Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25166

180 (2020) 104–110
March

Modeling the influence of future climatic variables on nutrient loading in the Yeongsan River Basin, South Korea

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Received 1 July 2019; Accepted 18 November 2019

ABSTRACT

Eutrophication is caused by the discharge of excess nutrients from various point and nonpoint sources. In particular, nonpoint sources of nutrients are difficult to identify because of diffuse sources and the effects of climate change. The objective of this study is to investigate the change in nutrient loading from land areas under climate change. In this study, the soil and water assessment tool (SWAT) model was applied to predict the sediment, total nitrogen (TN), and total phosphorus (TP) loads in the Yeongsan River Basin using geographical information (i.e., digital elevation map, land use, and soil type), observed data (i.e., meteorological data, streamflow, and water quality). Future climatic variables were obtained from a general circulation model, which was simulated using four representative concentration pathway (RCP) scenarios such as RCP 2.6, 4.5, 6.0, and 8.5. The results showed that flow rate, sediment load, TN load, and TP load were changed in terms of climate change under the different RCP scenarios. Impacts of climate change on a basin may be an important factor in eutrophication management in the Yeongsan River. The SWAT model provided an accurate prediction of the current nutrient pollutant loads and facilitated the reliable prediction of future nutrient pollutant loads under climate change.

Keywords: Climate change; Nutrients; Watershed; GCM; SWAT

1. Introduction

Global climate change is one of the critical issues in water resource management. The Intergovernmental Panel on Climate Change has reported that climate change has a high potential to influence the mean runoff, groundwater, soil moisture, and frequency and intensity of floods and droughts. Moreover, climate change has a significant effect on water quality, such as the water quality deterioration caused by drought and the discharge of pollutants in the watershed [1].

Several studies report on the impacts of climate change on hydrology and pollution using the soil and water assessment tool (SWAT), including four studies that were partially or completely supported by the European Union (EU) Climate Hydrochemistry and Economics of Surface Water Systems project [2]. Nearing et al. [3] compared runoff and erosion estimates from SWAT to that of six other models in

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response to six climate change scenarios that were simulated for the 150 km² Lucky Hills watershed in southeastern Arizona. The responses of all seven models were similar across the six scenarios for both watersheds, and it was concluded that climate change could potentially result in significant increases in soil erosion if necessary conservation efforts were not implemented. Boorman [4] evaluated the impacts of climate change for five different watersheds located in Italy, France, Finland, and the United Kingdom, including the three watersheds.

In Korea, various researchers have investigated the impact of climate change on hydrology. Past studies have predicted the effect of future climate change on evapotranspiration, streamflow, and groundwater. Park et al. [5] determined the future hydrological process and stream water quality in a mountainous basin using statistically downscaled climate data from two general circulation models. Modeling the future climate change impact on the Yeongsan River Basin is critical because the basin is predominantly an agricultural area and is important for food security [6]. In addition, the surface water in the basin is used for irrigation, industrial, and recreational purposes, and this resource may be affected by future climate change.

The objectives of this study are as follows: (1) to construct a watershed model to predict the total nitrogen (TN) and total phosphorus (TP) loads using SWAT and (2) to assess the impacts of climate change on variations in nutrient loads using future climate scenarios.

2. Materials and methods

2.1. Site description

The Yeongsan River Basin, located in the southwest region of the Korean Peninsula in the South Jeolla Province, is home to 1.7 million people (Fig. 1). The river stretches over 135 km in the western sector of the province, and the drainage basin includes the territories of three cities and 15 districts, with a total area of approximately 3,500 km². In the basin, agriculture is the dominant land use, with some forest coverage, and there are many artificial structures (e.g., dams, dikes, and weirs) to support the agricultural activities. Although no major commercial or industrial activities have occurred in the basin in recent decades, the river is subject to pressure from physical barriers and diffuse pollution due to agricultural and urban land uses [7–10]. Around 80% of the population in the Basin is urban, where the load capacity reached 14,160; 11,483; and 4,131 kg/d for the biochemical oxygen demand, TN, and TP, in 2005, respectively. Around the city, the average rainfall

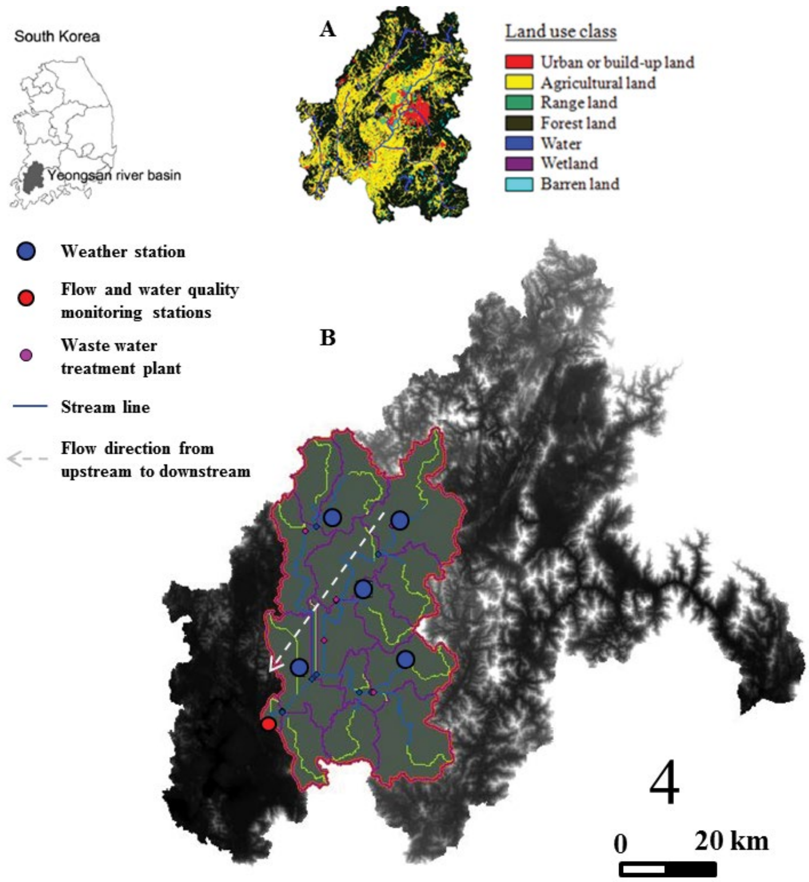

Fig. 1. (a) Land use class classification of Yeongsan Basin and (b) map of Yeongsan River Basin in the SWAT model with meteorological weather stations, flow and water quality monitoring station, and wastewater treatment plants.

amount and air temperature were 1,368 mm and 13.5°C, respectively, over a 30 years period (1971–2000).

2.2. Application of SWAT model

SWAT 2005 was applied to elucidate the effect of climate change on water quality in the watershed. It was developed at the U.S. Department of Agriculture-Agricultural Research Service Grassland, Soil, and Water Research Laboratory in Temple, Texas [11,12]. This well-established model has geographic information systems and graphical user interfaces, and it is an element of the Better Assessment Science Integrating Point and Nonpoint Sources modeling system from the United States Environmental Protection Agency [13].

Data were obtained from the Ministry of Environment in Korea for the flow direction, topography (e.g., digital elevation model, land use, and soil), slope, and other catchment information. Using the data, the stream network was delineated, and the basin was divided into sub-basins. Land use data were provided by the Environmental Geographic Information Service in Korea (https://egis.me.go.kr/main.do). Soil properties data including hydrologic group, soil depth, percentage of sand/silt/clay/organic carbon, saturated hydraulic soil loss equation, and the soil erodibility factor (K) were estimated from the National Academy of Agricultural Science soil map and available Korean soil information (http://www.naas.go.kr/english/). Based on these datasets, the hydrologic response units for the sub-basins were generated using a threshold value. Agricultural management data, including tillage operation, irrigation water application, fertilizer application, and plant growing season information, were obtained from the Rural Development Administration (www.rda.go.kr).

Observed meteorological data, streamflow, and water quality data are required to prepare the SWAT model. The daily streamflow data collected by the Ministry of Land, Infrastructure, and Transport at the flow measurement station (see the red circle in Fig. 1) were applied to calibrate the flow rate in the model. The daily maximum and minimum air temperature, precipitation, wind speed, relative humidity, and solar radiation monitored by the Korean Meteorological Administration at the weather stations (see the blue circle in Fig. 1) were used. The monthly sediment, TN, and TP collected by the Ministry of Environment at the water quality monitoring station (see the red circle in Fig. 1) were used to calibrate the water quality. Data from 5 years from 2006 to 2010 were used to calibrate and validate the SWAT model. The calibration for the sediment-, TN-, and TP-related model parameters was performed using a pattern search algorithm in terms of its objective function; the objective functions consisted of root-mean-square error values (i.e., prediction performance) between the observed and predicted sediment loads, TN loads, and TP loads.

3. Results and discussion

3.1. Calibration and validation for streamflow, sediment load, and nutrient loading

Based on the sensitivity analysis (results not shown), 11 flow-related parameters were calibrated to simulate streamflow; those parameters with calibrated values included Alpha-BF (1.0), BLAI (0.62), CANMX (10), CH-K2 (100.04), CH_N2 (0.25), CN2 (8.98), ESCO (0.03), GWQMN (367.12), SLOPE (-19.21), SOL-K (-2.95), and SURLAG (2.47). Predicted and observed flow rates in both the calibration (2006–2008) and validation step (2009–2010) are compared in Fig. 2. The results showed acceptable prediction accuracy for modeling flow rates (Nash–Sutcliffe efficiency (NSE) > 0.5 (Table 1), [14]). The predicted flow matched well with the observed flow except for the peak flow event. However, the model underestimated the peak flow values. The SWAT model is limited when simulating the high peak flow [15,16] because it only simulates daily flow rates when the actual peak flows occur within hours [17].

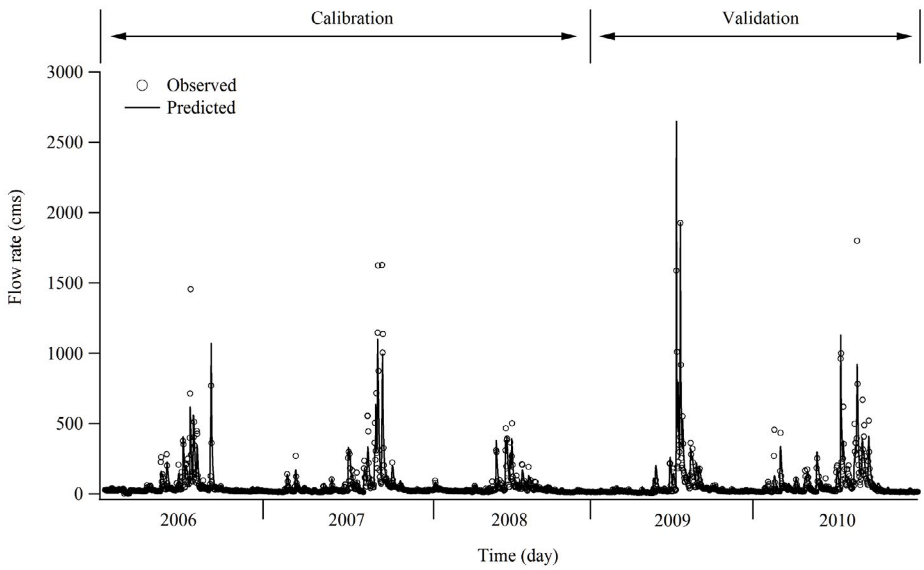

Fig. 2. Comparison of predicted and observed flow rates in the calibration and validation process.

Based on the sensitivity analysis (results not shown), six sediment-related parameters were calibrated to simulate sediment; those parameters with calibrated values were CH_COV (-0.001), CH_EROD (0.46), SPCON (0.001), SPEXP (1.0), PRF (0.39), and USLE_P (0.1). The predicted and observed sediments in both the calibration (2006–2008) and the validation step (2009–2010) are compared in Fig. 3. Based on the sensitivity analysis (results not shown), the calibrated parameters for TN and TP were RCN (0.25), ERORGN (0.86), BC1 (0.39), BC2 (0.93), RS4 (0.1), PHOSKD (399.98), GWSOLP (0.034), ERORGP (0.34), BC4 (0.07), RS5 (0.1), MUMAX (1.0), RHOQ (0.06), AI1 (0.07), and AI2 (0.02). The predicted and observed TN and TP in both the calibration (2006–2008) and validation step (2009–2010) are compared in Figs. 4 and 5, respectively. Overall, the predicted TN and TP matched well with the observed TN and TP, except for during the peak flow event.

Table 1
Prediction accuracy for streamflow, sediment, and nutrients in terms of R^2, NSE, and MAE

Variable	Accuracy index	Calibration process	Validation process
	R^2	0.73	0.78
Streamflow	NSE	0.73	0.74
	MAE (m^3/s)	23.49	31.15
	R^2	0.48	0.65
Sediment	NSE	0.45	0.46
	MAE (ton)	1,615.80	4,231.43
	R^2	0.66	0.64
TN	NSE	0.62	0.58
	MAE (kg)	279,992.60	303,629.00
	R^2	0.69	0.73
TP	NSE	0.67	0.66
	MAE (kg)	18,314.14	15,291.84

NSE: Nash–Sutcliffe efficiency
MAE: Mean absolute error
TN: Total nitrogen

3.2. Changes in future climatic variables from a regional climate model

Local climate change data were obtained from the Climate Change Information Center, which has been operating the HadGEM3-RA [18] model to simulate the regional climate change in Korea. The boundary conditions of this regional model were obtained from the HadGEM2-AO model. The four representative concentration pathways (RCP) [19–22] climate change scenarios were selected, based on integrated assessment modeling, climate modeling, and modeling and analysis of impacts. The RCPs used in this study (2.6, 4.5, 6.0, and 8.5) correspond to a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively). The spatial scale of the HadGEM3-RA model is 12.5 km, and the temporal scale is daily. The future five climatic variables (i.e., maximum and minimum air temperature, precipitation, relative humidity, and wind speed) were applied to the watershed model to predict the change in nutrient loading.

As shown in Table 2, the regional climate model outputs also showed a gradual increase in the maximum and minimum air temperature in the Yeongsan River Basin. The model, however, did not show a clear increase in precipitation in the Basin. The relative humidity and wind speed showed minor fluctuations.

3.3. Changes in nutrient loading in terms of climate change

The five climate variables (i.e., precipitation, relative humidity, maximum air temperature, minimum temperature, and wind speed) were applied to the watershed model to assess the change in flow rate, sediment load, TN load, and TP load due to global climate change. Table 3 presents the decade-averaged flow rate, sediment load, TN load, and

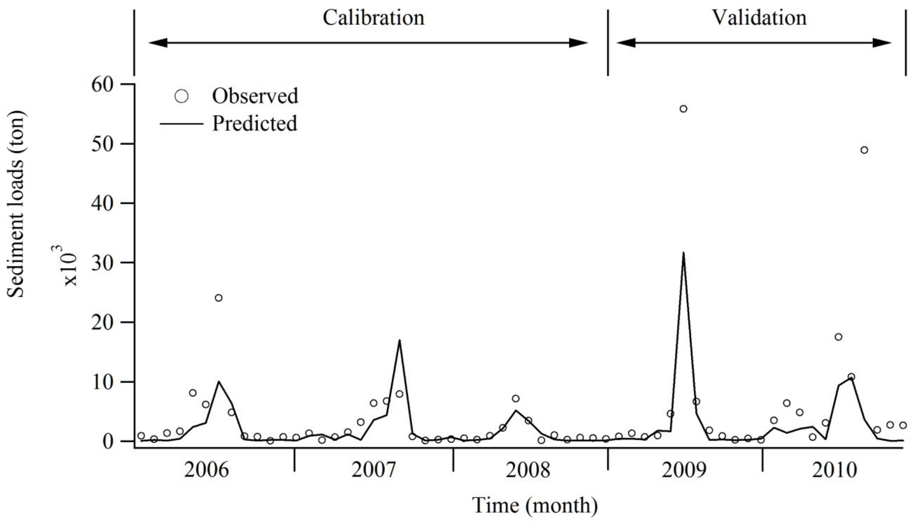

Fig. 3. Comparison of predicted and observed sediment loads in the calibration and validation process.

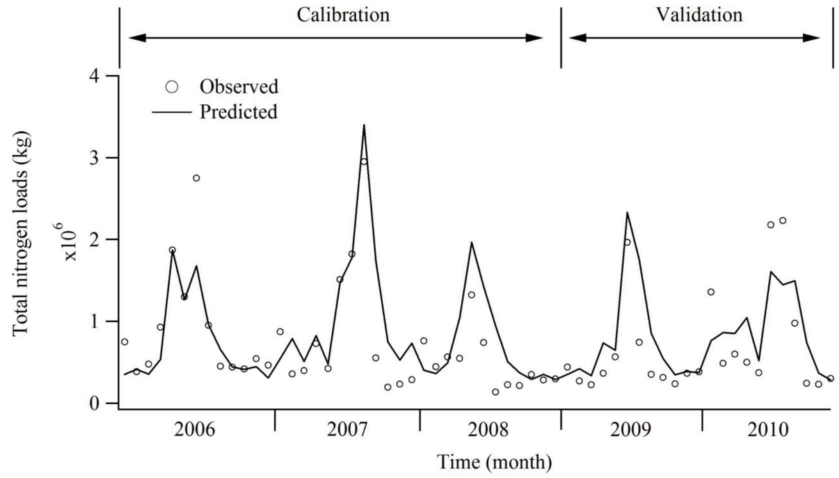

Fig. 4. Comparison of predicted and observed TN loads in the calibration and validation process.

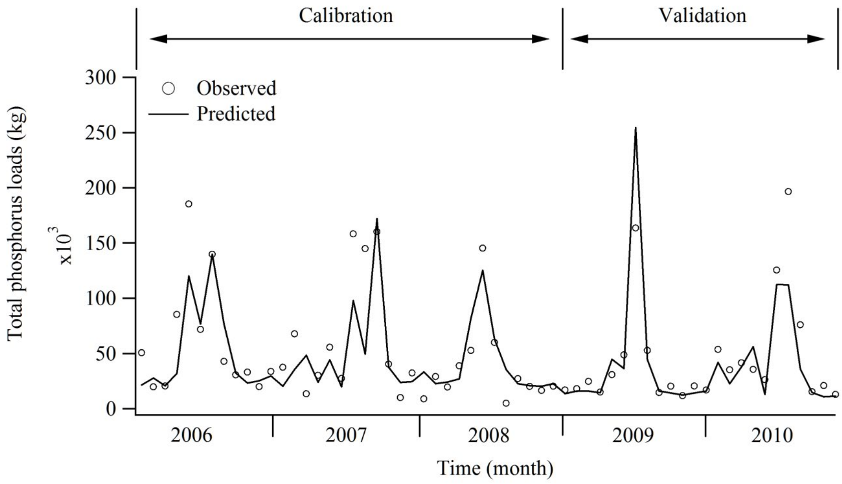

Fig. 5. Comparison of predicted and observed TP loads in the calibration and validation process.

Table 2
Changes in future climatic variables during the 2050s and 2090s with respect to different RCP scenarios

Variable	Period	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Precipitation	2050s	1,460.54 ± 177.29	1,554.98 ± 275.19	1,300.98 ± 234	1,467.3 ± 343.08
	2090s	1,474.25 ± 285.40	1,284.54 ± 223.96	1,439.53 ± 273.35	1,677.86 ± 358.12
Maximum air	2050s	18.45 ± 0.37	18.9 ± 0.57	18.02 ± 0.7	19.3 ± 0.46
temperature	2090s	18.39 ± 0.40	19.73 ± 0.5	20.13 ± 0.6	21.66 ± 0.81
Minimum air	2050s	10.13 ± 0.46	10.41 ± 0.48	9.43 ± 0.6	10.74 ± 0.52
temperature	2090s	10.04 ± 0.42	11.04 ± 0.34	11.54 ± 0.44	12.42 ± 0.54
Relative	2050s	74.83 ± 1.07	74.68 ± 0.83	74.34 ± 1.13	74.97 ± 1.84
humidity	2090s	74.80 ± 1.50	74.1 ± 2.68	74.44 ± 1.2	76.54 ± 1.2
Wind speed	2050s	2.92 ± 0.087	2.85 ± 0.08	2.93 ± 0.05	2.94 ± 0.1
	2090s	2.89 ± 0.083	2.81 ± 0.11	2.84 ± 0.11	2.82 ± 0.09

TP load in terms of the different RCP scenarios in the SWAT model. The flow rate, sediment load, TN load, and TP load varied in terms of the RCP scenarios. In the RCP 8.5 scenario, all variables in the 2090s were higher than those in the 2010s. The TN and TP loads in the RCP 2.6, 4.5, and 6.0 scenarios were lower than those in the 2010s. The climate change scenarios resulted in higher mean streamflow due to greater flooding and other high streamflow increases; however,

Table 3
Changes in streamflow, sediment, and nutrient loading during the 2050s and 2090s with respect to different RCP scenarios

Variable	Period	Current (2010 s)	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Streamflow	2050s	56.06 ± 28.61	58.56 ± 11.62	64.62 ± 17.34	48.51 ± 14.85	59.06 ± 24.97
(m^3/s)	2090s		60.17 ± 17.67	47.2 ± 12.15	56.51 ± 18.63	68.68 ± 25.39
Sediment	2050s	2,194.14 ± 1,744.54	2,095.97 ± 530.14	2,700.58 ± 1,317.07	1,892.36 ± 910.62	2,263.6 ± 1,412.76
load (ton)	2090s		2,397.11 ± 1,053.18	1,702.85 ± 516.86	2,200 ± 965.76	2,868.17 ± 1,802.63
TN load	2050s	651,653 ± 224,090	644,460 ± 149,127	694,983 ± 237,616	585,374 ± 193,718	631,098 ± 243,312
(kg)	2090s		603,311 ± 147,269	563,465 ± 177,703	625,474 ± 204,157	696,795 ± 157,340
TP load	2050s	31,417.6 ± 17,925.9	31,127.6 ± 13,972	36,689.4 ± 21,572.2	25,880.8 ± 17,168.3	29,585.3 ± 11,833.3
(kg)	2090s		27,199.6 ± 11,285.7	24,248.3 ± 13,424.2	28,557.3 ± 13,017.7	32,161.5 ± 11,223.9

normal and low streamflow decreased [23]. Varanou et al. [2] reported that the average streamflow, sediment yields, organic N losses, and nitrate losses decreased in most months in response to nine different climate change scenarios. Bouraoui et al. [24] reported that climate change caused an increase in TN and TP loads of 6% to 27% and 5% to 34%, respectively.

4. Conclusions

In this study, a comprehensive comparison of the current and future watershed response was performed in terms of water quality and quantity. We evaluated the use of the watershed modeling approach. This study provided a method to quantify the impacts of eutrophication on water quality in order to predict the effects of eutrophication. The SWAT model showed acceptable accuracy in the prediction of flow rates, sediment load, TN load, and TP load in both calibration and validation steps, showing satisfactory performance values. The flow rate, sediment load, TN load, and TP load were significantly altered under climate change. This result revealed that climate change impacts on eutrophication should be considered for developing efficient management plans in a watershed.

The SWAT model can generally provide a reliable simulation of flow and pollution from a watershed. This study offers a method for predicting pollution in response to significant land-use and climate change.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2019R1C1C1011366). This work was supported by the Korea Institute of Energy Technology Evaluation and Planning and the Ministry of Trade, Industry, and Energy (20174010201490).

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