf} is the surface runoff amount (mm) on day i, E_a denotes the evapotranspiration amount (mm) on day i, W_{seep} represents the total amount (mm) of water seeping from the soil surface into the subsurface layer on day i, and Q_{gw} represents the groundwater recharge amount (mm) on day i.

The input data for SWAT are GIS (digital elevation model, land use, and soil type) and meteorological data (precipitation (mm), max/min temperature (°C), wind speed (m/s), relative humidity (%), and solar radiation (MJ/m^2)). Figure 2a–c show the GIS data, and Figure 2d shows the HRUs categorized by soil and land cover characteristics. DEMs with a 30 m × 30 m resolution were sourced from the National Geographic Information System (NGIS). The land cover map at a 1:25,000 scale and the soil map were obtained from the Ministry of Environment and the National Institute of Agricultural Sciences, respectively.

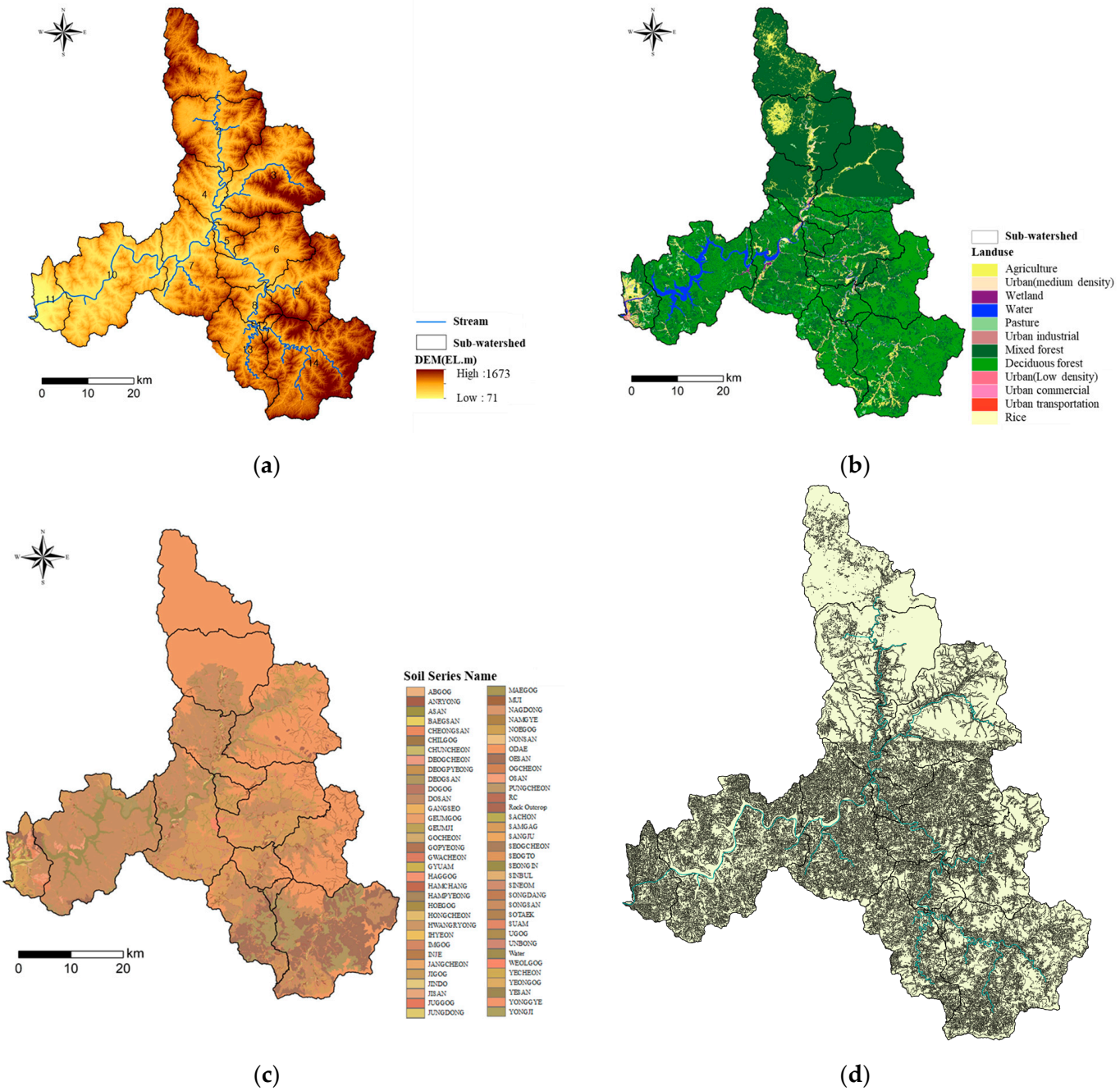

Figure 2. GIS data (**a**) DEM, (**b**) land use, (**c**) soil series, and (**d**) HRUs.

2.3. Climate Change Shared Socioeconomic Pathway (SSP) Scenarios

The Intergovernmental Panel on Climate Change (IPCC) presented SSP scenarios as new climate regime response scenarios in their 6th Assessment Report [25]. The SSP scenarios, divided into five categories, reflect future socioeconomic developments such as population, economy, land use, and energy use. They also account for the radiative forcing intensity by 2100 and the implementation of climate change adaptation and greenhouse gas reduction measures. These scenarios combine with the Representative Concentration Pathway (RCP) scenarios via common policy assumptions, thus enhancing the reasonability of future scenarios [26,27].

Table 1 shows the 15 General Circulation Models (GCMs) that provide all six meteorological variables as SWAT input. Since projecting future hydrological cycles using a single climate model has a high uncertainty, this study used all the GCMs listed in Table 1 for future projections. Additionally, among the five SSP scenarios, SSP2-4.5 (assuming moderate levels of climate change mitigation policies and socioeconomic development) and SSP5-8.5 (assuming rapid technological advancement with high fossil fuel use and extensive urban-centered development) were used to evaluate the sustainability of future groundwater.

Table 1. Description of the GCMs used in this study [28].

GCMs	Country	Institute	Resolution
ACCESS-CM2 ACCESS-ESM1-5	Australia	Commonwealth Scientific and Industrial Research Organization	1.25° × 1.875°
CanESM5	Canada	Canadian Centre for Climate Modelling and Analysis	2.8° × 2.8°
CNRM-CM6-1 CNRM-ESM2-1	France	Centre National de Recherches Meteorologiques	1.4° × 1.4°
GFDL-ESM4	United States	Geophysical Fluid Dynamics Laboratory	1.0° × 1.25°
INM-CM4-8 INM-CM5-0	Russia	Institute for Numerical Mathematics	1.5° × 2.0°
IPSL-CM6A-LR	France	Institute Pierre-Simon Laplace	1.26° × 2.5°
MIROC6	Japan	Japan Agency for Marine-Earth Science and Technology/Atmosphere and Ocean Research Institute/National Institute for Environmental Studies/RIKEN Center for Computational Science	1.4° × 1.4°
MPI-ESM1-2-HR MPI-ESM1-2-LR	Germany	Max Planck Institute for Meteorology	0.938° × 0.938° 1.875° × 1.875°
MRI-ESM2-0	Japan	Meteorological Research Institute	1.125° × 1.125°
NorESM2-LM	Norway	NorESM Climate modeling Consortium consisting of CICERO	1.875° × 2.5°
UKESM1-0-LL	United Kingdom	Met Office Hadley Centre	1.25° × 1.875°

2.4. Exploitable Groundwater (EGW) Resources

In South Korea, EGW is defined as the groundwater recharge calculated by applying a recharge coefficient to precipitation for a 10-year drought frequency, considering water supply reliability [29]. Due to the lack of time-series data on groundwater recharge, EGW is typically estimated using recharge data from hydrological watershed models or precipitation data. In this study, we aim to use three methods commonly employed in South Korea, selecting the most conservative results for the vulnerability assessment. The first method is defined by multiplying the average recharge rate by precipitation during a 10-year drought frequency, which is proposed in the Basic Groundwater Management Plan of Korea [29] and generally used in practice. The second method is based on a frequency analysis of the annual recharge amount. The final method is based on the linkage between surface water and groundwater, calculating EGW in a way that ensures that a minimum streamflow can continue to flow in rivers. This method separates baseflow from the natural streamflow hydrograph and estimates EGW by excluding the minimum streamflow required to maintain normal river conditions based on a flow duration curve analysis [30,31].

2.5. Sustainability of Groundwater

Water resource sustainability can be defined as the ability to secure a sufficient quantity of water resources over a long period of time. In this study, the sustainability of a groundwater system under climate change scenarios was quantitatively assessed using the indices of Reliability, Resilience, and Vulnerability based on a threshold level. The threshold concept commonly used in drought assessment [32] has been modified and applied to fit the objectives of this study. Figure 3 illustrates the conceptual diagram of the R-R-V approach used in this research.

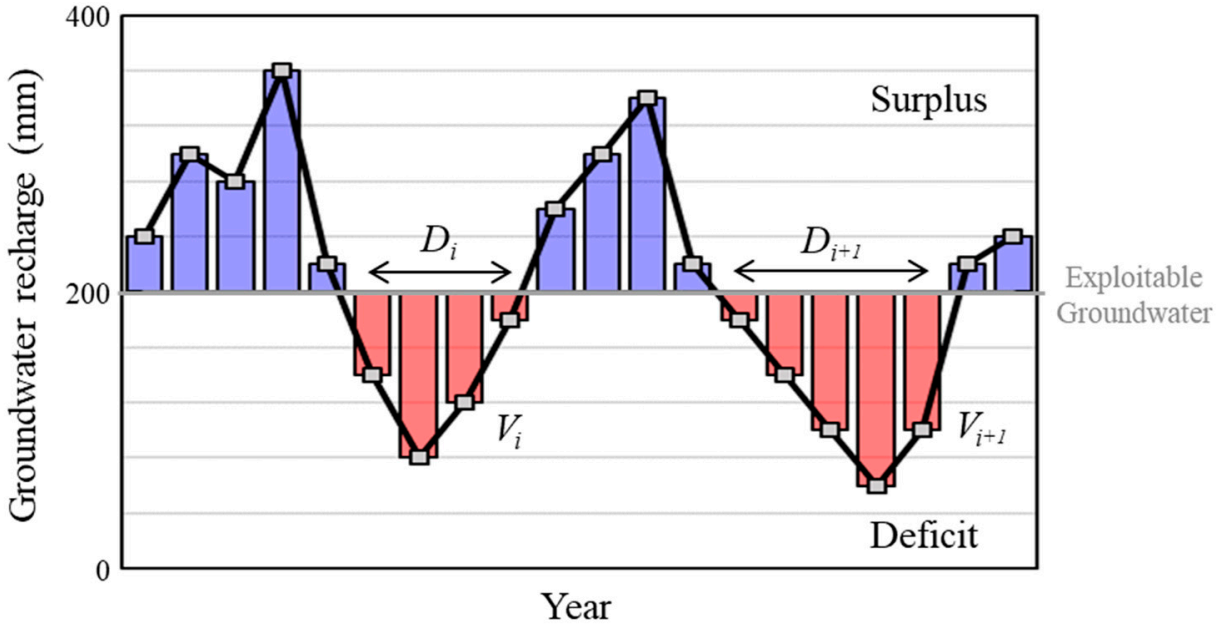

Figure 3. Schematic illustration of the R-R-V approach.

Groundwater development is considered feasible when the groundwater recharge is greater than the EGW, and the opposite case is considered a failure event. In Equations (2)–(4), D_i is the duration of the ith failure event, V_i is the cumulative deficit during a failure event, M is the total number failure events, and T is the total analysis period. Reliability (Re) is calculated using Equation (2) and represents the probability of practicable groundwater development. Resilience (Rs) is obtained based on Equation (3) and represents the probability of recovery to a normal state (in this study, the state of practicable groundwater development). Vulnerability (Vu) represents the magnitude of failure and is expressed dimensionlessly through Equation (4). Finally, sustainability is calculated by integrating the three indices based on Equation (5).

$$Re = 1 - \frac{\sum_{i=1}^{M} D_i}{T} \tag{2}$$

$$Rs = \left(\frac{1}{M} \sum_{i=1}^{M} D_i \right)^{-1} \tag{3}$$

$$Vu = \frac{\frac{1}{M}\sum_{i=1}^{M} V_i}{Annual\ demand} \tag{4}$$

$$SI = [Re \times Rs \times (1 - Vu)]^{1/3} \tag{5}$$

3. Results and Discussion

3.1. SWAT Model Calibration and Validation

In this study, the performance of SWAT was evaluated on an annual average by comparing the observed streamflow with the simulated streamflow results from SWAT using RMSE (root mean square error), NSE (Nash–Sutcliffe efficiency), and R^2 (coefficient of determination) measures. Streamflow calibration and validation were performed at three gauges (Figure 1). The SWAT calibration and validation periods were divided into 2018–2020 and 2021–2023, respectively. Table 2 summarizes the calibrated parameters, their physical meanings, and the default adjusted values applied in this study. Snow parameters were also applied to consider the high altitude and winter snow fall in the study area.

Table 2. SWAT parameters used in this study.

Parameters	Description	Default Value	Adjusted Value
ESCO	Soil evaporation compensation factor	0.95	0.8
CH_N2	Manning's roughness coefficient ("n" value) for the main channel	0.014	0.14/0.05
GW_DELAY	Groundwater delay time (days)	31	40
ALPHA_BF	Baseflow alpha factor for recession curve (1/days)	0.048	0.5
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	1000	500
SFTMP	Snowfall temperature (°C)	1	1.3
SMTMP	Snow melt base temperature (°C)	0.5	1.97
SMFMX	Melt factor for snow on June 21 (mm H_2O/°C day)	4.5	4.96
SMFMN	Melt factor for snow on December 21 (mm H_2O/°C day)	4.5	3.16
TIMP	Snowpack temperature lag factor	1	0.14
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover (mm H_2O)	1	38.38
SNI50COV	Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover	0.5	0.5

Figure 4 shows the graphs comparing the observed streamflow (gray) and SWAT simulated streamflow (red) at each calibration point. While SWAT appeared to poorly simulate the sharp decline in streamflow that occurred between the fall of 2020 and spring of 2021, it generally simulated the observed values well when analyzing the response to rainfall and the baseflow recession curve. For Gauge 1, which is located in the Inbuk stream, the RMSE, NSE, and R^2 values during the calibration period were 6.11 mm/day, 0.62, and 0.66, respectively, and during the validation period, they were 3.69 mm/day, 0.56, and 0.58, respectively. For Gauge 2, the RMSE for the calibration and validation periods was 2.66 mm/day and 2.61 mm/day, NSE was 0.77 and 0.70, and R^2 was 0.81 and 0.71, respectively. The results of the inflow to SYD (Gauge 3) showed that the RMSE, NSE, and R^2 values during the calibration period were 3.71 mm/day, 0.72, and 0.77, respectively, and during the validation period, they were 3.27 mm/day, 0.65, and 0.68. The SWAT calibration results satisfied the calibration criteria of NSE > 0.50 and R^2 > 0.60 proposed by Moriasi et al. [33] and were evaluated to simulate the watershed hydrological cycle well.

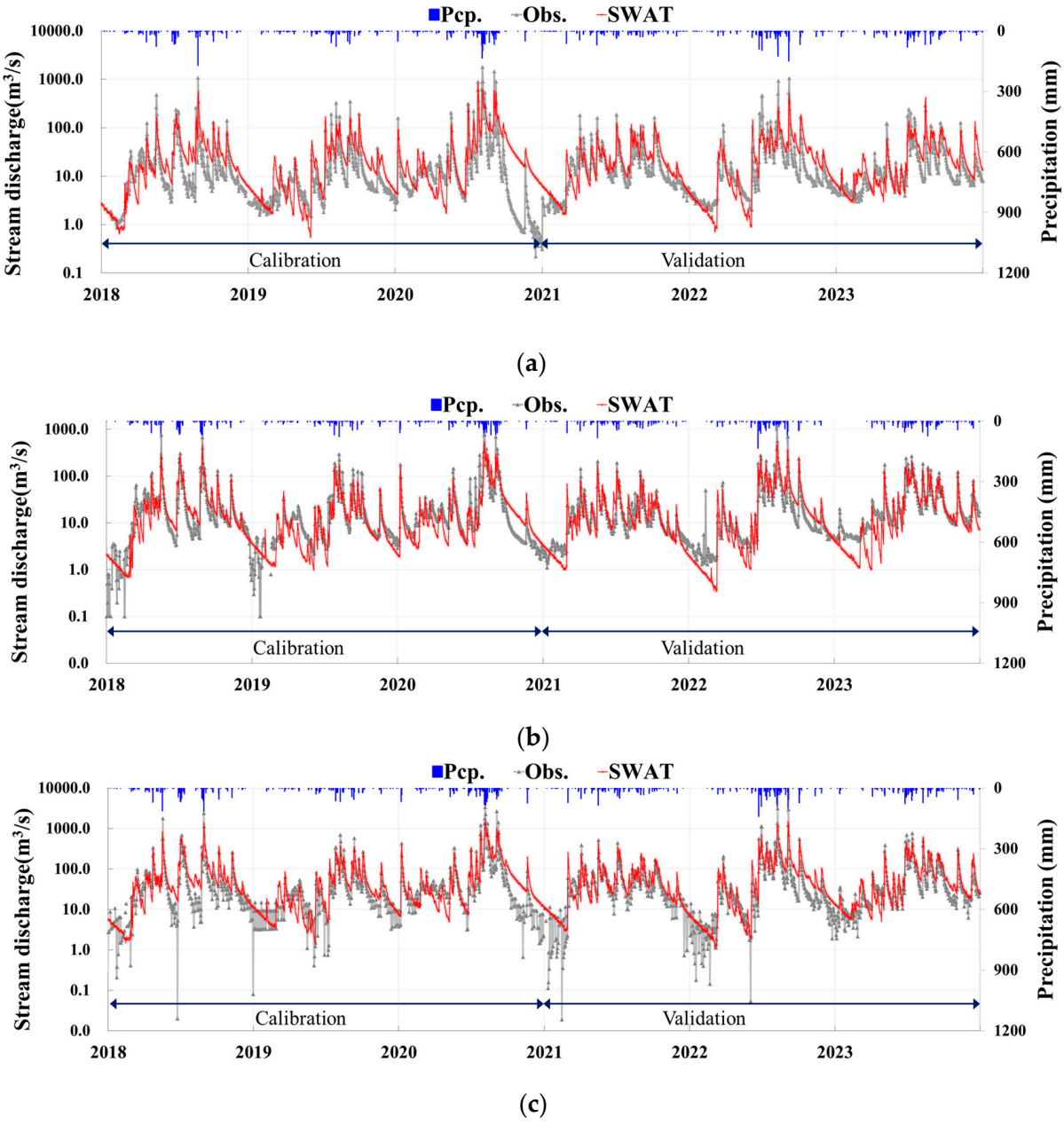

Figure 4. SWAT results of streamflow compared to the observed streamflow at (**a**) Gauge 1, (**b**) Gauge 2, and (**c**) Gauge 3.

3.2. Estimation of EGW

Figure 5 shows the comparison of annual average watershed recharge simulated by SWAT and the annual average EGW estimated based on three methods for the period from 1981 to 2023. The range of annual precipitation during the analysis period was 657–2007 mm, and the range of recharge was simulated to be 51–485 mm. The recharge rate ranged from 7% to 24%, fluctuating in proportion to the annual precipitation. Using the SWAT simulation results, the EGW of the watershed was estimated. The EGW1, calculated based on precipitation, was 164.9 mm/year; the EGW2, calculated based on recharge, was 164.0 mm/year; and the EGW3, calculated based on the surface water–groundwater linkage, was 149.3 mm/year.

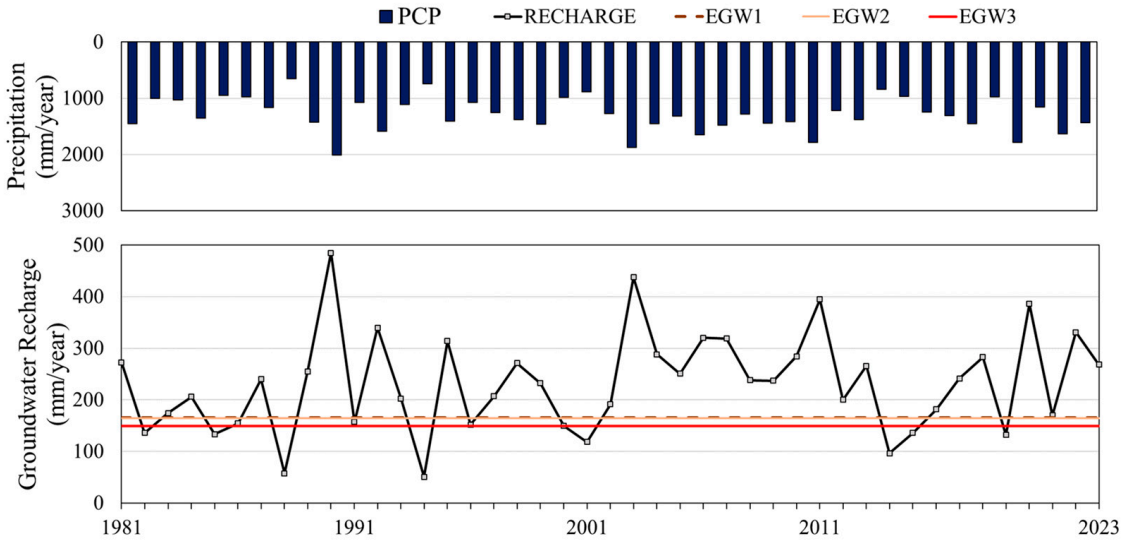

Figure 5. SWAT results of annual recharge and estimated EGW.

Table 3 summarizes the area of each sub-watershed, the annual average precipitation during the analysis period, the total water resources, the groundwater recharge simulated by SWAT, and the EGW calculated using the three methods. The total water resources for each sub-watershed ranged from 72 to 528 million m^3, with a total of 3586 million m^3 for the entire watershed. Recharge accounted for an average of 18% of the total water resources, with the recharge rate varying significantly from 11% to 32% depending on the sub-watershed. EGW1 was estimated to range from 7.5 to 81.7 million m^3, which is about 71% of the total recharge. EGW2 was estimated to range from 6.4 to 80.5 million m^3 per sub-watershed, approximately 66% of the total recharge. Finally, EGW3 was estimated to range from 8.8 to 84.8 million m^3 as the development potential. EGW1, being the simplest method, resulted in the highest value in all sub-watersheds. In contrast, EGW3 showed the largest variation in the ratio of EGW to recharge, ranging from 56% to 91%.

Table 3. Potential amount of water resources, recharge, and EGW by sub-watershed.

Sub-Watershed	Area (km^2)	PCP (mm)	Water Resource (10^6 m^3)	Recharge (10^6 m^3)		EGW1 (10^6 m^3)		EGW2 (10^6 m^3)		EGW3 (10^6 m^3)	
101101	220.1	1328.6	292.4	93.2	(32%)	66.0	(71%)	63.2	(68%)	52.7	(57%)
101102	262.3	1205.1	316.1	70.8	(22%)	53.3	(75%)	48.3	(68%)	45.7	(65%)
101103	304.1	1659.4	504.6	105.4	(21%)	63.2	(60%)	60.5	(57%)	58.7	(56%)
101104	144.7	1177.5	170.4	20.0	(12%)	14.8	(74%)	12.0	(60%)	18.2	(91%)
101201	403.5	1310.7	528.8	113.2	(21%)	81.7	(72%)	80.5	(71%)	84.8	(75%)
101202	173.6	1310.7	227.5	37.6	(17%)	27.1	(72%)	24.9	(66%)	27.1	(72%)
101203	62.6	1153.4	72.2	9.9	(14%)	7.5	(76%)	6.4	(65%)	8.8	(89%)
101204	194.5	1153.2	224.3	45.9	(20%)	35.0	(76%)	31.3	(68%)	34.6	(75%)
101205	250.2	1153.3	288.6	40.5	(14%)	30.9	(76%)	26.4	(65%)	34.2	(84%)
101206	278.2	1241.8	345.5	39.5	(11%)	28.7	(73%)	25.7	(65%)	31.6	(80%)
101207	400.5	1241.8	497.4	56.0	(11%)	40.7	(73%)	35.5	(63%)	40.6	(73%)
101208	88.9	1338.0	119.0	24.4	(21%)	17.4	(71%)	18.4	(75%)	16.3	(67%)
Total	2783.2	1287.8	3586.8	656.4	(18%)	466.2	(71%)	433.2	(66%)	453.4	(69%)

The most conservative EGW was selected for each sub-watershed for assessing future sustainability. To remove the influence of watershed area, EGW per unit area was spatially represented (Figure 6). The EGW ranged from 60 to 240 mm/year, demonstrating significant variability between the overall watershed average and the values for individual sub-watersheds. Notably, the EGW in the upper watershed was estimated to be higher than the watershed average, whereas the EGW in the downstream SYD region was calculated more conservatively.

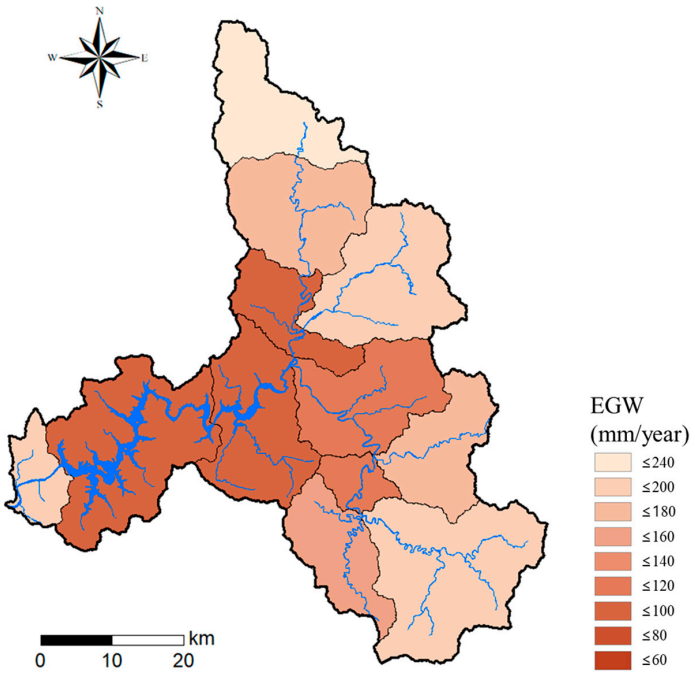

Figure 6. Conservative EGW distribution by sub-watershed.

The estimated recharge rates for the mountainous BX Creek watershed in Canada showed lower recharge rates at lower elevations, while higher elevations exhibited recharge rates of approximately 5–15% [34]. This result aligns with the findings of this study regarding recharge variations with elevation. Although recharge rates in this study were higher due to differences in soil and land cover characteristics, the variation was not significant when compared to recharge rates in other regions of Korea [31]. Additionally, while the traditionally estimated EGW accounts for around 10% of annual precipitation, this study estimates EGW to range from 7 to 18% of annual precipitation depending on regional differences, indicating a conservative and flexible approach [19].

3.3. Assessment of Sustainable Groundwater Resources

The sustainability of future groundwater resources was evaluated by comparing future groundwater recharge and EGW under climate change scenarios. Table 4 shows the results of the Reliability, Resilience, Vulnerability, and Sustainability indices for the entire watershed under each GCM's SSP2-4.5 and SSP5-8.5 scenarios. In the SSP2-4.5 scenario, *Re*, *Rs*, and *Vu* ranged from 0.72 to 0.98, 0.64 to 1.0, and 0.15 to 0.36, respectively. The *SI*, evaluated based on R-R-V, was estimated to be between 0.70 and 0.93. In the SSP5-8.5 scenario, *Re*, *Rs*, *Vu*, and *SI* were estimated to be 0.71–0.99, 0.87–1.0, 0.13–0.56, and 0.73–0.93, respectively. The SSP5-8.5 scenario showed larger variance in *Re* and *Vu* and a higher *Rs* compared to the SSP2-4.5 scenario. Additionally, under both SSP scenarios, the lowest *SI* was obtained from the INM-CM4-8 model.

Table 4. Evaluation of future *Re*, *Rs*, *Vu*, and *SI* values for the entire watershed under the SSP scenarios for each GCM.

GCMs	SSP2-4.5				SSP5-8.5			
	Re	*Rs*	*Vu*	*SI*	*Re*	*Rs*	*Vu*	*SI*
ACCESS-CM2	0.93	1.00	0.26	0.89	0.89	0.90	0.13	0.89
ACCESS-ESM1-5	0.89	0.90	0.24	0.85	0.90	1.00	0.21	0.89
CanESM5	0.98	1.00	0.17	0.93	0.99	1.00	0.56	0.76
CNRM-CM6-1	0.92	1.00	0.18	0.91	0.92	1.00	0.18	0.91
CNRM-ESM2-1	0.92	0.86	0.25	0.84	0.97	1.00	0.14	0.94
GFDL-ESM4	0.91	1.00	0.25	0.88	0.90	1.00	0.29	0.86
INM-CM4-8	0.72	0.64	0.26	0.70	0.74	0.78	0.32	0.73
INM-CM5-0	0.75	0.73	0.31	0.72	0.71	0.77	0.25	0.74
IPSL-CM6A-LR	0.92	0.86	0.36	0.80	0.91	1.00	0.24	0.88
MIROC6	0.80	0.83	0.24	0.80	0.85	0.92	0.17	0.87
MPI-ESM1-2-HR	0.93	1.00	0.15	0.92	0.96	1.00	0.29	0.88
MPI-ESM1-2-LR	0.94	0.60	0.19	0.77	0.93	1.00	0.14	0.93
MRI-ESM2-0	0.93	1.00	0.23	0.89	0.94	1.00	0.17	0.92
NorESM2-LM	0.96	1.00	0.19	0.92	0.91	1.00	0.17	0.91
UKESM1-0-LL	0.84	0.71	0.20	0.78	0.83	0.87	0.22	0.82

Figure 7 shows the future groundwater recharge projections under the SSP scenarios of the INM-CM4-8 model. The number of failure years—where groundwater recharge falls below the threshold level of EGW—was found to be 25 under the SSP 2-4.5 scenario and 23 under the SSP 5-8.5 scenario over a 90-year period. The number of failure events was calculated to be 16 and 18, respectively. Notably, the SSP2-4.5 scenario predicted a persistent groundwater shortage from 2045 to 2059, indicating that even the conservatively estimated EGW levels may not be sufficient during extended periods of low precipitation. Prolonged droughts could also lead to the depletion of surface water, causing a risk of water shortages across domestic, industrial, and agricultural sectors. Therefore, it is necessary to develop proactive measures to mitigate these potential impacts.

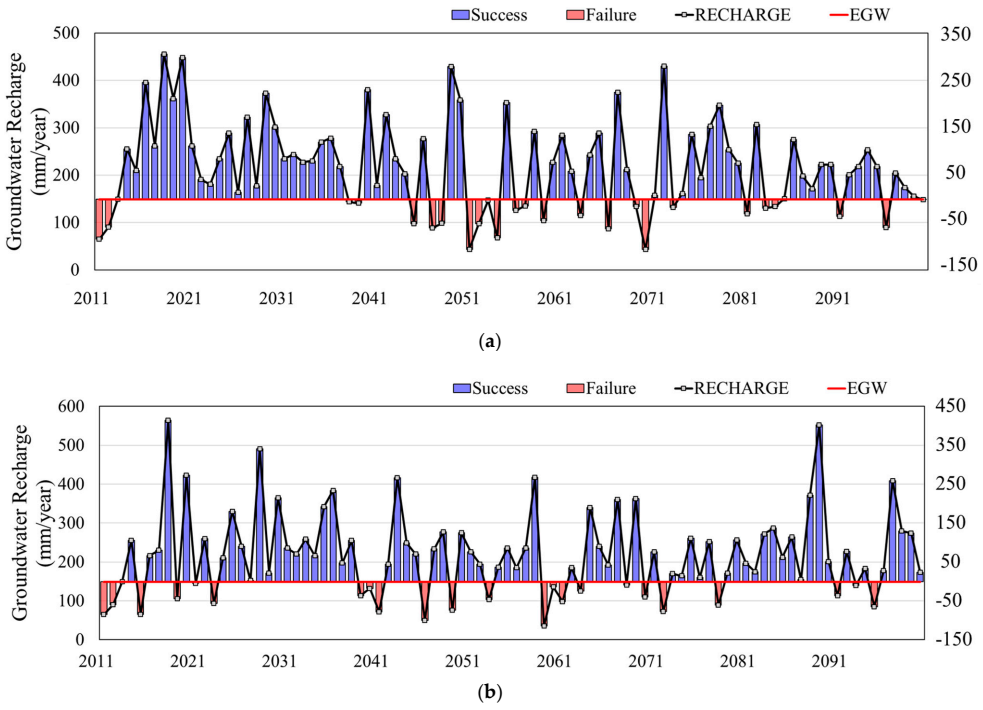

Figure 7. Comparison of EGW criteria with future annual recharges for 2011–2100 under the (**a**) SSP2-4.5 and (**b**) SSP5-8.5 scenarios of the INM-CM4-8 model.

Due to the significant variation in EGW and groundwater recharge between sub-watersheds, the results of the groundwater sustainability assessment for each sub-watershed are presented as a box plot in Figure 8. While the median values of each index showed little difference, it was determined that more outlier values were distributed in the SSP5-8.5 scenario. Furthermore, the variance in *SI* across sub-watersheds was larger in the SSP5-8.5 scenario compared to the SSP2-4.5 scenario.

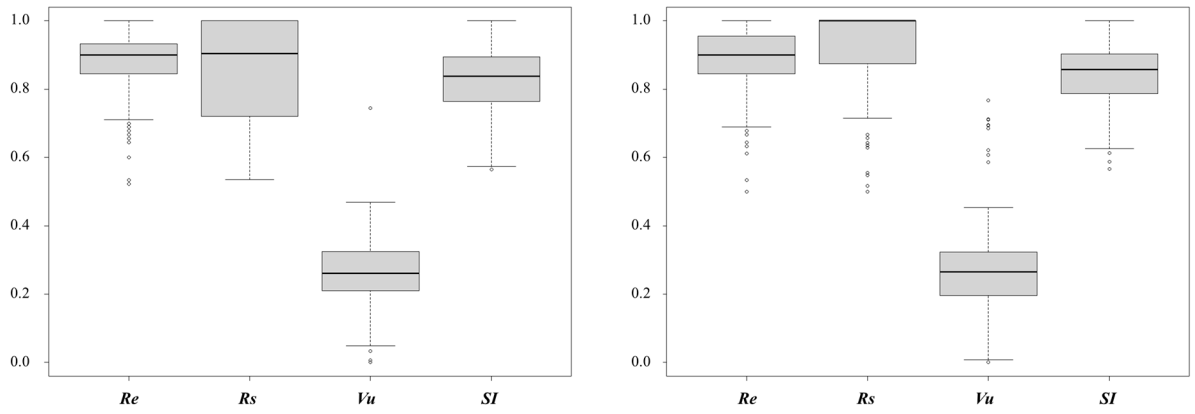

Figure 8. Boxplots of *Re*, *Rs*, *Vu*, and *SI* values under (**a**) SSP2-4.5 and (**b**) SSP5-8.5 scenarios.

Figure 9 displays the spatial distribution of the *SI* for each sub-watershed, based on the INM-CM4-8 model, which yielded the lowest *SI*. The future sustainability evaluated using the *SI* metric showed a similar pattern to the EGW results, indicating higher sustainability in the upstream regions and lower sustainability in the downstream areas. These results imply that applying a uniform EGW level across the entire watershed could lead to more rapid groundwater depletion in areas with lower recharge rates.

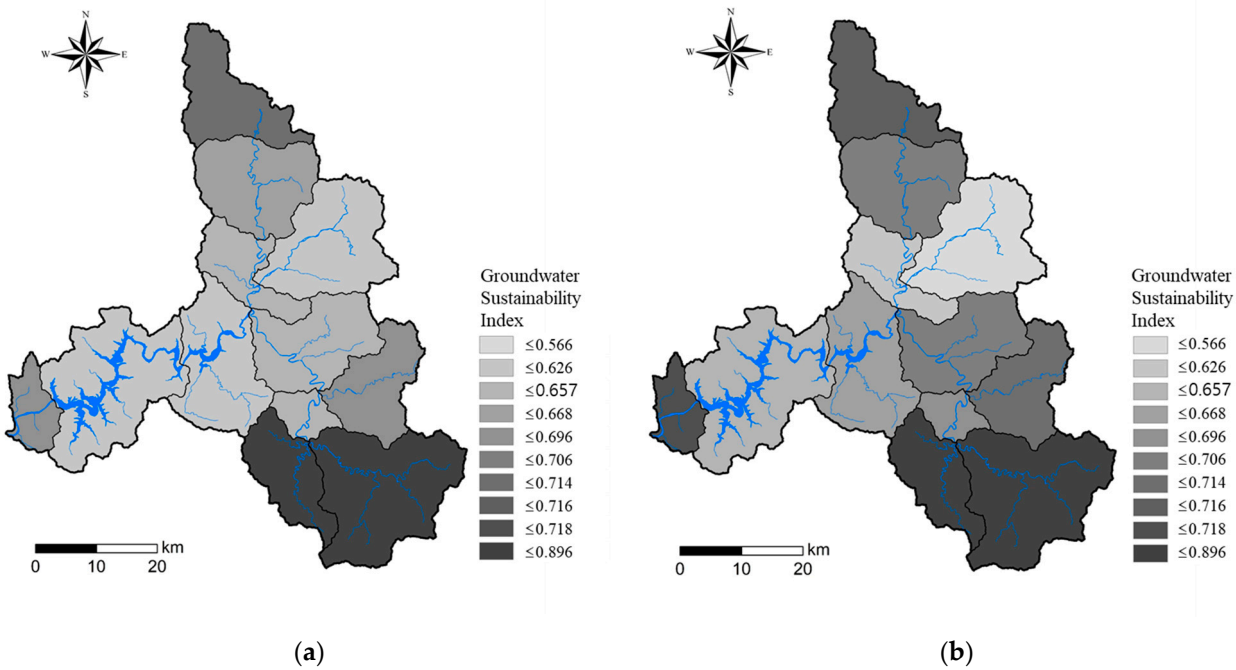

Figure 9. Evaluation of groundwater sustainability by sub-watershed under the INM-CM4-8 model's (**a**) SSP2-4.5 and (**b**) SSP5-8.5 scenarios.

The need for groundwater management in regions with limited groundwater resources or low recharge potential has also been emphasized in previous studies. Perrin et al. (2012) [35] employed a SWAT model to estimate recharge rates in a semi-arid crystalline watershed in southern India and observed that spatial variability in recharge and pumping was particularly pronounced during dry years. The study highlighted the constrained nature of recharge potential, underscoring the necessity for effective groundwater management measures.

The sensitivity and vulnerability of groundwater resources to future climate change scenarios have been indicated in other studies as well [36–39]. Groundwater recharge rates are highly correlated with and dependent on annual precipitation, meaning that a reduction in annual rainfall can lead to a corresponding decrease in recharge rates. On the other hand, even in cases of increased annual precipitation, variability in rainfall patterns may result in lower recharge rates [39]. Therefore, to ensure sustainability, it is essential to estimate future groundwater recharge rates under climate change conditions, taking into account seasonality and precipitation variability, and flexibly assess EGW for individual sub-watersheds based on their unique characteristics.

4. Conclusions

In this study, a SWAT model was established and calibrated for the SYD watershed. EGW was estimated using three metrics: precipitation, recharge, and surface water–groundwater linkage. Future groundwater sustainability was evaluated using Reliability, Resilience, and Vulnerability indices under the AR6 SSP2-4.5 and SSP5-8.5 scenarios.

The quantitative evaluation of simulated streamflow showed that the RMSE at calibration points ranged from 2.61 to 6.11 mm/day, NSE ranged from 0.56 to 0.77, and R^2 ranged from 0.55 to 0.81, indicating a good simulation of the observed streamflow. The EGW1, EGW2, and EGW3 estimated for the entire watershed using the SWAT simulation results were 164.9 mm/year, 164.0 mm/year, and 149.3 mm/year, respectively. The EGW range calculated for each sub-watershed was 60 to 240 mm/year, showing significant variability across sub-watersheds. The upstream watershed tended to have a higher EGW.

Lastly, future groundwater sustainability under the different climate change scenarios was assessed by calculating the *SI* based on the R-R-V index. Under the future climate change scenarios, the ranges of *Re*, *Rs*, *Vu*, and *SI* for each sub-watershed were 0.5 to 1.0, 0.5 to 1.0, 0 to 0.74, and 0.56 to 1.0, respectively. The results showed that the INM-CM4-8 model projected the lowest *SI*. Despite the conservative EGW levels, long-term droughts were shown to reduce groundwater recharge, leading to decreased groundwater sustainability. A spatial analysis indicated that sub-watersheds with a higher EGW also had higher groundwater sustainability due to a large groundwater recharge.

The findings of this study indicate that applying a uniform EGW standard across an entire watershed is not representative for some sub-watersheds and can lead to more rapid groundwater depletion in areas with low recharge rates. Additionally, even conservative EGW criteria may not prevent groundwater depletion during prolonged droughts. Therefore, it is crucial to adopt a flexible EGW estimation approach that both conserves groundwater and meets human needs.

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