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The relative impacts of climate change and urbanization on the hydrological response of a Korean urban watershed†

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Abstract:

We assessed the relative hydrological impacts of climate change and urbanization using an integrated approach that links the statistical downscaling model (SDSM), the Hydrological Simulation Program—Fortran (HSPF) and the impervious cover model (ICM). A case study of the Anyangcheon watershed, a representative urban region in Korea, illustrates how the proposed framework can be used to analyse the impacts of climate change and urbanization on water quantity and quality. The evaluation criteria were measurements of low flow (99, 95, and 90 percentile flow), high flow (10, 5, and 1 percentile value), pollutant concentration (30, 10, and 1 percentile value), and the numbers of days required to satisfy the target water quantity and quality for a sensitive comparison of subtle impacts of variations in these measures. Nine scenarios, including three climate scenarios (present conditions, A1B, and A2) and three land use change scenarios, were analysed using the HSPF model. The impacts of climate change on low flow (34·1–59·8% increase) and high flow (29·1–37·1% increase) were found to be much greater than those on the biochemical oxygen demand (BOD) (3·8–10·0% decrease). On the other hand, the impacts of urbanization on water quality (19·0–44·6% increase) are more significant than those on high (1·0–4·4% increase) and low flow (11·4–25·6% decrease). Furthermore, low flows are more sensitive to urbanization than high flows. The number of days required to satisfy the target water quantity and quality can be a sensitive criterion to compare the subtle impacts of climate and urbanization on human society, especially as they are much more sensitive than low flow and pollutant concentration. Finally, urbanization has a potent impact on BOD while climate change has a high impact on flow rate. Therefore, the impacts of both climate change and urbanization must be included in watershed management and water resources planning for sustainable development. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS climate change; hydrologic response; urbanization

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INTRODUCTION

Changes in climate and rapid population growth have brought the issues of water quantity and quality to the forefront in many communities and nations around the world. Addressing these issues requires the knowledge of how water resources are affected by changes in aspects of the regional hydrological cycle (Guo *et al.*, 2008). The hydrological characteristics of a watershed are dependent on a variety of factors, including the regional climate and the degree of development. Changes in either or both of these factors can significantly alter the volume and timing of run-off and the concentration and total load of pollutants throughout the watershed (Praskievicz and Chang, 2009).

Land use and climate are important factors influencing hydrological conditions. For example, land use changes can result in changes in flood frequency (Crooks and Davies, 2001; Brath *et al.*, 2006), severity (De Roo *et al.*, 2001), base flow (Wang *et al.*, 2006), annual mean discharge (Costa *et al.*, 2003; Lee and Chung, 2007a), and seasonal stream flow (Guo *et al.*, 2008; Im *et al.*, 2009), whereas climate variability can change the flow routing time, peak flows, and volume (Changnon and Demissie, 1996; Prowse *et al.*, 2006). Therefore, land cover as well as climatic changes and their impact on hydrological processes are of widespread concern and pose a particular challenge to researchers and policy makers. However, non-linear relationships, multiple causations, lack of mechanistic understanding, and lag effects together limit our ability to diagnose causes (Allan, 2004). Hence, the combined effect of climate change and urbanization has been under increased scrutiny in recent years to assess the regional impacts of climate change on urbanizing watersheds (Tollan, 2002; Lioubimtseva *et al.*, 2005). As this information is important for land use planning and water resources management, it is necessary to quantify the extent to which land use and climate influence hydrological conditions (Ewen and Parkin, 1996; Bronstert *et al.*,

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2002; Asselman *et al*., 2003; Chang, 2003; Legesse *et al*., 2003; Hejazi and Moglen, 2007; Juckem *et al*., 2008; Semadeni-Davies *et al*., 2008a,b; Wang *et al*., 2008; Cuo *et al*., 2009; Li *et al*., 2009; Ma *et al*., 2009). However, very few studies have analysed the combined effects of climate and land use on stream flow and water quality (Chang, 2004; Choi, 2008; Franczyk and Chang, 2009; Tu, 2009; Qi *et al*., 2009).

In this study, the potential impact of climate change and urbanization on water quantity and quality in the Anyangcheon watershed, which is a typical urban region in Korea, was assessed using a continuous rainfall-runoff simulation model with present conditions as well as under two climate change scenarios (A1B and A2) and two urbanization scenarios with the impervious catchment model (nine scenarios). Biochemical oxygen demand (BOD) was included for water quality assessment because the Korean government has a law requiring the maintenance of a particular BOD for the enhancement of stream flow quality.

METHODOLOGY

Procedure

This study used the framework shown in Figure 1. Future scenarios were developed to address climate change and urbanization. The precipitation and temperature data for future climate change scenarios of the study watershed were derived through downscaling using the statistical downscaling model (SDSM). The other method involved individual selection of land use change scenarios of all sub-watersheds depending on their present statuses, using the impervious cover model (ICM).

In the next step, the target water quantities and qualities for all sub-watersheds were determined by considering flow seasonality and fish habitat. The Hydrological Simulation Program—Fortran (HSPF) was formulated (calibrated/verified) for the study watershed using water quantity and quality data. Finally, all water quantity and quality scenarios were simulated using HSPF. Flow and BOD concentration duration curves of all sub-watersheds were derived, and the number of days required to satisfy the target water quantity and quality was calculated.

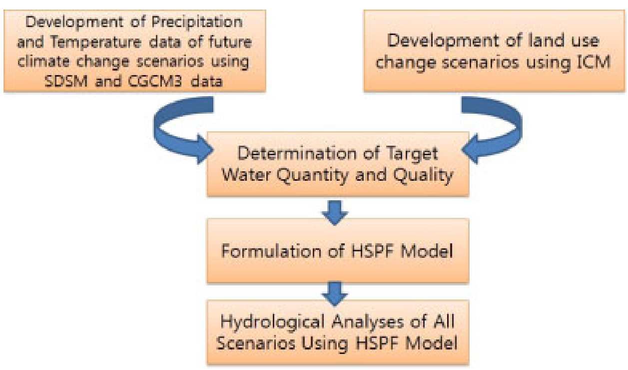

Figure 1. Procedure of this study

Selection of GCM scenarios

Global circulation models (GCM) were selected from among Hadley Centre's coupled ocean/atmosphere climate model (HadCM3), the Coupled Global Climate Model3 (CGCM3), the Commonwealth Scientific and Industrial Research Organisation model (CSIRO Mk2), and others. In addition, based on the realism and feasibility, the climate change scenarios were selected from among Special Report Emission Scenarios (SRES; IPCC, 2001), which are A1B and A2.

The outputs of CGCM3 developed by the Canadian Centre for Climate Modelling and Analysis (CCCma) were used as climate change scenarios for this study because this was the most recent model available. Atmospheric predictor variables used to calibrate the scenario tool were obtained from the National Center for Environment Prediction (NCEP) re-analysis (Kalnay *et al*., 1996). Future climate change scenarios originate from CGCM3, which makes use of the same ocean components as those used in the earlier CGCM2 model and the substantially updated atmospheric component of the AGCM3 model (the third-generation Atmospheric General Circulation Model; Scinocca *et al*., 2008). The spatial resolution of CGCM3 is roughly 3·75° latitude/longitude. The NCEP and GCM output contains 29 daily predictors (describing atmospheric circulation, thickness, and moisture content at the surface, 850 and 500 hPa levels) for four regions covering the Republic of Korea for the period 1961–2100. In this study, only predictors drawn from a grid-box overlying the Korean peninsula were used for the A1B and A2 scenarios of the IPCC SRES.

Two climate change scenarios (A1B and A2) were selected from the SRES (IPCC, 2001) because they were explicitly constructed to explore future developments in the global environment with special reference to the production of greenhouse and aerosol precursor emissions. Studies of climate change impacts in Korea have usually used these two scenarios because of their realism (Bae *et al*. 2007; Ahn *et al*., 2009).

We selected the CGCM3 and the two scenarios for the following reasons: (1) availability of output for more than one SRES emission scenario; (2) availability of primary downscaling variables achieved daily; (3) availability of an unbroken daily series for the entire period 1961–2010; and (4) realism of the GCM behaviour with respect to the NCEP reference data (Wilby *et al*., 2006).

Description of SDSM

To ensure that the predictive elements from the GCM are realistic, a statistical downscaling technique should be used to bridge the local and synoptic scale processes (Wilby and Wigley, 1997). Statistical downscaling uses a correlation between predictands (site-measured variables, such as mean temperature) and predictors (region-scale variables, such as GCM variables).

SDSM is a Windows-based decision support tool for regional and local scale climate change impact assessments. Full technical details, including model validation and usage, are described by Wilby *et al.* (2002). SDSM is best categorized as a hybrid of the stochastic weather generator and regression-based downscaling methods (Wilby and Wigley, 1997). The stochastic element is used to inflate the variance of downscaled output to better agree with the observed daily data and to generate ensembles of climate time series that differ in their individual time evolution, interannual means, and variance.

Description of ICM

Urban growth increases the impervious area because imperviousness is composed of two primary components: rooftops under which we live, work, and shop and the transport systems (roads, driveways, and parking lots) that we use to get from one roof to another (Schueler, 1994). Hence, imperviousness is a very useful indicator with which to measure the impacts of land development on aquatic systems. The ICM was developed by the Center for Watershed Protection, and it predicts the quality and character of a stream based on the percentage of impervious cover in the watershed. The ICM divides imperviousness impacts into four categories as follows (Schueler, 2003):

- 0–11% impervious cover = sensitive streams.
- 11–25% impervious cover = impacted streams.
- 25–60% impervious cover = degraded streams.
- >60% impervious cover = urban drainage.

The ICM relates an aquatic system's health (i.e. state of impairment) to the percentage of impervious cover in its contributing watershed. This method is largely based on the work of the Center for Watershed Protection, which has compiled and evaluated extensive data relating to watershed impervious cover to the hydrologic, physical, water quality, and biological conditions of aquatic systems (Schueler, 2003).

The relative portion of a watershed with impervious cover can be used as an effective means of determining aquatic system health. Urbanization, primarily through the construction of impervious cover, causes progressive hydrologic, physical, water quality, and biological impacts on aquatic health because it tends to increase annual storm water run-off, diminish base flow, degrade stream habitat conditions, deteriorate water quality, and cause declines in aquatic insect, riparian plant, and fish diversity (Center for Watershed Protection, 2005). Agricultural and other land-modifying activities can also contribute significantly to aquatic health degradation.

Future scenarios for land use change should incorporate regional urban planning. If existing urban planning is used, the exact urban area ratio and location can be identified. However, the development and redevelopment of cities are highly politicized in Korea. Therefore, such detailed urban planning is unlikely at best in Korea. The study watershed has experienced dynamic land use changes over the past 40 years regardless of previous urban plans (Lee, 2007). The urban area ratio rapidly increased from 16·7% in 1975 to 43·2% in 2000. The ratio continues to increase now through political connections and economic demands. In this case, the present implementation of urban plans has a high uncertainty factor. However, the ICM is very useful for watersheds experiencing dynamic urbanization. Therefore, this study used ICM to develop the future scenarios of climate change.

Description of HSPF

HSPF is a deterministic, lumped parameter continuous simulation model that has evolved out of the Stanford watershed model, the USEPA (Environmental Protection Agency) agricultural run-off management (ARM) model and a non-point source (NPS) model. A detailed description of the model is given by Bicknell *et al.* (2001). The model requires input information on land use, land cover, soil properties, sources of nitrogen (N) and phosphorus (P), stream reach characteristics, and time series of precipitation, temperature, solar radiation, and potential evapotranspiration. HSPF considers three types of modelling segments in a watershed: pervious land segment (PERLND) or sub-watershed, impervious land segment (IMPLND) or sub-watershed and stream/reach/reservoir (RCHRES). These modelling segments/modules have some components (ATEMP, PWATER, PQUAL, IWATER, and IQUAL) dealing with hydrological and water quality processes. The simulation results for each sub-watershed are hydrographs and pollutographs. The model predicts flow rate, sediment loads, and nutrient and pesticide concentrations. The sub-watershed run-off characteristics are then utilized by the model to simulate in-stream processes for determining hydrographs and pollutographs at all pertinent locations in the watershed. HSPF was used in this study because its accuracy has already been shown in several articles (Lee *et al*., 2007c; Chung and Lee, 2009; Kim *et al*., 2009).

HSPF formulation

HSPF was used to estimate flow rate and BOD loads from the 11 sub-watersheds in the Anyangcheon watershed. HSPF requires physical (topographic and land use) and climate data to parameterize methods and to provide input variables. In addition, stream flow and possibly water quality data are required for calibration and validation. A 1 : 25 000 digital elevation model (DEM) and land use map (as of the year 2000) of the study area were obtained from the National Geographic Information Institute (NGII) of the Ministry of Land and Ocean (MOLO) in Korea. The study area is located between the Suwon and Seoul stations of the Korea Meteorological Administration (KMA). Both stations provided daily (1993–2005) precipitation, temperature, average wind speed, average humidity, and average solar radiation data. Finally, stream flow quantity and quality were obtained from more than 100 field measurements during a 4-year period (2003–2006) (Lee, 2007) and from those of the Ministry of Environment of Korea (http://water.nier.go.kr/weis).

The HSPF model of the Anyangcheon watershed was subjected to a sensitivity analysis. The parameters suggested by AQUA TERRA (2004) were individually incrementally adjusted, and the impacts of the changes on total run-off volume, peak discharge, total BOD load, and peak BOD concentration were quantified. The results of the sensitivity analysis are shown in Figure 2. Of the water quantity parameters, those that had greater than a 1% impact on total run-off volume and peak discharge were LZSN, UZSN, INFILT, INTFW, IRC, and AGWRC. Of the water quality parameters, those that had greater than a 1% impact on total BOD load and peak BOD were KODSET, TCBOD, and KBOD20.

The HSPF model was calibrated by adjusting the nine parameters identified as important in the sensitivity analysis. A trial-and-error method with split samples was used to maximize the model efficiency of the water quantity results and minimize the root mean square error (RMSE) of the water quality results. The selected parameters, as well as their initial and determined values, are shown in Table I. Because the study watershed covers an area too large for complete calibration to be practical, the calibration was performed in five areas. Tables II and III list the periods of performance, the model efficiencies, and the RMSEs resulting from the calibration and validation. Figures 3 and 4 show the

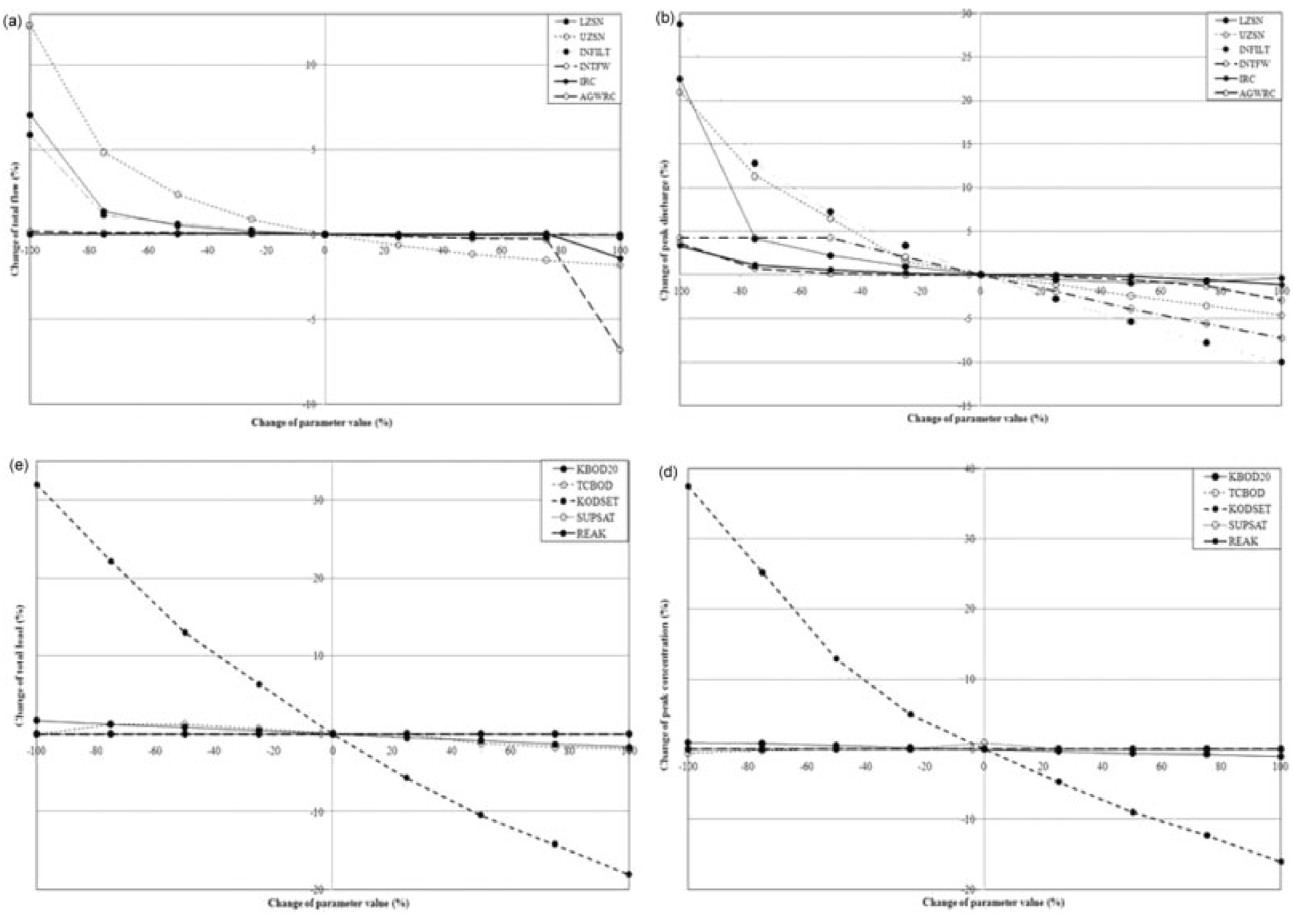

Figure 2. Results of sensitivity analysis of HSPF. (a) Water quantity (total flow), (b) water quantity (peak discharge), (c) water quality (total load), and (c) water quality (peak concentration)

Table I. Final values of nine parameters

Classification	Parameter	Definition	Initial value	Value
Water quantity	LZSN (inches)	Lower zone nominal soil moisture storage	6·0	6·0
	INFILT (inch/h)	Index to the infiltration capacity of the soil	0·16	0·20
	AGWRC (l/day)	Basic groundwater recession rate	0·98	0·97
	UZSN (inches)	Upper zone nominal soil moisture storage	1·128	1·128
	INTFW	Interflow inflow parameter	0·75	7·0
	IRC (l/day)	Interflow recession parameter,	0·5	0·5
Water quality	KBOD20 (per hour)	Unit BOD decay rate at 20 °C	0·004	0·011
	TCBOD	Temperature correction coefficient for BOD decay	1·047	1·355
	KODSET (feet/h)	Rate of BOD setting	0·027	0·035

Table II. Metrics of calibration and verification accuracy for water quantity indicator

Classification	Period	Model efficiency	RMSE (cm)
Calibration	~10 January 2006 10 May 2006	0·81	0·15
	~20 November 2004 31 December 2004	0·67	0·01
Verification	~1 January 2005 8 April 2005	0·62	0·01
	~6 October 2006 2 November 2006	0·72	0·002

Table III. Metrics of calibration and verification accuracy for water quality indicator

Water quality observation station		BOD	
		RMSE (mg/l)	R^2
AY 5	Calibration	2·89	0·70
	Verification	5·32	
AY 4	Calibration	2·84	0·67
	Verification	6·18	
AY 3	Calibration	4·43	0·72
	Verification	15·18	
AY 2	Calibration	3·83	0·73
	Verification	14·42	
AY 1	Calibration	1·61	0·66
	Verification	1·95	

calibrated and verified flow rates and BOD concentration to illustrate the performance of the HSPF model.

Evaluation criteria. Hydrological output was examined from the viewpoint of flow and concentration duration curves. Flow duration is described in terms of the exceeded percentage of the stream flow over a period of time. For example, Q_{99} is the daily average discharge that is exceeded by 99% of the daily stream flows over a study period, which may correspond to drought conditions. Q_1 is the daily average discharge that is exceeded by 1% of all discharges over a study period and corresponds to flood conditions (Hejazi and Moglen, 2008). The pollutant concentration duration curve is the same as the flow duration curve. Therefore, the flow and pollutant concentration duration behaviour of a watershed are useful for quantifying the stream flow quantity and quality variability. We used all the criteria of Hejazi and Moglen (2008), which were 99, 95, 90, 10, 5, and 1 percentile values for water quantity. Additionally, 10, 5, and 1 percentile flows were used to ascertain the possibility of flood damage and 99, 95, and 90 percentile flows were used for the stream flow variation during the dry period. We also selected three criteria to assess water quality, namely 30, 10, and 1 percentile values of the daily average pollutant concentrations.

Environmental flow requirement. Lee and Chung (2007b) addressed how the environmental flow requirement (EFR) can be calculated. The EFR is typically defined as the value of the minimum flow that must remain in the stream. It should not only be guaranteed hydrologically but also be satisfied environmentally. Therefore, the EFR is generally the maximum value of the hydrological low flow and the environmental flow. The environmental flow can be defined as the minimum flow required to ensure the environmental safety of the stream. The environmental flow is derived from factors such as water quality, ecosystem, recreation, scenery, and other environmental aspects. In this study, only the flow for fish habitats (called the fish flow) is considered and is compared with the hydrological low flow because fish flow is usually larger than that of others. The fish flow is the flow that results in little or no reduction in the numbers of fish.

The numerical definition of hydrological low flow varies by country. In Korea, the hydrological low is defined as the mean value of annual daily flows that exceeds 97th percentile flow (or Q_{355}, 355th value of the flow duration curve). Therefore, this study used the results of Lee *et al.* (2008), which identified the regional regression equation (Vogel and Kroll, 1992) and calibrated its parameters using six dam basins (Soyanggang Dam, Goesan Dam, Daechung Dam, Andong Dam, Imha Dam, and Hapcheon Dam) and nine gauging stations (Emokjeong, Baekokpo, Youngyang, Cheongsong, Donggok, Goro, Epyoung Bridge, Tanbu Bridge, and Gidae Bridge) as follows:

$$Q = 0{\cdot}0357\, A^{0{\cdot}55} \tag{1}$$

where Q is the average 97th percentile flow (m^3/s) and A is the basin area (km^2).

To calculate the fish flow, Lee *et al.* (2008) used Physical HABitat SIMulation system (PHABSIM) software, which was developed by the U.S. Geological Survey (2001). PHABSIM is a specific model designed to calculate an index of the amount of microhabitat available for different life stages at different flow levels. PHABSIM has two major analytical components: stream hydraulics and life stage-specific habitat requirements. PHABSIM calculates the relationship between the weighted usable area and discharge through hydraulic modelling of different flow levels and habitat modelling that combines the results of hydraulic modelling with habitat suitability criteria for a target species. After obtaining the relationship between the weighted usable area and the discharge by gradually increasing discharge, the discharge for the maximum weighted usable area is selected as a fish flow to preserve the ecosystem.

STUDY WATERSHED

The Anyangcheon watershed in central Korea near the capital city of Seoul was selected for this study because the Anyangcheon River has been observed to have serious water quantity and quality problems that have resulted in devastating flood damage, depleted streams, and even occasional fish kills (Han *et al.*, 2005; Lee *et al.*, 2008).

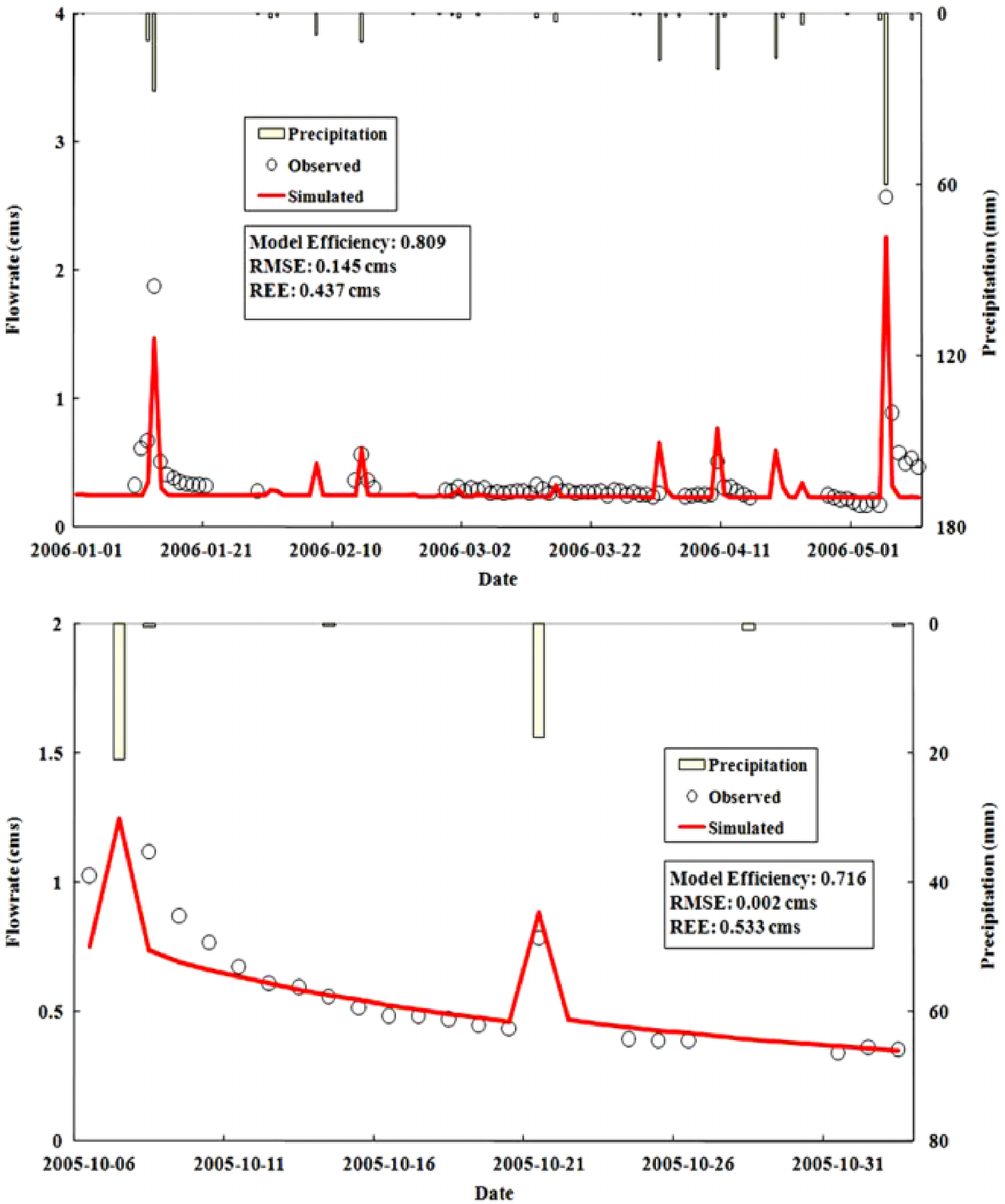

Figure 3. Calibrated and verified flowrate for OJ. (a) Calibration of flowrate and (b) verification of flowrate

In addition, it is a first-order tributary of the Han River (Figure 5), a river being targeted for river restoration in Korea. The main channel length of the Anyangcheon River is 32·38 km, draining a watershed area of 287 km^2, in which reside 388 million people (population density 13 500 persons/km^2). The watershed is bounded by latitudes 37°18′N and 37°33′N and longitudes 126°47′E and 127°04′E. The watershed land cover (as of 2000) is 43% urbanized, 40% forest, and 13% agricultural. Based on this topography, the natural stream network, and the storm drainage network, the watershed is divided into the 11 sub-watersheds shown in Figure 5: OJ, WG, DJ, SB (upstream), HU, SA, SB1, SS (middle stream), and SH, MG, DR (downstream). Characteristics of the study watershed and 11 sub-watersheds are shown in Table IV.

From 1972 to 2001, the average annual precipitation in Seoul was 1325 mm, with 927 mm (70%) occurring during the monsoon months of June through September. However, from 2002 to 2006, the average annual precipitation increased to 1468 mm, with 1086 (74%) occurring during the monsoon months. On average, approximately 57% of the precipitation input to the Anyangcheon watershed is discharged as direct run-off, and approximately 5% of the precipitation is discharged as base flow.

BOD concentrations have been observed every month since 1991 but not continuously (daily). Modelling studies were used to describe the water quality conditions, which have estimated the concentration to be approximately 15·0 mg/l and the daily load to be 21 852 kg/day (354 kg/ha/year) (Lee *et al.*, 2007c; Chung and Lee, 2009).

From the Mann–Kendall trend test, we note that the temperatures of the Seoul (1961–2008) and Suwon

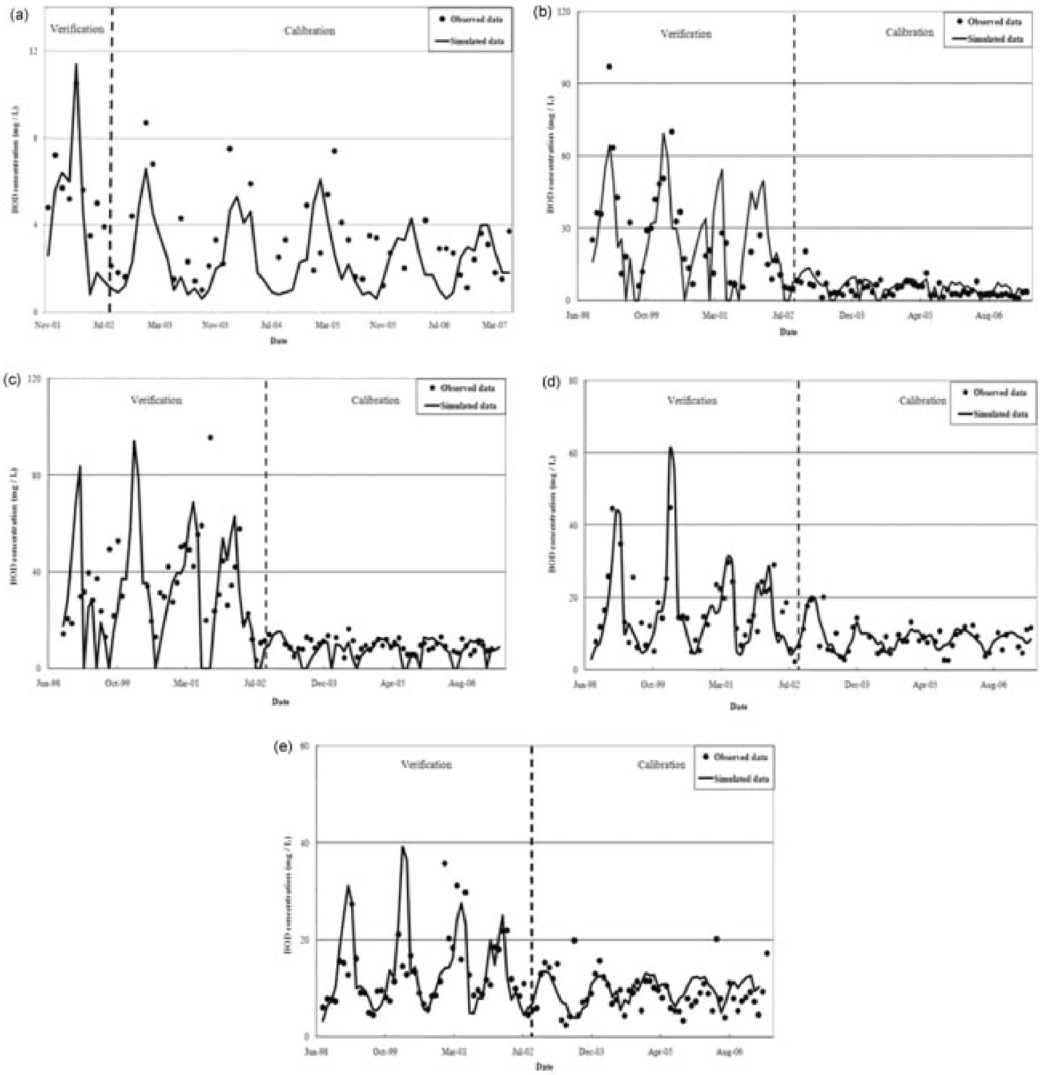

Figure 4. Calibrated and verified BOD concentration for five points to illustrate the performance of HSPF. (a) AY1, (b) AY1, (c) AY1, (d) AY1, and (e) AY1

Table IV. Characteristics of the Anyangcheon watershed and its sub-watersheds

Name of sub-watershed	Stream length (km)	Watershed area (km^2)	Total population (person)	Population density (person/km^2)	Urban area ratio (%)
AY	32·38	286·55	3 876 278	13 527	50·7
WG	3·82	3·78	7484	1980	9·6
OJ	2·85	4·26	26 370	6190	11·4
DJ	4·02	5·33	84 930	15 934	62·3
SB	4·32	10·3	132 390	12 853	49·9
HU	9·26	44·55	311 709	6997	30·4
SA	5·5	8·07	49 960	6191	25·4
SS	5·3	13·18	45 476	3450	13·8
SB1	2·76	4·59	23 695	5162	82·3
SH	2·68	3·26	109 364	33 547	50·4
MG	13·52	56·07	473 077	8437	37·8
DR	14·33	41·64	982 804	23 602	68·0

(1964–2008) stations have a strong tendency to increase, as shown in Table V, because the absolute values of the temperature test statistic, $u_c s$ are much larger than $u_{1-0{\cdot}0005/2}$ $(= 3{\cdot}291)$. In addition, the precipitation at Suwon station has a high probability of increasing because of a large u_c $(= 4{\cdot}075)$. The temperatures of Seoul and Suwon stations showed 1·7 and 2·2 °C increases, which are two times greater than the 100-year linear trend of the global average of 0·74 °C (1906–2005) (IPCC, 2007).

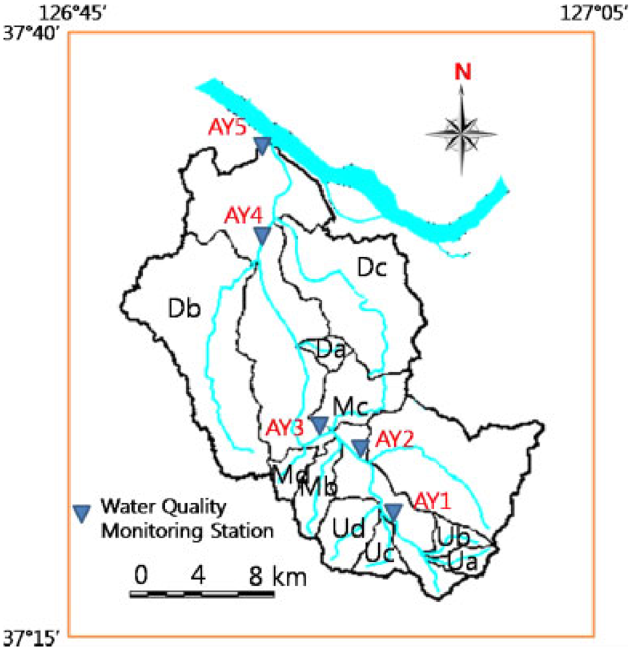

Figure 5. Map of the Anyangcheon watershed used in this study

Table V. Result of Mann–Kendall test of the past scenarios

Element	Seoul station (1961–2008)		Suwon station (1964–2008)	
	Temperature	Precipitation	Temperature	Precipitation
Variance	6·0 E+11	3·9 E+11	4·1 E+12	2·9 E+12
u_c	6·4	−1·0	19·9	4·1
p-value	1·3 E−10	0·3	2·2 E−16	4·6 E−15

RESULTS

Future scenarios of climate change

The daily mean temperature and precipitation are calculated for the Anyangcheon watershed using the CGCM3 model output from the A1B and A2 emission scenarios for the full period 1961–2100 and the SDSM. Calibration (Seoul: 1961–2000; Suwon: 1964–2000) and verification (2001–2008) were completed separately. The verification results of temperature and precipitation are shown in Figures 6 and 7. Figure 6 shows the time series of downscaled and observed daily temperature data, and Figure 7 presents the flow duration curves to identify how well the downscaled daily precipitation data agree with the observed data, according to Wilby (1994). The downscaled temperatures follow the observed temperatures closely, but that the small amounts of precipitation (under 2 mm) are usually overestimated. As the large amounts of downscaled precipitation having significant impacts on the annual precipitation follow the observed amounts well, this study utilized those results.

From the Mann–Kendall trend test (2010–2100), we note that the Seoul and Suwon stations have a strong tendency for increasing temperatures and precipitation due to a high u_c and small p-values, as shown in Table VI. The results of the SDSM are summarized in Table VII. The following describes the main changes in the two input variables for the HSPF model.

Temperature

From the SDSM analysis, we estimate that the annual average temperatures at the Seoul station would increase by 1·6 °C under A1B and by 2·0 °C under A2 during the period 2010–2100. The summer temperature during under A2 would increase up to 4·2 °C. In the case of the Suwon station, it was found that the annual average temperatures would increase by 2·0 °C under A1B and by 2·4 °C under A2 during the period 2010–2100. Comparison of these results to those of the Seoul station reveals that the values are not biased by season. These results are similar to those of Park *et al.* (2009) who estimated that the temperatures in the Chungjudam watershed during the period 2016–2100 would increase by 2·4 °C under A1B and by 2·3 °C under A2 using ECHAM5-OM.

Precipitation

The annual average precipitation at the Seoul station is 1896·9 mm under A1B and 2029·5 mm under A2. The summer intensity increases because 60·4% of the past ratio is changed to 64·7% under A1B and 63·9% under A2. Both because the total rainfall during summer increases and because the amount of rainfall in the remaining months decreases, flood control during the wet period and water security management during the dry period will be increasingly difficult (Im *et al*., 2008). It was estimated that the annual average precipitation at the Suwon station would be 1679·5 mm under A1B and 1803·6 mm under A2. Unlike the precipitation results for the Seoul station, the intensity during the summer reflects a likely decrease and those during the spring, fall, and winter an increase. These results are similar to Ahn *et al.* (2009) who estimated that the precipitation in the Gyeongancheon watershed during the period 2010–2099 would increase by 14·7% under A1B and by 14·5% under B1 using MIROC3·2 hires.

Future scenarios for land use change

All sub-watersheds of the study watershed were divided according to the impervious area ratio as follows:

- WG: Type I (0–11%)
- SS, OJ: Type II (11–25%)
- MG, SH, SA, HU, SB: Type III (25–60%)
- AY, DR, DJ, SB: Type IV (>60%)

All sub-watersheds were individually modelled using the ICM of CWP (distributed model) as shown in Table VIII. We developed three scenarios: (1) present

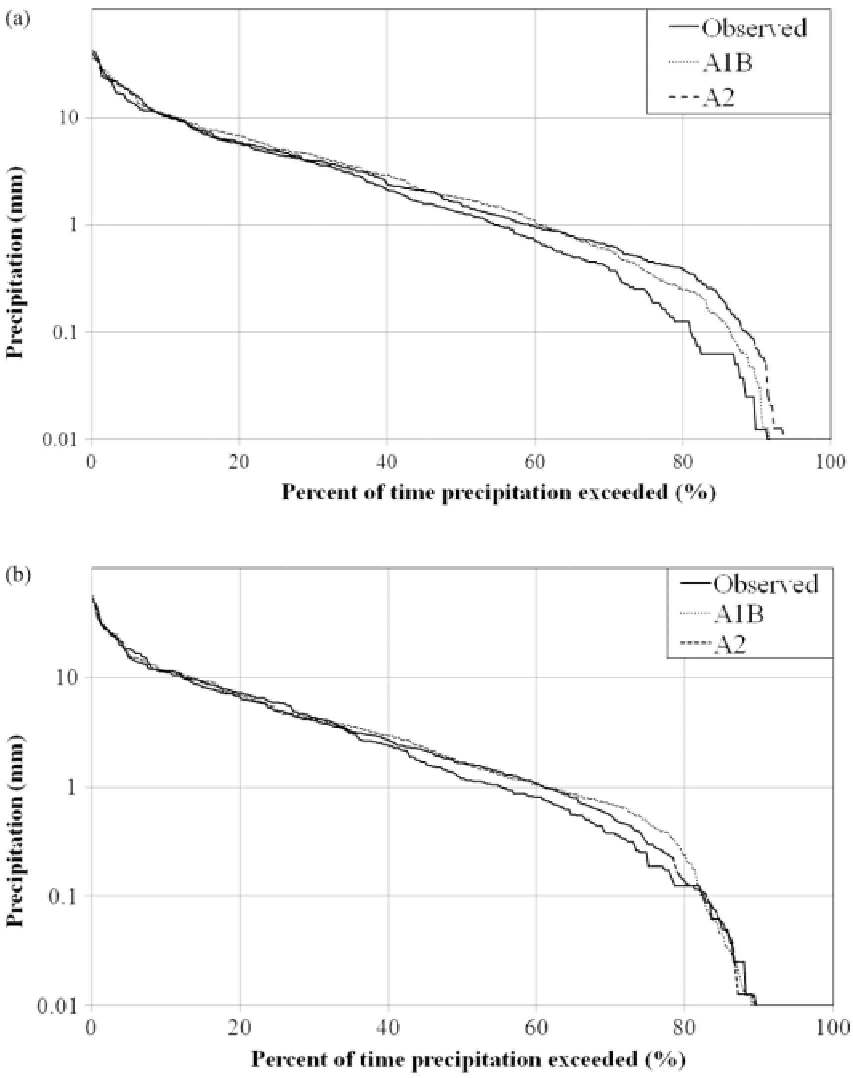

Figure 6. Duration curves of downscaled and observed precipitation data (verification). (a) Seoul and (b) Suwon

Table VI. Results of Mann–Kendall test of the future scenarios

Element	Seoul station				Suwon station			
	Temperature		Precipitation		Temperature		Precipitation	
Scenarios	A1B	A2	A1B	A2	A1B	A2	A1B	A2
Variance	4·1 E+12	4·1 E+12	3·8 E+12	2·8 E+12	4·1 E+12	4·1 E+12	2·9 E+12	2·9 E+12
u_c	12·9	20·4	2·6	4·6	12·5	19·9	1·9	4·1
p-value	2·2 E−16	2·2 E−16	0·002	4·8 E−16	2·2 E−16	2·2 E−16	0·1	4·6 E−15

Table VII. Summary of seasonal results

Station	Seoul						Suwon					
	Temperature			Precipitation			Temperature			Precipitation		
Scenario	PC	A1B	A2	PC	A1B	A2	PC	A1B	A2	PC	A1B	A2
Spring	11·6	13·2	13·6	229·1	299·9	308·3	10·9	13·1	13·5	224·9	334·6	347·5
Summer	24·0	25·9	28·2	845·9	1226·5	1317·3	23·8	25·9	26·3	767·3	962·6	1037·6
Fall	14·1	15·4	15·7	259·2	304·3	329·9	13·4	15·2	15·5	250·3	282·5	316·6
Winter	−1·04	0·41	1·02	67·1	66·2	74·1	−1·6	0·2	0·8	70·0	89·7	102·0
Total	12·2	13·8	14·2	1401·3	1896·9	2029·5	11·7	13·7	14·1	1312·5	1679·5	1803·6

PC, present climate condition.

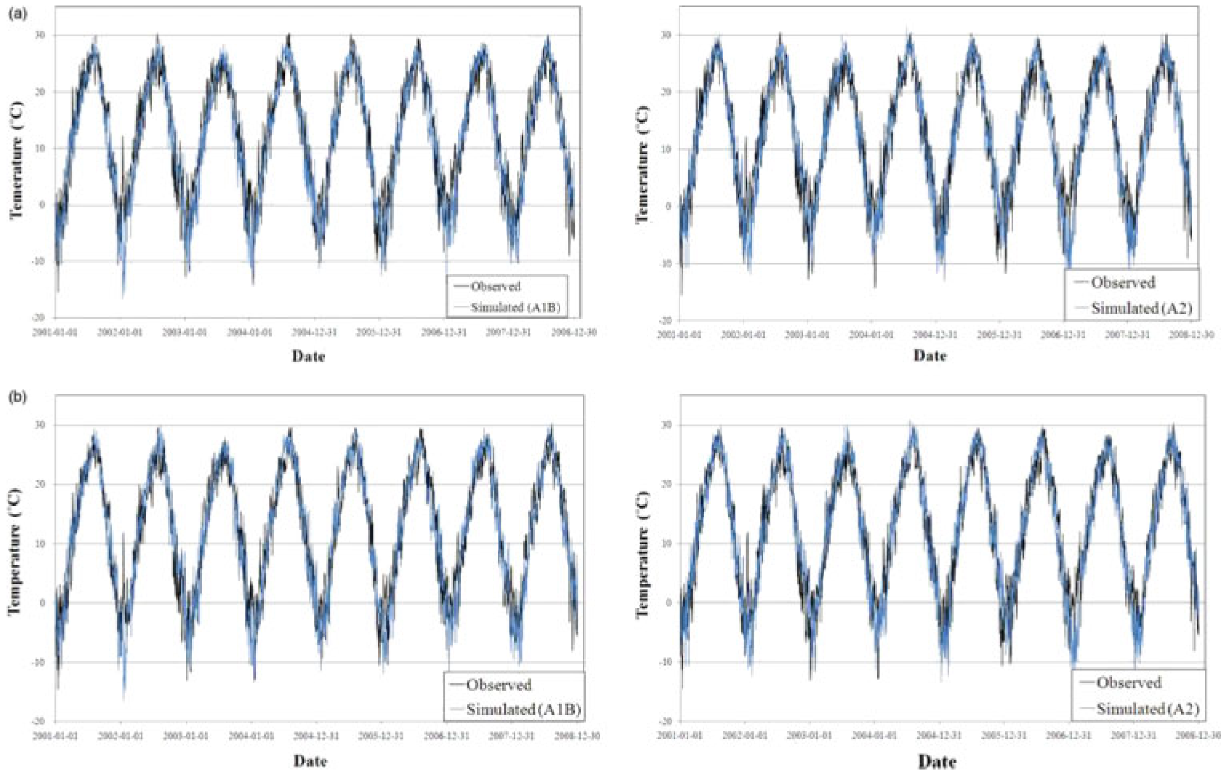

Figure 7. Comparison of monthly observed and simulated temperature data. (a) Seoul and (b) Suwon

Table VIII. Pervious and impervious ratios of all land use change scenarios

Name of sub-watershed	C1 (%)		C2 (%)		C3 (%)		Total area (km^2)
	PR	IR	PR	IR	PR	IR	
Total	47·4	50·7	36·0	62·1	33·7	64·4	286·6
AY	28·0	69·4	27·8	69·6	27·8	69·6	91·4
DR	31·1	68·0					41·6
MG	60·0	37·8	37·6	60·3			56·1
SH	49·5	50·4	39·7	60·2			3·3
SB1	17·6	82·3					4·6
SS	84·8	13·8	73·5	25·0	38·5	60·0	13·2
SA	73·7	25·4	39·1	60·0			8·1
HU	67·0	30·4	36·3	61·13			44·8
SB	50·0	49·9	39·3	60·7			10·3
DJ	37·3	62·3					5·3
OJ	88·1	11·4	74·5	25·0	39·5	60·0	4·3
WG	89·5	9·6	89·1	10·0	74·1	25·0	3·8

PR, pervious area ratio; IR, impervious area ratio.

conditions (C1), (2) one-grade degradation (C2), and (3) two-grade degradation (C3). One-grade degradation means that the imperviousness rates of types I, II, and III sub-watersheds increase to 10, 25, and 60%. Two-grade degradation means that the impervious area ratios of types I, II, and III become 25, 60, and 60%. It is assumed that sub-watersheds of type IV retain their present conditions due to their already high impervious area ratios. Three land use maps of the study watershed are shown in Figure 8.

In addition to the impervious area to the study watershed, a new hypothetical urban area was developed adjacent to the existing area. Although the new city can be constructed in the upstream region or without any consideration for the old cities, this study assumed homogeneity of urban growth.

Determination of EFR

This study cited the results from the Gyeonggi Research Institute (2003) and Lee *et al.* (2008), who investigated the dominant species for the study watershed. Using these studies, we selected *Carassius auratus* (the common goldfish) for the SH, MG, and DR sub-watersheds; *Zacco platypus* (the freshwater minnow) for the HU sub-watershed; and *Rhynchocypris oxycephalus* (the Chinese minnow) as the dominant species for the

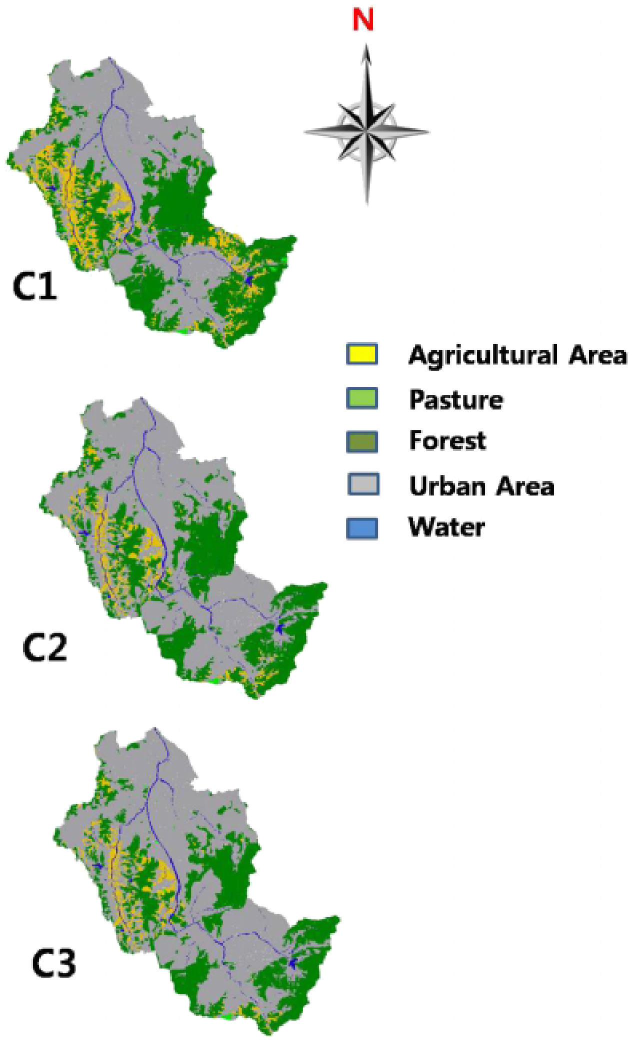

Figure 8. Land use maps of all scenarios

WG, OJ, DJ, SB, SS, SA, and SB1 sub-watersheds. This study also used information from prior studies, such as those by the Korea Institute of Construction Technology (1995), to derive the habitat suitability criteria for the target species. Increasing the discharge gradually, PHABSIM searches for the discharge that maximizes the weighted usable area as the fish flow. Note that the fish flows are available only for the spawning season from April to October.

The calculated average 97th percentile flow and the fish flow for each study sub-watershed are compared, and their maximum values are determined as EFR. The fish flows for the spawning season are always greater than the average 97th percentile flow in all sub-watersheds; the fish flow from April to October and the average 97th percentile flow from November to March were selected as EFR. The calculated monthly flows are shown in Figure 9.

Hydrological analyses of all scenarios using HSPF

Flow rate. All present and future scenarios of all sub-watersheds were analysed using the HSPF model. The flow duration curves of 11 sub-watersheds and of the entire watershed were obtained as shown in Figure 10. The simulation of each sub-watershed was different depending on the land use scenarios (C1, C2, and C3). All results are summarized in Table IX. Urbanization had a significant impact on the decrease in low flow and increase in high flow under both A1B and A2, and there was no significant difference between A1B and A2. Obviously, the change from present conditions to A1B makes the high flow (99, 95, and 90 percentile flow rates) even higher, but there is no strong relationship with low flows. Only some of the large sub-watersheds (HU, MG, DR, and AY) showed significant increases in low flows under the A1B scenario. In the case of the A2 scenario, both low flow and high flow were higher than those under present conditions. In addition, low flows in some large sub-watersheds (HU, MG, DR, and AY) significantly increased, and even the remaining sub-watersheds showed slight increases (around 10%). From Table IX, it can be seen that all increased ratios due to the A2 scenario are larger than those due to A1B; that is, A2 affects the water cycle more. Also, low flow is more sensitive to climatic change and urbanization than is high flow. Two-grade degradation of urbanization has more than twice the impact of one-grade degradation on low and high flows. In addition, the impacts of climate change on low flows (34·1–59·8% increase) and high flows (29·1–37·1% increase) are higher than those on BOD (3·8–10·0% decrease). The results of low flows are significantly similar to Im *et al.* (2009) who estimated that the Q_{90} and Q_{95} of the Soyang watershed during 2021–2050 would increase by 16·2–34·3% under the B2 scenario using the ECHO-G and the precipitation run-off modelling system (PRMS) model.

We counted the numbers of days required to satisfy the target quantities of all sub-watersheds, which were determined by Lee and Chung (2007b) using hydrological low flow estimation and PHABSIM, software as shown in Table X. The number of HU, SS, SA, MG, DR, and AY required to satisfy the target were estimated to decrease by over 40 days due to climate change, and those of HU, SS, SA, and MG showed significant decreases due to land use changes. The number of days can be a sensitive criterion for comparing the subtle impacts of variation.

BOD concentration. Using the HSPF model, the BOD concentration duration curves of all sub-watersheds and of the whole watershed were obtained, as shown in Figure 11. The simulation of each sub-watershed was different, depending on the land use scenarios (C1, C2, and C3) used. All results are summarized in Table IX. Urbanization had a strong impact on the increase in BOD concentration under both A1B and A2. However, climate changes decrease the concentration significantly due to the increase in stream flow. Some large sub-watersheds (HU, MG, DR, and AY) showed significant decreases in concentrations, and the A2 scenario showed the largest decrease. From Table IX, it can be seen that the two-grade degradation of urbanization has more than twice the impact of the one-grade degradation on

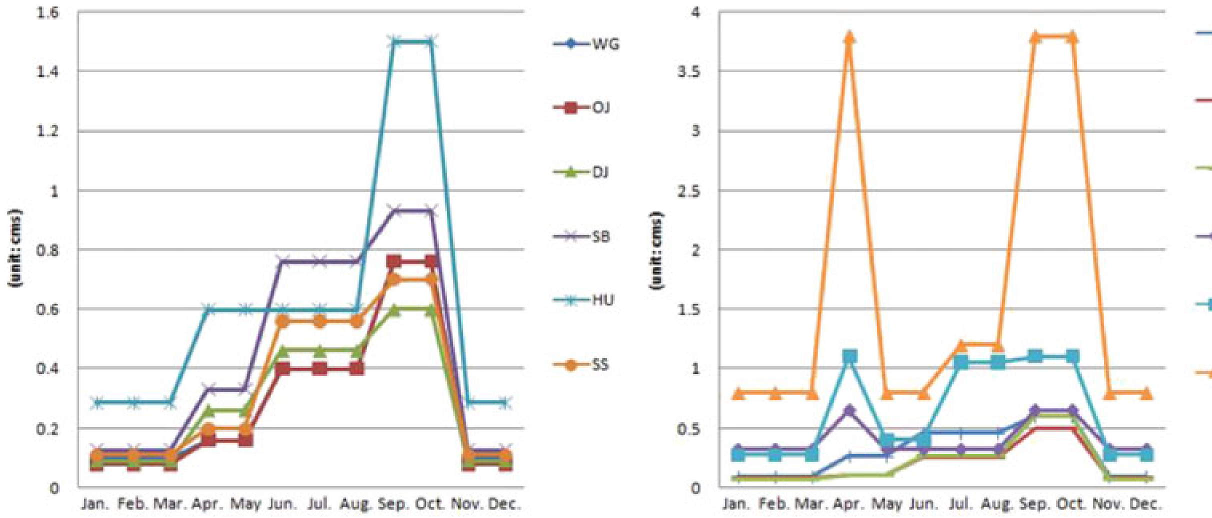

Figure 9. Monthly instream flow requirement of all sub-watersheds

Table IX. Summary of low flow, high flow, and quality of climate and land use changes

Cases	C1 (%)			C2 (%)			C3 (%)		
	Low	High	Quality	Low	High	Quality	Low	High	Quality
P → A1B	34·1	29·9	−3·8	51·0	29·6	−6·0	53·9	29·1	−5·0
P → A2	39·9	37·1	−6·9	57·0	36·3	−10·0	59·8	35·8	−8·5

Cases	A1B (%)			A2 (%)		
	Low	High	Quality	Low	High	Quality
C1 → C2	−11·5%	1·5	19·0	−11·4	1·0	19·2
C1 → C3	−25·6	4·4	44·6	−23·7	2·0	43·0

Table X. Numbers of days to satisfy the target water quantity of all sub-watersheds

Climate scenario	Present condition			A1B			A2		
Land use scenario	C1	C2	C3	C1	C2	C3	C1	C2	C3
WG	77·8	77·7	75·9	59·9	59·9	59·0	60·0	59·9	58·9
OJ	99·6	93·7	82·8	73·5	70·2	63·3	73·6	70·1	63·8
DJ	87·5			66·4			67·1		
SB	108·2	100·6		80·2	75·4		79·6	75·2	
HU	289·6	252·3		227·4	217·6		226·5	217·1	
SS	209·2	197·4	149·4	146·4	137·5	108·2	146·3	136·6	106·9
SA	143·8	115·8		102·3	85·3		102·0	84·8	
SB1	87·2			68·9			68·5		
SH	98·6	98·6		74·5	74·3		75·0	74·9	
MG	328·6	310·3		234·8	234·1		235·3	234·4	
DR	152·1			110·5			110·2		
AY	323·7	315·9	314·1	235·9	235·9	235·9	235·9	235·9	235·9

BOD concentration. Also, the impacts of urbanization on water quality (19·0–44·6% increase) are much greater than those on high flows (1·0–4·4% increase) and low flows (11·4–25·6% decrease). That is, urbanization has a significant influence on BOD concentration while climate change has a large impact on the flow rate.

We also counted the numbers of days required to satisfy the target qualities of all sub-watersheds that were determined by Lee and Chung (2007b), as shown in Table XI. The numbers of days required to satisfy the target qualities of OJ, SS, SA, and MG were estimated to decrease significantly due to urbanization. The number of HU and MG significantly increase, and those of SH and DR also showed a large increase due to climate change. These numbers can also be sensitive criteria for comparing the small impacts of transformation.

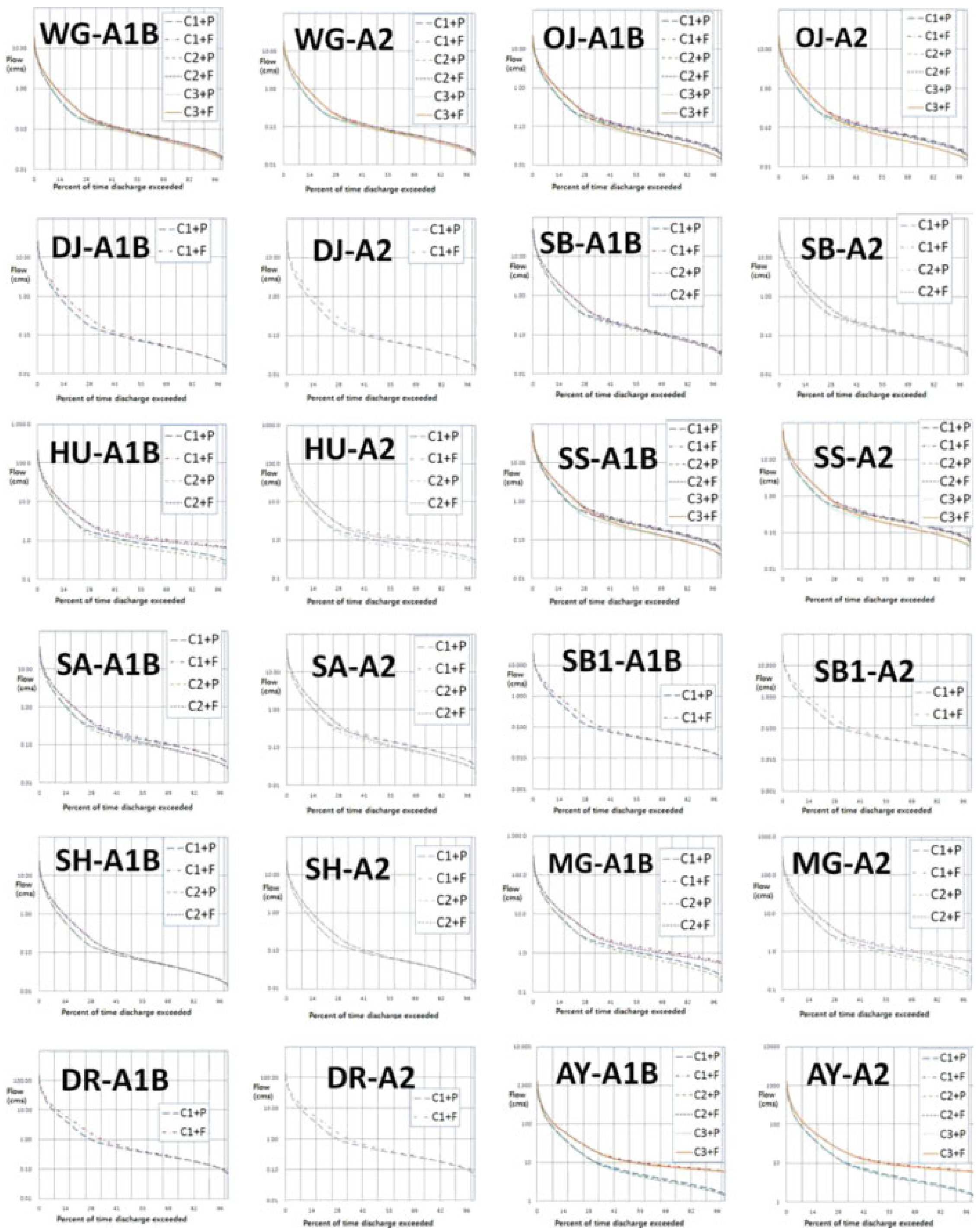

Figure 10. Flow duration curves of all sub-watersheds

Comparison of sub-watersheds

The comprehensive indices for low flow, high flow, and water quality are proposed as averages of 99th, 95th, and 90th percentile flow rates; 10th, 5th, and 1st percentile flow rates; and 30th, 10th, and 1st percentile concentrations, respectively. All values for all sub-watersheds for low flow, high flow, and water quality under all scenarios are presented in Figure 12. We can quantify the overall spatial vulnerabilities of flood damage increase, stream flow depletion, and water quality deterioration due to urbanization, and we can determine, by comparison, which sub-watersheds are more sensitive to climate change and which sub-watersheds are more sensitive to urbanization. Low flows of HU, MG, and AY are very sensitive to climate change. It is certain that low flows in all sub-watersheds decrease and high flows and concentration increase due to the urbanization. In addition, it is clear that low flows and high flows increase due to climate change. However, it is not clear whether the future BOD concentrations will follow particular trends due to the conflicting impacts of both urbanization and climate change when considered together.

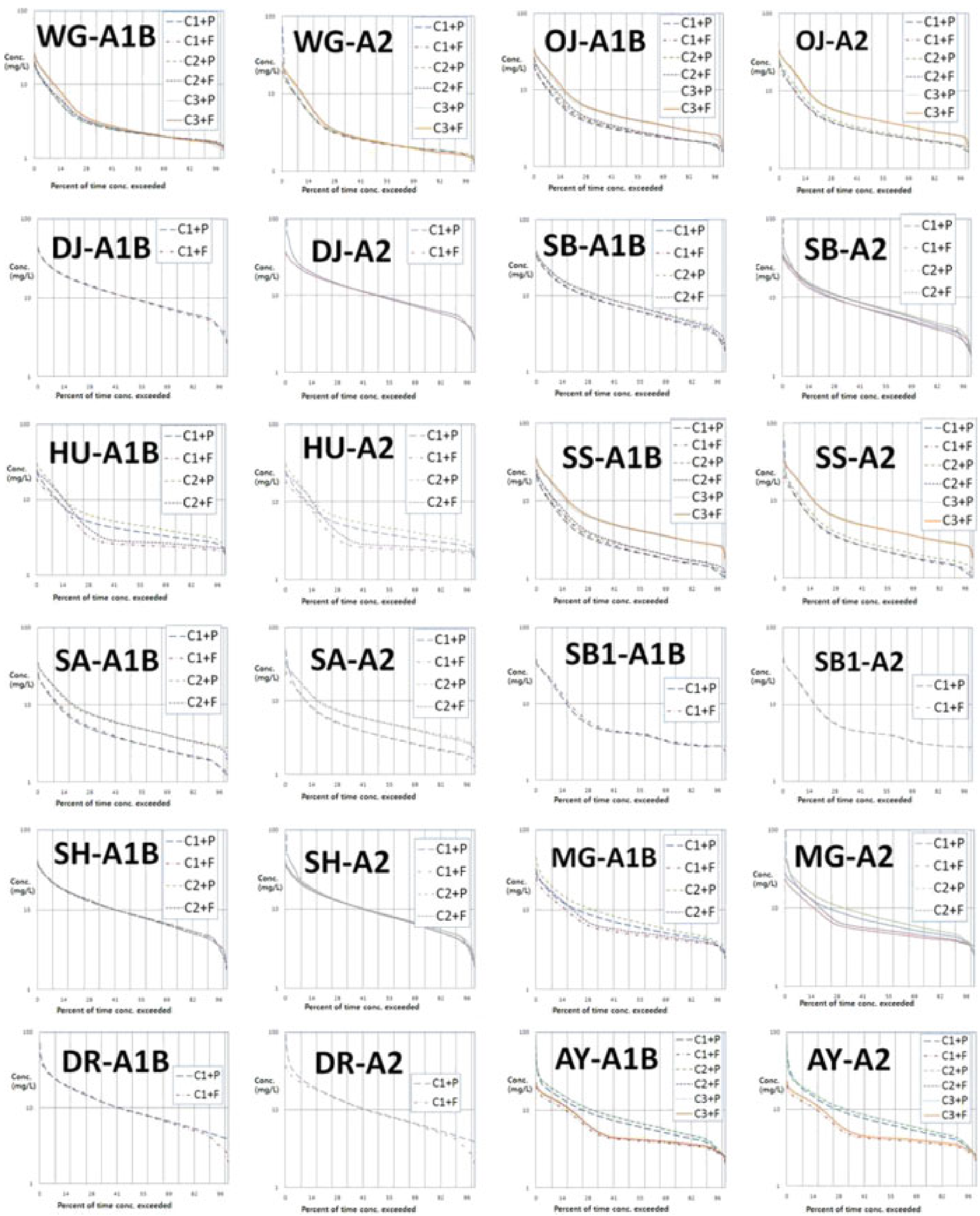

Figure 11. BOD concentration duration curves of all sub-watersheds

CONCLUSIONS

Assessment of the potential impact of climate change on water systems has been an essential part of hydrological research over the last two decades. However, the notion that such assessments should also include land use changes is relatively recent (Semadeni-Davies *et al*., 2008a, b).

This study developed an integrated approach to the assessment of the impact of climate and land use changes by linking the results of several models: SDSM, HSPF, and ICM. A case study of the Anyangcheon watershed, which is a representative urban region in Korea, illustrates how the proposed framework can be used to analyse the impacts of climate and land use changes in terms of water quantity and quality. To quantify the hydrologic changes under climate and land use changes, we introduced two criteria: flow duration and number of days required to satisfy the target. The number of days required to satisfy the target water quantity and quality, in particular, can be a sensitive criterion for comparing the subtle impacts of variation in human society because it is much more sensitive to climate change and urbanization than to low flow and pollutant concentration. As a result, climate change has a more

Table XI. Numbers of days to satisfy the target water quality of all sub-watersheds

Climate scenario	Present condition			A1B			A2		
Land use scenario	C1	C2	C3	C1	C2	C3	C1	C2	C3
WG	260·3	259·0	246·5	255·6	254·7	242·3	262·6	261·8	248·1
OJ	207·3	187·6	68·2	204·9	187·4	78·5	206·2	186·5	76·7
DJ	1·4			1·9			2·5		
SB	15·7	5·0		21·7	7·5		23·2	8·6	
HU	84·4	43·0		257·1	237·5		258·5	239·1	
SS	246·5	225·1	60·5	242·6	221·2	72·0	247·4	224·6	69·7
SA	160·4	31·0		163·2	42·7		163·1	43·2	
SB1	93·3			90·5			94·2		
SH	52·7	52·3		66·6	66·1		70·0	68·2	
MG	103·3	68·3		199·6	157·5		201·9	158·8	
DR	54·5			68·8			71·8		
AY	117·2	96·0	88·9	252·5	243·4	241·3	255·5	245·5	243·2

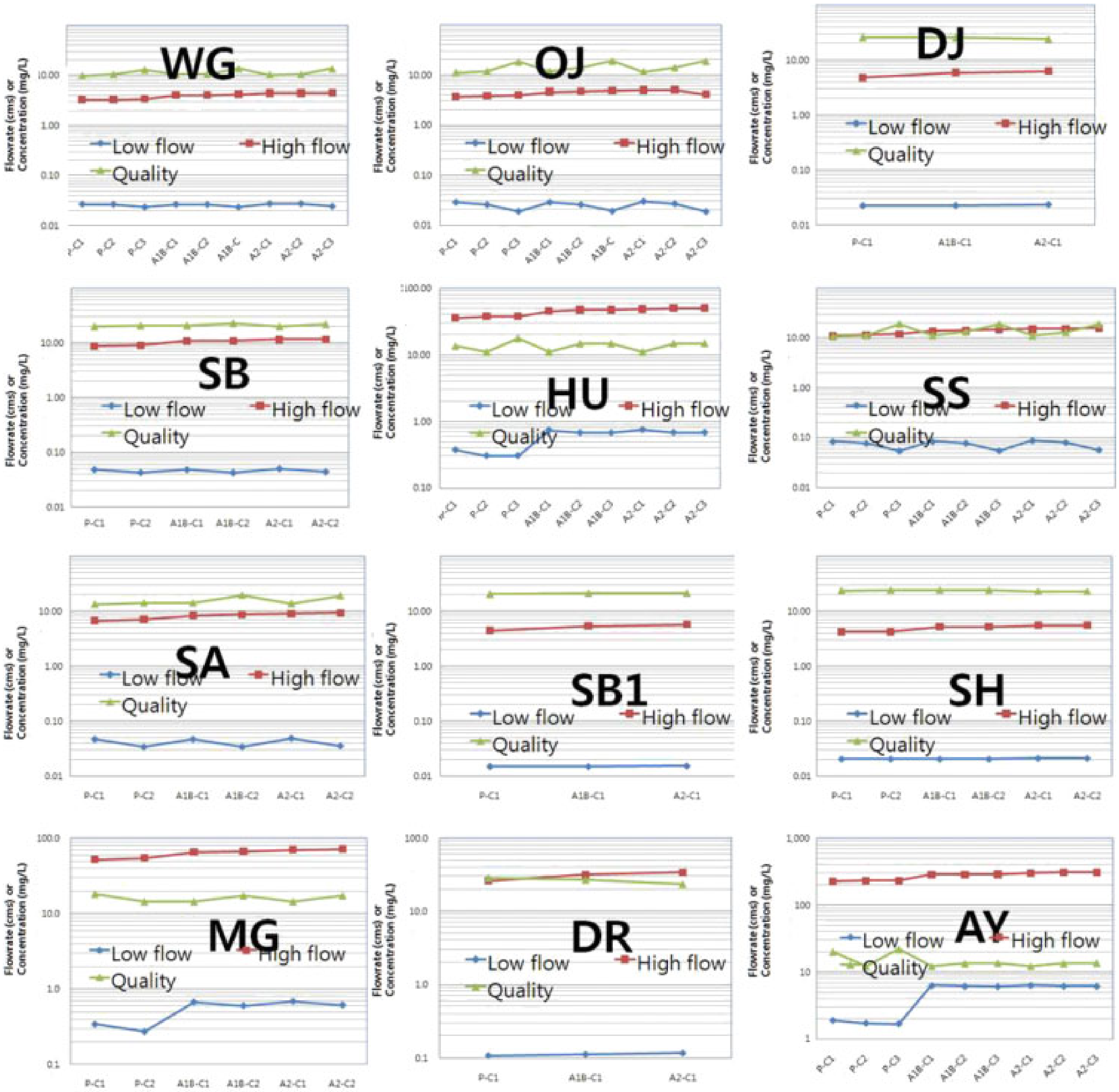

Figure 12. Changes of indices of all sub-watersheds for low flow, high flow and water quality under all scenarios

significant influence on low flow (34·1–53·9% increase) and high flow (29·1–37·1%) compared to BOD concentration (3·8–10·0%), and the land use change affects the pollutant concentration (19·4–44·6% increase) more significantly than high flow (1·5–4·4%) and low flow (11·4–25·6%). This finding is similar to that of Chang (2004) and Tu (2009). Coupling the effects of land use change with climate change leads to greater uncertainty in low flows, high flows, and pollutant concentrations than when climate change alone is used.

These findings indicate that models that combine land use and climate change data can demonstrate significant synergistic hydrologic changes. However, it should be noted that in this study, only two emission scenarios and one GCM were considered. This may induce great uncertainty, particularly in precipitation projection. In the near future, this study will be expanded to accomplish various simulations using recent high-resolution regional climate models (RCMs), GCMs, and more SRES.

This study has a critical limitation. The ICM is a simple empirical relationship between total impervious area and receiving water impact effects on data in some streams. Therefore, the use of this relationship to project the degree of future urbanization may be inappropriate. If this limitation could be overcome, the results of this study would be more generalizable.

This study has significant implications for adaptive management of water resource for future climate and land use changes. This study can be extended to decision making in water resources planning and management by analysing the effectiveness of climate change adaptation plans.

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REFERENCES

Ahn SR, Park MJ, Park GA, Kim SJ. 2009. Assessing future climate change impact on hydrologic components of Gyeongancheon watershed. *Journal of Korean Water Resources Association* **42**(1): 33–50. (in Korean).

Allan JD. 2004. Influence of land use and landscape setting on the ecological status of rivers. *Limnetica* **23**: 187–198.

Asselman NE, Middelkoop H, van Dijk PM. 2003. The impact of changes in climate and land use on soil erosion, transport and deposition of suspended sediment in the River Rhine. *Hydrological Processes* **17**: 3225–3244.

AQUA TERRA. 2004. *BASIN/HSPF Training Handbook.* U.S. EPA.

Bae DH, Jung IW, Chang H. 2007. Regional impacts of climate change on water resources in Korea by using a high resolution scenario. *Climate Research* **35**(3): 213–226.

Bicknell BR, Imhoff JC, Kittle Jr, JL, Jobes TH, Donigan AS. 2001. *Hydrologic Simulation Program—Fotran (HSPF) User's Manual for Version 12.* U.S. Environmental Protection Agency, National Exposure Research Laboratory: Athens, GA.

Brath A, Montanari A, Moretti G. 2006. Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of Hydrology* **324**(1–4): 141–153.

Bronstert A, Niehoff D, Burger G. 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modeling capabilities. *Hydrological Processes* **16**: 509–529.

Center for Watershed Protection. 2005. *Urban Subwatershed Restoration Manual Series: 1. An Integrated Framework to Restore Small Urban Watersheds Version 2.0*. Center for Watershed Protection: Ellicott City, MD.

Chang H. 2003. Basin hydrologic response to changes in climate and land use: the Conestoga River basin, Pennsylvania. *Physical Geography* **24**: 222–247.

Chang H. 2004. Water quality impacts of climate and land use changes in Southeastern Pennsylvania. *The Professional Geographer* **56**(2): 240–257.

Changnon SA, Demissie M. 1996. Detection of changes in streamflow and floods resulting from climate fluctuations and land use-drainage changes. *Climatic Change* **32**(4): 411–421.

Chung ES, Lee KS. 2009. Prioritization of water management for sustainability using hydrologic simulation model and multicriteria decision making techniques. *Journal of Environmental Management* **90**(3): 1502–1511.

Choi W. 2008. Catchment-scale hydrological response to climate-landuse combined scenarios: a case study for the Kishwaukee River Basin, Illinois. *Physical Geography* **29**: 79–99.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* **283**: 207–217.

Crooks S, Davies H. 2001. Assessment of land use change in the Thames catchment and its effect on the flood regime of the river. *Physics and Chemistry of the Earth Part B* **26**(7): 593–599.

Cuo L, Lettenmaier DP, Alberti M, Richey JE. 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. *Hydrological Processes* **23**: 907–933.

De Roo A, Odijk M, Schmuck G, Koster E, Lucieer A. 2001. Assessing the effects of land use changes on floods in the Meuse and Oder catchment. *Physics and Chemistry of the Earth Part B* **26**(7): 593–599.

Ewen J, Parkin G. 1996. Validation of catchment models for predicting land-use and climate change impacts. *Journal of Hydrology* **175**: 583–594.

Franczyk J, Chang H. 2009. The effects of climate change and urbanization on the runoff of the Rock Creek in the Portland metropolitan Area, OR, USA. *Hydrological Processes* **23**: 805–953.

Guo H, Hu Q, Jiang T. 2008. Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. *Journal of Hydrology* **355**: 106–122.

Gyeonggi Research Institute. 2003. *A Counterplan of Revival for the Anyangcheon Watershed*. Gyeonggido (in Korean).

Han JG, Lee YK, Kim TH, Hwang EJ. 2005. Analysis of seasonal water pollution based on rainfall feature at Anyang river basin in Korea. *Environmental Geology* **48**: 599–608.

Hejazi M, Moglen GE. 2007. Regression-based approach to low flow prediction in the Maryland Piedmont region under joint climate and land use change. *Hydrological Processes* **21**: 1793–1801.

Hejazi M, Moglen GE. 2008. The effect of climate and land use change on flow duration in the Maryland Piedmont region. *Hydrological Processes* **22**: 4710–4722.

Im ES, Gutowski WJ, Giorgi F. 2008. Consistent changes in twenty-first century daily precipitation from regional climate simulations for Korea using two convection parameterizations. *Geophysics Research Letter* **35**: L14706. DOI: 10.1029/2008GL034126.

Im E-S, Jung I-W, Chang H, Bae D-H, Kwon W-T. 2010. Hydroclimatological response to dynamically downscaled climate change simulations for Korean basins. *Climatic Change* **100**: 485–508.

Im ES, Jung IW, Bae DH. 2010. The temporal and spatial structures of recent and future trends in extreme indices over Korea from a regional climate projection. *International Journal of Climatology* (in press).

IPCC. 2001. Climate change 2001: The Science Basis. *Contribution of Working Group II to the IPCC Third Assessment Report*. Cambridge University Press, UK.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the IPCC Fourth Assessment Report*. Cambridge University Press, UK.

Juckem PF, Hunt RJ, Anderson MP, Robertson DM. 2008. Effects of climate and land management change on streamflow in the driftless area of Wisconsin. *Journal of Hydrology* **355**: 123–130.

Kalnay E, Kanamitsu M, Kirstler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewki C, Wang J, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–472.

KICT (Korea Institute of Construction Technology). 1995. *Development and Application of Method to Determine Instream Flow Requirement*. Korea Water Resources Corporation, Daejeon (in Korean).

Kim KT, Chung ES, Kim SU, Lee KS, Seong JY. 2009. Improvement and application of total maximum daily load management system of Korea: 1. Calculation of total amount of pollutant load in the Anyangcheon watershed. *Journal of Korean Society on Water Quality* **25**(6): 972–978 (in Korean).

Lee KS. 2007. *Rehabilitation of the Hydrologic Cycle in the Anyangcheon Watershed*. Seoul National University: Seoul. Sustainable Water Resources Research Center of 21st Century Frontier Research Program. Seoul National University: Seoul (in Korean).

Lee KS, Chung ES. 2007a. Hydrological effects of climate change, groundwater withdrawal, and landuse in the small Korea watershed. *Hydrological Processes* **21**(22): 3046–3056.

Lee KS, Chung ES. 2007b. Development of integrated watershed management schemes for intensively urbanized region in Korea. *Journal of Hydro-Environmental Research* **1**(2): 95–109.

Lee KS, Chung ES, Lee JS, Hong WP. 2007c. Analysis of hydrologic cycle and BOD loads using HSPF in the Anyangcheon watershed. *Journal of Korean Water Resources Association* **40**(8): 585–600 (in Korean).

Lee KS, Chung ES, Kim YO. 2008. Integrated watershed management for mitigating streamflow depletion in an urbanized watershed in Korea. *Physics and Chemistry of the Earth* **33**(5): 382–394.

Legesse D, Vallet-Coulomb C, Gasse F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* **275**: 63–85.

Li Z, Liu W, Zhang X, Zheng F. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology* **377**: 35–42.

Lioubimtseva E, Cole R, Adams JM, Kapustin G. 2005. Impacts of climate and land-cover changes in arid lands of Central Asia. *Journal of Arid Environments* **62**(2): 285–308.

Ma X, Xu J, Luo Y, Aggarwal SP, Li J. 2009. Response of hydrological processes to land-cover and climate changes in Kejie watershed, southwest China. *Hydrological Processes* **23**: 1179–1191.

Park JY, Park MJ, Ahn SR, Kim SJ. 2009. Watershed modeling for assessing climate change impact on stream water quality of Chungjudam watershed. *Journal of Korean Water Resources Association* **42**(10): 877–889 (in Korean).

Praskievicz S, Chang H. 2009. A review of hydrologic modeling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* **33**(5): 650–671.

Prowse TD, Beltaos S, Gardner JT, Gibson JJ, Granger RJ, Leconte R, Reters DL, Pietroniro A, Romolo LA, Toth B. 2006. Climate change, flow regulation and land-use effects on the hydrology of the Peace-Athabasca-Slave system: findings from the northern rivers ecosystem initiative. *Environmental Monitoring and Assessment* **113**: 167–197.

Qi S, Sun G, Wang Y, McNulty SG, Myers JAM. 2009. Streamflow response to climate and landuse changes in a coastal watershed in North Carolina. *Transactions of the ASABE* **52**: 739–749.

Schueler TR. 1994. The Importance of Imperviousness. *Watershed Protection Techniques* **1**(3): 100–111.

Schueler TR. 2003. Impacts of impervious cover on aquatic systems. *Watershed Protection Research Monograph No. 1*. Center for Watershed Protection.

Scinocca JF, McFarlane NA, Lazare M, Li J, Plummer D. 2008. The CCCma third generation AGCM and its extension into the middle atmosphere. *Atmospheric Chemistry and Physics* **8**: 7055–7074.

Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson L. 2008a. The impacts of climate change and urbanization on drainage in Helsingborg, Sweden: combined sewer system. *Journal of Hydrology* **350**: 100–113.

Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson L. 2008b. The impacts of climate change and urbanization on drainage in Helsingborg, Sweden: suburban stormwater. *Journal of Hydrology* **350**: 114–125.

Tollan A. 2002. Land use change and floods: what do we need most research or management?. *Water Science and Technology* **45**: 183–190.

Tu J. 2009. Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA.*Journal of Hydrology* **379**: 268–283.

US Geological Survey. 2001. *PHABSIM for Windows, User Manual and Exercises*. Midcontinent Ecological Science Center: Fort Collins, CO.

Vogel RM, Kroll CN. 1992. Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics. *Water Resources Research* **28**(9): 2451–2458.

Wang GX, Zhang Y, Liu GM, Chen L. 2006. Impact of land-use change on hydrological processes in the Maying River Basin, China. *Science in China Series D: Earth Sciences* **49**(10): 1098–1110.

Wang S, Kang S, Zhang L, Li F. 2008. Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes* **22**: 2502–2510.

Wilby RL. 1994. Stochastic weather type simulation for regional climate change impact assessment. *Water Resources Research* **30**(12): 3395–3403.

Wilby RL, Wigley TML. 1997. Downscaling general circulation model output a review of methods and limitations. *Progress in Physical Geography* **21**: 530–548.

Wilby RL, Dawson CW, Barrow EM. 2002. SDSM—a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software* **17**: 147–159.

Wilby RL, Whitehead PG, Wade AJ, Butterfield D, Davis RJ and Watts G. 2006. Integrated modelling of climate change impacts on the water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology* **330**: 204–220.

