Characterizing drought in the south of France using the standardized precipitation-evapotranspiration index SPEI

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ABSTRACT: The shrinkage-swelling of clayey soils has been known as one of the most important natural hazards in France. The climate change as well as the rate of evapotranspiration of soils, are the main origin of this natural hazard. Thought, it is crucial to evaluate drought periods in the framework of soil-atmosphere interaction. Standardized indexes are practical tools to recognize the type of drought and its associated periods. The aim of this paper is to evaluate the drought periods in a region with a high risk of shrinkage-swelling in the south of France, by using two standardized drought indexes. Therefore, climatic data since 1975 were used to calculate the SPEI standardized index which takes into account the rate of precipitation and evapotranspiration of unsaturated soils. The comparison with the SPI index which is based only on precipitation and other climatic parameters, revealed the importance of the evapotranspiration rate from the surface of clayey soils in this case study. Results are in great coherence with all drought periods observed in the history of France since 1975, meaning that the SPEI index is a more practical tool to recognize past drought events and even predict a drought period, if weather forecast data is available.

1 INTRODUCTION

The increasing rate of temperature and the climate change have become a big concern during last decades. The impacts of this natural hazard have been observed in different fields. Drought-humidification cycles can affect clayey soils surface conditions resulting in shrinkage and swelling phenomenon. Lightweight constructions like residential, industrial buildings or even roads are affected and damaged by the shrinkage-swelling of clayey soils that are in direct contact with them. In France, this natural disaster is now in the second range of all natural disasters after the floods and has costed around 5 billion euros between 1988 and 2007 for insurance companies and the government (Vincent et al. 2009). The south of France is mainly hit by this natural hazard because of its geological formation and the presence of clayey soils on the surface and top layer in a wide area. This phenomenon has been studied by different authors in the past years by taking into account coupled or uncoupled behavior of surface clays in contact with the atmosphere or the construction (Hemmati 2009; Ta 2009; Hemmati et al. 2012; Cui et al. 2013; Song 2014; Nowamooz et al. 2016). Nowadays, although the Geotechnical concept of this kinds of problems are not completely known or solved but it is crucial to have in priority an environmental and hydrogeological point of view of this natural hazard in order to better understand the intensity and the frequency of these drought-humidification cycles over time. Due to the complex nature and widespread effects of drought, it is difficult to give a universal definition of this phenomenon, which prevents the identification and monitoring of key drought characteristics such as duration, intensity, gravity and spatial distribution. Therefore, the aim of this paper is to perform a case study to evaluate the drought periods occurred in the south region of France which has a very highly concentrated number of declared damages, with two different standardized indexes (SPI and SPEI). A drought period is a period of below-average precipitation in a given region which results in prolonged shortages in the water supply and can be defined in different types, depending on the amount of water loss (meteorological, hydrological, agricultural and socio-economical drought). As the south of France has been hit by meteorological drought for several years since 1975, monthly data were gathered from the Toulouse-Blagnac meteorological station in the south allowing the calculation of these two indexes. The comparison of the observed and declared drought period over the region with the calculated indexes shows that the SPEI index performs better than the SPI index because of the evapotranspiration process from the soil surface, taken into account in the calculation of SPEI.

2 METHODOLOGY FOR INDEXES

To describe the physical characteristics of a drought, several indexes and indicators have been developed previously. In the same way, the diversity of the domains of application of droughts does not make it possible to have universal index for their characterization. However, WMO (World Meteorological Organization) recommended in 2009 the use of the Standardized Precipitation Index (SPI) as a standardized precipitation index for monitoring meteorological droughts. The calculation procedure of two standardized drought indexes is introduced in this section.

2.1 *The SPI index calculation procedure*

The SPI index (McKee et al. 1993, 1995) known as the Standardized Precipitation Index is powerful and simple to calculate. Precipitation data are in fact the only parameter required. The SPI index is based on the probability of rainfall over a given time scale. The probability of precipitation is transformed into an index through statistical analysis. A probability distribution is adjusted to this long series of data and is then transformed into a normal distribution so that the mean SPI for a location and for a specified time step becomes equal to zero (WMO 2012). According to Edwards et al. (1997), the Gamma probability function, was found as the best function that fits perfectly well on precipitation data. The Gamma distribution can be parameterized using a shape parameter α and an intensity parameter β:

$$g(x) = f(x;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)}\, x^{\alpha-1}\, e^{-\beta x} \quad (x > 0) \tag{1}$$

where α is a shape parameter; β is a scale parameter; x is the random variable (precipitation in this case); Γ(α) is the gamma function defined as follows:

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

The parameters α and β are obtained by adjusting the gamma distribution, but they can also be calculated by the Maximum likelihood estimate to obtain an optimal estimate of α and β. Once α and β are available, the gamma distribution function is calculated for the specified time step and for the associated rainfall record. The cumulative distribution function of the gamma distribution is calculated according to the following expression:

$$F(x) = \int_0^{x} f(x)dx = \frac{\gamma(\alpha,\beta x)}{\Gamma(\alpha)} \tag{3}$$

where γ is the incomplete function of gamma. This function is not defined for values of x equal to zero, while the record of precipitation may contain precipitation equal to zero. In these cases, it is essential to make a modification to the distribution function (F (x)). This correction is made with the term q which is equal to the ratio of number of precipitation zeros (m) to the number of precipitation records (n). The correction reported is written in this form:

$$H(x) = q + (1-q)\, F(x) \tag{4}$$

By performing this correction, the SPI index can be calculated by two methods. In the first method, H (x) is transformed into a normalized random variable (Z), with a mean zero and a standard deviation equal to 1 (the inverse of the normal distribution) for a given time step. The second method is based on the Abramowitz and Stegun approximation (1965) which is able to convert the cumulative probability to the random variable Z:

$$Z = SPI = -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) for \quad 0 < H(x) \le 0.5 \tag{5}$$

$$Z = SPI = +\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right) for \quad 0.5 < H(x) \le 1 \tag{6}$$

where:

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \qquad for \qquad 0 < H(x) \le 0.5 \tag{7}$$

$$t = \sqrt{\ln\left(\frac{1}{(1-H(x))^2}\right)} \quad for \quad 0 < H(x) \le 0.5 \tag{8}$$

where $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

2.2 *The application of the SPI index:*

Monthly rainfall data of the Toulouse-Blanganc station gathered since 1975 until 2015 is presented in figure 1. The Gamma probability density function is adjusted on these set of data and the cumulative distribution function is calculated (Figure 2). The modification was made on the distribution function using Equation 6, and the probability values were transformed through the inverse Gaussian distribution (The first cited method, mean zero μ = 0 and standard deviation equal to 1, σ = 1), which gives the value of SPI more precisely (Z = SPI). The cumulative distribution function for these monthly data is presented in parallel with the curve showing the cumulative probability of the standardized random variable (Z = SPI) in figure 3. The index is determined by linking a precipitation record to its cumulative probability and assigning it to the index based on the cumulative probability of the standardized random variable (SPI).

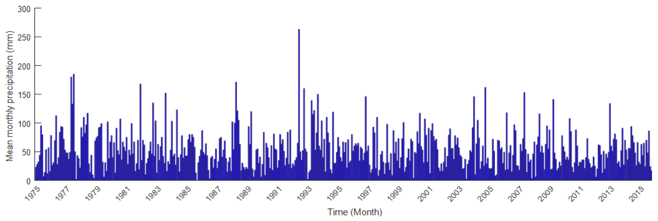

Figure 1. Precipitation data at Toulouse-Blagnac (1975 to 2015).

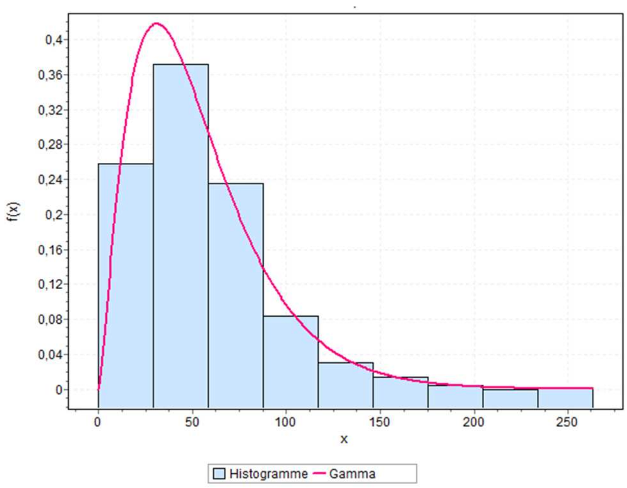

Figure 2. Fitting of the gamma distribution on the rainfall data at Toulouse-Blagnac from 1975 to 2015.

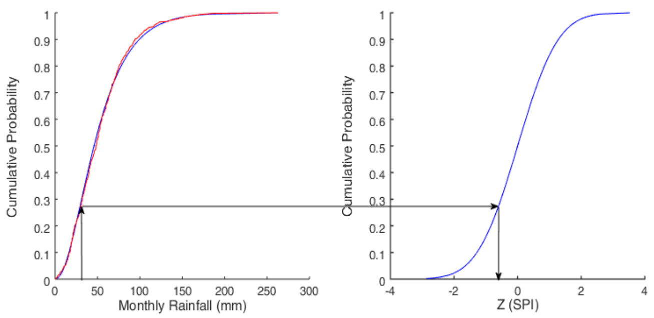

Figure 3: The SPI index calculation procedure

This method is mainly used for monthly time steps. It is suggested to use the Abramowitz and Stegun (1965) approximation adapted by Edwards et al. (1997) for larger time steps. The SPI is standardized in space (a specific station) because it represents the precipitation frequency distribution as well as the associated variation in the station. In addition, the SPI is standardized over time, as it can be calculated at a number of time scales. The advantage of this index is that precipitation is the only parameter that must be available and it is less complex than other indexes. It is possible to calculate the index for different time steps, making it possible to detect drought conditions quickly and to assess their severity.

2.3 *The SPEI index calculation procedure:*

The SPEI index was developed by Serrano et al. (2008). The need for the development of this index is due to the fact that other drought indexes like (SPI: standardized precipitation index, SWI soil moisture index, MSDI multi-variable drought index) are not completely relevant in the cases of an abnormal increase in temperature and an associated decrease in precipitation. The study by Serrano et al. (2008) examines the influence of climate change and the decreases in precipitation over the duration and severity of drought for a period of at least 50 years. Climate change is not limited to a decrease in precipitation but also to a gradual increase in temperature during the studied period. This has been the subject of the development of this index which takes into account precipitation and temperature data (evapotranspiration). Like the SPI (based on precipitation), the SPEI is calculated based on the difference between precipitation and the potential evapotranspiration. The methodology consists in using one of the methods of estimating potential evapotranspiration as a function of temperature. The Thornthwaite (1948) method was chosen because it does not require many parameters and is based on air temperature. Although other evapotranspiration formulas could be used for the index calculation like the Penman (1948) equation but they may require more climatic variables over a long period of time resulting in complex and time-consuming calculations. Nevertheless, Mavromatis (2007) showed that the use of different PET calculation methods leads to similar drought index results. The Thornthwaite (1948) equation is expressed as below:

$$PET = 1.6\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_a}{I}\right)^{a_1} \tag{9}$$

$$a_1 = 6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 - 1.79\times10^{-2}I + 0.49 \tag{10}$$

where PET is the Monthly potential evapotranspiration in (mm), L is the length of day in hours (h), N is the number of the day of the month, T_a is the mean air temperature and I is a heat index which depends on the 12 monthly mean temperatures T_{ai} as is calculated using the followed expression:

$$I = \left(\frac{T_{ai}}{5}\right)^{1.514} \tag{11}$$

Subsequently, the expression of the simplified water balance was used to find the difference between precipitation (P) and potential evapotranspiration (PET):

$$D = P - PET \quad (12)$$

According to Serrano et al. (2008) statistical analysis was carried out to find the best probability density function capable of being adjusted and fitted to the water balance data D. The log-logistic probability density function was chosen and is expressed as:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad (13)$$

In this expression, α is the scaling parameter, β is the shape parameter and γ is the original parameter for values of γ> D <∞. This function is also called the Generalized Log logistic, because it contains three parameters. The cumulative distribution function (cdf) of this probability function is defined as follows:

$$F(x) = \frac{1}{1+\left(1+\frac{\beta(x-\gamma)}{\alpha}\right)^{\frac{-1}{\beta}}} \quad (14)$$

With the cumulative distribution function, the SPEI can easily be obtained as standardized values of F(x). This goes through the same procedure of the SPI calculation by using the approximation of Abramowitz and Stegun (1965) in equation 7 to 10.

2.4 *The application of the SPEI index:*

Mean temperature data from 1975 to 2015 and the associated evapotranspiration from the surface (calculated using equation 11) are presented in Figure 4. These temperature data were measured near the surface of that area. The evapotranspiration is calculated and the rainfall data are available (Figure 1), therefore the difference can be calculated. Like the SPI calculation procedure, a suitable probability density function (in this case the Log Logistic function) is fitted this time on the obtained water balance data and not just on the rainfall data. Figure 5 shows the probability density function adjusted on the water balance data.

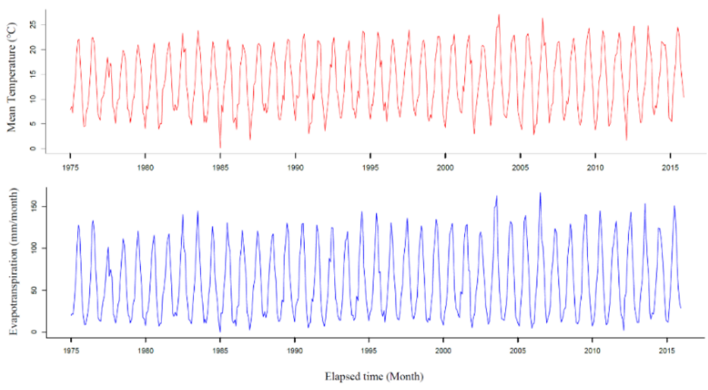

Figure 4: Temperature data and the calculated evapotranspiration at Toulouse-Blagnac from 1975-2015

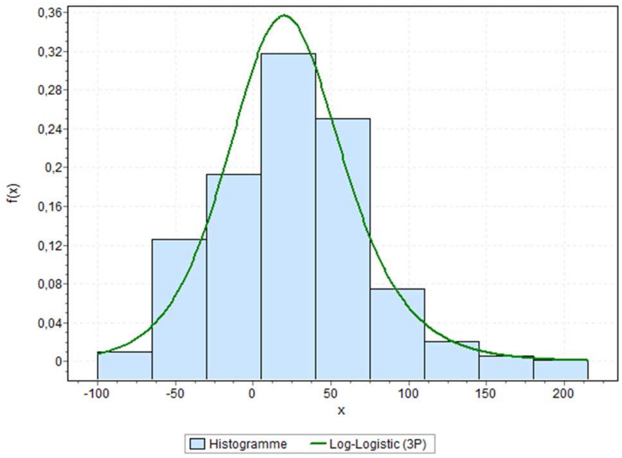

Figure 5: Fitting of the Log-Logistic distribution on the water balance data (D) at Toulouse-Blagnac from 1975 to 2015.

3 RESULTS, COMPARISON AND DISCUSSION

A drought begins when the indexes continuously show a negative value of -1.0 or less and ends when the index becomes positive. When the indexes show values between ±1 and ±1.49 the drought status becomes moderately dry for negative values and moderately wet for positive values. When they show values between ±1,5 and ±2 a very dry period or very wet period is observed and finally when the values are greater than 2 and less than -2 the period is in an extremely wet and extremely dry condition respectively. Therefore, for each period of drought, there is a duration, with a beginning and an end, and an intensity for each month during which the period continues.

These two indexes are now normalized and can be expressed over time. Primarily the SPEI results are being investigated. By applying the Abramowitz and Stegun expression the monthly SPEI index was calculated. The index clearly recognizes all observed and declared drought periods in France since 1975 (1976, 1988, 1989, 1990, 2003, 2006, 2011), mainly the year 2003 that was the costliest period in terms of damages and losses caused on lightweight constructions. The reason is visible in the figure 6(a). The intensity of the drought in 2003 is much higher, compared to the other periods and it also has a greater severity and its duration is almost distributed throughout the year. To investigate the obtained results of the SPEI index, a comparison was made with the standardized precipitation index (SPI) for the same period and at the same given station. Figure 6(b) shows that not all drought periods are recognized in the case which the SPI index is used. This is due to the fact that the SPI is based on rainfall data only and is independent of temperature and the evapotranspiration rate from soil surface. In other words, a large variation in temperature will not affect the SPI results, as the SPEI index is based on both parameters (temperature and rainfall). The drought periods that are not recognized by the SPI index are shown in figure 6(b) (1976, 1990, 2006, 2011). Precipitation did not fall much during these periods but there was of course an increase in temperature which could be recognized by the SPEI index. It is also seen in figure 6(b) that there are also dry periods on the SPI index which does not correspond to any observed or declared drought period in the past years in France. This confirms that the SPEI index performs better than the SPI index in monitoring meteorological drought in this specific region. The intensity and the duration of these metrological drought are in relation with the surface suction of soils. This can be confirmed by studying a specific year in which the intensity and duration is high. In this case study the 2003 drought was chosen. The concept of the drought index can be related to the rate of evapotranspiration (AE/PE) and the concept developed by Wilson et al. (1997) and Wilson (1990) based on the soil surface suction and the relative humidity, where AE is the actual evapotranspiration (Wilson et al. 1994). An important variation of surface suction during a dry period, would give an SPEI drought index with high intensity and long duration. To analyze this concept, two years have been taken into account: a dry year (2003) and a rather wet year (2000). Monthly mean relative humidity was calculated for these two years and by applying Kelvin's law the following curves were deduced (Figure 7). For the 2000 year, the driest month corresponds to the month of July and the wettest month corresponds to the month of January, nevertheless for the 2003 year, the driest month corresponds also to July but the wettest month corresponds to December. The year 2000 does not show much variation in suction because the relative humidity does not vary significantly over the course of the year as indicated also by the SPEI drought index which shows a global humid period. Nevertheless, the second curve shows greater variation of suction on the soil surface during the year 2003 (as it is also presented by the index). The driest month in year 2003 (RH=55.25%) generates larger suction values than the driest month of the 2000 year (RH=64.83%). However, the wettest month in 2003 (RH=86.13%) shows approximately the same suction values in the wettest month of the year 2000 (RH=83.6%) because the difference between relative humidities are not significant. For constant AE/PE values, when the air relative humidity increases, the suction value decreases. This is physically due to the fact that the air vapour pressure approaches the vapour pressure at the soil surface when the evaporation is lower and results in the air relative humidity reaching the soil's relative humidity and in consequence in a saturated state or lower suction values at the soil surface.

4 CONCLUSION

This case study investigated drought and humidification cycles during a long period of time by two different drought indexes in the south of France. The SPEI index showed better performance to fit the observed meteorological drought periods in the south of France by comparing it to the SPI index which is a universal drought index and is based only on rainfall data. The comparison confirms the non-negligible effect of temperature and soil evapotranspiration on the sensitivity of the drought index as the SPEI calculation method takes both precipitation and temperature into account. Based on the south France case study, the monitoring of these drought-

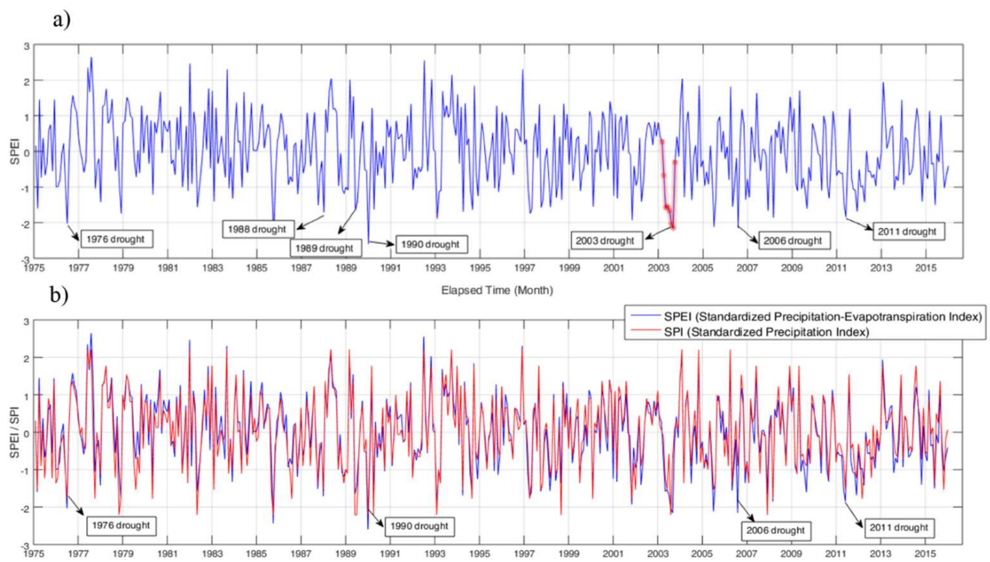

Figure 6: a) Calculated SPEI index for the 1975-2015 period at the Toulouse-Blagnac station (Zone with a high risk of shrinkage and swelling) b) Comparison of the SPEI index with the SPI index

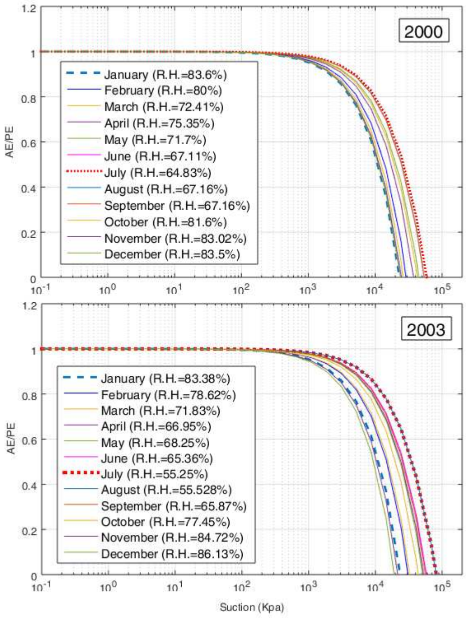

Figure 7: Comparison of surface suction variations for two different years (2003 dry year and 2000 wet year)

humidification cycles during a long period of time showed that when and how intense a drought period resulting in shrinkage and swelling, could be. It was also shown that drought indexes could be in relation with the soil surface suction and the rate of evapotranspiration. This was confirmed by comparing two years at different dry and wet state. The 2003 dry year shows more suction variations during the year in comparison with the 2000 year. It is now clear that the evapotranspiration process from the surface of clayey soils, triggering suction variations, may have caused those damages in the south region of France during past years. The results of this study could be useful in Engineering practice and construction industry by having a general view of the drought and humidification cycles over the period of the past time and it could also be of great importance to decision makers especially governmental organizations and insurance companies to manage the associated risks with these changes in climatic and surface parameters over time. A perspective of this study could be the comparison of these drought indexes with the soil water content, suction or soil settlement over time in order to establish a relationship with these physical parameters.

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