Development of a Streamflow Drought Severity-Duration-Frequency Curve Using a Threshold Level Method

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Abstract

This study developed a streamflow drought severity-duration-frequency (SDF) curve that is analogous to the well-known depth-duration-frequency curve used for rainfall. Severity was defined as the total water deficit volume to target threshold for a given drought duration. The fixed and variable threshold level methods were introduced to set the target instreamflow requirement, which can significantly affect the streamflow drought severity. The four threshold levels utilized were the fixed, monthly, daily, and desired yield for water use. The fixed threshold level in this study is the 70th percentile value (Q_{70}) of the flow duration curve (FDC), which is compiled using all the available daily streamflows, and the monthly threshold level is the monthly-varying Q_{70}s of each month's FDC. The daily variable threshold is the Q_{70} of the FDC obtained from the antecedent 365 daily streamflows. The desired yield threshold determined by the central government consists of domestic, industrial, and agricultural water uses as well as environmental instreamflow. As a result, the desired yield threshold can identify streamflow droughts using the total water deficit to the hydrological and socioeconomic targets, while the fixed, monthly, and daily streamflow thresholds derive the deficiencies or anomalies from the average of historical streamflow. Based on individual frequency analyses, SDF curves for four thresholds were developed to quantify the relation among severities, durations, and frequencies. For additional specification, the drought duration-frequency curve was developed. This curve can be an effective tool for identifying streamflow droughts using severities, durations, and frequencies.

Keywords: frequency analysis, streamflow drought, severity-duration-frequency (SDF) curve, threshold level method

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1. Introduction

A drought implies a period of time when the supply of water cannot meet its typical demand. Rainfall deficiencies of sufficient magnitude over prolonged durations and subsequent reductions in the streamflow interfere with the normal agricultural and economic activities of a region, leading to a decrease in agriculture production and thus affecting everyday life. Dracup et al. (1980) defined a drought using the following properties: 1) nature of water deficit (e.g., precipitation, soil moisture, or streamflow); 2) basic time unit of data (e.g., month, season, or year); 3) threshold for distinguishing low flows from high flows, while considering the mean, median, mode, or any other derived thresholds; and 4) regionalization and/or standardization. Based on these definitions, various indices were proposed over the years to identify drought. Recent studies have focused on such multi-faceted drought characteristics using various indices (Palmer, 1965; Rossi et al., 1992; McKee et al., 1993; Byun and Wilhite, 1999; Tsakiris et al., 2007; Pandey et al., 2008a; 2008b; 2010; Nalbantis and Tsakiris, 2009; Wang et al., 2011; Tabari et al., 2013; Tsakiris et al., 2013).

The American Meteorological Society (1997) groups drought definitions and types into four categories: meteorological or climatological, agricultural, hydrological, and socioeconomic droughts. The meteorological drought is a result of the absence or reduction of precipitation and short-term dryness results in an agricultural drought that severely reduces crop yields. Precipitation deficits over a prolonged period that reduce streamflow, groundwater, reservoir, and lake levels will result in a hydrological drought. If hydrological droughts continue until the supply and demand of numerous economic goods are damaged, a socioeconomic drought occurs (Heim, 2002).

Hydrological and socioeconomic droughts are very difficult to be approached. Hydrological drought is defined as a significant decrease in the availability of water in all its forms, appearing in the land phase of the hydrological cycle. These forms are reflected in various hydrological variables such as streamflows, which include snowmelt and springflow, lake and reservoir storage, recharge of aquifers, discharge from aquifers, and baseflow (Nalbantis and Tsakiris, 2009). Therefore, streamflow is the key variable to analyze in describing hydrological droughts because it take into account outputs of four different subsystems, i.e., surface runoff from the surface water subsystem, subsurface runoff from the upper and lower unsaturated zone, and baseflow from the groundwater subsystem (Tsakiris et al., 2013). Furthermore, streamflow crucially affects the socioeconomic drought for several water supply activities such as hydropower generation, recreation, and irrigated agriculture, where crop growth and yield are largely dependent on water availability in the stream (Heim, 2002). Hence, hydrological and socioeconomic droughts are related to streamflow deficits with respect to hydrologically normal conditions or target water supplies for economic growth and social welfare.

For additional specification, Tallaksen and van Lanen (2004) defined streamflow drought as a "sustained and regionally extensive occurrence of below average water availability". Thus, threshold level approaches to define the duration and severity of a drought event while considering the daily, monthly, seasonal, and annual natural runoff variations are widely applied for drought analyses (Yevjevich, 1967; Sen, 1980; Dracup et al., 1980; Dalezios et al., 2000; Kjeldsen et al., 2000; American Meteorological Society, 2002; Hisdal and Tallaksen, 2003; Wu et al. 2007; Pandey et al., 2008a; Yoo et al., 2008; Tigkas et al., 2012; van Huijgevoort, 2012). These approaches provide an analytical interpretation of the expected availability of river flow; a drought occurs when the streamflow falls below the threshold level. This level is frequently taken as a certain percentile flow for a specific duration and is assumed to be steady during the considered month, season, or year. Kjeldsen et al. (2000) extended the steady threshold concept to the variable method, employing seasonal, monthly and daily streamflows.

Therefore, there is a growing need to integrate drought severity duration, and frequency based on multivariate theory (Bonaccorso et al., 2003; Gonz´alez and Vald´ es, 2003; Mishra et al., 2009; Song and Singh, 2010a, b; De Michele et al., 2013). Thus, based on the typical drought characteristics (water deficit and duration) and threshold levels, this study developed quantitative relations between drought parameters, namely severity, duration, and frequency, and used them to plot drought iso-severity curves for certain return periods and durations. This study quantified the streamflow drought severity, which is closely related to hydrological and socioeconomic droughts, using fixed, monthly, daily, and desired yield threshold levels. Furthermore, this study proposed a streamflow drought severity-duration-frequency (SDF) curve using traditional frequency analyses. This framework was applied to the Seomjin River basin in South Korea.

2. Methodology

2.1 Procedure

This study consists of five steps, as shown in Fig. 1. Step 1 is to determine the threshold levels for the fixed, monthly, daily, and desired yield for water use. The threshold selection description is shown in section 2.3. Step 2 is to calculate the severities (total water deficits) and durations for all the drought events at the four threshold levels. The methodology to derive the severity and the duration is shown in section 2.2. Step 3 is to derive the annual maxima of severity and duration and to identify the best-fit probability distribution functions using L-moment ratio diagrams (Hosking and Wallis, 1997). The calculation procedure is shown in section 2.4 using related equations and descriptions. Step 4 is to calculate the streamflow drought severities using the selected probability distribution with best-fit parameters and to develop SDF curves. This is described in Section 2.5. Step 5 is to develop the duration-frequency curves of the four threshold levels using an appropriate probability distribution.

Fig. 1

2.2. Streamflow drought severity

In temperate regions where the runoff values are typically larger than zero, the most widely used method to estimate a hydrological drought is the threshold level approach (Yevjevich, 1967; Fleig et al., 2006; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012). The streamflow drought severity with threshold level method has the following advantages over the standardized precipitation index (SPI) in meteorology (Yoo et al., 2008) and the Palmer drought severity index (PDSI) in meteorology and agriculture (Dalezios et al., 2000): 1) no a priori knowledge of probability distributions is required and 2) drought characteristics, such as frequency, duration, and severity, are directly determined if the threshold is set by sectors impacted by the drought.

A sequence of drought events can be obtained using the streamflow and threshold levels. Each drought event is characterized by its duration D_i, deficit volume (or severity) S_i, and time of occurrence T_i as shown by the definition sketch in Fig. 2. With a prolonged dry period, the long drought spell is divided into several minor drought events. Because these droughts are mutually dependent, Tallaksen et al. (1997) proposed that an independent sequence of drought events must be described using some type of pooling as described below.

Fig. 2

If the 'inter-event' time t_i between two droughts of duration d_i and d_{i+1} and severity s_i and s_{i+1}, respectively, are less than the predefined critical duration t_c and the pre-allowed inter-event excess volume z_c, the mutually dependent drought events are pooled to form a drought event as (Zelenhasic and Salvai, 1987; Tallaksen et al., 1997)

$$d_{pool} = d_i + d_{i+1} + t_c$$
$$s_{pool} = s_i + s_{i+1} - z_c \, . \quad (1)$$

This study assumed t_c = 3 days and z_c = 10% of d_i or d_{i+1} for simplicity. These numbers will be studied in the future.

2.3 Threshold selection

The threshold might be fixed or vary over the course of a year. A threshold is regarded as fixed if a constant value is used for the whole series, and a variable threshold is a value that varies over the year, using monthly and daily variable levels (Hisdal and Tallaksen, 2003). If the threshold is derived from the flow duration curve (FDC), it implies that the whole streamflow record is used in its derivation. As shown in Fig. 3, obtained from the study area, fixed and monthly thresholds can be obtained from an FDC and twelve monthly FDCs based on the entire record period. The daily varying threshold can be derived using the antecedent 365 day streamflow.

The threshold choice is influenced by the study objective, region, and available data. In general, a percentile from the can be used as the threshold. Relatively low thresholds in the range of Q_{70} to Q_{95} are often used for perennial rivers (Kjeldsen et al., 2000). This study selected Q_{70} for the fixed threshold, considering the Korean hydrologic condition, namely, a monsoon climate. Q_{70} means a 70% flow of the FDC. Specifically, 70% is the percentage of time that the streamflow Q_{70} is exceeded. However, the threshold selection should be further analyzed because it is not clear that Q_{70} should be used as a representative threshold for rivers in a monsoon climate.

The time resolution, i.e., where to apply series of annual, monthly, or daily streamflows, depends on the hydrologic regime in the region of interest. In a temperate zone, a given year might include both severe droughts (seasonal droughts) and months with abundant streamflow, meaning that annual data would not often reveal severe droughts. Dry regions are more likely to experience droughts lasting for several years, i.e., multi-year droughts, which support the use of a monthly or annual time step. Hence, different time resolutions might lead to different results regarding the drought event selection. This study used daily streamflow data, and the time resolutions were selected from 30 days to 270 days because droughts in the region of interest have never been studied.

Fig. 3

The variable threshold approach is adapted to detect streamflow deviations for both high and low flow seasons. Lower than average flows during high flow seasons might be important for later drought development. However, periods with relatively low flow either during the high flow season, for example, caused by a delayed onset of a snow-melt flood, is not commonly considered a drought. Therefore, the events defined with the varying threshold should be called streamflow deficiencies or streamflow anomalies rather than streamflow droughts (Hisdal et al., 2004). In contrast, the desired yield for sufficient water supply and environmental instreamflow can be an effective way to identify a streamflow drought by considering hydrological and socioeconomic demands because environmental instreamflow has become important in recent years.

2.4 Probability distribution function

An L-moment diagram for various goodness-of-fit techniques was used to evaluate the best probability distribution function for datasets in several recent studies (Hosking, 1990; Chowdhury et al., 1991; Vogel and Fennessey, 1993; Hosking and Wallis, 1997). The L-moment ratio diagram is a graph where the sample L-moment ratios, L-skewness (τ_3), and L-kurtosis (τ_4) are plotted as a scatterplot and compared with the theoretical L-moment ratio curves of candidate distributions. L-moment ratio diagrams were suggested as a useful graphical tool for discriminating amongst candidate distributions for a dataset (Hosking and Wallis, 1997). Two representations used to assist in the selection of statistical distributions are the sample average and line of best fit, which can be plotted on the same graph to facilitate selecting the best-fit distribution.

When plotting an L-moment ratio diagram, the relation between the parameters and the L-moment ratios τ_3 and τ_4 for several distributions are required. In the case of a GEV distribution, the three-parameter GEV distribution described by Stedinger et al. (1993) has the following probability density function (PDF) and cumulative distribution function (CDF):

$$f(x) = \frac{1}{\alpha}\{1-\frac{\kappa}{\alpha}(x-\xi)\}^{1/\kappa-1} \cdot \exp[-\{1-\frac{\kappa}{\alpha}(x-\xi)\}^{1/k}] \quad \kappa \neq 0 \quad , \tag{3a}$$

$$f(x) = \frac{1}{\alpha}\exp\{-\frac{x-\xi}{\alpha} - \exp(-\frac{x-\xi}{\alpha})\} \quad \kappa = 0 \quad , \tag{3b}$$

$$F(x) = \exp[-\{1-\frac{\kappa}{\alpha}(x-\xi)\}^{1/\kappa}] \quad \kappa \neq 0 \quad , \tag{4a}$$

$$F(x) = \exp\{-\exp(-\frac{x-\xi}{\alpha})\} \quad \kappa = 0 \quad , \tag{4b}$$

where $\xi + \alpha/\kappa \leq x \leq \infty$ for $\kappa < 0$, $-\infty \leq x \leq \infty$ for $\kappa = 0$, and $-\infty \leq x \leq \xi + \alpha/\kappa$ for $\kappa > 0$. Here, ξ is a location, α is a scale, and κ is a shape parameter. For $\kappa = 0$, the GEV distribution reduces to the classic Gumbel (EV1) distribution with $\tau_3 = 0.17$. Hosking and Wallis (1997) provided more detailed information regarding the GEV distribution. The relation between the parameters and τ_3 and τ_4 for the shape parameter's GEV distribution can be obtained as follows (Hosking and Wallis, 1997):

$$\tau_3 = \frac{2(1-3^{-\kappa})}{(1-2^{-\kappa})} - 3 \quad (5a)$$

$$\tau_4 = \frac{5(1-4^{-\kappa}) - 10(1-3^{-\kappa}) + 6(1-2^{-\kappa})}{(1-2^{-\kappa})}. \quad (5b)$$

2.5 Development of SDF relationships

IDF or depth-duration-frequency (DDF) curves can be defined to "allow calculation of the average design rainfall intensity (or depth) for a given exceedance probability over a range of durations" and results from the rainfall frequency analysis (Okonkwo and Mbajiorgu, 2010). Statistical frequency analyses, such as rainfall analyses, are frequently utilized for drought events. This, however, cannot fully explain droughts without any consideration of severity and duration, which has resulted in the development of the SDF curve. Thus, extreme drought events can be specified by frequency, duration and either depth or mean intensity (i.e., severity). The frequency is usually described by its return period, which is defined as the average interval of time within which the magnitude of the event is reached or exceeded once. Because its magnitude is given by the total depth occurring in a particular duration, the SDF relation can be derived. For the estimation of the return periods for drought events of a particular depth and duration, the frequency distributions can be utilized (Dalezios et al., 2000).

3. Study region

The Seomjin River basin is located in southwestern Korea (Fig. 4). The area and total length of the Seomjin River are approximately 4,911.9 km^2 and 212.3 km, respectively. The altitude range is rather large, spanning from approximately 0 to 1,646 m (Fig. 4). The climate of South Korea is characterized by extreme seasonal variations. Winter is cold and dry under the dominant influence of the Siberian air mass, whereas the summer is hot and humid, with frequent heavy rainfall associated with the East Asian monsoon. In the Seomjin River basin, the measured precipitation is mainly concentrated in summer, and the measured mean annual precipitation varied from < 1,350 mm/yr^{-1} (in the north region) to > 1,600 $mmyr^{-1}$ (in the southeastern region) during the 1975-2012 observation period. In general, approximately 60% of the annual precipitation occurs during the wet season (July through September) in South Korea. This extreme seasonality in the precipitation causes periodic shortages of water during the dry season (October through March) and flood damage during the wet season.

Fig. 4.

The administrative districts where the basin is located cover three provinces, four cities, and 11 counties (Namwon City, Jinan County, Imsil County, and Sunchang County in the Northern Jeolla Province; Suncheon City, Gwangyang City, Damyang County, Gokseong County, Gurye County, Hwasun County, Boseong County, and Jangheung County in the Southern Jeolla Province; and Handing County in the Southern Gyungsang Province). Influx rates into the basin by province are 47% (Southern Jeolla Province), 44% (Northern Jeolla Province), and 9% (Southern Gyeongsang Province), and a total of 321,104 residents occupying 129,322 households live in these areas.

The land use consists of arable land (876.29 km^2), forest land (3,400.61 km^2), urban area (67.12 km^2), and other land uses (567.86 km^2). Additionally, 69.2% of the entire basin area (4,911.89 km^2) is forest land. Major droughts occurred in the Southern Jeolla Province from 1967 to 1968 and from 1994 to 1995. The Seomjin River basin had < 1,000 mm of precipitation on average in 1977, 1988, 1994, and 2008. Among these years, the annual precipitation in 1988 was only 782.7 mm (56.5%) of the annual average of 1,385.5 mm from 1967 to 2008, representing a serious drought.

4. Results

4.1. Determination of the threshold levels

This study used four threshold levels. The fixed threshold level is Q_{70} of the FDC, which resulted from 37-year daily streamflows. The monthly thresholds are twelve Q_{70}s of monthly FDCs, which incorporated data of all the daily streamflows of January through December for the past 37 years. The daily threshold is Q_{70} of the FDCs, which resulted from the antecedent 365 daily streamflows. Thus, the daily threshold level smoothly varies every day. The desired yield threshold for a sufficient water supply and environmental instreamflow was determined by the Korean central government. This is related to social and economic droughts because it associates the supply and demand of a number of economic goods and environmental safety. The desired yield threshold differed considerably from the other levels and represented more realistic conditions because the desired yield is equivalent to the planned water supply.

The four calculated thresholds are presented in Fig. 5, and the specific monthly-averaged values are listed in Table 1. The average levels were 1.9, 2.5, 2.8, and 13.8 m^3s^{-1} for the fixed, monthly, daily and desired yields, respectively. The daily threshold levels fluctuated significantly because of the natural streamflow variations for the antecedent 365 days and were the largest of the four threshold levels because a summer period (June, July, and August) was considered. The desired yield level was larger than the fixed, monthly, and daily thresholds. This phenomenon occurred during the winter in Korea, and, as a result, both the water demand and natural runoff during the winter (December, January, and February) were quite small. However, the threshold levels for the daily, monthly, and desired yields during the summer were much higher than those during the other seasons. The threshold levels for the desired yield during May and June were much higher than the levels for the other thresholds because the agricultural water demand was the highest in this season.

Fig. 5

Table 1

4.2 Calculations of streamflow drought severity and duration

The durations and severities for all the streamflow drought events were calculated based on the streamflow drought concept and threshold levels. The annual maxima values of duration and severity are shown in Fig. 6, and the summarized values are listed in Table 2. The maximum durations from the desired yield threshold approach were considerably higher than those from the other thresholds because the desired yields were highest during June and July because of agricultural water use. Similar to the results for the drought duration, the severities showed much higher values.

Table 2

Fig. 6

To compare the differences between the four threshold levels, the correlation coefficients were calculated as shown in Table 3. Similar trends were observed for the monthly and daily threshold levels. However, the durations and severities from the desired yield threshold level were completely different from those for the fixed, monthly and daily levels. Therefore, it is possible that the drought identification techniques based on general threshold levels cannot reflect the socioeconomic drought in terms of water supply and demand. Therefore, two-way approaches categorized by the time periods (fixed, monthly, and daily) for hydrological drought and desired yield threshold for socioeconomic drought should be separately included for specific drought characteristics identification.

Table 3

4.3 Identification of the probability distribution function

The L-moment diagrams of various goodness-of-fit techniques were used to evaluate the best probability distribution function for the datasets. To develop a streamflow drought SDF curve, the proper probability distribution function should be determined based on the statistical results as described in Section 2.4.

The L-moment ratio diagrams were derived for the four threshold approaches and are displayed in Fig. 7. Of the distribution models tested, three parameter distributions such as the Pearson type 3 (PT3), generalized normal (GNO), and generalized extreme value (GEV) distributions appeared to be consistent with their datasets. In the frequency analysis addressing extreme values, distributions that use more than three parameters are required to express the upper tail. The PT3, GNO, and GEV distributions can be applied in this study. As shown in Fig. 7, this study selected the GEV distribution for a representative probability distribution because most observations are appropriate for the GEV. This corresponds to Dalezios et al. (2000) for the PDSI and Yoo et al. (2008) for the SPI.

Fig. 7

4.4 Development of SDF curves

Streamflow drought SDF curves were developed using the derived probability distribution functions as shown in Fig. 8. For these plots, 10-, 20-, 50-, 80-, and 100-year-frequency severities were calculated at 30-, 60-, 90-, 120-, 150-, 180-, 210-, and 270-day durations. Because the amount of available data only corresponds to 37 years, we calculated up to a 100-year frequency. However, SDF curves from fixed, daily, and monthly thresholds were calculated using comparatively short durations because the annual maximum durations vary from 30 to 96 days. The SDF described the streamflow drought severities with respect to durations and frequencies. The severity increases with increasing frequency and duration. For a specific description, Table 4 compares all of the severities to specific frequencies and durations for the desired yield threshold. As the duration becomes larger, the difference ratio between return periods becomes much larger. Therefore, because the streamflow drought severity should be more crucial when the drought continues for a longer period, the frequency to long-drought should be approached with caution.

Fig. 8

Table 4

4.5 Development of duration-frequency curve

The drought can be characterized by a deficit volume using the threshold levels. However, using the deficit volume is not sufficient to explain the extreme droughts. Thus, analyzing streamflow drought durations can be another useful tool in identifying the drought event. Therefore, occurrence probabilities of various duration events were also estimated using a general frequency analysis. As a result, using the GEV distribution previously shown in Fig. 7, duration-frequency curves for four threshold levels were developed as shown in Fig. 9. For these plots, 2-, 3-, 5-, 10-, 20-, 30-, 50-, 70-, 80-, and 100-year-frequency severities were calculated. Similar to the SDF curves, the durations for the desired yield were much higher than those for the other three thresholds.

Fig. 9

5. Conclusions

This study developed a useful concept to describe the characteristics of streamflow droughts using frequency analyses. SDF curves for streamflow droughts were developed to quantify a specific volume based on a specific duration and frequency. In addition, duration-frequency curves were used to derive the relationship between drought duration and frequency. This study used severity, which represents the total water deficit for specific durations. Using the L-moment diagram method, the GEV was selected for the best-fit probability distribution. As a result, SDF curves were derived to identify the relationship among streamflow drought severity, duration and frequency. The severities increased with increasing duration and frequency. However, these values were quite different because the four threshold level approaches defined the streamflow drought differently.

The fixed threshold level in this study is the 70th percentile value (Q_{70}) of FDC, which is compiled using all the available daily streamflows, and the monthly threshold level is the monthly-varying Q_{70}s of each month's FDC. The daily variable threshold is the Q_{70} of the FDC obtained from the antecedent 365 daily streamflows. The desired yield threshold determined by the central government consists of domestic, industrial, and agricultural water uses as well as environmental instreamflow. As a result, the desired yield threshold can identify streamflow droughts using the total water deficit to the hydrological and socioeconomic targets, while the fixed, monthly, and daily streamflow thresholds derive the deficiencies or anomalies from the average of historical streamflow.

Streamflow drought SDF curves developed in this study can potentially be exploited to quantify the water deficit for natural streams as well as reservoirs. In addition, these will be extended to allow for regional frequency analyses, which can estimate streamflow drought severity at ungauged sites. Therefore, it can be an effective tool to identify any streamflow droughts using severity, duration, and frequency.

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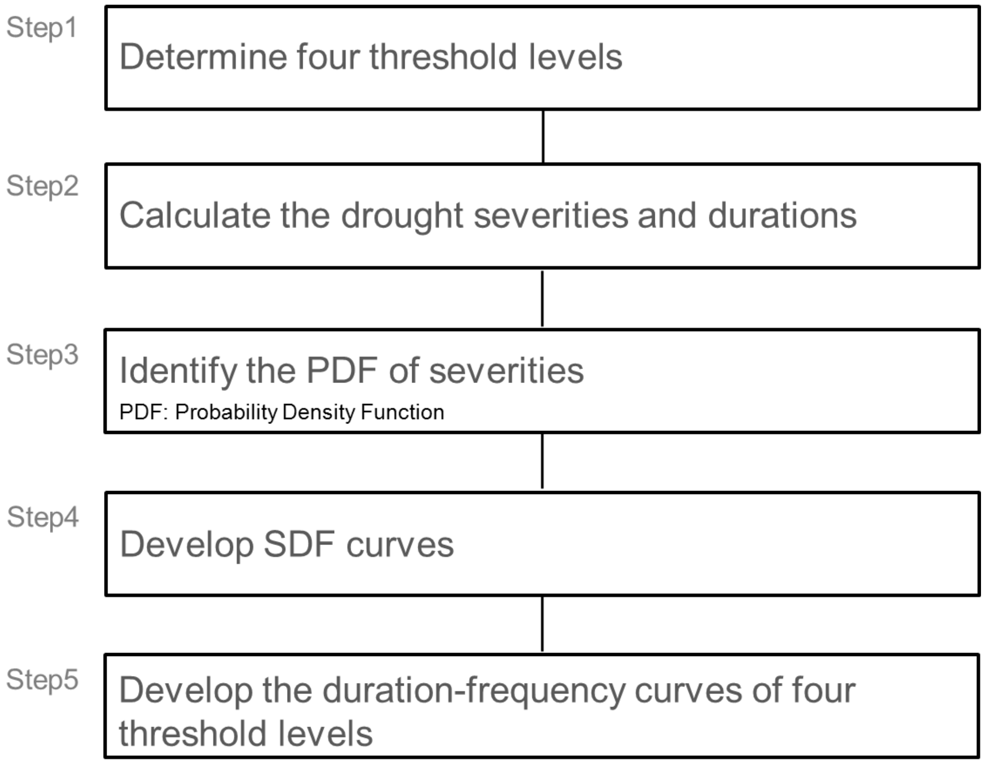


Fig. 1. Procedure used in this study.

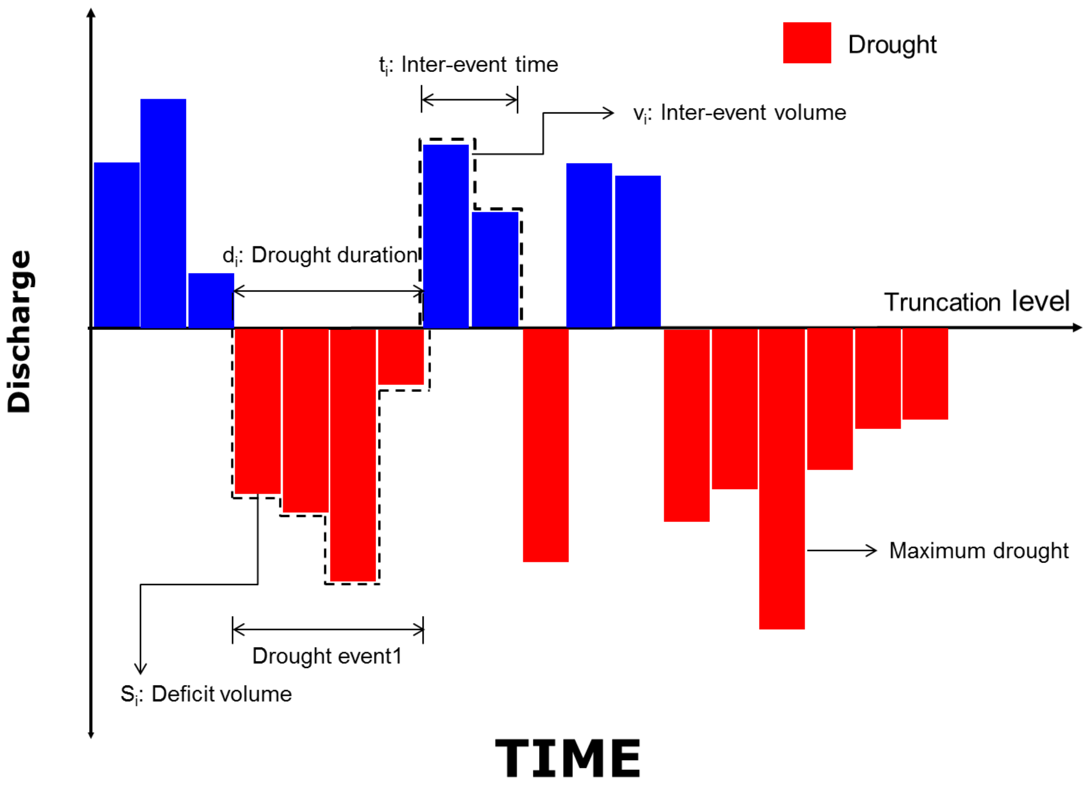


Fig. 2. A definition sketch of a general drought event.

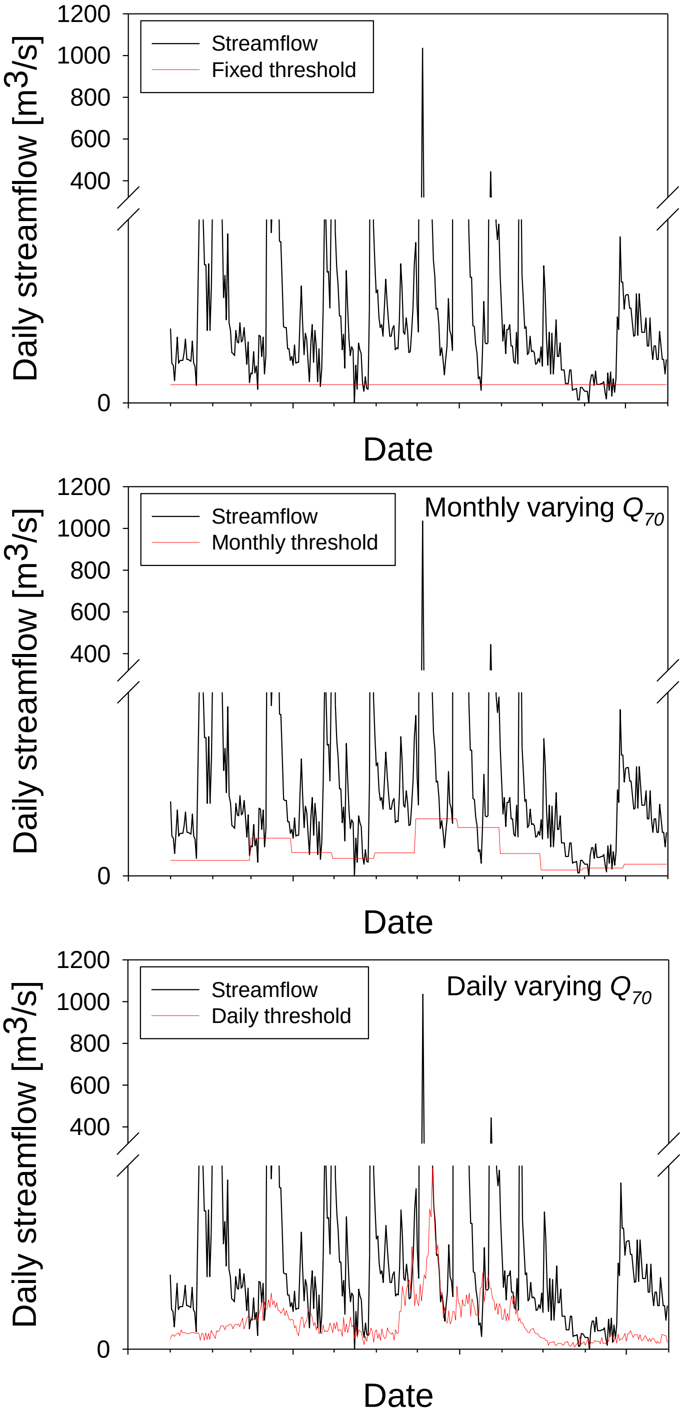


Fig. 3. Examples of threshold levels: fixed (top), monthly varying (middle), and daily varying (bottom).

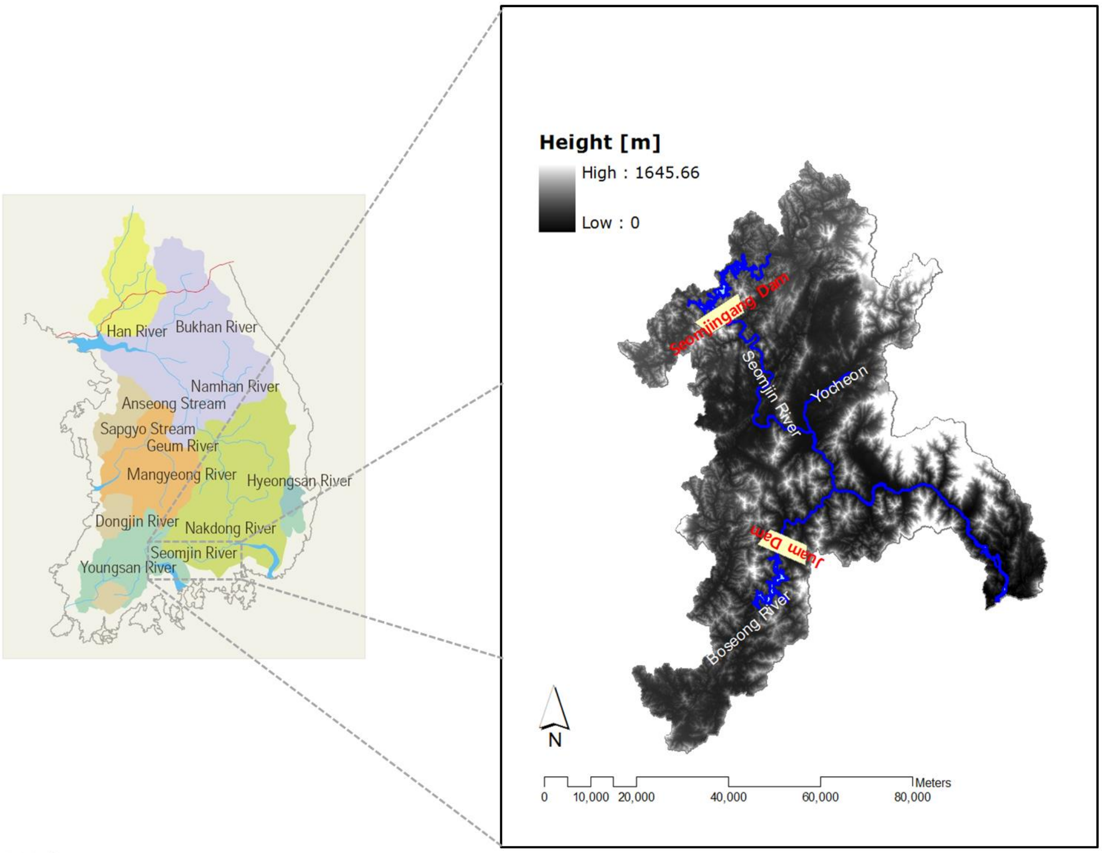


Fig. 4. Location of the selected river basin, including elevation and rivers.

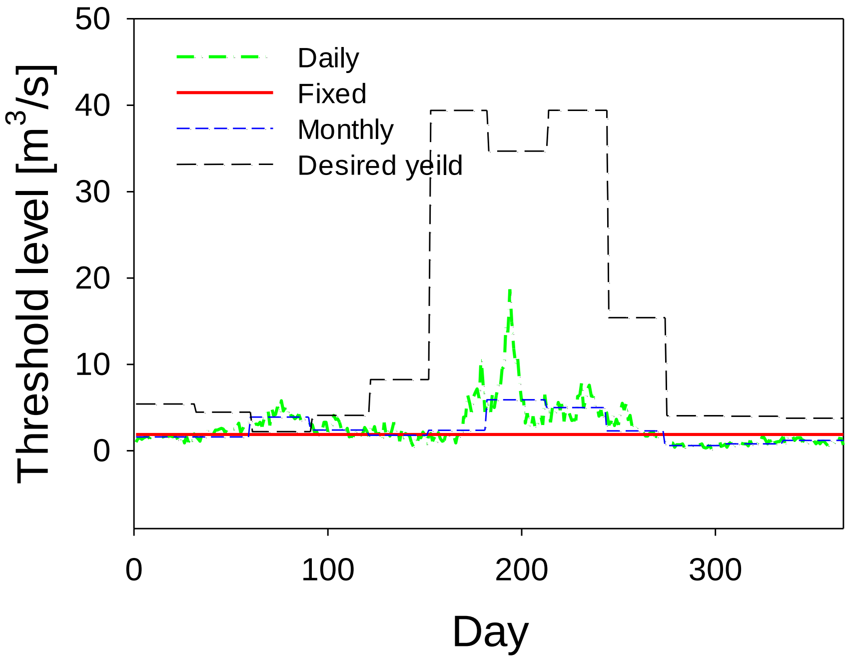
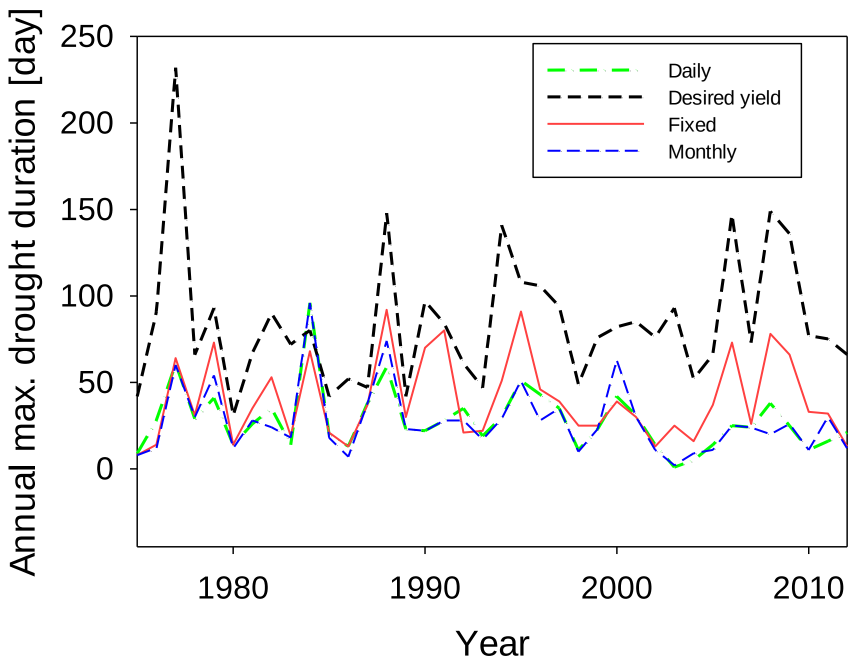
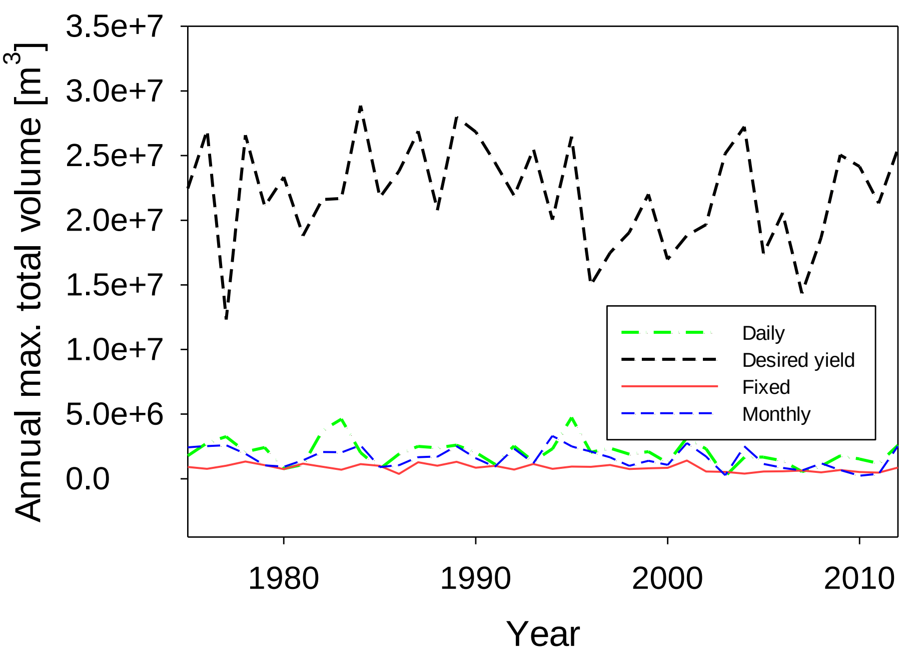


Fig. 5. Comparison of the four threshold levels used in this study.

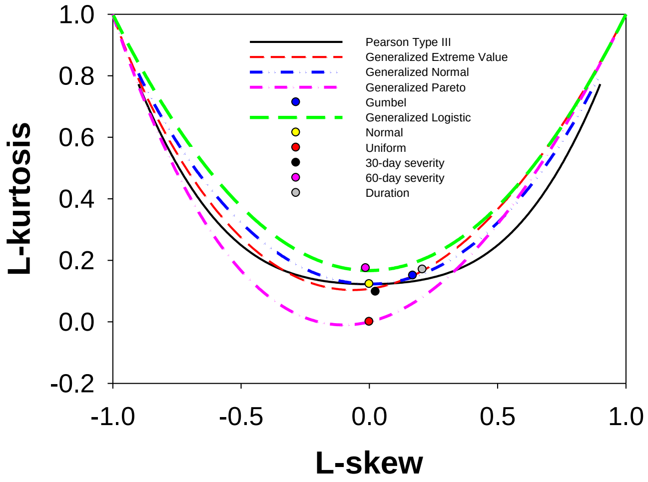


(a) Drought duration.

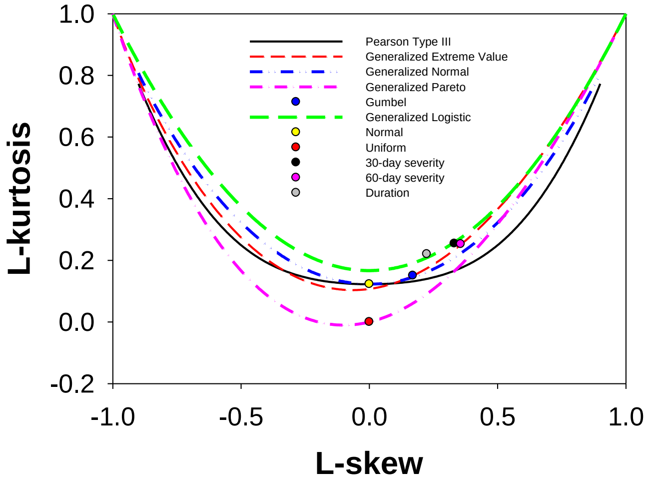


(b) Total water deficit volume (drought severity).

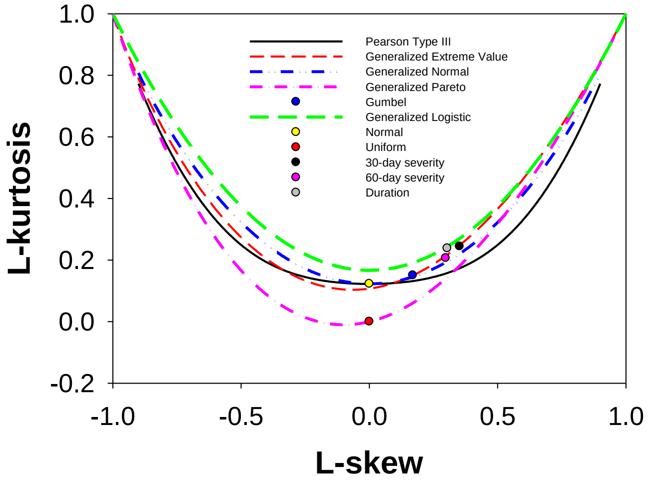
Fig. 6. Time series of the annual maxima values of duration and severity.



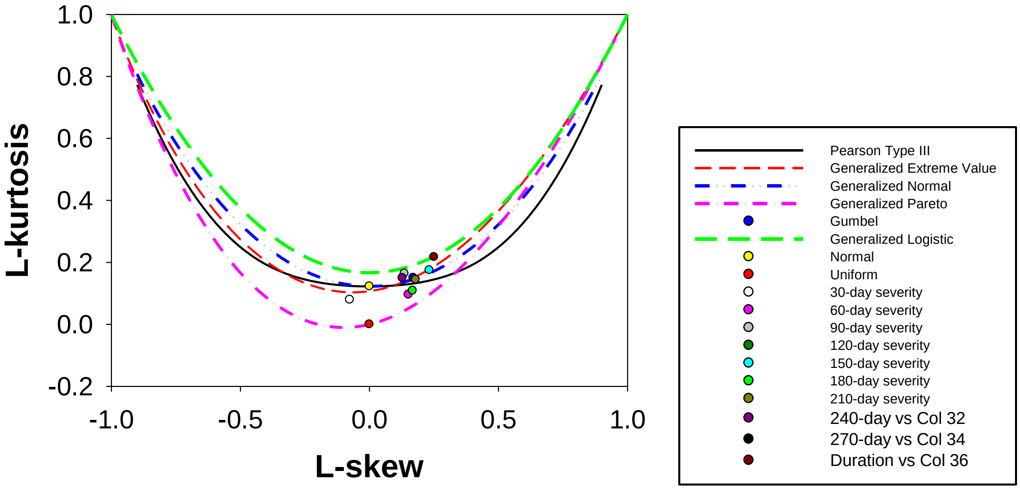
(a) Fixed.



(b) Daily.

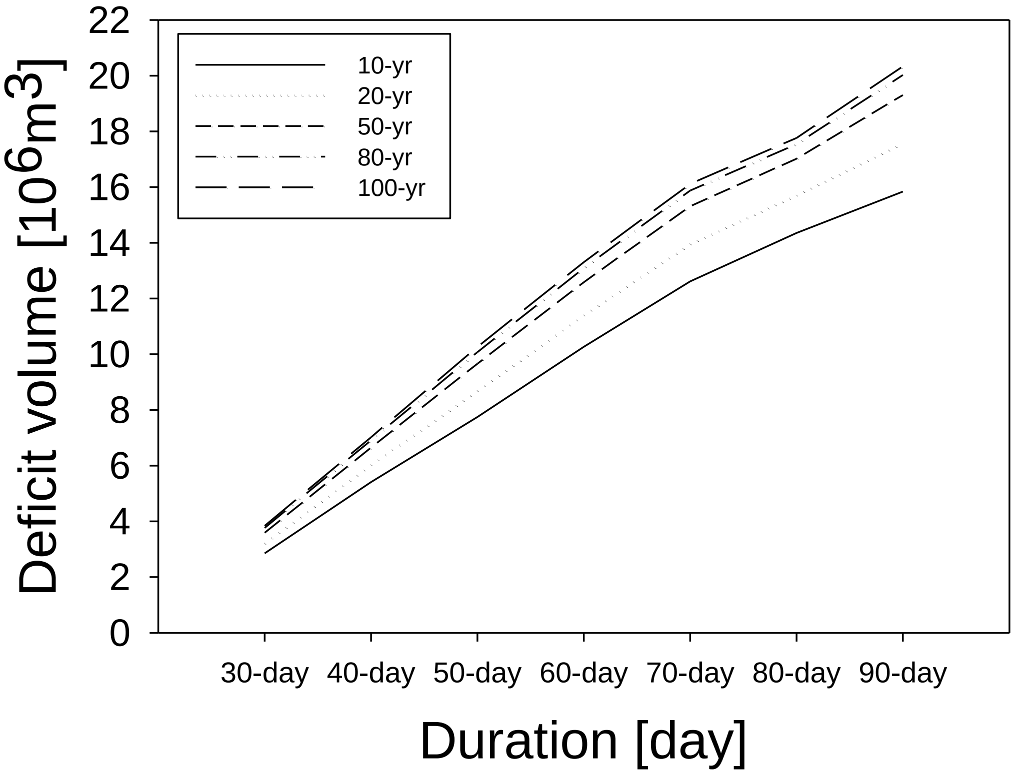


(c) Monthly.

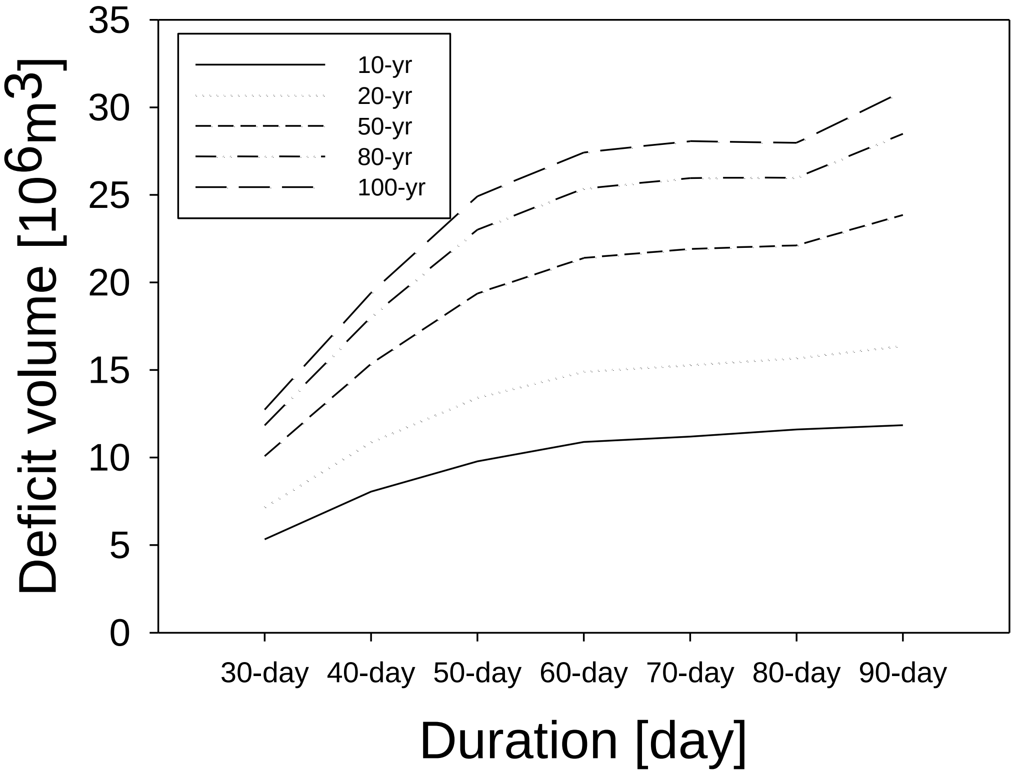


(d) Desired yield.

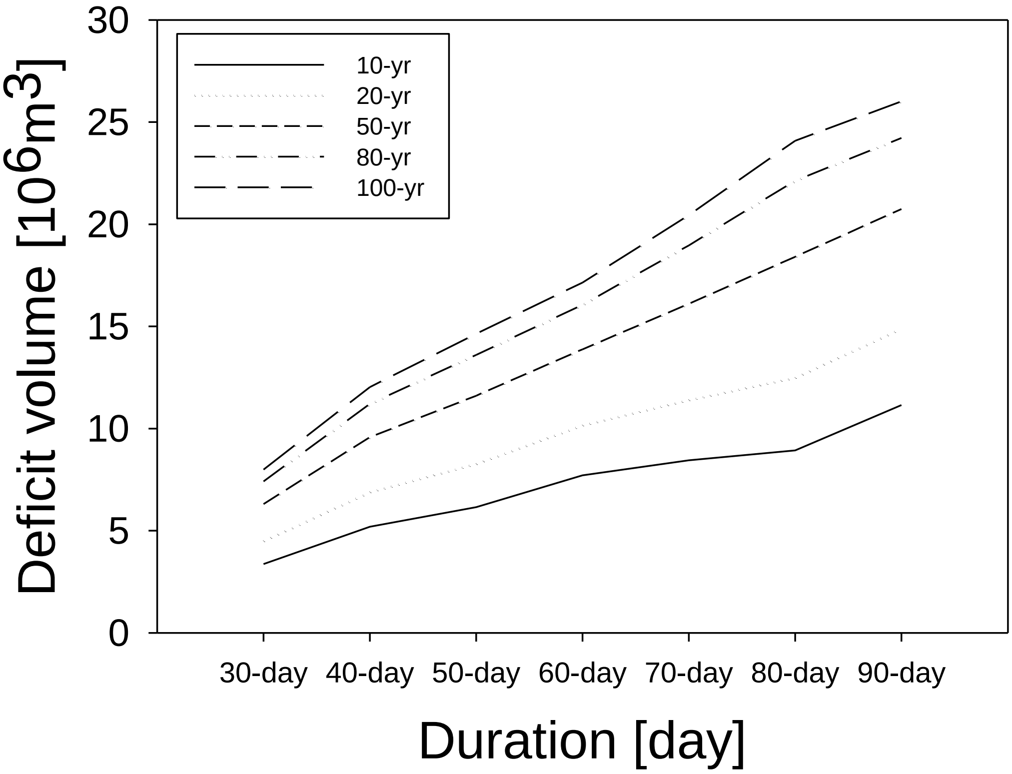
Fig. 7. L-moment diagram for probability distribution identification.



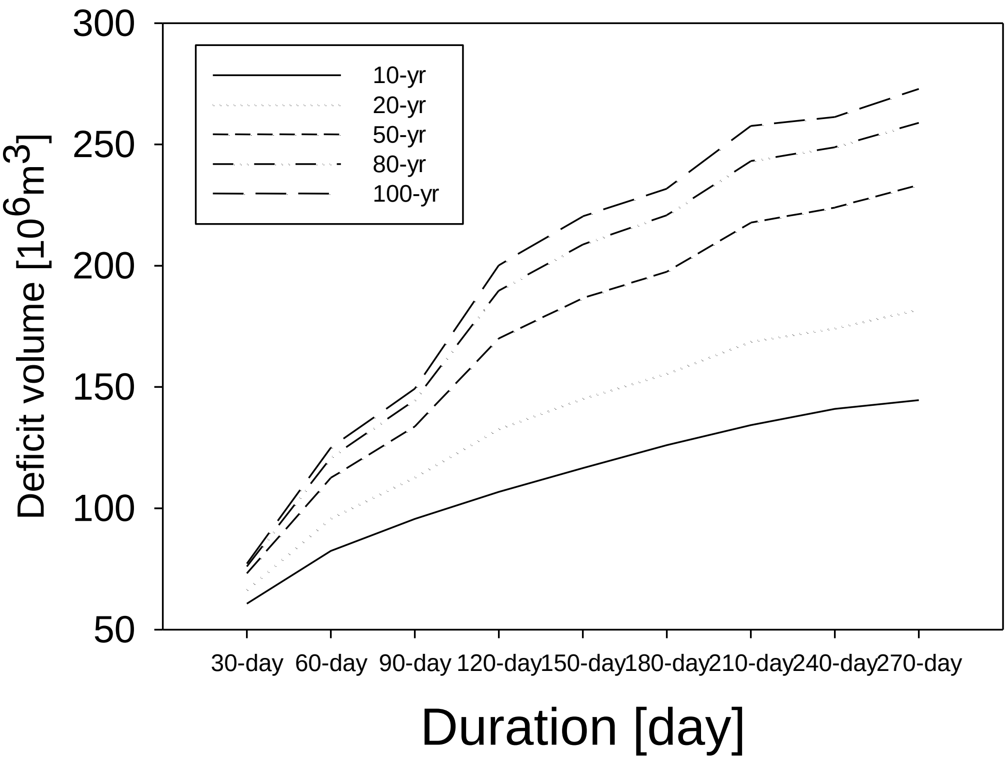
(a) Fixed.



(b) Daily.



(c) Monthly.



(d) Desired yield.

Fig. 8. SDF curves of the four threshold approaches in the Seomjin river basin.

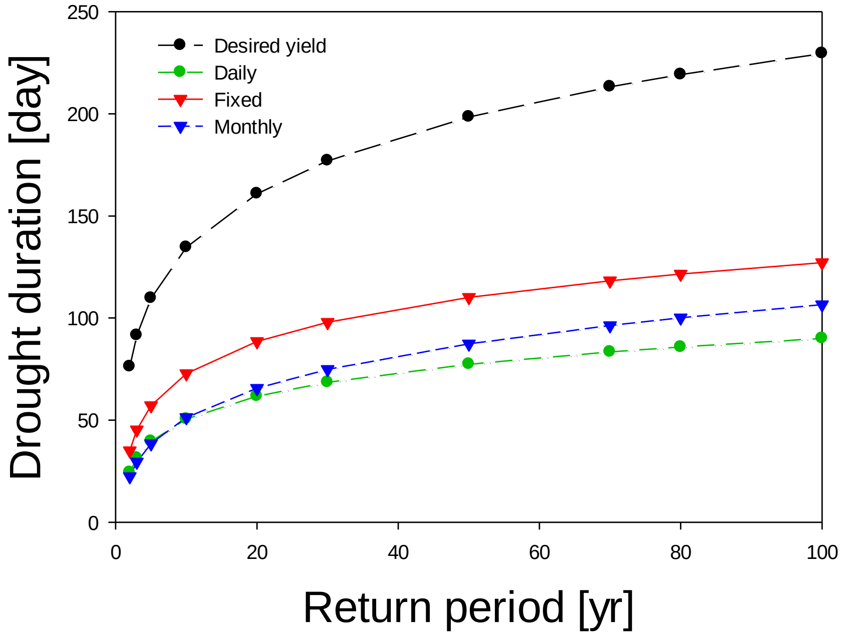


Fig. 9. Duration-frequency curves of the four threshold level approaches in the Seomjin river basin.

Table 1. Monthly average of the four threshold levels.

	Threshold level [m^3s^{-1}]			
	Fixed	Monthly	Daily	Desired yield
Jan	1.9	1.6	1.5	5.4
Feb	1.9	1.6	2.4	4.5
Mar	1.9	3.9	3.9	2.2
Apr	1.9	2.4	2.5	4.1
May	1.9	1.8	1.9	8.2
Jun	1.9	2.4	3.4	39.4
Jul	1.9	5.9	7.1	34.7
Aug	1.9	5.0	5.1	39.4
Sep	1.9	2.3	2.9	15.4
Oct	1.9	0.6	0.7	4.0
Nov	1.9	0.8	0.9	4.0
Dec	1.9	1.2	1.2	3.8

Table 2. Summary of the four threshold approaches.

Threshold level method	Maximum Duration (days)	Maximum Severity (m^3)
Fixed	92	9,304,762
Monthly	96	10,774,642
Daily	96	18,457,943
Desired yield	232	285,854,400

Table 3. Correlations between durations and severities for the four threshold levels.

Duration				
	Fixed	Monthly	Daily	Desired yield
Fixed	1			
Monthly	0.632	1		
Daily	0.632	0.923	1	
Desired yield	0.677	0.420	0.475	1

Severity				
	Fixed	Monthly	Daily	Desired yield
Fixed	1			
Monthly	0.441	1		
Daily	0.414	0.853	1	
Desired yield	0.281	0.551	0.599	1

Table 4. Severity-duration-frequency of the desired yield in the Seomjin river basin.

Duration [day]	Return period [yr]				
	10	20	50	80	100
30	60.7	66.4	73.1	75.9	77.2
60	82.4	95.9	112.5	120.8	124.9
90	95.6	112.8	133.7	144.6	149.3
120	106.8	132.7	170.0	189.7	200.1
150	116.6	145.2	186.6	208.7	220.3
180	126.0	155.5	197.5	220.8	231.7
210	134.3	168.7	217.7	243.1	257.6
240	141.0	174.2	223.9	248.8	261.3
270	144.6	182.0	233.3	258.9	272.9