Investigating the influence of natural events and anthropogenic activities on hydrological drought in South Korea

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ABSTRACT

Natural events and anthropogenic activities are the two major driving forces that alter hydrological cycle processes, leading to hydrological extreme events such as floods and droughts. Streamflows are directly influenced by these forces, however, their cumulative effects over time are considered as indirect effects. This study investigated the distinct effects of precipitation, temperature, and human activities on hydrological droughts in five major river basins in South Korea. Change points in the hydrological data were identified after the 1990s in all basins by the sequential Mann-Kendall test. We used two water balance models, the ABCD and the GR2M, in this study, and their integration was used for streamflow simulations. We applied the standardized runoff index (SRI) to identify hydrological drought under different data-driven scenarios (climate change, constant temperature with varying precipitation, constant precipitation with varying temperature, and human influence). Natural and anthropogenic variations had a greater effect on drought severity than on drought duration. Variation in precipitation increased streamflow by 12.42%, followed by human activity at 0.71%; temperature decreased streamflow by -0.7% on average. Precipitation was a dominant factor that increased drought severity by 41.38%, followed by human activity at 15.85%; temperature decreased drought severity by -0.86% on average. This study improves understanding of the response of streamflow and hydrological drought to precipitation, temperature, and human activities, which is beneficial for decision makers and water managers in developing adaptive strategies to alleviate extreme natural disasters.

1. INTRODUCTION

Natural events and human activities are the two main driving forces that alter hydrological cycles. Their impacts result in extreme natural disasters such as flood and drought, which have had devastating influences on global economies, agriculture, and environments over the past few decades. Many studies have highlighted the significance of drought occurrence in environmental changes (Hao and Singh 2015).

Drought is classified into four types: meteorological drought caused by absence or reduction of precipitation for a prolonged period of time; agricultural drought caused by deficiency of soil moisture in the surface layer (root zone) during the growing season, which significantly reduces crop yields (Dai 2011); hydrological drought caused by lack of precipitation for a long period of time that results in shortages of surface and subsurface water supplies; and socio-economic drought, which is related to the supply and demand of economic goods associated with the other types of drought (Heim 2002). According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and the International Hydrological Program (IHP), exploring the effects of environmental changes on hydrological drought is a crucial present and future issue (Zalewski et al. 2016). Global warming is increasing abruptly and changing precipitation patterns, which results in direct and vivid effects on streamflow (Pumo et al. 2016). The changes in streamflow can influence characteristics of hydrological drought

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such as drought duration (i.e., number of months when a drought index value is less than the threshold), drought severity (i.e., cumulative magnitude of drought index values during the duration), and drought peak (i.e., highest drought index value during the duration).

Environmental changes including climate change and anthropogenic activities such as deforestation, urbanization, population growth, and atmospheric warming can lead to direct impact on streamflow (Lutz et al. 2014; Ukkola et al. 2016). In contrast, the cumulative effects of these changes that exceed certain thresholds leading to hydrological drought result in indirect impacts (Rahmstorf and Coumou 2011; Jena et al. 2014). Ahn and Merwade (2014) quantified the impact of environmental changes on streamflow in the United States using three different methods: regression analysis, climate elasticity coefficient, and hydrological modelling, and concluded that human impact on streamflow was greater than that of climate change in some places. Sheffield and Wood (2007) noted that, so far in the 21th century, there has been abrupt increase in severity and frequency of hydrological drought in most locations due to increase in temperature without any increase in precipitation. Human impacts, such as modification of land use/land cover, industrialization, irrigation, and urbanization, can alter hydrological processes and exert effects on the environment with significant implications for water resources, which finally affect hydrological drought (Sheffield et al. 2012).

McCabe and Wolock (2011) investigated the influence of precipitation and temperature on runoff variability in the U.S. and concluded that precipitation has the largest effect on runoff in most parts of the country, whereas temperature had weaker influence. Wanders and Wada (2015) discussed the possible influences of climate variation and human activity on global hydrological drought for the period 2070 - 2099; they concluded that climate change and human activity will have significant impacts in large parts of the Middle East, Asia, and the Mediterranean, and that human activities will affect drought severity by 100%. Zou et al. (2017) investigated the impacts of past climate variation and anthropogenic activities on the Wei River basin in China at different time scales and found that human activities had greater effects on hydrological drought at shorter time scales, however climate change was a more dominant factor at longer time scales. Zhou et al. (2018) estimated the influence of climate change and human activity on runoff using the SWAT model and climate elasticity method and concluded that the contribution of climate change was slightly greater than that of human activity. Zhang et al. (2018) investigated impacts of environmental change on hydrological drought using a 12-month time scale in China and found that hydrological drought severity was increased by lack of precipitation, followed by potential evapotranspiration and human activity, although drought peaks were increased by potential evapotranspiration. Several previous

studies have found that the effects of climate change and human activities significantly change with time (Ahn and Merwade 2014; Zou et al. 2017; Zhang et al. 2018; Zhou et al. 2018). Thus, there is a dire need to examine how climate change and human activities influence hydrological drought at different time scales.

According to review of the literature on this topic, and to the best of our knowledge, there is no study on South Korea, that describes the individual impacts of precipitation, temperature, and human activity on streamflow directly and on hydrological drought indirectly. Some previous studies, such as Wanders and Wada (2015), used high-quality datasets, including hydro-meteorological and socioeconomic variables, to investigate the influences of climate change and human activity globally during the entire 21st century. Unfortunately, these datasets are not easily available in South Korea for predictive analysis, so this study used observed hydro-meteorological data for current analysis. The main purpose of this study was to investigate the direct and indirect impacts of individual factors of precipitation, temperature, and human activity on streamflow and hydrological drought. We developed a simple and effective framework using hydro-meteorological data to determine the impacts of environmental changes in five major river basins in South Korea. The uncertainties were removed from our streamflow simulations by applying an integrated hydrological model (IHM).

2. MATERIALS AND METHODS

2.1 Study Area and Data

The climate of South Korea is humid and greatly influenced by the monsoon season. The summer season is hot and humid leading to severe rainfall, while the winter is dry and cold. The average annual temperature ranges from 10 to 14.5°C. The average annual precipitation ranges from 1000 to 1400 mm in the central region and 1000 - 1800 mm in the southern region. More than half of the annual precipitation falls in the summer season.

This study was conducted in five major river basins: the Han River, Nakdong River, Geum River, Seomjin River, and Yeongsan River, as shown in Fig. 1. The basin areas ranges from 3469 to 34428 km², with the Han River basin being the largest and the Yeongsan River basin the smallest basin. The geographical characteristics of basins include 62% forests, 2.1% grassland, 2.6% water bodies, 24% agricultural fields, and 1.61% bare land, and 5.5% urbanized area, on average. Meteorological data on precipitation, and maximum, minimum, and mean temperatures for the period 1973 - 2017 were collected from 56 weather stations controlled by the Korea Meteorological Administration (KMA). Monthly discharge data for five major river basins were collected from the Water Resources Management Information System (WAMIS, http://www.wamis.go.kr). Population

and gross domestic product (GDP) data for the study areas were collected from Statistics Korea (http://kosis.kr) for the period 1970 - 2017.

2.2 Mann-Kendall Test

The aim of this study was to determine the direct and indirect impacts of climate variation and human activities on hydrological cycle processes. Accordingly, the streamflow data was divided into two parts, the natural period and the impacted period, by estimating the change points in the data series. A change point represents the initiation of human impacts in an area. Streamflow data before a change point represent the natural period, and those after a change point represent the impacted period. The sequential Mann-Kendall test is commonly used to find step change points because it is robust to outliers and provides good solutions to missing values. The M-K test can be applied in several ways (Wu et al. 2017; Wang et al. 2018; Zhou et al. 2018). Here, the variable D_c was defined, as follows:

$$D_c = \sum_{i=1}^{c} r_i \qquad c = 2, ..., n \tag{1}$$

$$r_i = \begin{cases} 1 & h_j < h_i \\ 0 & h_j \geq h_i \end{cases} \qquad j = 1, ..., i \tag{2}$$

where h_i and h_j are hydrological variables, i and j represent the series of data, and D_c is the count for the h series when h_i exceeds h_j.

The expectation and variance of D_c are expressed by Eqs. (3) and (4).

$$E(D_c) = c(c-1)/4 \tag{3}$$

$$var(D_c) = c(c-1)(2c+5)/72 \tag{4}$$

The forward sequential curve $UF(D_c)$ was calculated as

$$UF_c = \frac{D_c - E(D_c)}{\sqrt{var(D_c)}} \qquad c = 2, ..., n \tag{5}$$

Similarly, the backward sequential curve (UB_c) was computed by reversing the series. The intersection point of these two curves is a probable change point. If these series intersect at more than one point, then the intersection point after which the separation interval between these curves is large becomes a probable change point. Finally, if the UF_c and UB_c curves intersect and the value of U at the joining point satisfies $|U| < 1.96$, then the point is regarded as a change point at the 95% confidence level.

2.3 Sen's Slope Estimator

Sen's slope estimator is a non-parametric procedure for calculating the slope of a trend in a sample of N data pairs (Sen 1968) as

$$D_i = \frac{z_m - z_n}{m - n} \quad \text{for} \quad i = 1, ..., N \tag{6}$$

$$b_{med} = median(D_i) \tag{7}$$

where z_m and z_n are the data values at times m and n ($m > n$), respectively. The N values of D_i are sorted from smallest to largest, and the median of slope b_{med} is calculated. The sign of b_{med} shows the direction (positive or negative) of the trend, and its value shows the steepness of the trend.

2.4 Hydrological Simulations

Water balance models are most commonly used for forecasting and simulating various hydrological processes using various mathematical equations. Even though there are many water balance models in the literature, with varying robustness and limitations, the multi-model ensemble is an efficient way to reduce uncertainties in runoff simulations (Bai et al. 2015). Therefore, we integrated two water balance models, the two-parameter GR2M model proposed by Mouelhi et al. (2006) and the four-parameter ABCD model proposed by Thomas (1981), for streamflow simulations. The GR2M model is a parsimonious model that effectively transforms rainfall to runoff at a monthly time step. The ABCD model converts monthly precipitation and potential evapotranspiration into streamflow by diverting waters between two moisture storage stratums: the lower groundwater and the upper soil moisture storage (Steinschneider et al. 2012). Both hydrological models require two inputs of precipitation and potential evapotranspiration (PET). PET was calculated using Hargreaves equation (Hargreaves and Samani 1985). First, both models were calibrated, and then the optimized parameters of the GR2M model were estimated using Michel's calibration algorithm available in the airGR R-package. Genetic algorithm was used to estimate the optimized parameters of the ABCD model. The simulations were performed by each calibrated model, and their outputs were integrated to make the final simulation more effective and reliable for further analysis.

The hydrological runoff model was evaluated based on Kling-Gupta efficiency (KGE) (Gupta et al. 2009) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970).

$$KGE = 1 - \sqrt{(1-\gamma)^2 + (1-\alpha)^2 + (1-\beta)^2} \tag{8}$$

where, γ is the correlation coefficient, α is the variability, and

β is the bias ratio between observed and simulated runoff.

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{N}(Q_{obs,i} - \overline{Q_{obs}})^2} \quad (9)$$

where, Q_{obs} is the observed runoff, $\overline{Q_{obs}}$ is the mean of observed runoff, and Q_{sim} is the simulated runoff. The values of KGE and NSE assess the overall goodness-of-fit between observations and simulations. When the simulations entirely represent the observations, the values of KGE and NSE equal to one.

2.5 Estimation of Drought

This study employed the standardized runoff index (SRI) proposed by Shukla and Wood (2008). The procedure of computing the SRI is similar to that of the standardized precipitation index (SPI), but it uses long-term streamflow data. In this study, a three-parameter log-normal distribution was fitted to streamflow data, and the cumulative probability was transformed to standard normal variate Z, as follows:

$$SRI = \begin{cases} -\left(t - \dfrac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), \\ \quad t = \sqrt{\ln\left[\dfrac{1}{\{F(x)\}^2}\right]}, 0 < F(x) \le 0.5 \\[2ex] \left(t - \dfrac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), \\ \quad t = \sqrt{\ln\left[\dfrac{1}{\{1 - F(x)\}^2}\right]}, 0.5 < F(x) \le 1 \end{cases} \quad (10)$$

where, $F(x)$ is the cumulative probability distribution function, and c_0, c_1, c_2, d_1, d_2, and d_3 are constants. In the literature, different thresholds were adopted depending on the problem of interest. In this study, the SRI value less than -0.5 was selected as the threshold. The moving average (MA) method was used to pool minor drought events. In any calculated SRI, there are several minor drought and wet periods of short duration ($\le$ 1 month) between major drought events; we removed these minor events using the one-month moving window. More details of the MA method are found in Tallaksen et al. (1997).

2.6 Quantification of Climate Change and Human Activity on Hydrological Drought

We investigated the impacts of climate variation and human activity on hydrological drought characteristics under different scenarios. The reason for using different scenarios was to assess the individual contribution of each factor affecting hydrological drought. We used hydrological data before the change point to calibrate and validate the hydrological model, and then the calibrated model with natural period parameters (i.e., without anthropogenic effects) was used to simulate the runoff during human-impacted periods. Four scenarios (S1, S2, S3, and S4) were developed to identify the separate impacts of climate change and human activity on hydrological drought; (1) D_{CC} in S1 comprised the variability of drought in natural period; (2) D_T in S2 represented drought under the influence of temperature only, with the other factors help constant; (3) D_P in S3 denoted drought under the effect of varying precipitation, keeping the other
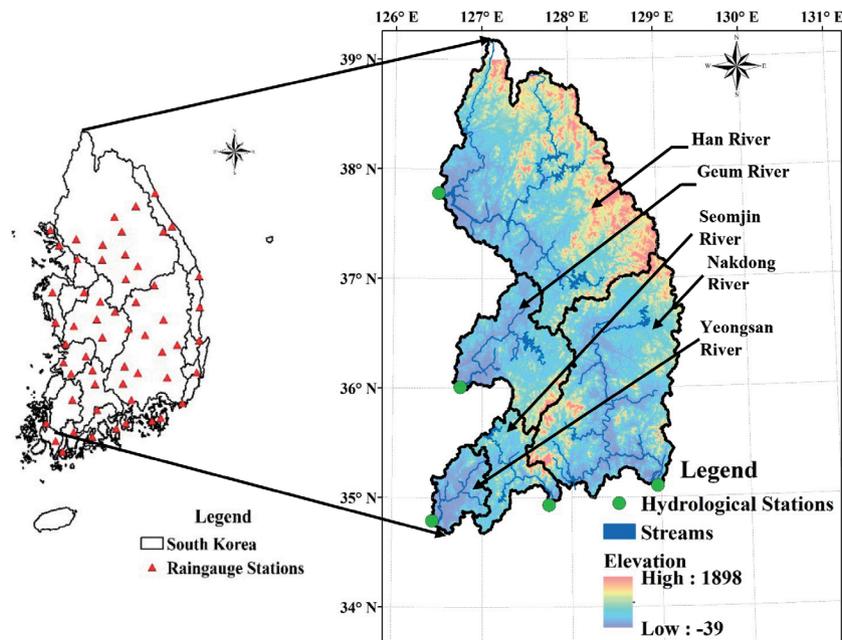

Fig. 1. Map of the study areas and observatory stations with topography.

factors constant; and (4) D_{obs} in S4 indicated drought under observed streamflow.

The first scenario, S1, was estimated by calibrating he hydrological model in the climate change natural period before the change point. The parameters of the calibrated model were used to simulate streamflow during the impacted period reflecting only the effect of climate change. In the S2 and S3 scenarios, the long-term mean monthly temperature and precipitation were calculated, respectively, and used for further analyses.

The percentage changes were calculated by Eq. (11).

$$C_T = \frac{D_{S1} - D_{S3}}{D_{S1}} \times 100 \qquad (11a)$$

$$C_P = \frac{D_{S1} - D_{S2}}{D_{S1}} \times 100 \qquad (11b)$$

$$C_H = \frac{D_{S4} - D_{S1}}{D_{S1}} \times 100 \qquad (11c)$$

where, C_T, C_P, and C_H are the relative proportions of temperature, precipitation, and human activity that influenced drought, respectively, and D_{S1}, D_{S2}, D_{S3}, and D_{S4} are the average of drought severity, drought duration, or drought peak corresponding to four scenarios. Drought duration (D) is the length of the period when the SRI value was less than the threshold of -0.5. Drought severity (S) is the sum of the SRI during the drought duration.

3. RESULTS AND DISCUSSION

3.1 Variation in Precipitation and Temperature

Changes in precipitation and temperature were observed throughout the study areas during the period 1973 - 2017. The increasing and deceasing trend in precipitation and temperature, with significant p-values, were estimated using the Sen's slope test, as shown in Fig. 2. In the Han River basin, precipitation increased at the rate of 4.23 mm yr^{-1} and temperature increased at the rate of 0.0319°C yr^{-1}. The variations in climate variable in the Han River basin were larger than in the other four basins. In the Nakdong River basin, precipitation increased at the rate of 1.889 mm yr^{-1} and temperature increased at the rate of 0.0259°C yr^{-1}. In the Geum River basin, precipitation and temperature increased

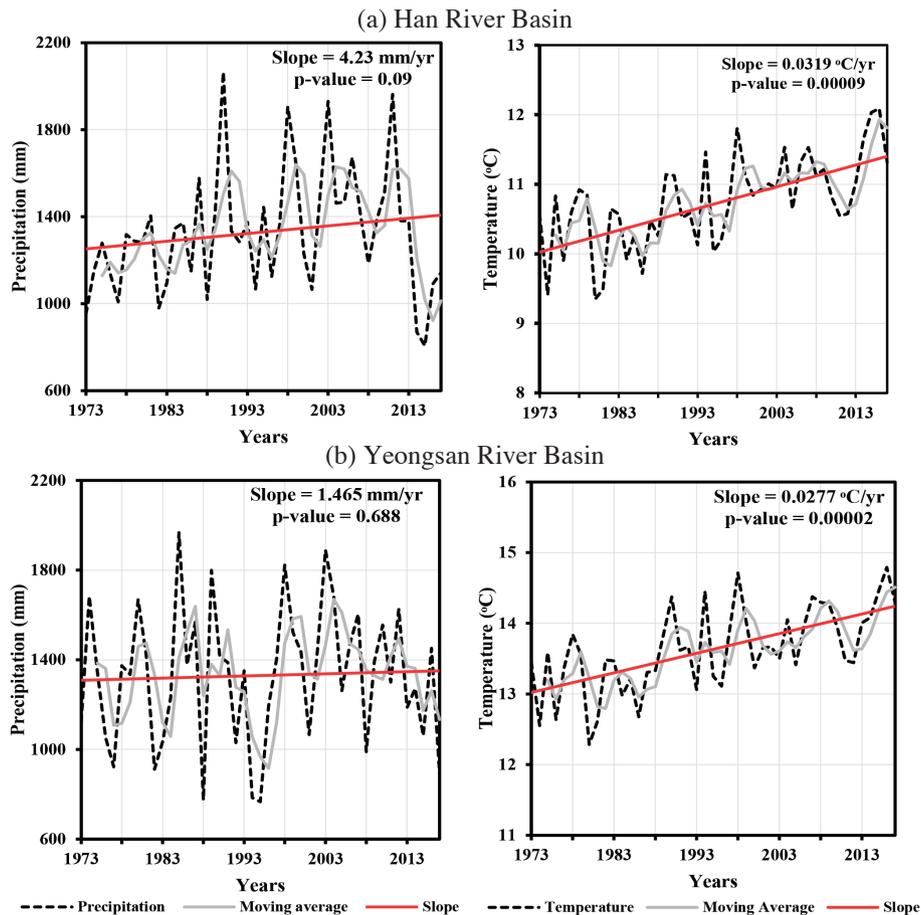

Fig. 2. Variations in precipitation and temperature. (a) Han River Basin (b) Yeongsan River Basin.

at the rate of 1.43 mm yr^{-1} and 0.0288°C yr^{-1}, respectively. In the Seomjin River basin, precipitation and temperature increased by 0.727 mm yr^{-1} and 0.016°C yr^{-1}, respectively. In the Yeongsan River basin, precipitation and temperature increased by 1.465 mm yr^{-1} and 0.0277°C yr^{-1}, respectively. The results of this study for temperature in the Nakdong and Yeongsan River basins are in agreement with Jung et al. (2002), which showed an increasing trend of temperature over South Korea. The results of increasing and decreasing trends of precipitation and temperature varied from region to region. Zhang et al. (2018) found decreasing trends in precipitation and potential evapotranspiration in Danjiangkou reservoir catchment, China.

3.2 Variation in Streamflow and Changing Point Analysis

The trends of streamflow were also estimated for the period of 1973 - 2017 using the Sen's slope test. It was observed that, in the Han, Nakdong, and Geum River basins, had increasing trends at the rate of 7.50, 0.759, and 2.226 mm yr^{-1}, respectively. However, in Seomjin and Yeongsan River basins had decreasing trends at the rate of -0.259 and -0.584 mm yr^{-1}, respectively. These results are in accordance with Bae et al. (2008).

Change points in the hydrologic series were calculated by the sequential Mann-Kendall test and the results are presented in Table 1. Each change point divides the series into two parts natural and human-impacted. In the Han River basin, the clear change point was observed in 1997, while in the Nakdong and Geum River basins, the change points were observed in 1995 and 1992, respectively. In the Seomjin and Yeongsan River basins, the UF and UB curves intersected at many points. The point of intersection after which a large difference was observed was considered a change point. In the Seomjin and Yeongsan River basins, similar change points were observed in 1993 because they are neighboring river basins and are smaller than the other basins. The results of trend of streamflow and change point in Han and Yeongsan River basins are shown in Fig. 3.

3.3 Hydrological Simulations of Streamflow

We used the integrated hydrological model (IHM) for streamflow simulations in this study, and the results are shown in Table 2. The results of our IHM simulation of the Han and Yeongsan River basins are shown in Fig. 4. We obtained a significant improvement in calibration and validation efficiencies using the IHM compared to previous studies (Zou et al. 2017; Zhou et al. 2018), which used a single water balance model for calibration and validation and reported average NSE below 0.85. Zhang et al. (2018) used the ABCD model for streamflow simulation and found average calibration and validation efficiency NSE below 0.90

in China. We found that the IHM significantly improved the results of our hydrological simulations. The simulated streamflow under four scenarios in the Han River basin are shown in Fig. 5. The results of scenarios S2 and S3 are in agreement with McCabe and Wolock (2011) conducted in the United States.

3.4 Effects of Climate Variables and Human Activity on Streamflow and Drought

The effects of climate variables and human activity on streamflow were examined using average of streamflow under four scenarios as given in Eq. (11). In the Han River basin, variation in precipitation, temperature, and human activity changed streamflow by 18.2, -0.68, and 4.17%, respectively. Very similar trends were observed in the basins except the Seomjin and Yeongsan River basins, where the effect of human activity on streamflow was negative. Our results on the effects of precipitation and temperature are in agreement with previous studies (Karl and Riebsame 1989; McCabe and Wolock 2011), which found that precipitation was the main driving force controlling runoff variability, whereas the effect of temperature on runoff was minimal.

The separate influences of climate variables and human activity on drought characteristics such as duration and severity were calculated using Eq. (11) and are shown in Table 3. The changes in precipitation, temperature and human activity in the Han River basin increased drought severity by 35.9, 3.9, and 7%, respectively. In the Nakdong River basin, the variations in drought severity due to precipitation, temperature and human activity were 48.5, -4.3, and 8.8%, respectively. The drought severity in the Geum River basin increased by 40.1% due to precipitation and decreased by -4.9% due to temperature. Precipitation increased drought severity by 33.2%, and temperature decreased drought severity by -7.2% in the Seomjin River basin. The increases in drought severity in the Yeongsan River basin due to precipitation, temperature, and human activity were 49.3, 8.2, and 17.3%, respectively. The results of this study on streamflow in S2 scenario and on drought in all scenarios are in agreement with a previous study in China (Zhang et al. 2018). Precipitation had the largest influence on drought

Table 1. Observed change points by sequential Mann-Kendall test in all basins.

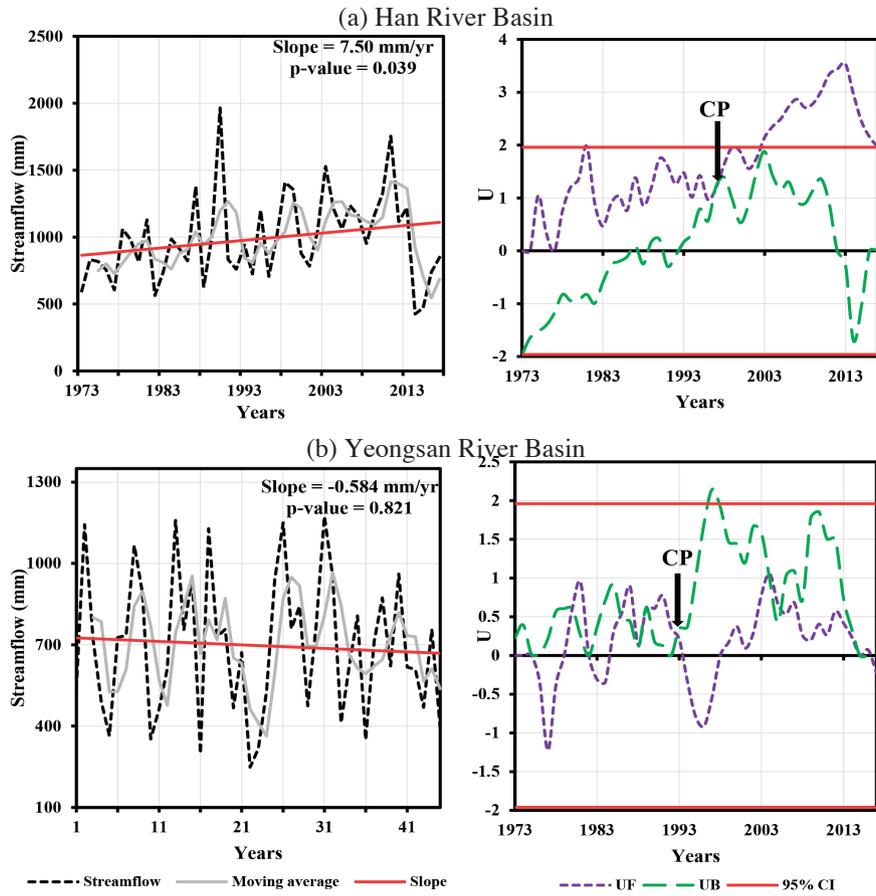| Basins	Change Point
Han River	1997
Nakdong River	1995
Geum River	1992
Seomjin River	1993
Yeongsan River	1993

Fig. 3. Trend in streamflow and change point by sequential Mann-Kendall test. (a) Han River Basin (b) Yeongsan River Basin.

Table 2. Performance measures of the ABCD, GR2M, and IHM models based on NSE and KGE criteria.

|				ABCD		GR2M		IHM	
Basins	**Calibration Period**	**Validation Period**		**Calibration**	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Han River	1973 - 1987	1988 - 1997	NSE (%)	0.95	0.96	0.95	0.96	0.95	0.96
			KGE (%)	0.98	0.95	0.91	0.94	0.95	0.97
Nakdong River	1973 - 1986	1987 - 1995	NSE (%)	0.91	0.94	0.92	0.94	0.92	0.94
			KGE (%)	0.96	0.97	0.91	0.91	0.95	0.95
Geum River	1973 - 1984	1985 - 1992	NSE (%)	0.90	0.95	0.91	0.90	0.92	0.95
			KGE (%)	0.95	0.98	0.95	0.85	0.96	0.93
Seomjin River	1973 - 1985	1986 - 1993	NSE (%)	0.93	0.94	0.92	0.94	0.93	0.95
			KGE (%)	0.96	0.89	0.92	0.88	0.95	0.89
Yeongsan River	1973 - 1985	1986 - 1993	NSE (%)	0.90	0.95	0.89	0.94	0.90	0.95
			KGE (%)	0.95	0.95	0.93	0.96	0.94	0.97
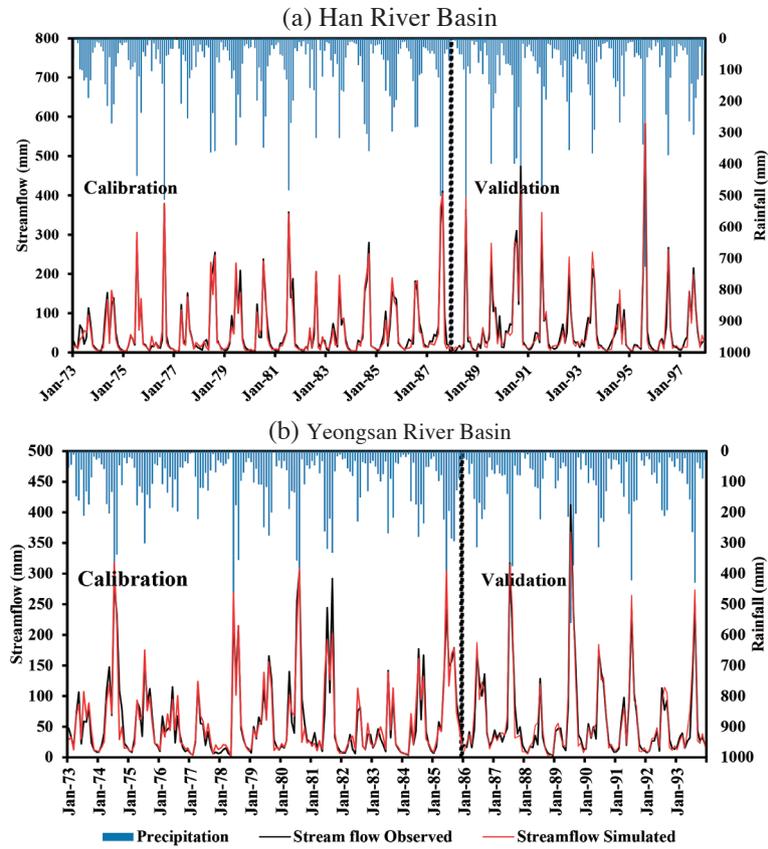
Fig. 4. The calibration and validation by the ensemble model. (a) Han River Basin (b) Yeongsan River Basin.
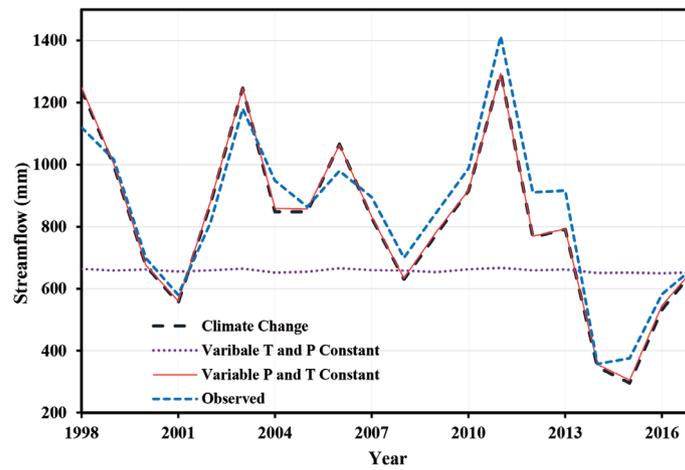

Fig. 5. Simulated streamflow time series under three different scenarios and observed flows in the Han River basin.

Table 3. Influence of climate variables and human activity on drought characteristics (severity and duration).

Influence on climate variation and human activity on Drought Characterization			
Basins	**Factors**	**Average Severity**	**Average Duration**
Han River	**P (%)**	35.9	31.6
	T (%)	3.9	2.3
	Human (%)	7.0	5.3
Nakdong River	**P (%)**	48.5	38.5
	T (%)	-4.3	-3.5
	Human (%)	8.8	9.1
Geum River	**P (%)**	40.1	28.8
	T (%)	-4.9	-4.7
	Human (%)	20.8	16.3
Seomjin River	**P (%)**	33.2	13.6
	T (%)	-7.2	-5.8
	Human (%)	25.4	28.9
Yeongsan River	**P (%)**	49.3	37.5
	T (%)	8.2	11.8
	Human (%)	17.3	17.7

severity and duration, whereas temperature had less of an effect. However, the impacts of human activity on drought properties were significant. Humans had the greatest effect on streamflow in the Geum River basin and on drought in the Seomjin River basin. The proportional impacts of climate variables and human activities on streamflow and hydrological droughts are shown in Fig. 6.

3.5 Discussion

Most of the studies found in the literature discuss the direct impacts of climate change and human activity on streamflow (e.g., Ahn and Merwade 2014; Wanders and Wada 2015; Wu et al. 2017), while McCabe and Wolock (2011) discussed the impacts of temperature and precipitation on streamflow. Recent decades saw rapid increases in gross domestic product (GDP) and gradual increases in population in our study area, as shown in Fig. 7. Mainly, the GDP increased rapidly after the 1990s due to significant human activities such as urbanization, industrialization, and agricultural irrigation. These human interventions altered the hydrological cycle, which was verified by sequential Mann-Kendall test revealing change points in streamflow after the 1990s. Our hydrological simulations were quite satisfactory, with the NSE and KGE values ≥ 90% in all basins except the Seomjin in which the KGE was ≤ 90% because of different climate conditions in the catchment. It is clearly shown in Fig. 5 that the lines of scenarios D_{CC} and D_P overlap each other because precipitation is the most dominant factor in altering climate change. Precipitation

also has overwhelming effects on streamflow, while temperature has very little effect (Karl and Riebsame 1989; McCabe and Wolock 2011). This is why the line of scenario D_T has minute fluctuations. These results also support the results of Bai et al. (2015), which found that the PET inputs have limited influence on monthly runoff estimates because temperature is the main driver of the PET and has minimal effect on streamflow.

Variance in precipitation and temperature increased drought occurrence by more than 33% in all the basins. Human activity intensified drought duration and drought severity in all the basins but in different proportions. When the effects of environmental changes on streamflow increased beyond a certain threshold (6 - 12 months), extreme hydrological drought occurred. Further investigation is required to quantify the impact of human activities such as dam operation, water diversion, and agricultural irrigation on extreme hydrological events.

4. CONCLUSION

This study investigated the relative effects of climate variables and human activities on drought characteristics in the humid environment of South Korea. The parsimonious integrated hydrological model (IHM) efficiently simulated streamflow in four different scenarios: climate change, constant temperature with varying precipitation, constant precipitation with varying temperature, and human influence. The standardized runoff index (SRI) effectively quantified hydrological drought under all scenarios, and drought events
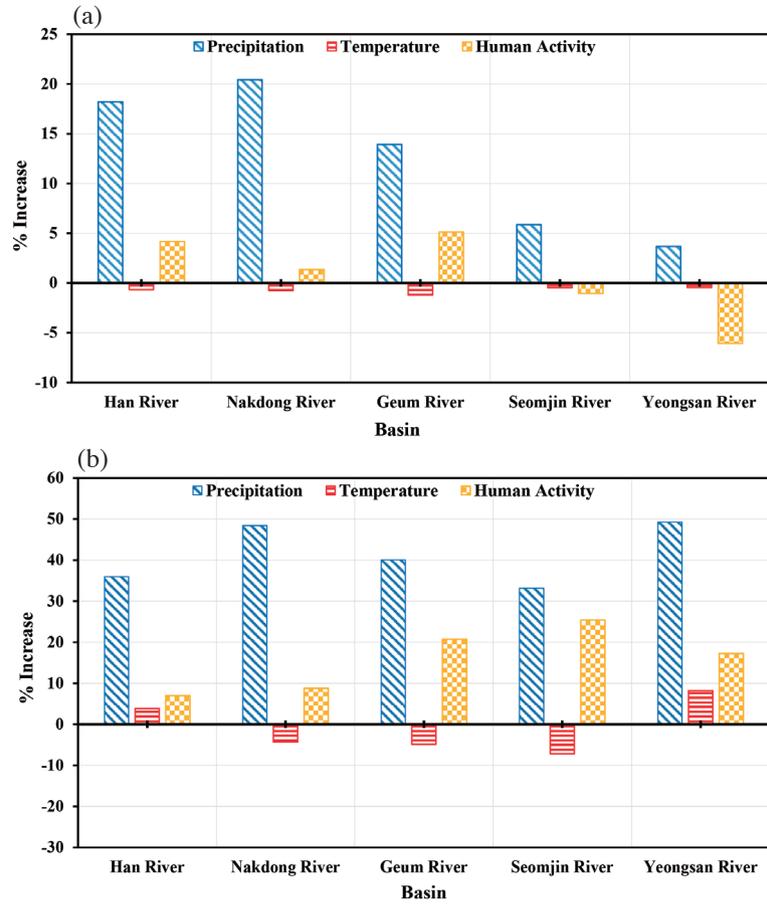
Fig. 6. Influence of climatic variables and human activity on (a) streamflow and (b) drought severity.
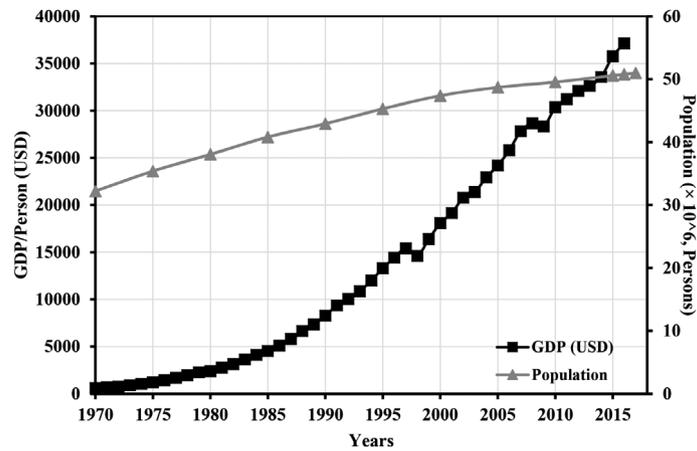

Fig. 7. Changes in GDP and population in the study area.

were refined by the moving average (MA) pooling method.

The effects of three primary factors of precipitation, temperature, and human activity on streamflow and drought were investigated individually. The influence of precipitation and temperature fluctuated in all the basins of South Korea, but precipitation proved to be the most dominant driving force on streamflow. Temperature has very little effect on streamflow, but temperature variation increased the frequency of drought. Human activities were also an important factor contributing to hydrological drought, increasing drought severity from 7 to 25% and lengthening drought duration from 5 to 28% across the study area.

This study also compared the direct and indirect impacts of natural events and anthropogenic activities on streamflow and hydrological drought. The indirect impacts of environmental changes were cumulative and were therefore greater than direct impacts such as major flood events, deforestation, urbanization, and population growth. Further investigations are needed to assess the effects of specific human activities such as irrigation, urbanization, and industrialization on hydrological drought and other natural disaster. The results of this study enhance our understanding of hydrological extremes as responses to environmental changes. This is very helpful for decision makers for predicting natural disasters and developing adaptation/mitigation strategies to cope with them.

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