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Mapping of Meteorological Drought Patterns using SPI and Different Interpolation Methods

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ABSTRACT: Drought is a normal part of climate and occurs in virtually all regions of the world. It is one of the major weather related disasters which is likely to continue for months, possibly years. It can affect large areas and may have serious environmental, social and economic impacts. Drought monitoring is an essential component of drought risk management. Drought indices, which are functions of precipitation records showing the severity of dryness during a particular time period, are often used for monitoring purposes. These indices may only be calculated originally at a limited number of sites where observations records on climate variables are available. However, what is required for monitoring and mapping is to estimate the spatial distribution of drought severity over larger areas. The paper demonstrates the implementation of different spatial interpolation techniques into meteorological data analysis from stations to large areas. The frequency of drought events is calculated using the Standardized Precipitation Index (SPI). Using daily precipitation records, the SPI is calculated for 1, 3, 6, 9, 12, and 24 months at 40 climatic stations covering the period 1972- 2009 in Germany. A software package, including a friendly Graphical User Interface (GUI), was developed for operational drought monitoring and mapping in Germany using several interpolation methods. This software generates maps showing the frequency isolines of moderate, severe and extreme droughts as well as of droughts in all classes.

Keywords: Drought Mapping, Standardized Precipitation Index SPI, Spatial Interpolation

1 INTRODUCTION

Water resources play an important role in most of human's activities. During the last decades water resources managers are facing severe challenges all over the world and the trends of increasing temperatures and decreasing precipitation intensify this situation (Ungtae Kim, 2008). Drought has been a major concern of mankind for centuries. It is considered by many to be the most complex but least understood of all natural hazards, affecting more people than any other hazard. Drought is a complex phenomenon and it is generally viewed as a sustainable and regionally extensive occurrence of below-average natural water availability either in the form of precipitation, river runoff or groundwater(Cacciamani et al., 2007). Drought is considered by many researchers to be the most complex but least understood of all natural hazards, affecting more people than any other hazard. It can affect large areas and may have serious environmental, social and economic impacts. These impacts depend on the severity, duration, and spatial extent of the precipitation deficit, but also and to a large extent on the socio-economic and environmental vulnerability of affected regions (Lehner et al., 2001) (Stahl, 2001). The World Meteorological Organization (WMO) reported that in the 25 years from 1967 to 1991 about 1.4 billion people were affected by drought and 1.3 million people were killed due to the direct and indirect cause of drought (Obasi, 1994).

Drought monitoring has much to offer to water decision making (Ana Paula A. Gutiérreza, 2o14). Drought monitoring, the ability to assess the current conditions and the prediction of future drought development are a key to any water resources management plan during drought periods(Wilhite et al., 2014). The drought management plan has mainly three phases, which are sequentially invoked as conditions dictate. These three phases are Drought Watch, Drought Warning and Drought Emergency.

The main purpose of any drought monitoring system is to identify various drought indices to provide information to resources manager and system operators. The indicators that are used to derive drought indices are precipitation, snow pack, streamflow and reservoir storage. A drought index value is typically a single number, far more useful than raw data for decision making (NDMC, 2006). Although none of the major indices is inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses. Some of the widely used drought indices are the Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Standardized Precipitation Index (SPI) and Surface Water Supply Index (SWSI) (Wilhite, 2005).These indices may only be calculated originally at a limited number of sites where observations records on climate variables are available. However, what is required for monitoring and mapping is to produce the maps of drought severity from point measurements to trace drought development in the entire region or country. The literature has ample a number of methods that have been proposed for surface interpolation of climate variables like rainfall and temperature (A. Irmak, 2010). The objective of this paper is to perform an evaluation of drought conditions in Germany and to demonstrate the implementation of different spatial interpolation techniques into the Standardized Precipitation Index SPI to use it for drought mapping.

2 METHODOLOGY

2.1 *Study Region and Data Collection*

Germany is situated in west-central Europe; it stretches from the Alps across the North European Plain to the North Sea and the Baltic Sea. Generally, the German territory can be divided geographically into the North German Lowlands, the Central German Upland, the Southwest Rhine River Valley, the Alpine Foreland and the German Alps (Huang, 2011). The precipitation occurs in all seasons, with substantial regional differences (more in the maritime western parts of Germany, less in the continental eastern parts of Germany). Generally, rainfall is higher in summer than in winter. In the North German Lowlands, annual rainfall varies between less than 500 (continental) to about 700 mm (maritime). The upland areas in the south receive 700-1500 mm of annual precipitation and the Alps more than 2000 mm (Fred F. Hattermann, 2013). The present analysis is based on the daily data for precipitation. The precipitation data used in this study stem from the German Weather Service records (http://www.dwd.de). In total, 40 stations including daily values of total precipitation. After doing homogeneity test of data using several homogeneity tests included absolute and relative homogeneity tests (Karabork et al., 2007; Peterson et al., 1998), 32 years statistical period is considered from 1978 to 2009. The location and the statistical properties of studied stations are listed in Table 1.

2.2 *Standardized Precipitation Index (SPI)*

Standardized precipitation index (SPI) is based on an equi-probability transformation of aggregated monthly precipitation into a standard normal variable (McKee et al., 1993a). McKee assumed an aggregated precipitation gamma distribution and used a maximum likelihood method to estimate the parameters of the distribution. Computation of the SPI involves the fitting of a gamma probability density function to a given frequency distribution of precipitation totals for a station (Thom, 1958). The parameters of the gamma probability density function are estimated for each station and for each time scale of interest (1 month, 3 months, 12 months, 48 months, etc.) for each month of the year. The classification system shown in Table 2 is used to define drought intensities resulting from the SPI. All details about the methodology and the calculations of SPI were presented in (Khadr et al., 2009).

2.3 *Methods for Interpolation*

Interpolation refers to the process of estimating the unknown data values for specific locations using the known data values for other points (Matthew Garcia, 2008). Interpolation techniques are classified into many categories based on several criteria (A. Irmak, 2010). A method could be termed deterministic if weights are assigned using a mathematical formula or stochastic if weights are assigned using a statistical formula. The technique could be also classified into exact or inexact based on whether the method assigns similar values to unknown points and measured points. It could also be local or global depending upon whether it accounts for local features. The inverse distance weighting (IDW) and ordinary Kriging interpolation methods were used in this study. The IDW is a part of deterministic interpolation and Kriging method falls into a category of geostatistical methods which adds the ability to determine some evaluation of accuracy of the resulting predicted surface. IDW relies on the theory that the unknown value of a point is more influenced by closer points than by points further away. The IDW computes SPI at unknown locations (u) as follows:

$$SPI_u = \sum_{i=1}^{n} \lambda_i \, SPI_i \quad (1)$$

$$\lambda_i = \frac{d_i^{-\propto}}{\sum_{i=1}^{n} d_i^{-\propto}} \quad (2)$$

Where SPI_u means the interpolated *SPI* at station u; SPI_i means the *SPI* values of known stations; *n* is the number of stations; λ_i means the weighting of each stations; d_i means the distance from each stations to the unknown site; $\propto$ means the power, and is also a control parameter. In the ordinary Kriging the weights are obtained such that the estimation is unbiased and the variance is minimized. The ORK system of (ns+1) equations, is as follow:

$$SPI^*(u) = \sum_{i=1}^{n} \lambda_i \,(u)\, SPI(u_i) + \left[1 - \sum_{i=1}^{n} \lambda_i \,(u)\right] m \quad (3)$$

where $SPI^*(u)$ is the ordinary kriging estimate at spatial location u, n are the n measuring locations, $SPI(u_i)$ located close to u, m is the mean of the distribution, and $\lambda_i\,(u)$ is the weight for location u_i computed from the spatial covariance matrix. The value of $\lambda_i\,(u)$ is based on the spatial continuity (semi-variogram) model as follows:

$$\lambda_i(u) = \frac{1}{2n} \sum_{i=1}^{n} [(SPI(u) - SPI\,(u_i) - SPI\,(u_i + h)]^2 \quad (4)$$

Where n is the number of data pairs separated by distance h, and $SPI\,(u_i)$ and $SPI\,(u_i + h)$ are the data values at locations separated by distance h. A detailed presentation of the investigated methods theories can be found in (A. Irmak, 2010; Liu, 2012; S. Ly, 2011).

Table 1. Location and statistical properties of the studied meteorological stations.

Stations	Lat.	Long.	Elev. (m)	Statistical properties of monthly rainfall series (1978-2009)					
				Mean (mm)	Min (mm)	Max (mm)	SD	Skewness	Kurtosis
Aachen	54.78	6.83	202	69.8	0.1	217.1	34.3	0.9	4.4
Augsburg	48.42	10.9	461	64.5	1.0	192.5	37.9	0.8	3.1
Bamberg	49.87	10.05	240	53.6	0.3	178.2	29.7	1.1	4.8
Berlin-Tempelhof	52.47	13.62	48	48.3	0.6	163.9	28.7	1.1	4.8
Brocken	51.78	10.75	1142	156.1	18.0	493.5	77.1	0.9	4.1
Dresden-Klotzsche	51.12	13.77	227	62.3	0.9	233.1	33.9	0.9	4.5
Düsseldorf	51.28	6.95	37	66.3	2.2	173.4	32.2	0.6	3.2
Erfurt-Bindersleben	50.98	10.58	315	43.8	0.9	140.9	26.9	1.0	4.1
Frankfurt/Main (Terminal)	50.03	8.95	111	52.9	0.1	182.4	30.6	1.2	4.9
Goerlitz	51.15	14.98	78	54.4	1.3	273.1	33.1	1.7	9.5
Hamburg-Fuhlsbüttel	53.63	9.67	11	66.6	0.6	210.0	36.9	0.9	3.8
Hannover	52.45	9.88	55	55.2	3.1	170.7	28.9	0.9	4.4
Helgoland	54.02	7.92	4	62.1	1.3	250.7	36.9	1.3	6.1
Hof	50.32	11.28	565	63.5	0.9	180.1	32.1	0.8	3.6
Kempten	47.75	10.12	705	106.0	1.3	360.8	58.3	0.9	4.1
Lindenberg	52.2	14.58	98	47.9	0.7	202.4	28.7	1.4	6.3
Neuruppin	52.9	12.05	38	44.4	0.0	184.2	26.5	1.3	6.2
Nürnberg	49.45	11.07	314	53.2	3.3	177.9	29.5	1.0	4.3
Rostock-Warnemünde	54.02	12.1	4	51.1	0.0	188.0	28.8	1.0	4.6
Saarbrücken-Ensheim	49.2	7.05	320	74.2	1.6	286.9	41.3	1.1	4.9
Schleswig	54.52	11.98	43	74.9	1.3	208.8	40.5	0.7	3.3
Schwerin	53.63	9.22	59	53.4	0.2	247.6	30.3	1.4	7.7
Stuttgart_Echterdingen	48.68	9.63	371	59.9	0.4	199.9	34.4	1.0	4.1
Trier-Petrisberg	49.82	6.98	265	65.9	0.1	218.2	36.0	1.0	4.6
Cottbus	51.47	14.19	69	61.7	0.0	800.2	121.9	3.4	15.6
Heimbach-Düttling	50.36	6.33	380	24.1	6.6	1293.8	75.2	13.4	216.1
Schwerin	53.39	11.23	59	53.2	0.2	165.5	29.1	0.9	4.2
Potsdam	52.23	13.04	81	48.4	0.3	183.3	28.2	1.2	5.2
Greifswald	54.06	13.24	2	49.6	0.0	175.4	26.9	1.1	5.4
Zugspitze	47.25	10.59	2961	174.1	7.2	553.5	86.2	0.8	4.0
Oberstdorf	47.24	10.17	806	145.9	4.5	422.2	75.5	0.7	3.5
Mannheim	49.31	8.33	96	56.1	0.7	191.2	31.3	1.1	4.9
Magdeburg	52.06	11.35	76	42.6	1.2	130.7	24.2	0.8	3.5

Table 2. Weather classification based on the SPI index.

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

3 RESULTS AND DISCUSSION

The overall meteorological drought vulnerability in the study area was assessed by reconstructing historical occurrences of droughts at varying time steps and drought categories with the SPI approach. In figure 1, it is shown the flowchart of procedures of the drought monitoring GUI developed in this study using MATLAB environment. On the first phase, historical time series of precipitation are collected coming from the 32 climatic stations located on the study area then the missing data gaps will be detected and completed basing on the statistical procedures described by Santos et al. (Santos and Henriques, 1999; Simolo et al., 2009). On a following phase the methodological procedure for the estimate of the SPI described by McKee (McKee et al., 1993b) will be done with the SPI software package developed by the authors (Khadr, 2011). SPI values are calculated for all station for particular month and for the whole period in time scales of 1 to 24 months. The spatial distribution of the SPI for all station for particular month and for consecutive months during the whole period can be determined through spatial interpolation techniques using a selected method of the methods presented in this paper. The classification of drought events based on the SPI index can be done in order to detect the moderately dry, severely dry, extremely dry events and the probability of each category.

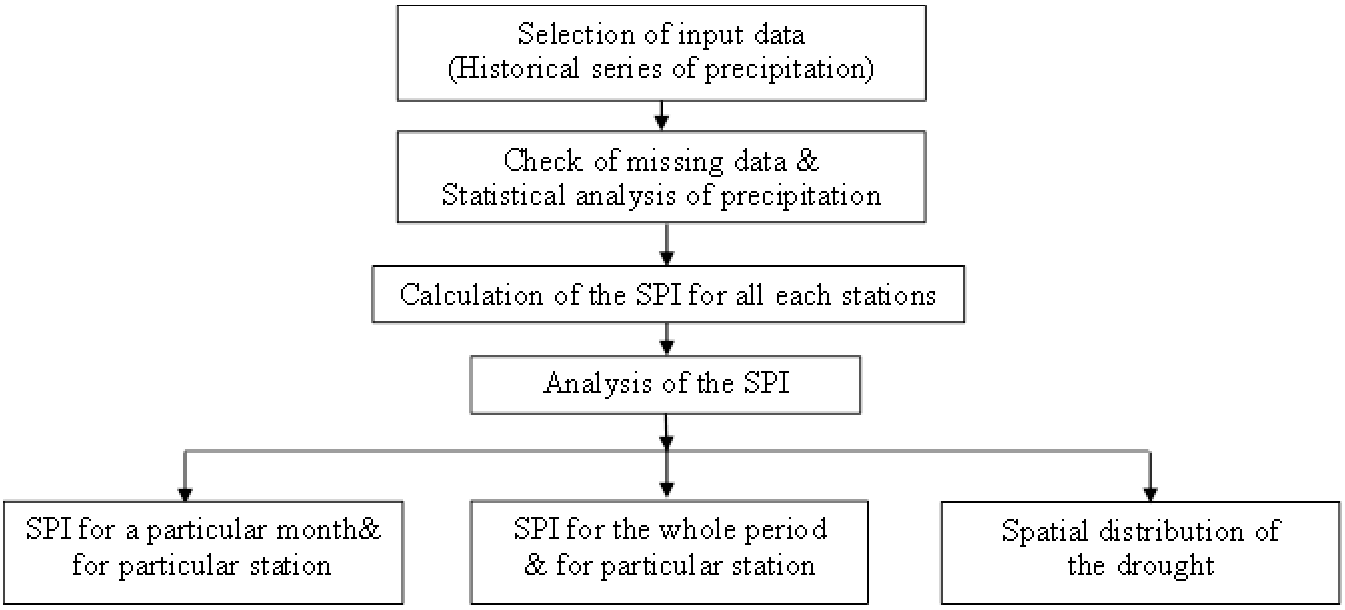
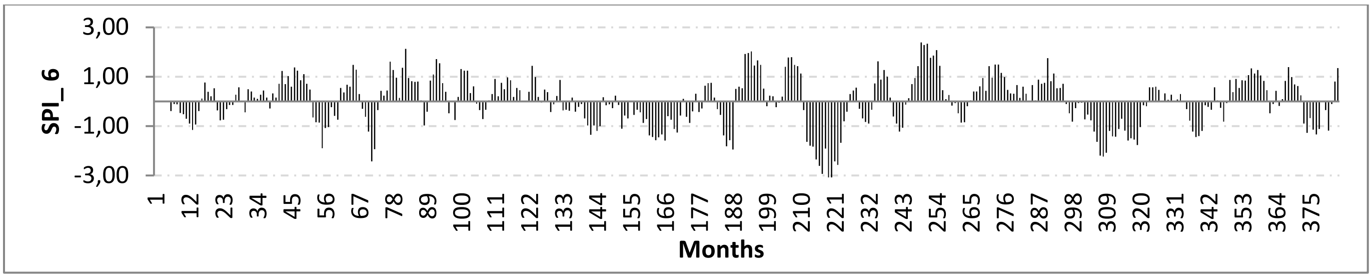


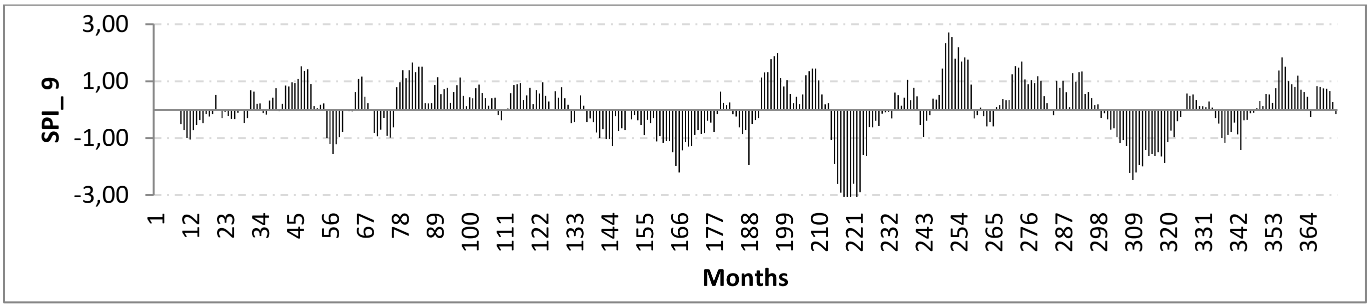
Figure 1. Flowchart of the developed model for drought monitoring and drought mapping in Germany

Figure 2 illustrates the SPI values based on 6 and 9 month time step respectively for Dusseldorf meteorological station. Several drought events with different duration were detected. Appearance of drought is defined when SPI is negative and its intensity comes -1.0 or lower. Several drought events were detected. These events have also different durations. Based on the analysis of SPI across the study area; results showed that SPI defines near normal events in 67.93 of the time, 2.93% of the time moderate drought in 7.48% of the time, severe drought in 3.9% of the time and extreme drought in 2.93% of the time. Because the SPI is standardized, these percentages are expected from a normal distribution of SPI. The 2.93% of SPI values within the "extreme drought" category is a percentage that is typically expected for an "extreme" event (NDMC, 2006). Table 3 summarizes the probabilities of moderate, severe and extreme drought for the investigated stations.

Figure 3 presents the SPI values for the months December and April that were calculated based on 3 months time step (quarter of a hydrological year). Several drought events that occurred were detected Results show that drought occurred in both summer and winter and several severely and extremely drought events occurred and the drought event in the winter of the hydrological year 1995-1996 was the most extremely event. Figure 3 shows the benefit of using several time steps when using Standardized Precipitation Index (SPI) for drought monitoring. When the SPI values were calculated based on one month time step, the detected event might be a drought event which cannot be detected if the SPI is calculated based on 3 months time step and vice versa. A practical example for this is shown in figure 3(a) for the month April, as SPI_1 was applied; the drought event which occurred in April 2007, which was a very dry month, was detected. But with SPI_3 this even was not detected as shown in figure 3(b). On the other hand, there was an extremely drought event in the winter of the hydrological year 1996, this event was detected by using SPI based on 3 months time step and did not appear in the results of SPI for one month time step (figure 3-c).

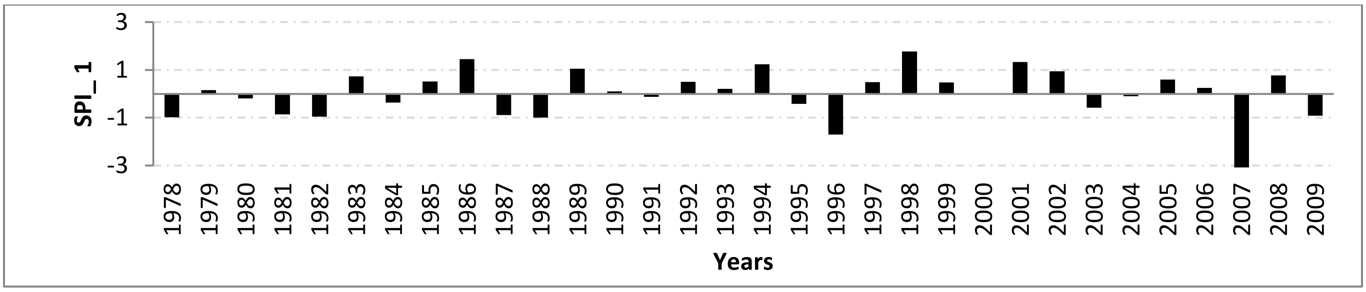


(a)

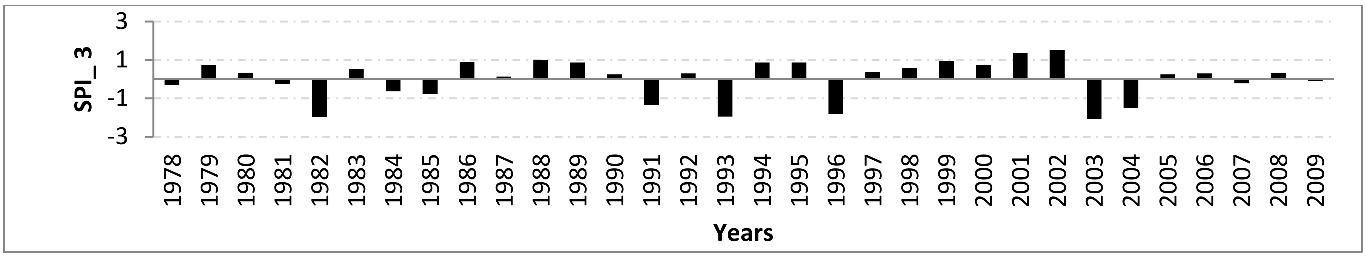


(b)

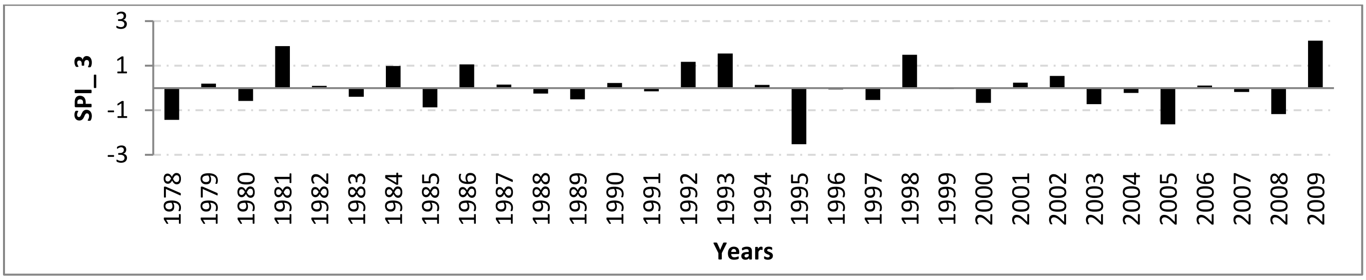
Figure 2. SPI time series based on the total monthly precipitation of station Dusseldorf (1978-2009): (a) SPI_6 (b) SPI_9



(a)



(b)



(c)

Figure 3. Drought severity index values representative of station Dusseldorf (1978-2009): (a) SPI1_1 April (b) SPI3 _ April (c) SPI_3 December

Table 3. Probabilities of moderate, severe and extreme drought during 1978-2009 – Germany

Stations	Probability (%) of drought			Stations	Probability (%) of drought		
	Moderate	Sever	Extreme		Moderate	Sever	Extreme
Aachen	8.07	2.86	3.39	Neuruppin	8.07	3.65	2.60
Augsburg	8.85	5.73	2.34	Nürnberg	8.07	6.25	2.60
Bamberg	7.81	3.91	2.86	Rostock-Warnemünde	6.77	3.65	3.13
Berlin-Tempelhof	7.03	4.69	3.13	Saarbrücken-Ensheim	7.55	5.73	2.34
Brocken	7.55	5.21	3.13	Schleswig	4.43	4.17	4.17
Dresden-Klotzsche	10.42	2.60	3.65	Schwerin	6.25	4.43	3.39
Düsseldorf	5.99	4.95	3.13	Stuttgart_Echterdingen	7.81	4.95	3.39
Erfurt-Bindersleben	9.64	3.65	3.13	Trier-Petrisberg	7.55	3.91	3.39
Frankfurt/Main (Terminal)	9.11	3.39	2.60	Heimbach-Düttling	1.04	0.52	0.26
Goerlitz	9.11	4.95	2.08	Schwerin	6.25	4.43	3.39
Hamburg-Fuhlsbüttel	6.51	3.39	3.91	Potsdam	7.81	4.43	3.13
Hannover	8.33	4.95	3.39	Greifswald	5.99	3.13	4.43
Helgoland	6.25	3.13	4.17	Zugspitze	9.90	4.17	2.86
Hof	8.33	3.65	2.86	Oberstdorf	8.33	3.13	4.17
Kempten	9.38	3.65	3.13	Mannheim	10.16	4.95	2.08
Lindenberg	11.46	2.86	2.86	Magdeburg	6.77	3.91	3.39

In this study, using the developed GUI, more than 4000 historical maps could be generated for SPI distribution over the study area according to the selected time scale of the SPI from the SPI1 to SPI24. The monitoring system also allows an analysis of the frequency, duration and intensity of the drought events that took place within the study area. The spatial distribution of the SPI was determined through spatial interpolation techniques employing the IDW and the Kriging methods. To visualize the results better, the SPI maps were generated for the drought periods of 1996, 2003 and 2007. Figure 4, 5 and 6 illustrate the example of drought maps for SPI3 of January 1996, SPI3 of May 2003 and SPI1 of April 2007 respectively. The similarities between Kriging and IDW methods are clear. The year 2007 was the sunniest, hottest and driest in Germany in the last two centuries(Luis Samaniego, 2011). In 2003, a remarkable deficit in rain and snow was reported. The event of 2003 was quite severe and long-term drought between February and September was detected. The accumulated magnitude of the negative values of the SPI during a drought event can be considered as drought magnitude and can be used as a guide for the selection of the driest years and to compare also between different droughts. The accumulated magnitude of the negative values of the SPI_1 for years 1996, 2003 and 2007 are; -366.23, 269.32 and – 173.1 respectively. The proof of interpolation of climate data is not so easy because of several reasons such as limited number of meteorological stations which give information. In this study, the root mean squared error (RMSE) was adopted to assess the models performances as well as coefficient of correlation (Cr) to find out if the estimated data fits observed data. In order to evaluate the model performance, the SPI values were assumed as unknowns at all stations consecutively. 33 runs were done for the studied stations and in each run the values of SPI were assumed to be unknowns at particular station of the 33 stations then the SPI was estimated using the developed models. Figure 7 illustrates the performance of the interpolation methods using the SPI3 for the month January during the drought period of 1996. Figure 7 show a significant accuracy of the predicted data during the tested period using the IDW and Kriging methods. A significant correlation was detected between estimated and observed data for the studied stations ($Cr \cong 0.97$).

4 CONCLUSION

In this research, efforts were made to develop a drought monitoring system using the standardized index of precipitation. Using the developed GUI, a climatic level, historical series of values of the SPI on time scales of 1 to 24 months can be created. The overall meteorological drought vulnerability was assessed by reconstructing historical occurrences of drought and drought categories using SPI. The spatial distribution of the SPI was determined through spatial interpolation techniques to analyze the meteorological drought with due emphasis to ungauged catchments. Results showed that SPI defines near normal events in 67.93 of the time, 2.93 % of the time moderate drought in 7.48 % of the time, severe drought in 3.9 % of the time and extreme drought in 2.93 % of the time. This study compared two methods for spatial interpolation of drought indices to create drought maps of the Germany. The methods investigated include IDW and Kriging. The Comparison of the IDW and Kriging using the detection of drought classes for study area reveals very close results. Evaluation of the model performance, using RMSE and coefficient of correlation (Cr), showed that the estimated SPI values fits observed ones.

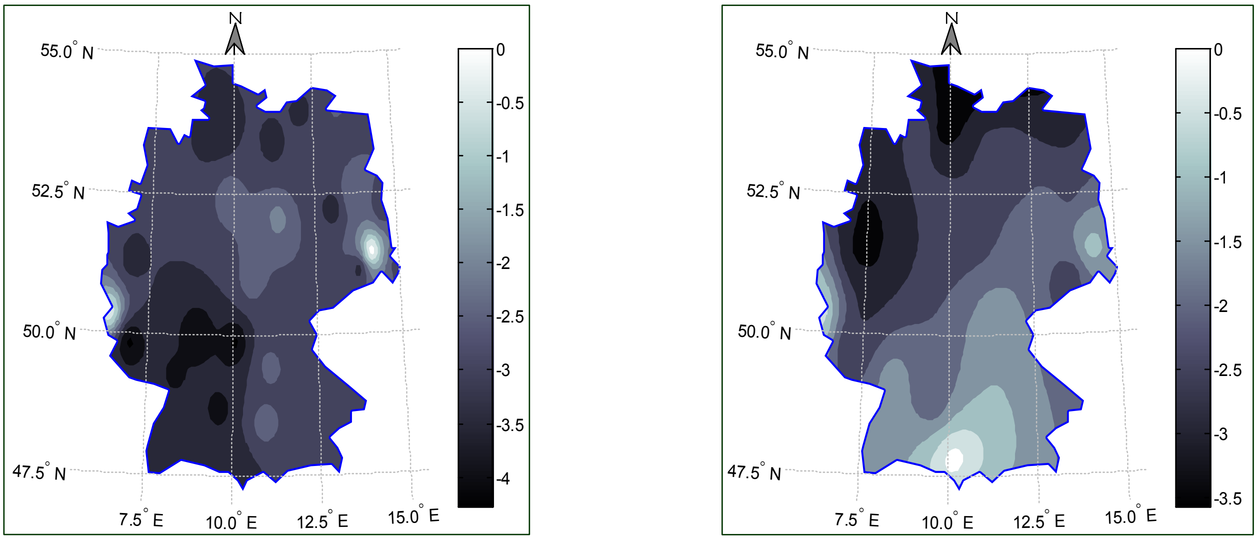


Figure 4. The SPI maps for the month January 1996 based on 3 month time scale: (a) IDW method (b) Kriging method

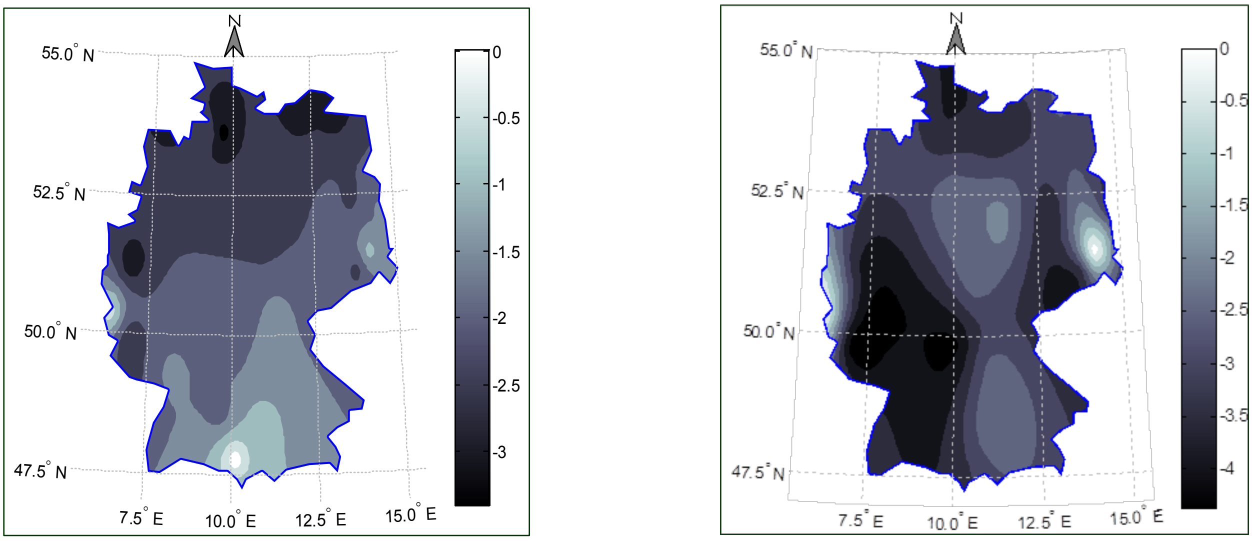


Figure 5. The SPI maps for the month May 2003 based on 3 month time scale: (a) IDW method (b) Kriging method

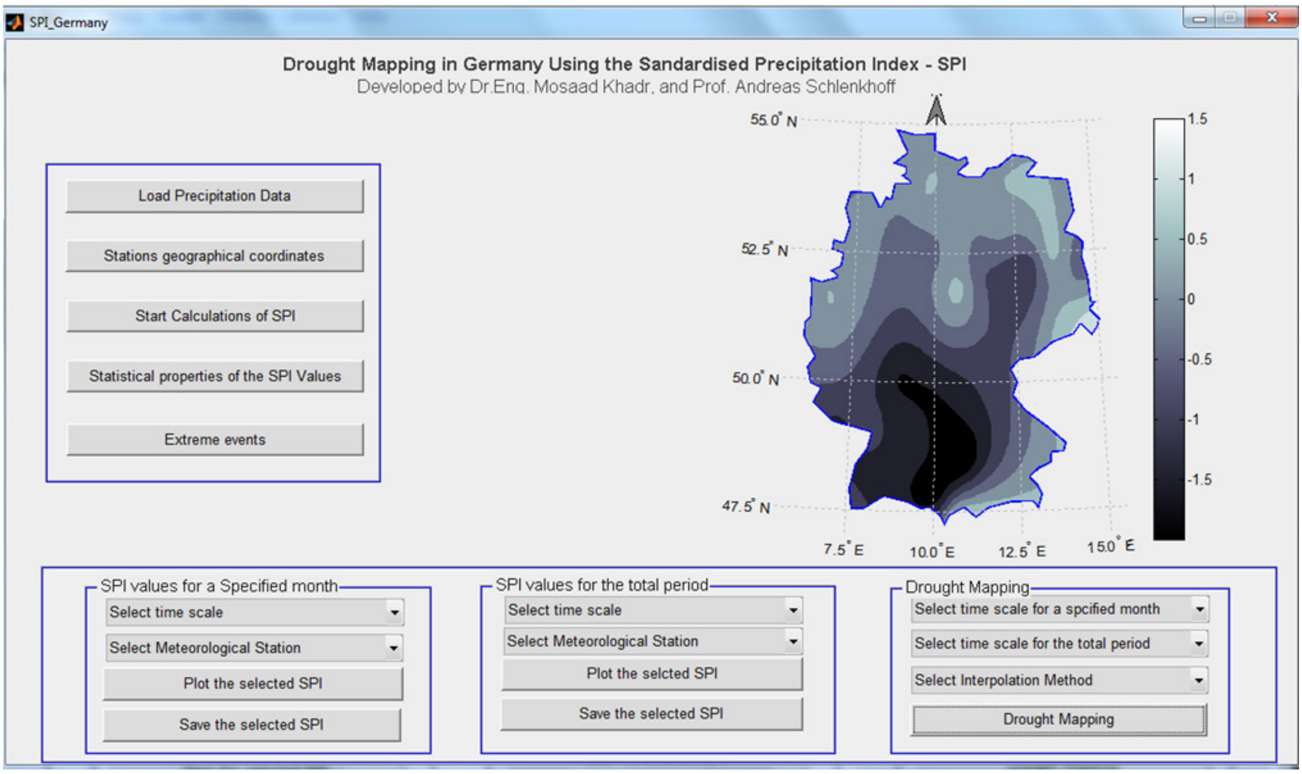


Figure 6. The SPI maps for the month April 2007 based on one month time step using the developed drought monitoring model

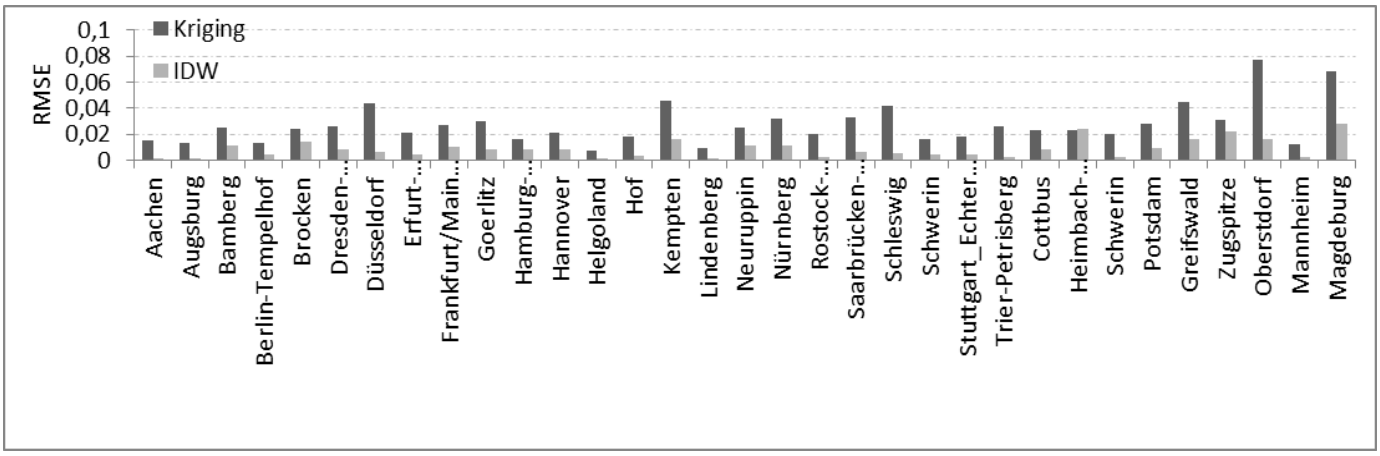


Figure 7. Results of the model performance evaluation for IDW and Kriging methods

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