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# Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea

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SUMMARY

In this paper, progressive methods for assessing drought severity from diverse points of view were conceived. To select a fundamental drought index, the performances of the Effective Drought Index (EDI) and 1-, 3-, 6-, 9-, 12-, and 24-month Standardized Precipitation Indices (SPIs) were compared for drought monitoring data accumulated over 200-year period from 1807 to 2006 for Seoul, Korea. The results confirmed that the EDI was more efficient than the SPIs in assessing both short and long-term droughts.

We then proposed the following methods for modifying and supplementing the EDI: (1) CEDI, a corrected EDI that considers the rapid runoff of water resources after heavy rainfall; (2) AEDI, an accumulated EDI that considers the drought severity and duration of individual drought events; and (3) YAEDI, a year-accumulated negative EDI representing annual drought severity. In addition to these indices, to more accurately measure and diagnose droughts, we proposed the utilization of (4) the Available Water Resources Index (AWRI), an existing index that expresses the actual amount of available water.

Using the improved methods above, we assessed and summarized important droughts that have occurred in Seoul over the 200 years from 1807 to 2006.

## Introduction

It is very difficult to detect a drought before it becomes a serious issue, because of its slow developmental nature. However, if the precise developmental pattern of drought in its early stages could be determined, then sufficient time would be available to prepare for the worst. Therefore, various drought indices have been developed to quantify drought status.

Drought indices that utilize an insufficient level of soil moisture include the Crop Specific Drought Index (CSDI; Meyer et al., 1993), Palmer Drought Severity Index (PDSI; Palmer, 1965), Soil Moisture Drought Index (SMDI; Hollinger et al., 1993), etc. Among these methods, the PDSI has historically been the most commonly implemented. However, because of its complex, empirical derivation and because the underlying computation is based on the climate of the Midwestern United States, many researchers have reported the low practicability of PDSI as an accurate index (Narasimhan, 2004; Keyantash and Dracup, 2002; Guttman et al., 1992; Akinremi and McGinn, 1996; Alley, 1984) and have proposed revisions to overcome its deficiencies. For instance, Wells et al. (2004) developed the “Self-Calibrated PDSI” which provided a solution to the inappropriately higher frequency of extreme drought (under −4) compared to ordinary drought (between −4 and −2) under the traditional PDSI. Burke et al. (2006) and Mavromatis (2007) replaced the traditional Thornthwaite method used to approximate potential evapotranspiration with the Penman–Monteith equation and the Priestley–Taylor formulation, respectively.

On the other hand, there have been numerous efforts to conduct a simple and effective diagnosis using the distribution of rainfall insufficiency, including the Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), Deciles Index (DI; Gibbs and Maher, 1967), Rainfall Anomaly Index (RAI; van Rooy, 1965), Standardized Precipitation Index (SPI; McKee et al., 1993), etc. Among these efforts, the SPI is the most commonly used index, and has been implemented as widely as the PDSI. However, the SPI also has limitations. First, it is calculated based on monthly precipitation, as are many other drought indices. Even if a drought occurs, an index value is not available until the last day of the month or the subsequent month, when statistical analyses of precipitation for the particular month are completed. In addition, droughts can be relieved by a single day of heavy rainfall; however, this situation continues to be considered a drought until statistics on precipitation for the month are available. This factor hinders accurate and timely implementation of disaster prevention measures. Second, the SPI utilizes a simple average of precipitation for each concerned period. For example, for a 12-month SPI, insufficient precipitation over the previous 12 months is assigned the same weight as

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precipitation in the most recent month. The SPI cannot take into consideration the fact that substantial water resources generated by rainfall that occurred many months ago may have already been lost due to outflow and evaporation. Similar issues exist for all of the other drought indices. Finally, the SPI provides drought severity over various timeframes, including 1-, 3-, 6-, 9-, 12-, 24-, and 48-month periods. This is both a positive and a negative aspect of the SPI; the element of subjectivity comes into play when determining whether a drought is occurring because the person responsible has to choose from among the time periods available.

To overcome these limitations, Byun and Wilhite (1999) developed the Effective Drought Index (EDI), which is an intensive measure that considers daily water accumulation with a weighting function for time passage. Compared to other drought indices, the EDI has several advantages. First, it is the only index that was specifically designed to calculate daily drought severity. This enables rapid detection of drought and precise measurement of short-term drought. Second, by utilizing a calculation method that places greater emphasis on recent precipitation, it more accurately calculates the current level of available water resources. Finally, because it calculates the total precipitation period, considering the continuity of the drought period during the entire calculation process, it is distinguishable from existing drought indices that only provide a calculation for a limited period (e.g., 12 months). Therefore, it becomes possible to diagnose prolonged droughts that continue for several years.

Thus, the work of Byun and Wilhite (1999) has provided an innovative breakthrough in the field of drought research (Akhtari et al., 2008; Morid et al., 2006, 2007; Pandey et al., 2007; Ajayi and Olufayo, 2007; Smakhtin and Hughes, 2007; Marinaki et al., 2007; Kim and Byun, 2006; Usman et al., 2006; Boken et al., 2005; Papaioannou et al., 2005; Kang and Byun, 2004; Yamaguchi and Shinoda, 2002). Especially, Morid et al. (2006) and Pandey et al. (2007) demonstrated that the EDI could be used to monitor droughts from Iran and India, respectively, more effectively than other drought indices, including the SPI. However, because they used only short-term SPIs (1- and 3-month), more comprehensive analysis is needed. Byun (2009) provides an overview of about 50 drought indices in use in the international community, and lists the following elements that a good drought index must possess. First, a drought index must be calculated based only on those aspects that are due to natural phenomena, and should not include phenomena that occur due to human activity (e.g., abrupt changes in demand for water). In other words, drought indices calculated using stream flow, dam water levels etc. are outside the scope of natural science, because they must also incorporate in their analysis elements other than natural phenomena, i.e., causes of human misuse of water resources or causes of spikes in water demand. Second, it is preferable that soil moisture or evaporation also be excluded from the process of calculating a drought index. These have the problem that because there are no large annual fluctuations in seasonal averages, the impact on the drought index is minor; also, they lack validity because little data has been observed. Therefore, the method of simply measuring drought by precipitation alone is actually more preferable. Olapido (1985), Guttman (1998), and Redmond (2002) have also made the same claim. Third, the calculation must be made with consideration for the fact that the quantity of rainfall that can be used as a water resource drops gradually over time after the rain has fallen. The index that has reflected these three characteristics well has been the EDI. Accordingly, the present study was carried out based on the EDI.

We have monitored droughts in real-time in Korea for the past 8 years using the EDI (http://atmos.pknu.ac.kr/~intra/), and have found that the EDI requires further research and improvement, as do many other drought indices. First, if a dry spell occurs after a period of heavy rainfall, the EDI underestimates the status of the drought even if damage actually occurs due to the drought. The reason for this is that the EDI cannot consider the enormous amount of runoff that occurs a short period after heavy rainfall. No index to date has taken this effect into account. Second, the EDI is not exactly proportionate to the actual damage due to droughts. In summer when it is climatologically humid, even if the EDI shows that a drought has occurred, little damage may actually have taken place. Conversely, for a dry spring, even if the EDI shows that only a minor drought has occurred, the damage may be wide spread. The reason for this is that the damage associated with droughts depends on the absolute value of water resources that are actually available rather than the deviation from the climatological mean value of water resources. Byun and Wilhite (1999) suggested that this issue could be resolved using the Available Water Resources Index (AWRI) derived while producing the EDI. Because they did not previously demonstrate a method for resolving this issue, we proposed such a method in this paper. The AWRI has been previously used for classification of hydrological seasons (Byun and Lee, 2002; Choi and Byun, 2007; Han and Byun, 2006) and calculation of soil moisture (Yamaguchi and Shinoda, 2002). Third, the primary purpose of drought indices is to measure the severity of a drought at a specific time; thus, the indices are limited to indicating the severity of past droughts as a single value representing each event or year. A drought is considered severe when it is prevalent for a long time or when it is very intensive even for a short time. Thus, if we could devise an index that considers both these factors when representing droughts for a given event or year, we could more accurately determine the most severe drought from the drought data or the year in which the most severe drought occurred.

In this paper, a method for improving and complementing the EDI is described to resolve the above three issues. In addition, the appropriateness of using the EDI rather than the SPI is demonstrated, and the primary droughts that have occurred in Seoul over the past 200 years are reassessed and summarized using the modified EDIs.

## Precipitation data

Precipitation data has been recorded for Seoul, Korea since 1778, thereby providing one of the longest records in the world; thus, these data are particularly useful for application and assessment of drought indices. Precipitation was measured from 1777 to 1907 using a Chukwookee (a traditional rain gauge of Korea) and restored by Jhun and Moon (1997). For this study, precipitation data accumulated over 200 years from 1807 to 2006 were used. The Chukwookee cannot measure less than 2 mm of precipitation (Jung et al., 2000); moreover, it measures precipitation from snowfall inaccurately (Jung et al., 2001). These two factors result in a total about 80 mm annually, which accounts for about 6% of the annual mean precipitation (1326 mm) in the 20th century. From September 1950 to December 1952, when the Korean War was in progress, precipitation was not measured by the Korea Meteorological Administration. Therefore, for the period April 1951–December 1952, precipitation data measured by the Air Force at Yoido Air Base were used. The missing data from September 1950 to March 1951 were compensated for by calculating the average precipitation for each calendar day based on the previous and succeeding 15 years. Precipitation data for February 29 of each leap year were averaged with data for March 1. Because the climate on February 29 tends to be very dry, the effect of including these data is negligible.

The method used to measure the precipitation from 1807 to 1907 was different from that used from 1908 to 2006; thus, the drought index for each period was calculated based on different

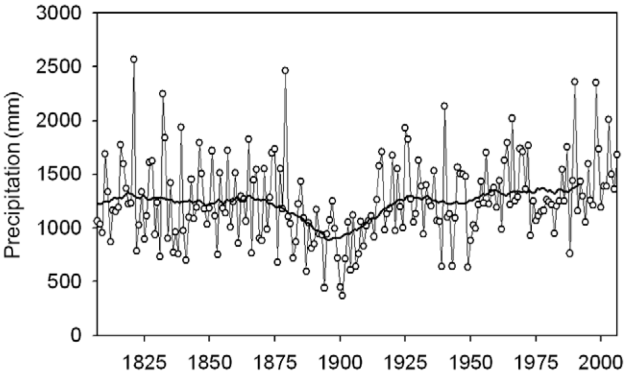


**Fig. 1.** Annual precipitation from 1807 to 2006. Solid line denotes the 30 years moving average.

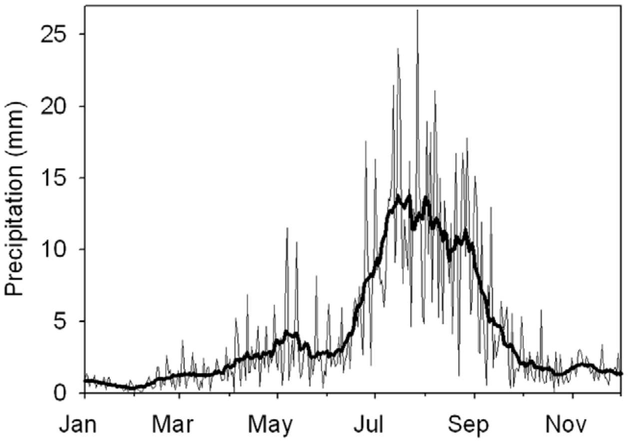


**Fig. 2.** Climatological seasonal cycle of precipitation. Solid line denotes the 15 days moving average.

calibration periods. The drought index for 1908 to 2006 was calculated based on the calibration period from 1977 to 2006 (the 20th calibration period), i.e., the most recent 30 years. This calibration period had the highest precipitation over this century (1404 mm, Fig. 1). Thus, the drought index from 1807 to 1907 was calculated based on the calibration period from 1807 to 1836 (1318 mm; 19th calibration period), when precipitation was the highest during that century. Considering that the annual precipitation that cannot be observed using the Chukwookee is about 80 mm, the difference in mean precipitation between the two calibration periods is not significant.

Fig. 2 shows the 20th climatological (1977–2006) seasonal cycle of precipitation in Seoul. Seoul is located in the summer monsoon region of East Asia, where rainfall occurs mainly in the summer (June–September). In particular, precipitation sharply increases from late June to late July under the influence of a monsoon front called "Jang-ma". After the summer monsoon, a dry winter monsoon occurs.

## Drought indices

### *The Effective Drought Index (EDI)*

As the first step in calculating the EDI, effective precipitation (EP) is calculated by summing precipitation over time, considering the loss of rainfall due to runoff or evaporation with the passage of time. Byun and Wilhite (1999) experimented with several types of EP models consisting of time functions and presented the model in Eq. (1) as the most appropriate, considering that runoff is highest immediately after rainfall (Lee, 1998; Shim et al., 1998):

$$\mathrm{EP}_i = \sum_{i}^{n=1}\left[\left(\sum_{n}^{m=1} P_m\right)\Big/ n\right] \tag{1}$$

where $i = 365$ is the period over which precipitation is summed, the most common precipitation cycle. $P_m$ denotes precipitation $m$ days ago. Thus, the EP denotes usable precipitation accumulated over 365 days. If 200 mm of precipitation occurs in 1 day, the weight applied to that day with the passage of time will decrease gradually, reaching 0 after 365 days, as shown in Fig. 3 (thick line).

The EDI is calculated as follows: (1) Calculate the daily EP. (2) Calculate the 30-year mean EP (MEP) for each calendar day. (3) Calculate the DEP, which is the difference between the EP and MEP (Eq. (2)):

$$\mathrm{DEP} = \mathrm{EP} - \mathrm{MEP} \tag{2}$$

(4) When the DEP is represented by a negative number, this signifies that it is drier than the average, and while this dry period continues, add the days of prolonged dryness to the existing period ($i = 365$) and recalculate the EP for that specific period. (5) Once again, calculate the MEP and DEP. (6) Divide the DEP for each calendar day by the standard deviation (SD) of the DEP over the past 30 years (Eq. (3)):

$$\mathrm{EDI} = \mathrm{DEP}/\mathrm{SD}(\mathrm{DEP}) \tag{3}$$

The resulting EDI value represents a standardized value for currently utilizable water resources, considering the continued dry period. If a negative DEP continues for more than 1 day, the addition period ($i$) of the EDI will increase as long as the continued days. This variable addition period is limitless. In this study, the EDI calculated considering precipitation for only 365 days, without considering any continued dry period, is called E365. The "drought range" of the EDI indicates extreme drought at $\mathrm{EDI} \leqslant -2$, severe drought at $-2.0 < \mathrm{EDI} \leqslant -1.5$, and moderate drought at $-1.5 < \mathrm{EDI} \leqslant -1.0$. Near normal conditions are indicated by $-1.0 < \mathrm{EDI} \leqslant 1.0$.

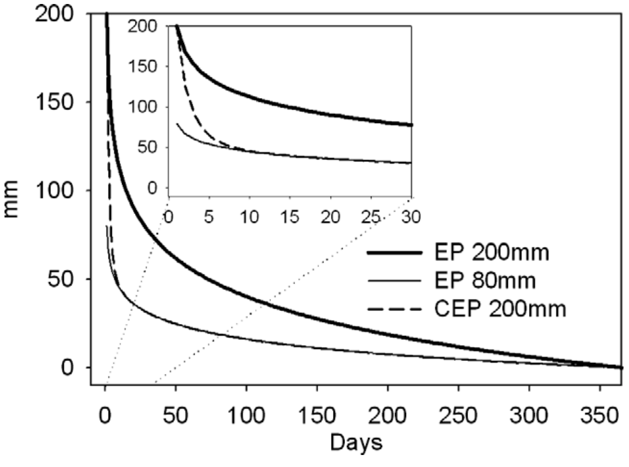


**Fig. 3.** Variation of the weight of 200 mm (thick solid line) and 80 mm (thin solid line) precipitation to EP (Eq. (1)) as the days pass, and that of 200 mm (dashed line) precipitation to CEP (Eq. (4)), which considers the rapid outflow of water resources that has been created through heavy rain.

### *The Standardized Precipitation Index (SPI)*

The SPI is calculated as follows: build a frequency distribution from the historical precipitation data (at least 30 years of data) at a location for a specified period (1, 3, 6, 9, 12, 24, or 48 months). Then, a theoretical probability density function (e.g., gamma distribution) is fitted to the empirical distribution of precipitation frequency for the selected time scale. An equiprobability transformation is then applied from the fitted distribution to the standard normal distribution (e.g., Edwards and McKee, 1997). Because the SPI is standardized in the same manner as the EDI, the range of droughts is the same as for the EDI. A 1-month SPI is abbreviated as SPI1; a 3-month SPI, as SPI3.

## Evaluation and comparison of the EDI with the SPI

A scatter diagram of monthly minimum EDI values vs. SPI values <−1 (Fig. 4) was prepared to assess how accurately the two indices measured drought. The scatter diagram of SPI1 and EDI is very scattered, and the $R^2$ value is close to 0. For 86.3% of the SPI values <−1, the EDI had negative values. For 48% of these SPI values, the EDI had values <−1 (Table 1). Thus, there was no clear correlation between the two indices; however, the results confirm that to some extent, the EDI detected short-term droughts detected using the SPI1. The relationship between the two indices improved for SPI3. For 92.2% of the SPI3 values <−1, the EDI had negative values. For 68.3% of these SPI3 values, the EDI had values <−1. On the other hand, the EDI had positive values for 29 out of the 372 months in which SPI3 < −1. These months ranged from November to April, which correspond to the hydrologic dry season in Seoul. These instances represent a relatively low amount of precipitation was short during the dry season following a summer rainy season with a high level of precipitation. Thus, the EDI value, in which precipitation accumulated for more than 1 year is considered, did not represent a drought; however, the SPI3 value, in where precipitation accumulated over three months is considered, represented a severe drought. Hayes et al. (1999) noted that SPI1 and SPI3 indicated a severe drought even if only a low amount of precipitation was short in dry seasons, since SPI1 and SPI3 are nearly the same concepts as percentage anomaly.

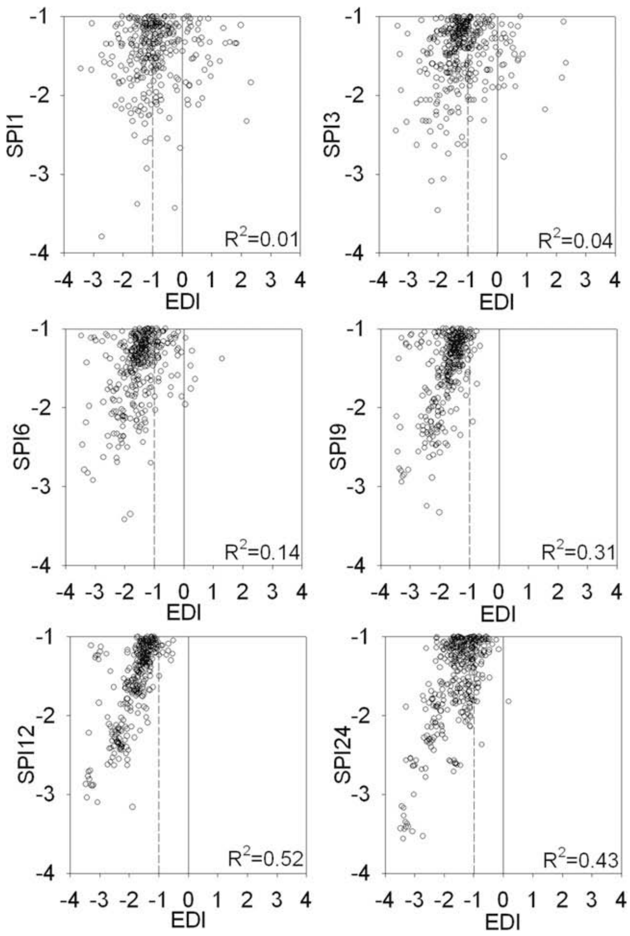


**Fig. 4.** Scatter diagram of SPI less than −1 and monthly minimum EDI from 1807 to 2006.

The SPIs on long time scales show similar behavior to the EDI as can be identified visually. The EDI had a negative value in all of the drought months identified by SPI9 and SPI12, and about 96% of the EDI values represented droughts. In particular, SPI12 had a high $R^2$ value of 0.52 and was the closest to the EDI, because both of these indices essentially consider 1-year precipitation. The difference between the EDI and SPI12 values was the greatest in April 1903 (EDI: −3.29, SPI12: −1.11). This drought event was characterized by an accumulated rainfall shortage of more than 3 years. Because the EDI considers a continued dry period, it can take into account an accumulated rainfall shortage over 3 years. However, the SPI12 considers rainfall shortage for only 1 year, and thus, the large observed difference in index values occurred (see next section for details). For 99.7% of all drought months identified by SPI24, the EDI had a negative value. For 82.9% of them, the EDI identified droughts.

There were 166 months for which SPI9, SPI12, and SPI24 simultaneously had values <−1. In these cases, the monthly minimum EDI was <−1 as well. On the other hand, there were 24 months for which SPI1, SPI3, and SPI6 had values <−1, while SPI9, SPI12, and SPI24 had values >−1, indicating short-term drought. In 21 (19) of these cases, the monthly minimum EDI was <0 (−1). Each of the three cases for which the EDI had values >0 occurred in February and April, in the latter part of the dry season. In these cases, precipitation in the previous summer rainy season (June–September) was higher than normal by >30%.

### *Long-term drought*

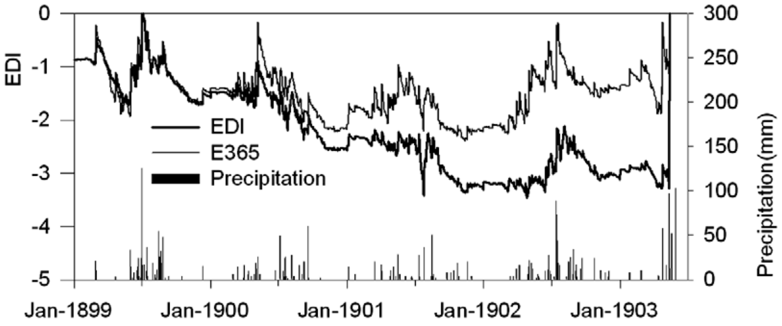
For 1406 days from July 6, 1899, to May 15, 1903, negative EDI values continued. This was the longest drought among all the events measured by the EDI within the 200-year study period (Fig. 5a). As low precipitation continued from 1899 to 1902, accounting for 54%, 34%, 28%, and 54% of normal annual precipitation, respectively, the drought gradually worsened. The EDI represented this drought well. On April 27, 1902, the EDI recorded its minimum value of −3.47. On the other hand, E365 did not indicate that the drought became more severe as the precipitation deficit continued over several years. This illustrates that droughts of more than 1 year are underestimated by E365, because it considers only precipitation accumulated for 1 year. In other words, this case clearly demonstrates the usefulness of the variable precipitation addition period that considers the continuity of the dry spell, which is one of the unique features of the EDI.

Fig. 5b shows a comparison of the EDI with the SPIs over the same period. As the drought period lengthened, the short-term SPIs underestimated the severity of the drought. While the drought continued, SPI1 and SPI3 indicated several times that the drought was relieved. In January 1903, when the drought had continued for about 3 years, SPI1 and SPI3 showed that the drought had been relieved. SPI6, SPI9, and SPI12 identified it as a moderate drought (about −1). Only SPI24 showed that it was an extreme drought (less than −2.5). This example illustrates that the short-term SPIs cannot detect the progress of long-term droughts.

**Table 1**
Frequency percentage of monthly minimum EDI in the cases of SPI < −1 for 200 years.

| −1> | SPI1 | SPI3 | SPI6 | SPI1,3,6 (SPI9,12,24 > −1) | SPI9 | SPI12 | SPI24 | SPI9,12,24 |
|---|---|---|---|---|---|---|---|---|
| Total months | 321 | 372 | 356 | 24 | 344 | 333 | 397 | 166 |
| EDI < 0 (%) | 86.3 | 92.2 | 98.0 | 87.5 | 100.0 | 100.0 | 99.7 | 100 |
| EDI < −1 (%) | 48.0 | 68.3 | 84.0 | 70.8 | 96.2 | 96.2 | 82.9 | 100 |

(a) EDI & E365 for long-term drought



(b) EDI & SPI for long-term drought

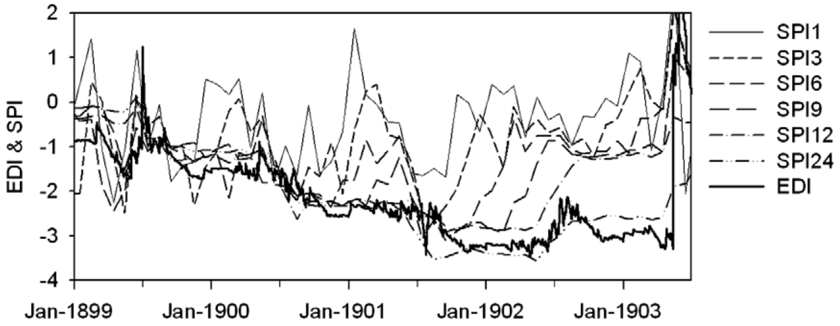


**Fig. 5.** Time-series of (a) EDI, E365, and precipitation and (b) EDI and 1-, 3-, 6-, 9-, 12-, 24-month SPIs from January 1, 1899 to June 30, 1903.

*Short-term drought*

As shown in Fig. 5b, the drought that occurred from April 1899 to May 1899, which was the initial stage of an extreme long-term drought, was detected by the EDI and short-term SPIs, but was not detected by the long-term SPIs (12- and 24-month).

Another example of a short-term drought is shown in Fig. 6a. This intensive, short-term drought occurred due to an extreme shortage of rainfall in spring and early summer. The total precipitation in March–June 1965 was 63 mm, comprising only 17% of the average rainfall for that period (367 mm). SPI12, which is the most similar to the EDI, was not able to detect this short-term drought, nor was SPI24. In May 1965, SPI9 was >0, indicating wetness; however, in June, the SPI9 value abruptly dropped to <−2, indicating an extreme drought. Such an abrupt decrease in an index value can hinder early warning of a drought. The reason for this phenomenon was that the 378.9 mm precipitation received in September 1964, 265% of precipitation in normal years, was considered in the SPI9 in May 1965 but was not considered in June 1965. This example clearly illustrates the disadvantage of a calculation method in which the same weight is applied to recent and past precipitation. In contrast, the EDI value accurately reflects the fact that a drought gradually becomes more severe as a precipitation shortage continues. On July 4, right before heavy rainfalls relieved the drought in early July 1965, the EDI recorded its minimum value of −2.0. The EDI is able to detect a short-term drought that cannot be detected by SPI12 because it uses the intensive measure method in which precipitation is summed on a daily basis, applying a higher weight to recent precipitation and a lower weight to past precipitation.

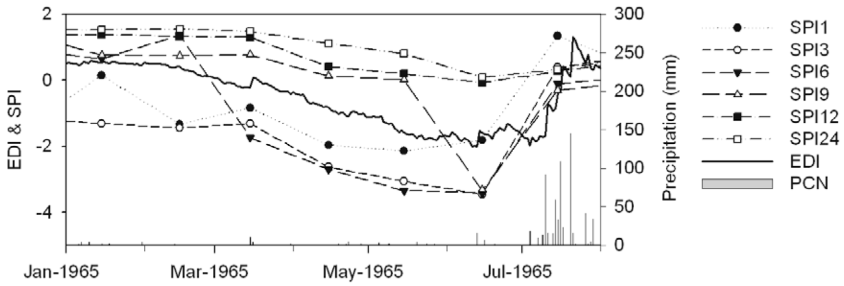
There were 92 months for which the monthly minimum EDI was <−1, while all of the SPIs were >−1. Of these 92 months, the month with the lowest EDI was July 1871 (Fig. 6b). This was a short-term drought in which a negative EDI continued for 48 days from June 4 to July 21, 1871. This period typically has the highest average precipitation in Seoul, with a mean total precipitation of about 410 mm. However, precipitation in the aforementioned period of 1871was only 98 mm, i.e., 24% of the mean value. As a result, the EDI dropped to −1.67 on July 21, 1871. Nevertheless, not all of the SPIs detected the drought because the SPIs deemed 410 mm of rainfall that occurred from July 22 to July 30, relieving the drought, to be the overall precipitation in July. For short-term rainfall shortages that do not occur in units of a calendar month, the accuracy of drought measurement by the SPI is very low. If the heavy rainfall that occurred at the end of July had occurred in early August of 1871, SPI1, SPI3, and SPI6 would have had low values of −2.74, −1.72, and −1.86, respectively, for July.

## Modifications of the EDI to improve quantification of drought severity

### *Consideration of excessive runoff after heavy rainfall*

During this study, we found that the EDI tended to underestimate drought intensity for a dry spell that occurred after a period

(a) EDI & SPI for short-term drought



(b) EDI Drought & SPI Nondrought

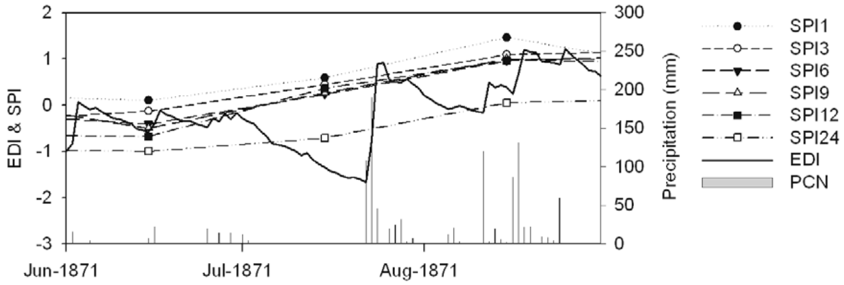


**Fig. 6.** Time-series of EDI, 1-, 3-, 6-, 9-, 12-, 24-month SPIs, and precipitation (a) from January 1 to July 31, 1965 and (b) from June 1 to August 31, 1871.

of heavy rainfall. In July 2006, heavy rainfalls of about 200 mm/day occurred three times in Seoul. However, as the amount of precipitation substantially decreased during August and September, there were serious drought problems. According to data accumulated by the Kyunggi Province Fire Disaster Headquarters, both the quantity and frequency of emergency water supply activities between September and November increased 5-fold compared to normal. However, the EDI diagnosed this as a wet period rather than a drought, because the EDI is not able to consider rapid runoff of water resources after heavy rainfall.

Generally, precipitation is absorbed by the soil and flows down to the lower regions as groundwater. The quantity of water absorbed and the time required for absorption varies according to soil composition, wetness of the soil, living organisms in the soil, and topography of the soil. However, when there is heavy rainfall, there is not enough time for the water to be absorbed into the soil. Thus, the majority of the rainfall flows into rivers and streams. In particular, if there is mountainous terrain or sandy soils, this tendency is intensified. In these cases, dams and reservoirs discharge water to prevent flooding.

The EDI reflects the total runoff amount for water resources relative to the passage of time. Therefore, if we apply extra weight to the total runoff amount after heavy rainfall, this could overcome the limitations identified above. In this study, heavy rainfall was defined as a daily precipitation of >80 mm (about 2.5 days per year), and extra weight was applied to the runoff after heavy rainfall using the following Eq. (4):

$$\mathrm{CEP} = \sum_{n=1}^{i} \left[ \left( \sum_{m=1}^{n} \{80 + ((P_m - 80)e^{-0.5(m-1)})\} \Big/ n \right) \right] \qquad (4)$$

Based on Eq. (4), any excess precipitation above 80 mm exponentially runs off as time goes by. Thus, after approximately 10 days, only the remaining 80 mm precipitation is counted. The newly derived EP in which weighted runoff after heavy rainfall is considered has been termed the Corrected EP (CEP). Fig. 3 shows a comparison between the weights of the EP the CEP with passage of time. The dashed line shows the CEP weight for 200 mm/day precipitation. When there is a 200 mm heavy rainfall, the excess 120 mm of rain from the 80 mm standard will runoff rapidly during the next 10 days, and at that time, a value equal to the existing EP value for 80 mm of rain would be applied. The index implementing this method has been termed the Corrected EDI (hereinafter the CEDI).

Fig. 7 presents the daily variations of the EDI, CEDI, SPI3, SPI12, and precipitation from July 1 to December 31, 2006. Within the month of July, there was a total of 1015 mm of rainfall, 270% greater than the annual average of 375 mm, with four heavy

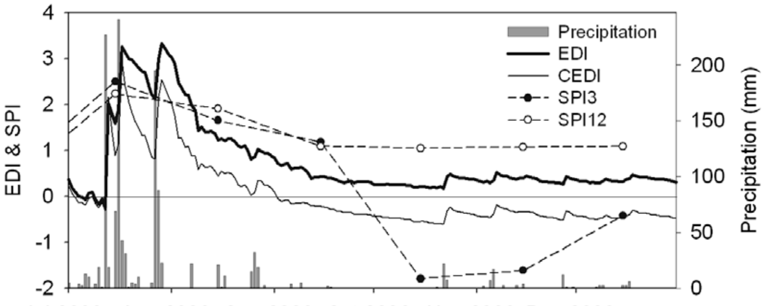


**Fig. 7.** Time-series of EDI, CEDI, 3-, 12-month SPIs, and precipitation from July 1, to December 31, 2006.

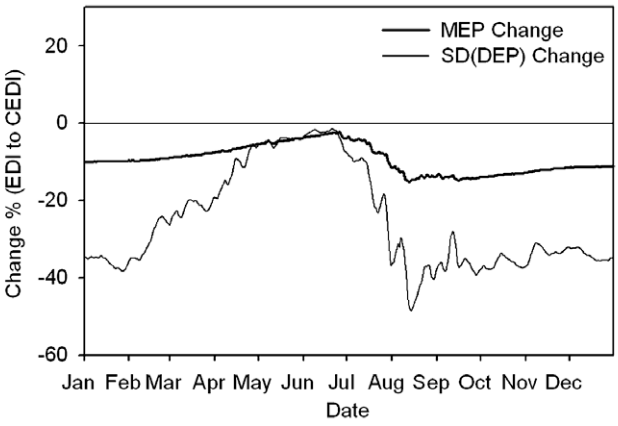


**Fig. 8.** Percentage changes of MEP (mean of EP; thick line) and standard deviation of DEP (SD(DEP); thin line) in the CEDI compared to those of the EDI.

rainfall events above 80 mm. However, from August to December, there was only 225 mm of rain, 36% of the average rainfall for this period (618 mm), which led to the rapid development of drought. SPI3 dropped to nearly −2 in October and November, because the precipitation in July was not considered. As noted above, due to the effects of the heavy rainfall in July, the EDI determined that the entire period from July 12 to December 31 was "wet." SPI12 indicated higher humidity than the EDI. However, when we applied the CEDI introduced in this study, rapid runoff of the heavy rainfall in July was considered, and the shortage of water from August to December was clearly described, as well as identification of September 1 as the beginning of the dry period.

The relationship of the EDI with the CEDI is analyzed as follows. When the EDI is replaced with the CEDI, the MEP (thick line) and the standard deviation of the DEP [SD(DEP); thin line], which are calibration factors, are replaced. The change rate for each calendar day is shown in Fig. 8. Because the CEDI disregards any excess amount of rainfall above 80 mm when calculating the CEP, the MEP is lower than that under the EDI. This phenomenon gets clear from July to September, when heavy rainfall frequently occurred. As both the EP and MEP decreased, the DEP accordingly decreased. Thus, the SD(DEP) values also decreased in proportion. Fig. 8 shows that the rate of decrease of the SD(DEP) was higher than that of the MEP. The SD(DEP) plays a role in the denominator of the index equation. Thus, a large decrease in the SD(DEP) increases the amplitude of the variability in the CEDI compared to the EDI, and therefore, the CEDI reaches a lower value than the EDI as a drought becomes more severe. This phenomenon is more apparent for droughts after heavy rainfalls.

In this case, a question whether to set the criterion for a heavy rainfall to 80 mm/day is raised. To investigate this issue, the criterion for a heavy rainfall was set to 20, 50, 80, and 110 mm/day, and the sensitivity of the CEDI to the criterion was evaluated (Fig. 9). CEDI-110 mm was very similar to the EDI. Rainfall greater than 110 mm/day is very rare (1.1 days per year). As noted above, the CEDI reaches lower values for severe droughts than does the EDI. These characteristics can clearly be seen for CEDI-80 mm. The scatter diagram showing the results of a 50 mm threshold (6.0 days per year) is very scattered. In addition, there is a group of events for which the CEDI ranges from −2 to 0, while the EDI ranges from −2 to −4. The scatter diagram for CEDI-20 mm (18.7 days per year) vs. the EDI is also very scattered, indicating that the low 20-mm criterion deteriorates the original performance of the EDI.

There is a group of events for which the CEDI-110 mm and CEDI-80 mm had values of −2.5 to −1, while the EDI was −1.8 to 0. These events are droughts that occurred after heavy rainfalls, and they clearly indicate that the CEDI represents the state of a drought after heavy rainfall more accurately than the EDI. However, for CEDI-50 mm and CEDI-20 mm, there is a group of events that show the opposite trend to the above, indicating that a criterion of 50 or 20 mm is not appropriate.

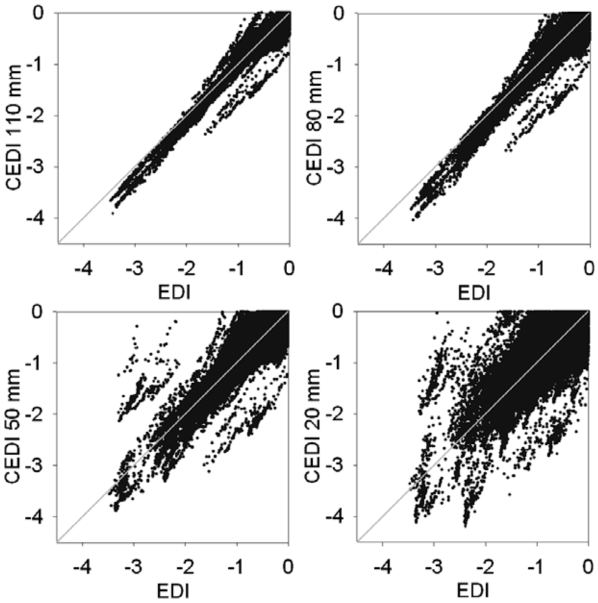


**Fig. 9.** Scatter diagram of EDI and CEDIs with 110, 80, 50, and 20 mm/day of heavy rainfall threshold from 1807 to 2006.

*Comparison of climatological drought severity with actual water shortage*

Most of the climatological drought indices, including the EDI, are calculated as the ratio of the quantity of current water resources to the climatological mean water resources; thus, the indices do not directly represent the sufficiency or shortage of water. Even if the EDI indicates a moderate drought, a severe water shortage may occur (may not occur) in a period with climatologically low (high) water resources. Thus, drought indices are not in proportion to actual damage from droughts.

Use of the Available Water Resources Index (AWRI), which represents the total amount of currently available water resources, as supplementary information for determining drought status can overcome these limitations to a certain extent. The AWRI (Eq. (5)) is an alteration of the EP and represents currently available water resources based on total precipitation over the previous 365 days.

$$\mathrm{AWRI} = \mathrm{EP} \Bigg/ \left( \sum_{N=1}^{365} (1/N) \right) \tag{5}$$

For convenience, an AWRI with a cumulative probability (CP) <0.001 of the AWRI values in each calibration period was categorized as an extreme water shortage (about 11 days/30 years), and an AWRI with a CP of 0.001–0.01 was categorized as a severe water shortage (about 3 months/30 years). An AWRI with a CP of 0.01–0.1 was categorized as a moderate water shortage (about 33 months/30 years) (Table 2).

The AWRI was applied to 1982, when the most severe drought out of the most recent 50 years occurred (Fig. 10). When the EDI was used, the period from April to early May was deemed to be a moderate drought, and the months of July and early October to early November were deemed to be a severe drought. SPI12 detected severe droughts that occurred in summer or autumn, but

**Table 2**
Classification of AWRI for the 19th and 20th calibration period.

| Class | Cumulative prob. | AWRI (mm) | |
|---|---|---|---|
| | | 1807–1836 | 1977–2006 |
| Extreme< | 0.001 | 47.7 | 64.7 |
| Severe< | 0.01 | 59.5 | 77.0 |
| Moderate< | 0.1 | 82.4 | 105.1 |

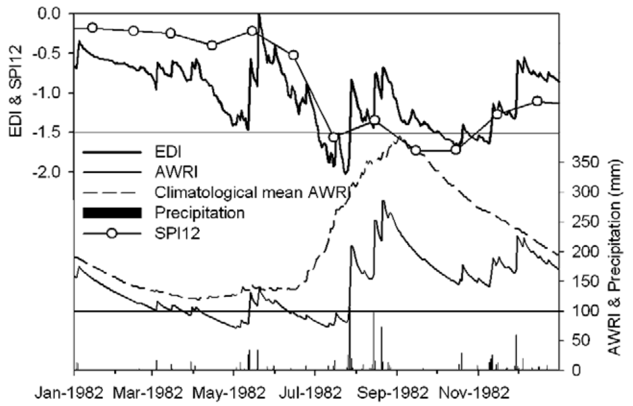


**Fig. 10.** Time-series of EDI, 12-month SPI, AWRI, and precipitation from January 1 to December 31, 1982. Dashed line denotes the climatological mean AWRI.

not in spring. The AWRI value is much lower in the spring or summer than in the autumn. For example, its minimum value of 71 mm, corresponding to a severe water shortage, was recorded on May 3. Thus, in 1982, climatological drought was more severe in the autumn than in the spring. However, the AWRI confirms that the shortage of available water was more severe in the spring.

Fig. 11 is a scatter diagram showing the dates of the annual minimum EDI, SPI12, and AWRI values over 200 years. For EDI and SPI12, minimum values were dispersed throughout the year. In July and August, when the quantity of water resources surges, the frequency of droughts is relatively high. Even though a drought index show that a drought has occurred in this period, actual damage from a drought may be little because the amount of available water resources is high on average. The annual minimum value of AWRI occurred primarily in the spring, when water resources accumulated in the summer dry up. If rainfall is short in spring (March–May), which is a climatologically dry period, water shortage may be very severe. Thus, we propose that the AWRI should be used as auxiliary data, in addition to the EDI, for diagnosing droughts.

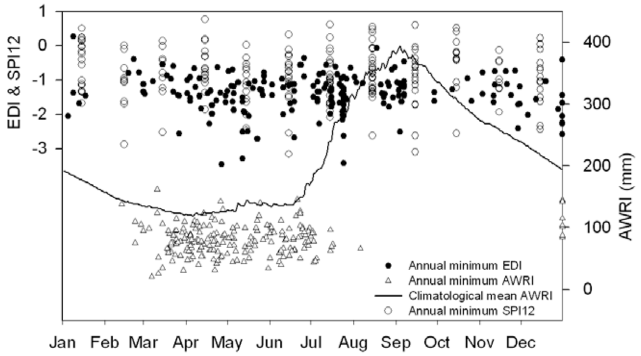


**Fig. 11.** Scatter plot of the date of annual minimum EDI (closed circle), 12-month SPI (open circle), and AWRI (open triangle) from 1807 to 2006. Solid line denotes the climatological mean AWRI.

### *Indexing drought severity per event and per year*

In this paper, it was found that the severity of droughts did not solely depend on the values of drought indices. That is, some droughts have low intensity, but are maintained for a long period of time. Some droughts have high intensity, but are of short duration. To allow comparison of the severity of drought events, drought duration with respect to continuity over time and drought intensity with respect to amount of rainfall shortage both need to be considered and represented as a single value. In order to do this, the run-sum method (Yevjevich, 1967) was utilized on the drought variables. This method calculates the sum of the drought variables over the period in which the drought variables fall below the standard values. When this method is applied to the EDI, the sum total of continuous negative EDI values is called the Accumulated EDI (hereinafter, AEDI).

The AEDI was applied to the droughts that had occurred in Seoul over 200 years (Fig. 12), and the most severe droughts were selected (Table 3). Within the 200-year period, droughts were most severe from 1882 to 1910; 6 out of 10 most severe droughts occurred during this period. In particular, the drought that began in 1899 (shown in Fig. 5) was the most severe drought within the 200-year period. This drought was distinguished from the other droughts by its AEDI of $-3360.6$, rather than by the minimum EDI of $-3.47$. The AEDI of this drought was 370% higher, the minimum EDI was 150% higher, and the dry duration was 200% longer than the next most severe drought (starting in 1886) over the 200-year period. Table 3 shows that the order of drought severities calculated based on the AEDI is different from those calculated based on the minimum EDI or duration. When drought events are compared, one of the three methods should be selected, depending on the purpose of the comparison. Generally, the AEDI is assumed to be the most appropriate.

However, because the AEDI quantifies the severity of each event separately, it has limitations for expressing annual drought severity. By applying the AEDI and calculating the sum of all of the negative EDI values using an annual unit, we can express drought severity on an annual basis. The sum divided by 365 days is termed the $\mathrm{YAEDI}_{365}$ (Eq. (6)), which represents the annual average dryness, and the sum divided by the total days of negative EDI values over 365 days is termed the $\mathrm{YAEDI}_{\mathrm{ND}}$ (Eq. (7)), which represents the intensity of the drought for the year. When the $\mathrm{YAEDI}_{365}$ is equal to the $\mathrm{YAEDI}_{\mathrm{ND}}$, it indicates that the entire year was dryer than normal.

$$\mathrm{YAEDI}_{365} = \frac{\text{Sum of negative EDI}}{365} \tag{6}$$

$$\mathrm{YAEDI}_{\mathrm{ND}} = \frac{\text{Sum of negative EDI}}{\text{Total days of negative EDI}} \tag{7}$$

$$\text{Sum of negative EDI} = \sum_{i=1}^{365} \mathrm{EDI}_i \ (\mathrm{EDI}_i < 0) \tag{8}$$

$\mathrm{YAEDI}_{365}$ and $\mathrm{YAEDI}_{\mathrm{ND}}$ were applied to the period of 200 years for droughts in Seoul (Fig. 13). It can clearly be seen that there was a prolonged dry period from 1882 to 1910, as indicated by almost equivalent $\mathrm{YAEDI}_{365}$ and $\mathrm{YAEDI}_{\mathrm{ND}}$ values. This was the mega-drought period in Seoul (Byun et al., 2008). Meanwhile, there were years (e.g., 1875 and 1990) when not a single day was drier than normal. Table 4 shows the 10 most severe drought years, selected from the mega-drought period (1882–1910) and other periods (1807–1881 and 1911–2006). In the mega-drought period,

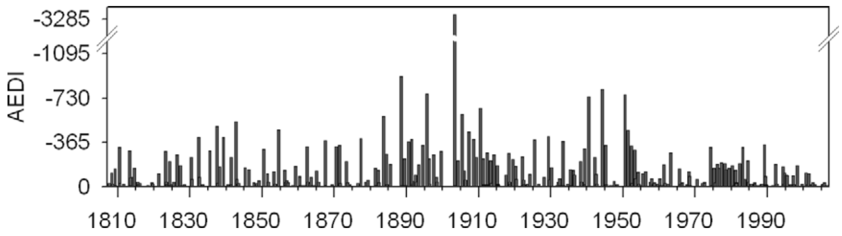


**Fig. 12.** Historical diagram of the drought events represented by the AEDI from January 1, 1807 to December 31, 2006. Each bar was plotted at the start date of the dry period.

**Table 3**
Top 10 drought cases based on the AEDI values for 200 years.

| Rank | Onset date | AEDI | Min. EDI | Dry duration |
|---|---|---|---|---|
| 1 | 1899-07-07 | −3360.6 | −3.47 | 1405 |
| 2 | 1886-08-09 | −911.8 | −2.27 | 699 |
| 3 | 1942-09-19 | −804.3 | −2.56 | 566 |
| 4 | 1894-07-09 | −767.0 | −2.63 | 390 |
| 5 | 1949-04-07 | −762.2 | −2.68 | 456 |
| 6 | 1939-06-11 | −742.5 | −2.51 | 389 |
| 7 | 1909-05-14 | −650.5 | −2.72 | 419 |
| 8 | 1904-04-16 | −598.7 | −2.28 | 386 |
| 9 | 1882-05-03 | −584.2 | −1.99 | 445 |
| 10 | 1841-07-03 | −536.6 | −1.88 | 416 |

droughts were most severe in 1902, 1901, 1900, 1895, 1903, 1894, 1908, 1910, 1887, and 1883. The annual minimum AWRI for eight of these years qualified as an extreme water shortage; actual damages from water shortages were very severe. The pinnacle of these droughts occurred in 1901 and 1902, with YAEDI$_{365}$ and YAEDI$_{DS}$ $< -2.5$ and annual minimum EDI and SPI24 values close to $-3.5$.

The 10 years when droughts were the most severe for the 171 years other than the mega-drought period were 1950, 1943, 1939, 1944, 1837, 1951, 1949, 1940, 1952, and 1982 (Table 4). Most of these severe droughts occurred from 1939 to 1952. In 8 of the 10 years, the annual minimum AWRI value indicated a severe water shortage level or lower. In particular, in 1837, 1940, 1944, and 1950, an extreme water shortage occurred. It has been confirmed that there was no actual water shortage in 1952, because the annual minimum AWRI value was greater than 105.1 mm. This illustrates that a drought year may be different from a water shortage year. When the EDI was replaced with the CEDI in Table 4, the annual minimum EDI value was somewhat lower (data not shown).

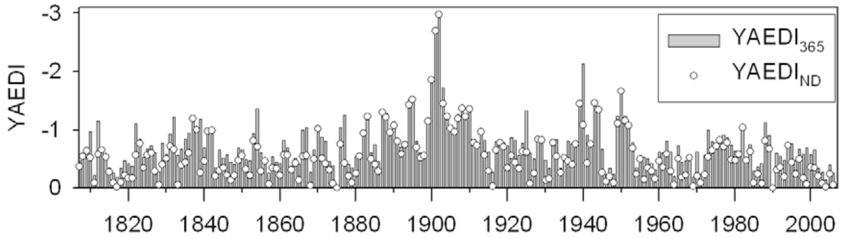


**Fig. 13.** Chronological annual dryness represented by the YAEDI$_{365}$ (bar) and YAEDI$_{ND}$ (open circle) from 1807 to 2006.

**Table 4**
The top 10 drought years during the mega-drought period (left) and during the other period (right).

| 1882–1910 (mega-drought period) | | | | | | | 1807–1881 & 1911–2006 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rank | Year | YAEDI$_{365}$ (YAEDI$_{DS}$) | Min. EDI | Min. SPI12 (SPI24) | Min. AWRI (mm) | Ann. Precip. (mm) | Year | YAEDI$_{365}$ (YAEDI$_{DS}$) | Min. EDI | Min. SPI12 (SPI24) | Min. AWRI (mm) | Ann. Precip. (mm) |
| 1 | 1902 | −2.98<br>(−2.98) | −3.47 | −2.88<br>(−3.56) | 19 | 712 | 1950 | −1.66<br>(−1.67) | −2.68 | −2.41<br>(−2.71) | 64 | 882 |
| 2 | 1901 | −2.69<br>(−2.69) | −3.43 | −3.1<br>(−3.53) | 34 | 374 | 1943 | −1.45<br>(−1.45) | −2.51 | −2.63<br>(−2.14) | 77 | 643 |
| 3 | 1900 | −1.85<br>(−1.85) | −2.58 | −2.63<br>(−2.33) | 49 | 446 | 1939 | −1.44<br>(−1.45) | −2.28 | −2.56<br>(−2.24) | 68 | 639 |
| 4 | 1895 | −1.52<br>(−1.56) | −2.63 | −3.16<br>(−1.93) | 21 | 940 | 1944 | −1.34<br>(−1.34) | −2.56 | −2.53<br>(−2.14) | 54 | 1089 |
| 5 | 1903 | −1.44<br>(−1.72) | −3.29 | −1.23<br>(−2.64) | 46 | 1052 | 1837 | −1.19<br>(−1.22) | −1.99 | −1.91<br>(−1.1) | 30 | 960 |
| 6 | 1894 | −1.42<br>(−1.51) | −2.41 | −2.34<br>(−1.8) | 40 | 442 | 1951 | −1.15<br>(−1.23) | −1.96 | −1.67<br>(−2.62) | 91 | 1028 |
| 7 | 1908 | −1.37<br>(−1.43) | −2.5 | −2.48<br>(−2.02) | 52 | 1061 | 1949 | −1.1<br>(−1.23) | −2.25 | −2.44<br>(−1.07) | 78 | 634 |
| 8 | 1910 | −1.36<br>(−1.39) | −2.72 | −2.02<br>(−2.06) | 50 | 1021 | 1940 | −1.08<br>(−2.13) | −2.51 | −2.55<br>(−2.44) | 61 | 2135 |
| 9 | 1887 | −1.29<br>(−1.29) | −2.04 | −1.71<br>(−1.15) | 45 | 594 | 1952 | −1.07<br>(−1.09) | −1.79 | −1.5<br>(−1.74) | 119 | 992 |
| 10 | 1883 | −1.22<br>(−1.23) | −2 | −1.36<br>(−1.34) | 53 | 866 | 1982 | −1.04<br>(−1.04) | −2.03 | −1.73<br>(−1.31) | 71 | 949 |

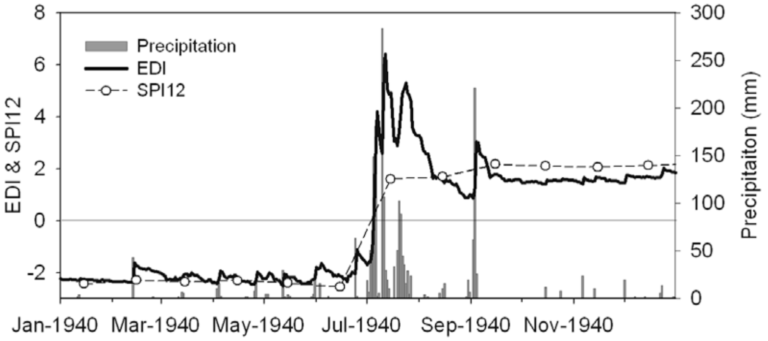


**Fig. 14.** Time-series of EDI, 12-month SPI, and precipitation from January 1 to December 31, 1940.

In addition, Table 4 shows that the ranking for annual precipitation shortage is different from that for annual drought severity. The reason for this is that a drought depends not only on the absolute quantity of the precipitation shortage but also on the temporal distribution of precipitation. For instance, annual precipitation for the year 1940 was recorded as 2135 mm, 161% of the average annual precipitation for the 20th century (1326 mm). 1940 had the third highest precipitation in the 20th century; however, the year was determined to be the eighth most severe drought, with a $\text{YAEDI}_{\text{DS}}$ of −2.13. This means that there was an extremely poorly-balanced distribution of precipitation in 1940.

In 1940 (Fig. 14), there was a prolonged drought for 6 months, with an EDI and SPI12 of about −2.0, which had continued from the previous year, prior to the commencement of the rainy season on July 1. The rainy season was accompanied by a total of 1733 mm of precipitation, 248% of the average rainfall for the period (697 mm). Therefore, when we viewed this from a simple annual precipitation perspective, this year could be classified as a “flood” period. However, when you use the YAEDI, it is categorized as a severe drought year, thus showing the practicability of the YAEDI.

To express the annual drought level, we could also utilize either the total precipitation per year or the annual average drought index. However, when the total precipitation is used, the precipitation during the summer, which comprises 50–60% of all the precipitation, has a great influence on the outcome, making it difficult to detect a drought resulting from dry periods during other times of the year. The annual average drought index can be affected when a shortage of water is canceled out by excessive water conditions during other periods of the same year. Thus, unless a drought is prolonged over the entire year, an annual average drought index cannot successfully reflect drought conditions.

## Summary and conclusion

The results of this study confirmed that the EDI has the following advantages over the 1-, 3-, 6-, 9-, 12-, and 24-month SPIs when diagnosing droughts:

1. The EDI detects long-term droughts that cannot be detected by the short-term SPIs.
2. The EDI detects extreme long-term droughts that are detected only by the 24-month SPI.
3. The EDI detects short-term droughts that cannot be detected by the long-term SPIs.
4. The short-term SPIs do not detect a short-term rainfall that does not occur in units of a calendar month; however, the EDI does.
5. The various SPIs produce many different values for the same period, while the EDI calculates a single value.
6. Because the SPI gives long-past precipitation and recent precipitation the same weight, the index value may drop abruptly in a single time-step, depending on whether a high amount of rainfall in a specific past month is included in the period of interest or not. However, the EDI is able to represent the gradual development of droughts.
7. There are many cases where short-term SPIs overestimate a relatively small rainfall shortage in the period of interest as a severe drought even if excessive rainfall occurs right before the period of interest. This misreading of drought severity does not occur in the EDI.

The EDI can thus measure both long-term droughts and short-term droughts, and the EDI is superior to SPI in that quantities of accumulated water resources are calculated rationally. These are necessary elements for accurate drought monitoring (Byun, 2009). However, beyond this, in the calculation of the quantity of accumulated water resources, the present study suggests that it is possible to conduct more accurate drought monitoring by using improved techniques such as the following. First, we devised an index (CEDI) that considers rapid runoff of water after a heavy rainfall in a short period of time, and we evaluated this method with the Seoul data to demonstrate its usefulness. The criterion for a heavy rainfall in the CEDI was set variously to 20, 50, 80, and 110 mm/day, and a sensitivity analysis was conducted. The results indicated that 80 mm/day was the most appropriate threshold. The quantity and timing of water runoff after heavy rainfall are affected by geographical features, soil quality, and vegetation; thus, a more precise analysis should be performed to accurately simulate runoff in a specific area. In this study, however, a method that can be generally applied was proposed. This method can be applied using only the EDI among the drought indices, which calculates precipitation on a daily basis, detects heavy rainfalls, and considers the loss of water resources with passage of time. The CEDI is particularly useful in areas (e.g., the Korean Peninsula) with frequent heavy rainfall and steep geographical features. Second, damage from droughts depends on the absolute value of actually available water resources rather than on deviation of water resources from climatological mean values. A climatological drought index can underestimate (overestimate) the actual drought damage during a dry season (rainy season). We propose that droughts can be better assessed using the AWRI, which enables calculation of the absolute quantity of available water resources, as a supplementary index for assessing droughts.

Main purpose of drought indices is to measure the status of a drought at a specific time. Thus, although the evaluation of past droughts is an important research task for many drought researchers, there remain limits to the evaluation of past drought severities on a case-by-case or annual basis, based on drought indices alone.

**Table 5**
Specifications of EDI and its derivative indexes.

| Type | Explanation | Characteristics | Use |
|---|---|---|---|
| EDI | • Intensive measure that considers the daily water accumulation with the weighting function of time passage<br>• Although the calculation period for total precipitation is set at 365 days, when a dry period begins, the total days of the dry period is added to the 365 days | • Measures the drought severity on a daily basis<br>• Measures the drought severity without time-scale limitations | • Monitoring ongoing drought severity<br>• Defining the onset and secession of drought. |
| CEDI | • In case of heavy rain, it considers the factor of large outflow over a short period of time | • Corrects the lowered description of the drought severity arisen by the intermittent heavy rainfall. | • As EDI but at regions that experience occasional periods of heavy rainfall |
| AEDI | • Summation of negative EDI values during the consecutive dry period | • Approximation of accumulated drought severity during the case<br>• Provides effective scale in comparing different drought cases | • Comparative analysis of severity between drought events<br>• Estimation of the accumulated damage |
| $\text{YAEDI}_{365}$ | • Sum the negative EDI values for yearly unit and then divide it by 365 | • Quantitative expression of the dryness of each year | • Comparative analysis on the annual drought severity |
| $\text{YAEDI}_{\text{ND}}$ | • As in $\text{YAEDI}_{365}$ but divide it by the number of days that EDI was negative during that year. | • Shows how intensive the drought was during the year | • Utilized as supplementary material in measuring annual drought severity |
| AWRI | • Estimates current available water resources accumulated for 365 days | • Reflects the actual amount of available water resources<br>• An absolute scale that is independent of seasonality | • Utilized as supplementary material in determining drought status |

To overcome this limitation, we conceived methods (AEDI and YAEDI) for quantifying the severity of droughts by event and by year. These methods were developed by applying the run-sum method to the EDI. Using these indices, we can represent drought severity as a single value by taking into account both intensity and duration. In addition, these methods are helpful for assessing, comparing, and analyzing past drought events and drought years. The run-sum method can be applied to the SPI as well; however, because the EDI is superior to the SPI in several aspects of drought assessment as noted above, it is more efficient to use the EDI. The characteristics and applications of EDI and its derivative indices are summarized in Table 5.

Application of the five drought indices to the 200-year study period for Seoul demonstrated that they can be selectively used depending on the purpose of drought diagnosis. Drought severity was quantified and analyzed by year and event, and a useful method of comparing drought severity was demonstrated. The most severe drought of the past 200 years lasted for a total of 1406 days, from July 6, 1899, to May 12, 1903, and had the lowest EDI value, falling below $-3$. This drought was embedded within an extremely long-term dry period that lasted for three decades, from the 1880s to the 1900s. In addition, a climatic feature where extreme droughts occurred several times from 1939 to 1952 was identified. The existence of such severe droughts in the historic record raises concern over the possibility of a similar drought occurring in the future.

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