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The effect of climate change on Byeongseong stream's water quantity and quality

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ABSTRACT

For the assessment of climate change impacts for the Byeongseong stream, CSIRO-Mk3.0 is selected as future climate information. The projections come from CSIRO Mark 3.0 used to simulate the green house gases emission scenario known as A2. Air temperature and precipitation information from the global climate model simulations are converted to regional scale data using the statistical downscaling method known as Multi-Site Precipitation Generator. Downscaled climate data from global climate model are then used as the input data for the Soil and Water Assessment Tool to generate regional runoff and water quality estimates in the Byeongseong stream. As a result of simple sensitivity analysis, the increase of CO_2 concentration leads to increase water yield through reduction of evapotranspiration and increase of soil water. Hydrologic responses to climate change are in phase with precipitation change. Climate change is expected to increase water yields in wet season. In dry season, stream flow is expected to be reduced slightly. Soil losses and nutrient discharges are also in phase with precipitation change. However, it should be noted that there are many uncertainties in such multiple-step analysis used to convert climate information from global climate model based future climate projections into hydrologic information.

Keywords: Byeongseong stream; Climate change; Global climate model; Soil and water assessment tool; Water quality; Water quantity

1. Introduction

Climate change is a major cause of hydrologic changes in watersheds. Currently, a majority of diverse climactic experiments and analyses of historical climatic data predict that future climate will be different from that of the present [1]. In the case of Korea, a comparison of climate data from 1999 to 2008 with the ones for three decades from 1971 to 2000 shows that annual average rainfall and temperature have respectively increased 9.1% and 0.6°C [2]. From a short term perspective hydrologic change caused by climate change can result in unusual meteorological phenomena such as drought and flood. Long-term continuation of hydrologic change could influence local water resources and related water quality and vegetation.

Internationally, hydrological researches for understanding the impact of climate change have in general used future climate information from single or multiple

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global climate models (GCMs) or have applied down scaling results to rainfall-runoff model by using appropriate techniques to analyze runoff responses of watersheds [3–7]. Impacts on water quality have been also analyzed as in the case of Bouraoui et al. [8] in particular. Furthermore, uncertainty analysis based on results from GCMs and uncertainty analysis following the application of the results of GCMs to watershed models can be also found [9].

In line with such research trends, hydrological and water quality responses in a typical farming area in Korea to future climate change are investigated in this study. CSIRO Mark 3.0 (CSIRO-Mk3.0) driven by A2 green house gas emission scenario is applied as future climate information (PCMDI, 2009). Air temperature and precipitation information from CSIRO-Mk3.0 simulations are converted to regional-scale data using a statistical downscaling method known as Mult-Site Precipitation Generator (MSPG). Downscaled climate data from CSIRO-Mk3.0 are used as the input data for the Soil and Water Assessment Tool (SWAT) to gene rate regional hydrologic estimates for runoff, soil water, soil losses, and nutrient discharges.

The specific objectives of this study are to: (1) calibrate and validate the SWAT water quantity and quality components over a 20-year period (1988–2007) by using historical climate data and comparing simulated output with observed streamflows and water quality variables; (2) replicate and verify present precipitation and temperature field simulated by using CSIRO-Mk3.0 and MSPG; (3) investigate the effect of changing atmospheric carbon dioxide in the range of 330–660 ppmv on the catchment hydrologic response; and (4) estimate fluctuations in seasonal water quantity and quality with SWAT in response to future climate scenarios.

2. Methods

2.1. Watershed studied

Byeongseong Stream (Korea) is the first tributary of the Nakdong River, which flows into the right bank of the river at the 258.9 km upstream from the estuary of the river. The area of the watershed is 433.11 km^2; the river length is 32.79 km; and the length of the main stream is 5.51 km. The land use of Byeongseong Stream watershed is characterized by a very large proportion of forests and cultivated land, which is mostly composed of paddy fields and orchards. Most of the area is characterized a soil that is easily drained [10]. More details on the water quality based characteristics are described in Han et al. [11].

2.2. Collection of present and future climate data

To predict climate change, future climate change scenarios to which greenhouse gas increase is applied are necessary. Climate change simulation based on GCM is widely used globally as a basic tool of the task. This study uses the results of CSIRO-Mk3.0, which was developed by Commonwealth Scientific and Industrial Research Organization, Australia, and is one of the GCMs recommended by Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC AR4). A2 scenario of Special Reports on Emissions Scenarios [12], is applied to CSIRO-Mk3.0. According to CSIRO-Mk3.0 predictions for the Korean peninsula based on A2 scenario, daily maximum temperature will increase by about 4°C at the end of the 21st century whereas the daily minimum temperature will increase by about 3.5°C. Annual total precipitation will increase by more than 10%.

In accordance with the characteristics of its goals, GCM provides future climate data in a low resolution. Even CSIRO-Mk3.0 provides a resolution of 1.9° (longitude) × 1.9° (latitude) and the size of a grid is approximately 190 km × 190 km. Considering that the area of South Korea is about 100,000 km^2, climate variables simulated from several grids explains the climate of South Korea as a whole. Therefore, the climate information provided by GCM is not appropriate for the analysis of the climate change on Byeongseong Stream watershed.

Therefore, the multi-site daily precipitation generator (MSPG) derived from CSIRO-Mk3.0 results, which was proposed by Keem et al. [13], is used to reconstruct future precipitation data for Byeongseong Stream watershed. Then, past observed data of humidity, solar radiation, wind speed, and daily minimum/maximum temperature for the years from 1986 to 2007 are divided into wet days and dry days, and the Monte-Carlo simulation based on log-normal distribution is applied to each of the data to generate the corresponding future climate data. In the case of the temperature data, future climate data are produced by applying simple difference correction for the difference between GCM-predicted future data and current data to the data produced by the past observed data. As for humidity, solar radiation, and wind speed, future climate data are generated under the assumption that statistical characteristics of the past observed data will be identical in the future.

2.3. Production of the watershed model

Table 1 shows data necessary for the creation of SWAT model. Broadly speaking, building SWAT model necessitates topographic data and climatic data. Topographic data and climatic data are acquired through Water Management Information System (WAMIS) and Korea Meteorological Administration (KMA). Using the stream network map and the digital elevation model, the watershed is divided into smaller watershed areas and the soil map and the land use map are used to create hydrological response units. Then physical variables are established before running simulation of the climate data, which are entered to the model. Because of the lack of long-term climatic data for Byeongseong Stream watershed, climatic data from Gumi and Mungyeong, which are neighboring regions, are used. As for solar radiation data, those from Andong are used.

To analyze long-term hydrologic change in the watershed, long-term observed daily stream flow data and water quality data are necessary. Such long-term data for Byeongseong Stream watershed are not available. However, Nakdong River Environment Research Center (NRERC) of National Institute of Environmental Research (NIER) provides 8-day interval stream flow and water quality data of Byeongseong Stream watershed outlet for the period since 2004. TANK model ([14]), which is characterized by outstanding reproduction of data, is applied to the data to reconstruct the daily discharge data for the period from 1986 to 2007. More details on the procedure are described in Kim and Kim [15]. As for the water quality data, minimum variance unbiased estimator (Bradu and Mundlak., 1970) [16] is used in accordance with the research by Han et al. [17] to establish the relationship between stream flow and pollutant load and the stream flow data, which is reconstructed at a one-day interval, are used to produce one-day interval pollutant load data. More details on the procedure are described in Han et al. [18]. Later, parameter estimation by SWAT model is carried out by considering such data as observed data at the outlet points of Byeongseong Stream watershed.

Figure 1 is a map of the sub-basins of Byeonseong Stream watershed to which SWAT-Byeongseong Stream model is applied. In running the simulation based on the long-term climatic data, which cover 22 years from 1986 to 2007, the first two years are set as the warming-up period. Then, the calibration of parameters involving stream flow, SS, and TN is carried out by comparing simulated and observed data of the first ten years and the data for the second ten years from 1998 to 2007 are used for verification. Coefficient of determination R^2 and Nash-Sutcliffe Coefficient (NSC) proposed by Nash and Sutcliffe [19] are used as the indexes for the accuracy of model calibration. Basically, default values of the model are used and parameters modified by the calibration are shown in Table 2. Figure 2 illustrates the comparison between simulated data produced by the model and observed data.

Table 1
Model input data information.

Data type	Source	Description
DEM	WAMIS	30 m × 30 m resolution (grid. file)
SoilType	WAMIS	30 m × 30 m resolution (grid. file)
Landuse	WAMIS	30 m × 30 m resolution (grid. file)
Stream	WAMIS	30 m × 30 m resolution (shp. file)
Rainfall	KMA	Mungyeong and gumi data (dbf.file)
Max/Min temp	KMA	Mungyeong and gumi data (dbf.file)
Wind speed	KMA	Mungyeong and gumi data (dbf.file)
Humidity	KMA	Mungyeong and gumi data (dbf.file)
Solar radiation	KMA	Andong data (dbf.file)

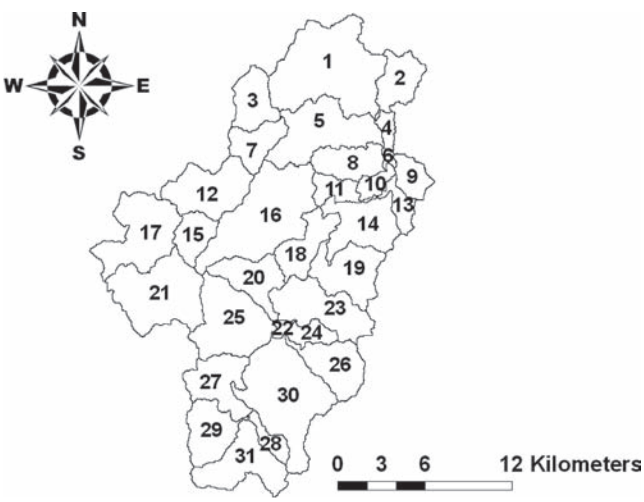


Fig. 1. Sub-basins of Byonseong stream watershed.

Table 2
Parameter values in SWAT after calibration.

Parameter	Model process	Range	Calibrated value	Description
SPCON	Sediment	0.0001–0.01	0.0003	Coefficient in sediment transport equation
SPEXP	Sediment	1.0–2.5	1.2	Exponent in sediment transport equation
RHOQ	Nutrient	0.05–0.50	0.3	Local algal respiration rate at 20°C
AI1	Nitrogen	0.07–0.09	0.09	Fraction of algal biomass that is nitrogen
NPERCO	Nitrogen	0.00–1.00	1.0	Nitrate percolation coefficient
SOL_ORGN	Nitrogen	All	600	Initial organic N concentration in soil layer
SOL_NO_3	Nitrogen	All	5	Initial NO_3 concentration in soil layer

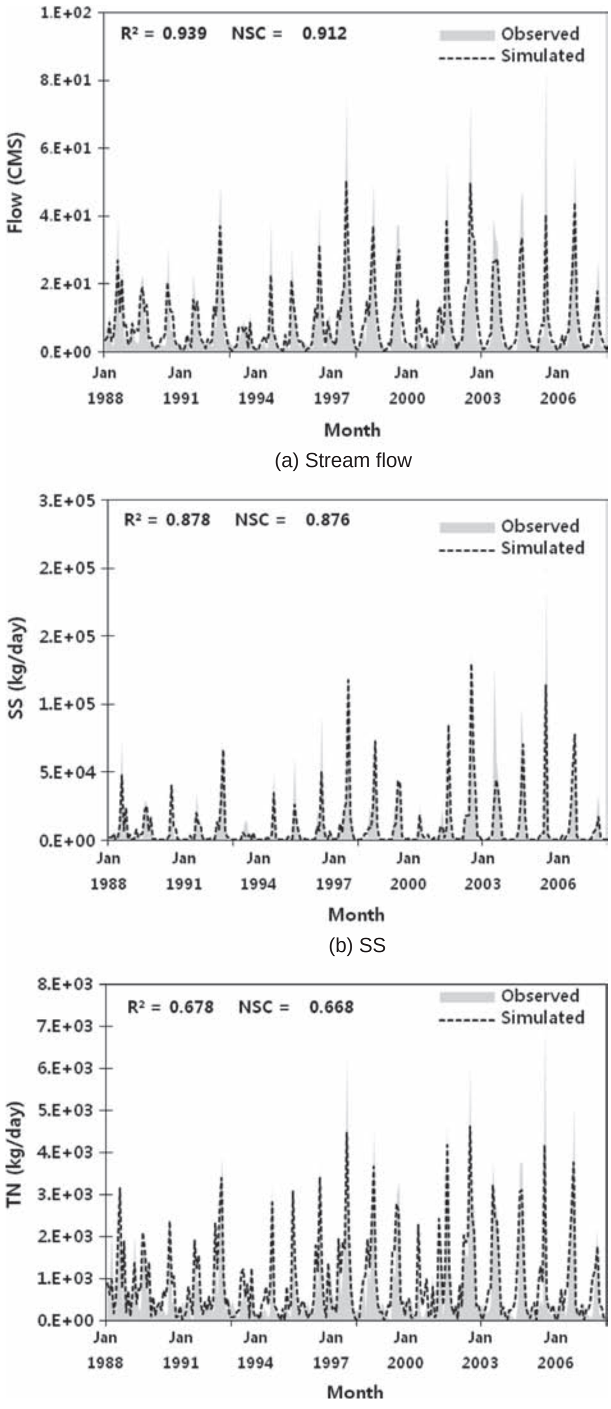


Fig. 2. Calibrations of simulated variables against observed values.

3. Results and discussion

3.1. Production of current and future climate data

Future climate (2001–2100) data simulated by CSIRO-Mk3.0 are divided into Future 1 (2011–2040) and Future 2 (2071–2100). In addition, present climate data simulated by GCM are defined as Present (see Table 3). Furthermore, Present is divided into 1-A and 1-B to analyze the sensitivity of watershed response affected by changes in the atmospheric carbon dioxide concentration.

Table 4 shows observed/simulated precipitation and air temperature of Byeongseong Stream watershed. In the case of Present scenario, which shows the current climate condition, the annual rainfall was –0.2% smaller than that of the observed data whereas the annual temperature does not change. Overall, changes in the annual precipitation and temperature are similar to those of the observed data. The margin of error during the summer is relatively more prominent. As for Future 1, the annual precipitation is projected to increase and the annual temperature is projected to increase by about 1°C. In the case of Future 2, the annual precipitation is projected to decrease –0.3% by a small margin in spring and winter although it increases in summer. The temperature is expected to evenly increase for every month by about 3 °C.

Table 3
Climate change scenarios.

No	Description			
	Scenario	Temperature difference (°C)	Precipitation difference (%)	CO_2 (ppmv)
1-A	Present_(GCM): CSIRO-Mk3.0 1988–2007	0.0	–0.2	330
1-B	Present_(GCM): CSIRO-Mk3.0 1988–2007	0.0	–0.2	660
2	Future 1: CSIRO-Mk3.0 A2 2011–2040	+0.9	2.9	660
3	Future 2: CSIRO-Mk3.0 A2 2071–2100	+3.0	–0.3	660

3.2. Evaluation of the ability of model to reproduce the current climate condition

Before analyzing the impact of climate change on hydrological and water quality response, it is necessary to assess the validity of climate simulation technique. Therefore, observed data and Present-simulated data are compared to check the extent to which the present climate simulated by GCM faithfully replicates current observed hydrological and water quality condition.

Figure 3 shows that results from the observed climate data are similar to the ones produced by simulation of the current climate data. In the case of SS, however, there

Table 4
Monthly mean precipitation and temperature of each scenario.

	Precipitation (*mm*)				Temperature (°C)			
	Observed	Present	Future 1	Future 2	Observed	Present	Future 1	Future 2
Jan	38.2	37.4	36.2	44.2	0.6	0.6	1.5	3.9
Feb	42.0	41.3	34.0	37.7	1.9	1.9	3.6	5.3
Mar	64.6	63.0	60.3	64.3	6.6	6.6	7.7	9.7
Apr	93.3	94.0	92.3	84.3	12.2	12.2	13.2	15.0
May	104.8	104.9	118.0	105.1	17.4	17.4	18.2	20.1
Jun	165.6	166.0	181.1	198.6	20.8	20.8	21.3	23.8
Jul	248.9	249.0	279.1	256.9	25.0	25.0	25.9	28.0
Aug	257.6	254.3	295.0	257.1	25.8	25.8	26.4	28.5
Sep	149.4	153.0	126.3	141.3	20.7	20.7	21.3	23.7
Oct	59.3	59.0	40.6	45.5	15.7	15.7	16.4	18.6
Nov	56.3	56.6	54.3	44.3	8.8	8.8	9.3	11.6
Dec	31.8	32.0	32.5	28.7	3.2	3.2	4.8	6.6
Year	1312.3	1310.6	1350.5	1307.9	13.2	13.2	14.1	16.2

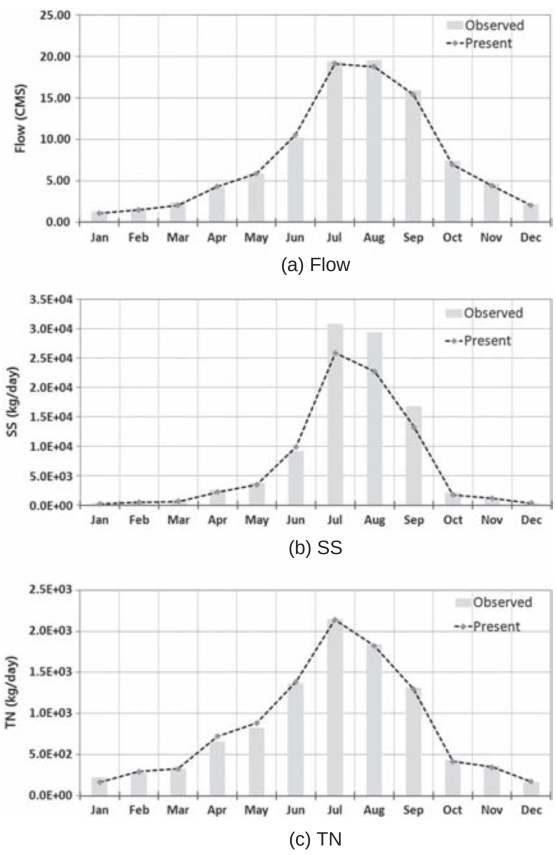


Fig. 3. Comparisons between observed and present scenario.

has quite differences on July and August. Therefore, this extent of uncertainty should be noted in analyzing the impact of climate change on future hydrological and water quality response using future climate information.

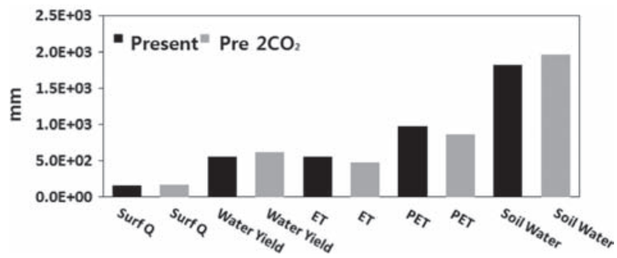


Fig. 4. Comparison of hydrological components between 1-A scenario and 1-B scenario.

3.3. Simulation results by scenarios

The milti-site precipitation generator developed by Keem et al. [13] and climatic data produced by the Monte-Carlo simulation are applied to SWAT model. Variables analyzed include stream flow, SS, and TN replicated by the calibrated model as well as evapotranspiration, potential evapotranspiration, and soil water simulated by SWAT.

SWAT model provides a function that simulates changes in leaves in accordance with the changes in the atmospheric carbon dioxide concentration. The function is based on the research by Morison and Gifford [20] according to which stomatal conductivity decreases by 40% when carbon dioxide increases from 330 to 660 ppmv. Therefore, scenarios 1-A and 1-B are comparatively analyzed to identify hydrologic change influenced by changes in carbon dioxide.

Analysis shows that doubling of carbon dioxide results in annual decrease in evapotranspiration and potential evapotranspiration by about –15% and –13% respectively. As for soil water, surface runoff, and water yield, an annual increase around 10% is recorded. The increase stems from the decrease of evapotranspiration emitted to the atmosphere, which led to the increase of soil water (Fig. 4).

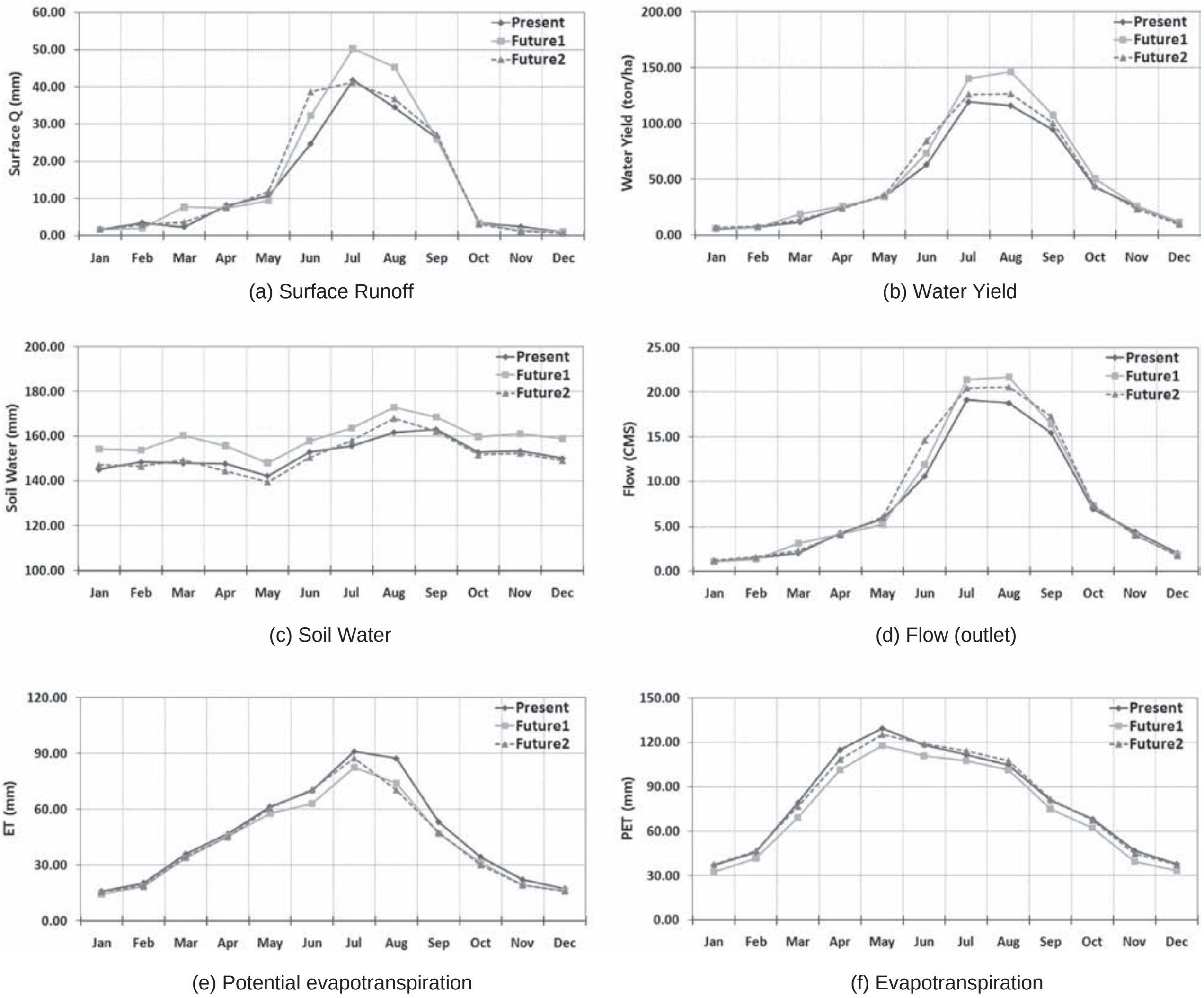
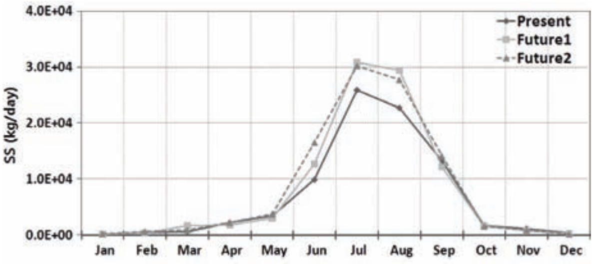


Fig. 5. Comparison of hydrological components among future scenarios.

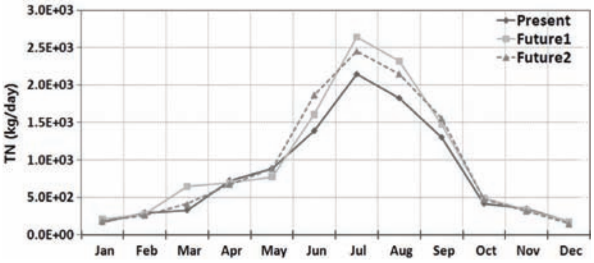
Figure 5 shows the results of the analyses of hydrologic change in Present and future scenarios. Decrease occurs in all variables except for the soil water in Future 1. This stems from the increase of precipitation in Future 1. The increase in soil water can be explained by the effect of evapotranspiration decrease caused by the increase of carbon dioxide concentration. A closer examination reveals a number of changes: surface runoff (17%), water yield (16%), soil water (5%), stream flow at watershed outlet (8%), evapotranspiration (–9%), and potential evapotranspiration (–8%). In the case of Future 2, quantitative increase of a majority of water resources variables is noticed. In particular, quantitative increase in the summer is pronounced. In the case of Future 2, this can be attributed to the increase of summer rainfall and carbon dioxide concentration. A number of changes can be noticed: surface runoff (10%), water yield (8%), soil humidity (1%), stream flow at the watershed outlets (10%), evapotranspiration (–7%), and potential evapotranspiration (–1%).

Figure 6 shows the results of the analyses of SS and TN. Monthly behavior of SS for both Future 1 and 2 is predicted to be similar to that in Present. As for Future 1, summer SS and TN increase by 25% and 22%. Annual SS and TN also increase by 16% and 14%. As for Future 2, because of the increase of rainfall in summer, summer SS and TN increase by 30% and 33%. Annual SS and TN increase by 21% and 26% in Future 2, respectively. In summary, SS and TN responses are in phase with rainfall change.

Table 5 shows a comparison of deviation by climate scenario based on annual average values. When present data are compared with observed data, stream flow of watershed outlets, SS and TN decrease by –3%, –17%



(a) SS



(b) TN

Fig. 6. Comparison of water quality components among future scenarios.

Table 5
Errors or differences of climate scenario with annual values.

	Precipitation (%)	Flow (%)	SS (%)	TN (%)
Present (vs observed)	–0.2	–3.1	–16.6	0.1
Future 1 (vs present)	4.1	7.9	15.7	16.5
Future 2 (vs present)	–0.6	10.3	20.9	13.8

and 0.1% respectively as rainfall decreases by –0.2%. Here, except for TN, it should be noticed that watershed response rather than changes in rainfall may be more amplified. As for rainfall in Future 1, the amount vis-à-vis that of Present increases by a large margin of 4%. Because of the increase of soil water caused by the increase of carbon dioxide and other factors, the increase of stream flow is about 8%, which is larger than the extent of change in rainfall. SS and TN respectively is changed to 16% and 17%; the amount of change far exceeded that of rainfall. In Future 2, rainfall decreases by 0.6% while stream flow, SS and TN increased by 10%, 21% and 14% respectively since the summer rainfall increases. Meanwhile, a comparison of the errors in the current condition (errors between observed data and present data) and the differences between future and current conditions (differences between results from present data and results from projected data) reveals that much uncertainty is involved in future hydrological and water quality response.

4. Conclusions

In this study A2 scenario of CSIRO-Mk3.0 was adopted as future climate information. Future climate data including precipitation data acquired from CSIRO-Mk3.0 were downscaled to regional-scale data by multi-site precipitation generator. SWAT model was used to establish Byeongseong Stream watershed and future climate data were used to analyze changes in hydrological attributes and water quality in the watershed. In the case of the climate scenario that reproduced the years from 1971 to 2000, annual changes were satisfactorily reproduced. When this was applied to the watershed model, the stream flow of watershed outlet and SS decreased by –3% and –17% respectively. It was shown that even under the same climate condition, the increase in carbon dioxide would lead to increase of soil water caused by the decrease of evapotranspiration and the increase of runoff. For the years from 2011 to 2040, temperature was projected to increase by 0.9°C and precipitation increased by 4%. Because of the double increase in carbon dioxide, stream flow increased by 8% that is more than increase of precipitation. SS was expected to increase by 16%. For the years from 2071 to 2100, the temperature was expected to increase by 3.0°C whereas precipitation decreased by 0.6%. In spite of slight decrease in rainfall but resulted in double carbon dioxide and intense rainfall on summer season, stream flow and SS is projected to increase by 10% and 21% respectively. Under future climate condition, stream flow and SS co-varied with annual changes in rainfall. TN is also projected to increase by 14% during the period from 2071 to 2100. The findings of this research point to much uncertainty. The uncertainty may stem from a number of steps taken in the research: downscaling of low-resolution GCM; the process of establishing the watershed model; and assumptions and uncertainty involving the application of future climate scenarios. The development of analysis techniques and availability of high quality data will enable production of reliable results. Procedures adopted in this research will help future analyses on the impact of climate change on watershed-size scale.

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