International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:3, No:9, 2009

Analysis of Meteorological Drought in the Ruhr Basin by Using the Standardized Precipitation Index

Mosaad Khadr, Gerd Morgenschweis, and Andreas Schlenkhoff

Abstract**—**Drought is one of the most damaging climate-related hazards, it is generally considered as a prolonged absence of precipitation. This normal and recurring climate phenomenon had plagued civilization throughout history because of the negative impacts on economical, environmental and social sectors. Drought characteristics are thus recognized as important factors in water resources planning and management. The purpose of this study is to detect the changes in drought frequency, persistence and severity in the Ruhr river basin. The frequency of drought events was calculated using the Standardized Precipitation Index (SPI). Used data are daily precipitation records from seven meteorological stations covering the period 1961-2007. The main benefit of the application of this index is its versatility, only rainfall data is required to deliver five major dimensions of a drought : duration, intensity, severity, magnitude, and frequency. Furthermore, drought can be calculated in different time steps. In this study SPI was calculated for 1, 3, 6, 9, 12, and 24 months. Several drought events were detected in the covered period, these events contain mild, moderate and severe droughts. Also positive and negative trends in the SPI values were observed.

Keywords**—**Drought, Germany, Precipitation, Ruhr River, Standardized Precipitation Index (SPI), Trend Test.

I. Introduction

DROUGHT is a disastrous natural phenomenon that has significant impact on socio-economical, agricultural, and environmental spheres. Drannbauer et al. [1] reported that Wilhite [3] uncovered more than 150 published definitions of drought in the early 1980s. In general, drought is the consequence of a natural reduction in the amount of precipitation received over an extended period of time, usually a season or more in duration, although other climatic factors (such as high temperatures, strong wind and low relative humidity) are often associated with it in many regions of the world and can significantly aggravate the severity of the event [2]. Drought severity is dependent not only on the duration, intensity, and spatial extent of a specific drought episode, but also on demands on a region's water supply caused by human activities and vegetation [3]. In general, drought gives an impression of water scarcity due to insufficient precipitation, high evapotranspiration, and over-exploitation of water resources or combination of these parameters [4]. The primary cause of a drought is the lack of precipitation over a large area and an extensive period of time; this type is called meteorological drought [5]. This water deficit propagates to the hydrological cycle and gives rise to different types of droughts. The drought problems are always existing somewhere in the world so that the economy of some nation or nations is always being adversely influenced by this factor. Although drought is a natural component of climate in arid and semi-arid areas, it can occur in areas which normally receive adequate precipitation. In Europe, drought is a recurrent feature of the European climate that is not restricted to the mediterranean region: it can occur in high and low rainfall areas and in any season [6]. Recent analyses clearly show summer warming and drying trends in Europe in recent decades [7]. The 2003 summer was exceptionally hot over most of central and Western Europe, ranging from Spain to Hungary and from Iceland to Greece [8].It clearly showed that water availability issues and water management represent a challenge in large parts of Europe, even in parts of Germany [9]. Many European river basins experienced severe droughts in the late 1980s and during the 1990s [10]. Hege Hisdal [10] reported that the Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK) (1998) concluded that in recent decades the drought situation in most parts of Central and Eastern Europe has worsened because the frequency, duration and severity of the drought events have increased. Over the years, operational definitions of drought formulated in form of indices have emerged to answer such questions as: when, how long, and how severe is a drought. Drought planners usually rely on some mathematical indices to decide when to start implementing water conservation or mitigation measures. Many indices have been developed to measure drought severity [11]. So the Palmer Drought Severity Index (PDSI) has been the drought index most used worldwide, however, the Standardized Precipitation Index (SPI) has come into use as an alternative to the PDSI [12]. The objective of the study is to perform an evaluation of drought conditions in Ruhr river basin by using the SPI methodology provided by T. McKee in 1993 [13].

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II. Study Area

The Ruhr River is an important tributary of the lower Rhine

River, it rises on the eastern side of the mountainous region near Winterberg and flows 219 km westwards to pour at Duisburg into the Rhine River (cp. Fig. 1). Considering its length, runoff and the size of its catchment area, the Ruhr River is a comparatively small river. It is 219 km in length and yields a mean yearly runoff of 76 m³.s^{-1} at its mouth. So the runoff of the Ruhr River remains clearly under that of the River Rhine at Duisburg whose mean yearly runoff is 2510 m³.s^{-1}. In the Ruhr catchment area, 4485 km², the mean annual precipitation varies between 640 mm and 1389 mm (with an average of 1056 mm).On an average 2.4 billion m³ of water flow per year from the Ruhr River into the Rhine River . The Ruhr River provides population and industries in the Rhenish-Westphalian industrial distric, the so-called “Ruhr district” with drinking and process water. The Ruhr district is one of the most important densely populated areas of Europe. More than 5 million people live and work here – that is about 6.5 % of the population of the entire Federal Republic of Germany. This region derived its name from the river, which runs along on its south side – the "Ruhr". It is due to this highly densely populated industrialized area that water consumption per unit of area is approximately seven times higher than the average consumption in the Federal Republic of Germany. Special measures are therefore necessary in order to guarantee the supply of drinking water and the disposal of wastewater.[14].

Germany- Ruhr river basin

Fig. 1 Ruhr river basin
Source: http://www.talsperrenleitzentrale-ruhr.de/gewaesser.html

III. Data Collection

A database containing with 7 stations with a time series of daily precipitation starting at 1960 has been established. Source of data is the Ruhrverband (Ruhr River Association). Fig. 2 shows the location of each station used in the study. Table I contains information about the stations, and the covered period. Table II presents the correlation factor between the stations.

Fig. 2 Location of stations used in the study
Source: http://www.talsperrenleitzentrale-ruhr.de/daten/internet/veroeffentlichungen/ruhrwassermenge_2006.pdf

TABLE I
Names of Stations, and the Covered Period of the Series of Data Set of Records

Station	Ref. No. on Fig. (1)	Precipitation covered period
Sorpetalsperre	3	1960-2007
Versetalsperre	5	1960-2007
Listertalsperre	6	1960-2007
Drolshagen_Bleche	8	1960-2007
Willertshagen_Volmehof	9	1960-2007
Ennepetalsperre	14	1960-2007
Essen_Ruhrhaus	24	1960-2007

TABLE II
Correlation Factor between Stations: Precipitation (1960-2007)

Station No. in Table I	8	14	24	6	3	5
8						
14	0.85					
24	0.72	0.81				
6	0.89	0.84	0.72			
3	0.77	0.81	0.72	0.81		
5	0.88	0.90	0.76	0.90	0.84	
9	0.91	0.86	0.74	0.89	0.77	0.89

IV. Standardized Precipitation Index

Precipitation is a climatologically phenomenon more difficult to study than temperature, because it is discontinuous with some days receiving no precipitation, while other days receive abundant amounts of precipitation. For this reason, the basic measurement period for many precipitation studies is the total precipitation for each month. The Standardized

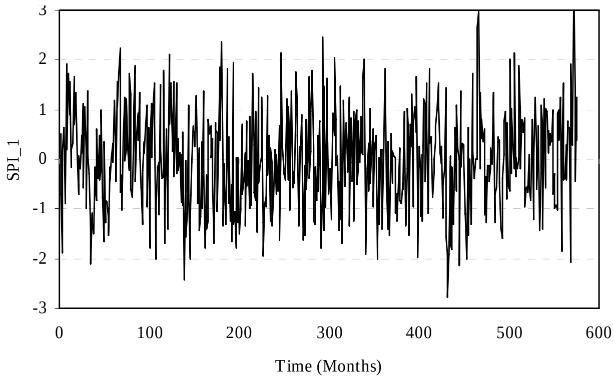
Precipitation Index (SPI)is a tool developed by McKee et al [13] for the purpose of defining and monitoring local droughts. It was conceived to identify drought periods and the severity of droughts, at multiple time scales. Shorter or longer time scales may reflect lags in the response of different water resources to precipitation anomalies. McKee [13] defined the criteria for a "drought event" for any of the time scales: A drought event occurs if the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and the end, and an intensity for each month the event continues. The cumulated magnitude of a drought can be considered as drought magnitude, being defined by the positive sum of the SPI for all the months within a drought event. The Standardized Precipitation Index (SPI) is an index widely used for drought monitoring purposes. Since its computation requires the preliminary fitting of a probability distribution to monthly precipitation aggregated at different time scales, the SPI value for a given year and a given month will depend on the particular sample of observed precipitation data adopted for its estimation and in particular on the sample size. Furthermore, the presence of a trend in the underlying precipitation will affect adversely the estimation of parameters, and therefore the computation of SPI [15]. The calculation of SPI requires that there is no missing data in the time series. The data record length is required to be at least 30 years [16]. A number of advantages arise from the use of the SPI index [17]. First of all, the index is simple and is based only on the amount of precipitation so that its valuation is rather easy. Also the SPI index can be computed for multiple time scales (i.e., 1, 2 ,3, . . .72 months), thus allowing the comparison between different time periods. This can be an excellent communication tool to the public and to policy makers [18]. In addition, these various time scales can be useful in assessing effects on different components of the hydrologic system (e.g., streamflow, reservoir levels, and ground water levels). McKee [13] used the classification system shown in Table III to define drought intensities resulting from the SPI. The Standardized Precipitation Index aims to provide a concise overall picture of drought, regardless to the actual probability distribution of the observed cumulative amounts of rainfall for a given time scale [19]. It consists in realizations of standard gaussian distribution with mean zero and variance one obtained by applying appropriate transformation to each of the observed cumulative amount of precipitation. But one should notice that applying the inverse of the cumulative probability function of the standard gaussian distribution to the actual cumulative probability function of each observed amount of precipitation fails to give gaussian deviates as precipitation data may include many zeros corresponding to period with no precipitation. In this study, there is no zero monthly precipitation for the covered period. SPI was applied on 1, 3, 6, 9, 12, and 24 month time scales. A detailed mathematical description of the method of SPI index calculation is given in the appendix.

TABLE III
CLASSIFICATION OF DROUGHT BASED ON THE SPI INDEX

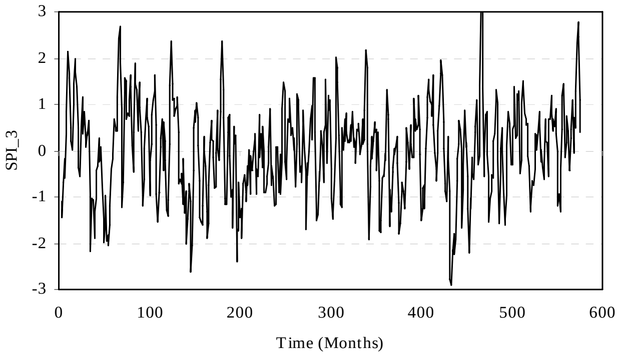
SPI	Classification
2 or more	Extremely wet
1.5 to 1.99	Very wet
1 to 1.49	Moderately wet
0.99 to -0.99	Near normal
-1 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

V. RESULTS AND DISCUSSION

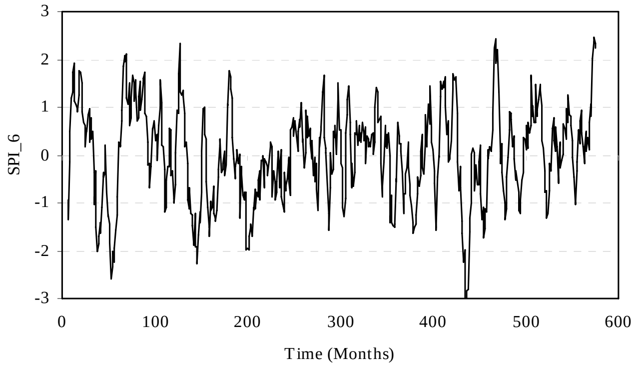
In this study the overall meteorological drought vulnerability in the Ruhr river basin was assessed by reconstructing historical occurrences of droughts at varying time steps and drought categories by employing the SPI approach. The basic idea is that this can be a guide to the decision makers in the Ruhr basin to develop strategies of water resources management in the context of drought. Drought occurrences in the Ruhr basin have been investigated based on the frequency of the events for each drought category at multiple-time steps. The SPI index has been applied to long-term precipitation data at 7 stations for the period 1960-2007 (January 1960 to December 2007). The occurrences in varying drought categories at 1, 3, 6, 9, 12, and 24 month time steps were analyzed. The SPI values were calculated for the total period and also for a specific month. Fig. 3 (a through f) illustrates the SPI values based on 1, 3, 6, 9, 12, and 24 month time steps respectively. Appearance of drought is happening every time when SPI is negative and its intensity comes to -1.0 or lower. Several drought events were detected. Also these events have different durations. As mentioned before the duration of an event is defined as the time between the zero crossings that bound the events. In this study a program called SPI_Analysis was used to calculate and analyze the SPI values. This program was developed as a part of the PhD thesis of the first author. All severely, and extremely drought events in the covered period (1960-2007) are presented in Table V, and Table VI respectively. Fig. 4 illustrates the percentage of dry events in each year of the covered period in the Ruhr river basin based on one month values for the SPI. Each value for any year (for example extreme drought in year 1962) presents the ratio of an event to the summation of dry events during this year i.e. summation of extreme, severe, moderate and mild drought events. As shown in Fig. 4 occurrences of severely and extremely drought events are typical .The last extremely event was in April 2007. Fig. 5 presents the total percentage of wet and dry periods in the Ruhr basin based on one month SPI values. Fig. 5 shows that the probability of the occurrence of a dry or a wet event according to the category is approximately the same.



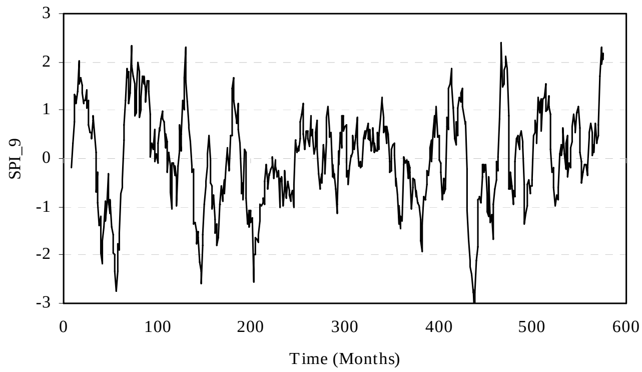
(a) SPI values based on 1 month time step



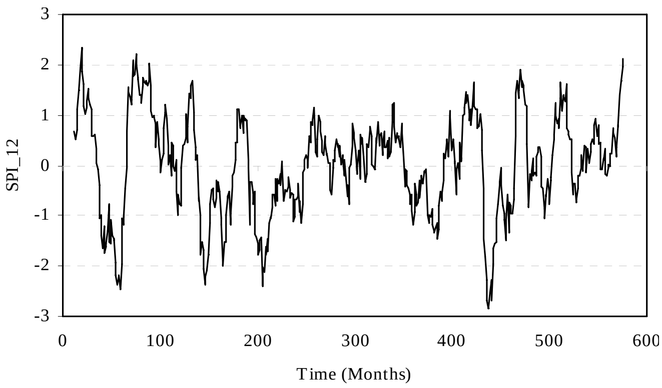
(b) SPI values based on 3 months time step



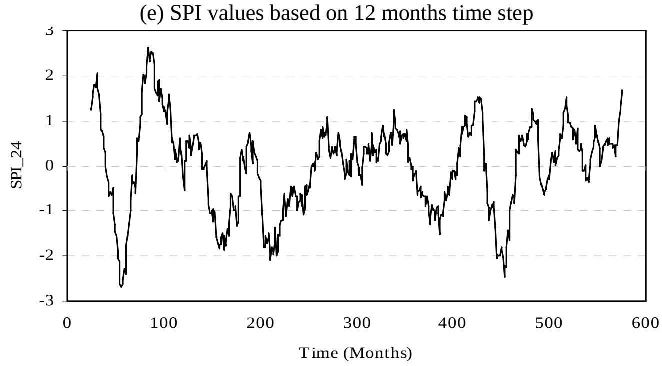
(c) SPI values based on 6 months time step



(d) SPI values based on 9 months time step



(e) SPI values based on 12 months time step



(f) SPI values based on 24 months time step

Fig. 3 (a-f) SPI time series based on the total monthly precipitation in the Ruhr River Basin (1960-2007)

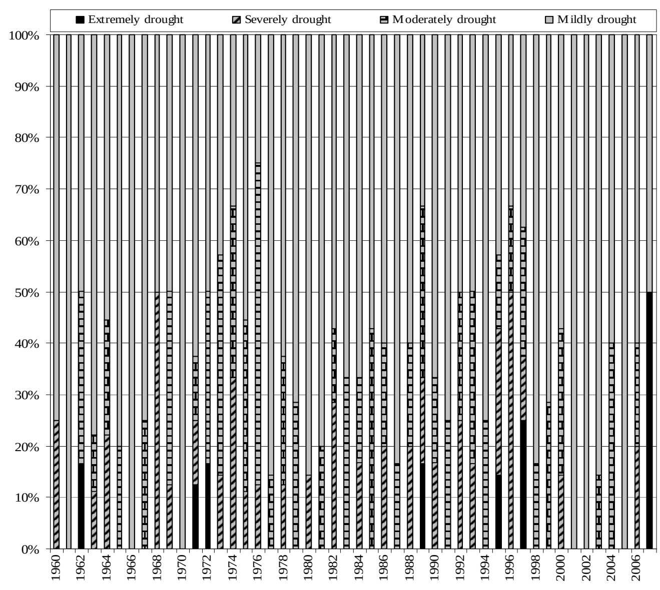


Fig. 4 Time series for the percentage of annually dry events based on the results of one month SPI values (1960-2007)

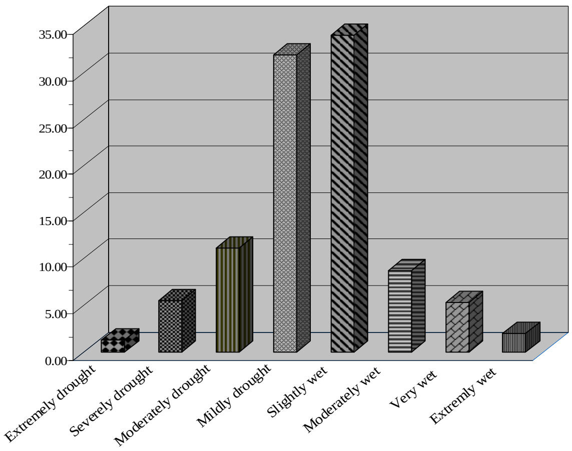
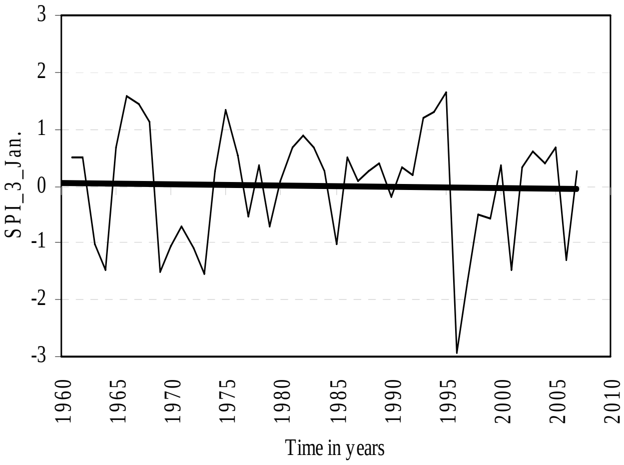
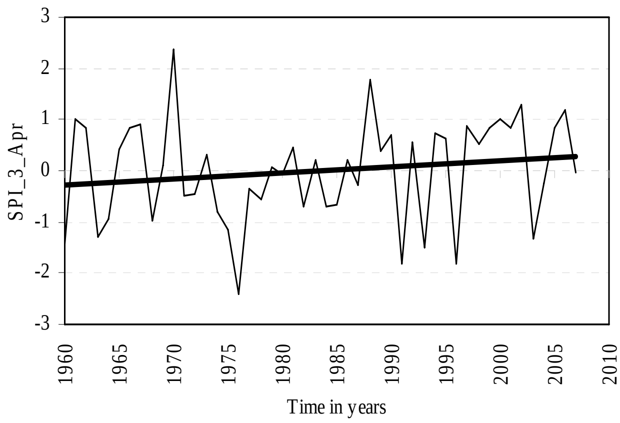


Fig. 5 Percentage of dry and wet events based on one month SPI values. The percentage of an event is sum of the percentage of all similar events through the covered period (1960-2007)

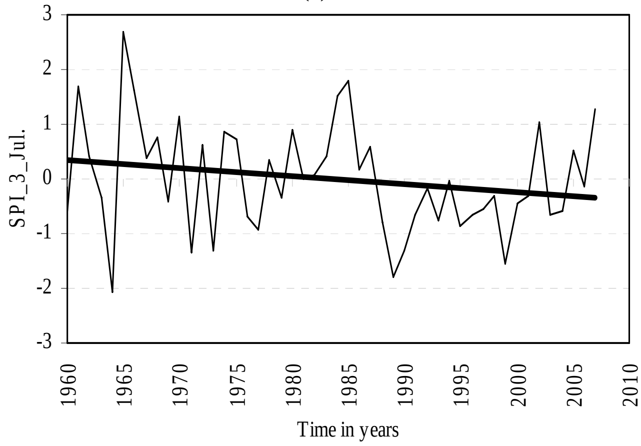
The next SPI values were calculated based on 3 months time step (quarter of a hydrological year) for the months January, April, July, and October as shown in Fig. 6 (a through d). Results show that drought occurred in both summer and winter. Although there is a significant increase in the winter precipitation as shown in Fig. 8 as reported by Morgenschweis et al [20]. The most extremely drought events in the basin was in the winter as shown in Fig. 6-a. Fig. 7 presents the time series of SPI data values based on 6 months time step (winter & summer of a hydrological year). It shows that several severely and extremely drought events occurred in the Ruhr basin and the drought event in the winter of the hydrological year 1995-1996 was the most extremely event.



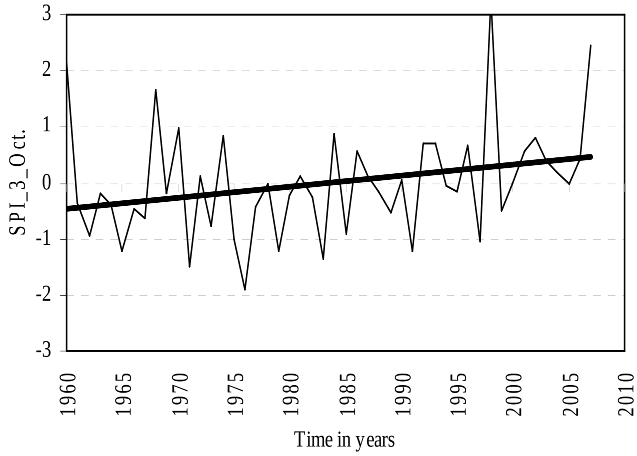
(a)



(b)



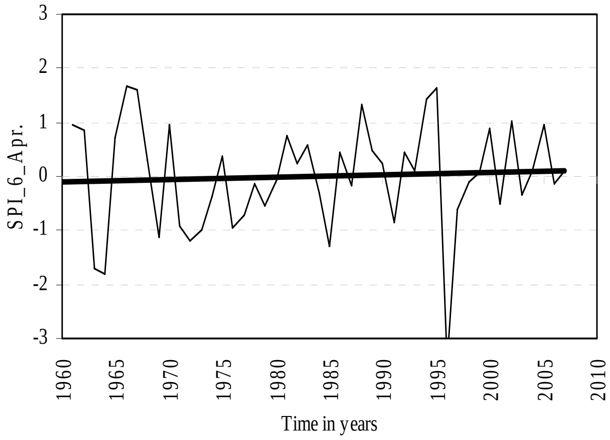
(c)



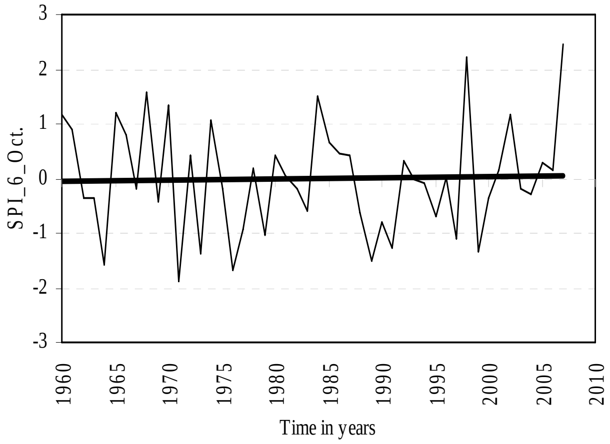
(d)

Fig. 6 Drought severity index values representative of the Ruhr River Basin (1960-2007) based on three months SPI values.
a) SPI-3-Jan.(November, December, and January)
b) SPI-3-Apr. (February, March, and April)
c) SPI-3-Jul. (May, June, and July)
d) SPI-3-Oct. (August, September, and October)

International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:3, No:9, 2009



(a)



(b)

Fig. 7 Drought severity index values representative of the Ruhr River Basin (1960-2007) based on 6 months SPI values
a) SPI-6- Apr. (November, December, January, February, March, and April) – (Winter)
b) SPI-6-Oct. (May, June, July, August, September, and October)- (Summer)

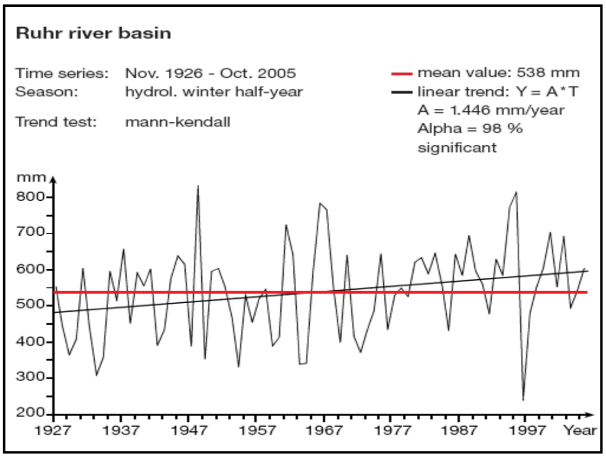


Fig. 8 Trend analysis of the areal winter precipitation of the Ruhr catchment basin from 1927 to 2005 ([20])

To examine the trends in the SPI data series the Mann-Kendall test was applied to SPI_3_Jan, SPI_3_Apr, SPI_3_Jul, SPI_3_Oct, SPI_6_Apr, and SPI_6_Oct. Table IV summarizes the results of the Mann-Kendall test. It shows that there is a positive significant trend in the data series of SPI_3 for the months April and October, and insignificant trend in SPI_3 for the month July.

TABLE IV
RESULTS OF MANN-KENDALL TEST

SPI Category	T-value	Type of trend
SPI_3_Jan	-0.0642	insignificant
SPI_3_Apr	1.80	Significant at confidence level of 90%
SPI_3_Jul	-1.24	insignificant
SPI_3_Oct	2.15	Significant at confidence level of 95%
SPI_6_Apr	0.725	insignificant
SPI_6_Oct	-0.133	insignificant

Drought events which occurred in the Ruhr river basin were detected. Table V, and Table VI present the severely and the extremely drought events respectively based on 1,3,6,9,12, and 24 months of SPI values. Table V and Table VI show the advantage of using several time steps when applying the SPI approach. For example if we calculate the SPI values based on one month time step we may detect a drought event which can not be detected if we apply SPI based on 3 months time step and vice versa. A practical example for this is shown in Table VI, when we applied SPI_1 we detected the drought event which occurred in April 2007 which was a very dry month, but with SPI_3 this even was not detected. Also as shown in Table VI there was an extremely drought event in the summer of the year 1996, this event was detected by using SPI based on 3 months time step and did not appear in the results of SPI based on one month time step. The results in Table V and Table VI show that the Ruhr river basin received several severely and extremely drought events in the period 1960-2007.

International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
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TABLE V
SEVERELY DROUGHT EVENTS ACCORDING TO SEVERLA TIME STEPS

Severely Drought Events																	
SPI_1			SPI_3			SPI_6			SPI_9			SPI_12			SPI_24		
Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value
1960	3	-1.87	1963	3	-1.89	1963	1	-1.51	1963	4	-1.95	1963	5	-1.64	1964	3	-1.55
1963	2	-1.51	1964	2	-1.97	1963	3	-1.84	1963	6	-1.71	1963	7	-1.74	1964	4	-1.90
1964	1	-1.66	1964	3	-1.58	1963	4	-1.70	1964	4	-1.58	1963	8	-1.63	1965	1	-1.79
1964	7	-1.54	1964	5	-1.96	1963	6	-1.63	1964	5	-1.96	1963	9	-1.56	1965	2	-1.56
1968	4	-1.79	1964	6	-1.81	1964	4	-1.81	1964	6	-1.99	1963	12	-1.51	1965	3	-1.59
1968	11	-2.00	1964	8	-1.61	1964	9	-1.96	1964	10	-1.78	1964	1	-1.55	1972	10	-1.59
1969	9	-1.71	1969	1	-1.53	1964	10	-1.57	1964	11	-1.89	1964	6	-1.94	1972	11	-1.57
1971	9	-1.58	1973	1	-1.55	1971	10	-1.88	1964	12	-1.55	1964	12	-1.97	1972	12	-1.73
1973	6	-1.80	1973	2	-1.60	1971	12	-1.93	1971	9	-1.51	1971	10	-1.78	1973	1	-1.82
1974	4	-1.70	1973	8	-1.89	1972	1	-1.93	1971	10	-1.76	1971	11	-1.54	1973	2	-1.75
1975	12	-1.65	1973	9	-1.56	1972	3	-1.67	1971	11	-1.52	1971	12	-1.67	1973	3	-1.75
1976	4	-1.79	1975	12	-1.65	1973	3	-1.69	1971	12	-1.63	1972	5	-1.78	1973	4	-1.58
1978	11	-1.94	1976	5	-1.70	1976	7	-1.97	1972	4	-1.80	1972	6	-1.76	1973	5	-1.50
1980	5	-1.64	1976	6	-1.75	1976	8	-1.97	1972	5	-1.59	1973	8	-1.89	1973	6	-1.87
1982	7	-1.62	1976	10	-1.90	1976	9	-1.98	1973	6	-1.54	1973	9	-1.99	1973	7	-1.57
1982	9	-1.54	1982	9	-1.70	1976	10	-1.69	1973	8	-1.81	1973	10	-1.51	1973	8	-1.78
1984	3	-1.80	1983	9	-1.52	1976	11	-1.52	1973	9	-1.63	1973	11	-1.52	1973	9	-1.68
1986	2	-1.69	1988	6	-1.93	1977	1	-1.71	1976	12	-2.00	1976	8	-1.54	1973	11	-1.56
1988	5	-1.91	1989	6	-1.75	1983	12	-1.57	1977	1	-1.66	1976	9	-1.76	1976	12	-1.81
1989	6	-1.62	1989	7	-1.78	1989	10	-1.50	1977	2	-1.69	1976	10	-1.68	1977	1	-1.81
1990	7	-1.54	1989	8	-1.52	1991	7	-1.62	1977	3	-1.72	1977	4	-1.62	1977	2	-1.55
1992	5	-1.52	1990	5	-1.62	1991	8	-1.51	1977	4	-1.57	1977	5	-1.78	1977	3	-1.72
1993	3	-1.97	1991	4	-1.80	1993	8	-1.58	1991	9	-1.71	1977	7	-1.72	1977	4	-1.58
1995	10	-1.56	1991	5	-1.58	1995	12	-1.63	1991	10	-1.93	1996	2	-1.81	1977	6	-1.91
1995	11	-1.91	1996	4	-1.80	1996	2	-1.98	1995	12	-1.67	1996	10	-1.95	1977	8	-1.80
1996	1	-1.93	1996	6	-1.92	1996	7	-1.60	1996	9	-1.85	1996	11	-1.64	1977	9	-1.92
1996	3	-1.72	1997	1	-1.68	1997	11	-1.73	1998	2	-1.66	1996	12	-1.54	1977	10	-1.97
1996	4	-1.80	1999	7	-1.54	1997	12	-1.54				1997	1	-1.53	1977	11	-1.65
1997	11	-1.52	2000	6	-1.57										1978	2	-1.91
2000	12	-1.59	2000	12	-1.59										1978	3	-1.53
2006	6	-1.85													1978	4	-1.55
															1992	2	-1.51
															1997	2	-1.95
															1997	3	-1.98
															1997	4	-1.98
															1997	5	-1.99
															1997	6	-1.82
															1997	7	-1.88
															1997	12	-1.82
															1998	2	-1.64

TABLE VI
EXTREMELY DROUGHT EVENTS ACCORDING TO SEVERLA TIME STEPS

Extremely Drought Events																	
SPI_1			SPI_3			SPI_6			SPI_9			SPI_12			SPI_24		
Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value	Year	Month	Value
1962	11	-2.10	1962	11	-2.18	1963	2	-2.02	1963	5	-2.19	1964	7	-2.19	1964	5	-2.07
1971	7	-2.41	1964	7	-2.06	1964	5	-2.58	1964	7	-2.35	1964	8	-2.36	1964	6	-2.11
1972	1	-2.00	1971	9	-2.01	1964	6	-2.33	1964	8	-2.76	1964	9	-2.21	1964	7	-2.63
1989	5	-2.00	1972	2	-2.62	1964	7	-2.01	1964	9	-2.33	1964	10	-2.17	1964	8	-2.70
1995	12	-2.77	1972	3	-2.04	1964	8	-2.23	1972	1	-2.16	1964	11	-2.47	1964	9	-2.62
1997	1	-2.13	1976	4	-2.41	1972	2	-2.27	1972	2	-2.34	1972	1	-2.05	1964	10	-2.51
1997	9	-2.02	1995	12	-2.77	1996	1	-2.22	1972	3	-2.58	1972	2	-2.36	1964	11	-2.27
2007	4	-2.09	1996	1	-2.92	1996	3	-3.12	1976	10	-2.55	1972	3	-2.21	1964	12	-2.41
			1996	2	-2.13	1996	4	-3.43	1976	11	-2.00	1972	4	-2.10	1977	7	-2.10
			1996	3	-2.18	1996	5	-2.85	1996	1	-2.13	1977	1	-2.40	1978	1	-2.00
			1996	5	-2.25	1996	6	-2.82	1996	2	-2.25	1977	2	-2.02	1997	1	-2.06
			1997	9	-2.21				1996	3	-2.40	1977	3	-2.12	1997	8	-2.03
									1996	4	-2.77	1996	3	-2.29	1997	9	-2.47
									1996	5	-2.71	1996	4	-2.68	1997	10	-2.20
									1996	6	-3.40	1996	5	-2.84	1997	11	-2.24
									1996	7	-2.77	1996	6	-2.83			
									1996	8	-2.12	1996	7	-2.54			
												1996	8	-2.27			
												1996	9	-2.69			

VI. CONCLUSION

By applying the SPI approach, the obtained results indicate that the drought randomly affect the Ruhr river basin. Several drought events occurred during the period under study. Results also indicate that although the significant positive trend in winter precipitation drought visited the Ruhr basin in both summer and winter and that the most severely event was in the winter. Trends in SPI data series indicate that the proportion of the Ruhr catchment drought condition has changed insignificantly during the period under study.

Results and the conclusion reached in this study can be an essential step toward addressing the issue to drought vulnerability in the Ruhr river basin and will be used as a guide for the optimization of the reservoirs in the Ruhr river basin during droughts which will b the future study for the authors.

At the end it is worth to be mentioned that in reality extreme drought events in the last decades presented no severe challenges to the water supply of the Ruhr district due to the reservoir system existing in the Ruhr catchment basin.

VII. APPENDIX - FORMULA AND COMPUTATION OF THE STANDARDIZED PRECIPITATION INDEX-SPI

McKee et al. [13] developed the Standardized Precipitation Index (SPI) for the purpose of defining and monitoring drought. Among others, the Colorado Climate Center, the Western Regional Climate Center, and the National Drought Mitigation Center use the SPI to monitor current states of drought in the United States. The nature of the SPI allows an analyst to determine the rarity of a drought or an anomalously wet event at a particular time scale for any location in the world that has a precipitation record.

In the most cases, the distribution that best models observational precipitation data is the Gamma distribution. The density probability function for the Gamma distribution is given by the expression [17]:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \qquad \text{for} \quad x>0 \qquad (1)$$

Where:

$\alpha > 0$ is a shape parameter

$\beta > 0$ is a scale parameter

$x > 0$ x is the precipitation amount

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \qquad (2)$$

$\Gamma(\alpha)$ is the Gamma function

Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each time scale of interest (1 month, 3 months, 12 months, 48 months, etc.), and for each month of the year.

The maximum likelihood solutions are used to optimally estimate α and β [21]:

$$\alpha = \frac{1}{4A}\left(1+\sqrt{1+\frac{4A}{3}}\right) \quad (3)$$

$$\beta = \frac{\bar{x}}{\alpha} \quad (4)$$

$$A=\ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (5)$$

Where n= number of precipitation observations

After estimating coefficient alpha and beta the density of probability function g(x) is integrated with respect to x and we obtain an expression for cumulative probability G(x) that a certain amount of rain has been observed for a given month and for a specific time scale.

$$G(x)=\int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1}e^{\frac{-x}{\beta}}dx \quad (6)$$

Taking t= x/ $\hat{\beta}$ this equation becomes the incomplete Gamma function:

$$G(x)=\frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t}dt \quad (7)$$

The Gamma function is not defined by x= 0 and since there may be no precipitation the cumulative probability becomes:

$$H(x)=q+ (1 - q)\, G(x) \quad (8)$$

Where q is the probability of no precipitation. The cumulative probability is then transformed into a normal standardized distribution with null average and unit variance from which we obtain the SPI index. The above approach, however, is neither practical nor numerically simple to use if there are many grid points or many station on which to calculate the SPI index. In this case, an alternative method was described in Edwards and McKee in 1997 as reported in [18] using the technique that converts the cumulative probability into a standard variable Z.

The SPI Index is then defined as:

$$Z=SPI=-\left(t-\frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) \quad \text{for } 0< H(x) < 0.5 \quad (9)$$

$$Z=SPI=+\left(t-\frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) \quad \text{for } 0.5 < H(x) <1 \quad (10)$$

Where

$$T=\sqrt{\ln\left[\frac{1}{(H(x))^2}\right]} \quad \text{for} \quad 0< H(x) < 0.5 \quad (11)$$

and

$$T=\sqrt{\ln\left[\frac{1}{(1-H(x))^2}\right]} \quad \text{for} \quad 0.5< H(x) < 1 \quad (12)$$

Where x is precipitation, H(x) is the cumulative probability of precipitation observed and c_0, c_1, c_2, d_1, d_2, and d_3 are constants with the following values:

c_0=2.515517 c_1=0.802853 c_2=0.010328
d_1=1.432788 d_2=0.189269 d_3=0.001308

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