Journal of the Korean Society of Civil Engineers
Vol. 39, No. 1: 155-163/ February, 2019
DOI: https://doi.org/10.12652/Ksce.2019.39.1.0155

ISSN 1015-6348 (Print)
ISSN 2287-934X (Online)
www.kscejournal.or.kr

Water Engineering **수공학**

Probabilistic Analysis of Drought Propagation Over The Han River Basin Under Climate Change

Muhammad Nouman Sattar*, Kim, Ji-Eun**, Lee, Joo-Heon***, Kim, Tae-Woong****
무하마드 누만 사타르* · 김지은** · 이주헌*** · 김태웅****

기후변화에 따른 한강 유역의 확률론적 가뭄 전이 분석

ABSTRACT

The knowledge about drought propagation is very important in accurate estimation of hydrological drought characteristics and efficient development of early warning system. This study investigated a probabilistic relationship of drought propagation based on Bayesian network model for historic period and for future projection under climate change scenario RCP 8.5 over the Han River basin. The results revealed that the propagation rate and lag time have increasing and decreasing trends from the historic period of 1967-2013 to the future periods of 2014-2053 and 2054-2100 under climate change, respectively. The probabilistic results of Bayesian model revealed that the probability of occurrence of lag time varied spatially and decreased when the intensity of meteorological drought changed from moderate to severe and extreme condition during 1967-2013. The values of probability increased in the first future period of 2014-2053 in several sub-basins and slight decreased in the second period of 2054-2100. The proposed probabilistic results will be useful for the decision makers to develop related policies with an appropriate insight toward the future drought status.

Key words : Climate change, Propagation, Bayesian network, Drought

초 록

가뭄 전이는 수문학적 가뭄 특성에 대한 정확한 평가 및 조기 경보 시스템 구축에서 매우 중요한 역할을 한다. 이에 따라, 본 연구에서는 베이지안 네트워크를 이용하여 한강 유역의 가뭄 전이의 확률론적 관계를 분석하였다. 이를 위하여 과거 관측자료와 기후변화 시나리오 RCP 8.5 자료를 활용하였다. 가뭄 전이 및 지체시간을 분석한 결과, 1967~2013년 기간에 비해 2014~2053년 기간에는 증가하는 경향을 나타냈으며, 2054~2100년 기간에는 감소하는 경향을 나타냈다. 또한 베이지안 네트워크를 적용하여 지체시간의 발생확률을 분석하였다. 그 결과, 1967~2013년 동안에 기상학적 가뭄이 보통가뭄에서 심한가뭄 또는 극한가뭄으로 변화함에 따라, 지체시간의 발생빈도가 공간적으로 변화하거나 감소하였다. 이러한 확률은 2014~2053년에 몇몇 유역에서 약간 증가하는 경향이 나타났으나, 2054~2100년에 다시 감소하였다. 본 연구에서 제안된 확률론적 가뭄 전이 결과는 향후 미래 가뭄 상태에 대한 정책에서 의사결정시에 유용할 것으로 판단된다.

검색어 : 기후변화, 전이, 베이지안 네트워크, 가뭄

* 한양대학교 대학원 건설환경공학과 박사수료 (Hanyang University · engr_nouman847@yahoo.com)
** 한양대학교 대학원 건설환경시스템공학과 석박사통합과정 (Hanyang University · helloje2@hanyang.ac.kr)
*** 종신회원 · 중부대학교 공과대학 건축토목공학부 교수 (Joongbu University · leejh@joongbu.ac.kr)
**** 종신회원 · 교신저자 · 한양대학교 공학대학 건설환경공학과 교수, 공학박사 (**Corresponding Author** · Hanyang University · twkim72@hanyang.ac.kr)

Received November 14, 2018/ **revised** December 22, 2018/ **accepted** January 15, 2019

1. Introduction

The drought is a natural phenomenon resulted from complex linkages of hydrological conditions, environmental conditions and bio-geophysical mechanism. Meteorological drought may start quickly as it mainly depends on the deficiency of precipitation while hydrological drought lags behind it. The hydrological drought lag indicates a relationship between two drought types, which can be understood by the term propagation of drought (Peters et al., 2006; Vidal et al., 2010). However, it is difficult to understand the drought propagation since it depends on the catchment and climatic properties as well (Mishra et al., 2010). Presently, a great threat is the global warming which resulted in climate change that ultimately causes variations in drought characteristics. Therefore, accurate representation of drought over historic and future time period under climate change is necessary for making any adaptation and mitigation plan.

There exists a degree of variation in the climate on all time scales, and drought is among one of the extreme events depending on variation of precipitation. Tallaksen and Van Lanen(2004) presented a detailed study on the development of droughts in different climates around the world. South Korea has been already classified by the United Nations as a country suffering from more frequent and extreme droughts and floods since the late 1990s (Choi et al., 2008), and the drought risk is likely to increase over the course of the twenty-first century due to climate change (Boo et al., 2004; Yoo et al., 2012).

In literature on drought, limited works have been focused on estimating the propagation rate and lag time between drought types. For instance, Liu et al.(2012) estimated a lag time of two-month between Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) at a small drought-prone basin in Oklahoma of the USA. Zhao et al.(2014) found that nine out of eleven meteorological drought events were propagated to streamflow drought and lag time was observed as 127 days in comparison between SPI and SRI in Jinghe River basin, China. Similarly, Wu et al.(2016) and Huang et al.(2017) found seasonal variations in lag time from SPI to the Standardized Streamflow Index (SSI). Sattar and Kim(2018) found the drought propagation varied with intensity of meteorological drought and with the type of drought index in the Han River basin of South Korea.

These drought propagation studies are based only on the historical analysis but no one perceives the future influence of climate change on drought propagation. Therefore, the main objective of this study is to find distribution patterns of propagation rate and lag time with space and under future climate change scenario, and to find spatial and temporal probabilistic relationship of lag time with intensity of meteorological drought.

2. Materials and Methods

2.1 Climate Change Scenario and Target Area

For more realistic prediction of future climate change, the Intergovernmental Panel for Climate Change (IPCC) published its fifth assessment report in which they introduced the climate change scenarios on the basis of greenhouse gas emission and human impact to the atmosphere, known as Representative Concentration Pathway (RCP) (Moss et al., 2010). These scenarios provide more rational information based on all possible combinations of greenhouse gas emission and human influence in the form of RCP 2.6, 4.5, 6.0, and 8.5 (Meinshausen et al., 2011). The RCP 2.6 scenario assumes that the greenhouse gas emissions reach a peak between 2010 and 2020 and then decline gradually. The RCP 4.5 represents the case where the emissions reach a peak around 2040 and then decline. In the RCP 6.0, the emissions reach the peak around 2080 and then decline. However, in the RCP 8.5 scenario, greenhouse gas emissions continue to rise throughout the 21st century with the continuity of the present level of greenhouses gas emission (Riahi et al., 2011). Therefore, we employed the RCP 8.5 scenario in our targeted area to investigate the worst future changes in drought propagation.

The Han River basin is the largest river basin of South Korea, and a big source of water for drinking, industry, irrigation, and hydropower generation. The mean annual precipitation in this basin is about 1,300 mm with seasonal variations (Chang and Kwon, 2007). The Han River basin has 24 subbasins, as shown in Fig. 1, and the detail of the subbasins can be found in Yoon et al.(2013).

Historical precipitation data of period 1967-2013 were collected from Korea Meteorological Administration (KMA) and runoff data for each subbasin were calculated using the widely adopted TANK model. For future period RCP 8.5 scenario data from 2014-2100 were downscaled using the HadGEM2-AO model

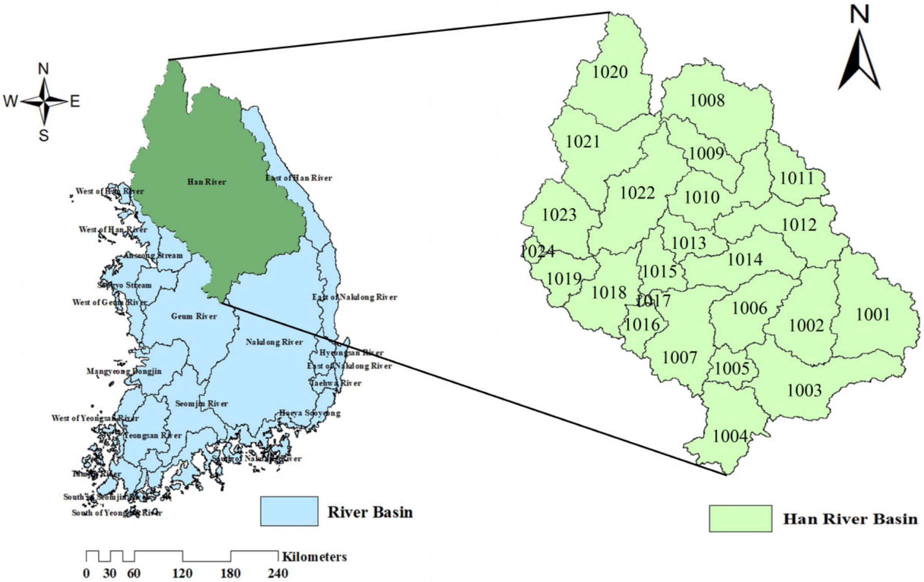


Fig. 1. Location of Han River Basin and its Sub-Basins

with a 1-degree resolution. For more detail visualization this future period was further subdivided into two periods of 2014-2053 and 2054-2100.

2.2 Drought Indices

The meteorological and hydrological drought were estimated using Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI), respectively, on weekly time scale. To calculate the SPI and SRI, firstly, the daily data (precipitation for SPI and runoff for SRI) were aggregated into weekly time scales, and then set of marginal distributions were tested to find the best-fit distribution. After selecting the best-fit distribution, it was transformed into the standard normal distribution having mean zero and standard deviation one. In this study, after investigating various distributions as candidates for the marginal distribution, the two-parameter gamma distribution and lognormal distribution were selected as the best fitted distribution for the SPI and SRI, respectively, based on the Akaike information criterion (AIC), as shown in Table 1.

After identifying drought events from the time series of SPI and SRI based on the run theory, as shown in Fig. 2, the main characteristics of drought event were calculated with the

Table 1. AIC Test Values to Select the Best Distribution for Drought Indices

Distribution		AIC values	
Name	Probability Density Function	SPI	SRI
Gamma	$f(x)=\dfrac{1}{\alpha\Gamma(\beta)}\left(\dfrac{x}{\alpha}\right)^{\beta-1}\exp\left(-\dfrac{x}{\alpha}\right)$	20440	23510
GEV	$f(x)=\dfrac{1}{\alpha}\left[1-\beta\left(\dfrac{x-x_0}{\alpha}\right)\right]^{\frac{1}{\beta}-1}\exp\left\{-\left[1-\beta\left(\dfrac{x-x_0}{\alpha}\right)\right]^{\frac{1}{\beta}}\right\}$	21580	22640
Log-normal	$f(x)=\dfrac{1}{\sigma_y\sqrt{2\phi}}\dfrac{1}{x}\exp\left[-\dfrac{1}{2}\left(\dfrac{\ln x-\mu_y}{\sigma_x}\right)^2\right], y=\ln x$	23500	22210
Weibull	$f(x)=\dfrac{\beta}{\alpha}\left(\dfrac{x}{\alpha}\right)^{\beta-1}\exp\left[-\left(\dfrac{x}{\alpha}\right)^{\beta}\right]$	25220	23340
Exponential	$f(x)=\lambda\exp(-\lambda x)$	21350	23800

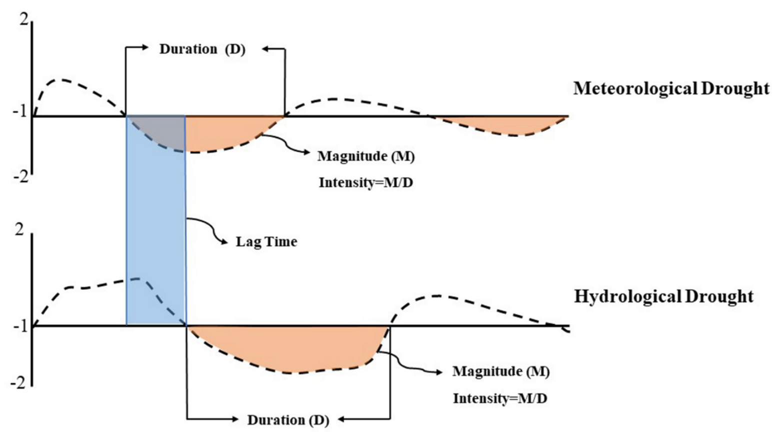


Fig. 2. Definition of Drought Characteristics and the Lag Time of Drought Propagation

Table 2. Classification of Drought Intensity According to Standardized Indices

SPI/SRI	Classification
Greater than 0	No drought
-1 to 0	Near Normal
-1.5 to -1	Moderate drought
-2 to -1.5	Severe drought
Less than -2	Extreme drought

threshold value of -1. Table 2 provides the major classification of different drought events based on SPI and SRI.

2.3 Drought Propagation Rate and Lag Time

To estimate the propagation rate and its spatial distribution, we employed the response rate which creates a connection between meteorological and hydrological droughts (Zhao et al., 2016). If the percentage of propagation is high, hydrological drought is more sensitive to meteorological drought, whereas a lower percentage indicates that the relationship is weak. The mathematical expression of the response rate is given as:

$$R_r = \frac{m}{n} \times 100 \quad (1)$$

where R_r is the response rate in percentage, n is the number of meteorological droughts during the record period, and m is the number hydrological droughts responded to meteorological droughts.

As an indicator of drought propagation, in this study, we used a lag time which was defined as the time taken by meteorological drought to propagate through the terrestrial part of the hydrological cycle into hydrological drought, as shown in Fig. 2. The lag time was estimated by finding the time difference between start of meteorological and hydrological drought, mathematically it can be expressed as:

$$LT = T_M - T_H \quad (2)$$

where LT is the lag time in weeks, T_M is the time when meteorological droughts started and T_H is the time of starting of hydrological drought. Based on the response rate, we separated the propagated drought events and their characteristics identified through the SPI and SRI were used for further analysis.

2.4 Probabilistic Analysis of Drought Propagation Using a Bayesian Network

A Bayesian network (BN) is among a family of probabilistic graphical models, incorporating the concept of conditional dependencies to estimate the relationship between random variables (X), e.g., in this study, drought intensity or lag time. The BN model has two parts: (1) the qualitative part, that is called the network structure, and (2) the quantitative part that incorporates the probability concept associated with each random variable. The joint probability of the set of random variables $X = (X_{t1}, \cdots, X_{tm})$, can be written as the product of individual marginal distribution of variable conditional on their parent variables.

$$P(X_{t1}, \cdots, X_{tn}) = P(X_{tn} | X_{t1}, \cdots, X_{tn-1}) P(X_{t1}, \cdots, X_{tn-1}) \quad (3)$$

By rearranging Eq. (3) we obtained:

$$P(X_{tn}|X_{t1},\cdots,X_{tn-1})=\frac{P(X_{t1},\cdots,X_{tn})}{P(X_{t1},\cdots,X_{tn-1})} \tag{4}$$

To find out the joint probability function on the right hand side of Eq. (4), we employed copula functions, more details can be found at Madadgar and Moradkhani (2014). If u_i is the univariate marginal distribution and C is the cumulative copula function, then Eq. (4) can be written as:

$$P(X_{tn}|X_{t1},\cdots,X_{tn-1})=\frac{C(u_{t1},\cdots,u_{tn})}{C(u_{t1},\cdots,u_{tn-1})} \tag{5}$$

If there are two random variables, i.e., n = 2, this case could be named as Bayesian network of first order (BNFO) and Eq. (5) leads to form the following expression:

$$P(X_{t2}|X_{t1})=\frac{C(u_{t1},u_{t2})}{u_{t1}} \tag{6}$$

Eq. (6) was used to find the relationship between lag time and intensity of meteorological drought. The procedural steps are given in Fig. 3. Since we had event-based data of lag time and intensity of meteorological drought, we applied a Poisson distribution on lag time and intensity to find the marginal probability of each random variable. Thus, the probability of lag time conditioned on the intensity of meteorological drought was given as:

$$P(LT|I_M\in M_i)=\frac{P(I_M\in M_i,LT)}{P(I_M\in M_i)}=\frac{C(I_M\in M_i,LT)}{P(I_M\in M_i)} \tag{7}$$

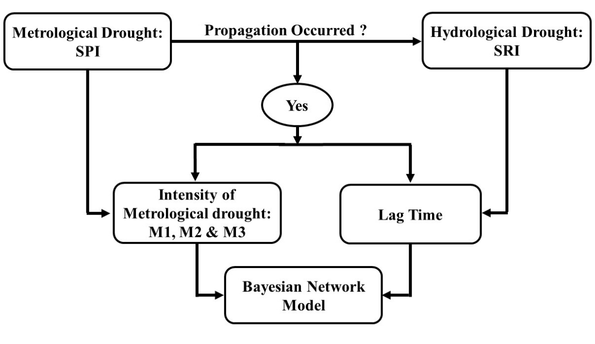


Fig. 3. Procedure of the Bayesian Network Model for Probabilistic Analysis

where $P(LT)$ is the probability the lag time and $P(I_M\in M_i)$ is the probability of meteorological drought intensity to which class it belongs. M_i is the class which meteorological drought have, i.e., M_1 = Moderate, M_2 = Severe, and M_3 = Extreme, respectively. $P(I_M\in M_i,LT)$ is the joint probability between the lag time and the intensity of drought, which can be estimated using a copula function as $C(I_M\in M_i,LT)$. We used four types of copula functions: Gaussian, t, Clayton, and Gumbel to find out the joint probability function, and based on the p-value of Kolmogorov-Smirnov test the best copula function was selected.

3. Results and Discussion

3.1 Identification of Drought Events and Their Relationship

The evaluation of meteorological and hydrological drought events was done using the SPI and SRI at different time scales. Most data used in previous studies was on monthly basis, however, in this study, we calculated the SPI on different weekly time scale of 1-, 4-, 8-, 12-, 16-, 20-, and 24-week. A four-week time scale of SRI was selected to compare the characteristics of hydrological drought events with meteorological drought events calculated by the SPI at different time scales. Suitable time scale of SPI was very necessary to identify the accurate relationship between the SPI and SRI. In order to select the most relevant time scale, this study performed a cross correlation analysis between the different time scales of SPI with the 4-week SRI. As a result, the 8-week time scale of SPI was selected as appropriate to compare characteristics with SRI in this study. The average number of drought events recorded across all sub-basins for historical period of 1967-2013 was 36 in case of meteorological droughts and 28 in case of hydrological droughts. For the first future period of climate change scenario, from 2014 to 2053, the average number of meteorological droughts recorded were 27 and hydrological droughts were 21 in number. For the second future period of climate change scenario, from 2053 to 2100, the number of droughts were 29 for meteorological one and 19 in case of hydrological droughts. The number of drought events become decreases moving from historical period to first future period, while in case of first to second future period there was slight increase in the meteorological drought while hydrological drought showed a decreasing trend.

3.2 Spatial Distribution of Drought Propagation Rate and Lag Time

We considered here the lag time to explain the relationship between the SPI and SRI according to Eq. (7). The propagation phenomena are complex, because it depends on various factors related to land, rainfall intensity, season, groundwater level etc. In this study, we incorporated the response rate to explain the relationship of hydrological drought to respond meteorological drought in terms of propagation. The percentage of response rate varied from to 6 % to 60 % in the historical period of time 1967-2013, in case of future climate change the percentage varies from 33 % to 88 % for the first future period (2014-2053), and for second future period (2054-2100) it varies from 0 % to 80 %. The results show that the propagation rate increased from historical period to first future period and slight decreased in second future period. However, the trend shifted spatially from south to north region. Table 3 clarifies the average characteristics of drought propagation over whole river basin under climate change.

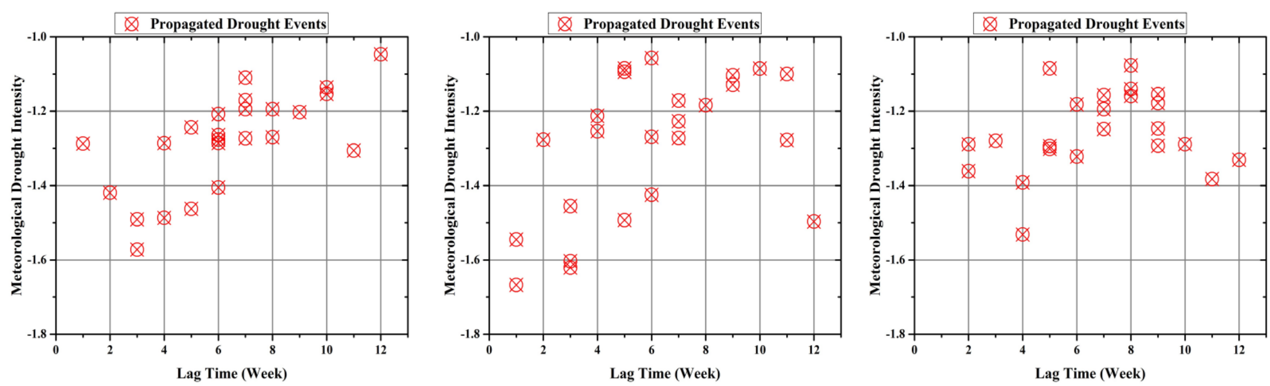
Similarly, lag time show patchy pattern with increasing values from historical period to future climate change. For the historical period of 1967-2013 the lag time varied from 1 to 15 weeks, for the first future period the lag time increased and varied from 3 to 16 weeks, and for the second future period there was slight decrease in lag time and varied from 0 to 15 weeks. Table 3 also shows the average variation of lag time over whole river basin under climate change. These results of response rate and lag time for propagation clarified that the hydrological drought was highly dependent on the meteorological conditions. The reason for spatial distribution in propagation rate and weekly lag time was due to the variation in annual average precipitation and seasonal distribution of runoff in the basin. The annual average precipitation of some sub-basins located in the western and central regions of the Han River basin was high as compared to sub-basin located on eastern side (Yoon et al., 2013).

3.3 Probabilistic Relationship of Lag Time with Meteorological Drought

As we used the lag time as an indicator of propagation, our next task is to make relationship of lag time with intensity of meteorological drought. The illustration of lag time variations with different intensities of meteorological drought is shown in Figs. 4(a), (b), and (c) for historical, future first and second period time of climate

Table 3. Summary of Drought Propagation Over Han River Basin

Period	Avg. number of meteorological droughts (n)	Avg. number hydrological droughts responded (m)	Avg. RT (%)	Avg. LT (Week)
Historical period 1967-2013	36	13	37	6.42
First future period 2014-2053	27	17	65	8.46
Second future period 2054-2100	29	14	48	8.25



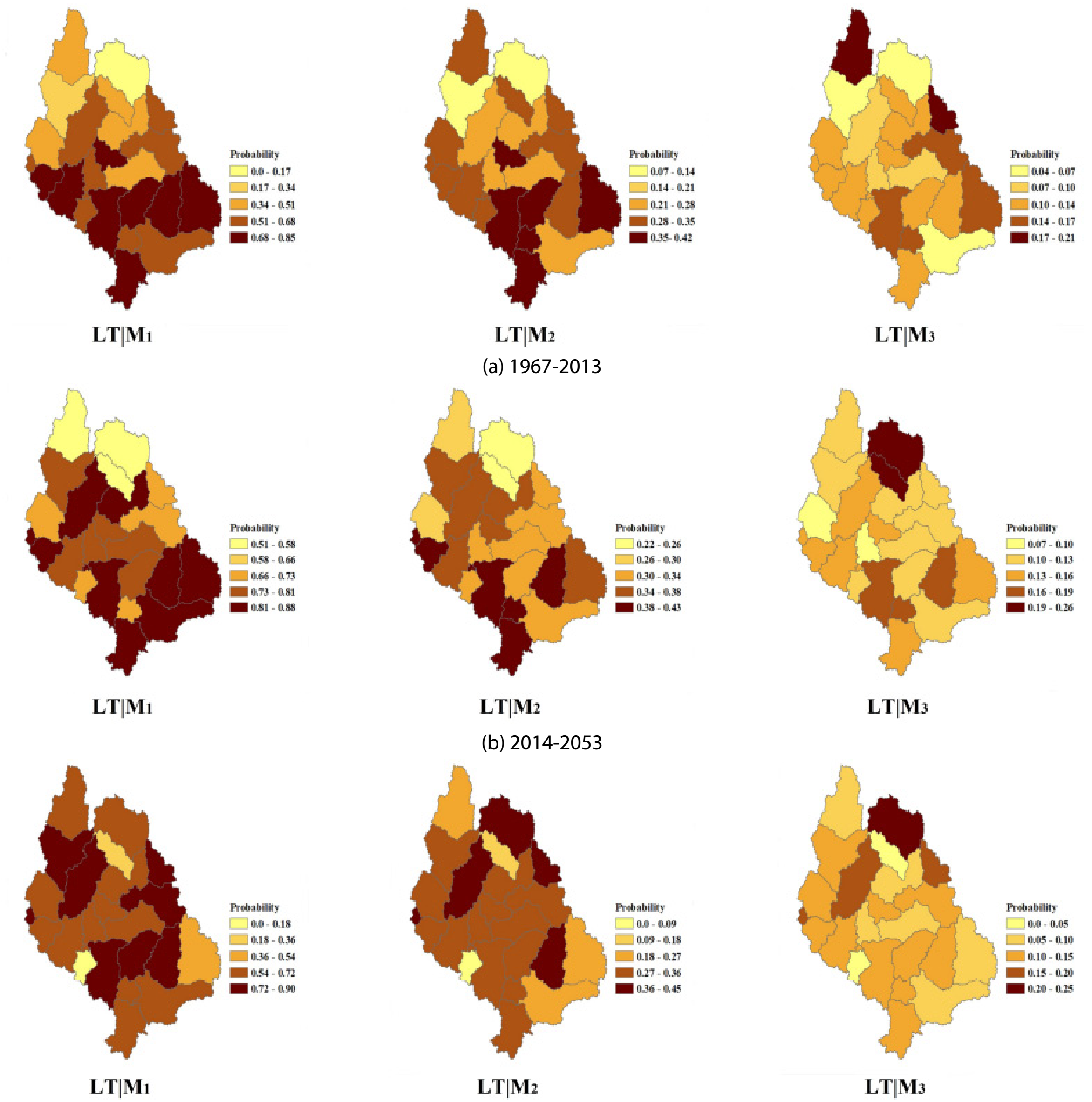
(a) 1967-2013 (b) 2014-2053 (c) 2054-2100

Fig. 4. Relation between Lag Time and Meteorological Drought

change, respectively. It is cleared that the propagation occurred mostly when the meteorological drought was of moderate intensity, as the intensity of meteorological drought became severe to extreme, the propagation occurrence decreased and lag time also showed lower value. If the proper relationship between these results is established, then this relationship will be very helpful

Table 4. Statistics of K-S GOF Test to Find Best Copula for Joint Distribution

Copula	P-Value for Eq. (7)
Gaussian	0.74
T	0.66
Gumbel	0.47
Clayton	0.84



(c) 2054-2100

Fig. 5. Probability of Lag Time Occurrence Given Intensity of Propagated Meteorological Drought

in forecasting of propagation of drought events and estimating the lag time to hydrological drought. Thus, we proposed a probabilistic relationship of lag time with intensity of meteorological drought based on Bayesian network model explained in Eq. (7), as the lag time developed when the propagation occurred.

According to the p-value of Kolmogorov-Smirnov test, Clayton copula was chosen as most suitable to find joint distribution among others, as shown in Table 4. Figs. 5 (a), (b), and (c) show the probability of occurrence of lag time with intensity of meteorological drought, for historical and future periods of climate change, respectively. The probabilistic results of Bayesian model revealed that the probability of lag time occurrence varied under different intensities of meteorological drought, and varied spatio-temporally as well. The probability of occurrence of lag time decreased when the intensity of meteorological drought changes from moderate to severe and extreme condition during 1967-2013. The similar results were found for both future periods but with difference in spatial distribution, the values of probability increased in the first future period of 2014-2053 in some sub-basins and slight decreased in the second period of 2054-2100. The similar pattern can be observed in Fig. 4 as the lag time mostly observed when the intensity was lower. The most of the areas having high percentage propagation had more probability values.

4. Summary & Conclusion

In this study, we analyzed the propagation of drought over historical period of 1967-2013 and for future period of 2014-2100 under climate change scenario RCP 8.5, over the Han River basin. Meteorological and hydrological drought events were estimated using the SPI and SRI, respectively. The response rate was used to estimate the propagation rate and the lag time was used as an indicator of propagation, which further analyzed for making a probabilistic relationship with the intensity of meteorological drought using a Bayesian Network model.

The results revealed that the propagation rate and lag time show increasing and decreasing trends from the historical period to the first and second future period, respectively. The probabilistic results of Bayesian model revealed that the probability of lag time occurrence varied under different intensities of meteorological drought, and varied spatio-temporally as well. The probability of occurrence of lag time decreased when the intensity of meteorological drought changed from moderate to severe and extreme condition during 1967-2013. The similar results were found for both future periods but with difference in spatial distribution. These probabilistic results will help the water managers in making planning and forecasting of hydrological drought characteristics under changing conditions of climate. In the future, studies using various climate change scenarios should be conducted to derive more detailed forecasts of hydrological drought characteristics.

Acknowledgements

This study was supported by Korea Ministry of Environment (MOE) as “Water Management Research Program (18AWMP-B079625-05).” The authors would like to acknowledge the Higher Education Commission (HEC) of Pakistan for granting a scholarship to Muhammad Nouman Sattar to pursue his Ph.D. degree. 본 논문은 2018 CONVENTION 논문을 수정·보완하여 작성되었습니다.

References

Boo, K. O., Kwon, W. T., Oh, J. H. and Baek, H. J. (2004). “Response of global warming on regional climate change over Korea: An experiment with the MM5 model.” *Geophysical Research Letters*, Vol. 31, p. L21206.

Chang, H. and Kwon, W. T. (2007). “Spatial variations of summer precipitation trends in South Korea, 1973-2005.” *Environmental Research Letters*, Vol. 2, p. 045012.

Choi, G., Kwon, W. T., Boo, K. O. and Cha, Y. M. (2008). “Recent spatial and temporal changes in means and extreme events of temperature and precipitation across the Republic of Korea.” *Journal of the Korea Geographical Society*, Vol. 43, pp. 681-700.

Huang, S., Li, P., Huang, Q., Leng, G., Hou, B. and Ma, L. (2017). “The propagation from meteorological to hydrological drought and its potential influence factors.” *Journal of Hydrology*, Vol. 547, pp. 184-195.

Liu, L., Hong, Y., Bednarczyk, C. N., Yong, B., Shafer, M. A., Riley, R. and Hocker, J. E. (2012). “Hydro-climatological drought analyses and projections using meteorological and hydrological drought indices: a case study in Blue River Basin, Oklahoma.” *Water Resources Management*, Vol. 26, pp. 2761-2779.

Madadgar, S. and Moradkhani, H. (2014). “Spatio-temporal drought forecasting within Bayesian networks.” *Journal of Hydrology*, Vol. 512, pp. 134-146.

Meinshausen, M., Smith, S. J., Calvin, K. V., Daniel, J. S., Kainuma, M., Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A. M., Velders, G. J. M. and Van Vuuren, D. (2011). “The RCP greenhouse gas concentrations and their extensions from 1765 to 2300.” *Climatic Change*, Vol. 109, pp.

213-241.

Mishra, V., Cherkauer, K. A. and Shukla, S. (2010). "Assessment of drought due to historic climate variability and projected future climate change in the midwestern United States." *Journal of Hydrometeorology*, Vol. 11, pp. 46-68.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Cater, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. and Wilbanks, T. J. (2010). "The next generation of scenarios for climate change research and assessment." *Nature*, Vol. 463, pp. 747-756.

Peters, E., Bier, G., Van Lanen, H. and Torfs, P. (2006). "Propagation and spatial distribution of drought in a groundwater catchment." *Journal of Hydrology*, Vol. 321, pp. 257-275.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N. and Rafaj, P. (2011). "RCP 8.5 - A scenario of comparatively high greenhouse gas emissions." *Climatic Change*, Vol. 109, pp. 33-57.

Sattar, M. N. and Kim, T. W. (2018). "Probabilistic characteristics of lag time between meteorological and hydrological droughts using a Bayesian model." *Terrestrial Atmospheric and Oceanic Sciences*, Vol. 29, pp. 1-12.

Tallaksen, L. M. and Van Lanen, H. A. (2004). *Hydrological drought: processes and estimation methods for streamflow and groundwater*, Elsevier, Amsterdam.

Vidal, J., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J. M., Blanchard, M. and Baillon, M. (2010). "Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite." *Hydrology and Earth System Sciences Discussions*, Vol. 14, pp. 459-478.

Wu, J., Chen, X., Gao, L., Yao, H., Chen, Y. and Liu, M. (2016). "Response of hydrological drought to meteorological drought under the influence of large reservoir." *Advances in Meteorology*, Vol. 2016, pp. 1-11.

Yoo, J., Kwon, H. H., Kim, T. W. and Ahn, J. H. (2012). "Drought frequency analysis using cluster analysis and bivariate probability distribution." *Journal of Hydrology*, Vol. 420, pp. 102-111.

Yoon, S. K., Kim, J. S., Lee, J. H. and Moon, Y. I. (2013). "Hydrometeorological variability in the Korean Han River Basin and its sub-watersheds during different El Niño phases." *Stochastic Environmental Research and Risk Assessment*, Vol. 27, pp. 1465-1477.

Zhao, L., Lyu, L., Wu, J., Hayes, M., Tang, Z., He, B., Liu, J. and Liu, M. (2014). "Impact of meteorological drought on streamflow drought in Jinghe River Basin of China." *Chinese Geographical Science*, Vol. 24, No. 6, pp. 694-705.

Zhao, L., Wu, J. and Fang, J. (2016). "Robust response of streamflow drought to different timescales of meteorological drought in Xiangjiang River Basin of China." *Advances in Meteorology*, Vol. 2016.