Assessment of Future Climate Change Impacts on Water Quantity and Quality for a Mountainous Dam Watershed Using SWAT

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Abstract. *The aim of this study was to assess the potential impacts of climate change on hydrology and stream water quality for a 6642 km² mountainous dam watershed in South Korea using the Soil and Water Assessment Tool (SWAT). The model was calibrated for three years (1998-2000) and validated for another three years (2001-2003) using daily streamflow data at three locations and monthly stream water quality data at two locations. For future evaluation, the MIROC3.2 HiRes and ECHAM5-OM climate data by Special Report on Emissions Scenarios (SRES) A2, A1B, and B1 of the Intergovernmental Panel on Climate Change (IPCC) were adopted. The future biased data (2007-2099) were corrected using 30 years (1977-2006, baseline period) of weather data, and downscaled by the change factor (CF) statistical method. The future (2020s, 2050s, and 2080s) watershed hydrology and stream water quality were evaluated based on the 2000 data. The MIROC3.2 HiRes A1B 2080s temperature and precipitation showed an increase of +4.8°C and 34.4%, respectively, based on the 2000 data. The impacts of projected future climate change scenarios on the evapotranspiration, groundwater recharge, and streamflow were increases of +23.1%, +28.1%, and +39.8%, respectively. The future sediment load showed a general tendency to decrease in the A2, A1B, and B1 emission scenarios of the two GCM models. The increase of the future T-N load may come from the increase of the subsurface lateral flows from January to June and the groundwater recharges from January to July. The future T-P load showed an increase of +19.6% in the 2080s under the MIROC3.2 HiRes A1B scenario and a decrease of -48.4% in the 2050s under the ECHAM5-OM B1 scenario.*

***Keywords.** Climate change, Downscaling, GCM, Nonpoint-source pollution, SWAT, Watershed modeling.*

In South Korea, the climate is intermediate, between continental and oceanic climates, and features four distinct seasons. It is hottest during June to August, and the average temperature in August is 25.4°C. The average temperatures during December to February range from -8°C in the north to 0°C in the south. Annual precipitation averages 1260 mm, and about 60% of the precipitation takes place during the wet season (June to early September), which is a characteristic of monsoon weather in eastern Asia (Lee and Lee, 2000). It has been reported that an unequivocal global average temperature increase of about 0.74°C occurred from 1906 to 2005. The increase in the temperature in South Korea has been almost doubled the figure since 1912 (Korea Meteorological Administration, 2009).

The Intergovernmental Panel on Climate Change (IPCC) report reaffirms that the climate is changing in ways that cannot be accounted for by natural variability and that global warming is occurring (IPCC, 2007). Climate changes affect the hydrological cycle, thus modifying the transformation and transport characteristics of sediment and nutrients (Bouraoui et al., 2002). The scientific consensus is that future increases in atmospheric greenhouse gas concentrations will result in elevated global mean temperatures, with subsequent effects on regional precipitation, evapotranspiration, soil moisture, and altered flow regimes in streams and rivers (Wilby et al., 1994; Arnell, 2003, 2004).

In general, assessment of the impacts of climate change on water quantity and quality will need to combine watershed models with the results of general circulation models (GCMs). Recently, several studies have been carried out assessing climate change impacts on water quantity and quality. Bouraoui et al. (2002) evaluated the impact of potential climatic change on nutrient loads from agricultural areas to surface water using the Soil and Water Assessment Tool (SWAT) combined with four GCMs (CSIRO-Mk2, ECHAM4, CGCM1, and HadCM2) in the Ouse River basin in northern England. The simulation results of climate scenarios showed significant effects on water quality and nutrient loads from agricultural areas as well as crop growth patterns. Jha et al. (2004) performed an evaluation of the im-

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pact of climate change on streamflow in the upper Mississippi River basin by use of a regional climate model (RCM) coupled with a hydrologic model (SWAT). The combined performance of SWAT and the RCM (RegCM2) was examined using observed weather data as lateral boundary conditions in the RCM. Marshall and Randhir (2008) evaluated the impact of warming trends on water quantity and quality at a watershed scale in the Connecticut River watershed in New England using the SWAT model. They projected that climate change had significant impacts on nutrient cycles and on the N:P ratio of annual loading in the watershed.

Many SWAT applications have focused on agricultural watersheds (Hanratty and Stefan, 1998; Hotchkiss et al., 2000; Stonefelt et al., 2000; Vache et al., 2002; Chanasyk et al., 2003; Stone et al., 2003; Arabi et al., 2008). A single growth model in SWAT is used for simulating all crops based on a simplification of the EPIC crop growth model (Williams et al., 1984). The main reason for this is that SWAT was developed primarily for watersheds dominated by agricultural crops rather than forests. Several researchers have pointed out that the suitability of SWAT for applications to watersheds dominated by forests is limited due to its inability to accurately simulate forest growth (Kirby and Durrans, 2007). In recent years, several researchers have modified SWAT to make it more suitable for watersheds dominated by different types of forests around the world (Wattenbach et al., 2005; Kirby and Durrans, 2007; Watson et al., 2008).

SWAT has been applied worldwide for hydrologic and water quality simulation (Zhang et al., 2008). Putz et al. (2003) reviewed four hydrologic models that were considered for adoption during the initial stages of the Forest Watershed and Riparian Disturbance (FORWARD) project (Prepas et al., 2006): TOPMODEL (Beven et al., 1995), SWAT (Arnold et al., 1998), DHSVM (Wigmosta et al., 1994), and HSPF (Donigian et al., 1995). They established 11 criteria as a means to select the most suitable model for simulating disturbance effects and recovery in boreal plain forests. Of the four models that were short-listed by Putz et al. (2003), it was found that SWAT fulfilled more criteria than the other models. Hence, it was selected as the model of choice for fulfilling the objectives of the FORWARD project. Further, Putz et al. (2003) also showed that SWAT can apply not only in agricultural watersheds but also in forest watersheds. However, few of the SWAT applications were successfully validated in forested watersheds (Fohrer et al., 2001; Im et al., 2003; Govender and Everson, 2005; Wu and Johnson, 2008; Ahl et al., 2008; Ye et al., 2009).

Climate change scenarios can be considered for modeling future impacts on hydrology and water quality. Climate change impacts can be simulated directly in SWAT by accounting for: (1) the effects of increased atmospheric CO_2 concentrations on plant development and transpiration, and (2) changes in climatic inputs (Gassman et al., 2007). Gassman et al. (2007) reviewed climate change impact studies that reported on SWAT applications and concluded that the model is a flexible and robust tool that can be used to simulate a variety of watershed processes. The reported SWAT results focused on approaches that relied on downscaling of climate change projections generated by GCMs or GCMs coupled with RCMs (Stone et al., 2001; Muttiah and Wurbs, 2002; Eckhardt and Ulbrich, 2003; Rosenberg et al., 2003; Takle et al., 2005; Thomson et al., 2005; Gosain et al., 2006; Jha et al., 2006). Moreover, several studies reported climate change impacts on both hydrology and pollutant losses using SWAT, including four studies that were partially or completely supported by the Climate Hydrochemistry and Economics of Surface-water Systems (CHESS) project (Bouraoui et al., 2002; Varanou et al., 2002; Boorman, 2003; Bouraoui et al., 2004).

However, many of the previous research studies have focused on the influence of change in pollutant loss using SWAT without giving enough representation of the future change in hydrologic components. In South Korea, most studies during the past ten years have been conducted to assess the impact of climate change mainly on streamflow for several watersheds of South Korea. Many of these studies have indicated water resource variability associated with climate change. This study deals with future climate impact on watershed evapotranspiration (ET), surface runoff, and groundwater flow in addition to streamflow. We used a statistical downscaling approach to assess change in future climate as modeled by two GCMs, and considered future hydrologic behavior and stream water quality using SWAT. Park et al. (2011) evaluated the impacts of future potential climate and land use changes on SWAT watershed hydrology for the Chungju dam watershed by applying the MIROC3.2 HiRes A1B scenario for climate and CLUE-s (Conservation of Land Use and its Effects at Small regional extent) for land use.

The aim of this study is to evaluate the impacts of future potential climate change on water quantity and quality for a mountainous dam watershed in South Korea, The SWAT model was adopted for analysis of hydrologic behavior and evaluation of nonpoint-source (NPS) pollution loads using the downscaled MIROC3.2 HiRes and ECHAM5-OM data by Special Report on Emissions Scenarios (SRES) A2, A1B, and B1. The SWAT2005 version with the ArcSWAT 2.0 interface was used. By applying the A2, A1B, and B1 scenarios of MIROC3.2 HiRes and ECHAM5-OM downscaled data, the future NPS pollution loads for dam inflow are discussed through analysis of the hydrologic impacts.

Study Area and Data

The Chungju dam watershed has a total area of 6642 km^2 and is located in the northeast region of South Korea, within the latitude and longitude range of 127.9° to 129.0° E and 36.8° to 37.8° N (fig. 1). The elevation ranges from 112 to 1562 m, with an average overland hillslope of 36.9% and an average elevation of 609 m. The large variation of elevation in the watershed affects surface runoff (runoff volume and peak runoff rate) by the slope in the calculation of time of concentration, and sediment yield by the LS (topographic) factor of the Modified Universal Soil Loss Equation (MUSLE) in SWAT modeling. The annual average precipitation is 1261 mm, and the mean temperature was 9.4°C over the last 30 years. More than 82.3% of the watershed area is forested, and 12.2% of the lowland area is cultivated. Detailed spatial information and a description of the study watershed can be found in Park et al. (2011).

Thirty years (1977-2006) of daily weather data obtained for the Korea Meteorological Administration were collected from six ground stations. In addition, continuous daily streamflow data were obtained from three gauging stations (YW #1 and YW #2 located upstream, and CD at the watershed outlet) of the Han River Flood Control Office, and discontinuous (once per month) stream water quality data (sediment, T-N, and T-P) were obtained at two sites (YW #1

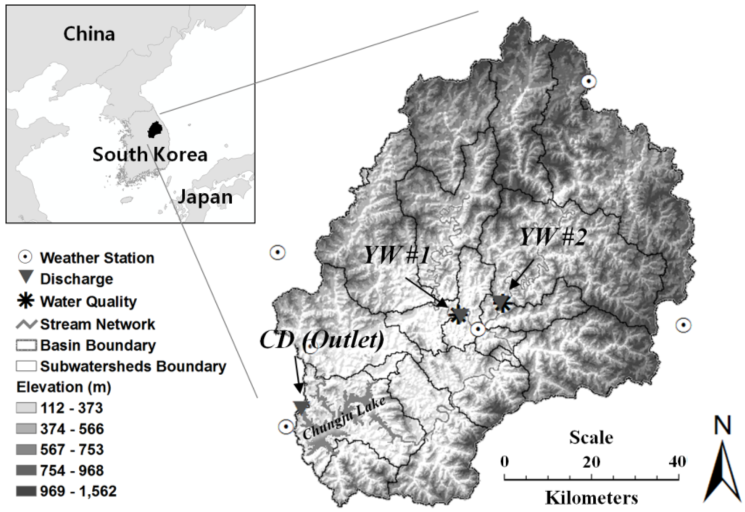

Figure 1. Locations of the Chungju dam watershed and the weather stations, streamflow, and water quality stations.

and YW #2) of the Korean Ministry of Environment. Six years (1998-2003) of point-source data for the modeling was prepared from each point-source facility, including discharge rates and nutrient loads.

The GCM data source used for this study is future climate data, which were obtained from the MIROC3.2 HiRes and ECHAM5-OM model outputs. Among the 24 GCM of the IPCC Fourth Assessment Report (AR4), we selected the two GCMs having fine spatial resolution and having opposite trends for future summer and autumn rainfalls in Korea (tables 2a and 2b). The MIROC3.2 HiRes model, developed at the National Institute for Environmental Studies in Japan, has a spatial resolution of approximately 1.1°. The ECHAM5-OM model, developed at the Max Planck Institute for Meteorology in Germany, has a spatial resolution of approximately 1.9°. We adopted the MIROC3.2 HiRes (scenarios A1B and B1) and ECHAM5-OM (scenarios A2, A1B, and B1) data for 1900 to 2100 using three SRES climate change scenarios of the IPCC AR4: A2 is the "high" greenhouse gas (GHG) emission scenario, A1B is the "middle" GHG emission scenario, and B1 is the "low" GHG emission scenario. These experiments started as 20th Century Climate in Coupled Models (20C3M) simulations and were run up to the year 2100.

Methods

The SWAT Model

SWAT is a physically based continuous, long-term, distributed-parameter model designed to predict the effects of land management practices on the hydrology, sediment, and contaminant transport in agricultural watersheds under varying soils, land use, and management conditions (Arnold et al., 1998). It is a public-domain model supported by the USDA Agricultural Research Service (USDA-ARS) at the Grassland, Soil, and Water Research Laboratory in Temple, Texas.

SWAT is based on the concept of hydrologic response units (HRUs), which are portions of a subbasin that possess unique land use, management, and soil attributes. The runoff, sediment, and nutrient loadings from each HRU are calculated separately using input data about weather, soil properties, topography, vegetation, and land management practices and then summed together to determine the total loadings from the subbasin. SWAT functions on a continuous daily time step with input options for hydrology, nutrients, erosion, land management, main channel processes, water bodies, and climate data. The SWAT model predicts the influence of land management practices on constituent yields from a watershed and includes agricultural components such as fertilizer, crops, tillage options, and grazing; SWAT can also include point-source discharges. Further details can be found in the SWAT theoretical documentation (Neitsch et al., 2001).

Bias Correction and Downscaling of the GCM Climate Data

In this study, the future weather data were regenerated using the bias correction and the change factor (CF) downscaling methods (Diaz-Nieto and Wilby, 2005; Wilby and Harris, 2006; Park et al., 2009). The detailed procedures can be found in Park et al. (2011). The downscaling procedure was used to apply the percentage changes for weather variables in the study watershed to the data for 2010-2039 (2020s), 2040-2069 (2050s), and 2070-2099 (2080s) using year 2000 daily weather data as the baseline. The year 2000 data were selected as the baseline for future assessment because they had a precipitation and temperature pattern that was similar to the average values for the 30-year period (1977-2006) for six weather stations.

Results and Discussions

SWAT Model Calibration and Validation

The SWAT model was calibrated for three years (1998-2000) of daily streamflow data at three locations (YW #1, YW #2, and CD) and monthly stream water quality (sediment, T-N, and T-P) data at two locations (YW #1 and YW #2), and validated for another three years (2001-2003). Table 1 shows a statistical summary of the model calibration and validation, and figures 2 and 3 show comparisons of the observed and simulated streamflow and water quality (sediment, T-N, and T-P), respectively. Detailed calibrated parameters and streamflow results of model calibration and validation can be found in Park et al. (2011). After flow cal–

Table 1. Calibration and validation results of streamflow and NPS pollution loads at three calibration points.[a]

Model Output		Evaluation Criteria	YW #1		YW #2		CD (Outlet)	
			Cal.	Val.	Cal.	Val.	Cal.	Val.
Streamflow		RMSE (mm d^{-1})	2.80	2.38	2.98	2.67	2.01	1.58
		R^2	0.76	0.71	0.76	0.69	0.89	0.87
		NSE	0.73	0.68	0.64	0.58	0.81	0.78
NPS loads	Sediment	R^2	0.79	0.95	0.69	0.53	N/A	
	T-N	R^2	0.70	0.78	0.81	0.94		
	T-P	R^2	0.82	0.88	0.35	0.88		

[a] Cal. = calibration period (1998-2000), Val. = validation period (2001-2003), and N/A = not available.

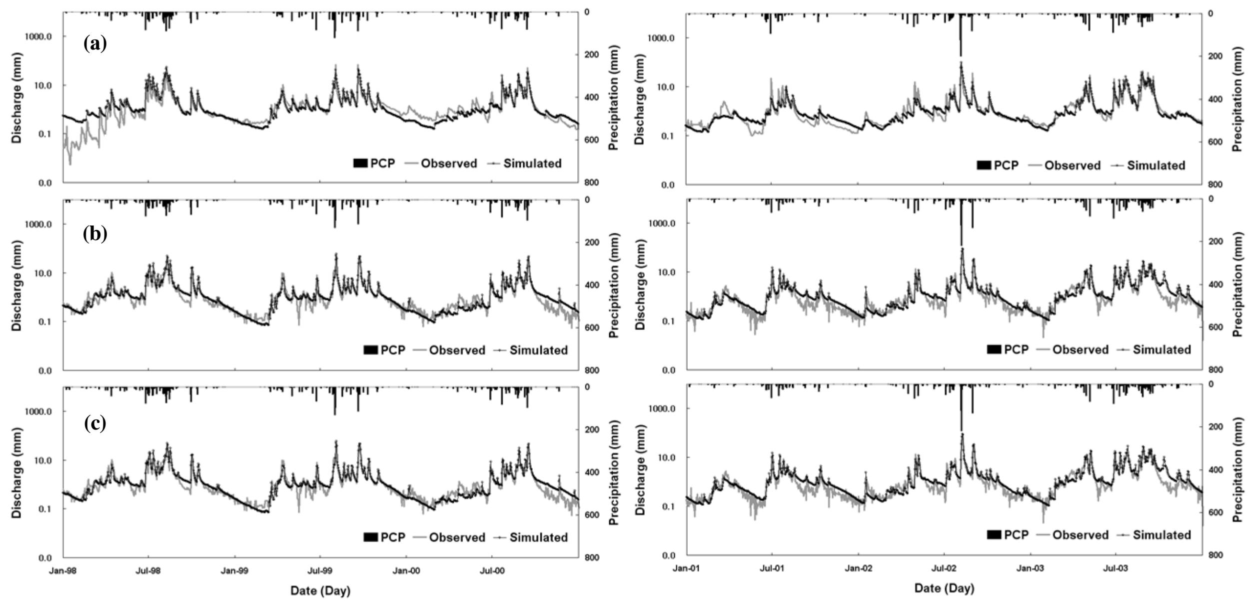

Figure 2. Comparison of the observed and SWAT-simulated streamflow during calibration (left graphs) and validation (right graphs) periods at three locations: (a) YW #1, (b) YW #2, and (c) CD.

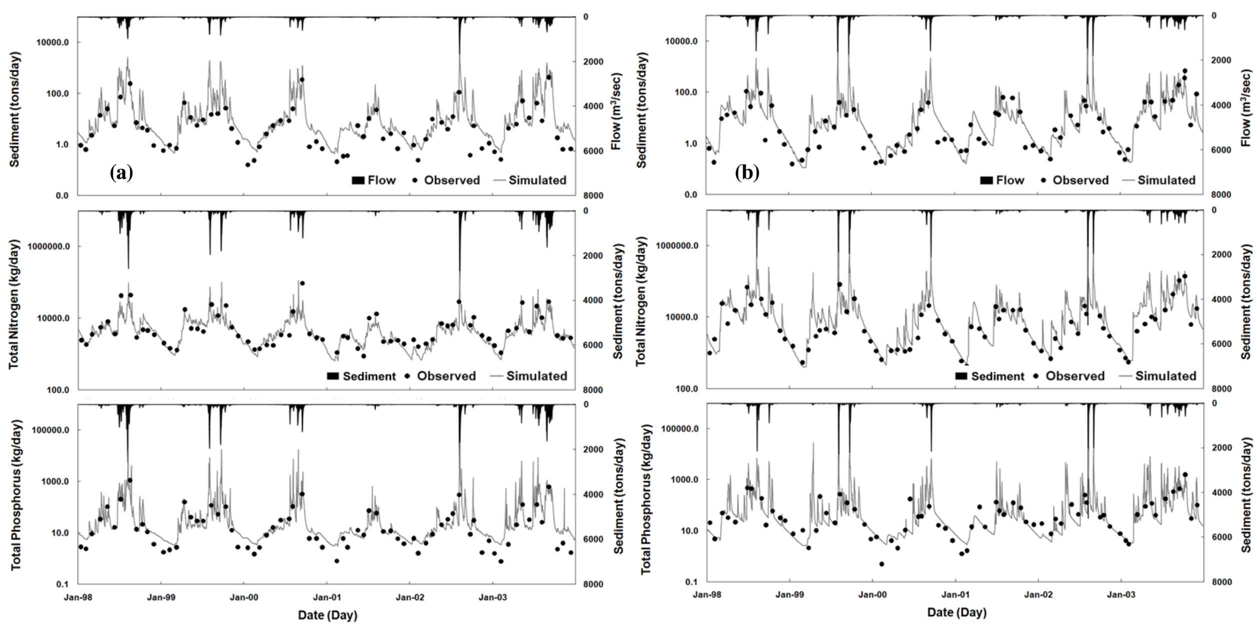

Figure 3. Comparison of the observed and SWAT-simulated sediment, T-N, and T-P loads at two locations: (a) YW #1 and (b) YW #2.

ibration, the sediment and nutrient loads were calibrated. In this study, eight parameters were selected for sediment, total nitrogen (T-N), and total phosphorus (T-P) loads in two subwatersheds (YW #1 and YW #2). Model parameters adjusted to calibrate sediment loads were the channel cover and erodibility factors (CH_COV and CH_EROD) and the linear co–

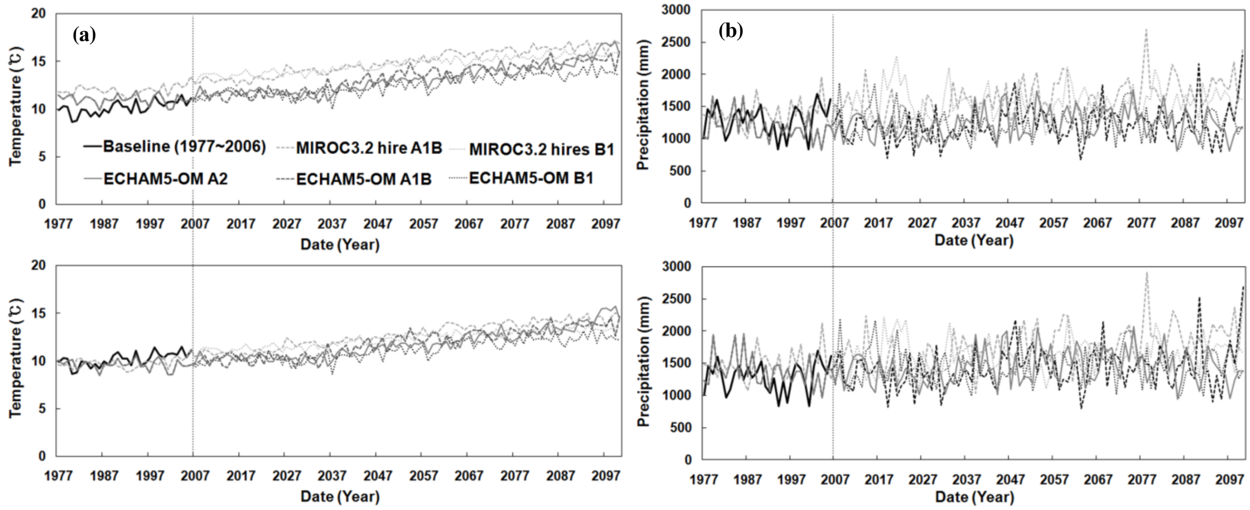

Figure 4. Annual (a) temperature and (b) precipitation of the A2, A1B, and B1 scenarios adjusted by using the output from MIROC3.2 HiRes and ECHAM5-OM. Observed and 20C3M data for the period 1977-2006 are shown for comparison before (upper graphs) and after (lower graphs) bias correction.

Table 2a. Changes in future seasonal precipitation and temperature with MIROC3.2 HiRes and the CF downscaling method.

Season		Precipitation (%)		Temperature (°)	
		A1B	B1	A1B	B1
Spring (Mar.-May)	2020s	+43.9	+57.8	+1.0	+0.9
	2050s	+58.0	+60.2	+2.4	+2.0
	2080s	+82.7	+69.4	+3.6	+2.5
Summer (June-Aug.)	2020s	+11.1	+15.0	+1.4	+1.5
	2050s	+19.7	+16.4	+3.0	+2.3
	2080s	+25.9	+15.0	+4.3	+3.1
Autumn (Sept.-Nov.)	2020s	-16.2	-11.0	+2.3	+2.3
	2050s	-0.4	+0.1	+3.9	+3.2
	2080s	+14.4	-8.0	+5.3	+4.2
Winter (Dec.-Feb.)	2020s	+161.6	+132.2	+2.9	+2.8
	2050s	+138.8	+141.0	+4.8	+4.2
	2080s	+154.3	+116.0	+6.1	+5.0
Annual	2020s	+12.9	+17.1	+1.9	+1.9
	2050s	+23.1	+21.8	+3.5	+2.9
	2080s	+34.4	+18.7	+4.8	+3.7

Table 2b. Changes in future seasonal precipitation and temperature with ECHAM5-OM.

Season	Precipitation (%)			Temperature (°)		
	A2	A1B	B1	A2	A1B	B1
Spring (Mar.-May)						
2020s	+47.9	+62.7	+60.3	+0.5	+0.3	-0.1
2050s	+69.5	+60.4	+53.4	+1.7	+2.0	+1.0
2080s	+69.0	+58.7	+81.8	+3.4	+3.1	+2.4
Summer (June-Aug.)						
2020s	-14.8	-10.6	-14.6	-0.1	-0.1	+0.1
2050s	-7.1	-6.6	+0.3	+0.9	+1.8	+0.9
2080s	-13.4	-0.7	-13.1	+2.6	+2.6	+1.6
Autumn (Sept.-Nov.)						
2020s	-35.0	-33.1	-44.2	+1.7	+1.8	+1.8
2050s	-33.3	-33.3	-31.5	+3.2	+3.5	+2.9
2080s	-23.8	-41.0	-38.3	+5.2	+4.9	+3.8
Winter (Dec.-Feb.)						
2020s	+131.9	+151.6	+161.1	+1.1	+0.8	+1.0
2050s	+187.7	+126.7	+182.2	+2.6	+3.3	+1.9
2080s	+174.1	+178.8	+192.9	+4.8	+4.6	+3.3
Annual						
2020s	-7.4	-2.0	-7.4	+0.8	+0.7	+0.7
2050s	+2.0	-1.1	+4.5	+2.1	+2.7	+1.7
2080s	+0.8	-+1.7	-1.0	+4.0	+3.8	+2.8

efficient for in-stream channel routing (SPCON). Nutrient outputs were calibrated by modifying initial organic N and P concentrations in the surface soil layer (SOL_ORGN and SOL_ORGP), initial mineral phosphorus (SOL_SOLP), nitrate concentration in the groundwater (GWNO3), and biological mixing efficiency (BIOMIX).

The average Nash and Sutcliffe (1970) efficiency (NSE) for streamflow during the validation period was 0.68 at YW #1, 0.58 at YW #2, and 0.79 at CD. This means that the model made better predictions by 68%, 58%, and 79% compared to simply using the average streamflow value during that period. The average root mean square error (RMSE) for streamflow during the calibration and validation periods was 2.59 mm d^{-1} at YW #1, 2.83 mm d^{-1} at YW #2, and 1.80 mm d^{-1} at CD. The average coefficients of determination (R^2) for monthly sediment, T-N, and T-P loads during the calibration and validation periods were 0.87, 0.74, and 0.85 at YW #1 and 0.61, 0.88, and 0.62 at YW #2, respectively.

As seen in figure 2, the error for YW #2 streamflow during winter periods showed the biggest RMSE, and most errors came from the difference in the peak runoff for storms. Therefore, it can be inferred that the YW #2 low flow errors arose from the uncertainties of the forest humus layer function, soil, and groundwater parameters.

The peak runoff errors may be caused by the difference between the real and simulated runoff mechanisms in paddy fields. Unlike the unsaturated flow mechanism in a natural environment, a paddy has artificial factors, such as irrigation scheduling and levee height management, which increase the uncertainty of the water budget. During paddy cultivation periods, farmers artificially control levee heights for their own water management. Irrigating before rainfall and draining water after rainfall also affect streamflows to a significant degree.

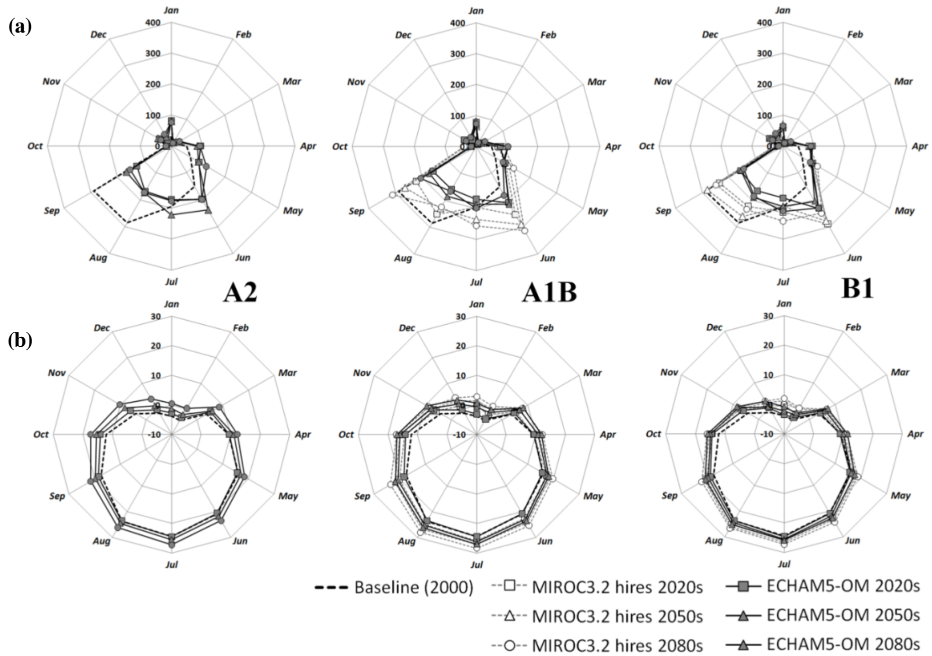

Figure 5. Comparison of the downscaled precipitation (mm) and temperature (°C) of the A2 (left graphs), A1B (center graphs), and B1 (right graphs) scenarios by the CF downscaling method: (a) daily precipitation amounts and (b) monthly mean temperature.

Table 3. Summary of future predicted annual hydrologic components for the A2, A1B, and B1 scenarios of the MIROC3.2 HiRes and ECHAM5-OM data in the 2020s, 2050s, and 2080s (values in parentheses are percent change in hydrologic components based on the baseline).[a]

Scenario	Years	P	ET	SR	LAT	GW	ST
Baseline	2000	1155.1	407.2	419.2	35.5	232.5	691.2
MIROC3.2 HiRes (A1B)	2020s	1304.2 (+12.9)	453.9 (+11.5)	470.1 (+12.2)	40.6 (+14.3)	262.8 (+13.1)	772.6 (+11.8)
	2050s	1421.6 (+23.1)	479.2 (+17.7)	537.8 (+28.3)	46.3 (+30.2)	278.7 (+19.9)	861.8 (+24.7)
	2080s	1552.1 (+34.4)	501.4 (+23.1)	619.1 (+47.7)	49.5 (+39.4)	297.8 (+28.1)	966.0 (+39.8)
MIROC3.2 HiRes (B1)	2020s	1352.6 (+17.1)	457.3 (+12.3)	504.2 (+20.3)	41.3 (+16.1)	270.6 (+16.4)	815.8 (+18.0)
	2050s	1406.5 (+21.8)	479.0 (+17.6)	543.0 (+29.5)	43.4 (+22.3)	270.0 (+16.1)	856.2 (+23.9)
	2080s	1371.6 (+18.7)	476.1 (+16.9)	493.8 (+17.8)	46.8 (+31.7)	275.8 (+18.7)	815.6 (+18.0)
ECHAM5-OM (A2)	2020s	1069.7 (-7.4)	444.8 (+9.2)	273.7 (-34.7)	36.7 (+3.4)	246.8 (+6.2)	555.9 (-19.6)
	2050s	1206.7 (+4.5)	454.5 (+11.6)	360.5 (-14.0)	42.3 (+19.1)	267.4 (+15.0)	669.2 (-3.2)
	2080s	1143.5 (-1.0)	475.5 (+16.8)	275.2 (-34.3)	48.5 (+36.4)	263.5 (+13.3)	585.5 (-15.3)
ECHAM5-OM (A1B)	2020s	1069.5 (-7.4)	441.9 (+8.5)	284.5 (-32.1)	36.9 (+3.9)	239.5 (+3.0)	560.1 (-19.0)
	2050s	1178.3 (+2.0)	458.1 (+12.5)	330.9 (-21.1)	43.8 (+23.4)	266.6 (+14.7)	640.2 (-7.4)
	2080s	1164.4 (+0.8)	473.0 (+16.2)	304.2 (-27.4)	47.0 (+32.3)	262.8 (+13.0)	612.6 (-11.4)
ECHAM5-OM (B1)	2020s	1131.7 (-2.0)	447.5 (+9.9)	323.7 (-22.8)	36.7 (+3.3)	248.2 (+6.7)	607.1 (-12.2)
	2050s	1142.1 (-1.1)	453.0 (+11.2)	316.2 (-24.6)	39.3 (+10.6)	253.4 (+9.0)	607.6 (-12.1)
	2080s	1174.1 (+1.7)	467.1 (+14.7)	325.3 (-22.4)	43.6 (+22.8)	261.4 (+12.4)	629.0 (-9.0)

[a] P = precipitation (mm), ET = evapotranspiration (mm), SR = surface runoff (mm), LAT = subsurface lateral flow (mm), GW = groundwater recharge (mm), and ST = streamflow (mm).

Downscaled Climate Change Scenarios

Figure 4 shows the future A2, A1B, and B1 scenarios from MIROC3.2 HiRes and ECHAM5-OM before and after bias correction of precipitation and temperature using 30 years of historical data. The precipitation from 20C3M for the A2, A1B, and B1 scenarios of two GCM models is less than the baseline data. However, the temperatures of the two scenarios (A1B and B1) of MIROC3.2 HiRes have a negative bias of +2.20°C and +2.19°C, respectively, and the three scenarios (A2, A1B, and B1) of ECHAM5-OM have a negative bias of +1.52°C, +1.39°C, and +1.46°C, respectively.

Table 2 summarizes the changes in seasonal temperature and precipitation by applying the CF downscaling method. In addition, figure 5 shows that the differences among the downscaled temperature and precipitation scenarios become even more apparent at monthly timescales. The future precipitation in the spring and winter seasons showed an increase regardless of the MIROC3.2 HiRes and ECHAM5-OM data. For the autumn season, future precipitation showed a general tendency to decrease except in the 2080s under the MIROC3.2 HiRes A1B scenario. In contrast, for the summer season, future precipitation showed a tendency to increase in the MIROC3.2 HiRes data. The biggest change in temperature was +6.1°C in the winter season of the 2080s under the MIROC3.2 HiRes A1B scenario. The biggest differences in the other three seasons were +5.3°C in autumn, +4.3°C in summer, and +3.6°C in spring, respectively, for the 2080s under the MIROC3.2 HiRes A1B scenario. The biggest change

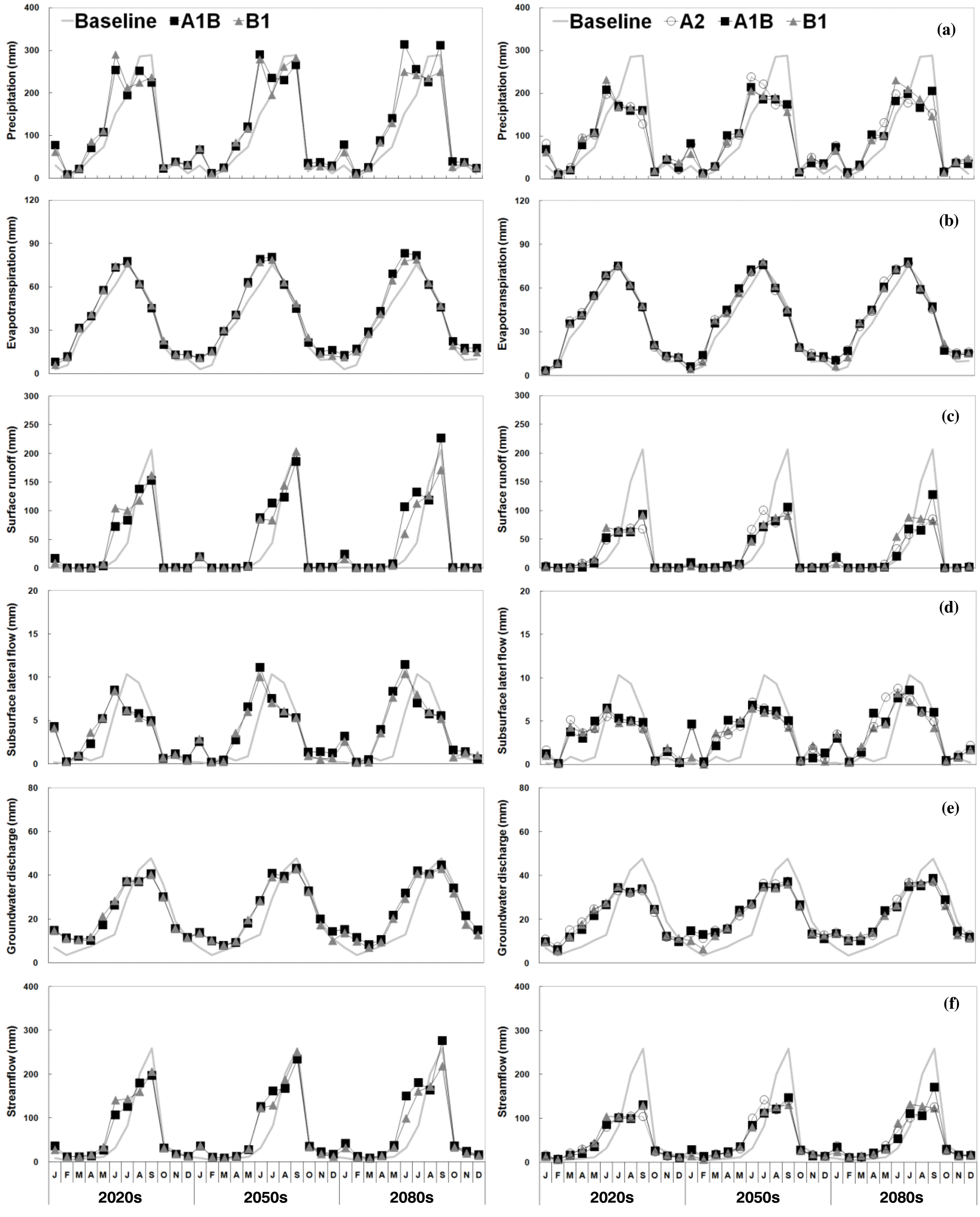

Figure 6. Change in the future predicted hydrologic components under the A2, A1B, and B1 scenarios of MIROC3.2 HiRes (left graphs) and ECHAM5-OM (right graphs) in the 2020s, 2050s, and 2080s: (a) precipitation, (b) evapotranspiration, (c) surface runoff, (d) subsurface lateral flow, (e) groundwater recharge, and (f) streamflow.

in precipitation was +192.9% in the winter season of the 2080s under the ECHAM5-OM B1 scenario. The uncertainty of future precipitation causes evaluation difficulties for prediction of the future hydrologic behavior and stream water quality. Three emission scenarios from the two GCM models adequately reproduced the precipitation and temperature distribution during the whole monsoon season. Overall, the MIROC3.2 HiRes and ECHAM5-OM data accurately reproduced the observed data.

Hydrologic Impact Assessment

To evaluate the climate change impact on hydrological components, i.e., evapotranspiration (ET), surface runoff, groundwater recharge, and streamflow, the SWAT model was run with the future downscaled climate data based on the 2000 data. Table 3 summarizes the future predicted hydrologic components for the A1B and B1 scenarios, and figure 6 shows a comparison of the future predicted ET, surface runoff, subsurface lateral flow, groundwater recharge, and streamflow at the watershed outlet.

Surface runoff is directly linked to NPS pollution loads. As shown in table 3, the future annual surface runoff showed a large range of changes, between +12.2% and +47.7%, under the A1B scenario of MIROC3.2 HiRes and between -34.7% and -14.0% under the A2 scenario of ECHAM5-OM. Looking at the monthly results, as shown in figure 6, we can detect similar characteristics for future hydrological behavior between the two GCM models. The June and July surface runoff values increase, and the subsurface lateral flow from January to June and the groundwater recharge from January to July are increased by the future increase in precipitation. These three components affected the increase in streamflow from January to July for both emission scenarios. In the case of the 2020s A2 scenario of ECHAM5-OM, considerable streamflow changes, within -59.5%, were predicted for three months (August, September, and October) because of the future rainfall decrease and evapotranspiration increase. The future ET increased in all months except August and September, with the maximum possible change in ET appearing in January, as in the 2080s A1B scenario of MIROC3.2 HiRes, and reaching +260.5%. The decrease of the inflow into the lake through the decrease of projected precipitation by ECHAM5-OM is especially serious from the water use and control viewpoint because it may lead to a water shortage problem. Therefore, there is a necessity to consider long-term adaptation and mitigation strategies for climate change for the dam operation and watershed management.

We can infer that the maximum change in January is because of the future precipitation increase and the future average temperature increase up to 0°C from the negative temperatures of the present. The rise in temperature associated with climate change leads to a general reduction in the proportion of precipitation falling as snow, and a consequent reduction in many areas in the duration of snow cover (Nijssen et al., 2001). This has implications for the timing of streamflow in such regions, with a shift from spring snowmelt to winter runoff. In this study, we defined runoff as the difference between precipitation and evapotranspiration, taking into account any storage of water on the land surface and in the soil. Thus, the projected increase in winter precipitation will lead to a particularly pronounced increase in runoff. This change from snow to rain will have a major effect on the watershed hydrology (Samuelsson, 2010). The magnitude of the snowmelt peaks in the study area will also be reduced, and there will be a marked shift in the timing as winters become warmer and spring temperatures increase.

A key for the long-term planning and management of the water resources in a watershed, considering future changes in the patterns of the climate, water demand, and water availability, is not only the possible changes in the annual hydrologic components under climate change but also the possible changes in the seasonal hydrologic components (Park et al., 2009). Paddy irrigation by release from agricultural reservoirs is mainly started in mid-May and finished in September in South Korea. The future decrease in the summer and autumn streamflows and reservoir inflow will have an impact on paddy irrigation during this period. Therefore, the reservoir operation has to be more conservative in supplying water for paddy irrigation. Figure 6f shows the future change in monthly dam inflow (streamflow at the watershed outlet) predicted by the climate change scenarios. Discharge from the Chungju dam is divided into gate discharge, water consumption for hydraulic power generation, water supply for irrigation, and water for stream maintenance. Therefore, future changes will also affect the dam operation, such as determination of dam outflow in August and September (a heavy rainfall period) with regard to flood control, and reservoir water level management in October to meet irrigation requirements, which carries over to April of the following year, i.e. the beginning of agricultural irrigation.

Water Quality Impact Assessment

After evaluation of the hydrologic impact, the impact of climate change on stream water quality was evaluated in terms of sediment, T-N obtained as the sum of nitrate and particulate organic nitrogen losses, and T-P obtained as the sum of orthophosphorus and particulate phosphorus losses at the watershed outlet. Table 4 shows a summary of the percent change in annual sediment, T-N, and T-P loads for the A2, A1B, and B1 scenarios of the two GCM models, and figure 7 shows the future monthly changes in sediment, T-N, and T-P dynamics. The future sediment load showed a tendency to increase in June and July and to decrease in August and September, depending on the surface runoff change. In spite of the increased surface runoff and water yield, the future decrease in the total sediment load may be explained by the overall decrease in the peak runoff. The two GCM models showed a tendency to increase the annual T-N load up to +87.3% in the 2080s under the MIROC3.2 HiRes A1B scenario. However, the annual T-P load showed a change between -7.8% and +19.6% under the MIROC3.2 HiRes scenarios and between -48.4% and -25.1% under the ECHAM5-OM scenarios.

Figure 8 shows a comparison of future predicted results during wet and dry days based on the 2000 data. A wet day means a day on which surface runoff occurs. As seen in figure 8, the future sediment load showed a general tendency to decrease for the two GCM models in wet days. The biggest

Table 4. Changes in percent for annual NPS pollution loads at the watershed outlet.

Scenario	Years	NPS Pollution Loads (% Change)		
		Sediment	T-N	T-P
MIROC3.2 HiRes (A1B)	2020s	-14.5	+25.2	-3.6
	2050s	+3.4	+57.2	-4.1
	2080s	+27.3	+87.3	+19.6
MIROC3.2 HiRes (B1)	2020s	-0.1	+31.0	-6.5
	2050s	+6.6	+41.5	-1.3
	2080s	-4.3	+52.4	-7.8
ECHAM5-OM (A2)	2020s	-61.2	-14.2	-44.5
	2050s	-41.3	+7.9	-28.8
	2080s	-57.6	+23.2	-33.1
ECHAM5-OM (A1B)	2020s	-59.1	-15.4	-47.6
	2050s	-45.4	+9.4	-30.3
	2080s	-46.8	+28.8	-25.1
ECHAM5-OM (B1)	2020s	-52.3	-8.9	-39.9
	2050s	-51.2	-4.4	-48.4
	2080s	-48.8	+10.5	-29.5

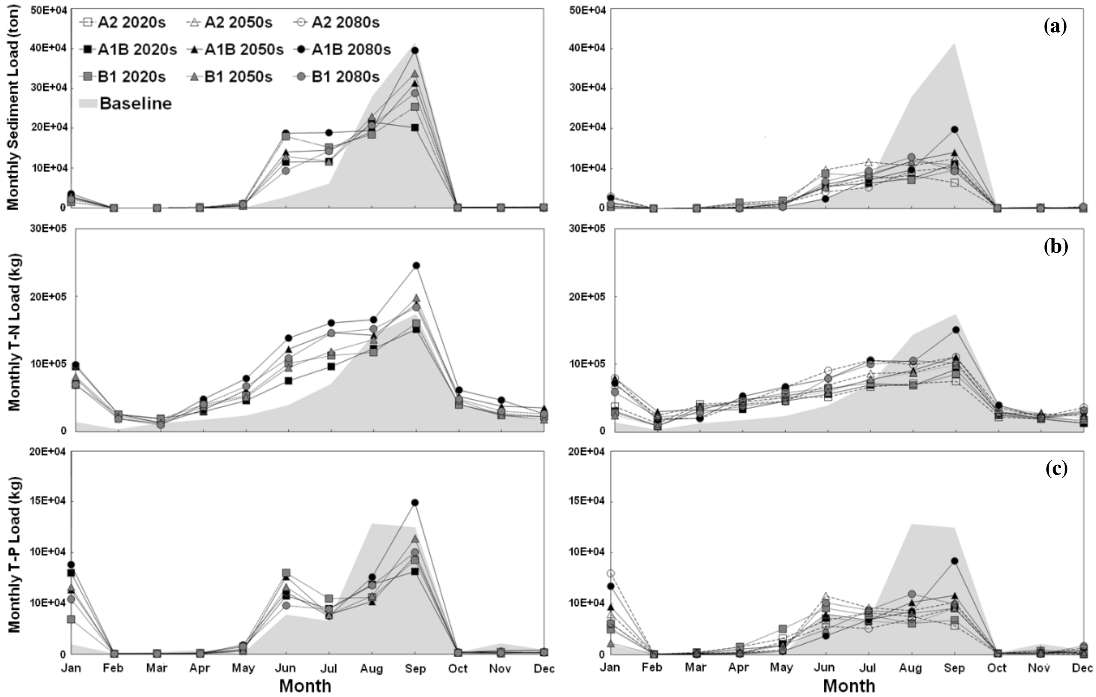

Figure 7. Effects of climate change on monthly (a) sediment, (b) T-N, and (c) T-P loads under downscaled A2, A1B, and B1 scenarios of MIROC3.2 HiRes (left graphs) and ECHAM5-OM (right graphs).

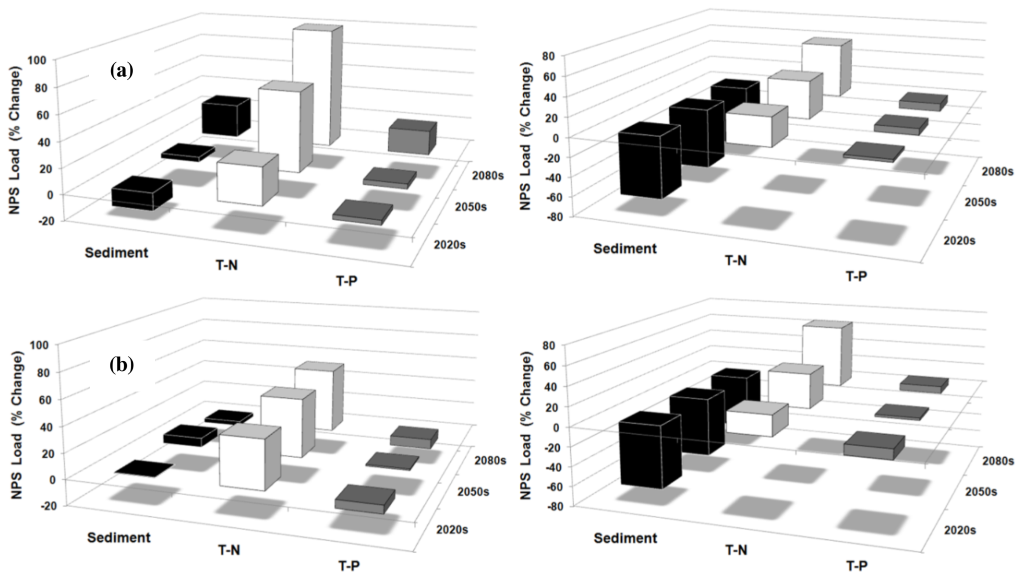

Figure 8a. Changes in the percent of annual NPS pollution loads for wet (left graphs) and dry (right graphs) days by the downscaled (a) A1B and (b) B1 scenarios of MIROC3.2 HiRes at the watershed outlet.

changes for MIROC3.2 HiRes and ECHAM5-OM in sediment load were +28.3% and -61.2% on wet days and -67.2% and -64.9% on dry days, respectively. The future decrease in sediment was directly affected by the decrease in surface runoff during the summer and autumn seasons. Meanwhile, the small change in future sediment on wet days was affected by the change in rainfall increases in June and July and decreases in August and September. The future T-N load showed a general tendency to increase for the three emission scenarios of the two GCM models on wet and dry days. The biggest changes for MIROC3.2 HiRes and ECHAM5-OM in T-N load were +99.1% and +18.6% on wet days and +65.8% and +79.3% on dry days, respectively. The future T-P load showed comparatively little change. The biggest changes for MIROC3.2 HiRes and ECHAM5-OM in T-P load were +20.1% and -49.1% on wet days and -10.3% and -20.6% on dry days, respectively.

The nutrient (T-N and T-P) loads are often correlated with surface runoff and sediment transport rates (USDA-SCS, 1972). However, fugitive sediment from the landscape is carried by overland flow (runoff), although the dominant pathway for nitrate loss is through leaching to groundwater and

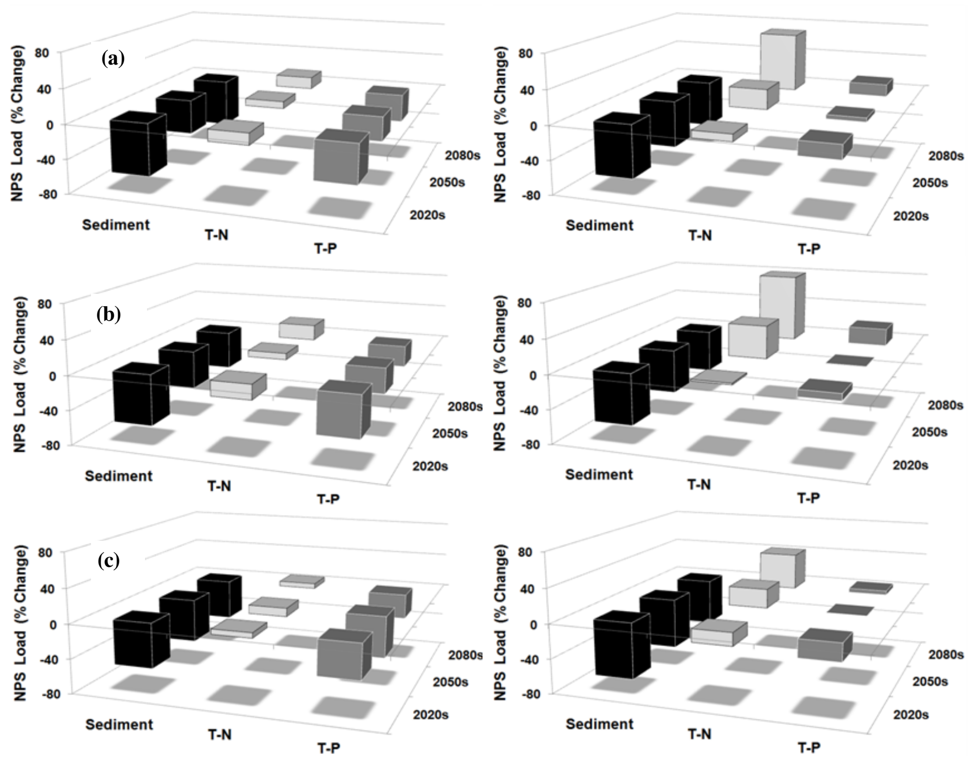

Figure 8b. Changes in the percent of annual NPS pollution loads for wet (left graphs) and dry (right graphs) days by the downscaled (a) A2, (b) A1B, and (c) B1 scenarios of ECHAM5-OM.

then via baseflow or tile drains (Randall and Mulla, 2001). Thus, as seen in figure 7, the increase in the future T-N load from January to July for both emission scenarios may come from the increase in subsurface lateral flows from January to June and in groundwater recharges from January to July, as described earlier in the Hydrologic Impact Assessment section. Nitrate is quickly leached into the soil profile and not picked up by water runoff. The decrease in the future annual T-P load can be explained by the decrease in the sediment load during wet days. On the other hand, the June and July future T-P load showed a tendency to increase due to the surface runoff increase in the corresponding periods (fig. 6). In runoff, sediment with high phosphate adsorption capacity can remove phosphate from the solution phase (Ghadiri and Rose, 1992).

The water quality of largest rivers in South Korea is poor because of industrialization, the tendency of the population to reside in cities, and NPS pollution loads from agriculture. Further, seasonal variation in river flow is very large. A large fluctuation in the river regime coefficients (the ratio of maximum flow to minimum flow ranging from 300 to 400) results in difficulties in supplying water, controlling floods, and managing water quality (Cho et al., 2004). In the drought season, presently from December to May, low flows lead to an increase in the pollution level. Pollution is a serious problem in the middle and lower parts of Korean rivers because many industrial facilities, large cities, and agricultural NPS sources are located around them. Because adaptation to climate change is considered as a necessity for the future, watershed decision makers require quantitative results for the establishment of adaptation strategies.

Summary and Conclusions

This study performed an assessment of the impacts of climate change on water quantity and quality for a 6642 km^2 forest-dominated dam watershed in South Korea. A continuous, distributed-parameter model (SWAT) was adopted for the evaluation, and the model was calibrated and validated using six years (1998-2003) of daily discharge data at three locations and monthly stream water quality (sediment, T-N, and T-P) data at two locations.

For future climate data, MIROC3.2 HiRes and ECHAM5-OM climate data of IPCC scenarios A2, A1B, and B1 from 1977 to 2100 were adopted, and the data were downscaled by applying the change factor (CF) statistical method after correcting the bias of the GCM data by using 30 years of observed data (1977-2006). The projected future climate data of the three emission scenarios showed that the temperature increased in all seasons, and that the precipitation increased in the spring and winter seasons.

The downscaled MIROC3.2 HiRes and ECHAM5-OM climate data showed that surface runoff increases in June and July, subsurface lateral flow increases from January to June, and groundwater recharge increases from January to July. These three components affect the increase in streamflow from January to July for the three emission scenarios of the two GCM models.

The evaluation of future annual NPS pollution loads showed that the sediment load showed a tendency to increase in June and July and to decrease in August and September depending on the surface runoff change. The annual T-N load in the A2, A1B, and B1 scenarios showed a tendency to increase up to +87.3%, but the annual T-P load showed a change between -48.4% and +19.6%. We inferred that the increase in the future T-N load may come from the increase in subsurface lateral flow from January to June and in groundwater recharge from January to July, and that the decrease in the future T-P load can be explained by the decrease in the sediment load. The monthly changes, especially for the future increase in June and July NPS loads, indicate that there should be a management plan to conserve watershed soil, carry out best management practices, and prevent eutrophication of the reservoir about two months in advance compared to the present situation.

Climate change can affect various socio-economic sectors. Higher temperatures may threaten winter tourism in winter sports areas. The hydrological changes will increase flood risk during winter, while low flows during summer will adversely affect inland navigation and reduce water availability for agriculture and industry (Middelkoop et al., 2001). This approach considers the impacts of climate change on watershed hydrology and water quality. It will enable the reassessment of future irrigation development and dam construction, and it will help decision makers reconsider the operating rules of existing reservoirs and investigate adaptation strategies for reducing the impacts of global warming. For example, climate change will affect the regional water supply (e.g., hydraulic power, irrigation and stream maintenance) and water security (e.g., flood and drought) in the study area. Thus, it will increase the vulnerability of the water resource system and further affect the water quality in Lake Chungju. This result will be further applied to a water quality model for Lake Chungju, to assess how the changes in lake water quality will be affected by climate change in the future.

Future hydrologic conditions and water quality cannot be projected exactly due to the uncertainty in climate change scenarios and GCMs outputs. However, the annual change and seasonal variation of hydrological components due to future temperature increases and precipitation changes should be evaluated and incorporated into water resources planning and management, in order to promote more predictable water demand and sustainable water availability for this important watershed (Ahn et al., 2008).

Finally, we did not consider potential changes in land use or vegetation cover. Hence, we strongly recommend a thorough investigation of the combined effects of climate, land use, and vegetation cover change on the variability of hydrological processes, water quality, and water resources. To enable adaptation due to climate change as a widely accepted future occurrence, watershed decision makers require quantitative results for the establishment of adaptation strategies. For example, through future research, we can design vegetation buffer strips to decrease NPS loads to streams, and we can take measures to prevent soil loss.

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References

Ahl, R. S., S. W. Woods, and H. R. Zuuring, 2008. Hydrologic calibration and validation of SWAT in a snow-dominated Rocky Mountain watershed, Montana, U.S.A. *J. American Water Resources Assoc.* 44(6): 1411-1430.

Ahn, S. R., Y. J. Lee, G. A. Park, and S. J. Kim. 2008. Analysis of future land use and climate change impact on stream discharge. *J. Korean Soc. Civil Eng.* 28(2B): 215-224.

Arabi, M., J. R. Frankenberger, B. A. Engel, and J. G. Arnold. 2008. Representation of agricultural conservation practices with SWAT. *Hydrol. Proc.* 22(16): 3042-3055.

Arnell, N. W. 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: Future streamflows in Britain. *J. Hydrol.* 270(3-4): 195-213.

Arnell, N. W. 2004. Climate-change impacts on river flows in Britain: The UKCIP02 scenarios. *J. Chartered Inst. Water Environ. Mgmt.* 18(2): 112-117.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resources Assoc.* 34(1): 73-89.

Beven, K., R. Lamb, P. Quinn, R. Romanowicz, and J. Freer. 1995. TOPMODEL. In *Computer Models of Watershed Hydrology*, 627-668. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Boorman, D. B. 2003. Climate, hydrochemistry, and economics of surface-water systems (CHESS): Adding a European dimension to the catchment modelling experience developed under LOIS. *Sci. Total Environ.* 314-316: 411-437.

Bouraoui, F., L. Galbiati, and G. Bidoglio. 2002. Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (U.K.). *Hydrol. Earth Syst. Sci.* 6(2): 197-209.

Bouraoui, F., B. Grizzetti, K. Granlund, S. Rekolainen, and G. Bidoglio. 2004. Impact of climate change on the water cycled and nutrient losses in a Finnish catchment. *Climate Change* 66(1-2): 109-126.

Chanasyk, D. S., I. R. Whitson, E. Mapfumo, J. M. Burke, and E. E. Prepas. 2003. The impacts of forest harvest and wildfire on soils and hydrology in temperate forests: A baseline to develop hypotheses for the boreal plain. *J. Environ. Eng. Sci.* 2(supp. 1): S51-S62.

Cho, J. H., K. S. Sung, and S. R. Ha. 2004. A river water quality management model for optimizing regional wastewater treatment using a genetic algorithm. *J. Environ. Mgmt.* 73(3): 229-242.

Diaz-Nieto, J., and R. L. Wilby. 2005. A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in the River Thames, United Kingdom. *Climatic Change* 69(2-3): 245-268.

Donigian, A. S., Jr., B. R. Bicknell, and J. C. Imhoff. 1995. Hydrological simulation program - FORTRAN (HSPF). In *Computer Models of Watershed Hydrology*, 395-442. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Eckhardt, K., and U. Ulbrich. 2003. Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *J. Hydrol*. 284(1-4): 244-252.

Fohrer, N., S. Haverkamp, K. Eckhardt, and H. G. Frede. 2001. Hydrologic response to land use changes on the catchment scale. *Phys. Chem. Earth* 26(7-8): 577-582.

Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold. 2007. The soil and water assessment tool: Historical development, application, and future research directions. *Trans. ASABE* 50(4): 1211-1250.

Ghadiri, H., and C. W. Rose. 1992. *Modeling Chemical Transport in Soils: Natural and Applied Contaminants*. Boca Raton, Fla.: Lewis Publishers.

Gosain, A. K., S. Rao, and D. Basuray. 2006. Climate change impact assessment on hydrology of Indian river basins. *Current Sci*. 90(3): 346-353.

Govender, M., and C. S. Everson. 2005. Modelling streamflow from two small South African experimental catchments using the SWAT model. *Hydrol. Proc.* 19(3): 683-692.

Hanratty, M. P., and H. G. Stefan. 1998. Simulating climate change effects in a Minnesota agricultural watershed. *J. Environ. Qual.* 27(6): 1524-1532.

Hotchkiss, R. H., S. F. Jorgensen, and M. C. Stone, and T. A. Fontaine. 2000. Regulated river modeling for climate change impact assessment: The Missouri River. *J. American Water Resources Assoc*. 36(2): 375-386.

Im, S. J., K. M. Brannan, S. Mostaghimi, and J. P. Cho. 2003. Predicting runoff and sediment yield on a forest-dominated watershed using HSPF and SWAT models. *J. Korean Soc. Rural Planning* 9(4): 59-64.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis, Contribution of Working Group 1 to the 4th Assessment Report of the Intergovernmental Panel on Climate Change*. S. Salomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds. Cambridge, U.K.: Cambridge University Press.

Jha, M., Z. Pan, E. S. Takle, and R. Gu. 2004. Impacts of climate change on streamflow in the upper Mississippi River basin: A regional climate model perspective. *J. Geophys. Res.* 109: D09105.

Jha, M., J. G. Arnold, P. W. Gassman, F. Giorgi, and R. Gu. 2006. Climate change sensitivity assessment on upper Mississippi River basin streamflows using SWAT. *J. American Water Resources Assoc.* 42(4): 997-1015.

Kirby, J. T., and S. R. Durrans. 2007. PnET-II3SL/SWAT: Modelling the combined effects of forests and agriculture on water availability. *J. Hydrol. Eng.* 12(3): 319-326.

Korea Meteorological Administration. 2009. Impacts of climate change on the Korean penisula. Seoul, Korea: Korea Meteorological Administration. Available at: http://web.kma.go.kr/4rivers/sub_02_03.jsp.

Lee, J. Y., and K. K. Lee. 2000. Use of hydrologic time series data for identification of recharge mechanism in a fractured bedrock aquifer system. *J. Hydrol.* 229(3-4): 190-201.

Marshall, E., and T. Randhir. 2008. Effect of climate change on watershed system: A regional analysis. *Climate Change* 89(3-4): 263-280.

Middelkoop, H., K. Daamen, D. Gellens, W. Grabs, J. C. J. Kwadijk, H. Lang, B. W. A. H. Parmet, B. Schadler, J. Schulla, and K. Wilke. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climate Change* 49(1-2): 105-128.

Muttiah, R. S., and R. A. Wurbs. 2002. Modeling the impacts of climate change on water supply reliabilities. *Water Intl., Intl.* 27(3): 407-419.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrol.* 10(3): 282-290.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2001. *Soil and Water Assessment Tool Theoretical Documentation, Version 2000*. Draft (April 2001). Temple, Tex.: USDA-ARS Grassland, Soil, and Water Research Laboratory, Blackland Research Center.

Nijssen, B., G. M. O'Donnell, A. F. Hamlet, and D. P. Lettenmaier. 2001. Hydrologic sensitivity of global rivers to climate change. *Climate Change* 50(1-2): 143-175.

Park, G. A., S. R. Ahn, Y. J. Lee, H. J. Shin, M. J. Park, and S. J. Kim. 2009. Assessment of climate change impact on the inflow and outflow of two agricultural reservoirs in Korea. *Trans. ASABE* 52(6): 1869-1883.

Park, J. Y., M. J. Park, H. K. Joh, H. J. Shin, H. J. Kwon, R. Srinivasan, and S. J. Kim. 2011. Assessment of MIROC3.2 HiRes climate and CLUE-s land use change impacts on watershed hydrology using SWAT. *Trans. ASABE*: 1713–1724.

Prepas, E. E., J. M. Burke, I. R. Whitson, G. Putz, and S. W. Smith. 2006. Associations between watershed characteristics, runoff, and stream water quality: Hypothesis development for watershed disturbance experiments and modelling in the Forest Watershed and Riparian Disturbance (FORWARD) project. *J. Environ. Eng. Sci.* 5(supp. 1): S27-S37.

Putz, G., J. M. Burke, D. W. Smith, D. S. Chanasyk, E. E. Prepas, and E. Mapfumo. 2003. Modelling the effects of boreal forest landscape management upon streamflow and water quality: Basic concepts and considerations. *J. Environ. Eng. Sci.* 2(supp. 1): S87-S101.

Randall, G. W., and D. J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. *J. Environ. Quality* 30(2): 337-344.

Rosenberg, N. J., R. A. Brown, R. C. Izaurralde, and A. M. Thomson. 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections in agricultural productivity and irrigation water supply in the conterminous United States: I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. *Agric. Forest Meteor.* 117(1-2): 73-96.

Samuelsson, P. 2010. Using regional climate models to quantify the impact of climate change on lakes. In *The Impact of Climate Change on European Lakes*, 15-32. D. G. George, ed. Dordrecht, The Netherlands: Springer.

Stone, M. C., R. H. Hotchkiss, C. M. Hubbard, T. A. Fontaine, L. O. Mearns, and J. G. Arnold. 2001. Impacts of climate change on Missouri River basin water yield. *J. American Water Resources Assoc.* 37(5): 1119-1130.

Stone, M. C., R. H. Hotchkiss, and L. O. Mearns. 2003. Water yield responses to high and low spatial resolution climate change scenarios in the Missouri River basin. *Geophys. Res. Lett.* 30(4): 3-6.

Stonefelt, M. D., T. A. Fontaine, and R. H. Hotchkiss. 2000. Impacts of climate change on water yield in the upper Wind River basin. *J. American Water Resources Assoc.* 36(2): 321-336.

Takle, E. S., M. Jha, and C. J. Anderson. 2005. Hydrological cycle in the upper Mississippi River basin: 20th century simulations by multiple GCMs. *Geophys. Res. Lett.* 32(18): L18407.1-L18407.5.

Thomson, A. M., R. A. Brown, N. J. Rosenberg, R. Srinivasan, and R. C. Izaurralde. 2005. Climate change impacts for the conterminous USA: An integrated assessment: Part 4. Water resources. *Climate Change* 69(1): 67-88.

USDA-SCS. 1972. Section 4: Hydrology. In *National Engineering Handbook.* Washington, D.C.: USDA Soil Conservation Service.

Vache, K. B., J. M. Eilers, and M. V. Santelmann. 2002. Water quality modeling of alternative agricultural scenarios in the U.S. Corn Belt. *J. American Water Resources Assoc.* 38(3): 773-787.

Varanou, E, E. Gkouvatsou, E. Baltas, and M. Mimikou. 2002. Quantity and quality integrated catchment modelling under climatic change with use of Soil and Water Assessment Tool model. *J. Hydrol. Eng*. 7(3): 228-244.

Watson, M. B., R. A, McKeown, G. Putz, and J. D. MacDonald. 2008. Modification of SWAT for modelling streamflow from forested watersheds on the Canadian boreal plain. *J. Environ. Eng. Sci.* 7(supp. 1): S145-S159.

Wattenbach, M., F. Hattermann, R. Weng, F. Wechsung, V. Krysanova, and F. Badeck. 2005. A simplified approach to implement forest eco-hydrological properties in regional hydrological modeling. *Ecol. Model.* 187(1): 40-59.

Wigmosta, M. S., L. W. Vail, and D. P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resource Res.* 30(6): 1665-1679.

Wilby, R. L., and I. Harris. 2006. A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, U.K. *Water Resource Res.* 42: W02419.

Wilby, R. L., B. Greenfield, and C. Glenny. 1994. A coupled synoptic-hydrological model for climate change impact assessment. *J. Hydrol.* 153(1-4): 265-290.

Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.

Wu, K., and C. A. Johnson. 2008. Hydrologic comparison between a forested and a wetland/lake dominated watershed using SWAT. *Hydrol. Proc.* 22(10): 1431-1442.

Ye, L., S. W. Chung, S. W. Yoon, and D. G. Oh. 2009. Impact of climate change on water cycle and soil loss in Daecheong reservoir watershed. *J. Korean Soc. Water Quality* 25(6): 821-831.

Zhang, X., R. Srinivasan, and M. V. Liew. 2008. Muti-site calibration of the SWAT model for hydrologic modeling. *Trans. ASABE* 51(6): 2039-2049.