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신경망을 이용한 우리나라의 시공간적 가뭄의 해석

Spatial-Temporal Drought Analysis of South Korea Based On Neural Networks

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Abstract

A new methodology to analyze and quantify regional meteorological drought based on annual precipitation data has been introduced in this paper In this study, based on posterior probability estimator and Bayesian classifier in Spatial Analysis Neural Network (SANN), point drought probabilities categorized as extreme, severe, mild, and non drought events has been defined, and a Bayesian Drought Severity Index (BPSI) has been introduced to classify the region of interest into four drought severities. In addition, to estimate the regional drought severity for the entire region, regional extreme, severe, mild, and non drought probabilities which are the areal averages of point drought probabilities over the region has been computed and applied. In this study, the proposed methodology has been applied to analyze the regional drought of South Korea during 1967 - 1996 years. The drought severity for the whole South Korea region was defined spatially at each year and each year was classified in a drought severity criterion. The results may be useful for water manager to understand the South Korean drought with respect to the spatial and temporal variation.

Keywords: Drought, Neural Networks, Drought Probability, Bayesian Drought Severity Index, South Korea

요 지

본 연구에서는 공간적으로 분포되어 있는 연강우량 자료를 이용한 지역 기상학적인 가뭄을 정의하고 해석하는 모형을 제시하였다. 비선형, 비매개변수법에 기초한 공간 해석 신경망(Spatial Analysis Neural Network; SANN)모형을 이용하여, 각 년에 대하여 공간의 임의 점에서의 극심, 심, 경심, 및 비 가뭄 확률을 전 대상 지역에 대하여 산출을 통하여 가뭄확률도를 작성하며, Bayesian 가뭄 심도 지수(BDSI)를 통하여 전 대상 지역을 가장 적절하게 극심, 심, 경심, 비 가뭄 지역으로 분류하는 방법을 제시하였다. 또한, 각 년의 대표적인 가뭄의 형태를 제시하여줄 수 있는 지역 가뭄 확률과 지역 가뭄 확률 지수를 소개하였다. 이 모든 시공간적 가뭄 해석의 방법은 실제로 우리나라 (남한) 전역에 대하여 실시하여, 과거 1967년부터 1996년 까지의 공간적이고 시간적인 가뭄의 발생 현황과 그 특징을 조사하였다. 본 연구는 우리나라 장기 수자원 개발 및 유역 관리를 위한 공간적이고도 시간적인 가뭄 정보를 제공하였다는 데 그 의의가 있을 것이다.

핵심용어 : 가뭄, 신경망, 가뭄 확률, Bayesian 가뭄 심도 지수, 남한

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1. Introduction

For the water resource planning and management, defining and analyzing of drought have been of big concern to meteorologist and hydrologist in the several decades. Drought analysis may be made based on single site data (Yevjevich, 1967; Dracup et al., 1980) and multisite data (Tase, 1976; Santos et. al, 1983; Soule, 1992; Guttman et al., 1992) depending on the specific purpose of the study at hand. In this paper, we are concerned with regional drought analysis.

Choosing the variable to define a regional drought depends usually on the purpose of the study. Among various variables such as precipitation, streamflow, soil moisture, and moisture content in the air, precipitation has been commonly applied for meteorological drought analysis (see for instance, Tase, 1976; Santos et. al., 1983; Chang, 1991). Annual precipitation will be considered as the key variable for drought analysis in this study.

In general, the historical annual precipitation data estimated in a region arises from data which are observed at a limited number of gaging stations and which are usually of different record lengths. Variability in space may be considered by using an interpolation technique so as to estimate precipitation at any ungaged location in the area. Several interpolation methods such as Thiessen Polygons, Inverse Distance, Multi-quadric, Polynomial, and Kriging have been applied to solving water resources problems. Among those, Tase (1976) used the polynomial method to regionalize precipitation data and Chang (1992) used the Kriging method for investigating monthly precipitation droughts. Recently, Shin and Salas (1997) developed a nonparametric spatial analysis model constructed with a neural network computational scheme, namely Spatial Analysis Neural Network (SANN) and verified for several applications such as groundwater contamination region classification and mean annual precipitation field (Shin, 1997). In that paper, SANN was used for analyzing the spatial variability of annual precipitation.

In literature, various drought severity indices related to precipitation data have been introduced. Gibbs and Maher (1967) developed the concept of deciles of precipitation for drought analysis. The Palmer Drought Severity Index (PDSI) which was developed by Palmer (1965), may be most well known meteorological drought index. The PDSI relates drought severity to the accumulated weighted differences between actual precipitation and the precipitation requirement of evaporation. It has been widely used for a variety of applications (Karl and Quayle, 1981; Guttman et al., 1992; Akinremi et al., 1996). Recently, McKee et al. (1993) introduced the Standardized Precipitation Index (SPI) which is designed to quantify the precipitation deficit for multiple time scales and calculated by taking the difference of the precipitation from the mean for a particular time scale and then dividing by standard deviation. In this study, based on the posterior probabilities of drought severities at any point in the region such as extreme drought, severe drought, mild drought, and non-drought from SANN, we provide a new drought severity index, namely Bayesian Drought Severity Index (BDSI). The detail description will be appeared below sections.

For defining droughts into various degrees of severity appropriate truncation levels of annual precipitation must be specified. In principle, truncation levels may vary in space and time, but this would require determining annual demands of precipitation varying over the region, data which are not readily available. In addition, the problem becomes too complex because of the variety of geomorphic or climatic conditions over the region and over time. That is why the historical annual precipitation data are usually normalized and standardized to enable the comparison of data on the same basis at various points in space. Thus, we followed the same approach and used constant truncation levels over the region and over time. The South Korea region is used as an example to illustrate the proposed regional drought analysis procedure and its spatial and temporal characteristics of drought is analyzed and quantified.

2. Methodology of Spatial and Temporal Drought Analysis

Consider that annual precipitation data are represented by $R_t(k)$, $t = 1, \ldots, N$ and $k = 1, \ldots, S$, where N = the length of record, k is a specific site, and S = total number of sites. Figure 1 further defines the data arrangement and notation. Note that the actual record length for a given site k may be shorter than N, so N covers the period from the station with the earliest year to the station with the latest year of record. Also site k is located at the point $\mathbf{X}_t(k)$ which is two dimensional coordinate vector. The historical data $R_t(k)$ for each site k are normalized and standardized so to make the data at all stations comparable on the basis of the standard normal distribution. Here, the normalized and standardized annual precipitation data is denoted by $Z_t(k)$ which corresponds to site with coordinate vector $\mathbf{X}_t(k)$. The next step is to estimate the process $z_t(\mathbf{x})$ at any point $\mathbf{x}$ in the area and to estimate a number of point and spatial statistics useful for the problem at hand. For this purpose, we use the Spatial Analysis Neural Network (SANN) model introduced by Shin and Salas (1997). The overall procedure related to regional drought analysis based on SANN is schematically summarized in Fig. 2. It involves training SANN, determining the spatial distribution of drought severity, and determining the regional drought severity.

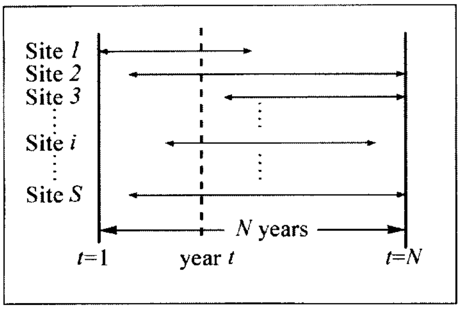


Fig. 1. Definition of Historical Annual Precipitation Data Considering Missing Years for Each Site.

The drought severity at a point is obtained by partitioning the event $z_t(\mathbf{x})$ into four classes $\{C^1, C^2, C^3, C^4\}$ which are associated with extreme, severe, mild, and non-drought events, respectively. This is accomplished by using three truncation levels *TL(1)*, *TL(2)*, and *TL(3)*. Then, for each year t and for a system of grid points $\mathbf{x}^m$, $m = 1, \ldots, M$, which are equally spaced over the region, various statistics are obtained such as conditional mean, $\hat{z}(\mathbf{x}^m)$ posterior probabilities $\hat{P}(C^1 \mid \mathbf{x}^m)$, $\hat{P}(C^2 \mid \mathbf{x}^m)$, $\hat{P}(C^3 \mid \mathbf{x}^m)$, and $\hat{P}(C^4 \mid \mathbf{x}^m)$, and a point drought severity indicator $d(\mathbf{x}^m)$. Here, the posterior probabilities are denoted respectively as *Point Extreme Drought Probability* $EDP_t(\mathbf{x}^m)$, *Point Severe Drought Probability* $SDP_t(\mathbf{x}^m)$, *Point Mild Drought Probability* $MDP_t(\mathbf{x}^m)$, and *Point Non-Drought Probability* $NDP_t(\mathbf{x}^m)$. Based on this information, one can obtain drought probability maps for each drought severity by contouring the estimated

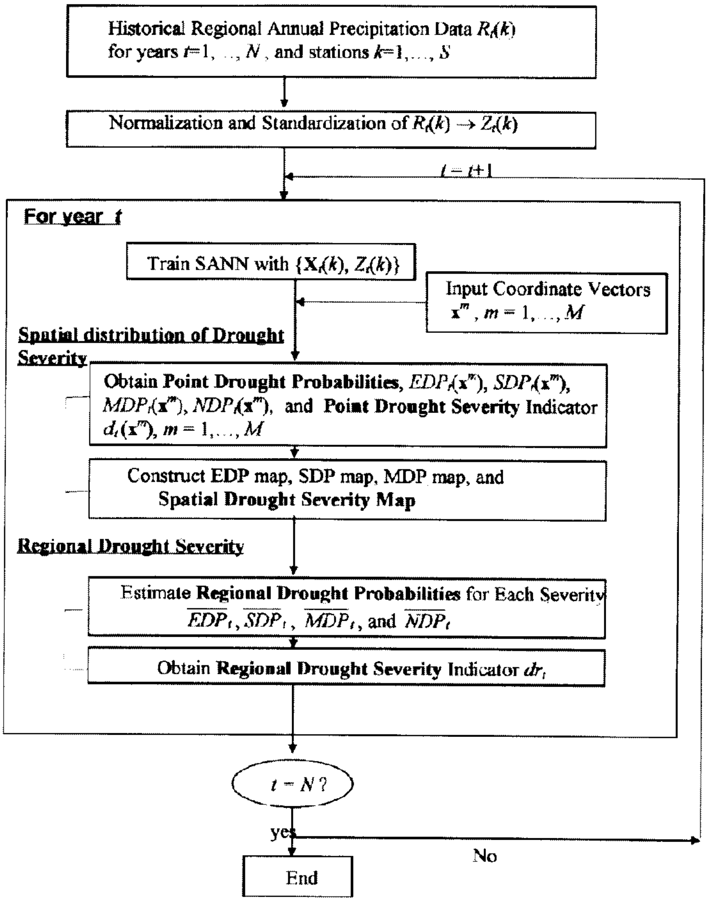


Fig. 2. Diagram to Illustrate the Procedure of Regional Drought Analysis Based on SANN

drought probabilities over the region. Then, each point $\mathbf{x}^m$ is assigned a point drought severity $d(\mathbf{x}^m)$ by taking the maximum of the referred point drought probabilities. They provide the spatial distribution of drought severity. Here, we denote the point drought severity indicator $d(\mathbf{x}^m)$ as a *Bayesian Drought Severity Index* (BPSI). In addition, one may want to know what is the drought severity which represents the entire region in a given year, we call it "*regional drought severity*". The time series of such regional drought severity can provide the characteristics of drought duration for the region. This will be done by estimating the areal averages of drought probabilities for each drought severity, namely $\overline{EDP_t}$, $\overline{SDP_t}$, $\overline{MDP_t}$, and $\overline{NDP_t}$, respectively for extreme, severe, mild, and non-drought. Then, these areal average probabilities will be used for determining the regional drought severity for each year.

2.1 Descriptions of Normalization, Standardization, and Truncation Levels

The first step in the analysis is to normalize and standardize the historical annual precipitation data. Many tests are available for

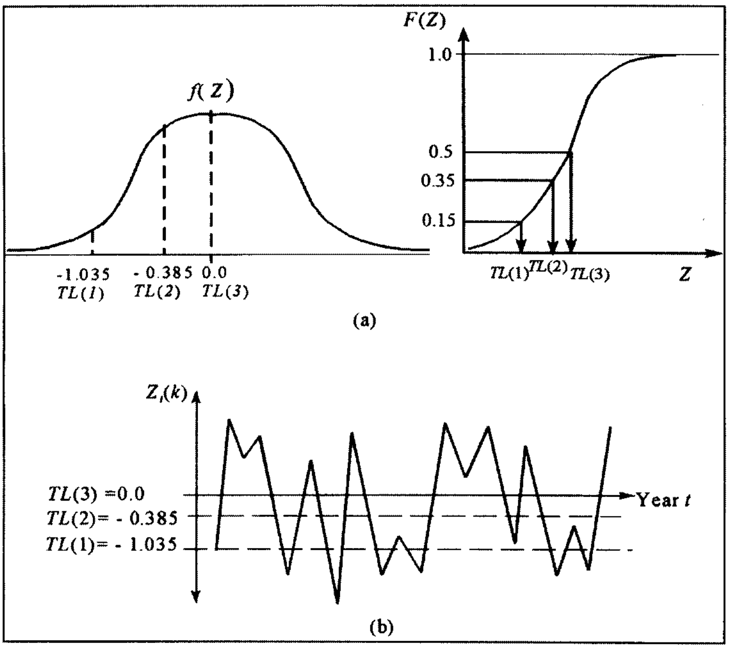


Fig. 3. (a) Definition of Truncation Levels Based on the Probability Density Function $f(z)$ and the Cumulative Density Function $F(Z)$ of the Standard Normal Distribution, and (b) Standardized -Normalized Annual Precipitation $Z_t(k)$ at Site k.

testing the null hypothesis of normality. Here we applied the skewness test of normality. The power- and log transformations have been widely used to transform the historical annual precipitation data into normal. For instance, Tase (1976) and Kingery (1992) applied the cube-root (p =1/3) transformation to normalize precipitation data. In this study, both the log and the cube root transformation were applied. Let $Q_t(k)$ be the annual precipitation data after transformation. This data was further standardized as

$$Z_t(k) = \frac{Q_t(k) - \overline{Q}(k)}{S_Q(k)} \tag{1}$$

where $\overline{Q}(k)$ and $S_Q(k)$ are respectively the mean and standard deviation of $Q_t(k)$.

Hence, the normalized and standardized annual precipitation at each site is assumed to be normally distributed with mean zero and standard deviation one. Then constant truncation levels over the region and throughout the historical period are defined to indicate the severity of a drought. Four drought severities are considered, namely C^1, C^2, C^3, and C^4 representing extreme, severe, mild, and non-droughts, respectively. They are defined by the truncation levels determined by $F[TL(1)] = P[Z \leq TL(1)] = 0.15$, $F[TL(2)] = P[Z \leq TL(2)] = 0.30$, and $F[TL(3)] = P[Z \leq TL(3)] = 0.50$, where $F(.)$ represents the standard normal CDF and $TL(.)$ is the quantile for the specified probability, thus the truncation levels obtained from standard normal tables are: $TL(1)=$ 1.035, $TL(2)= -0.385$, and $TL(3)= 0.0$. Figure 3. illustrates the definition of truncation levels.

2.2 Spatial Analysis Neural Network (SANN)

A nonparametric spatial analysis model based on a neural network computational scheme has been developed (Shin and Salas, 1997) for point estimation and classification of spatial data. The spatial analysis is based on further developments of Parzen's nonparametric point density estimators, Bayesian classifier, and the computational scheme based on a multi-layer feed-forward neural network form. For more detail description of SANN, the reader can refer to Shin and Salas (1997) and the previous paper (Shin, 1998). Note that all notations related with SANN are used in the same manner and the difference for defining the variables are described in detail in this paper.

2.3 Bayesian Drought Severity Index (BDSI)

Considering the four drought severities as described above, the four posterior probabilities estimated at an arbitrary point $\mathbf{x}$ for year t are denoted as point extreme drought probability $EDP_t(\mathbf{x})$, point severe drought probability $SDP_t(\mathbf{x})$, point mild drought probability $MDP_t(\mathbf{x})$, and point non-drought probability $NDP_t(\mathbf{x})$, respectively. They are defined as:

(a) Point Extreme Drought Probability (=the probability of extreme drought given a point $\mathbf{x}$)

$$\begin{aligned} EDP_t(\mathbf{x}) &= P[C^1 \mid \mathbf{x}] \\ &= P[z_t(\mathbf{x}) \le TL(1) \mid \mathbf{x}] \end{aligned} \tag{2a}$$

(b) Point Severe Drought Probability (= the probability of severe drought given a point $\mathbf{x}$)

$$\begin{aligned} SDP_t(\mathbf{x}) &= P[C^2 \mid \mathbf{x}] \\ &= P[TL(1) < z_t(\mathbf{x}) \le TL(2) \mid \mathbf{x}] \end{aligned} \tag{2b}$$

(c) Point Mild Drought Probability (= the probability of mild drought given a point $\mathbf{x}$)

$$\begin{aligned} MDP_t(\mathbf{x}) &= P[C^3 \mid \mathbf{x}] \\ &= P[TL(2) < z_t(\mathbf{x}) \le TL(3) \mid \mathbf{x}] \end{aligned} \tag{2c}$$

(d) Point Non-Drought Probability (= the probability of non-drought given a point $\mathbf{x}$)

$$\begin{aligned} NDP_t(\mathbf{x}) &= P[C^4 \mid \mathbf{x}] \\ &= P[TL(3) < z_t(\mathbf{x}) \mid \mathbf{x}] \end{aligned} \tag{2d}$$

Then, any point $\mathbf{x}$ in the region of interest has a probability of belonging to a certain drought severity, so the Bayesian drought severity at point $\mathbf{x}$ is that which has a maximum probability. Furthermore, the drought severity at a given point is assigned a numerical value $d(\mathbf{x})$ or index as specified in Table 1. Thus Bayesian Drought Severity Indices (BDSI), 3, 2, 1, and 0 represent extreme, severe, mild, and non-drought conditions, respectively. These indices are

Table 1. Bayesian Drought Severity at a Point and Bayesian Drought Severity Index (BDSI)

Decision Condition	Bayesian Drought Severity	Bayesian Drought Severity Index (BDSI)
if max ($EDP_t(\mathbf{x}), SDP_t(\mathbf{x}), MDP_t(\mathbf{x}), NDP_t(\mathbf{x})$) = $EDP_t(\mathbf{x})$	Extreme Drought	4
if max ($EDP_t(\mathbf{x}), SDP_t(\mathbf{x}), MDP_t(\mathbf{x}), NDP_t(\mathbf{x})$) = $SDP_t(\mathbf{x})$	Severe Drought	3
if max ($EDP_t(\mathbf{x}), SDP_t(\mathbf{x}), MDP_t(\mathbf{x}), NDP_t(\mathbf{x})$) = $MDP_t(\mathbf{x})$	Mild Drought	2
if max ($EDP_t(\mathbf{x}), SDP_t(\mathbf{x}), MDP_t(\mathbf{x}), NDP_t(\mathbf{x})$) = $NDP_t(\mathbf{x})$	Non Drought	1

useful for representing the areal pattern of drought severity at a certain point in time as well as the time evolution of drought severity as a given point.

2.4 Regional Drought Severity

In addition to estimation of Bayesian drought severity and drought severity index at a point, one may be interested on assessing the drought severity for the entire region. This information may be useful for many purposes such as applying for emergency public relief funds because a region has been declared as being on an extreme drought severity condition on a particular year and determining the duration and intensity of droughts over a certain period of time.

First, regional drought probabilities can be determined by averaging the point drought probabilities for each drought severity as:

(a) Regional extreme drought probability
(= the probability of occurrence of extreme drought over the entire region)

$$\overline{EDP_t} = \frac{1}{M} \sum_{m=1}^{M} EDP_t(\mathbf{x}^m) \qquad (3a)$$

(b) Regional severe drought probability
(= the probability of occurrence of severe drought over the entire region)

$$\overline{SDP_t} = \frac{1}{M} \sum_{m=1}^{M} SDP_t(\mathbf{x}^m) \qquad (3b)$$

(c) Regional mild drought probability
(= the probability of occurrence of mild drought over the entire region)

$$\overline{MDP_t} = \frac{1}{M} \sum_{m=1}^{M} MDP_t(\mathbf{x}^m) \qquad (3c)$$

(d) Regional non drought probability
(= the probability of occurrence of non drought over the entire region)

$$\overline{NDP_t} = \frac{1}{M} \sum_{m=1}^{M} NDP_t(\mathbf{x}^m) \qquad (3d)$$

where M = number of points of the grid. Then, based on the regional drought probabilities, $\overline{EDP_t}$, $\overline{SDP_t}$, $\overline{MDP_t}$, and $NDP_t(\mathbf{x})$, the *regional drought severity* for year t, $\overline{RDS_t}$ is determined by:

if $\overline{EDP_t} \geq (\overline{SDP_t} + \overline{MDP_t} + \overline{NDP_t})$ then RDS_t = extreme regional drought = E or else if $(\overline{EDP_t} + \overline{SDP_t}) \geq (\overline{MDP_t} + \overline{NDP_t})$, then RDS_t = severe regional drought = S or else if, $(\overline{EDP_t} + \overline{SDP_t} + \overline{MDP_t}) \geq \overline{NDP_t}$, then RDS_t = mild regional drought = M otherwise, RDS_t = regional non-drought = N (4)

Because $\overline{EDP_t} + \overline{SDP_t} + \overline{MDP_t} + \overline{NDP_t} = 1.0$, (4) implies

if $\overline{EDP_t} \geq 0.5$, then RDS_t = E
else if $(\overline{EDP_t} + \overline{SDP_t}) \geq 0.5$, then RDS_t = S
else if $(\overline{EDP_t} + \overline{SDP_t} + \overline{MDP_t}) \geq 0.5$, then RDS_t = M
otherwise $\overline{RDS_t}$ = N (5)

In other words, the identification of the severity of a regional drought must be carried out sequentially as above suggested. In this way, any inconsistency is avoided. For instance, the second and third conditions in Eqns. (4) and (5) always hold if $\overline{EDP_t} \geq (\overline{SDP_t} + \overline{MDP_t} + \overline{NDP_t})$.

Once the severity of regional drought is identified for a given year, the time pattern of drought severities can be determined for the entire period of record or for the period of simulation if the drought analysis id done based on simulated data. The following section will illustrate this point more fully.

3. Spatial and Temporal Drought Analysis of South Korea

3.1 Data Description

In this study, the region of South Korea located between 126 and 130 degrees East longitude and 34.0 and 38.0 degrees North latitude was used for regional drought analysis. Annual precipitation data was collected considering that: (1) the number of observation points is sufficient to cover the entire area, (2) the records are consistent both spatially and temporally, and (3) the period of observation is enough and sufficient for each year. Thus, a total of 39 precipitation stations were assembled with records covering the period 1967-1996, which are most recent years. Then, the total record length was N = 30 and the sample size for all stations varied from 27 to 30. Table 2 provides the basic information such as station number, coordinate for all the 33 stations used in this study, mean annual precipitation and statistics constructed by 30 years data for each station were denoted.

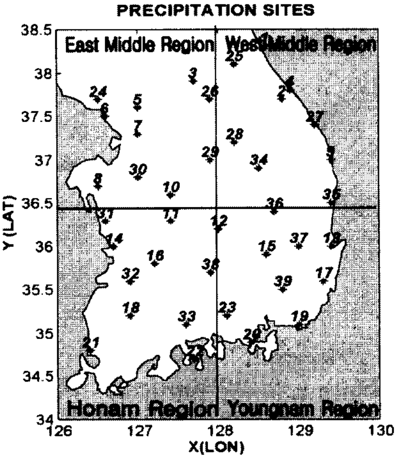


Fig. 4. Location of the Study Area, South Korea with 39 Precipitation Stations.

Figure 4 shows the South Korean region and the precipitation stations used in this study. As shown in this figure, the whole South Korean region was devided into four representative subregions: East Middle Subregion, West Middle Subregion, Youngnam Subregion, and Honam Subregion.

The historical annual precipitation data for each station were normalized and standardized following the procedures outlined in Section 2.1. The skewness test of normality was applied to check whether the data was normally distributed. While the data for some of the sites were approximately normal, most of the sites required the cubic root- or log-transformations. After completing the normalization of historical data, the data for each station was standardized based on the Eqn. (1).

3.2 Spatial Distribution of Drought Severity

Based on the Spatial Analysis Neural Network (SANN) model and the procedure to analyze the Baysian Drought Index as described in Section 2.3, the normalized and standardized annual precipitation field at a grid system between 126 and 130 degrees East longitude and 34.0 and 38.0 degrees North latitude were involved in analyzing the spatial distribution of drought severity for each year. Each raster cell is confined in 0.1 degree of latitude and longitude. Each sub-area is assumed to be hydrological and meteorological homogeneous. This assumption implies that every point in a sub-area has approximately the same precipitation characteristics.

For instance, the results for regional drought analysis for the year 1994 are shown in Fig. 5. Figures 5(a), (b), and (c) show the point drought probability maps for extreme, severe, and mild drought severities, respectively, which were constructed based on the Eqn. (2). These maps display the spatial distribution of

Table 2. Summary of Basic Statistics for Annual Precipitation at 39 Stations in South Korea

Site No.	Station ID	Station Name	(Longitude, Latitude)	Mean Annual Precipitation, MAP(mm)
1	90	Sokcho	(128.6, 38.3)	1291
2	100	Taeganryung	(128.8, 37.7)	1491
3	101	Chunchun	(127.7, 37.9)	1247
4	105	Kangreung	(128.9, 37.8)	1377
5	108	Seoul	(127, 37.6)	1310
6	112	Inchun	(126.6, 37.5)	1134
7	119	Suwon	(127, 37.3)	1250
8	129	Susan	(126.5, 36.7)	1186
9	130	Uljin	(129.4, 37)	1051
10	131	Chungju	(127.4, 36.6)	1200
11	133	Taejun	(127.4, 36.3)	1257
12	135	Chupungryung	(128, 36.2)	1130
13	138	Pohang	(129.4, 36)	1093
14	140	Kunsan	(126.7, 36)	1147
15	143	Taegu	(128.6, 35.9)	1010
16	146	Junju	(127.2, 35.8)	1247
17	152	Ulsan	(129.3, 35.6)	1272
18	156	Kangju	(126.9, 35.2)	1314
19	159	Pusan	(129, 35.1)	1453
20	162	Tongyoung	(128.4, 34.9)	1354
21	165	Mokpo	(126.4, 34.8)	1075
22	168	Yeosu	(127.7, 34.7)	1386
23	192	Jinju	(128.1, 35.2)	1391
24	201	Kanghwa	(126.5, 37.7)	1128
25	211	Inje	(128.2, 38.1)	946
26	212	Hongchun	(127.9, 37.7)	1118
27	214	Samchuk	(129.2, 37.4)	1088
28	221	Jechun	(128.2, 37.2)	1137
29	223	Chungju	(127.9, 37)	1028
30	232	Asan	(127, 36.8)	1064
31	235	Boryung	(126.6, 36.3)	1076
32	245	Jungeup	(120.9, 35.6)	1092
33	256	Sunchun	(127.6, 35.1)	1274
34	272	Youngju	(128.5, 36.9)	1035
35	277	Youngduk	(129.4, 36.5)	893
36	278	Eusung	(128.7, 36.4)	850
37	281	Youngchun	(129, 36)	867
38	284	Kuchang	(127.9, 35.7)	1087
39	288	Milyang	(128.8, 35.5)	1062
Basic Statistics of MAP			Mean	1165
			Standard Deviation	157
			Coefficient of Variation	0.13
			Coefficient of Skewness	0.06
			75 % percentile	1256
			50 % percentile	1135
			25 % percentile	1079
			Minimum	850
			Maximum	1491

drought severity. They may be useful for making a probabilistic statement of drought occurrence and severity at any arbitrary point or area. For instance, Youngnam and Honam subregions have over 90 % probability that these subregions were experienced by extreme

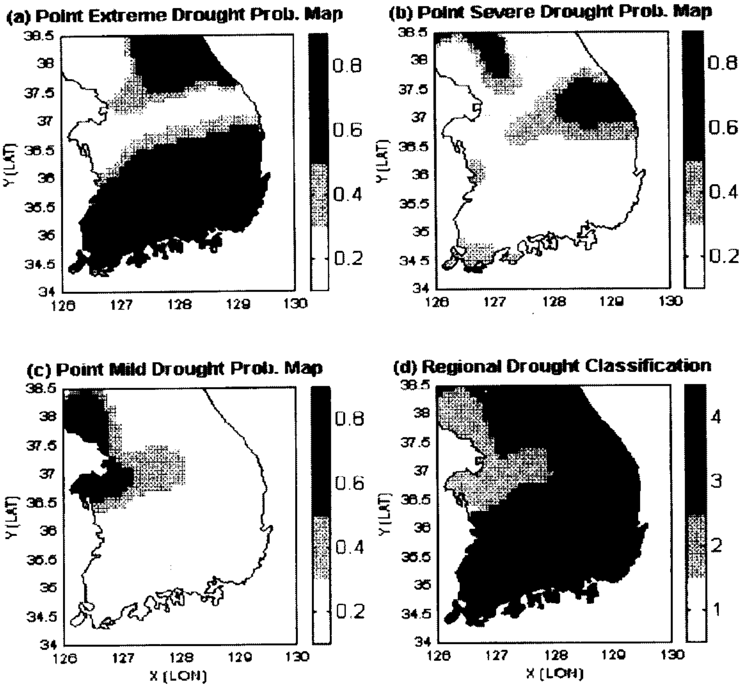


Fig. 5. Regional Drought Analysis for Year 1994

drought at the year of 1994. In addition, Fig. 5 (d) displays the spatial distribution of drought severity based on the Bayesian Drought Severity Index (BDSI) illustrated in Table 1. They are indicated by the color scale with 4 (black) = extreme drought area, 3 (dark gray) = severe drought area, 2 (light gray)= mild drought area, and 1 (white)= non-drought area. It is shown that the West Middle, Youngnam, and Honam subregions had an extreme drought. Overall most of the region in 1994 was affected by an extreme drought. The same graphical results were obtained for all years of the period 1967-1996.

Figure 6. shows the results of regional drought analysis for the period of 1967-1996 for the whold region of South Korea. These figures may be useful to recognize the spatial distribution of drought severities for each year and help someone to define the extreme, severe, mild, or non drought regions for each year. For instance of the year 1968, the Honam subregion experienced extreme drought and the Youngnam sub region was affected by severe drought, while the East and West subregions experienced mild drought. In addition, the Youngnam and Honam subregions were affected by extreme drought at the year 1995, while the East and West Middle subregions did not experienced the drought. Overall, the years of 1967-1968, 1973, 1976-1977, 1982, 1988, 1992, and 1994-1996 were affected by severe drought. The last column of Table 3 indicates the subregions where the severe droughts were experienced.

3.3 Regional Drought Severity

Even though we can recognize the spatial distribution of the drought severities for the proposed year based on the above approach, certainly one may want to define a particular year based on the criteria of areal coverage of

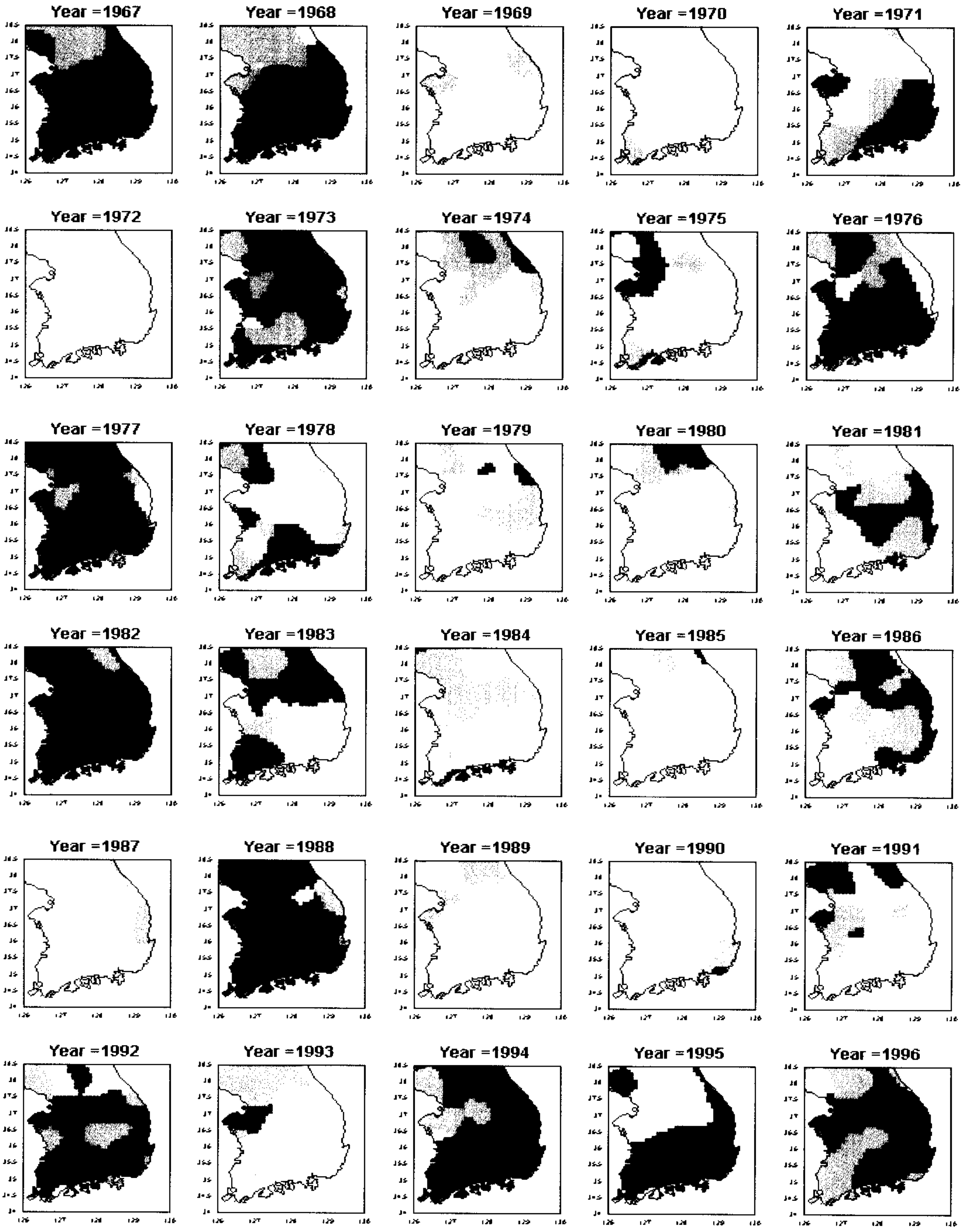


Fig. 6. Regional Drought Classification for the Period of 1967-1996 at South Korea (White: Non Drought Region, Light Gray: Mild Drought Region, Dark Gray: Severe Drought Region, Black: Extreme Drought Region)

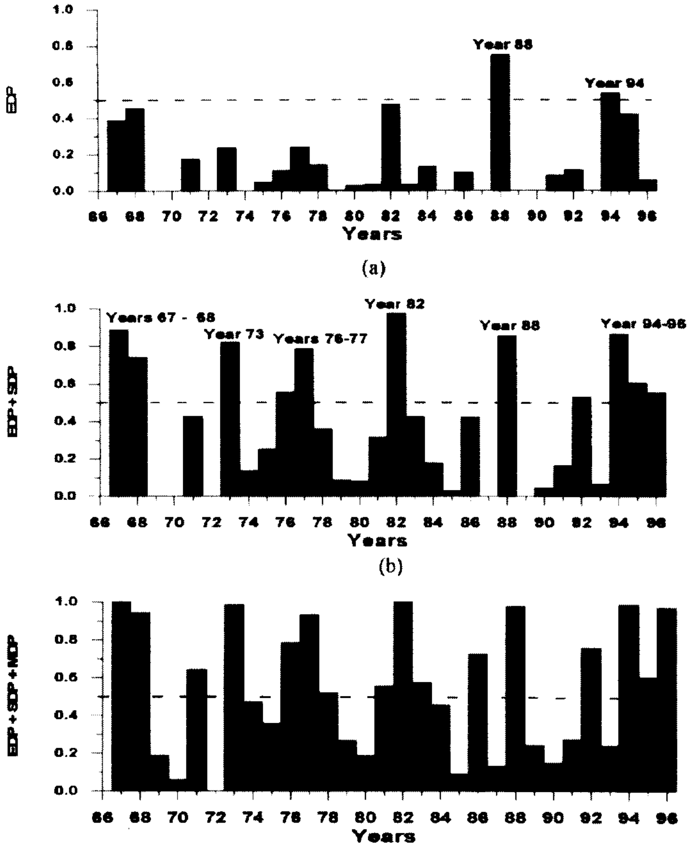
Table 3. Annual Precipitation, Regional Drought Probabilities, and Regional Drought Severity for the Period 1967-1996 for South Korea.

Year	Annual Precipitation (mm)	$\overline{EDP_t}$	($\overline{EDP_t}$ + $\overline{SDP_t}$)	$\overline{EDP_t}$ + $\overline{SDP_t}$ + $\overline{MDP_t}$	$\overline{NDP_t}$	Regional Drought Severity RDS_t	**Drought SubRegion** **EM: East Middle** **WM: Wast Middle** **Y: Youngnam** **H: Honam**
1967	1008	0.39	0.89	1.00	0.00	Severe	Y, H
1968	1028	0.46	0.74	0.94	0.06	Severe	Y, H
1969	1543	0.00	0.00	0.19	0.81	Non	
1970	1525	0.00	0.00	0.06	0.94	Non	
1971	1154	0.17	0.43	0.64	0.36	Mild	
1972	1574	0.00	0.00	0.00	1.00	Non	
1973	1007	0.24	0.82	0.99	0.01	Severe	EM, Y
1974	1312	0.00	0.14	0.47	0.53	Non	
1975	1324	0.05	0.25	0.36	0.64	Non	
1976	1112	0.11	0.55	0.78	0.21	Severe	EM, Y, H
1977	1031	0.24	0.78	0.93	0.07	Severe	EM, WM, Y, H
1978	1236	0.14	0.36	0.52	0.48	Mild	
1979	1341	0.00	0.09	0.27	0.73	Non	
1980	1440	0.03	0.08	0.19	0.81	Non	
1981	1233	0.03	0.32	0.56	0.44	Mild	
1982	948	0.51	0.97	1.00	0.00	Severe	WM, Y, H
1983	1170	0.03	0.42	0.57	0.43	Mild	
1984	1282	0.13	0.18	0.46	0.54	Non	
1985	1587	0.00	0.03	0.09	0.91	Non	
1986	1173	0.10	0.42	0.73	0.27	Mild	
1987	1489	0.00	0.00	0.13	0.87	Non	
1988	898	0.75	0.86	0.98	0.02	Extreme	EM, WM, Y, H
1989	1470	0.00	0.00	0.24	0.76	Non	
1990	1587	0.00	0.04	0.15	0.85	Non	
1991	1382	0.08	0.16	0.27	0.73	Non	
1992	1129	0.11	0.53	0.76	0.24	Severe	Y, H
1993	1392	0.00	0.06	0.34	0.76	Non	
1994	906	0.54	0.86	0.99	0.01	Extreme	EM, Y, H
1995	1110	0.42	0.60	0.60	0.40	Severe	Y, H
1996	1087	0.06	0.55	0.97	0.03	Severe	EM, Y

a given drought severity. The process of Section 2.4 was applied in this section to answer the answer.

Based on the Eqn. (4), the regional drought severity probabilities, $\overline{EDP_t}$, $\overline{SDP_t}$, $\overline{MDP_t}$ and NDP_t are calculated and summarized as shown in Table 3. Using this information, one can make a probabilistic statement about the regional drought occurrence for each year. For instance, one can state that there was 54 % probability that in the year 1994 the South Korea was affected by an extreme drought. Figure 7 shows the, $\overline{EDP_t}$, $\overline{EDP_t}$, $\overline{SDP_t}$ and $\overline{EDP_t}$, $\overline{SDP_t}$, $\overline{MDP_t}$ for the period 1967-1996, respectively. Based on these graphs, one may recognize easily the probabilistic drought severity for the entire period. For instance of severe drought as shown in Fig. 7(b), the years which exceeded 50 % of probability of severe drought were 1967-1968, 1973, 1976-77, 1982, 1988, and 1994-1996.

In the seventh column of Table 3 also gives



(a)

(b)

(c)

Fig. 7. Time Series of (a) Regional Extreme Drought Probability (EDP), (b) Regional Extreme+Severe Drought (SDP) Probability, and (c) Regional Extreme+Severe+Mild Drought (MDP) Probability.

the regional drought severity indices determined by the expression of Eqn. (6) for the years of 1967-1996. The 1967 was an extreme drought year, followed by the 1968 with extreme drought severity. The droughts of the periods of 1976-1978, 1981-1983, and 1994-1996 lasted three years. Besides, the droughts of 1974 and 1988 years lasted just a year. Overall, in terms of regional drought severity and drought duration, the 1967-1968 and 1994-1996 were most significantly affected by severe drought among the period 1967-1996.

4. Summary and Conclusions

In this paper, we have two purposes: (1) to develop and introduce an approach to analyze and quantify the regional meteorological drought for the region of interest based on annual precipitation data; (2) to apply the proposed method to the entire region of South Korea. After normalization and standardization, the annual precipitation data were classified into four classes (drought severities), namely: extreme drought, severe drought, mild drought, and non-drought. The definition of these classes were done based on three truncation levels corresponding to the 15 %, 35 %, and 50 % quantiles of the standard normal distribution. The posterior probabilities of each drought severity for a given point $\mathbf{x}$ in the region were determined, i.e. $P(C^j \mid \mathbf{x}^m)$, $j=1,2,3,4$, and the point was assigned a (point) drought index $d(\mathbf{x})$ either as 4, 3, 2, or 1, depending on whether the maximum posterior probability corresponded to either extreme, severe, mild, or non-drought, respectively. We called the index as "Bayesian Point Drought-Severity Index (BPDI)". This information was useful for constructing a BPDI map and displaying the spatial variability of drought severity for the whole region on a yearly basis.

Furthermore, one may like to identify the severity of the drought event for the region as a whole. For this purpose the areal average of the (point) drought severity probabilities were determined and a decision rule was established to identify various levels of drought severities. This is called "Regional Drought Severities". Based the RDS, each year was defined by four classes: E (extreme drought), S (severe drought). M (mild drought) and N (Non drought). This drought identification procedure was also useful for determining the sequence of drought episodes through time and their durations.

The proposed regional drought analysis approach was applied to analyze and quantify the regional meteorological droughts for the South Korean region. Annual precipitation data at 39 sites available for the period 1967-1996 were utilized. Based on the proposed method, several information related with the regional drought of South Korea was produced: the point drought probability maps, the BDSI map to visualizing the spatial pattern of droughts over the region, the regional drought probability, and the regional drought severity to define the yearly drought type for each year in the period 1967-1996. Then, the South Korea region was classified into extreme, severe, mild, and non drought severities spatially and temporally. The results obtained above suggest that the proposed approach is valuable and practical tool for analyzing regional droughts.

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