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Impact of Climate Change on Hydrological Droughts in the Upper Namhan River Basin, Korea

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Abstract

Droughts are natural disasters that greatly affect the environment, the ecosystem and water resources. The objective of this study is to analyze the impact of climate change on hydrological droughts and predict future hydrological droughts using the SRES A1B scenario of IPCC AR4 and KMA(Korea Meteorological Administration) RCM climate models. Future droughts are analyzed by considering the joint probability distribution derived by applying the copula method. Results of this study show that severe droughts of short durations will occur more frequently in the near future. In order to determine drought frequencies in the future, SDF (Severity-Duration-Frequency) curves are suggested.

Keywords: *climate change, hydrological drought, joint probability distribution, copula theory*

1. Introduction

In recent years, droughts have occurred more frequently all over the world and it is surmised that the increased drought frequency is due to climate change (Burke *et al.*, 2006). There are many on-going investigations analyzing droughts considering future climate change (Gianninia and Biasuttia, 2008; Win *et al.*, 2009; Strzepek *et al.*, 2010; Wang *et al.*, 2011; Vijaya Venkata Raman *et al*., 2012). Shepherd *et al*. (2003) analyzed the relationship between precipitation and drought in Canada using the GCM (Global Circulation Model) results. Burke *et al.* (2006) estimated the PDSI (Palmer Drought Severity Index) until the 2100 year using the HadCM3 model, while Blenkinsop *et al.* (2007) investigated drought variability with climate change using an RCM (Regional Climate Model). Yin *et al.* (2009) determined the frequency distribution of PDSI index with a GCM model. Much of the reported research has analyzed drought indices using GCM and RCM models (Mpelasoka *et al*., 2007; Dubrovsky *et al*., 2009; Mishra and Singh, 2009; Kim and Jagath, 2009; Mishra *et al*., 2010; Strzepek *et al*., 2010; Yu *et al*., 2012). Many studies have also considered climate change in drought analyses (Mpelasoka *et al*., 2007; Giannini *et al*., 2008; Hirabayashi *et al*., 2008; Li *et al*., 2009; Wang *et al*., 2011; Kim *et al.*, 2006; Kim *et al.*, 2008; Kim *et al.*, 2010a; Kim *et al.*, 2010b).

In the Korean Peninsula, Rim (2013) suggested that the droughts in South Korea are becoming more severe in spring for the short- and seasonal term; however, the droughts in all seasons are becoming less severe for the long term. Kwak (2012) investigated droughts under climate change, and determined the drought frequency distribution using the RCM model of KMA (Korea Meteorological Administration), whereas Kim *et al*. (2010) studied changes in runoff and water balance due to climate change. However, methods of drought analysis, based on precipitation alone, are insufficient for the study of hydrological droughts (Tallaksen and Lanen, 2004; Mishra and Singh, 2010). Kwak *et al*. (2013) estimated the joint probability distribution and return periods of drought severity and drought duration using the copula method for the upper Namhan River basin, Korea.

However, copula-based hydrological drought analyses (Shiau, 2006; Shiau *et al*., 2007; Serinaldi *et al*., 2009; Shiau and Modarres, 2009; Mirakbari *et al*., 2010; Chen *et al*., 2012; Lee *et al.*, 2013; Mirabbasi *et al.*, 2013) have a limitation in that their results are hard to apply directly to water resources management (WRM). Also, KMA provides a drought index map on the KMA database

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(Korea Meteorological Administration, 2014) but it also hard to apply directly. Therefore, the objective of this study is to determine future hydrological drought (hereafter referred to as drought) severity and duration values by using the KMA RCM models (Climate Change Information Center, 2012) for the upper Namhan River basin which is the same basin, with the same data and method as used by Kwak *et al.* (2013), and then determine quantitatively droughts using their joint probability distribution. The study will simulate future streamflow, derive future droughts, calculate future return periods of droughts, and then derive future drought severity-duration-frequency(SDF) curves for WRM.

2. Simulation of Future Streamflow under Climate Change

2.1 Simulation of Climatic Data under Climate Change

Using the method and study area of Kwak *et al.* (2013) that determine the joint probability distribution of severity, duration and frequency of hydrological droughts obtained from streamflow (Mishra and Singh, 2011; Lee *et al.*, 2013), this study analyzes hydrological droughts that may be caused by future climate changes. For application of this method, simulation of future streamflow data is essential. However, streamflow is estimated from rainfall based on the physical elements of the basin, and future observed data do not exist. Therefore, this study will simulate future streamflow on the upstream of Namhan River (2447.85 km^2) using climate change scenarios, climate models, and rainfall-runoff models, and then will do drought analysis as Kwak *et al.* (2013) did.

To simulate future meteorological data, a climate change scenario and a climate model should be selected first. There are a variety of climate models in use, but all of them are not considered suitable for the Korean Peninsula. Reviewing the applicability of 24 climate models, provided by IPCC, to the Korean Peninsula, Kyoung *et al.* (2009) selected 4 climate models (BCM2, CNCM3, FGOALS, MIHR). Then, Kyoung *et al.* (2010) analyzed meteorological characteristics, such as temperature and precipitation, and found the CNCM3 climate model as the most suitable model for the Korean Peninsula. Accordingly, this study selected the CNCM3 GCM model as well as the KMA RCM model developed by KMA. In addition to the climate models, socio-economic scenarios are also needed to simulate future climate data. In general, the climate change scenario refers to the 'Special Report on Emission Scenario (SRES)' announced together with the 4th IPCC report. It is largely divided into A1, A2, B1, and B2 storylines. Among them, the A1 scenario is again divided into A1F1 (mostly uses fossil fuel), A1T (mostly uses non-fossil fuel), and A1B (uses fuel in consideration of future energy resources) scenarios, depending on the kind of fuel used in the future. Considerable global efforts are being made to maximize the efficiency of energy resources and to find alternative energies. Kwon *et al.* (2007) found the A1B scenario as the scenario that corresponds most closely to the expected conditions. Therefore, the SRES A1B scenario was employed for future drought simulations. Accordingly, monthly rainfall series were generated using the CNCM3 (113 × 113 km and monthly resolution) and KMA RCM (27 × 27 km and daily resolution) climate models and the A1B scenario.

Since the generated climate data are forward-looking monthly data, spatio-temporal downscaling was performed at the Daegwallyeong and Jecheon observatories in the upper Han River basin using the Nearest Neighbor-Genetic Algorithm (NN-GA) and Simple Kriging with Local Mean (SKLM) methods, because it shows good results for upper Namhan River basin (Kim *et al.*, 2011b). Unlike GCM, KMA RCM simulates the entire Korean Peninsula by dividing it into 27 × 27 km grid and providing daily precipitation predictions. This study used daily precipitation from the grids containing Daegwallyeong and Jecheon observatories, calibrating the bias by applying the quantile mapping method

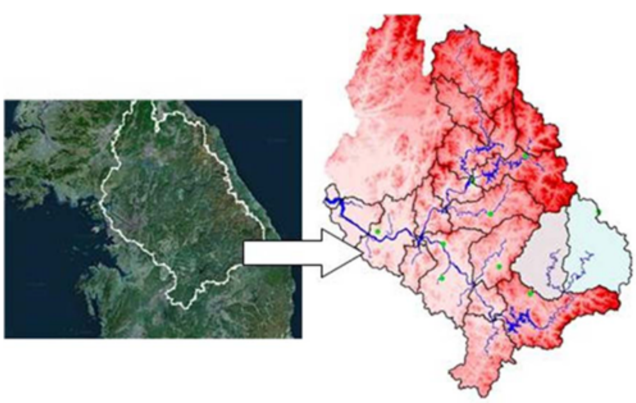

Fig. 1. Study Area (Kwak *et al.*, 2013)

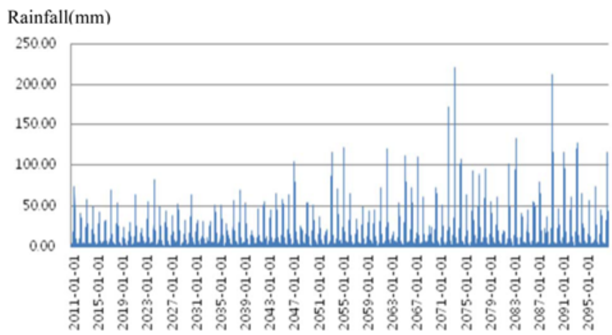

Fig. 2. 2011~2100 Year Daily Rainfall in the Upper Namhan River Basin (CNCM3)

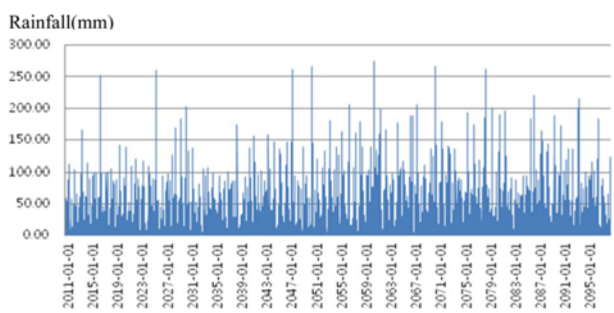

Fig. 3. 2011~2100 Year Daily Rainfall in Upper Namhan River Basin (KMA RCM)

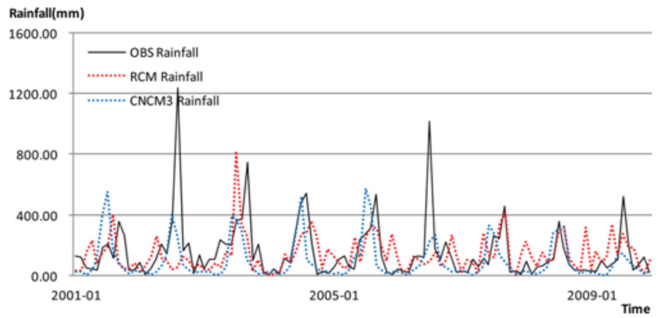

Fig. 4. Comparison of Monthly Total Rainfalls under Each Climate Model at Daegwallyeong Observatory

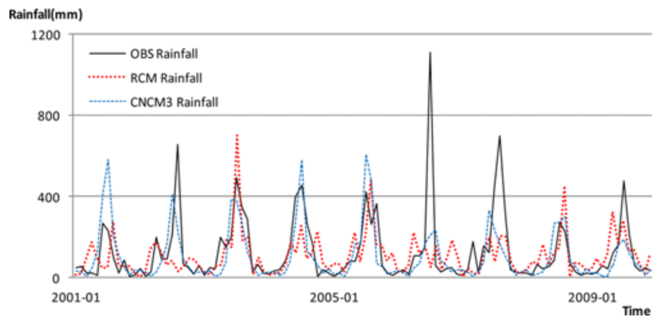

Fig. 5. Comparison of Monthly Total Rainfall under Each Climate Model at Jecheon Observatory

Table 1. Model Evaluation Results at Daegwallyeong and Jecheon Observatories (years 2001 to 2009)

Station	Evaluation Func.	Observation	KMA RCM	CNCM3
Daewallyeong	NRMSE	-	0.23	0.35
	Nash	-	0.61	0.46
	Total Precipitation (mm)	16594.4	15193.2	10272.7
	Skewness	3.1	2.1	2.0
	Kurtosis	12.2	8.1	3.3
Jecheon	NRMSE	-	0.23	0.28
	Nash	-	0.63	0.41
	Total Precipitation (mm)	13331.6	11575.3	11164.8
	Skewness	2.9	2.7	2.1
	Kurtosis	11.0	11.0	4.1

(Block *et al.*, 2009) to correct the general underestimation of the total value of annual precipitation as described by Kyoung *et al.* (2010). Future daily rainfall values in the upper Namhan River basin were simulated using the CNCM3 GCM and KMA RCM models, as shown in Figs. 2 and 3.

2.2 Analysis of Simulated Climate Data

For testing, rainfall series simulated using each climate model were compared to past observed rainfall values, as shown in Figs. 4 and 5. The simulation results from KMA RCM are made available from 1971 and simulation results from CNCM3 from 2001. Monthly total precipitation data from 2001 to 2010 were used. Comparison with observed rainfall values shows that neither of the climate models reflects the extreme values of monthly total rainfall but they all seem to reflect the total amount of rainfall and its trend comparatively well (Figs. 4 and 5 and Table 1).

Climate models were also evaluated using model evaluation criteria, including Nash-Sutcliff efficiency (Nash) (Nash and Sutcliffe, 1970), skewness and kurtosis as well as NRMSE (Non-dimensional Root Mean Square Error; Hyndman and Koehler, 2006). For total precipitation, these values are given in Table 1. The values of Nash, NRMSE and total precipitation showed comparatively better results for the RCM climate model than for the CNCM3 climate model. In addition, the RCM climate model seemed to better simulate data than did the CNCM3 climate model from the perspective of skewness and kurtosis. As skewness is closely associated with the scale parameters of probability density function and kurtosis is leptokurtic distribution in this case (Buldygin and Kozachenko, 1980), the RCM model was considered more suitable for frequency analysis. Of course, KMA RCM also has some uncertainties which show low correlation coefficient with precipitations (Block *et al.*, 2009; Baek *et al.*, 2011) and it will be affected to the simulation results, but it is the most suitable option for the Upper Namhan River basin (Kwak, 2012; Climate Change Information Center, 2012) with quantile mapping (Block *et al.*, 2009; Kim *et al.*, 2011). Therefore, we performed frequency anaysis with KMA RCM.

2.3 Future Streamflow Simulation Considering Climate Change

Long-term streamflow simulation was carried out using the climate data of 2 observatories located inside the upper Namhan River basin and the TANK model. For calibrating model parameters, daily data for 8 years from 2000 to 2007 were used because the impact of climate change can only be properly evaluated with data from 2000 onwards, when rainfall frequency and intensity appeared to have actually changed (Choi, 2004), even though the observed data exist from 1967. Accordingly, data from 2000 onwards was used as input data for constructing models. Daily rainfall-runoff data from 2000 to 2005 were used for calibration of models and daily rainfall-runoff data from 2006 to 2007 were used for verification. Results of model calibration showed that simulated values appeared to be in agreement with observed values, but there was a disagreement in the peak discharge values, which is often a problem in long-term streamflow simulation. Since for drought assessments low flow is considered more important than peak discharge, this study used the simulation results as they were. The calibrated model was then used to simulate streamflow values from 2006 to 2007, as shown in Fig. 6.

Generally, simulated values appeared to reproduce the observed values well. The value of NRMSE was 0.051 for verification. Since the model appeared to reproduce the observed data well for the upper Namhan River basin with KMA RCM, this study carried out future streamflow simulation by using rainfall data obtained from the climate model as input to the model. The simulated daily streamflow series was aggregated on a monthly

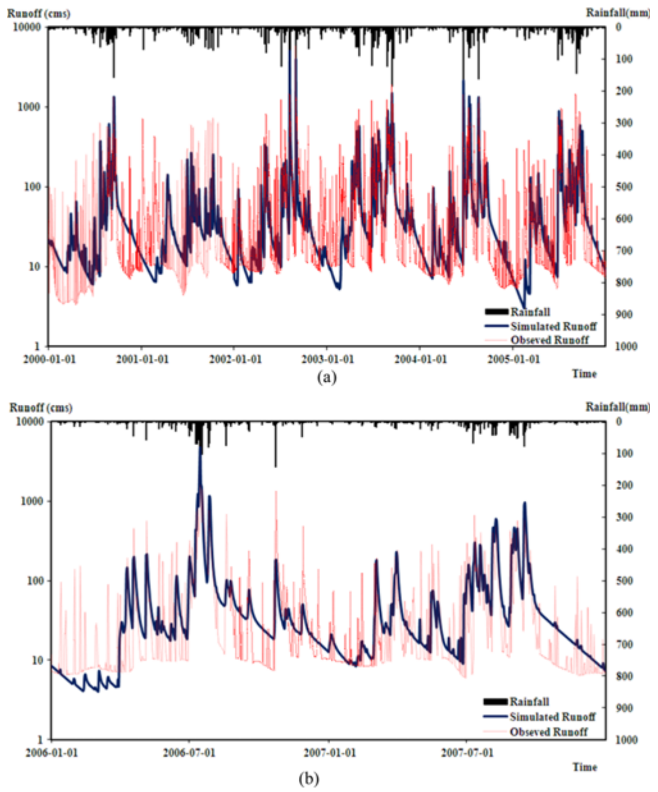

Fig. 6. Calibration and Verification of Long-term Streamflow Simulation for the Upper Namhan River Basin: (a) Model Calibration, (b) Model Verification

basis to obtain future monthly streamflow, as shown in Fig. 7.

Results of future streamflow estimated through future climate data of KMA RCM show that simulated future streamflow would generally increase compared to the current situation. The monthly mean streamflow from 1967 to 2007 was 57.03 m^3/sec, but increased by about 15.0 m^3/sec in CASE 3 (see a section 3.1) in RCM. As streamflow increases, the deviation also increases in RCM, which reflects the future possibility of great streamflow variability. This deviation will have an effect on the occurrence of future floods and droughts.

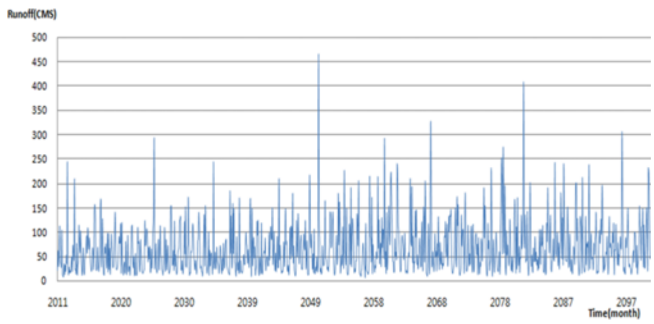

Fig. 7. Future Monthly Streamflow in the Upper Namhan River Basin (KMA RCM)

3. Future Drought Analysis Considering Climate Change

3.1 Analysis of Future Drought Characteristics

To analyze future droughts, this study uses the data of KMA RCM with joint probability distribution (drought severity, duration and frequency). To forecast short and long term trends of climatic variability using simulated future climate data, this study simulated future climate data, classified by the following projection periods:

OBS CASE: Jan. 1967 – Dec. 2007 (Observation Period)
CASE 1: Jan. 2011 – Dec. 2039 (Simulation #1 Period)
CASE 2: Jan. 2040 – Dec. 2069 (Simulation #2 Period)
CASE 3: Jan. 2070 – Dec. 2100 (Simulation #3 Period)

From the run theory, a drought can be defined as the time when x_t falls below the truncation level x_0. The time when streamflow falls below the truncation level defines drought duration and the accumulated shortage during the drought duration defines drought (Yevjevich, 1967; Loaiciga and Leipnik, 1996; Mishra *et al.*, 2007). Streamflow was truncated using the truncation level of 75% of monthly discharge duration curve suggested with historical drought data (National Institute for Disaster Prevention, 1995; 1998; Ministry of Public Administration and Security, 2002) in Kwak *et al.* (2013) using the future streamflow series through which the drought series was deduced. Basic statistics of drought

Table 2. Future Drought Series Characteristics of the Upper Namhan River Basin (KMA RCM)

CASE	Drought Variable	Mean	Standard Deviation	Coefficient of Variation	Skewness	Kurtosis
OBS CASE	Duration (Months)	2.13	1.63	2.67	1.74	2.78
	Severity (mm)	20.99	23.36	545.55	1.40	1.77
	Interval (Months)	8.84	5.64	31.78	1.20	0.88
CASE 1	Duration (Months)	1.60	0.94	0.88	1.42	0.89
	Severity (mm)	42.70	36.02	1297.64	0.82	0.19
	Interval (Months)	8.44	5.46	29.84	1.44	3.32
CASE 2	Duration (Months)	1.45	0.85	0.72	2.44	7.16
	Severity (mm)	35.37	36.18	1309.00	1.76	3.09
	Interval (Months)	9.70	6.76	45.65	1.42	3.25
CASE 3	Duration (Months)	1.46	0.74	0.55	1.66	2.44
	Severity (mm)	34.53	29.09	846.39	0.81	0.16
	Interval (Months)	9.49	4.85	23.51	0.52	0.49

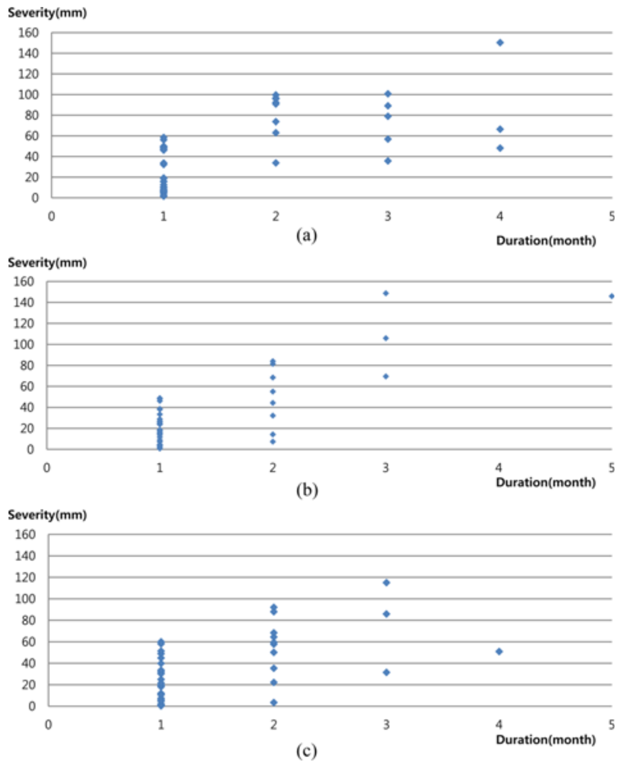

Fig. 8. Drought Events of Each CASE in the Upper Namhan River Basin (KMA RCM): (a) CASE 1 (2011-2039 year), (b) CASE 2 (2040-2069 year), (c) CASE 3 (2070-2100 year)

events in the upper Namhan River basin are shown in Table 2.

Results in CASE 1 show that future droughts appear to decrease in average drought duration, but appear to increase in their severity. This means that severe droughts of short durations are predicted to occur more frequently in the near future. This trend is also indicated in CASE 2 and CASE 3. The estimated drought events in each CASE are shown in Fig. 8.

3.2 Joint Probability Analysis of Drought Variables

Using drought characteristic analysis for the target basin and also using the drought series data from 2011 to 2100 produced through the TANK model with Genetic Algorithm, the predicted future drought events in the upper Namhan River basin until 2100 were separated and truncated at the 75% level. The joint probability distribution for drought duration and severity was estimated using the copula method (Kwak *et al.*, 2013). The copula function was employed to understand the dependence structure between drought variables and it shows the ratio of joint probability distribution function from the product of marginal probability distributions. This study employed the Clayton copula ($L^2 = 0.0019$ and p = 0.045 with the Kolmogorov-Smirnov test) to determine the joint probability distribution of droughts (Shiau *et al.*, 2007; Shiau and Modarres, 2009; Laux *et al.*, 2010; Zhang and Song, 2010; Chen *et al.*, 2012; Lee *et al.*, 2013). The marginal probability distribution of drought duration and severity each and the corresponding joint probability distribution can be formulated as:

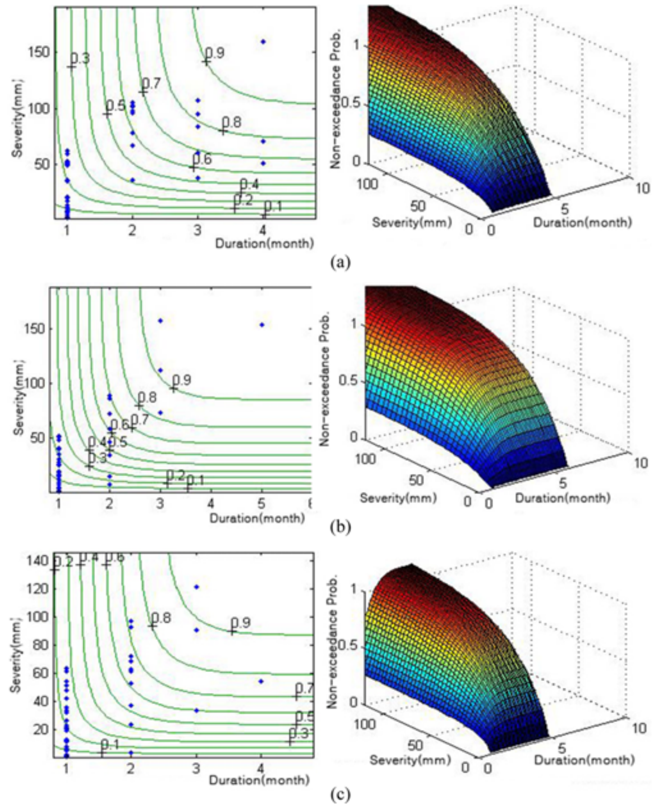

Fig. 9. Cumulative Density Function of Each CASE in Upper Namhan River Basin (KMA RCM): (a) Cumulative Density Function of CASE 1 Droughts, (b) Cumulative Density Function of CASE 2 Droughts, (c) Cumulative Density Function of CASE 3 Droughts

$$F_{Namhan}(d)(x) = 1 - e^{-\left(\frac{x}{4.024}\right)^{1.171}} \quad (1)$$

$$F_{Namhan}(d)(x) = \frac{1}{124.912^{0.711}\Gamma(0.711)} x^{0.711-1} e^{-\left(\frac{x}{124.912}\right)} \quad (2)$$

$$F_{Namhan}(F_d(d), F_s(s)) = [(F_d(d))^{-0.9925} + (F_s(s))^{-0.9925} - 1]^{-\frac{1}{0.9925}} \quad (3)$$

where $F_d(d)$, $F_s(s)$ are the marginal distributions of drought duration and severity, respectively. Statistical analysis was performed using the copula method and the cumulative joint probability distribution of each relevant case was estimated, as shown in Fig. 9.

As in Kwak *et al.* (2013), for future droughts in CASE 1, the drought duration appears to decrease but the drought severity appears to increase for the drought events with the same non-exceedance probability, and for the droughts in CASE 2, the drought duration will consistently decrease in the future, because the non-exceedance probability of the duration is consistently decreasing. Finally, CASE 3 is similar to CASE 2.

3.3 Conditional Return Period of Drought

From the joint probability distribution of future droughts, drought return periods are determined for each CASE as ($F_D(d)$

and $F_S(s)$ are the cumulative distribution functions of drought duration and severity, C is the copula function and $E(L)$ is the average inter-arrival time (Kwak *et al.*, 2013).

$$Return\ Period_{D>d \text{ and } S>s} = \frac{E(L)}{P(D>d \text{ and } S>s)} = \frac{E(L)}{1-F_D(d)-F_S(s)+C(F_D(d),F_S(s))} \quad (4)$$

$$Return\ Period_{D>d \text{ or } S>s} = \frac{E(L)}{P(D>d \text{ or } S>s)} = \frac{E(L)}{1-C(F_D(d),F_S(s))} \quad (5)$$

In determining the conditional return period, it is common practice to analyze the joint probability by classifying into the exceedance probability of both the drought duration and severity (‘$D>d$ and $S>s$’) and the exceedance probability of either the drought duration or the severity (‘$D>d$ or $S>s$’). However, considering that the overall drought severity increases as the drought duration increases and the uncertainty of future drought simulation, analyzing droughts with the probability of ‘$D>d$ and $S>s$’ will be more appropriate. Therefore, the probability of ‘$D>d$ and $S>s$’ was used in this study.

Results of return periods estimated, using Eq. (4), in the KMA RCM climate model are shown in Fig. 10. From the figure, when a drought with the same return period occurs, droughts with shorter duration and comparatively far greater severity than the present ones are likely to occur in CASE 1, indicating that droughts with shorter duration and high severity will occur in the near future. In CASE 2, droughts keep the same trend but drought duration and severity decrease. Lastly in CASE 3, drought severity slightly decreases, while drought duration slightly increases, but the drought types with comparatively shorter duration than the present ones are likely to occur.

3.4 Discussion of Results Based on Severity-Duration-Frequency Curve

The joint probability distribution can be expressed as a conditional probability. This can be converted into a drought return

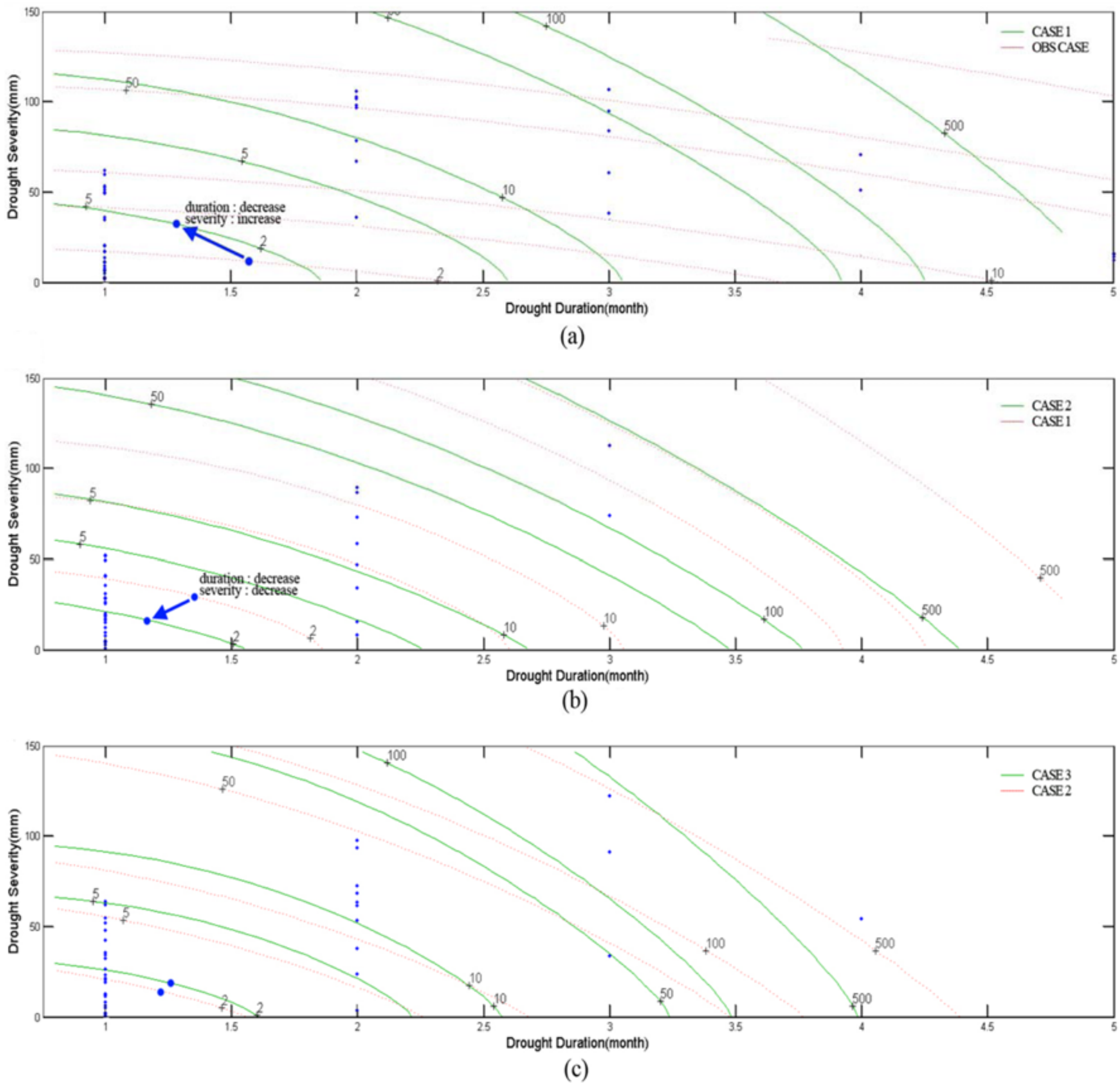

Fig. 10. Return Period of Each CASE in Upper Namhan River Basin (KMA RCM, $D>d$ and $S>s$): (a) CASE 1; (b) CASE 2; (c) CASE 3

period curve. Accordingly, the conditional probability or the return period appearing according to the other probability variable can be defined, based on the specific drought duration or severity. This can be formulated as follows:

$$
\begin{aligned}
Return\ Period_{S\ and\ D>d} &= \frac{E(L)}{P(S \text{ and } D>d)} \\
&= \frac{E(L)}{1-F_d(d)} \frac{1}{1-F_D(d)-F_S(s)+C(F_D(d),F_S(s))} \\
&= \frac{E(L)}{[1-F_d(d)][1-F_D(d)-F_S(s)+C(F_D(d),F_S(s))]} \qquad (6)
\end{aligned}
$$

Using Eq. (6), a drought duration-severity-frequency curve can be produced for the exceedance probability of both drought duration and severity. The drought duration and severity for each return period are shown as drought SDF curves.

The frequency-based drought severity from the present to future can be quantitatively estimated using the conditional return period curve and SDF curve for each CASE droughts. For instance, when the frequency based drought severities with the same 50 year return period and 2-month duration are estimated, the present streamflow shortage (frequency based drought severity) is 39.94 mm/month, and it will change to 57.99 mm/month in CASE 1 (in the next 30 years, streamflow shortage will increase to 18.05 mm/month), 42.95 mm/month in CASE 2 (in the next 30 to 60 year, streamflow shortage will increase to 2.99 mm/month), and 40.12 mm/month in CASE 3 with SDF curve in Fig. 11.

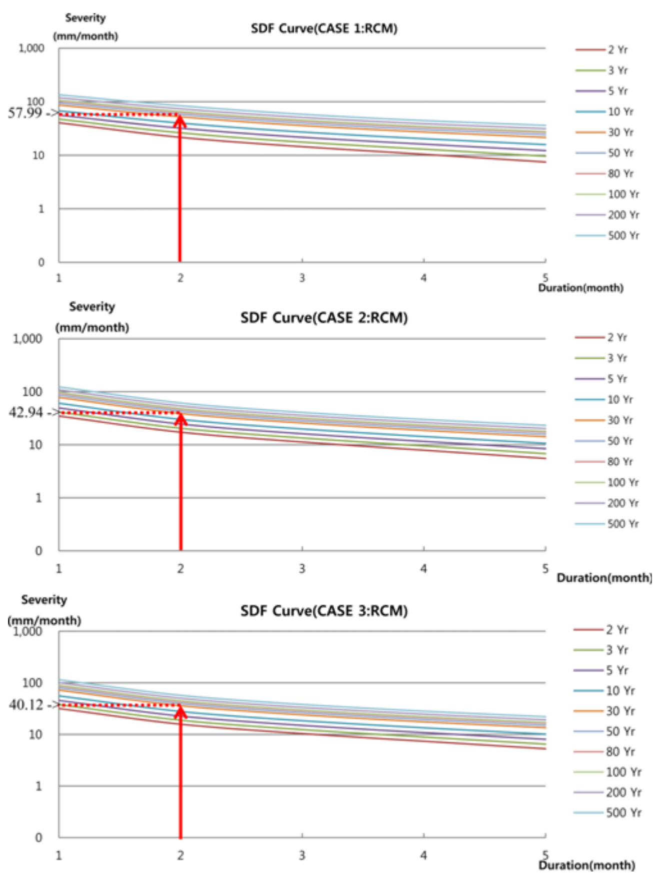

Fig. 11. Duration-Severity-Frequency Curve of Upper Namhan River Basin in Each CASE (KMA RCM)

As a result of this study, future droughts of upper Namhan River basin show a different trend than present. Hydrological droughts in the near future (present – 2039 years) will have more severity and less duration than before as Fig. 10(a) and Fig. 11(a). In the 2040 to 2069 years, hydrological droughts would become shorter and less severe than in the near future, but they will still show 2 mm/month higher than present droughts as the SDF curves in Fig. 11(b). The hydrological drought duration and severity would be reduced until 2100 years and the drought severity would be 0.18 mm/month higher than in the present droughts. Therefore, hydrological droughts in the upper Namhan River basin would significantly increase in the near future, and they would decrease until 2100 years. This indicates that far more severe droughts than the presently observed droughts would occur in the near future; this would translate into a 44 million tons per month shortage with a 50 year return period and a 2 month duration (18.05 mm/month), making it necessary to prepare for the looming situation.

4. Conclusions

This study performed an analysis of the impact of climate change on hydrological droughts in the upper Namhan River basin. The present OBS CASE and future meteorological data were simulated using the climate change scenario based on the KMA RCM and CNCM3 GCM climate models, and the NN-GA and SKLM downscaling method, and the evaluation of OBS Case meteorological data was assessed by comparison with previously observed meteorological data. As a result of the assessment of meteorological data according to climate models, KMA RCM appears to properly simulate past observations. Accordingly in this study, future streamflow was simulated using the simulated climate data in the KMA RCM climate model and a streamflow model (TANK Model) was calibrated and verified. Future drought analysis was performed by simulating future drought events. Results of the future drought frequency analysis by applying the joint probability distribution to the estimated future streamflow series show that compared to the present drought severity is expected to increase but drought duration is expected to decrease from 2011~2039. Both drought severity and duration are expected to decrease during the period of 2040~2069 and from 2070~2100, drought duration is expected to slightly increase but the severity is expected to decrease. Drought duration is expected to decrease and drought severity is expected to greatly increase particularly during the period of 2011~2039, indicating the possibility of multiple short-duration, high-severity droughts in the near future. Further, the drought frequency curve suggested in this study will be used to indicate the quantitative shortage of water resources in the future Water Resources Management (WRM) plans.

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