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DROUGHT MONITORING USING DECILES INDEX, STANDARDIZED PRECIPITATION INDEX AND EFFECTIVE DROUGHT INDEX IN TEHRAN PROVINCE, IRAN

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ABSTRACT

Drought monitoring is difficult, though it is essential for risk management of this destructive natural disaster. A number of indices which play a major role in detection of drought severity, its onset and end for monitoring purposes, have been introduced and applied in this regard. This paper compares the capabilities of three drought indices for the 1997-2000 droughts in Tehran province, Iran. A series of maps of the province are used to illustrate how the indices would have been able to detect the onset of the drought, as well as monitor its progress on a monthly timescale. The results show that the DI (Deciles Index) is very responsive to the rainfall events of this year, but with inconsistent spatial and temporal variations. The SPI (Standard Precipitation Index) shows a slow response to the drought according to the applied timescale. Finally, the EDI (Effective Drought Index), a relatively new drought index, is able to detect the onset of drought and its spatial as well as temporal variations very consistently, and seems the most promising as an operational index for local and regional drought watch system in the province. Also, EDI the ability of EDI to detect drought status on a daily basis is another advantage of this index for the management of drought risk.

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پایش خشکسالی با استفاده از شاخص‌های DI، SPIو EDI در استان تهران، ایران

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چکیده

پایش خشکسالی، به رغم مشکلاتی که دارد، برای مدیریت این بلیه طبیعی لازم است. در این خصوص، چندین شاخص، تدوین و ارائه شده اند که نقش مهمی در پایش خشکسالی و سیستم‌هایی دارند که برای این منظور، طراحی می‌شوند. در این پژوهش، کارآیی سه شاخص DI، SPI و EDI برای پایش خشکسالی استان تهران بین سال های آبی ۱۹۹۷-۲۰۰۰ به طور ماهیانه، مقایسه و ارزیابی شدند. نقشه‌های تهیه شده از این سه شاخص، چگونگی اعلام وضعیت خشکسالی را نشان دادند. نتایج نشان داد که شاخص DI نوسانات شدیدی نسبت به بارندگی داشت و در مقابل، SPI نوسانات کمتری داشت. EDI، به عنوان یک شاخص نسبتاً جدید خشکسالی، قادر به تعیین مطلوبی از اعلام وضعیت خشکسالی و تغییرات مکانی آن بود و کارآترین شاخص برای پایش خشکسالی در این استان تشخیص داده شد. کارآیی این شاخص برای تعیین وضعیت خشکسالی به طور روزانه، یکی دیگر از مزیت‌های آن برای مدیریت خشکسالی در منطقه مطالعاتی است.

INTRODUCTION

Monitoring is one of the main tools for efficient drought management, which is mainly based on drought indices. Selection of drought indices should be based on their ability to consistently detect spatial and temporal variations in a drought event, as well as using readily available data. Since one of the main objectives of such monitoring systems is triggering predefined responses to cope with this natural disaster, their time scale is also of great importance.

The Palmer Drought Severity Index (PDSI) (15) is the most commonly used index for drought monitoring, but is still viewed as problematic. For example, Hayes *et al.* (11) point out the limited success of the index for operational drought monitoring. The index requires weekly or monthly precipitation, temperature, and local antecedent soil moisture conditions. This latter input is not readily available, in many cases, which limits its application, especially in developing countries. Late response to drought onset and difficult computational procedure are other limitations of the index (3). More discussions about the limitations of the PDSI are available in Kogan (12), McKee *et al.* (13) and Guttman (10).

In addition to the PDSI, there are a number of indices that use only rainfall data. The DI (Decile Index) is one example (9), and is well documented in Palmer and Rodda (16). To overcome part of the aforementioned limitations of the PDSI, McKee *et al.* (13) developed the SPI that gains from simplicity and relying only on precipitation data. The SPI's (Standard Precipitation Index) flexibility to observe different timescales is another advantage of the index, although at the shorter time scale the results of the index may be very close to the percent of normal representation of rainfall (11). This index is presently used as one of the indices for drought monitoring for the entire United States (2).

Byun and Wilhite (4) reported limitations of the present indices in terms of a lack of indicating the start and the end of the drought period, the drought duration, the period of water deficit, as well as requiring extensive data. They proposed a new daily index named EDI (Effective Drought Index) to rectify some of the mentioned disadvantages.

This paper follows the development and progress of the severe drought in Tehran province during 1997-2000 using the DI, SPI and EDI indices to evaluate their capabilities as a relevant index for a drought monitoring system. For this drought spell the province average temperature increased by 4°C and water storages of its main dams including Karadj, Latian and Lar reduced to 50% of its long term average (8).

Seven climate stations (Bagher Abad, Mehra Abad, Bilaghan, Rodak, Siera, Hamand Absard, and Abali) were selected for the analysis. The observations from these stations contain no missing data and have records lengths from October 1970 to September 2000 (note that the Iranian water year starts in October). For studies of a real drought extent, the precipitation records from other 36 stations in the province were also utilized. The missing data of these stations have been recovered by regression methods.

The evaluations have been done by comparisons of the indices to the rainfall events and providing a series of maps that track progression of the drought within the province to assess spatial and temporal versatility of the indices. The selection of SPI and DI is based on their relines on precipitation data and wide usage. Whereas in case of EDI, in addition to using readily available precipitation data, the novelty of the index has been considered, too.

The Drought Indices

In this section, brief explanations are presented about the DI and SPI indices. As the literature available for the EDI is more limited, it is explained in more detail below.

The Deciles Index (DI)

The Deciles Index divides a series of precipitation data into ten deciles using the normal distribution (9). Comparing the amount of precipitation for the desired time period and deciles, the status of drought can be identified. The index widely uses in Australia (6). Table 1 shows the classes of DI. For this study, to apply DI, the monthly rainfall data are normalized using the Box-Cox transformation (14).

The Standard Precipitation Index (SPI)

The SPI calculation for any location is based on the long-term precipitation. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (7). Table 1 shows the classes of SPI.

The Effective Drought Index (EDI)

The EDI is an index based on a daily timescale. It offers several advantages over the DI and SPI indices, such as detecting the onset, end, and accumulated stress of drought. The general EDI classes are also shown in Table 1. This index includes extensive computational steps (5), which are described here.

Calculation of Effective Drought Index

This index is based on the new concept of Effective Precipitation (EP), which refers to the summation of all daily precipitation with a time reduction function. EP for any day is a function of precipitation of the current day, as well as previous days but with lower weights.

The calculation procedure of the index starts by applying a dummy water deficit period as a requirement to determine the real period. The dummy duration can vary, for example, it could be 365 d, a representative value of the total water resources available or stored for longer period, or it could be as short as 15 d, as a representative of a short period. In this study, a dummy value of 365 d is chosen as it represents a dominant precipitation cycle globally.

Once the duration is set, the *Daily Effective Precipitation* is calculated according to the following equation:

Table 4. Correlation coefficient between eleven traits measured from calli initiated and grew on media contained six different NaCl levels.

Variables	Fresh weight	Water content	Dry matter	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	K^{+}/Na^{+} ratio	Ca^{2+}/Na^{+} ratio	Cl^{-}	Proline
Fresh weight	1.0000										
Water content	0.9990 ***	1.0000									
Dry matter	0.7558 ***	0.7261 ***	1.0000								
Ca^{2+}	0.3018 **	0.3220 ***	-0.0765 ns	1.0000							
Mg^{2+}	0.0409 ns	0.0603 ns	-0.2565 **	0.1118 ns	1.0000						
Na^{+}	-0.2980 **	-0.3112 **	-0.0262 ns	-0.3360 ***	-0.0690 ns	1.0000					
K^{+}	0.5633 ***	0.5725 ***	-0.2806 **	0.0695 ns	0.1767 ns	-0.2479 *	1.0000				
K^{+}/Na^{+} ratio	0.3362 ***	0.3517 ***	0.0194 ns	0.3348 ***	0.1542 ns	-0.7669 ***	0.3373 ***	1.0000			
Ca^{2+}/Na^{+} ratio	0.3051 **	0.3220 ***	-0.0250 ns	0.5731 ***	0.1164 ns	-0.7263 ***	0.1679 ns	0.9291 ***	1.0000		
Cl^{-}	-0.2898 **	-0.2997 **	-0.0690 ns	-0.2766 **	-0.0471 ns	0.7884 ***	-0.2760 **	-0.5743 ***	-0.5269 ***	1.0000	
Proline	-0.3210 ***	-0.3302 ***	-0.1010 ns	-0.2511 *	0.2176 *	-0.0489 ns	-0.3208 ***	-0.0997 ns	-0.1308 ns	0.0298 ns	1.0000

ns, *, ** and *** not significant, significant at $P<0.05$, significant at $P<0.01$, and significant at $P<0.001$, repectively.

$$EP_i = \sum_{n=i}^{i}[(\sum_{m=1}^{n} P_m)/n] \quad [1]$$

where i = Duration of Summation and Pm = Precipitation of $m-1$ d before. For better understanding of this equation a simple example is presented. If i is equal to 3 then EP_3 becomes $(P_1+(P_1+P_2)/2+(P_1+P_2+P_3)/3)$. For any investigated drought period, *EP* should be calculated each day for the dummy duration. It is clear that the calculation procedure should start at the second year (i.e., if there are 30 years of data, 365×29 *EP* values should be calculated).

To obtain each day's *Mean of EP* (*MEP*), *EPs* related to each day of the period are summed and then averaged. This number illustrates the climatologically characteristics of water resources.

The Deviation of *EP* from *MEP (DEP*) is then calculated by the equation:

$$DEP=EP-MEP \quad [2]$$

DEP is calculated on daily basis. Negative values of *DEP* indicate a deficiency of water resources for a particular date and place while the positive ones indicate surplus.

The Standardized value of *DEP (SEP)* is then calculated from the equation:

$$SEP=DEP/ST(EP) \quad [3]$$

where *ST(EP)* denotes the standard deviation of each day's *EP*. *SEP* enables one location's drought severity to be compared to another location's, regardless of climatic differences.

Defining actual drought duration

Since negative values of *DEP* or *SEP* denote below-normal precipitation, periods of consecutive negative values in *DEP* and *SEP* denote consecutive drier periods than normal. A dry duration can then be defined as the period of consecutive negative values of *SEP*, and the actual duration as the sum of the dummy duration and the number of days in the past in either wet or dry conditions.

Precipitation needed for a Return to Normal (PRN)

After the calculation of each day's *DEP*, the *PRN* for each day should be calculated considering the actual duration. The *PRN* shows the needed precipitation for recovery from the accumulated deficit. It is calculated by the following equation:

$$PRN_j = \frac{DEP_j}{\sum_{N=1}^{j}(1/N)} \quad [4]$$

where j is actual duration.

Effective Drought Index (EDI)

Finally, the EDI is calculated as the standardized value of *PRN* using eq. [5]. The index is capable for worldwide application because it is independent of climatic characteristics of the location.

$$EDI_j = \frac{PRN_j}{ST(PRN_j)} \quad [5]$$

where *ST(PRN)* denotes the standard deviation of each day's *PRN*.

RESULTS AND DISCUSSION

Drought Status Based on the Selected Indices

The SPI is based on statistical distributions, needs at least 30 years of recorded data to be robust (11) and similarly the DI. But, the EDI does not use a statistical distribution, and can be viewed as a nonparametric drought index not requiring such minimum lengths of recorded data.

In order to develop comparable indices with these three methods, the analyses have been done only for the seven stations with 30 or more years of record. The results of the application of these indices for the drought of 1997-2000 are shown in Tables 2 to 4 Table 2 demonstrates that DI varies significantly across both the months and the stations.. For instance, during Jan 1999, the DI shows a drought class of -4 (Very much below normal) to 3 (Much above normal) in the selected stations, while in the case of the Rodak station, the index rages from -4 (Very much below normal) to 4 (Very much above normal) in this drought event. Contrary to the DI, the response of the SPI to this drought varies little. For most of the months and stations, the SPI shows normal conditions, while in fact this drought was quite harsh (Table 3). The EDI, however, shows the drought status more consistently, both spatially and temporally (Table 4). This index warns of the

Table 2. The DI drought classes for Tehran Province during 1997-2000

Year	1997			1998												1999												2000								
Station	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se
Bagher Abad	2	-3	-2	1	-2	0	-2	-1	-2	4	4	-2	0	4	0	-4	4	-2	-2	-3	-2	2	-2	-2	4	2	4	-4	0	-2	-3	0	3	-1	4	1
Mehr Abad	3	-4	1	0	-4	0	-3	-3	-4	4	0	-2	-3	4	-3	-4	2	-3	-2	-4	-4	-1	-2	4	3	0	4	-3	-3	-2	-3	0	3	-1	4	1
Bilaghhan	0	-3	-2	1	-4	-1	-3	-2	-3	4	-2	-2	0	3	-2	-4	2	-3	-3	-4	-3	-2	-2	3	4	0	4	-4	-2	-2	-2	0	-2	2	3	3
Rodak	0	-4	0	1	0	-2	0	0	-3	4	0	-3	-2	3	-2	-3	4	-2	-3	-4	-4	3	-2	0	4	0	4	-4	-4	-3	-4	-1	2	3	4	4
Siera	0	-2	-3	2	-1	-2	-2	-2	-3	4	3	4	-3	3	-2	-1	3	-3	-1	-3	-4	2	-3	4	4	-3	2	-4	-4	-4	-3	-1	0	2	3	4
Hamand Absard	3	-4	-4	-3	-3	-2	4	-4	1	3	-3	-3	-1	0	0	3	3	-1	3	0	2	0	4	3	0	-2	0	4	0	3	0	-2	-4	4	-3	-3
Abali	2	-3	-2	1	-2	0	-1	-2	-4	3	4	-2	0	3	-3	-2	3	-3	-3	-4	-4	0	4	-3	4	0	4	-4	-4	-4	-3	0	1	2	4	3

1= Slightly above normal, 2=Above normal, 3= Much above normal, 4= Very much above normal,0= Normal, -1=Slightly below normal, -2= Below normal, -3= Much below normal, -4= Very much below normal

Table 3. The SPI drought classes for Tehran Province during 1997-2000

Year	1997			1998												1999												2000								
Station	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se
Bagher Abad	0	0	0	0	0	0	0	0	0	1	1	0	0	3	0	-1	1	0	0	0	0	0	0	0	2	0	2	-1	0	0	-1	0	0	0	2	0
Mehr Abad	0	-1	0	0	-3	0	0	0	-1	2	0	0	0	2	0	-3	0	0	0	-1	-1	0	0	1	2	0	1	0	0	0	-1	0	0	0	1	0
Bilaghhan	0	0	0	0	-2	0	0	0	0	2	0	0	0	1	0	-3	0	-1	-1	-2	0	0	0	0	3	0	1	-2	0	0	0	0	0	0	0	0
Rodak	0	-1	0	0	0	0	0	0	0	1	0	0	0	1	0	-1	1	0	0	-1	0	0	0	0	2	0	1	-3	-2	0	-2	0	0	0	0	3
Siera	0	0	0	0	0	0	0	0	-1	2	0	0	0	1	0	0	1	-1	0	0	-1	0	0	0	2	-1	0	-1	-2	-1	0	0	0	0	0	2
Hamand Absard	0	-2	-3	0	-1	0	1	-1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	2	0	0	0	0	1	0	1	0	0	0	2	0	0
Abali	0	-1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1	0	0	0	0	1	1

1=Moderately wet, 2= Very wet, 3=Extremely wet, 0= Near normal, -1=Moderately dry, -2= Severely dry, -3= Extremely dry

Table 4. The EDI drought classes for Tehran Province during 1997-2000

Year	1997			1998												1999												2000								
Station	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	Ma	Ju	Jl	Au	Se
Bagher Abad	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	1	0	0	0	0	-1	-1	-1	-1	-1	0	1	1	1	1	0	0	0	0	0	0	0
Mehr Abad	0	0	0	0	-1	-1	-1	-2	-2	-2	-1	-1	-1	0	0	0	0	0	-1	-2	-2	-2	-2	-2	-1	0	0	0	0	-1	-1	-1	-1	-1	-1	-1
Bilaghhan	1	0	0	-1	-1	-1	-1	-2	-2	-2	-1	-2	-2	0	0	-1	0	0	-1	-2	-2	-2	-2	-2	0	0	1	0	0	-1	-1	-1	-1	-1	-1	-1
Rodak	2	0	0	0	0	0	0	0	-1	-1	0	-1	-1	0	0	0	0	0	-1	-1	-2	-2	-1	-1	0	0	1	0	0	-1	-2	-2	-2	-2	-1	-1
Siera	1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	-1	-1	-1	-1	-1	0	0	0	0	-1	-2	-2	-2	-2	-2	-2	-1
Hamand Absard	1	0	0	-1	-1	-1	0	0	-1	0	-1	-1	-1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	1	1	0	0	0	0	0
Abali	0	0	0	-1	0	0	0	-1	-1	-1	0	0	-1	0	0	-1	0	0	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	-1	-2	-1	-1	-1	-1	-1

1= Slight surplus of water, 2= High surplus of water, -1= Dry, -2= Moderate drought, -3=Severe drought, -4= Extreme drought onset of the drought in April for two of the stations and gradually detects the drought in other stations as well. As stated before, the EDI timescale is daily and values of EDI in Table 4 are averages of these daily values.

Fig. 1 explains the aforementioned variation of the indices more precisely. In the figures, in addition to the indices, monthly rainfall values are also included. Very fast response of the DI to rainfall events can be observed from the figure. This causes high fluctuations in the detected drought classes. In case of the EDI, it is vise versa. But, one point can be concluded from both the DI and SPI that they responsed to monthly rainfall regardless of the previous situation. For instance both indices end to the drought after the rainfalls of Nov. and Feb. 1998 or Dec. 2000. The figure shows consistent responses of the EDI to rainfall event. The EDI curve is very smooth with no fluctuation, as it is seen in case of the DI and SPI. This capability can be attributed to the memory *EP*, which exists in the index. It is avoidant that this specification makes the EDI detects drought onset and end, after other indices. Because of the clear advantages of the EDI as illustrated in these tables, the EDI is selected for further analyses.

The Daily Drought Status Based on EDI

For each of the selected stations, the EDI has been calculated at daily bases for the 3 years drought spell. To keep this manustrip short, only the results of Mehr Abad station, which is the most important station of the province have been presented (Fig. 2), but results are consistent with other stations. The figure is very clear, meaningful and precise in showing and presenting the daily drought status by using a number of the parameters. Fig. 2a shows *EP*, *MEP*, and *DEP*, while Fig. 2b indicates precipitation, *PRN* and *EDI*. Decreasing EP relative to MEP detects drought condition. For more suitability in presenting the results, precipitation depth and *PRN* have been multiplied by 10 and the *EDI* by 100.

The figure shows that up to the 19th day of the first water year, *EP* is higher than *MEP,* and *DEP* is positive. But, for the rest of the three years in most of the time, drought condition governs the region. The PRN and EDI graphs show the magnitude of rainfall needed to return to normal condition and its daily index value, respectively.

For this period, the maximum shortage occurred in the day 226 or on 9 March 1999 where 31 mm rainfall deficit in the station was detected. It is also interesting that the index has reacted to the winter and autumn rainfalls event (e.g. Oct. 1998 to March 1999), but the reactions are limited to a few days. A continuous drought from 22 March 1999 to 31 Oct. 1999 for 224 days was also monitored and recorded at the station. This shows how catastrophic was this drought. The worst daily drought situation was related to the day 24 May 1999 where its EDI value was -1.88, indicating a Sever Drought condition.

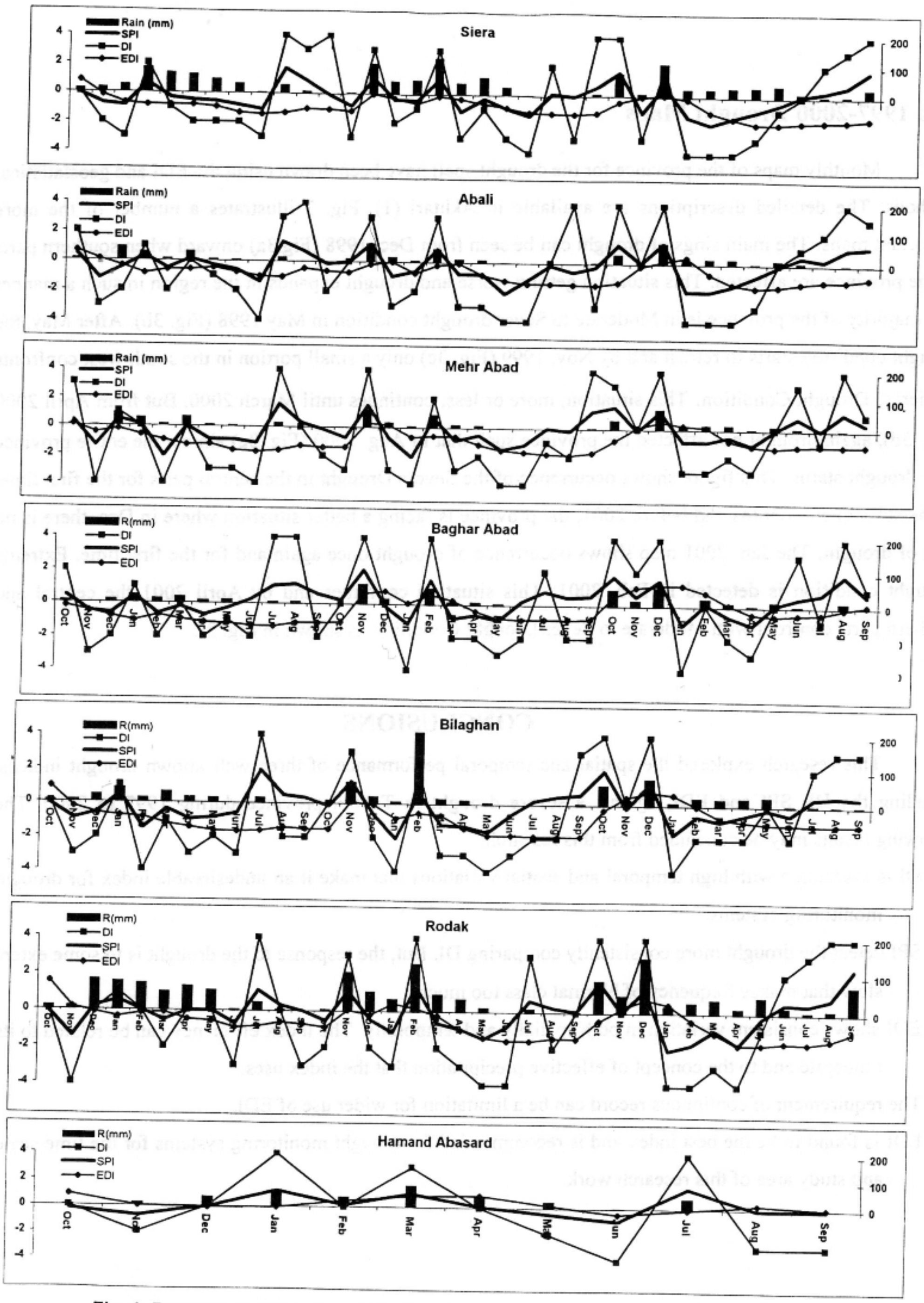


Fig. 1. Responces of the drought indices to rainfall events (Starting from Oct. 1997)

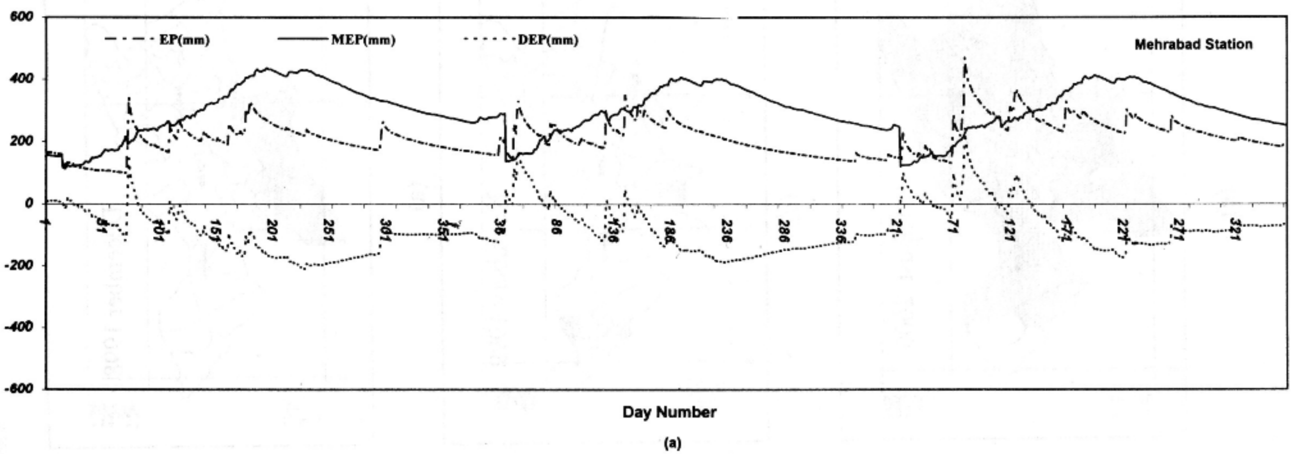
The 1997-2000 Drought Maps

Monthly maps of the province for the drought spell have been drawn using the EDI and geostatistical methods. The detailed descriptions are available in Akhtari (1). Fig. 3 illustrates a number of the more important maps. The main sings of drought can be seen from Dec. 1998 (Fig.3a) onward when southern parts of the province are affected. This situation getting worse and drought expands in the region in such a manner that majority of the province is in Moderate to Sever drought condition in May 1998 (Fig. 3b). After May, the drought condition starts to retreat and by Nov. 1999 (Fig. 3c) only a small portion in the south west confronts Moderate Drought Condition. This situation, more or less, continues until March 2000. But from April 2000 (Fig. 3d), again drought has affected the province such that in Aug. 2000 (Fig. 3e) almost the entire province is in drought status. This figure shows occurrence of the Severe Drought in the central parts for the first time. In the subsequent months and before 2001, the province is facing a better situation where in Dec. there is no sign of drought. The Jan. 2001 map shows occurrence of drought once again and for the first time, Extreme Drought condition is detected in Feb. 2001. This situation continues and by April 2001 the central and northern parts confront with Moderate to Sever Drought Condition as shown in Fig. 3f.

CONCLUSIONS

This research explored the spatial and temporal performance of three well known drought indices, including the DI, SPI and EDI, against a severe drought in Tehran province during 1997 to 2000. The following results may be concluded from this research:

1. DI is associated with high temporal and spatial variations that make it an undesireable index for drought monitoring systems.
2. SPI detect the drought more consistently comparing DI. But, the response to the drought is to some extent slow that makes frequency of Normal class too much.
3. EDI shows consistent variation in both spatially and temporally. The index efficiency can be related to its timescale and to the concept of effective precipitation that the index uses.
4. The requirement of continuous record can be a limitation for wider use of EDI.
5. EDI is found to be the best index and is recommended for drought monitoring systems for the time scale and study area of this research work.



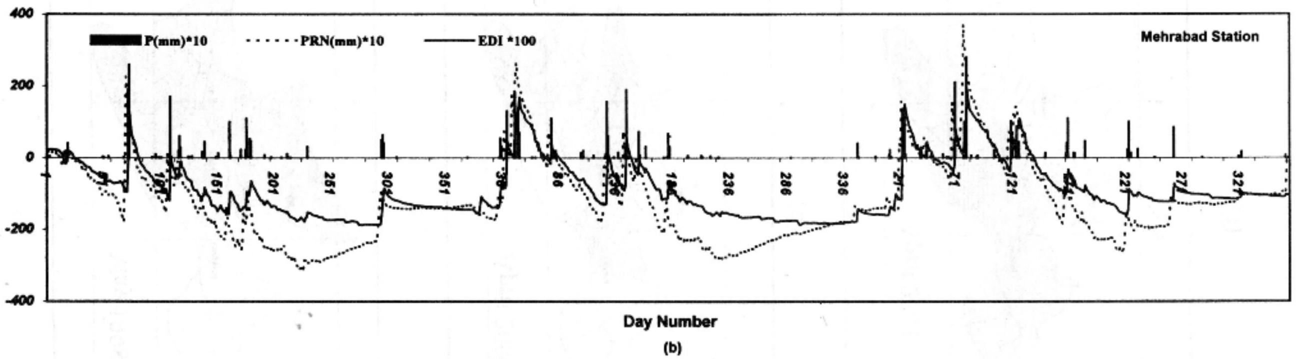
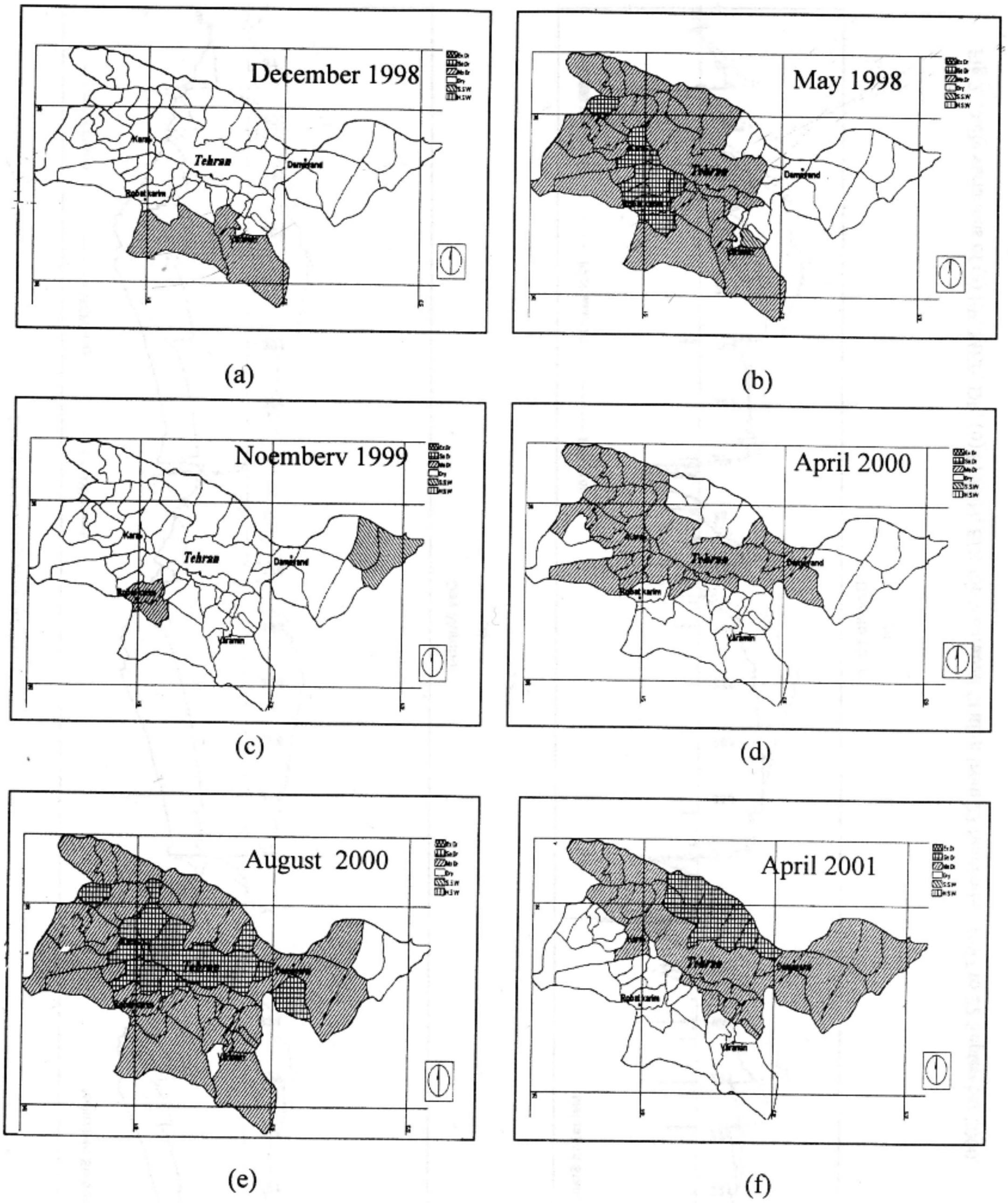


Fig 2. Daily variations of (a) EP, MEP, DP, (b) P, PRN, EDI for Mehrabad Station from 23 September 1997 to 22 September 2000.



Legend:
Ex.Dr = Extreme Drought, Sv.Dr = Severe Drought, Md.Dr = Moderate Drought
MO.We = Moderate Wet,Ve.We=Very Wet

Fig. 3. Status of Tehran Province during the 1997-2000 drought, using EDI.

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