

# 1 Development of Streamflow Drought Severity-Duration-Frequency 2 Curves Using the Threshold Level Method

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## 10 11 Abstract

12 This study developed a streamflow drought severity-duration-frequency (SDF) curve  
13 that is analogous to the well-known depth-duration-frequency (DDF) curve used for rainfall.  
14 Severity was defined as the total water deficit volume to target threshold for a given drought  
15 duration. Furthermore, this study compared the SDF curves of four threshold level methods:  
16 fixed, monthly, daily, and desired yield for water use. The fixed threshold level in this study  
17 is the 70<sup>th</sup> percentile value ( $Q_{70}$ ) of the flow duration curve (FDC), which is compiled using  
18 all available daily streamflows. The monthly threshold level is the monthly varying  $Q_{70}$   
19 values of the monthly FDC. The daily variable threshold is  $Q_{70}$  of the FDC that was obtained  
20 from the antecedent 365 daily streamflows. The desired-yield threshold that was determined  
21 by the central government consists of domestic, industrial, and agricultural water uses and  
22 environmental instreamflow. As a result, the durations and severities from the desired-yield  
23 threshold level were completely different from those for the fixed, monthly and daily levels.  
24 In other words, the desired-yield threshold can identify streamflow droughts using the total  
25 water deficit to the hydrological and socioeconomic targets, whereas the fixed, monthly, and  
26 daily streamflow thresholds derive the deficiencies or anomalies from the average of the  
27 historical streamflow. Based on individual frequency analyses, the SDF curves for four  
28 thresholds were developed to quantify the relation among the severities, durations, and  
29 frequencies. The SDF curves from the fixed, daily, and monthly thresholds have  
30 comparatively short durations because the annual maximum durations vary from 30 to 96  
31 days, whereas those from the desired-yield threshold have much longer durations of up to 270  
32 days. For the additional analysis, the return period-duration curve was also derived to quantify  
33 the extent of the drought duration. These curves can be an effective tool to identify

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34 streamflow droughts using severities, durations, and frequencies.

35

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

38

## 39 **1. Introduction**

40 The rainfall deficiencies of sufficient magnitude over prolonged durations and extended  
41 areas and the subsequent reductions in the streamflow interfere with the normal agricultural  
42 and economic activities of a region, which decreases agriculture production and affects  
43 everyday life. Dracup et al. (1980) defined a drought using the following properties: 1) nature  
44 of water deficit (e.g., precipitation, soil moisture, or streamflow); 2) basic time unit of data  
45 (e.g., month, season, or year); 3) threshold to distinguish low flows from high flows while  
46 considering the mean, median, mode, or any other derived thresholds; and 4) regionalization  
47 and/or standardization. Based on these definitions, various indices were proposed over the  
48 years to identify drought. Recent studies have focused on such multi-faceted drought  
49 characteristics using various indices (Palmer, 1965; Rossi et al., 1992; McKee et al., 1993;  
50 Byun and Wilhite, 1999; Tsakiris et al., 2007; Pandey et al., 2008a; 2008b; 2010; Nalbantis  
51 and Tsakiris, 2009; Wang et al., 2011; Tabari et al., 2013; Tsakiris et al., 2013).

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

60 Hydrological and socioeconomic droughts are notably difficult to approach. Nalbantis and  
61 Tsakiris (2009) defined a hydrological drought as “a significant decrease in the availability of  
62 water in all its forms, appearing in the land phase of the hydrological cycle”. These forms are  
63 reflected in various hydrological variables such as streamflows, which include snowmelt and  
64 spring flow, lake and reservoir storage, recharge of aquifers, discharge from aquifers, and  
65 baseflow (Nalbantis and Tsakiris, 2009). Therefore, Tsakiris et al. (2013) described that  
66 streamflow is the key variable in describing hydrological droughts because it considers the  
67 outputs of surface runoff from the surface water subsystem, subsurface runoff from the upper  
68 and lower unsaturated zones, and baseflow from the groundwater subsystem. Furthermore,  
69 streamflow crucially affects the socioeconomic drought for several water supply activities

70 such as hydropower generation, recreation, and irrigated agriculture, where crop growth and  
71 yield largely depends on the water availability in the stream (Heim, 2002). Hence,  
72 hydrological and socioeconomic droughts are related to streamflow deficits with respect to  
73 hydrologically normal conditions or target water supplies for economic growth and social  
74 welfare.

75 For additional specification, Tallaksen and van Lanen (2004) defined a streamflow  
76 drought as a “sustained and regionally extensive occurrence of below average water  
77 availability”. Thus, threshold level approaches, which define the duration and severity of a  
78 drought event while considering the daily, monthly, seasonal, and annual natural runoff  
79 variations, are widely applied in drought analyses (Yevjevich, 1967; Sen, 1980; Dracup et al.,  
80 1980; Dalezios et al., 2000; Kjeldsen et al., 2000; American Meteorological Society, 2002;  
81 Hisdal and Tallaksen, 2003; Wu et al. 2007; Pandey et al., 2008a; Yoo et al., 2008; Tigkas et  
82 al., 2012; van Huijgevoort, 2012). These approaches provide an analytical interpretation of  
83 the expected availability of river flow; a drought occurs when the streamflow falls below the  
84 threshold level. This level is frequently considered a certain percentile flow for a specific  
85 duration and assumed to be steady during the considered month, season, or year. Therefore,  
86 Kjeldsen et al. (2000) applied three variable threshold level methods using seasonal, monthly  
87 and daily streamflows.

88 There has been a growing need for new planning and design of natural resources and  
89 environment based on the aforementioned scientific trends. For design purposes, IDF curves  
90 have been used for a long time to synthesize the design storm. Therefore, many studies have  
91 integrated drought severity and duration based on the multivariate theory (Bonaccorso et al.,  
92 2003; Gonz ález and Vald ´es, 2003; Mishra et al., 2009; Song and Singh, 2010a, b; De  
93 Michele et al., 2013). However, these studies cannot fully explain droughts without  
94 considering the frequency, which resulted in the development of drought iso-severity curves  
95 for certain return periods and durations for design purposes.

96 Thus, based on the typical drought characteristics (water deficit and duration) and  
97 threshold levels, this study developed quantitative relations among drought parameters,  
98 namely severity, duration, and frequency. This study quantified the streamflow drought  
99 severity, which is closely related to hydrological and socioeconomic droughts, using fixed,  
100 monthly, daily, and desired-yield threshold levels. Furthermore, this study proposed a  
101 streamflow SDF curve using the traditional frequency analyses. In addition, this study also  
102 developed duration frequency curves of four threshold levels from the occurrence  
103 probabilities of various duration events using a general frequency analysis because the deficit  
104 volume is not sufficient to explain the extreme droughts. This framework was applied to the  
105 Seomjin River basin in South Korea.

106

107 **2. Methodology**

108 **2.1 Procedure**

109 This study consists of five steps as shown in Fig. 1. Step 1 determines the threshold levels  
110 for the fixed, monthly, daily, and desired-yield levels for water use. The threshold selection  
111 description is shown in section 2.3. Step 2 calculates the severities (total water deficits) and  
112 durations for all drought events at the four threshold levels. The method to derive the severity  
113 and duration is shown in section 2.2. Step 3 derives the annual maxima of severity and  
114 duration and identifies the best-fit probability distribution functions using the L-moment ratio  
115 diagrams (Hosking and Wallis, 1997). The calculation procedure is shown in section 2.4  
116 using related equations and descriptions. Step 4 calculates the streamflow drought severities  
117 using the selected probability distribution with the best-fit parameters and develops the SDF  
118 curves. This step is described in Section 2.5. Step 5 develops the duration-frequency curves of  
119 the four threshold levels using an appropriate probability distribution.

120

121 Fig. 1

122

123 **2.2. Streamflow drought severity**

124 In temperate regions where the runoff values are typically larger than zero, the most  
125 widely used method to estimate a hydrological drought is the threshold level approach  
126 (Yevjevich, 1967; Fleig et al., 2006; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012).  
127 The streamflow drought severity with the threshold level method has the following  
128 advantages over the standardized precipitation index (SPI) in meteorology (Yoo et al., 2008)  
129 and the Palmer drought severity index (PDSI) in meteorology and agriculture (Dalezios et al.,  
130 2000): 1) no a priori knowledge of probability distributions is required, and 2) the drought  
131 characteristics such as frequency, duration, and severity are directly determined if the  
132 threshold is set using drought-affected sectors.

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

139

140 Fig. 2

141

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

$$146 \quad d_{pool} = d_i + d_{i+1} + t_c$$

$$147 \quad s_{pool} = s_i + s_{i+1} - z_c. \quad (1)$$

148 This study assumed  $t_c = 3$  days and  $z_c = 10\%$  of  $d_i$  or  $d_{i+1}$  for simplicity.

149

### 150 **2.3 Threshold selection**

151 The threshold may be fixed or vary over the course of a year. A threshold is considered  
 152 fixed if a constant value is used for the entire series and variable if it varies over the year  
 153 based on the monthly and daily variable levels (Hisdal and Tallaksen, 2003). If the threshold  
 154 is derived from the flow duration curve (FDC), the entire streamflow record is used in its  
 155 derivation. As shown in Fig. 3, which is obtained from the study area, fixed and monthly  
 156 thresholds can be obtained from an FDC and twelve monthly FDCs based on the entire record  
 157 period. The daily varying threshold can be derived using the antecedent 365-day streamflow.

158 The threshold choice is influenced by the study objective, region, and available data. In  
 159 general, a percentile of the data can be used as the threshold. Relatively low thresholds in the  
 160 range of  $Q_{70} - Q_{95}$  are often used for perennial rivers (Kjeldsen et al., 2000). The fixed  
 161 threshold level in this study is the 70<sup>th</sup> percentile value ( $Q_{70}$ ) of FDC, which is compiled  
 162 using all available daily streamflows, and the monthly threshold level is the monthly varying  
 163  $Q_{70}$ s of each month’s FDC. The daily variable threshold is the  $Q_{70}$  value of the FDC, which  
 164 is obtained from the antecedent 365 daily streamflows. However, the threshold selection  
 165 should be further analyzed because it is not clear that  $Q_{70}$  should be used as a representative  
 166 threshold for rivers in a monsoon climate.

167 The time resolution, i.e., whether to apply series of annual, monthly, or daily streamflows,  
 168 depends on the hydrologic regime in the region of interest. In a temperate zone, a given year  
 169 may include both severe droughts (seasonal droughts) and months with abundant streamflow,  
 170 which indicates that the annual data do not often reveal severe droughts. Dry regions are more  
 171 likely to experience droughts that last for several years, i.e., multi-year droughts, which  
 172 supports the use of a monthly or annual time step. Hence, different time resolutions may lead  
 173 to different results regarding the drought event selection. This study used the daily streamflow  
 174 data, and various time resolutions (30, 60, 90, 120, 150, 180, 210, 240 and 270 days) were  
 175 selected to identify the temporal characteristics.

176

177 Fig. 3

178

179 The variable threshold approach is adapted to detect streamflow deviations for both high-  
180 and low-flow seasons. Lower than average flows during high-flow seasons may be important  
181 for later drought development. However, periods with relatively low flow either during the  
182 high-flow season, which can be caused by a delayed onset of a snowmelt flood, are not  
183 commonly considered a drought. Therefore, the events that are defined with the varying  
184 threshold should be called streamflow deficiencies or streamflow anomalies instead of  
185 streamflow droughts (Hisdal et al., 2004). In contrast, the desired yield for sufficient water  
186 supply and environmental instreamflow can be an effective method to identify a streamflow  
187 drought by considering hydrological and socioeconomic demands because environmental  
188 instreamflow has become important in recent years.

189

## 190 2.4 Probability distribution function

191 An L-moment diagram for various goodness-of-fit techniques was used to evaluate the  
192 best probability distribution function for datasets in several recent studies (Hosking, 1990;  
193 Chowdhury et al., 1991; Vogel and Fennessey, 1993; Hosking and Wallis, 1997). The L-  
194 moment ratio diagram is a graph where the sample L-moment ratios, L-skewness ( $\tau_3$ ), and L-  
195 kurtosis ( $\tau_4$ ) are plotted as a scatterplot and compared with the theoretical L-moment ratio  
196 curves of the candidate distributions. The L-moment ratio diagrams were suggested as a  
197 useful graphical tool to discriminate amongst candidate distributions for a dataset (Hosking  
198 and Wallis, 1997). The sample average and line of best fit were used to select statistical  
199 distributions, and they can be plotted on the same graph to select the best-fit distribution.

200 When plotting an L-moment ratio diagram, the relation among the parameters and the L-  
201 moment ratios  $\tau_3$  and  $\tau_4$  for several distributions are required. For a generalized extreme  
202 value (GEV) distribution, the three-parameter GEV distribution described by Stedinger et al.  
203 (1993) has the following probability density function (PDF,  $f(x)$ ) and cumulative distribution  
204 function (CDF,  $F(x)$ ):

$$205 \quad f(x) = \frac{1}{\alpha} \left\{ 1 - \frac{\kappa}{\alpha} (x - \xi) \right\}^{1/\kappa - 1} \cdot \exp \left[ - \left\{ 1 - \frac{\kappa}{\alpha} (x - \xi) \right\}^{1/\kappa} \right] \quad \kappa \neq 0 \quad , \quad (3a)$$

$$206 \quad f(x) = \frac{1}{\alpha} \exp \left\{ - \frac{x - \xi}{\alpha} - \exp \left( - \frac{x - \xi}{\alpha} \right) \right\} \quad \kappa = 0 \quad , \quad (3b)$$

$$207 \quad F(x) = \exp \left[ - \left\{ 1 - \frac{\kappa}{\alpha} (x - \xi) \right\}^{1/\kappa} \right] \quad \kappa \neq 0 \quad , \quad (4a)$$

208 
$$F(x) = \exp \left\{ -\exp \left( -\frac{x - \zeta}{\alpha} \right) \right\} \quad \kappa = 0 \quad , \quad (4b)$$

209 where  $\zeta + \alpha/\kappa \leq x \leq \infty$  for  $\kappa < 0$ ,  $-\infty \leq x \leq \infty$  for  $\kappa = 0$ , and  $-\infty \leq x \leq \zeta + \alpha/\kappa$  for  
 210  $\kappa > 0$ . Here,  $\zeta$  is a location,  $\alpha$  is a scale, and  $\kappa$  is a shape parameter. For  $\kappa = 0$ , the GEV  
 211 distribution reduces to the classic Gumbel (EV1) distribution with  $\tau_3 = 0.17$ . Hosking and  
 212 Wallis (1997) provided more detailed information regarding the GEV distribution. The  
 213 relation among the parameters and  $\tau_3$  and  $\tau_4$  for the GEV distribution of the shape  
 214 parameters can be obtained as follows (Hosking and Wallis, 1997):

215 
$$\tau_3 = \frac{2(1 - 3^{-\kappa})}{(1 - 2^{-\kappa})} - 3 \quad (5a)$$

216 
$$\tau_4 = \frac{5(1 - 4^{-\kappa}) - 10(1 - 3^{-\kappa}) + 6(1 - 2^{-\kappa})}{(1 - 2^{-\kappa})} . \quad (5b)$$

217

## 218 **2.5 Development of the SDF relationships**

219 The IDF or depth-duration-frequency (DDF) curves can be defined to “allow calculation  
 220 of the average design rainfall intensity (or depth) for a given exceedance probability over a  
 221 range of durations” (Stedinger et al., 1993). Statistical frequency analyses such as rainfall  
 222 analyses are frequently used for drought events. However, this method cannot fully explain  
 223 droughts without considering the severity and duration, which resulted in the development of  
 224 the SDF curve. Thus, extreme drought events can be specified using the frequency, duration  
 225 and either depth or mean intensity (i.e., severity). The frequency is usually described by the  
 226 return period of the drought. Because its magnitude is given by the total depth that occurs in a  
 227 particular duration, the SDF relation can be derived. To estimate the return periods of drought  
 228 events of a particular depth and duration, the frequency distributions can be used (Dalezios et  
 229 al., 2000).

230

## 231 **3. Study region**

232 The Seomjin River basin is located in southwestern Korea (Fig. 4). The area and total  
 233 length of Seomjin River are approximately 4,911.9 km<sup>2</sup> and 212.3 km, respectively. The  
 234 altitude range is notably large, spanning from approximately 0 to 1,646 m (Fig. 4). The  
 235 climate of South Korea is characterized by extreme seasonal variations. Winter is cold and  
 236 dry under the dominant influence of the Siberian air mass, whereas the summer is hot and  
 237 humid with frequent heavy rainfalls, which are associated with the East Asian monsoon. In  
 238 the Seomjin River basin, the measured precipitation is mainly concentrated in summer, and  
 239 the measured mean annual precipitation varied from < 1,350 mm/yr<sup>-1</sup> (in the north region) to

240 > 1,600 mmyr<sup>-1</sup> (in the southeastern region) during the 1975-2012 observation period. In  
241 general, approximately 60% of the annual precipitation occurs during the wet season (July  
242 through September) in South Korea. This extreme seasonality in the precipitation causes  
243 periodic shortages of water during the dry season (October through March) and flood damage  
244 during the wet season.

245

246 Fig. 4.

247

248 The administrative districts where the basin is located cover three provinces, four cities,  
249 and 11 counties (Namwon City, Jinan County, Imsil County, and Sunchang County in the  
250 Northern Jeolla Province; Suncheon City, Gwangyang City, Damyang County, Gokseong  
251 County, Gurye County, Hwasun County, Boseong County, and Jangheung County in the  
252 Southern Jeolla Province; and Hadong County in the Southern Gyeongsang Province). The  
253 influx rates into the basin from these province are 47% (Southern Jeolla Province), 44%  
254 (Northern Jeolla Province), and 9% (Southern Gyeongsang Province), and a total of 321,104  
255 residents, who occupy 129,322 households, live in these areas.

256 The land use consists of arable land (876.29 km<sup>2</sup>), forest land (3,400.61 km<sup>2</sup>), urban area  
257 (67.12 km<sup>2</sup>), and other land uses (567.86 km<sup>2</sup>). Major droughts occurred in the Southern  
258 Jeolla Province from 1967 to 1968 and from 1994 to 1995. The Seomjin River basin had <  
259 1,000 mm of precipitation on average in 1977, 1988, 1994, and 2008. Among these years, the  
260 annual precipitation in 1988 was only 782.7 mm (56.5%) of the annual average of 1,385.5  
261 mm from 1967 to 2008, which represents a severe drought.

262

## 263 **4. Results**

### 264 **4.1. Determination of the threshold levels**

265 This study used four threshold levels. The fixed threshold level is  $Q_{70}$  of the FDC, which  
266 resulted from 37-year daily streamflows. The monthly thresholds are twelve  $Q_{70}$  values of  
267 monthly FDCs, which incorporated the data of all daily streamflows from January to  
268 December for the past 37 years. The daily threshold is  $Q_{70}$  of the FDCs, which resulted from  
269 the antecedent 365 daily streamflows. Thus, the daily threshold level smoothly varies  
270 everyday. The desired-yield threshold for a sufficient water supply and environmental  
271 instreamflow was determined by the Korean central government. This threshold is related to  
272 social and economic droughts because it associates the supply and demand of a number of  
273 economic goods and environmental safety. The desired-yield threshold is considerably  
274 different from the other levels and represents more realistic conditions because the desired



275 yield is equivalent to the planned water supply.

276 The four calculated thresholds are presented in Fig. 5, and the specific monthly averaged  
277 values are listed in Table 1. The average levels were 1.9, 2.5, 2.8, and 13.8 m<sup>3</sup>s<sup>-1</sup> for the fixed,  
278 monthly, daily and desired-yield levels, respectively. The daily threshold levels, which  
279 significantly fluctuated because of the natural streamflow variations during the antecedent  
280 365 days, were the largest among the four threshold levels because a summer period (June,  
281 July, and August) was considered. The desired-yield level was larger than the fixed, monthly,  
282 and daily thresholds. This phenomenon occurred during the winter in Korea, which  
283 significantly decreased both the water demand and natural runoff during the winter  
284 (December, January, and February). However, the thresholds for the daily, monthly, and  
285 desired-yield levels during the summer were much higher than those during the other seasons.  
286 The desired yield during May and June had much higher threshold levels than the other  
287 thresholds because this season had the highest agricultural water demand.

288

289 Fig. 5

290 Table 1

291

292

#### 293 **4.2 Calculations of the streamflow drought severity and duration**

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

301

302 Table 2

303

304 Fig. 6

305

306 To compare the differences among the four threshold levels, the correlation coefficients  
307 among the water deficits from four different threshold levels were calculated as shown in  
308 Table 3. Similar trends were observed for the monthly and daily threshold levels. However,  
309 the durations and severities from the desired-yield threshold level were completely different  
310 from those for the fixed, monthly and daily levels. In other words, the drought identification

311 techniques based on general threshold levels cannot reflect the socioeconomic drought in  
312 terms of the water supply and demand. Therefore, two-way approaches that are categorized  
313 using the time periods (fixed, monthly, and daily) for hydrological drought and the desired-  
314 yield threshold for socioeconomic droughts should be separately included to identify specific  
315 drought characteristics.

316

317 Table 3

318

### 319 **4.3 Determination of the probability distribution function**

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

324 The L-moment ratio diagrams were derived for the four threshold approaches and are  
325 shown in Fig. 7. Among the examined distribution models, three parameter distributions (the  
326 Pearson type 3 (PT3), generalized normal (GNO), and GEV distributions) appeared consistent  
327 with their datasets. In the frequency analysis that addressed extreme values, the distributions  
328 that use three parameters were required to express the upper tail. The PT3, GNO, and GEV  
329 distributions can be applied in this study. As shown in Fig. 7, this study selected the GEV  
330 distribution for a representative probability distribution because most observations are  
331 appropriate for the GEV.

332

333 Fig. 7

334

### 335 **4.4 Development of SDF curves**

336 Streamflow drought SDF curves were developed using the derived probability distribution  
337 functions as shown in Fig. 8. The SDF curves described the streamflow drought severities  
338 with respect to durations and frequencies. The severity increases with increasing frequency  
339 and duration. For these plots, 10-, 20-, 50-, 80-, and 100-year-frequency severities were  
340 calculated at 30-, 60-, 90-, 120-, 150-, 180-, 210-, and 270-day durations. Because the amount  
341 of available data only corresponds to 37 years, we calculated up to a 100-year frequency.  
342 However, the SDF curves from the fixed, daily, and monthly thresholds were calculated using  
343 comparatively short durations because the annual maximum durations vary from 30 to 96  
344 days. Nonetheless, the SDF curve from the desired-yield levels showed the water deficits for  
345 much longer durations of 30~270 days. In addition, the water deficits from the desired-yield  
346 levels are much higher than those from other levels even for the same duration.

347 For a specific description, Table 4 compares all severities to specific frequencies and  
348 durations for the desired-yield threshold. When the duration increases, the severity differences  
349 among the return periods significantly increase. Therefore, because the streamflow drought  
350 severity should be more crucial when the drought continues for a longer period, the frequency  
351 of long droughts should be approached with caution.

352

353 Fig. 8

354 Table 4

355

#### 356 **4.5 Development of duration-frequency curve**

357 Using the same traditional frequency analysis, the duration-frequency curves for four  
358 threshold levels were developed as shown in Fig. 9. In other words, the annual maxima  
359 durations are derived based on the four threshold level methods. As shown in the SDF  
360 relationship, the GEV distribution was selected from the L-moment ratio diagram. For these  
361 plots, 2-, 3-, 5-, 10-, 20-, 30-, 50-, 70-, 80-, and 100-year-frequency severities were calculated.  
362 Similar to the SDF curves, the durations for the desired-yield threshold were much higher  
363 than those for the other three thresholds.

364

365 Fig. 9

366

### 367 **5. Summary and Conclusions**

368 This study developed a useful concept to describe the characteristics of streamflow  
369 droughts using threshold level methods. The SDF curves for streamflow droughts were  
370 developed to quantify a specific volume based on a specific duration and frequency. This  
371 study compared the SDF curves of four threshold level methods: fixed, monthly, daily, and  
372 desired-yield levels for water use. In addition, the duration-frequency curves for four  
373 thresholds were used to derive the relationship between the drought duration and the drought  
374 frequency. This study used the severity, which represents the total water deficit for specific  
375 durations. From this study, we can make the following conclusions:

376 1) The daily threshold levels significantly fluctuated because of the natural streamflow  
377 variations for the antecedent 365 days and were the largest threshold level because a summer  
378 period (June, July, and August) was considered. The desired-yield level was larger than the  
379 fixed, monthly, and daily thresholds. This phenomenon occurred during the winter in Korea;  
380 thus,, both the water demand and natural runoff during the winter (December, January, and  
381 February) were notably small.

382 2) The durations and severities from the desired-yield threshold level were completely

383 different from those for the fixed, monthly and daily levels. In other words, the desired-yield  
384 threshold can identify streamflow droughts using the total water deficit to the hydrological  
385 and socioeconomic targets, whereas the fixed, monthly, and daily streamflow thresholds  
386 derive the deficiencies or anomalies from the average of historical streamflow.

387 3) The GEV distribution for a representative probability distribution was selected for the  
388 streamflow drought severities because most observations are appropriate for the GEV.

389 4) The severities increased with increasing duration and frequency. However, these  
390 values were notably different because the four threshold level approaches defined the  
391 streamflow drought differently. The SDF curves from the fixed, daily, and monthly thresholds  
392 were calculated using comparatively short durations because the annual maximum durations  
393 vary from 30 to 96 days. However, the SDF curve from the desired-yield levels shows the  
394 water deficits for longer durations of 30~270 days. In addition, the water deficits from the  
395 desired-yield levels are significantly higher than those from the others even in the same  
396 duration.

397 5) For the SDF curve of the desired-yield threshold, when the duration increases, the  
398 severity differences among return periods significantly increase. Therefore, because the  
399 streamflow drought severity should be more crucial when the drought continues for a longer  
400 period, the frequency of long droughts should be approached with caution.

401 6) Duration-frequency curves for four threshold levels were also developed to quantify  
402 the streamflow drought duration. Similar to the SDF curves, the desired-yield level had much  
403 longer durations for the other three thresholds.

404 7) In the end, the drought identification techniques based on the general threshold levels  
405 cannot reflect the socioeconomic drought in terms of water supply and demand. Therefore,  
406 the two-way approaches that are categorized by the time periods (fixed, monthly, and daily)  
407 for hydrological drought and the desired-yield threshold for socioeconomic drought should be  
408 separately included to identify specific drought characteristics.

409

410 The streamflow drought SDF curves that were developed in this study can be used to  
411 quantify the water deficit for natural streams and reservoirs. In addition, these curves will be  
412 extended to allow for regional frequency analyses, which can estimate the streamflow drought  
413 severity at ungauged sites. Therefore, they can be an effective tool to identify any streamflow  
414 droughts using the severity, duration, and frequency. If more basins and climatic zones are  
415 considered, more useful applications will be presented and this concept will be further  
416 improved.

417

418

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421

422

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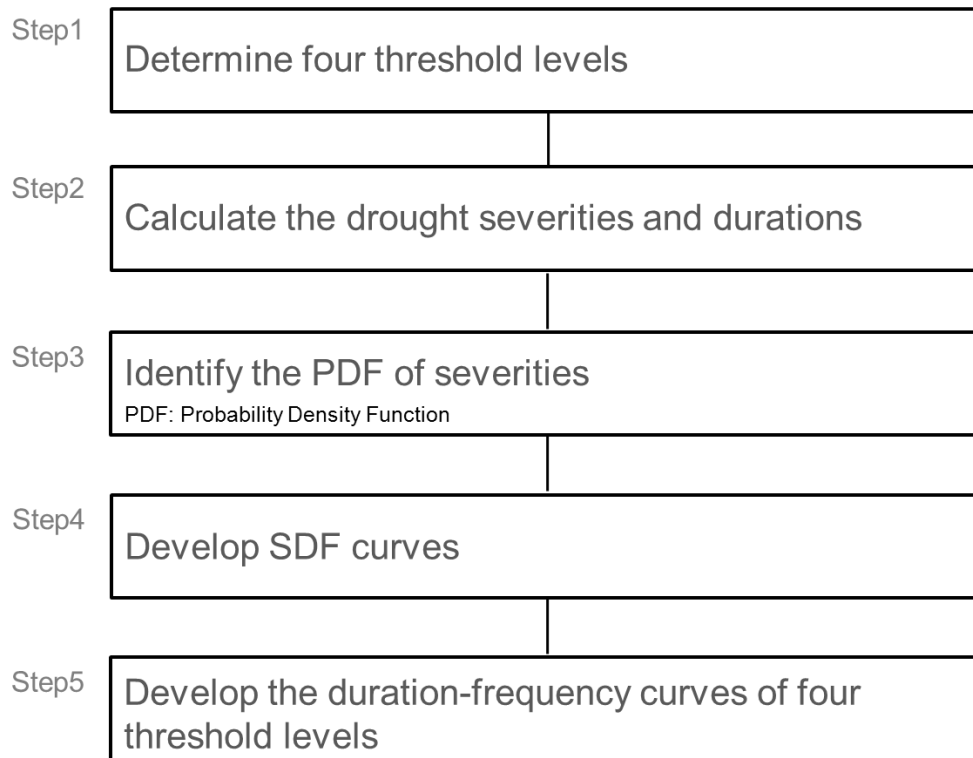
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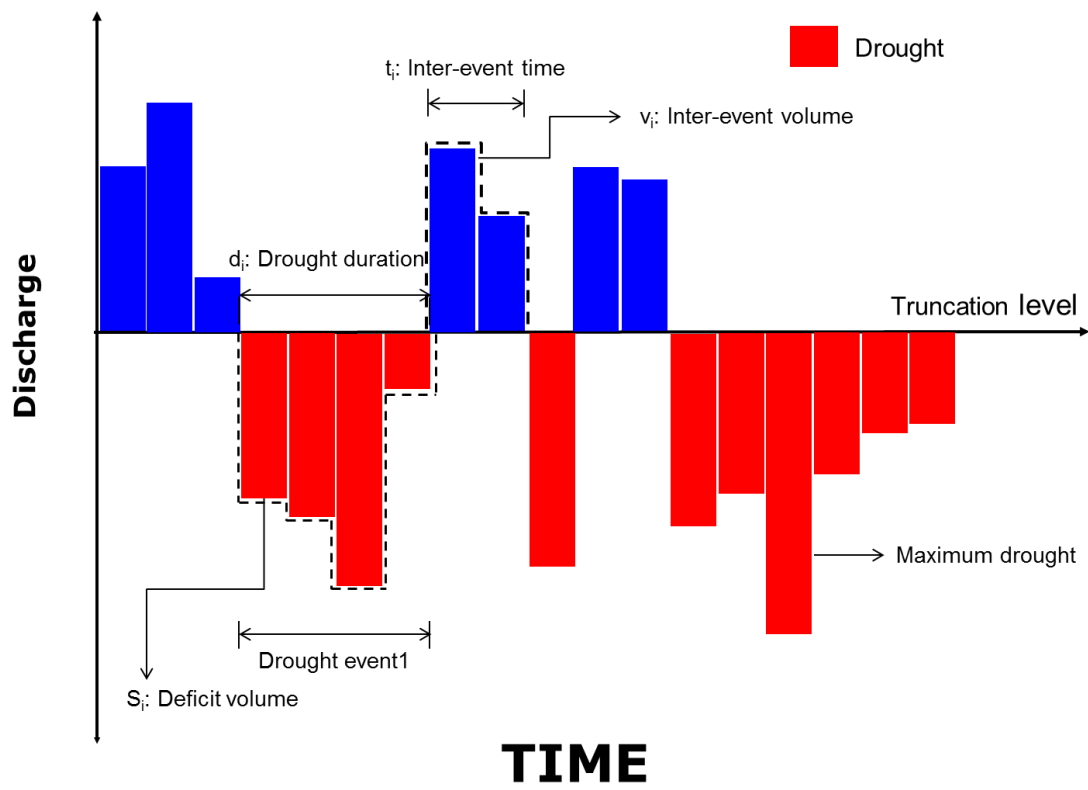


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533 Fig. 1. Procedure in this study.

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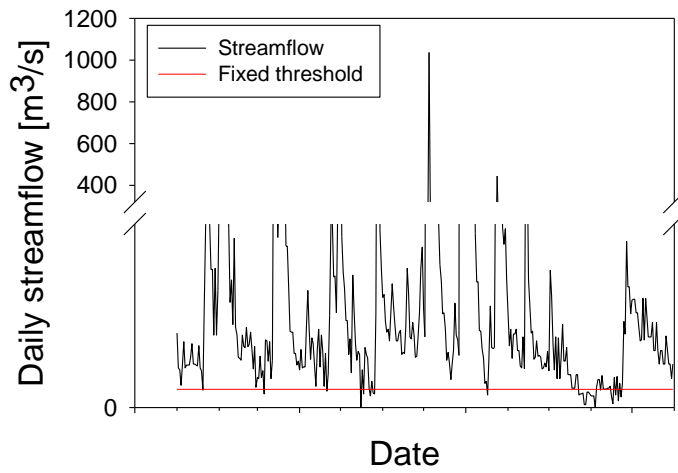


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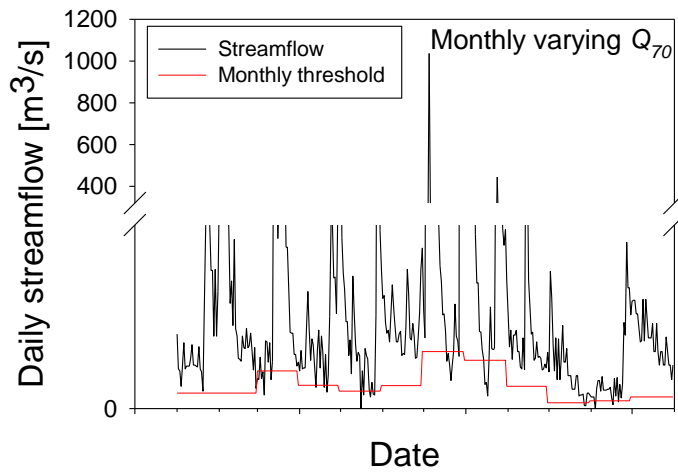
537 Fig. 2. Definition sketch of a general drought event.

538

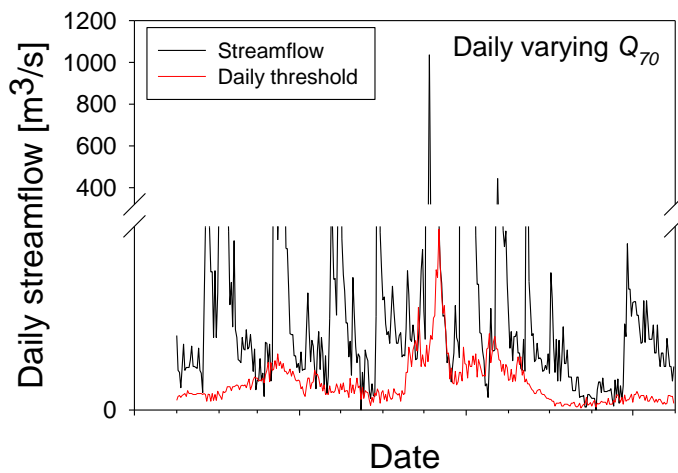
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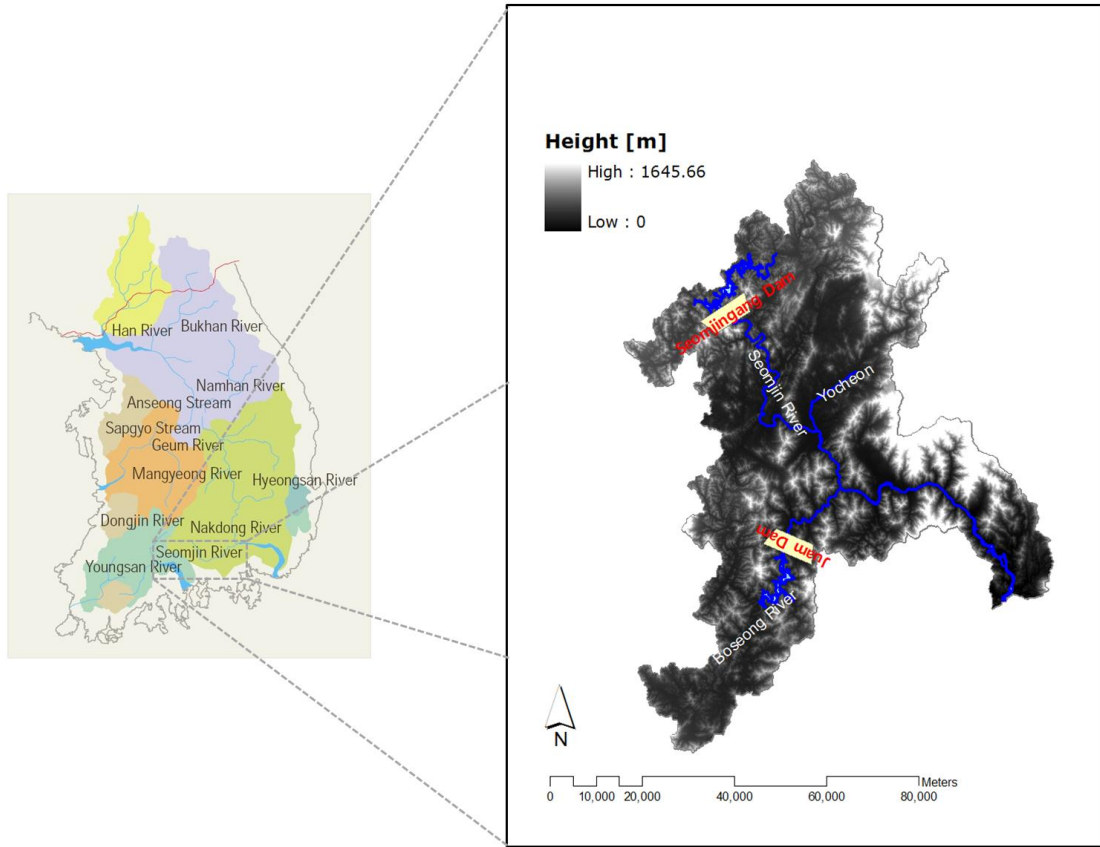


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543 Fig. 3. Examples of threshold levels: fixed (top), monthly varying (middle), and daily varying

544 (bottom).

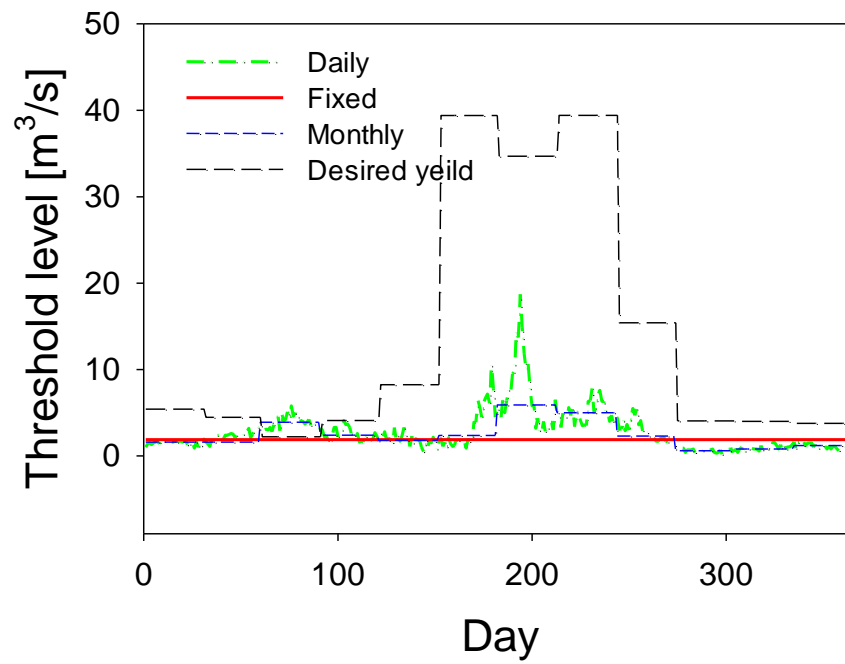
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547 Fig. 4. Location of the selected river basin, including elevation and rivers.

548

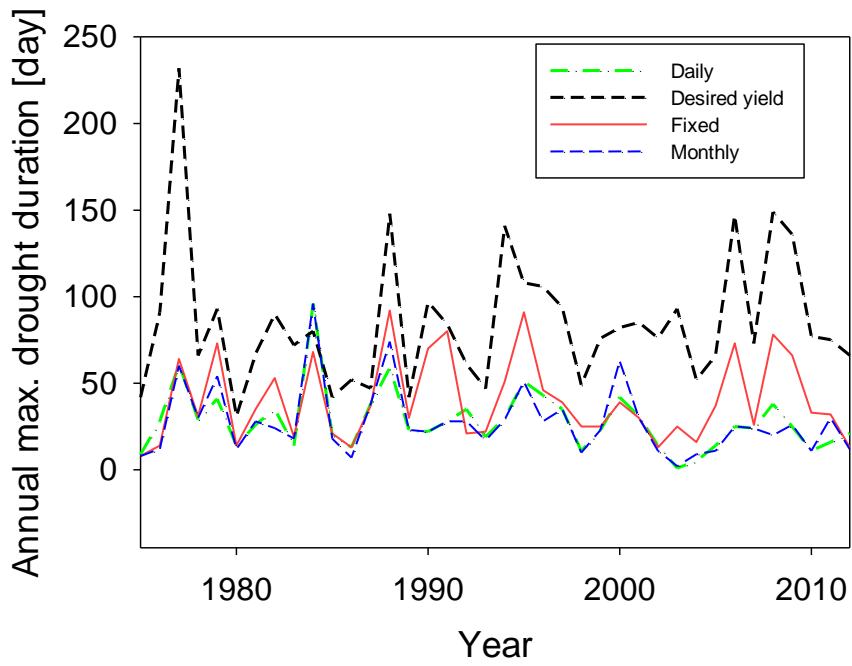


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551 Fig. 5. Comparison of the four threshold levels in this study.

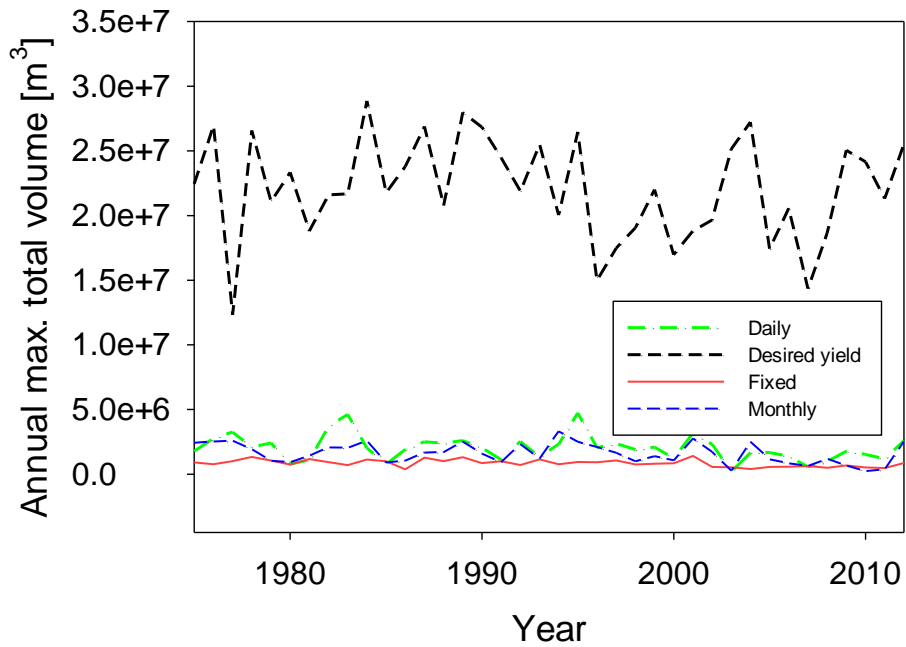
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555 (a) Drought duration.

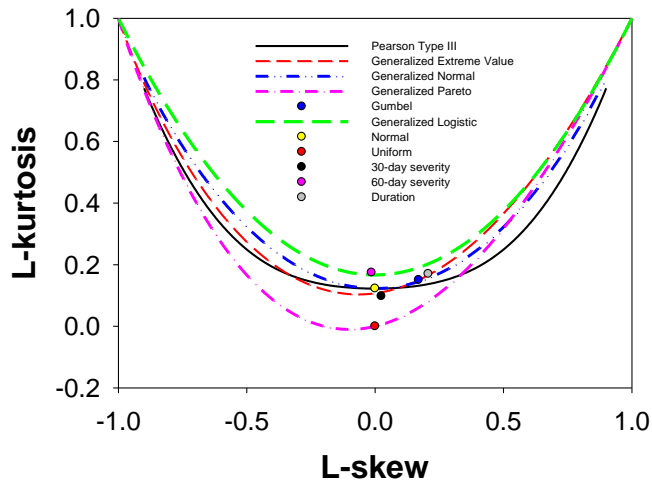


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557 (b) Total water deficit volume (drought severity).

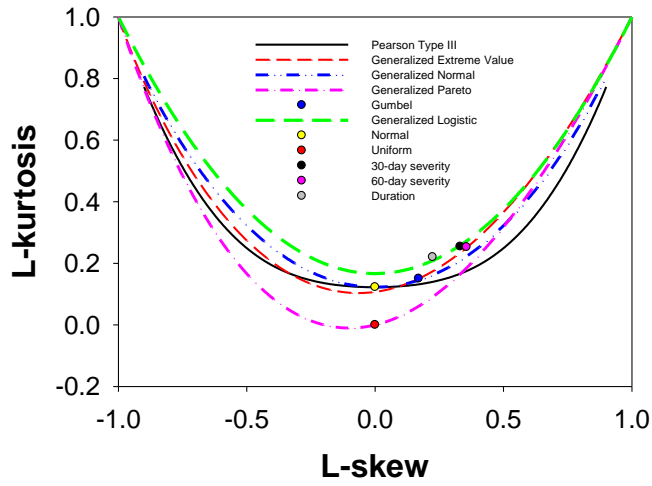
558 Fig. 6. Time series of the annual maxima values of duration and severity.

559



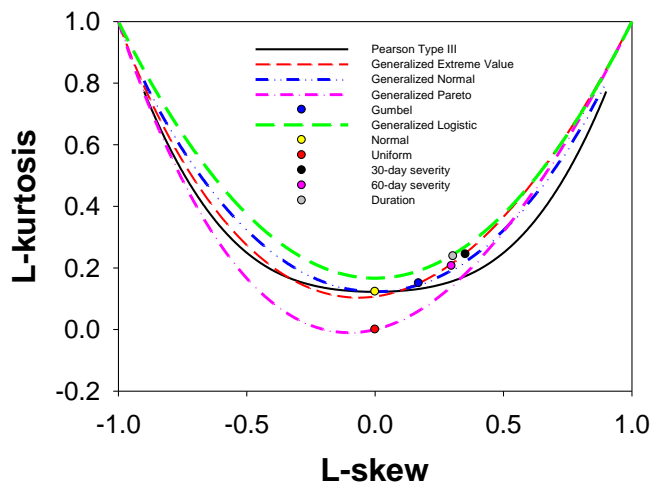
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561 (a) Fixed.



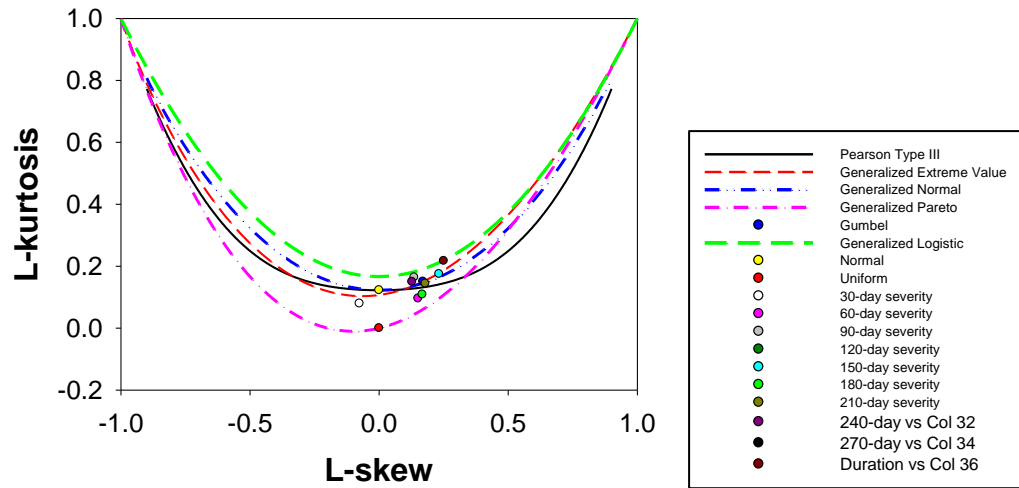
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563 (b) Daily.



564

565 (c) Monthly.



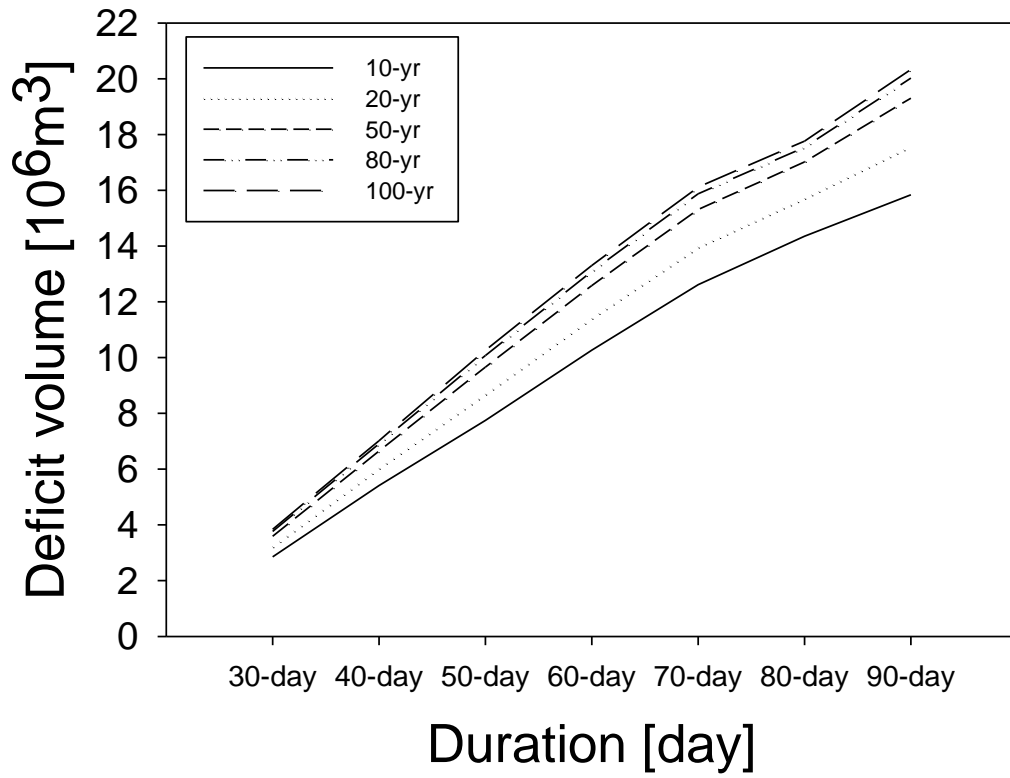
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567 (d) Desired yield.

568 Fig. 7. L-moment diagram to identify the probability distribution.

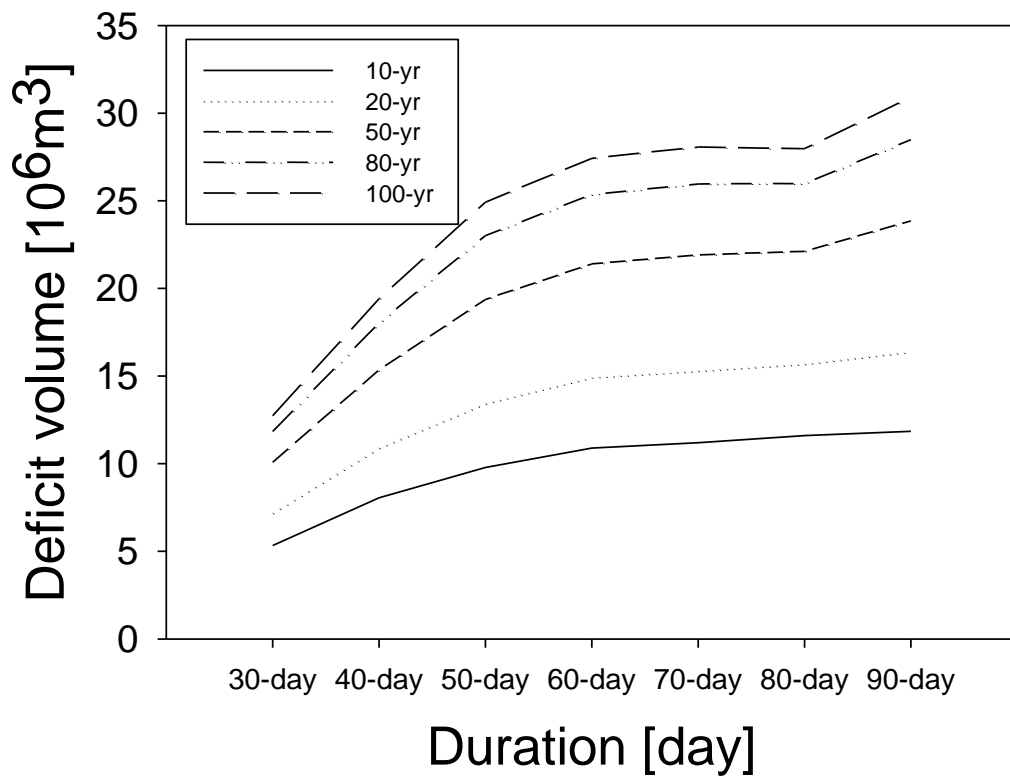
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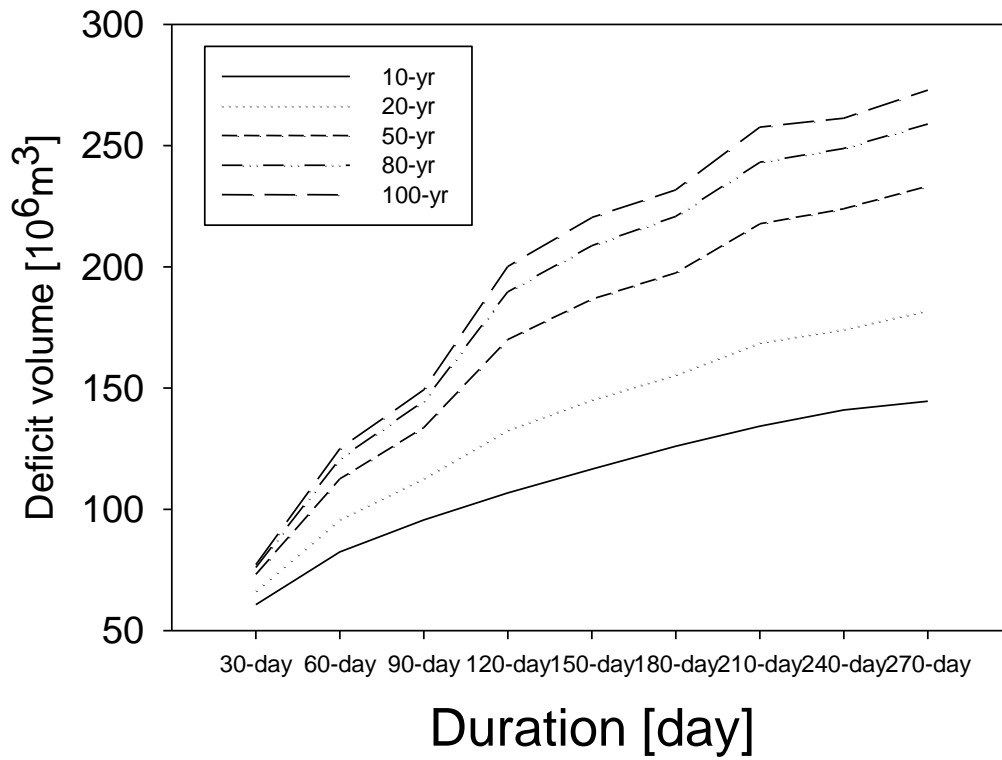
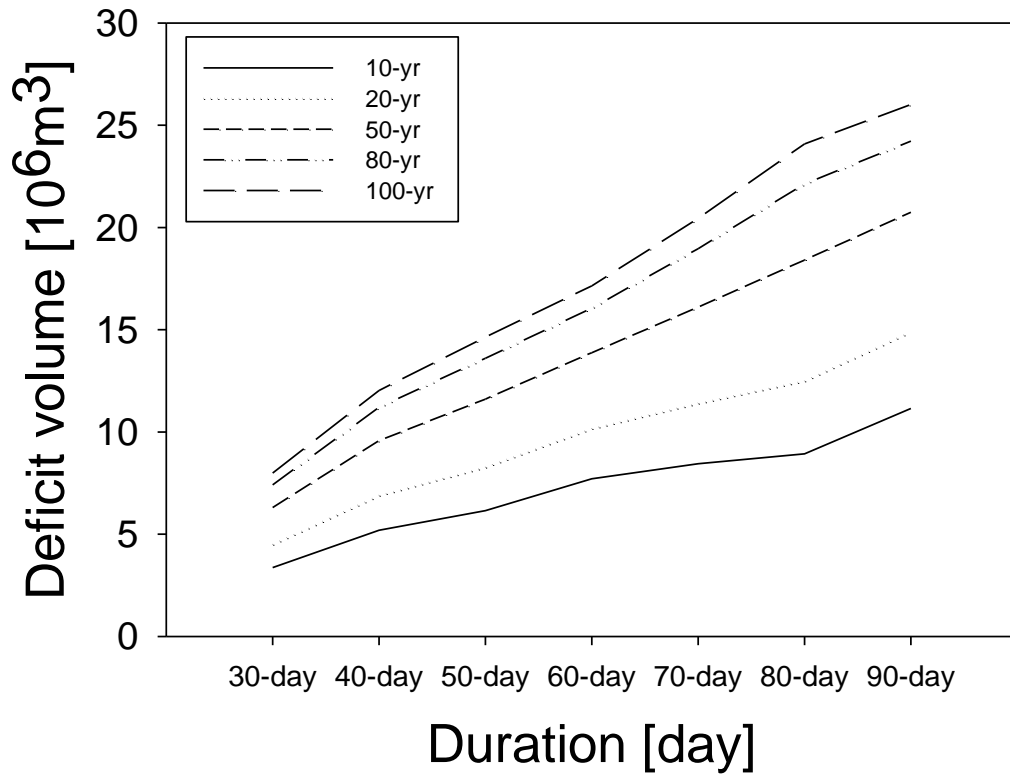
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571 (a) Fixed.

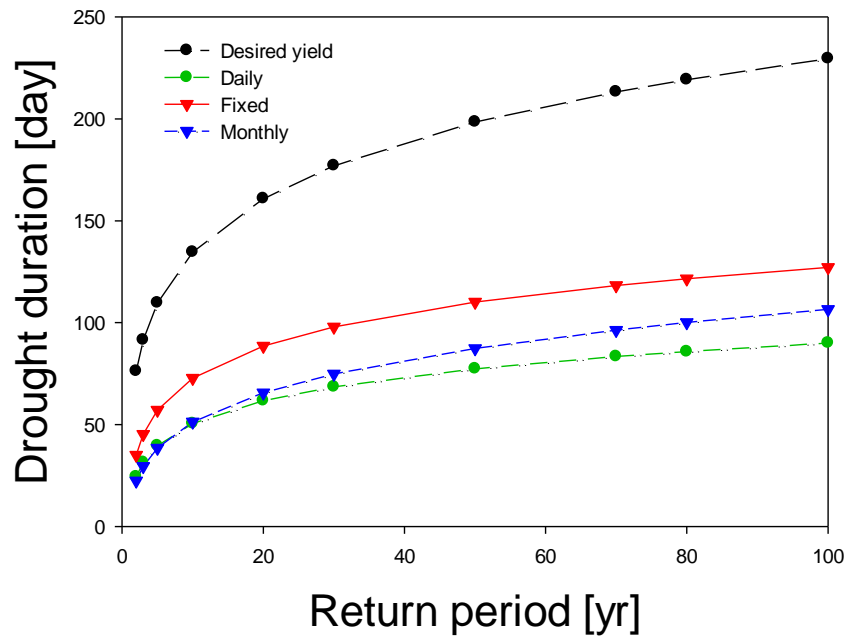


572

573 (b) Daily.



580



581

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

583 basin.

584

585

586 Table 1. Monthly average of the four threshold levels.

	Threshold level [m <sup>3</sup> s <sup>-1</sup> ]			
	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

587  
588 Table 2. Summary of the four threshold approaches.

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

589  
590 Table 3. Correlations between the durations and the severities of 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

591  
592

593 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

594