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

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Abstract

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

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 streamflow intervene with the normal agricultural and economic activities of a region, leading to a decrease in agriculture production and in turn affecting everyday life. Dracup et al. (1980) defined drought as follows: 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 have been proposed over the years to identify drought. That is, 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).

American Meteorological Society (1997) groups drought definitions and types into four categories: meteorological or climatological, agricultural, hydrological, and socioeconomic droughts. The meteorological drought is resulted from 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 reducing streamflow, groundwater, reservoir and lake levels, will result in a hydrological drought. If hydrological drought continues until the supply and demand of some economic goods is damaged, a socioeconomic drought happens (Heim, 2002).

Especially, 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 streamflow including snowmelt and springflow, lake and reservoir storage, recharge of aquifers, discharge from aquifers and baseflow (Nalbantis and Tsakiris, 2009). That is, streamflow is the key variable to analyze in describing hydrological droughts since it embeds outputs of four different sub-systems, 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 many 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 a hydrological and socioeconomic drought event is related to streamflow deficit with respect to hydrological normal condition or target water supply for economic growth and social welfare.

For more specifications, 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 have been 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 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.

Based on the typical drought characteristics (water deficit and duration) and threshold levels, this study developed a comprehensive concept to quantify the streamflow drought severity which is closely related to hydrological and socioeconomic drought, using fixed, monthly, daily and desired yield threshold levels. Furthermore, this study proposed the streamflow drought severity-duration-frequency (SDF) curve using traditional frequency analyses. This methodology 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 fixed, monthly, daily, and desired yield for water use. Step 2 is to calculate the severities (total water deficits) and durations for all drought events at the four threshold levels. Step 3 is to derive the annual maxima of severity and duration and to identify the best-fitted probability distribution functions using L-moment ratio diagrams (Hosking and Wallis, 1997). Step 4 is to calculate the streamflow drought severities using the selected probability distribution with best-fitted parameters and to develop SDF curves. Step 5 is to develop the duration-frequency curves of four threshold levels using 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 SPI (Standardized Precipitation Index) for meteorology (Yoo et al., 2008) and PDSI (Palmer Drought Severity Index) for 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 produced 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 a number of minor drought events. Because these droughts are mutually dependent, Tallaksen et al. (1997) proposed that the independent sequence of drought events must be described using some types 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 were pooled to form a drought event as (Zelenhasic and Salvai, 1987; Tallaksen et al., 1997)

$$d_{pool} = d_i + d_{i+1} + t_c,$$

$$s_{pool} = s_i + s_{i+1} - z_c \tag{1}$$

This study assumed t_c = 3 days and z_c = 10% of d_i or d_{i+1} for simplicity. This numbers should be studied later in more detail.

2.3 Threshold selection

The threshold might be fixed or vary over the 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 a FDC and twelve monthly FDCs based on the entire record period. The daily varying threshold can be derived using the antecedent 365 daily streamflow.

The threshold choice is influenced by the study objective and region and available data. In general, a percentile from FDC 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 FDC. That is, 70% is the percentage of time that the streamflow, Q_{70}, is exceeded. However, the threshold selection should be more studied, because Q_{70} doesn't have any obvious evidences to be a representative threshold for the monsoon climate rivers.

The time resolution, where to apply series of annual, monthly or daily streamflow, depends on the hydrologic regime under study area. In the temperate zone a given year might include both severe droughts (seasonal droughts) and months with abundant streamflow, meaning that annual data wouldn't often reveal severe droughts. Dry regions are more likely to experience droughts lasting for several years, multi-year droughts, which supports the use of a monthly or an annual time step. Hence, different time resolutions might lead to difference 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 of the study area have never studied.

Fig. 3

The variable threshold approach is adapted to detect streamflow deviations for both high and low flow seasons. Lower than normal 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, due to a delayed onset of a snow-melt flood, isn't commonly considered a drought. Therefore, the events defined with the varying threshold should be called streamflow deficiency or streamflow anomalies rather than streamflow drought (Hisdal et al., 2004). On the other hand, the desired yield for sufficient water supply and environmental instreamflow can be an effective way to identify the streamflow drought with the consideration of hydrological and socioeconomic demands since environmental instreamflow becomes important in recent years.

2.4 Probability distribution function

L-moment diagram among 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 have been 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 relationship between the parameters and 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):

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

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

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

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 relationship 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):

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

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

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 varies 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 countries (Namwon City, Jinan County, Imsil Country, 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% (the Northern Jeolla Province), and 9% (Southern Gyeongsang Province), and a total of 129,322 households and 321,104 residents 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. According to the "River Survey Report (K-water, 1992)", a drought in Seomjin river basin occurs approximately every 10 years.

4. Results

4.1. Determination of the threshold levels

This study used four threshold levels. The fixed is Q_{70} of FDC which resulted from 37-year daily streamflows. The monthly thresholds are twelve Q_{70}s of monthly FDCs which resulted from all daily streamflows of January, February … and December for the past 37 years, respectively. The daily threshold is Q_{70} of FDCs which resulted from the antecedent

365 daily streamflows. Thus, the daily changes smoothly every day. The desired yield threshold for sufficient water supply and environmental instreamflow was determined by Korean central government. That is, it is related to social and economic droughts since it associates the supply and demand of some 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 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 were highly fluctuating 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 thresholds 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 larger 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 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 due to agricultural water use. Similar to the results for drought duration, the severities showed much higher values.

Table 2

Fig. 6

To compare the differences from four threshold levels, the correlation coefficients were calculated as shown in Table 3. The similar trend was observed in the monthly and daily threshold levels. However, the durations and severity from the desired yield threshold level were completely different from those for fixed, monthly and daily levels. That is, it can be guessed 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 which are anomaly type (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 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, 3 parameter distributions such as the Pearson Type 3(PT3), Generalized Normal (GNO), and Generalized Extreme Value (GEV) distributions appeared consistent with their datasets. In the frequency analysis dealing with extreme values, the distributions which have more than 3 parameters are required for expression of upper tail. PT3, GNO, and GEV distribution can be applied in this study. As shown in Fig. 7, this study selected GEV distribution for a representative probability distribution because most observations are appropriate for the GEV. It corresponds to Dalezios et al. (2000) for PDSI and Yoo et al. (2008) for SPI.

Fig. 7

4.4 Development of SDF curves

Streamflow drought SDF curves were developed using the derived probability distribution functions, as shown in Figs. 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 record length of available data is only 37 years, we calculated up to 100-year frequency. However, SDF curves from fixed, daily, and monthly thresholds were derived using comparatively short durations since the annual maximum durations varies from 30 to 96 days. SDF described streamflow drought severities with respect to any durations and frequencies. The severity increases with increasing frequencies and durations. For 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 bigger. Therefore, because the streamflow drought severity should be more crucial when the drought continues for long 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 deficit volume using threshold levels. However, using the deficit volume isn't sufficient to explain the extreme droughts. Thus, analyzing streamflow drought durations can be another useful tool to identify the drought event. So, occurrence probabilities of various duration events were also estimated using general frequency analysis. As a result, using GEV distribution, already 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 SDF curves, the durations for desired yield showed 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 drought were developed to quantify a specific volume according to a specific duration and frequency. Also duration-frequency curves were used to derive the relationship between drought duration and frequency. This study used severity which represented the total water deficit for the specific durations. Using the L-moment diagram method, the GEV was selected for the best-fit probability distribution. As a result, SDF curve were derived to identify the relationship among streamflow drought severity, duration and frequency. The severities increased with increasing durations and frequencies. However, these values were quite different because the four threshold level approaches defined the streamflow drought differently.

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

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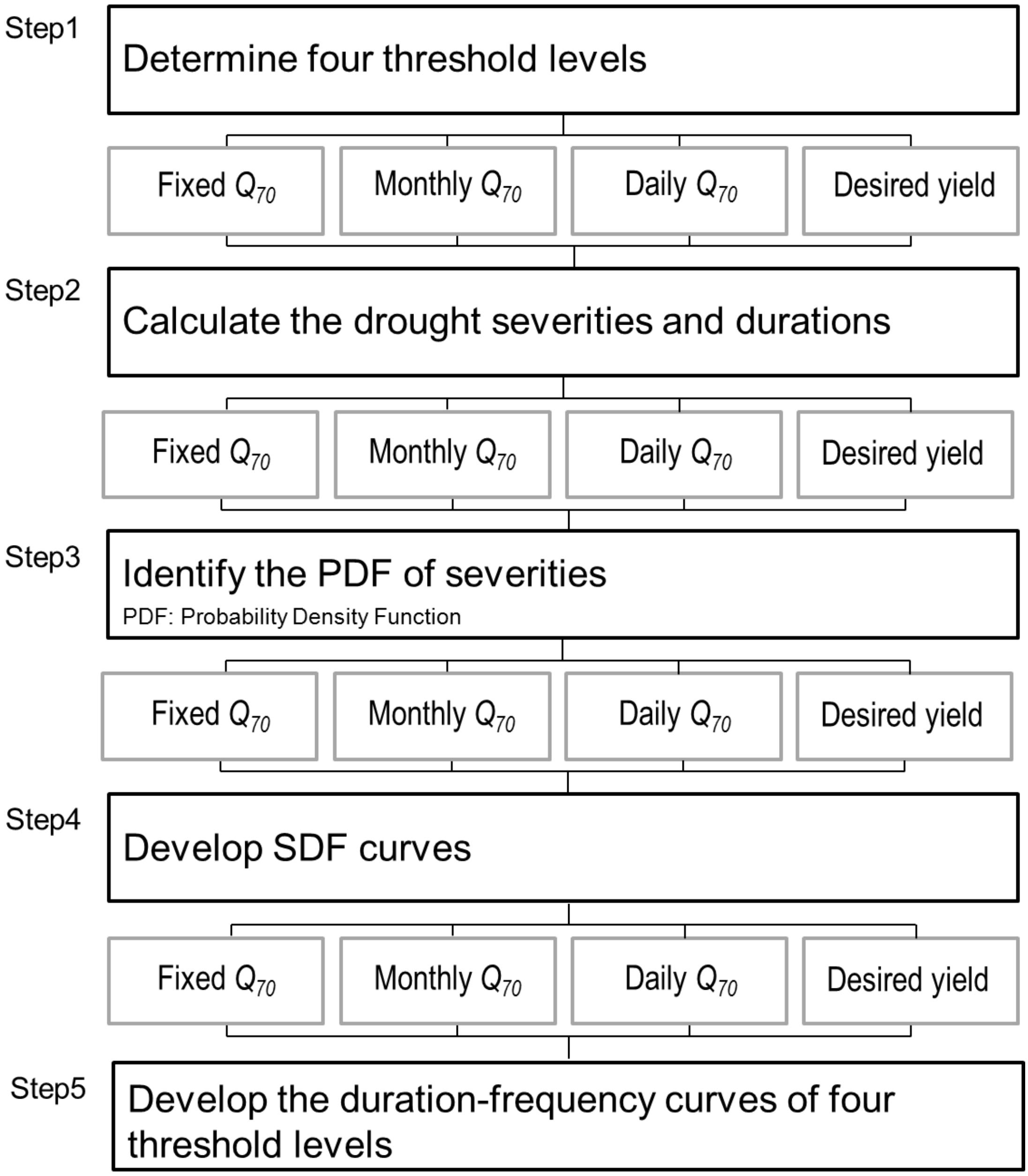


Fig. 1. Procedure of this study

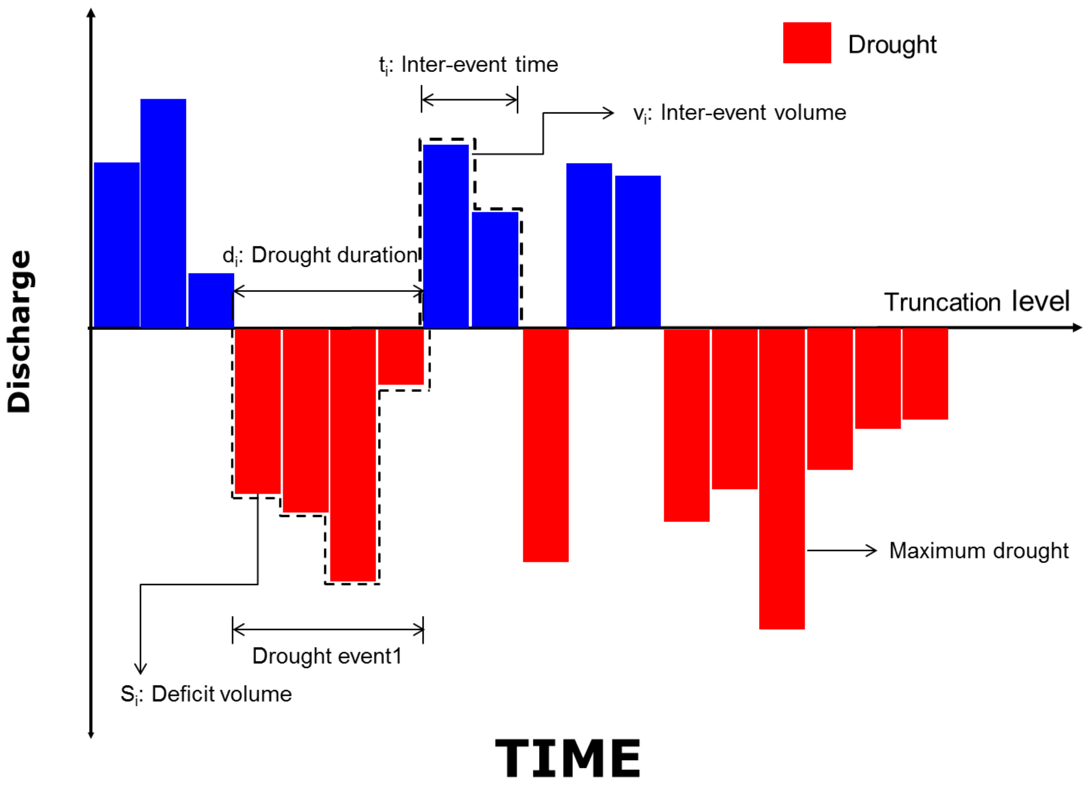


Fig. 2. A definition sketch of general drought events

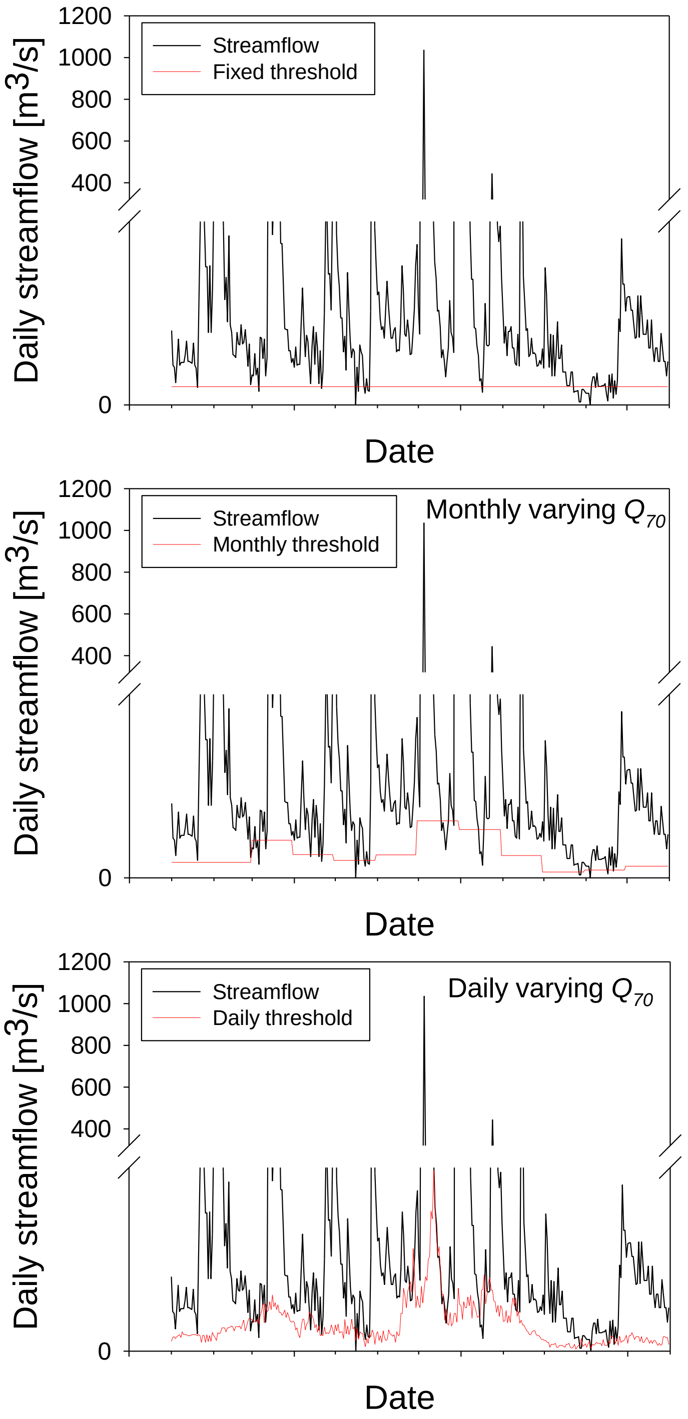


Fig. 3. Examples of threshold levels: Fixed (top); monthly varying (middle); daily varying (bottom)

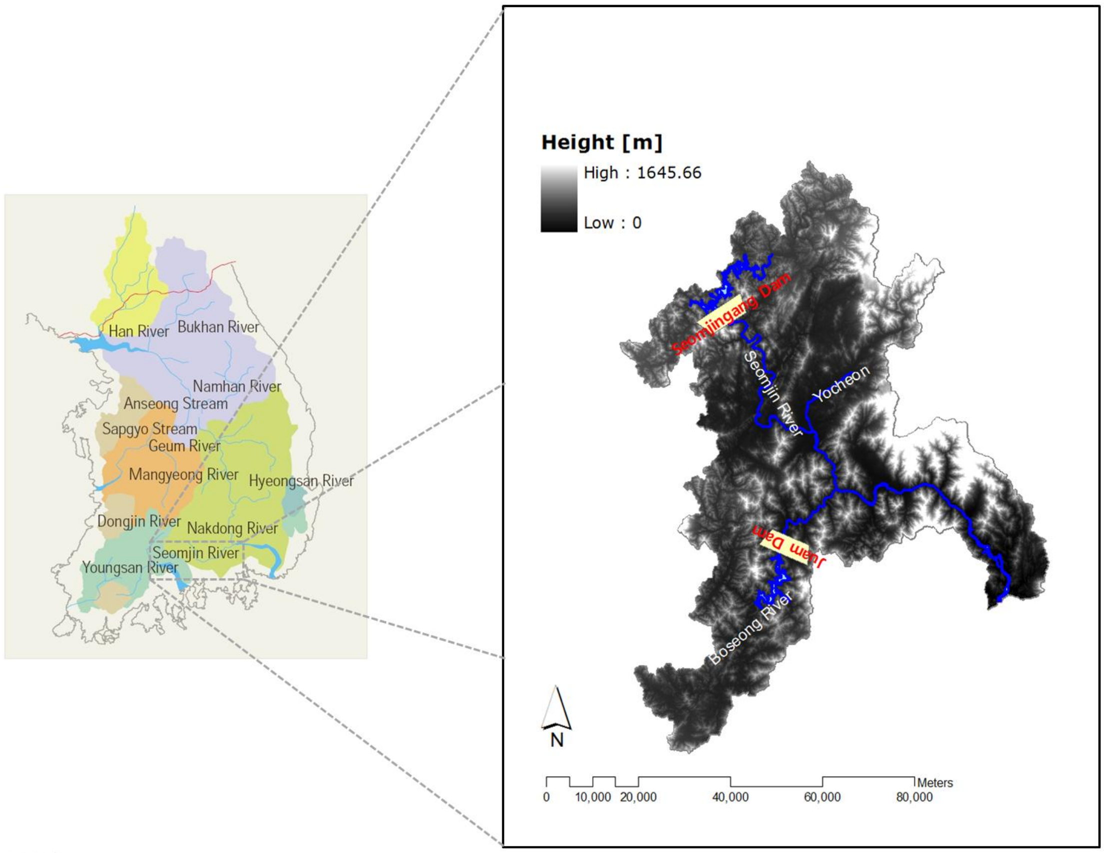


Fig. 4. Location of the selected river basin, including elevation and river

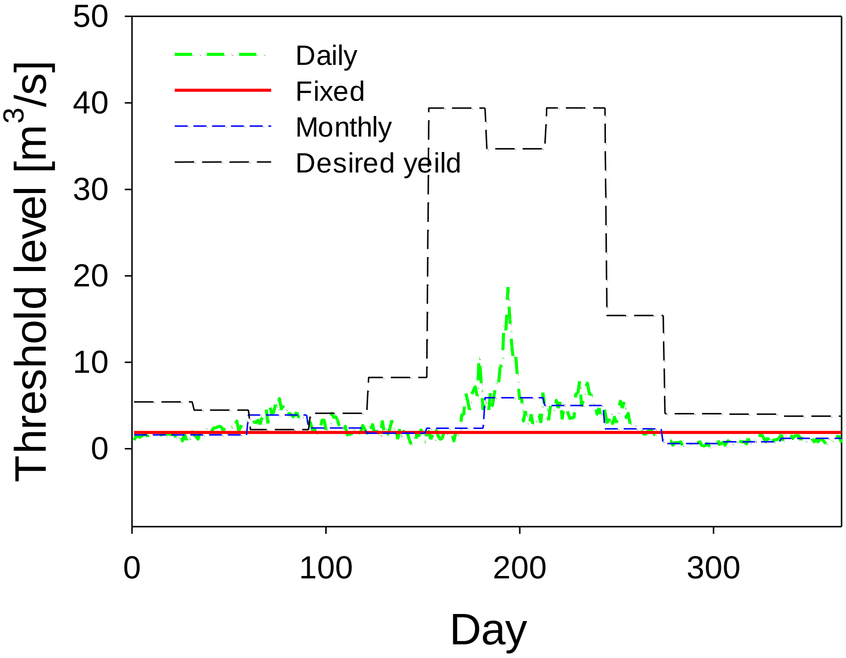
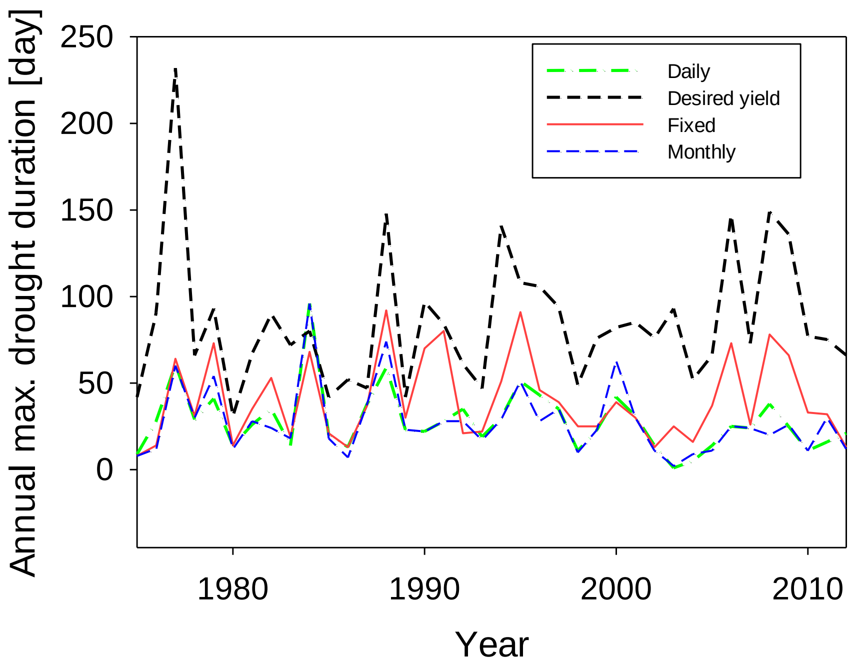
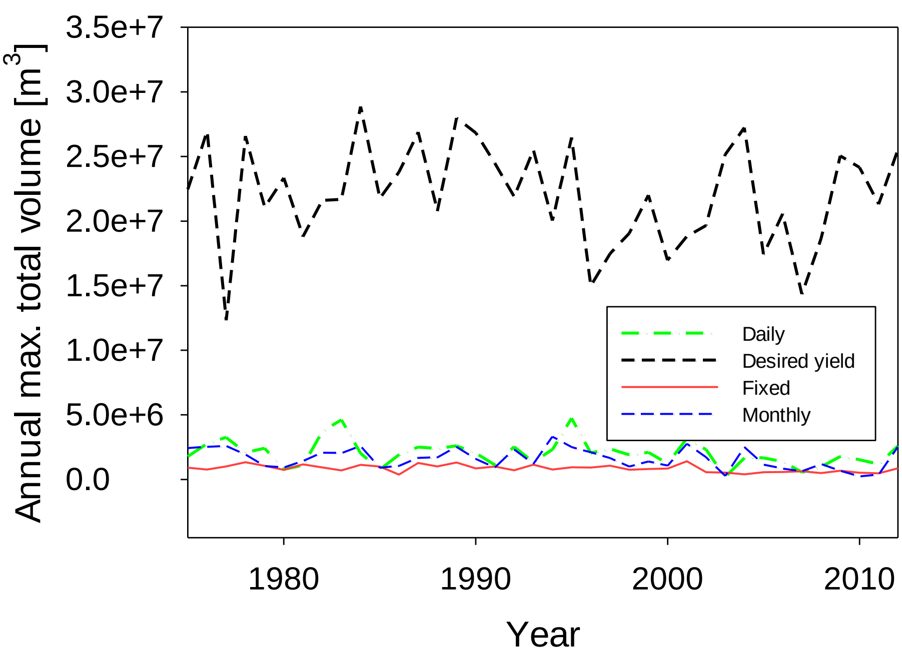


Fig. 5 Comparative four threshold levels used in this study

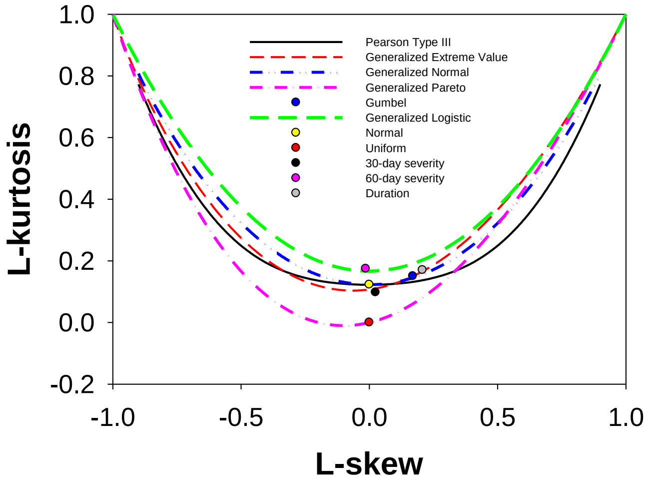


(a) Drought duration

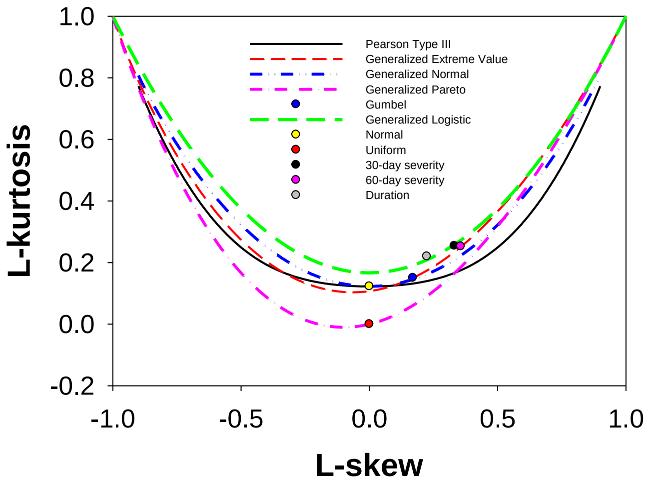


(b) Total water deficit volume (drought severity)

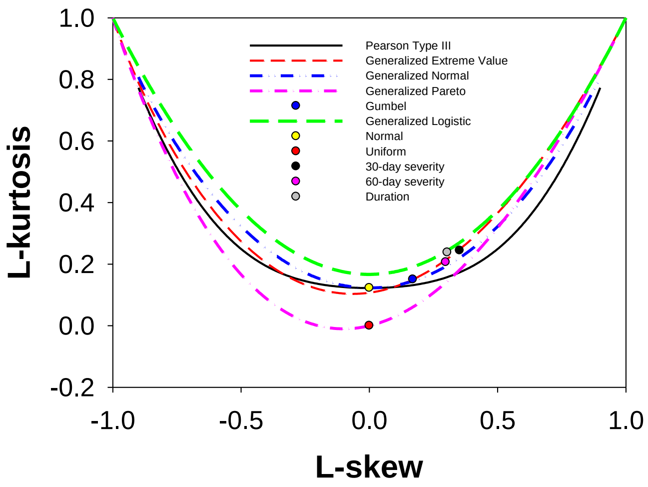
Fig. 6. Time series of annual maxima values of duration, severity



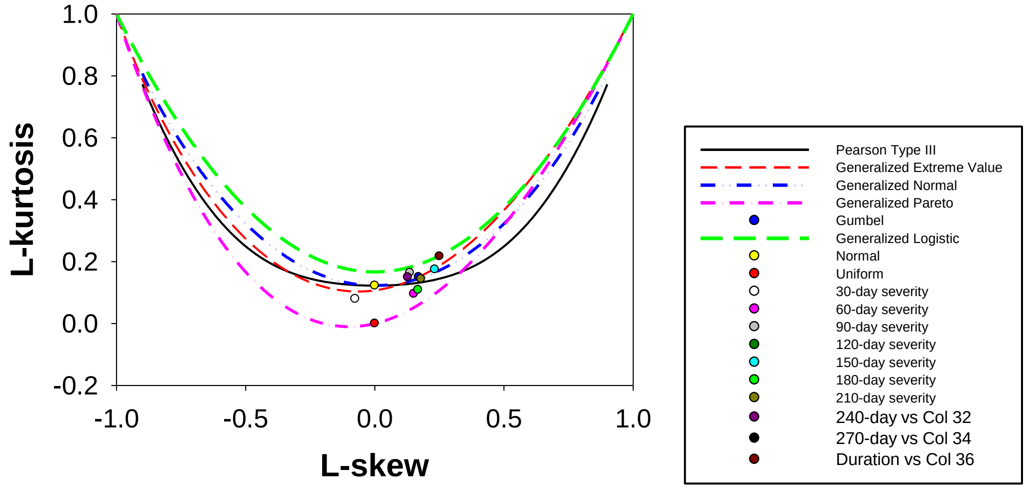
(a) Fixed



(b) Daily

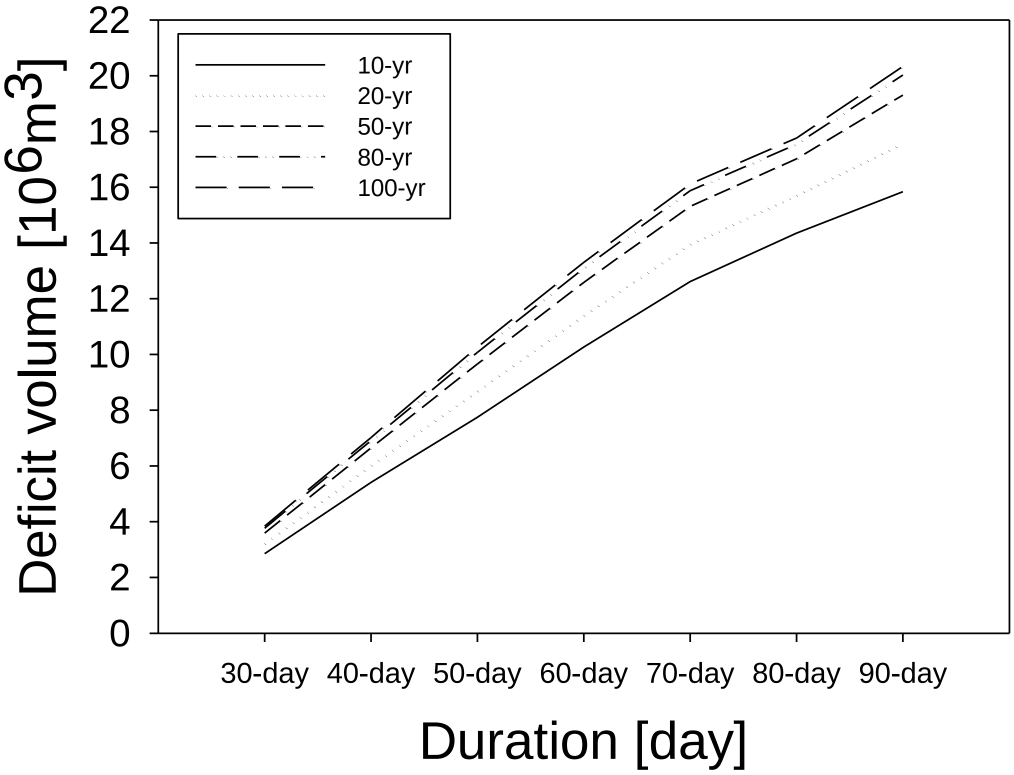


(c) Monthly

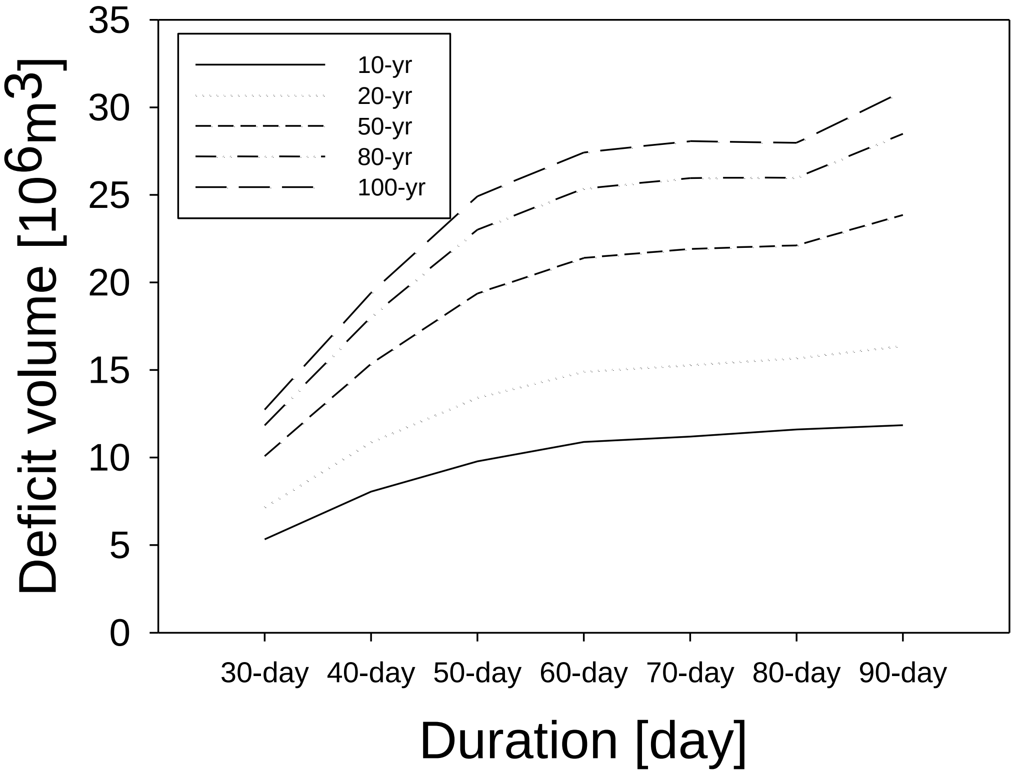


(d) Desired yield

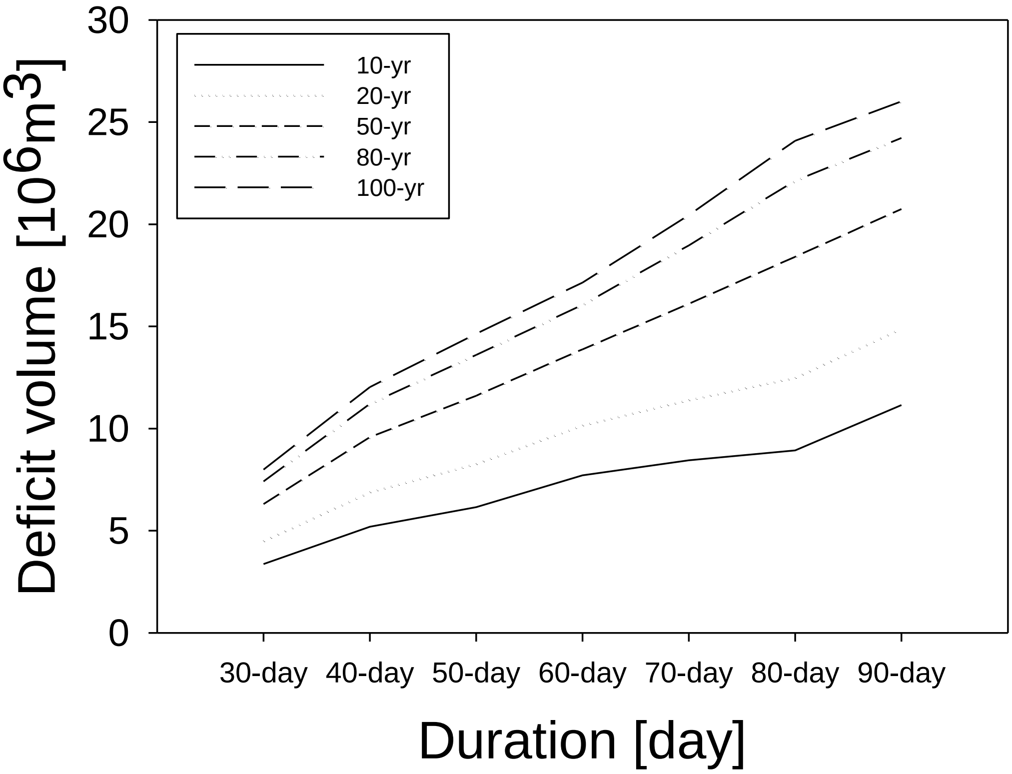
Fig. 7 L-moment diagram for probability distribution identification



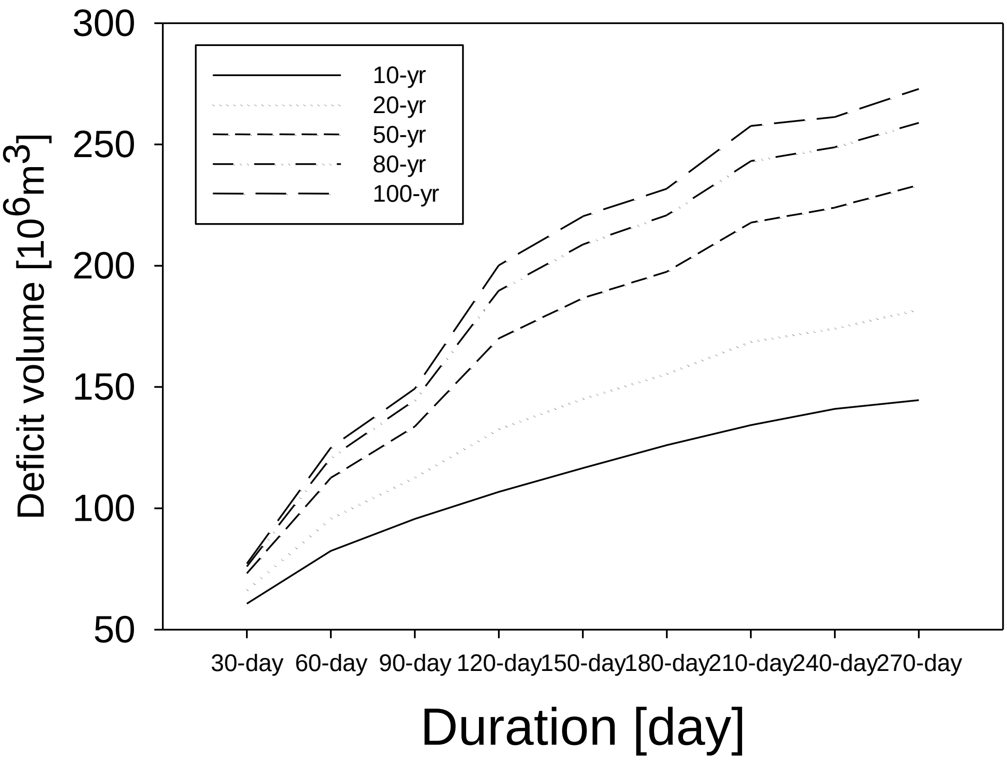
(a) Fixed



(b) Daily



(c) Monthly



(d) Desired yeild

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

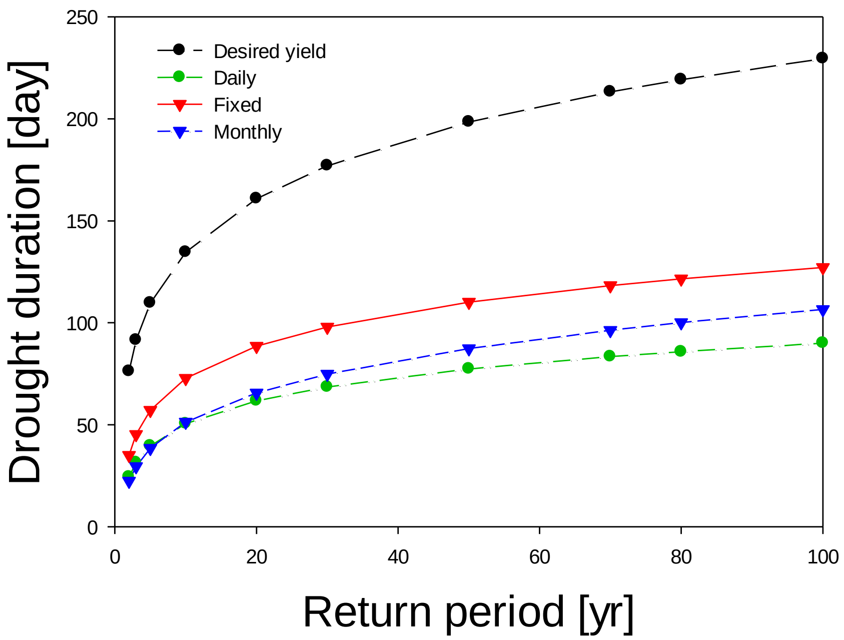


Fig. 9. Duration frequency curves of four threshold level approaches in Seomjin river basin

Table 1. Monthly averaged of 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 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 from 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 desired yield in 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