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Estimation of Streamflow Depletion Caused by Groundwater Withdrawal in the Bokhacheon Watershed in South Korea Using the Modified SWAT Model

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Abstract: Understanding the effects of groundwater withdrawal on streamflow depletion is important for effectively managing water resources. The Soil and Water Assessment Tool (SWAT) model has a groundwater module to calculate the groundwater budget and groundwater discharge. However, the water pumped from the aquifer is not considered in the SWAT module that estimates groundwater discharge. Therefore, this module was modified to consider the impact of groundwater pumping on the changes in groundwater discharge in the Bokhacheon watershed, South Korea. The model's water transfer module was improved to allow water from the aquifer to be transferred to destination locations, such as residential, industrial, and agricultural lands. Using the modified SWAT, streamflow responses to groundwater extraction were simulated for 2011–2019. The groundwater withdrawal induced decreases of 14.6 and 24.2% in low and drought flows, respectively, at the watershed's outlet. The groundwater withdrawals decreased groundwater flow and total water yield by 23.5% and 9.8%, respectively, and increased surface flow, lateral flow, percolation, soil water, and evapotranspiration owing to the increased soil moisture resulting from the partial re-infiltration of the groundwater pumped for agricultural irrigation. The modified SWAT can effectively estimate streamflow depletion resulting from groundwater pumping without extensive hydrogeological input data and computational time.

Keywords: streamflow depletion; groundwater withdrawal; SWAT; hydrological components

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1. Introduction

Excessive groundwater use causes a reduction in the groundwater level and its outflow from the aquifer to the stream, eventually resulting in streamflow depletion. In the case of excessive groundwater use, the groundwater level may become lower than that of the stream, and a fraction of the stream water enters the groundwater system. This also results in streamflow depletion. Groundwater withdrawal directly relates to stream water intake and an instream ecological environment. Therefore, groundwater should be used and managed rationally, considering the effects of groundwater withdrawal on streamflow.

Various analytical solutions have been derived to estimate streamflow depletion caused by groundwater pumping using aquifer hydraulic properties and distance from stream to well, under conditions in which a stream fully penetrates the aquifer [1–3], partially penetrates an aquifer with a semi-pervious streambed [4,5], or in which there is a two-layered leaky aquifer system [6,7]. To describe the complicated actual conditions in detail, numerical models of groundwater flow, such as MODFLOW [8], have been widely used to analyze the effects of groundwater pumping on streamflow [9–11]. Furthermore, surface water and groundwater integrated models, such as MODHMS [12,13], FHM [14], SWATMOD [15], and SWAT-MODFLOW [16–18], have often been used to consider various hydrological conditions and to understand the watershed scale effects of groundwater withdrawals on streamflows. Recently, artificial intelligence (AI) techniques have been widely applied to simulate and forecast streamflow [19–21]. There are various studies using AI for groundwater analyses [22,23].

However, analytical solutions may not be suitable for complicated hydrogeological conditions with numerous wells, because the solutions are derived from a simplified representation of a single well–aquifer–stream system. Numerical models require high computational costs as well as extensive input data for hydrogeological formations and their properties. AI techniques have the ability to capture these complex nonlinear hydrologic characteristics, but there are limitations in understanding the physical processes. Therefore, a physically based semi-distributed hydrological model with a simple groundwater module, such as the Soil and Water Assessment Tool (SWAT) [24,25], can be useful for baseflow analysis when hydrogeological data are insufficient to establish numerical models.

The SWAT, a semi-distributed continuous hydrological model developed by the United States Department of Agriculture (USDA), is widely used to simulate water cycles and assess water resources [26,27]. The model has a linear reservoir groundwater module, which assumes that the groundwater flow to the channel is proportional to the groundwater storage [28]. Modulations of the groundwater module in SWAT have been conducted to better represent the base flow via the addition of another storage layer [29–33] and the use of nonlinear aquifer storage–discharge relationships [28,31,34]. Several studies have simulated groundwater level variations caused by evapotranspiration [35], groundwater withdrawal [36], and climate change [37]. Liu et al. [18] compared streamflows using SWAT and SWAT-MODFLOW for drinking and irrigation groundwater withdrawal scenarios, indicating that SWAT-MODFLOW produced more realistic signals for streamflow changes, whereas SWAT showed unrealistically minor changes in streamflow. With the exception of the research by Liu et al. [18], most studies on groundwater analyses using the SWAT model have focused on enhancing base flow simulation and estimating groundwater depletion. However, no study related to streamflow depletion due to groundwater pumping has been performed using SWAT, although the model has a groundwater module. This is possibly because consideration of the water pumped from any aquifer is included in the volumetric water balance equation in the groundwater module; however, it is not explicitly considered in the algorithm for calculating groundwater outflow.

Therefore, this study aimed to modify the groundwater module in SWAT to quantify the impacts of groundwater extraction on changes in groundwater discharge. We applied the modified SWAT to the Bokhacheon watershed in South Korea to estimate streamflow depletion caused by groundwater withdrawal.

2. Materials and Methods

2.1. Study Area

The Bokhacheon watershed was selected for this study (Figure 1). The Bokha stream, which originates from the Dogobong peak (elevation 440 m) located in Yongin-si, Gyeonggi-do, flows through Icheon-si, Gyeonggi-do, and into the left bank of the Han river, which is the second longest river in South Korea. The channel length is 39.84 km, and the drainage area is 309.5 km^2, which is equivalent to 0.9% of the 34,674.0 km^2 of the Han river basin. The geographical location is between 37°07′–37°22′ N and 127°22′–127°33′ E, which is the central part of the Han river basin. The topography of the watershed forms a boundary with the Cheongmicheon, Yanghwacheon, and Gyeongancheon watersheds, with relatively low mountains of approximately 100–600 m in elevation. The administrative district includes 1 province, 4 cities, and 13 eups/myeon, including Icheon-si, Yeoju-si, Yongin-si, and Gwanju-si, and has a total of more than 150,000 residents. Regarding the land use status, of the total watershed area of 309.50 km^2, forests occupy 128.42 km^2 (41.49%), and paddy fields occupy 68.86 km^2 (22.25%).

Figure 1. Study area.

The streamflow in the Bokhacheon watershed is affected by the water taken from the stream, the discharge of sewage-treated water to the stream, and groundwater withdrawals within the watershed. Therefore, sophisticated hydrological modeling is required for water balance assessment, considering the complex effects of water use and return flow.

2.2. Model Description

The SWAT model [24,25], which was developed by the USDA, is a hydrological model used to predict long-term loads of water, sediment, pollutants, and agricultural chemicals according to changes in soil and land-use management conditions. The major components that can be simulated using this model are hydrology, weather, sediment, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The hydrologic component simulation is performed in the order of precipitation interception, surface flow and infiltration, evaporation and transpiration, lateral flow and percolation, recharge, and groundwater flow, with the hydrologic response unit (HRU) as the basic spatial unit of calculation.

The amount of precipitation interception is determined as a function of the leaf area index, and the surface flow was calculated using the modified Natural Resources Conservation Service runoff curve number method or the Green–Ampt method, which separates precipitation on the ground into surface runoff and infiltration according to the quantity of soil water content. Potential evapotranspiration is calculated using the Penman–Monteith, Priestley–Taylor, and Hargreaves methods, and actual evapotranspiration is calculated considering soil water deficiency. The lateral flow through the soil layers is calculated using a kinematic storage model, which is a function of the saturated hydraulic conductivity, slope, and slope length of the soil layer. Simultaneously, the quantity of vertical downward percolation is calculated using a storage routing model. Groundwater recharge is calculated as the weighted sum of the present day's percolation and the recharge of the previous day by considering the unsaturated zone under the soil layers as a linear reservoir. Groundwater flow is calculated as the weighted sum of the current recharge and groundwater flow of the previous day, considering the saturated zone as a linear reservoir. Surface runoff, lateral flow, and groundwater flow are added to the discharge into the main channel of the subbasin, and the streamflow was calculated through a channel routing process [25].

2.3. Model Modification

In the SWAT model, groundwater aquifers are divided into shallow and deep aquifers, and the water balance for the shallow aquifer that contributes flow in the reach of the subbasin is expressed as

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg,sh,i} - Q_{gw,i} - w_{revap,i} - w_{pump,i} \tag{1}$$

where $aq_{sh,i}$ is the quantity of water stored in the shallow aquifer on day i, $aq_{sh,i-1}$ is the quantity of water stored in the shallow aquifer on day $i-1$, $w_{rchrg,sh,i}$ is the recharge entering the shallow aquifer, $Q_{gw,i}$ is the groundwater flow into the reach, $w_{revap,i}$ is the groundwater re-evaporation that is the quantity of water moving into the soil zone in response to soil water deficiencies, and $w_{pump,i}$ is the water pumped from the aquifer on day i. The groundwater flow on day i from the shallow aquifer to the channel is calculated using Equation (2) under the linear relationship between the aquifer storage and groundwater flow. In the equation, the groundwater discharge is calculated as the weighted sum of the groundwater flow of the previous day and the current groundwater recharge.

$$Q_{gw,i} = Q_{gw,i-1} \exp\left[-\alpha_{gw}\Delta t\ \right] + w_{rchrg,sh,i}\left[1 - \exp\left(-\alpha_{gw}\Delta t\right)\right] \tag{2}$$

where α_{gw} is the recession constant of the base flow, and Δt is the time interval. Equation (2) is obtained by substituting the linear relationship $S = KO$ into the continuity equation, $dS/dt = I - O$ in which the temporal change in storage volume (S) is equal to the difference between inflow (I) and outflow (O). The storage coefficient K is related to the recession constant of the base flow, and the inflow and outflow represent the groundwater recharge and discharge, respectively. The groundwater discharge is allowed when the shallow aquifer storage exceeds a user assigned threshold value.

However, the removed water of $w_{revap,i}$ and $w_{pump,i}$ is not explicitly considered in Equation (2), hence the reduction of groundwater discharge due to groundwater re-evaporation and pumping on groundwater discharge cannot be reflected. To resolve this problem, the groundwater recharge $w_{rchrg,sh,i}$ in Equation (2) was replaced by the net groundwater recharge $w'_{rchrgsh,i}$ expressed in Equation (3), and the subroutine gwmod.f, which calculates the groundwater recharge and runoff in the model, was modified in this study.

$$w'_{rchrg,sh,i} = w_{rchrg,sh,i} - w_{pump,sh,i} - w_{revap,i} \tag{3}$$

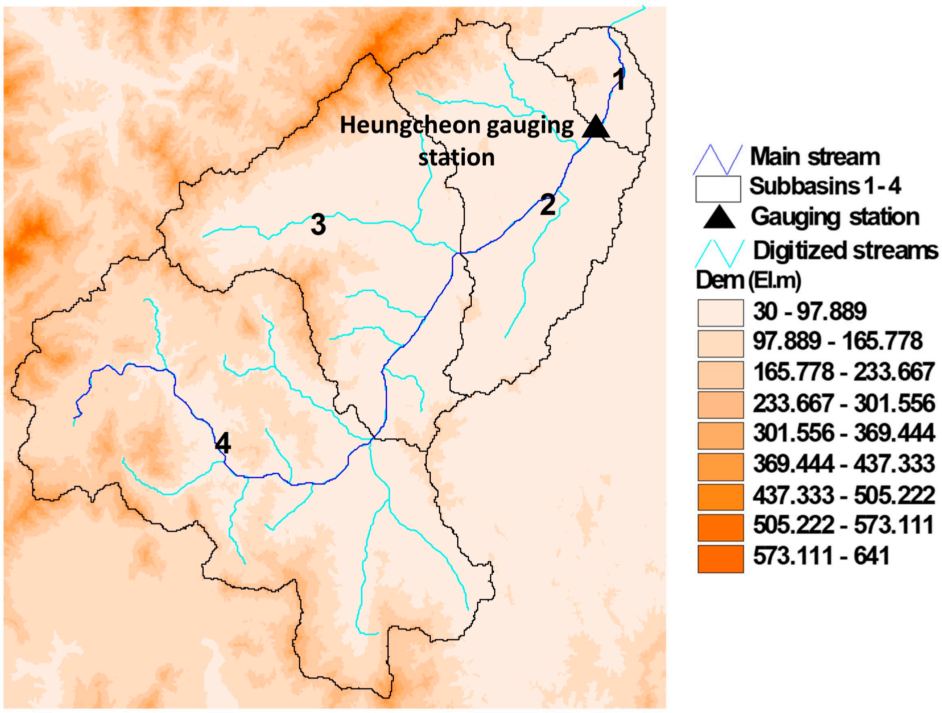
Water management practices can be modeled using SWAT with various water management options, such as irrigation, tile drainage, impounded/depressional areas, water transfer, consumptive water use, and point source loadings. Among these water management options, irrigation options can specify groundwater as the source of irrigated water, and consumptive water use options allow water to be removed from shallow and deep aquifers monthly. In this study, the water transfer module of the model was improved to allow water from the aquifer to be transferred to destination locations, such as reaches, residential, industrial, and agricultural lands, within any subbasin in the watershed. In the original SWAT, irrigation in an HRU can be scheduled by the user or automatically applied in response to a water deficit in the soil. The quantity of water for irrigation obtained from water sources such as reach, reservoir, and aquifer is directly added to soil water in response to soil water deficit. For using the irrigation options of SWAT, users must specify irrigation efficiency and irrigation surface runoff ratio for manual operation, which are not easy to set. In the modified SWAT of this study, the quantity of pumped water is moved to the agricultural land cover instead of the soil layers. The pumped water is added to the precipitation on the ground and is then separated into direct runoff and infiltration volume according to the soil moisture condition. Some of this water is returned to the channel through hydrological processes such as surface runoff, infiltration into the soil, evapotranspiration, percolation, recharge, and groundwater discharge. For groundwater withdrawal for living and industrial water use, the improved model allows a fraction of the pumped groundwater to be directly discharged into the channel by multiplying the return coefficient with groundwater withdrawal rates and removing the rest from the watershed. The default value of the return coefficient was set to 0.65 because this value is used to estimate the return flow rate when permitting residential and industrial water use in South Korea.

3. Model Setup

3.1. Watershed Delineation and Spatial Maps

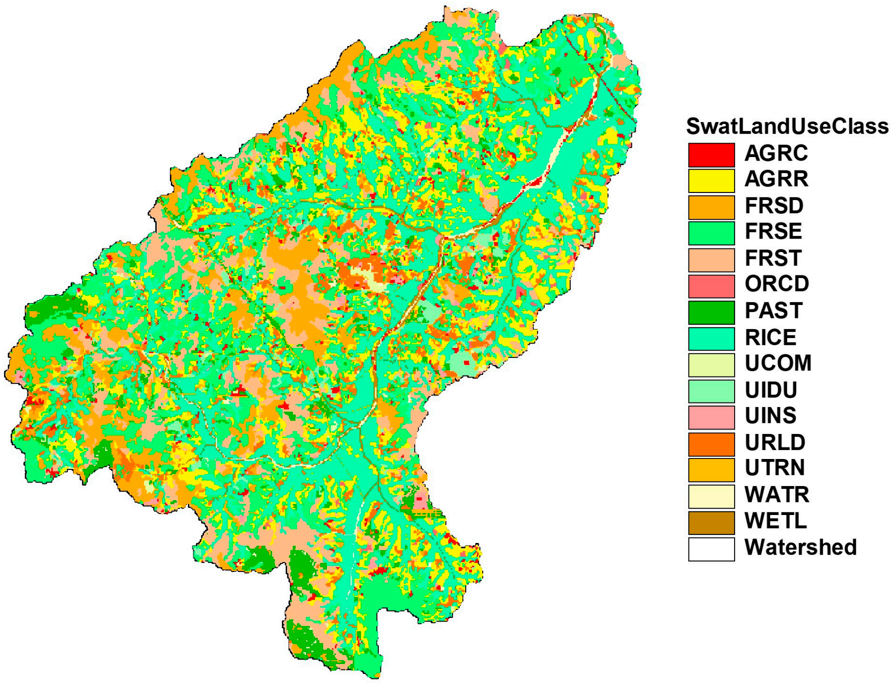
A digital elevation model (DEM) representing the shape of the basin, a land cover map representing the land use situation within the basin, and a soil map representing soil characteristics are required as spatial characteristics data for building the model. Figure 2a shows the DEM with a grid size of 30 m for the Bokhacheon watershed, the division of the sub-watersheds, and the river network. In the figure, upper-right sub-basin outlet no. 1 is the outlet of the watershed used in this study and it is divided into four sub-basins.

A 1:25,000 land-cover map (intermediate classification) provided by the Ministry of Environment was applied, and a soil classification map with a scale of 1:25,000 provided by the National Institute of Agricultural Sciences was used. Figure 2b shows the land use of the watershed, which is largely forest area and agricultural land. The soil map shows the distributions of 54 soil types (Figure 2c).

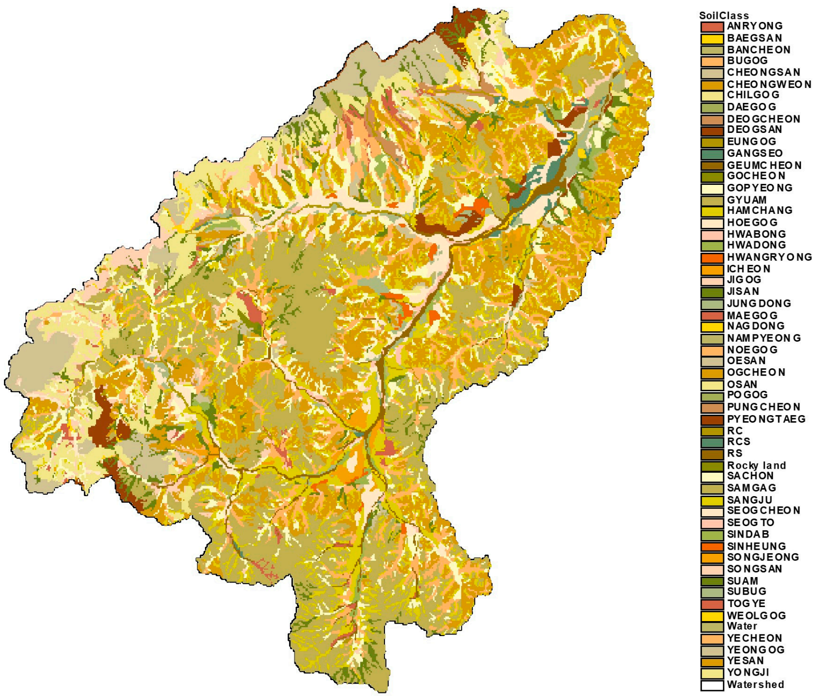


(**a**) DEM

Figure 2. *Cont.*



(**b**) Land use map



(**c**) Soil type map

Figure 2. DEM, land use, and soil type maps for the Bokhacheon watershed, South Korea.

3.2. Hydrometeorological Data

Hydrometeorological data were constructed from 2010 to 2019, of which 2010 was used as a warm-up period to stabilize the initial conditions of the model, e.g., initial soil moisture (Table 1). Data from 2011 to 2019 were used as inputs for analysis. Eight rainfall observation stations are located in the Bokhacheon watershed: Sangsang, Yeoju, Icheon, Namgok, Taepyeong, Seolseong, and Samjuk rainfall observatories, and Icheon meteorological observatory. The collected rainfall data were input into the SWAT model. Meteorological data, such as maximum/minimum temperature, relative humidity, wind speed, and solar radiation, were collected from the Icheon meteorological observatory and inputted into the model.

Table 1. Annual meteorological data for the study area.

Meteorological Data	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Precipitation (mm/y)	1445.9	2051.0	1613.7	1447.9	751.0	797.9	882.3	1030.5	1412.4	926.7
Average daily air temperature (°C)	11.1	11.0	11.1	11.4	11.9	12.4	12.7	11.7	11.7	12.3
Average daily relative humidity (%)	69.1	66.8	64.4	66.0	62.8	62.4	62.6	62.1	64.5	66.9
Average daily wind speed (m/s)	1.4	1.4	1.3	1.3	1.3	1.4	1.3	1.4	1.4	1.3
Average daily solar radiation (MJ/m^2)	11.6	12.4	13.7	13.5	13.5	13.8	13.5	14.1	14.2	13.4

During the 10 years from 2010 to 2019, the rainfall ranged from 751 mm to 2051 mm, with a mean of 1213 mm, slightly lower than the average annual precipitation in Korea. During the same period, the average annual solar radiation in Icheon was 13.4 MJ/m^2, average annual temperature was 11.7 °C, average annual relative humidity was 66.5%, and average annual wind speed was 1.4 m/s.

3.3. Water Use Data

Groundwater use data were collected from annual groundwater survey reports published by the Ministry of the Environment. In these reports, groundwater wells and their usage were surveyed in administrative districts. Hence, we converted the quantity of groundwater extracted per administrative district into that of a sub-watershed using area ratios. Furthermore, the effects of the return flow of groundwater were considered in this study.

Stream water intake data from the Jinro water intake plant, Jinri pumping station and some other stations were collected from the Han River Flood Control Office (HRFCO), an organization under the Ministry of Environment. Data on posttreatment discharges from sewage treatment plants, for example, the Icheon, Danwol, and Maegok facilities, were also collected from the HRFCO. Therefore, when simulating the model, the quantity of water intake was subtracted from the streamflow rates, and the quantity of water discharged from the sewage treatment plant was added to the flow rate of the stream. The annual averaged data of stream water intake, groundwater withdrawal, and sewage treated water discharge are shown in Figure 3.

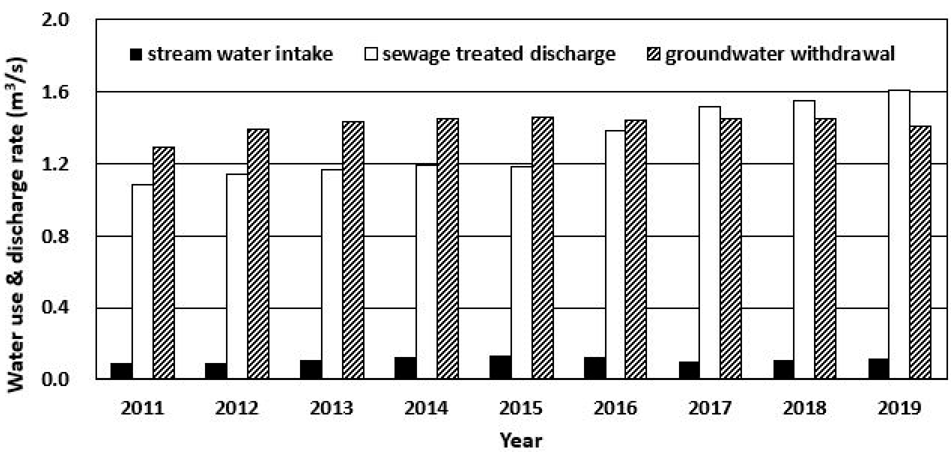


Figure 3. Annual averaged water use and discharge data for the study area.

3.4. Baseline Scenario

Data, such as subdivision, meteorological, land use and soil, water use (groundwater pumping rates and river water intake rates), and sewage-treated water discharge rates were entered into the SWAT model. The model was repeatedly run by adjusting the parameters of the model until the simulated and observed stream flows matched. After the calibration of the model was completed, the data on groundwater pumping rates, stream water intake rates, and the sewage-treated water discharge rates that caused the disturbance of the streamflow were removed from the model, and the streamflow was simulated again and considered as in a naturalized flow condition (baseline scenario). This baseline flow was compared with the streamflow only with groundwater withdrawal to assess the groundwater extraction effects.

4. Results and Discussion

4.1. Model Calibration

In this study, the measured water level records at the Heungcheon gauging station, located approximately 5.0 km upstream from the confluence with the Han river—the end of the Bokha stream—were converted to streamflow data using the water level–discharge relationship at the measured point. The model parameters were corrected based on the observed daily streamflow data at the Heungcheon gauging station, which is the outlet of sub-watershed No. 2 in Figure 2a. The model calibration period was set after 2013, when the quality of the flow observations was secured, such as with the installation of an automatic flow meter.

To fit the simulated and observed flow rates, model parameters, such as runoff curve number for AMC II condition (CN2), soil evaporation compensation factor (ESCO), transpiration compensation coefficient (EPCO), groundwater recharge lag variable (GWDELAY), threshold water depth to occur groundwater discharge (GWQMN), baseflow recession constant (ALPHA_BF), and Manning's roughness in the channel (CH_N), were corrected. Table 2 summarizes the calibrated parameters and their values.

Table 2. Calibrated parameters and values.

Parameters	Explanation	Calibrated Value
CN2	NRCS runoff curve number for moisture condition II	−10% of default value
SURLAG	Surface runoff lag time	0.5
EPCO	Plant water uptake compensation factor	0.5
ESCO	Soil evaporation compensation factor	0.8
GWDELAY	Groundwater delay to the water table	3.1 days
ALPHA_BF	Baseflow alpha factor for recession curve	0.01
GWQMN	Threshold water depth to occur goundwater flow occurs	50 mm
CH_N	Channel Manning's n value	0.04

Figure 4 compares the observed and simulated values of the daily runoff hydrograph and visually confirms that the simulated value fits well with the observed value regarding the overall runoff trend. The coefficient of determination (R^2) was calculated to determine the suitability of the calibration. The simulation result was considered good at $R^2 = 0.745$.

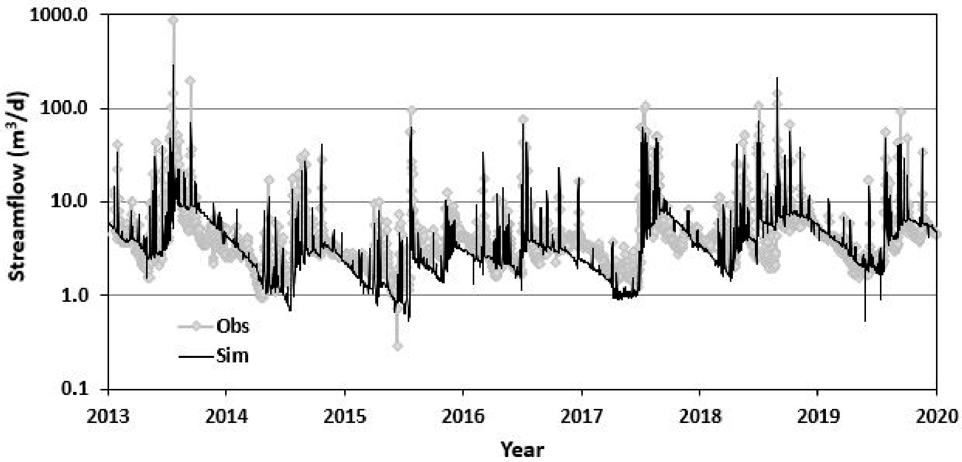


Figure 4. Comparison of observed and simulated streamflows at the Heungcheon gauging station.

4.2. *Streamflow Depletion Caused by Groundwater Withdrawal*

Using the calibrated SWAT model, natural flow rates were generated by simulating the streamflow rate again without considering groundwater pumping, stream water intake, or sewage treatment water discharge, which causes disturbances in the streamflow. Similarly, the impact of groundwater pumping on streamflow was simulated using a calibrated model. The effects of groundwater pumping on streamflow changes were then estimated by comparing the naturalized flow with the streamflow affected by groundwater pumping.

Figure 5 shows a comparison of the simulated daily streamflows with and without groundwater withdrawal at the outlet of the study watershed. The dotted grey line represents the simulated streamflow for the naturalized state without groundwater withdrawal, and the solid black line considers only the use of groundwater withdrawal. The decrease in stream flow due to groundwater pumping is clearly shown when compared with the natural flow, particularly for the dry years of 2014, 2015, 2017, and 2019.

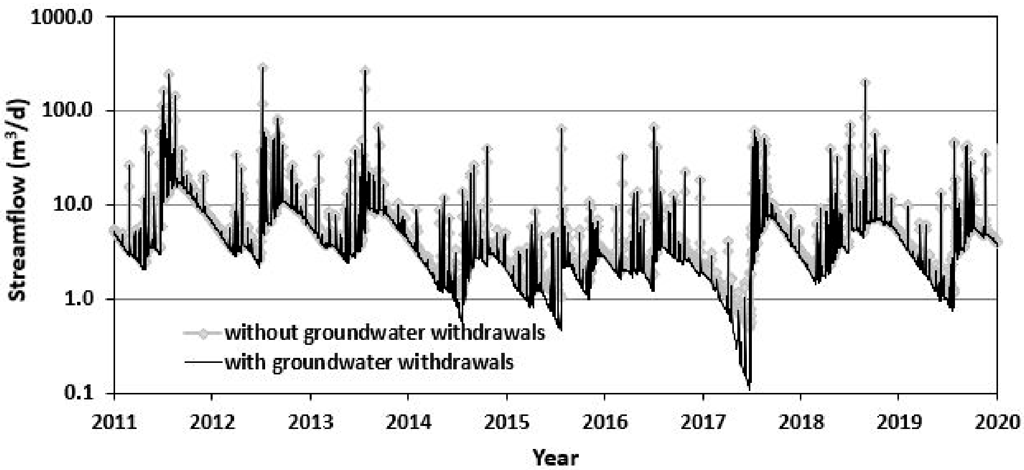


Figure 5. Comparison of the simulated daily streamflows with and without groundwater withdrawal at the outlet of the study watershed.

From the simulated daily streamflows, Q275 and Q355 are the discharge rates that did not fall below these quantities for 275 and 355 days out of the 365 days in a year, respectively. Korea's Ministry of Environment has implemented a policy to set and manage the total amount of pollutant discharge allowed to achieve and maintain the target water quality. When implementing this policy, the Q275 value was used as a criterion to calculate the discharged pollutant loads. The value of Q355 was used to calculate the 10-year frequency of drought flow, which is the standard flow rate for permission to use river water in Korea.

Therefore, Q275 and Q355 are important indices for managing the quantity and quality of rivers.

Figure 6a,b show the low flow (Q275) and drought flow (Q355) for the period 2011–2019, which were obtained from the simulated streamflows of Figure 5. The results indicate that the variability of low and drought flows was high, owing to the influence of rainfall. The low flow varied from 1.22 to 4.03 m^3/s for the naturalized condition without groundwater withdrawal, while it ranged from 0.8 to 3.67 m^3/s, with groundwater withdrawal showing an average decrease of 14.6%. The drought flow ranged from 0.56 to 3.00 m^3/s without groundwater abstractions, and was reduced to 0.13 to 2.51 m^3/s with an average decrease rate of 24.2%, resulting from groundwater abstractions. The rate of decrease was the largest, at 76.8%, in 2017, followed by 49.8 and 43.7% in 2013 and 2014, respectively. Therefore, groundwater abstractions have a greater effect in dry years.

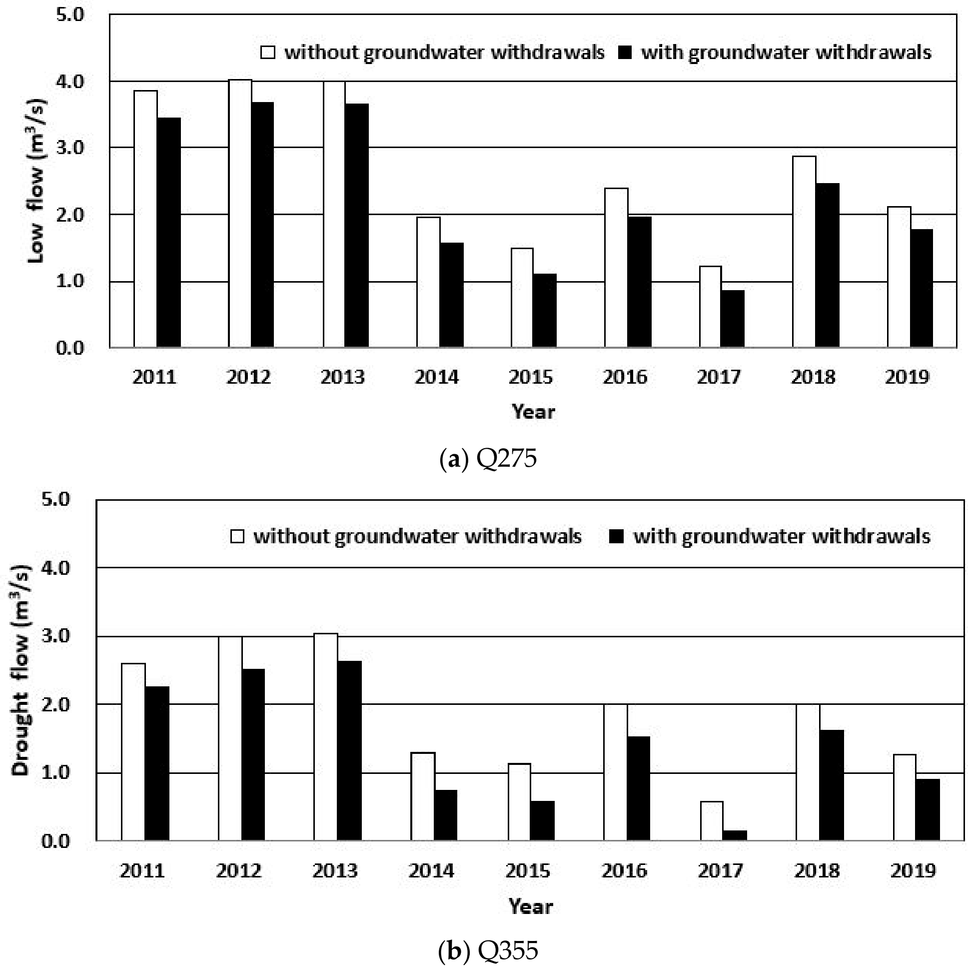


Figure 6. Comparison of the simulated low (Q275) and drought flows (Q355) with and without groundwater withdrawal at the outlet of the study watershed.

4.3. Impacts of Groundwater Withdrawal on Hydrological Components

The simulated hydrological components and their changes resulting from groundwater withdrawal are summarized in Table 3. In the table, Surq is the surface flow, Latq is the lateral flow, Gwq is the groundwater flow, Perc is the percolation, SW is the soil water, ET is the actual evapotranspiration, and Yield is the total flow. The values in parentheses represent the change rates (%) due to groundwater extraction compared with the natural state without groundwater extraction.

Table 3. Effects of groundwater withdrawal on hydrological components.

Scenarios	Hydrological Components (mm/y)						
	Surq	**Latq**	**Gwq**	**Perc**	**SW**	**ET**	**Yield**
With groundwater withdrawal	315.8 (9.3%)	23.7 (3.1%)	322.4 (23.5%)	441.6 (6.0%)	83.9 (4.5%)	502.3 (4.3%)	660.0 (−9.8%)
Without groundwater withdrawal	289.0	23.0	421.2	416.5	80.3	481.5	731.8

Notes: Surq: surface flow, Latq: lateral flow, Gwq: groundwater flow, Perc: percolation, SW: soil water, ET: actual evapotranspiration, Yield: total water yield.

The mean annual Surq, Latq, Perc, SW, and ET increased by 9.3, 3.1, 6.0, 4.5 and 4.3%, respectively. These increases were due to the transfer of groundwater for irrigation to the agricultural land surface in the form of additional rainfall. The annual mean groundwater flow decreased by 98.8 mm (−23.5%) from 421.2 mm in the naturalized state to 322.4 mm after pumping groundwater. The annual mean total yield, contributing to streamflow rates, was reduced to 660.0 mm with groundwater pumping when compared with 731.8 mm for the naturalized condition. The reduction of groundwater discharge due to groundwater pumping is greater than the increases in surface and lateral flows that occur after irrigation, which resulted in the decrease in a total water yield of 71.8 mm (−9.8%).

5. Conclusions

This study presented a methodology to simulate baseflow by considering groundwater pumping and modification of the discharge–storage relationship of the groundwater module in the SWAT model. The modified SWAT was then applied to the Bokhacheon watershed, in which the streamflow has been highly impacted by human impact factors such as groundwater pumping, stream water intake, and sewage treatment water discharge that causes disturbances in the streamflow. Among the human impacts, the effects of groundwater withdrawal on streamflow depletion, which are difficult to measure, were estimated by simulating streamflow changes with and without considering the groundwater withdrawal using the modified SWAT.

The simulated streamflow results for a historical nine-year period (2011–2019) during which it was impacted by groundwater withdrawal show a significant difference from the naturalized streamflow that would have occurred in the absence of water withdrawal and sewage-treated water discharges. Groundwater withdrawal induced a decrease of 14.6% in low flow against naturalized streamflow and a decrease of 24.2% in drought flow at the outlet of the study watershed during the simulation period.

Groundwater abstraction caused a decrease in the hydrological components of groundwater flow and total water yield by 23.5 and 9.8%, respectively, compared with the results for the naturalized state. Owing to the transfer of pumped groundwater to the irrigated area, the mean annual surface flow, lateral flow, percolation, soil water, and evapotranspiration increased by 9.3, 3.1, 6.0, 4.5, and 4.3%, respectively. In particular, the increased surface and lateral flows and percolation contributed to the increased return flow to the channel, in contrast with the decreased groundwater discharge.

Consequently, the modified version of the SWAT developed in this study can effectively assess streamflow depletion from groundwater pumping without extensive hydrogeological input data and computational time. Further studies will be conducted to compare the performance of the modified SWAT with more complex physically based models, such as SWAT-MODFLOW.

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Data Availability Statement: Data is available on request form the authors.

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

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