Korean Journal of Remote Sensing, Vol.24, No.1, 2008, pp.25~33

Assessment of Future Climate Change Impact on DAM Inflow using SLURP Hydrologic Model and CA-Markov Technique

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Abstract : To investigate the hydrologic impacts of climate changes on dam inflow for Soyanggang-dam watershed (2694.4 km^2) of northeastern South Korea, SLURP (Semi-distributed Land Use-based Runoff Process) model and the climate change results of CCCma CGCM2 based on SRES A2 and B2 were adopted. By the CA-Markov technique, future land use changes were estimated using the three land cover maps (1985, 1990, 2000) classified by Landsat TM satellite images. NDVI values for 2050 and 2100 land uses were estimated from the relationship of NDVI-Temperature linear regression derived from the observed data (1998-2002). Before the assessment, the SLURP model was calibrated and verified using 4 years (1998-2001) dam inflow data with the Nash-Sutcliffe efficiencies of 0.61 to 0.77. In case ofA2 scenario, the dam inflows of 2050 and 2100 decreased 49.7 % and 25.0 % comparing with the dam inflow of 2000, and in case of B2 scenario, the dam inflows of 2050 and 2100 decreased 45.3 % and 53.0 %, respectively. The results showed that the impact of land use change covered 2.3 % to 4.9 % for the dam inflow change.

Key Words : SLURP, Climate change, CA-Markov technique, NDVI.

1. Introduction

Water is one of the vital resources that are sensitive to climatic changes (IPCC, 1996; Gleick, 2000; Water Resources Update, 2003). Future available water can be evaluated by the hydrological impact studies using outputs from General Circulation Models (GCMs). GCMs are the credible tool for predicting climate change and for providing inputs to hydrological models. Recently, a number of climate impacts on runoff have been accomplished by coupling GCM outputs and hydrological model. Kite *et al.* (1994) and Kite and Haberlant (1999) estimated the runoffs by connection of CCC GCM and SLURP model for Mackenzie and Columbia basins of Canada. Kwadijk *et al.* (1995) evaluated the climate impact for the runoff of Rhine river of Germany with the connection of GCM and RHINFLOW. Gellens *et al.* (1998) used the seven GCMs and IRMB (Integrated Runoff Model) to analyze the impact of

Received 16 January 2008; Accepted 1 February 2008.

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climate change for the runoffs of eight basins of Belgium(Kite, 1999). Ahn *et al.* (2001) used the water balance model to investigate the runoff change of Daecheong-dam watershed of South Korea by using the results of GCM.

The performance of climate impact by hydrological models is primarily influenced by the quality of the input climate data, followed by the future land use, seasonal variation of vegetation cover and estimated model parameters, with model structure being the least significant. Many modeling studies deal with the impact of climate change on river flows, however most of these studies are limited to the application of present land cover and vegetation cover condition. Land use changes directly affect evapotranspiration, infiltrationand soil water storage changing the dynamics of surface runoff, subsurface runoff and groundwater recharge. The accompanying spatial and temporal distributions of vegetation cover influence the parameters of calculating evaporation from soils and transpiration from vegetation.

The main goal of this study is to assess the potential impact of climate change on dam inflow by considering future land use changes and their vegetation cover conditions. The future land use information was prepared by applying the CA (Cellular Automata)-Markov technique with the past temporal series of land cover maps classified by Landsat TM satellite images. The corresponding seasonal vegetation cover conditions were derived by the NOAA NDVI (Normalized Difference Vegetation Index) values estimated from the relationship of NDVI-Temperature linear regression. The SLURP model was applied to evaluate the future climate impact on dam inflow using the climate change results of CCCma CGCM2 based on SRES A2 and B2.

2. The Model for Assessing Hydrological Impact

The SLURP (Kite, 1995) basin-level hydrological model was adopted for assessing hydrological impact of dam inflow by future climate and land use change scenarios. SLURP is a continuous simulation semi-distributed hydrological model in which the parameters are related to landcover (vegetation type). The model can take into account changes in the distribution and type of land cover over time and is therefore suitable for climatic change impact studies (Kite, 1993).

The SLURP model divides the watershed into hydrologically-consistent sub-units known as aggregated simulation areas (ASA). An ASA is not a homogeneous area but is a grouping of smaller areas with known properties. Land cover pixels are aggregated into areas that are more convenient for modeling. The number of ASAs used in modeling a watershed depends on the size of the watershed and the scales of data available.

At each time increment, the model is applied sequentially to each element of the matrix of ASAs and land covers. Each element of the matrix is simulated by four nonlinear reservoirs representing canopy interception, snowpack, rapid runoff (considered as a combined surface storage and top soil layer storage) and slow runoff (considered as groundwater). The model routes precipitation through the appropriate processes and generates outputs (evaporation, transpiration and runoff) and changes in storage (canopy interception, snowpack and soil moisture). Runoffs are accumulated from each land cover within an ASA using a time/contributing area relationship for each land cover and the combined runoff is converted to streamflow and routed between each ASA.

3. Model Setup

1) Watershed, soils and land use

The study watershed has a total area of 2,694.4 km^2 located in northeast of South Korea. It lies between the coordinates of latitude N 37° 41′ 42″ to N 38° 31′ 29″ and longitude E 127° 45′ 39″ to E 128° 39′ 50″. The watershed location and elevation are seen in Fig. 1. At the outlet of the watershed, Soyanggang multi-purpose dam that is 123 m in height, 530 m in length and has a volume of 9.6 million m^3 is located. Soil information (type and depth) was obtained from soil survey data of the Korea Rural Development Administration. The subsurface unsaturated layer of most soils is permeable with soil depths ranging from 0.3 m to 1.5 m. Sandy loam and clay loam dominate, covering 36.6 % and 32.9 % of the watershed, respectively. More than 92.0 % is forested and 25.0 % of lowland is paddy fields. The remaining area is dry field farming (34.3 %) and a farm village (8.3 %) scattered between the forest and the paddy.

2) Map data

Elevation data were rasterized from a vector map at a 1:5,000 scale that was supplied by the Korea National Geography Institute. The flow direction map and flow accumulation map were generated using elevation data, respectively. Soil data were rasterized from a vector map at a 1:50,000 scale that was supplied by the Korea Rural Development Administration. The land use map was prepared using a Landsat TM (Thematic Mapper) image of 1985, 1990 and2000. Land cover analysis was achieved through a maximum likelihood classification with an average overall accuracy of 93.2 %.

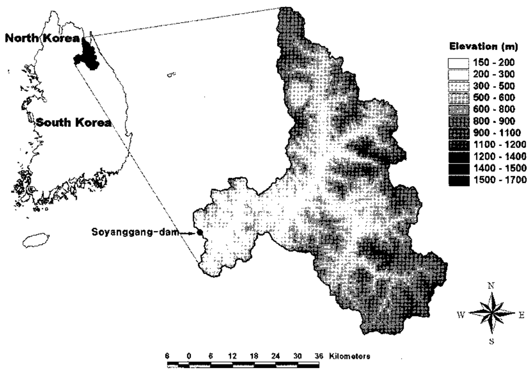


Fig. 1. Study area.

3) Model calibration and validation

The weather data needed by the model are daily average and dew point temperatures, relative humidity, wind speed, sunshine hour, and daily precipitation. The Korea Meteorological Administration measured them at five sites within and near the watershed. The dam inflow has been gauged since 1974 by the Korea Water Resources Corporation (KOWACO).

Three years of data, from 1998 and 2000, were selected for model calibration and one year of data (2001) were used for validation. Five years (1998-2002) of monthly NDVI were prepared from NOAA-AVHRR images. Monthly NDVI was created by MVC (Maximum Value Composite) method. The MVC image was produced to extract the maximum value of each pixel comparing the values among the series of NDVI images.

During the calibration period (1998 - 2000), the 10 hydrological parameters (Table 1), were optimized using the built-in Shuffled Complex Evolution global optimization method developed at the University of Arizona (SCE-UA) (Duan *et al.*, 1994). The sensitivity analysis was conducted using the data of the calibration period. A simple test was performed consisting of changing the optimal parameters one by one, keeping the other parameters constant, by increasing and decreasing the parameter values. The results of sensitivity analysis show that maximum

Table 1. SLURP hydrological parameters and sensitivity

No.	Parameter name	Sensitivity
1	Initial contents of snow store (mm)	Medium
2	Initial contents of slow store (% of max)	Medium
3	Maximum infiltration rate (mm/day)	High
4	Manning roughness, n	Low
5	Retention constant for fast store	Medium
6	Maximum capacity for fast store (mm)	High
7	Retention constant for slow store	High
8	Maximum capacity for slow store (mm)	Medium
9	Precipitation factor	High
10	Rain/snow division temperature (°C)	Low

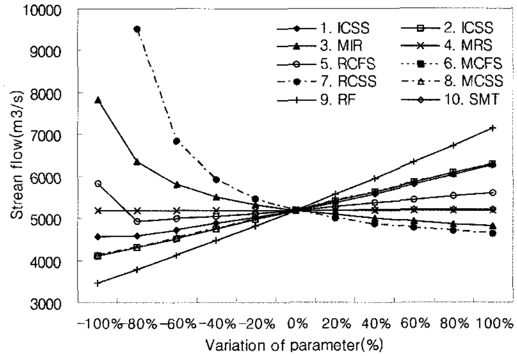


Fig. 2. Sensitivity analysis of parameters.

infiltration rate, maximum capacity for fast store, retention constant for slow store and precipitation factor are the most sensitive parameters (Table 1, Fig. 2).

So, manual calibration based on sensitive parameters was performed to set the limits within which the parameters can vary. Table 2 shows the average value of calibrated model parameters. The model was verified for a year (2001) using the average value of calibrated parameters. A summary of model validation is given in Table 3. The average Nash-Sutcliffe efficiency E2 (Nash and Sutcliffe, 1970) for the model was 0.68.

Table 2. The calibrated model parameters

No.	Description	Water	Urban	Bare-ground	Wetland
1	Initial contents of snow store (mm)	83.2	39.8	99.2	139.4
2	Init. contents of slow store (% of max)	31.9	29.3	56.1	28.3
3	Maximum infiltration rate (mm/day)	155.6	121.9	91.9	110.3
4	Manning roughness, n	0.0	0.0	0.0	0.0
5	Retention constant for fast store	33.7	17.3	24.0	1.0
6	Maximum capacity for fast store (mm)	157.8	204.9	224.0	259.9
7	Retention constant for slow store	40,586.7	40,247.7	41,284.3	34,940.0
8	Maximum capacity for slow store (mm)	57,583.3	67,253.3	40,581.7	70,076.7
9	Precipitation factor	1.3	1.5	1.0	1.5
10	Rain/snow division temperature (°C)	0.0	0.0	0.0	0.0
No.	Description	Grassland	Forest	Paddy	Upland crop
1	Initial contents of snow store (mm)	66.4	83.1	147.0	92.0
2	Init. contents of slow store (% of max)	40.6	56.4	33.5	61.6
3	Maximum infiltration rate (mm/day)	66.3	69.3	93.3	118.7
4	Manning roughness, n	0.0	0.1	0.0	0.1
5	Retention constant for fast store	17.3	29.5	17.3	1.0
6	Maximum capacity for fast store (mm)	470.0	314.8	238.3	94.0
7	Retention constant for slow store	49,423.3	77,323.3	47,746.7	75,276.7
8	Maximum capacity for slow store (mm)	53,293.3	33,556.7	43,700.0	53,280.0
9	Precipitation factor	1.3	1.0	1.3	1.3
10	Rain/snow division temperature (°C)	0.0	0.0	0.0	0.0

Table 3. Summary of streamflow statistics: predicted versus observed

Year	Rainfall (mm)		Total runoff (mm)		Runoff ratio (%)		ME	Note
	Observed	Predicted	Observed	Predicted	Observed	Predicted		
2001	1,090.0	912.0	537.9	482.3	49.4	52.9	0.62	V
2000	1,282.0	1,124.0	700.0	710.8	54.6	63.2	0.77	C
1999	1,778.0	1,453.0	1,139.0	1,125.0	64.1	77.4	0.61	C
1998	1,770.0	1,493.0	1,093.0	1,038.0	61.8	69.5	0.72	C

V: validation, C: calibration, ME: Nash-Sutcliffe model efficiency

4. Data Preparation for Model Application

1) GCM climate change scenarios

The climate data from the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM2) of IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) A2 and B2 scenarios were adopted.

CGCM2 is the second generation coupled global climate model with some improvements in the ocean mixing parameterization and sea-ice dynamics of the earlier CGCM1. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other scenarios. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

For the SLURP model input, daily mean temperature (C) (Fig. 3), daily maximum temperature (C), humidity (kg/kg), mean wind speed (m/sec), snow water content (kg/m^2), precipitation (mm), incident solar flux at surface (W/m^2) of CCCma CGCM2 were used.

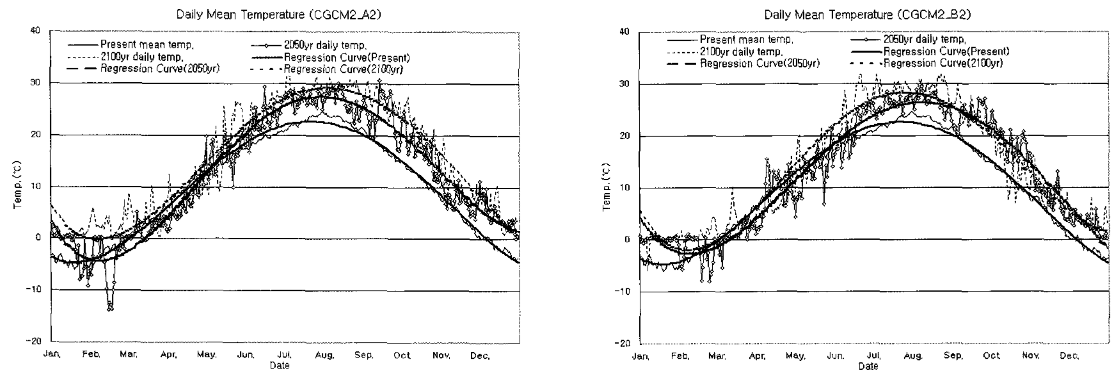


Fig. 3. Meteorological data based on SRES A2 and B2 scenarios

2) Land cover data by CA-Markov technique

CA-Markov uses cellular automata procedures in combination with Markov Chain analysis and MCE (Multi-Criteria Evaluation) / MOLA (Multi-Objective Land Allocation) routines. The algorithm works as follows: The transition areas file from a Markov Chain analysis of two prior land use maps establishes the quantity of expectation land cover change from each existing category to each other category in the next time period. The basis land cover image (the later land cover image used in the Markov Chain analysis) is used as the starting point for change simulation. Suitability maps for each land cover (typically produced using MCE) supplied by the user) establish the inherent suitability of each pixel for each land cover type. However a contiguity filter down-weights the suitability of pixels far from existing areas of that class (as of that iteration), thus giving preference to contiguous suitable areas. The number of iterations chosen establishes the number of time steps that will be used in the simulation. Within each time step, each land cover is considered in turn as a host category. All other land cover classes act as claimant classes and compete for land (only within the host class) using the MOLA procedure. The area requirements for each claimant class within each host are equal to the total established by the transition areas file divided by the number of iterations. The results of each MOLA operation are overlaid to produce a new land cover map at the end of each iteration.

To predict the 2050 and 2100 year land use information, land use data from Landsat TM satellite images of 1985, 1990 and 2000 supplied by KOWACO were used. Using the 1985 and 1990 land use data, 2000 land use generated by CA-Markov technique was compared with the KOWACO 2000 land use previously. Table 4 summarizes the comparison and prediction results.

3) Vegetation cover data using NOAA NDVI-temperature relationship

To predict the future vegetation cover information, a linear regression between monthly NDVI of each land cover and monthly mean temperature was accomplished. Table 5 shows the regression result using five years (1998-2002) monthly NDVI and monthly mean temperature from March to November. The monthly NDVIs of each land use from December to February could not be derived because of snow cover, thus they were extrapolated using the linear regression.

Table 5. Relation of NDVI and Temperature using linear regression

Land use	Regression equation	R^2
Urban	NDVI = 0.0165 temp + 0.1846	0.63
Bare ground	NDVI = 0.0200 temp + 0.1285	0.76
Wetland	NDVI = 0.0149 temp + 0.2164	0.64
Grassland	NDVI = 0.0176 temp + 0.1917	0.66
Forest	NDVI = 0.0188 temp + 0.1789	0.70
Paddy	NDVI = 0.0189 temp + 0.1484	0.73
Upland crop	NDVI = 0.0178 temp + 0.1778	0.69

Table 4. Comparison of observation and prediction for 2000 land use

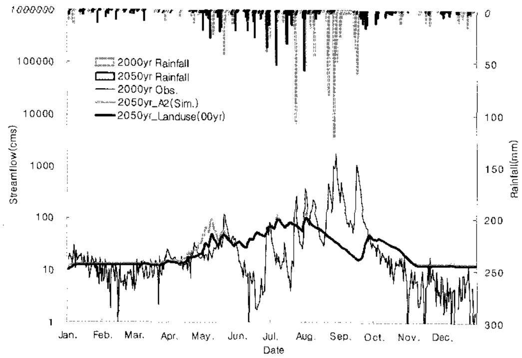
Land use	Area (km^2 [%])					
	Observed			Predicted		
	1985	1990	2000	2000	2050	2100
Water	60.1 [2.2]	31.2 [1.2]	43.7 [1.6]	18.7 [0.7]	67.7 [2.5]	67.7 [2.5]
Urban	9.8 [0.4]	13.2 [0.5]	17.9 [0.7]	12.2 [0.5]	50.5 [1.9]	51.1 [1.9]
Bare ground	4.6 [0.2]	11.0 [0.4]	9.0 [0.3]	22.6 [0.8]	23.0 [0.9]	23.6 [0.9]
Upland crop	77.8 [2.9]	86.6 [3.2]	73.8 [2.7]	198.1 [7.4]	221.6 [8.2]	218.7 [8.1]
Total	2,694.4 [100.0]	2,694.4 [100.0]	2,694.4 [100.0]	2,694.4 [100.0]	2,694.4 [100.0]	2,694.4 [100.0]

5. Assessment of Hydrological Impact on DAM Inflow by Climate and Land Use Changes

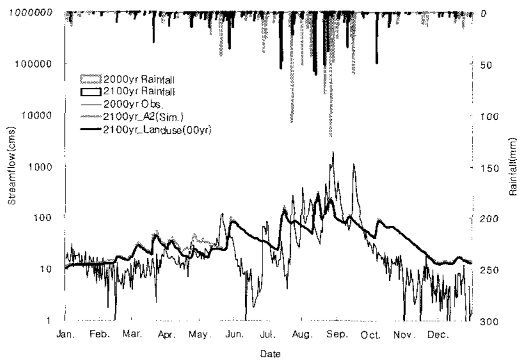
For hydrological impact evaluation on dam inflow, the SLURP model was run with the 2050 and 2100 CCCma CGCM2 data, CA-Markov generated land use data and NOAA derived vegetation cover data, respectively. Fig. 4 shows the SRES A2 and B2 simulated with (2100yr_A2) and without land use change versus 2000 observed dam inflow and Table 6 summarizes the prediction results.

In case of A2 scenario considering future land use change, the dam inflows of 2050 and 2100 decreased 49.7 % and 25.0 % comparing with the dam inflow of 2000 for the precipitation decrease of 40.8 % and 13.6 %, respectively. In case of B2 scenario, the dam inflows of 2050 and 2100 decreased 45.3 % and 53.0 % comparing with the dam inflow of 2000 for the precipitation decrease of 32.6 % and 43.2 %, respectively.

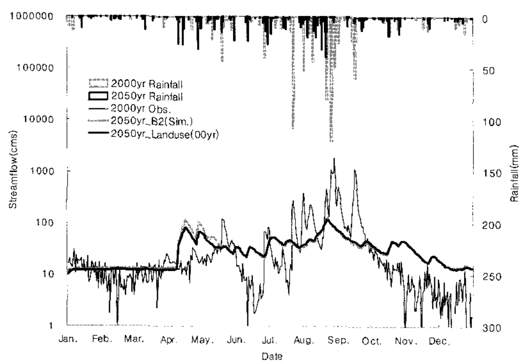
Looking at our results, the consideration of future land use change caused 4.0 % and 4.9 % increase of 2050 and 2100 dam inflow in case of A2 scenario and 2.3 % and 3.5 % increase in case of B2 scenario comparing with the results of no land use change. Especially, the watershed runoff from April to June showed a sensible increase for land use change. We can infer that the time of snowmelt runoff was advanced primarily by the climate impact and the surface runoff from the increased impervious area increased secondarily by the land use impact.



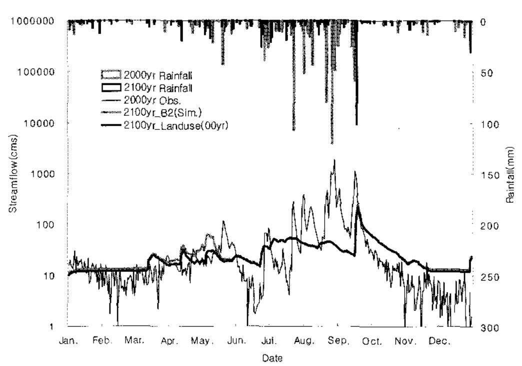
(a) 2050 yr_A2



(b) 2100 yr_A2



(c) 2050 yr_B2



(d) 2100 yr_B2

Fig. 4. Comparison of predicted and observed streamflow with CGCM2 SRES A2 and B2 scenarios.

Table 6. Summary of runoff ratio with SRES A2 and B2 scenarios

Scenario	Year	Rainfall (mm)			Runoff (mm)	Runoff ratio (%)		
		SRES	SLURP	Decrease from 2000 (%)		SRES	SLURP	Decrease from 2000 (%)
A2	2050_C	794.8	671.1	40.3	380.4	29.7	33.8	45.7
	2050_L	794.8	665.0	40.8	352.4	27.5	31.4	49.7
	2100_C	1,159.0	976.8	13.1	559.1	43.6	49.7	20.1
	2100_L	1,159.0	970.7	13.6	525.0	41.0	46.7	25.0
B2	2050_C	904.7	764.7	32.0	398.7	31.1	35.5	43.0
	2050_L	904.7	757.8	32.6	383.2	29.9	34.1	45.3
	2100_C	716.6	642.0	42.9	353.8	27.6	31.5	49.5
	2100_L	716.6	638.0	43.2	328.7	25.6	29.2	53.0
	2000	1,282.0	1,124.0	-	700.0	54.6	62.3	-

Year_C : simulated using 2000 land use, Year_L : simulated using CA-Markov land use

6. Conclusions

The basin-level hydrological model SLURP was applied to assess the potential impact of climate change on dam inflow by considering future land use changes and their vegetation cover conditions. The CA-Markov technique was applied for generating future land use information using Landsat TM satellite images and the NOAA NDVI-Temperature was regressed linearly for the corresponding vegetation cover information. For the GCM scenarios CCCma CGCM2 based on SRES A2 and B2, the dam inflows of 2050 and 2100 decreased ranging from 25.0 % to 53.0 %. The result from the impact assessment of land use change showed that the watershed runoff increased sensibly as the time of snowmelt runoff was advanced primarily by the climate impact and the surface runoff from the increased impervious area increased secondarily by the land use impact. The evaluation approach in this paper and the model results could be useful in assessing the potential effects of future watershed development and reestablishing the rule of dam operation under the climate change environment. Even though the results of this study give plausible evidence for the decrease of dam inflow for the future climate impact, further research is needed for applying downscaled regional GCM climate data for the hydrological model.

Acknowledgements

This research was supported by a grant (07KLSGC03) from Cutting-edge Urban Development - Korean Land Spatialization Research Project funded by Ministry of Construction & Transportation of Korean government.

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