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Spatiotemporal characteristics of dryness and drought in the Republic of Moldova

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Abstract This paper presents the results of a study on the estimation of climatic conditions of dryness and drought in the Republic of Moldova. The evaluation of drought was based on data from 18 weather stations, which were selected according to the length of the period of measurement (1945–2006) and from the Chisinau observatory, which has the longest statistical series from Moldova (1891–2006). Some of the basic principles in the selection of the drought identification indices were: to characterize the same period of time, provide information on the regional hydrothermic regime, and not to rely on constants that are specific to certain physical/geographical regions. Firstly, the registers of the droughts for spring, summer and autumn have been identified and processed. Secondly, the frequency, duration and tendency of the dryness and drought phenomena have been evaluated. Thirdly, the manifestation of dryness and drought, as well as their spatial distribution, have been estimated with a probability of 95%. As a result of the analysis of the drought register for a period of over 100 years, an increase in tendencies of frequency and intensities of the given phenomena after the 1980s was revealed. The longest drought periods were noticed at the beginning of the 1950s and 1960s, reaching their highest points in the decades of 1981–1990 and 1991–2001, with the lowest point in the 1970s. Accordingly, during the past 20 years, in 11 cases of drought, 9 of them were registered as being of either a severe or extreme intensity degree.

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1 Introduction

The Republic of Moldova is situated in the SE part of Europe, between 45°28′–48°28′ northern latitude (350 km) and between 26°40′–30°06′ eastern longitude (150 km), on an area of 33,844 km^2. In general, the territory of Maldova is hilly but also includes plains, the plateaux being located mostly in the central part, which is slightly inclined NW–E. The relief altitudes vary from 5 m (Giurgiulesti) to 429 m (Balanesti). The geographical position of the territory of Moldova gives its climate a marked continental character, with frequent occurrences of drought. The average annual precipitation diminishes NE–SE from 680 to 420 mm. The climate and geographical zone peculiarities of this area lead to the presence of three agroclimate regions: north, central and south. The following is typical for the north region: the sum of active average daily temperatures in 2,700–3,000°C is limiting; the precipitation maximum is 451–711 mm/year; temperature above 10°C equates to 167–176 days/year. For the central agro-climatic region, in comparison with the north region, the following is typical: higher level of active average daily temperatures (100–200°C higher); longer period with temperatures higher than 10°C (6–10 days longer) and slightly less precipitations (14–93 mm less). The southern region is the warmest and less moist than the northern zone. The sum of active average daily temperatures here is up to 3,300°C and the duration of the period with the temperature higher than 10°C is longer, 11–12 days, and the precipitation quantity is less than in the north zone (70–120 mm/year; Hydrometeorological Centre 1982).

This complex study of drought brings important theoretical contributions, since it allows a more detailed and causal knowledge of this phenomenon and of its role in the characterization of the climate of the territory. Also, the study of droughts has a special practical importance, since it offers reference material for the redistribution of crops in the territory, i.e. the development of the most suitable agricultural technology and the choice of the species that can resist and produce most under the given conditions. Dryness always precedes drought; the state of dryness and drought are two distinct stages, in which the plant experiences the lack of humidity with different intensity. During the state of dryness, the plant does not yet suffer a lack of humidity since there still is a water reserve in the ground; however, if dryness persists then drought results.

The main economic activity of Moldova is agriculture; thus, the country is highly dependent on the climatic conditions. The unfavourable natural limiting factors such as frost, dryness, drought, showers and thundershowers play an important role that determines the evident annual challenge to agricultural crops. Climatic features such as dryness and drought are regional particularities to a certain extent caused by the physical-geographical position of the country. The territory of Moldova is under the influence of the high atmospheric pressure of the subtropical zone that moves to the north during the warm period of the year, reaching the northern latitude of 50°. As a result, the trajectory of the anticyclones that move in parallel with the western masses, spreads over the territory of Moldova and determines the humidity conditions during this period). Additionally, the northern anticyclones that are very frequent in spring, block the air masses coming from the Atlantic Ocean. All these together determine the manifestation of the above phenomena.

It should be added, that in recent years, droughts of high intensity have been observed that cause damage to the economy, especially to agriculture. According to the data of the International Panel on Climate Change, the 1990s was the warmest decade ever recorded in the millennium (IPCC 2001). The intensifying warming of the global climate leads to an increase in the probability of manifestation of climatic risks at the regional level. In this decade, Moldova has experienced severe drought for six different years—1990, 1992, 1994, 1998 and 2000. In all these years, the degree of drought was extreme and greatly reduced agricultural crops.

The greatest part of Europe's territory suffers from droughts of moderate and severe intensity. The whole territory of the Republic of Moldova is situated in a zone, which is completely dominated by this phenomenon. Droughts are the costliest natural disaster of the world and affect more people than any other natural disaster (Wilhite 2000). The recent wave of drought episodes was experienced not only in southern Europe but also throughout the central Europe during 2000, 2002, 2003 and 2006. The drought of 2000 was relatively short in duration but had a significant impact, especially on the early sown spring crops. The next event of 2003, which was much more pronounced in a number of regions of Europe (Moldova, Romania, France, Italy, Portugal, Spain, Russia, Czech Republic, Germany, Switzerland, Austria, etc.), clearly demonstrated that prolonged periods of rainfall deficit, combined with extremely high summer temperatures, might have influenced the full range of ecosystem services starting with the elimination of the fodder production (Dubrovsky et al. 2005; Schaumberger et al. 2006) and ending with the negative carbon sequestration of the European biosphere (Ciais et al. 2005).

A different approach is to subdivide the environmental group based on whether the drought event is based on one or several variables. A single variable or simple index would typically be rainfall or stream flow deficits. Multivariable or complex indices include many elements of the hydrological cycle, e.g. a combination of meteorological factors such as precipitation and evapotranspiration. A rather comprehensive list of complex and simple dryness and drought indices as well as statistical measures applied as drought indices can be found in WMO (1975).

In most studies, some type of a drought index is employed to quantify the dryness of the evaluated periods. Such an index can be used to quantify the humidity condition of a region and thereby detect the onset and measure the severity of drought events in time, and the spatial extent of a drought event, allowing a comparison of moisture supply conditions between regions (Alley 1984). Of these, the most common indices used worldwide include the standardized precipitation index (SPI; developed by McKee et al. 1993) and the Palmer Drought Severity Index developed by Palmer (Alley 1984). Another index that has been widely used in various regions of the world is the Z-index (Scian 2004; Ntale and Gan 2003; Heim 2002; Karl et al. 1987; Keyantash and Dracup 2002). Based on the previous research (Guttman 1998, 1999), we have chosen the SPI index as the most appropriate indicator for measuring climatological drought on a seasonal basis in Moldova. A temporal scale of 3 months was used to calculate the SPI due to its strong relationship with agricultural droughts (Ji and Peters 2003). The SPI has been applied to develop early drought warning systems (Svoboda et al. 2002) and to determine the spatial extent and magnitude of droughts (Hayes et al. 1999). In addition, the spatial and temporal analysis of droughts using the SPI has some advantages regarding the use of precipitation series because the SPI series are comparable in time and space (Lana et al. 2001).

Thus, SPI quantifies the precipitation deficit for multiple time scales and reflects the impact of drought on the availability of different types of water resources. For example, the moisture stored in the soil is highly affected by the short-term precipitation anomalies, whereas stream flow, groundwater and reservoir storage respond to longer-term precipitation anomalies slowly. Wetter and drier climates can be represented by SPI in the same way, because it is a normalized index.

In the Republic of Moldova, the most common index is the Selianinov hydrothermic coefficient (CHT):

$$CHT = \frac{10 \times \sum r}{\sum t \geq 10^{o}C} \quad (1)$$

where $\sum r$ is the total precipitations amounts (mm), and $\sum t \geq 10^{o}C$ is the sum of temperatures equal or higher than $10°C$ for some time length: month, seasonal or vegetation period (Selianinov 1928).

During the past 25 years in the Commonwealth of Independent States (CIS) countries, the index of aridity Si, introduced by Pedey (Ped 1975) of the Russian Hydrometcenter has been frequently used for the identification of atmospheric drought. Using this index, it is easy to classify weather conditions (drought or damp). In our opinion, a highly individual solution for the principle of a relative climatological drought was reflected in Pedey's (Si) index of drought:

$$Si(\tau) = \frac{\Delta T}{\sigma T} - \frac{\Delta R}{\sigma R} \quad (2)$$

It presents a difference of monthly anomalies of temperature (ΔT) and precipitation (ΔR), both relative to their standard deviations (σT and σR), where τ is a selected year. If Si>0, one observes a mild atmospheric drought; while 1≤Si<2 is moderate; 2≤Si<3 severe; and Si≥3 is extreme. However, if Si<0, there is an excess of humidity: –1≥Si>–2 = mean; –2≥Si>–3 = strong and Si<–3 = very strong. Application of normalized values allows exercising this index for comparing purposes in various situations, since it describes a specific meteorological situation regarding some mean level. Conditions of both–humidity content and heat content–can be characterized through application of the Si since, in contrast to a hydrothermal coefficient, it reflects an alternating quantity: positive values of Si correspond to dry periods, negative to humid ones. Another interpretation may be made as follows: positive values of Si correspond to a warmer thermal regime during some period, whereas the negative ones reflect a colder thermal regime.

The percentage (P) of the long-term mean precipitation is one of the simplest measurements of rainfall for a location. It is calculated by dividing actual precipitation by the long-term mean precipitation and multiplying it by 100%. This can be calculated for a variety of time scales. One of the disadvantages of using the percentage of normal precipitation is that the mean, or average, precipitation is often not the same as the median precipitation, which is the value exceeded by 50% of the precipitation occurrences in a long-term climate record (WMO 1975).

The number of months/year when the drought and dryness spells occur is shown by the Walter-Lieth climograms where, 10°C on the temperature scale always corresponds to 20 mm of rain on the precipitation scale. Arid and humid months can be directly read off. Arid months are months when the temperature line is higher than the precipitation line. These months are dry. Humid months are the months when the precipitation line is higher than the temperature line. Climate diagrams can also be shown in different formats (Walter and Lieth 1961–1967).

2 Materials and methods

When studying a complex topic such as drought it is necessary to select the direction of investigation (meteorological or climatological, agricultural, hydrological, and socioeconomic), the genesis type (atmospherical drought and pedological drought), the identification and elaboration of the register of droughts on the basis of which one can classify (intensity, duration, spatial extent, and timing) and the season of manifestation: spring drought, summer drought, autumn drought (AMS 2004).

In the study under consideration, the drought was climatologically evaluated for the entire warm period of the year (April–October), separated into months, seasons (spring, summer and autumn) and as atmospheric drought. For the study of the regional atmospheric drought the following items were carried out:

– The analysis and evaluation of the climate indices and the selection of the most informative ones for the characterization of the drought in Moldova
– The creation of the data basis for computing the climate indices that reflect the manifestation of the dryness
– The creation of a register of droughts of various intensities
– The climatic evaluation of the periods without precipitations, of the periods of dryness and drought
– The evaluation of the temporal and spatial distribution of the dryness and drought

Moldova has a meteorological network which currently includes 18 meteorological stations situated in various physical-geographical regions. One of them, the Chişinau station, has a sequence of observations that were recorded over more than 100 years (1891–2006). For all the other meteorological stations, the statistical sequence covers the interval from 1945 to the present. The data basis has included the following meteorological elements from all the stations: daily and monthly precipitation amounts (mm), daily and monthly average temperatures (°C), the sum of temperatures higher than 10°C.

The aridity index Si is of the greatest interest in terms of the climate change, since it incorporates the values of temperatures and precipitation in the form of normalized observations, thus permitting the objective comparison of the trends displayed by various stations during different months. The criteria of the index Si are useful for estimating the monthly droughts. Certain researchers disagree with this conclusion, since the droughts can appear in one month and extend into the following month. It has therefore been proposed that the atmospheric drought should be determined according to the Pedey index (Si) and use another procedure. That is, if we consider the data of the neighbouring months to be independent, we take Si≥2/√*r*, where *r* is the number of the combined months (Bagrov 1995). Application of the above procedure has been put to test in the evaluation of the droughts in Moldova, both for the entire warm period and for individual seasons. In this case, for the warm period the computation has been carried out with the following data: Si≥1/√7; Si≥2/√7; Si≥3/√7, Si≥4/√7 that provided the thresholds given in Table 1. In the evaluation of the drought during the spring and autumn seasons, the period of vegetation was taken into account and hence the computation was carried out for only 2 months. The criteria obtained for these seasons are Si≥1/√2; Si≥2/√2; Si≥3/√2, Si≥4/√2. For the summer, when the drought was calculated for 3 months, the following data were obtained: Si≥1/√3; Si≥2/√3; Si≥3/√3, Si≥4/√3.

Using index P, drought is defined as occurring when the precipitation is less than 80% of the long-term mean value. In Moldova, the CHT index varies from 0.7 in the south and 1.2 in the north of the country. The criteria are included in Table 1. Besides these three indices mentioned so far, the SPI has also been calculated. The majority of drought indices have a fixed time scale. The main advantage of the SPI, in comparison with other indices, is the fact that the SPI enables both determination of drought conditions at different time scales and monitoring of different drought types (Vicente-Serrano and Cudrat-Prats 2007).

Consequently, from the various studied indices, we selected those that provide information on the regional hydrothermic regime and they are independent of the constants that are specific for certain physical-geographical regions. We believe that the disadvantage of some complicated methods in the evaluation of drought is in the difficulty of obtaining the initial meteorological data and, moreover, many of the parameters used to compute the indices are only approximated. For the identification of drought, a set of meteorological and agrometeorological indices has been used. The research has confirmed that applying a single index is not adequate for the identification of drought. Instead, it was recommended to evaluate a complex of several indices which complement each other; this is due to the fact that the indices are not perfect, although they have their advantages and disadvantages. When the numerical values of most of the indices coincided, the year was considered a drought year and therefore, it was included in the register. Thus, if three indices determined moderate to extreme drought, that year was dry. As an example from Table 2, drought of the year 1961 is depicted by only two indices–CHT and SPI for a mild magnitude drought—and 1961 was not considered a dry year.

Next, the percentages of sensitivity was calculated for each index of drought of diverse magnitudes during the spring, summer, autumn and warm periods. In the test results, the indices applied proved that those which are most informative determine, in most cases, the drought with mild and moderate intensity for all seasons. As shown by the results in Table 3, the best informative indices in the identification of mild and moderate droughts for all seasons are CHT (85.0–100%) and SPI (75.5–100%). The best indices for the determination of severe magnitude droughts are Si (84.6–100%) and P (33.3–98.9%). In regards to extreme droughts, no indices were able to determine any drought during the warm period, even though the droughts occurred during this time. However, in the remaining seasons, the most sensitive indices for extreme droughts proved to be CHT (77.8–100%) and Si (55.6–100%). Also, as shown in the Table 3, the index P is less informative in the determination of the summer drought, because in Moldova, the monthly precipitations are not distributed uniformly. On the basis of the above results it is clear that the longer the period under study (e.g. 7 months or longer), the more inaccurate the determination of the intensity of drought.

Using the indices CHT, Si, P and SPI in the evaluation of the drought requires an analysis of the dry condition for a sufficiently long interval (month, season, vegetation period). However, for the crops it is more useful to evaluate the climatic conditions for a shorter interval (a few days). A month can be also considered dry even if the rain has produced more water than the standard, but was not distributed at the correct time, i.e. when needed by the plants, or if the whole amount was concentrated into 2–3 days and there was no other precipitation for the rest of the month. In such cases, we

Table 1 The drought criteria proposed for different indices

Indexes	Drought categories and values			
	Mild	Moderate	Severe	Extreme
CHT	0.8≥CHT>0.7	0.7≥CHT>0.6	0.6≥CHT>0.5	CHT≤0.5
Si at time scale 7 months	0.38≤Si<0.76	0.76≤Si<1.13	1.13≤Si<1.53	Si≥1.53
SPI	0 to –0.99	–1.00 to –1.49	–1.50 to –1.99	≤–2.00
P	80–70%	70–60%	60–50%	<50%

Table 2 An example of the application of a set of indices to identify autumn drought events for Comrat weather station (south)

Year	D	CHT				Si				SPI				P			
		M	m/e	S	E	M	m/e	S	E	M	m/e	S	E	M	m/e	S	E
1945	+				0.33				2.81				−2.03				46
1946	+				0.41				3.52			−1.65				61	
1952	+	0.75				0.89				−0.91							
1953	+			0.58			1.25				−1.43			78			
1954		0.79															
1957	+			0.59				2.58			−1.50						
1959		0.78								−0.93							
1960	+				0.44			2.75			−1.42						49
1961		0.80								−0.96							
1962	+			0.5				2.26								53	
1963										−0.88							
1973	+		0.61			1.24									63		
1976	+		0.66								−1.00				62		
1981	+			0.55			1.13									55	
1986	+			0.59			1.57				−1.39					59	
1987	+			0.56			1.99				−1.45					55	
1988	+			0.59			1.32								60		
1990	+			0.58				1.78									
1992	+				0.46				2.77			−1.84					48
1993	+		0.62				1.42								61		
1994	+				0.48				2.86			−1.56					
1995	+	0.80								−0.97				78			
1996	+				0.41				2.91				−2.00				45
2000	+			0.52								−1.82				54	
2002	+		0.63			1.22					−1.11					56	
2003	+				0.30				3.01				−2.04				33
2005	+				0.43			2.27				−1.55					42
2006	+				0.48				3.05				−2.21				48
n		5	4	9	9	3	6	4	8	5	7	5	4	2	5	6	7
Total			27				21				21				21		

D drought, *M* mild, *m/e* moderate, *S* severe and *E* extreme, *n* number of drought of diverse intensity for each index, *Total* the toal number of droughts for each index

cannot deny the need of considering the duration of the period without effective precipitations as one of the criteria of evaluation of the dry spells. Effective precipitations are those that are useful for the plant. Several methods of evaluating the intervals without precipitations are known (Cheval et al. 2004). In the given case we can, in essence, consider a condition under which, during at least 10 consecutive days there is no precipitation or the daily amount does not exceed 0.1 mm.

Another method that can be used in the evaluation of the dryness and drought spells is the Walter Lieth climogram. The reason for using this method is that drought can start at the end of one month and extend into the next month, or continue for several successive months. The Walter Lieth climogram aims to provide the ratio of temperature/precipitations, on the scale of 1/2 for the drought spells and on the scale of 1/3 for the dryness spells. This makes it possible to determine the dryness or drought spells, without the need to resort to using any indices.

3 Results

3.1 The creation of the register of droughts

Since the Chisinau meteorological station (situated in the central part of the country) has a sequence of observations for more than 100 years, it was adopted as a standard for the evaluation of the drought years. According to the obtained data, within the interval under consideration, the droughts were observed during 36 years in the warm periods, 34 years in the spring, 37 years in the summer and 41 years experienced autumn droughts (Table 4). Please, note that the term warm period covers the months of April to October, i.e. parts of spring, the whole summer and part of autumn. This makes it possible to determine droughts in different seasons of the year and for different time scales.

This table describes only the data that relate to the central part of Moldova. Data for all other parts of the country were

Table 3 Evaluation sensibility indices using in created register of drought

Indices	Spring	Summer	Autumn	Warm period
Mild drought (%)				
CHT	100.0	91.7	100.0	85.0
Si	40.0	75.5	84.2	100.0
P	45.8	36.9	98.7	28.3
SPI	100.0	75.5	98.5	92.9
Moderate drought (%)				
CHT	73.4	66.7	100.0	60.0
Si	54.5	83.3	10.0	80.0
P	27.3	6.3	33.3	50.0
SPI	75.6	88.0	68.4	100.0
Severe drought (%)				
CHT	58.3	72.7	11.1	57.1
Si	84.6	96.8	100.0	85.7
P	100.0	50.3	98.9	33.3
SPI	35.3	28.7	33.3	45.6
Extreme drought (%)				
CHT	80.0	100.0	77.8	-
Si	80.0	55.6	100.0	-
P	41.6	22.2	66.7	-
SPI	50.0	23.0	21.5	-

processed in the same way as well. From the total number of drought years in the warm period, 12 are of mild intensity, 14 of moderate intensity and 10 of severe intensity. The severe and extreme droughts characterize all seasons of the warm period. Concerning a part of spring, the whole summer and a part of autumn seasons, the severe droughts are prevalent in 15–20 cases, and the extreme ones in 3–11 years. However, the severe or extreme droughts during 9 years each, respectively, are predominant in the summer months.

When the register of the droughts that have occurred during the period of approximately one century is analysed, we can highlight the tendency of increased frequency and intensity of the given phenomena. Figure 1 shows the evolution of the Si, SPI, P and CHT in individual seasons from the regional series between 1891 and 2006. According to all indices, the longest drought periods were noticed at the beginning of the 1950s and 1960s, reaching their highest points in the decades of 1981–1990 and 1991–2001 and the lowest points in the 1970s. After the 1980s, the intensity of the droughts increases. Similarly, during the last 20 years in 11 cases of drought, 9 were registered as being of both a severe intensity degree and an extreme intensity degree.

Taking into consideration the nonhomogeneity of the agroclimatic conditions in Moldova such as the degree of warmth, humidity and the various physical-geographical conditions (relief, soil type), the characterization and evaluation of drought was carried out in more detail for agroclimatic regions (Hydrometeorological Centre 1982). For each of the 18 meteorological stations distributed in agroclimatic regions, the numerical values of the drought indices were calculated, which then allowed us to evaluate the years according to the drought intensity in the given regions. Having analysed the characteristic features of the drought in the whole territory of the country, we can state that approximately every third year suffers from drought during the spring and/or summer, and every second one during the autumn season. In the meantime, the moderate and severe intensity droughts are most frequent in the spring and summer, while in the autumn the droughts are mostly severe and/or extreme. The spatial distribution of the droughts can be observed. For the period under consideration, even for the agroclimatic region I (north of the country), where the humidity conditions are evaluated as optimal during the vegetation period, 10 years were recorded with moderate drought and 3 years with severe drought. Towards the south, the severe and extreme droughts become more frequent. In the second agroclimatic region (centre of the country), there were 5 years recorded with moderate drought and 9 with severe ones, but in the third region (south of the country), out of 18 drought years, 10 experienced severe and extreme droughts.

3.2 Walter Lieth's climograms as criteria for detemining a dryness and drought-spell length

Using the Walter Lieth method, a set of climograms was created for each year for the north, the centre and the south regions of the country for the time interval of 1945–2006. The analysis of the climograms set allowed us to highlight the peculiarity of this phenomenon's manifestations in Maldova.

In the northern part of the republic, 27 cases of drought (once in 2 years) were recorded out of 61 analysed years. The sum of the duration of the studied phenomena was 51 drought months, which constituted 35 drought periods. The longest period of the phenomenon was four consecutive months in 1953, which was classified as severe drought. Using the estimation of the statistical data on the basis of the climograms, we can distinguish three more cases of a 4-month duration divided into 2–3 periods. Such cases were noticed in the following years: 1946, 1967 and 1973, with the longest period running from July to October.

The climogram method allows the estimation not only of drought but that of dryness as well. The dryness phenomenon has occurred during 79 months (50 periods). The maximum duration of the phenomenon had constituted six consecutive months in 1953 and 1967. According to the climograms in the central part of the country, the phenomenon of drought and dryness were recorded in 32 cases. Overall, 86 months of drought and 58 periods were detected. The maximum duration was 6 months (in 1946 and in 1994) divided into 2–3 periods with small intervals between them. During these years, the phenomenon had begun in the month of March and had ended in September 1946 and October 1994. In the central part of the

Table 4 The droughts register of Chisinau meteorological station for the years 1891–2006

N/or	Warm period					Spring					Summer					Autumn				
	Years	Mild	Moderate	Severe	Extreme	Years	Mild	Moderate	Severe	Extreme	Years	Mild	Moderate	Severe	Extreme	Years	Mild	Moderate	Severe	Extreme
1	1892			+		1892			+		1892		+			1891				+
2	1895			+		1900			+		1893		+			1892			+	
3	1896			+		1901		+			1894		+			1894		+		
4	1900	+				1905		+			1895			+		1896				+
5	1902		+			1907			+		1896			+		1899		+		
6	1908	+				1908			+		1902			+		1906				+
7	1909	+				1927	+				1905			+		1909		+		
8	1916	+				1928		+			1916		+			1913		+		
9	1917		+			1936			+		1917		+			1916	+			
10	1921		+			1938			+		1921		+			1917			+	
11	1923			+		1939			+		1923		+			1921				+
12	1924		+			1946	+				1924			+		1923			+	
13	1928			+		1947			+		1928		+			1924			+	
14	1929			+		1949		+			1929			+		1925			+	
15	1938			+		1951		+			1935		+			1928			+	
16	1945		+			1952				+	1938				+	1945			+	
17	1951			+		1956		+			1939				+	1947				+
18	1953			+		1957		+			1945		+			1948			+	
19	1957	+				1959	+				1946				+	1949			+	
20	1959	+				1963			+		1951				+	1953			+	
21	1960	+				1964	+				1953				+	1959		+		
22	1961	+				1967			+		1957	+				1961			+	
23	1962	+				1968				+	1959	+				1962		+		
24	1963		+			1969		+			1960			+		1963				+
25	1967		+			1971		+			1961		+			1967			+	
26	1969	+				1976	+				1962	+				1969			+	
27	1973			+		1982			+		1973		+			1970			+	
28	1981		+			1986				+	1981			+		1973			+	
29	1982	+				1989			+		1988	+				1975			+	
30	1986		+			1994			+		1990				+	1982			+	
31	1990		+			1998		+			1992		+			1983				+
32	1992		+			2000		+			1996				+	1984	+			
33	1994	+				2002			+		2000			+		1985		+		
34	2000		+			2003			+		2002				+	1986			+	
35	2002		+								2003				+	1992	+			
36	2003		+								2005				+	1994				+
37											2006					2000				+
38																2002				+
39																2003				+
40																2005			+	
41																2006			+	
		12	14	10	0		5	11	15	3		4	13	9	11		3	7	20	11

The table includes the drought years for every season of the warm period. It also contains droughts which are related to the entire warm period (with indices, which had been calculated for 7 months from April–October); + marks the drought year

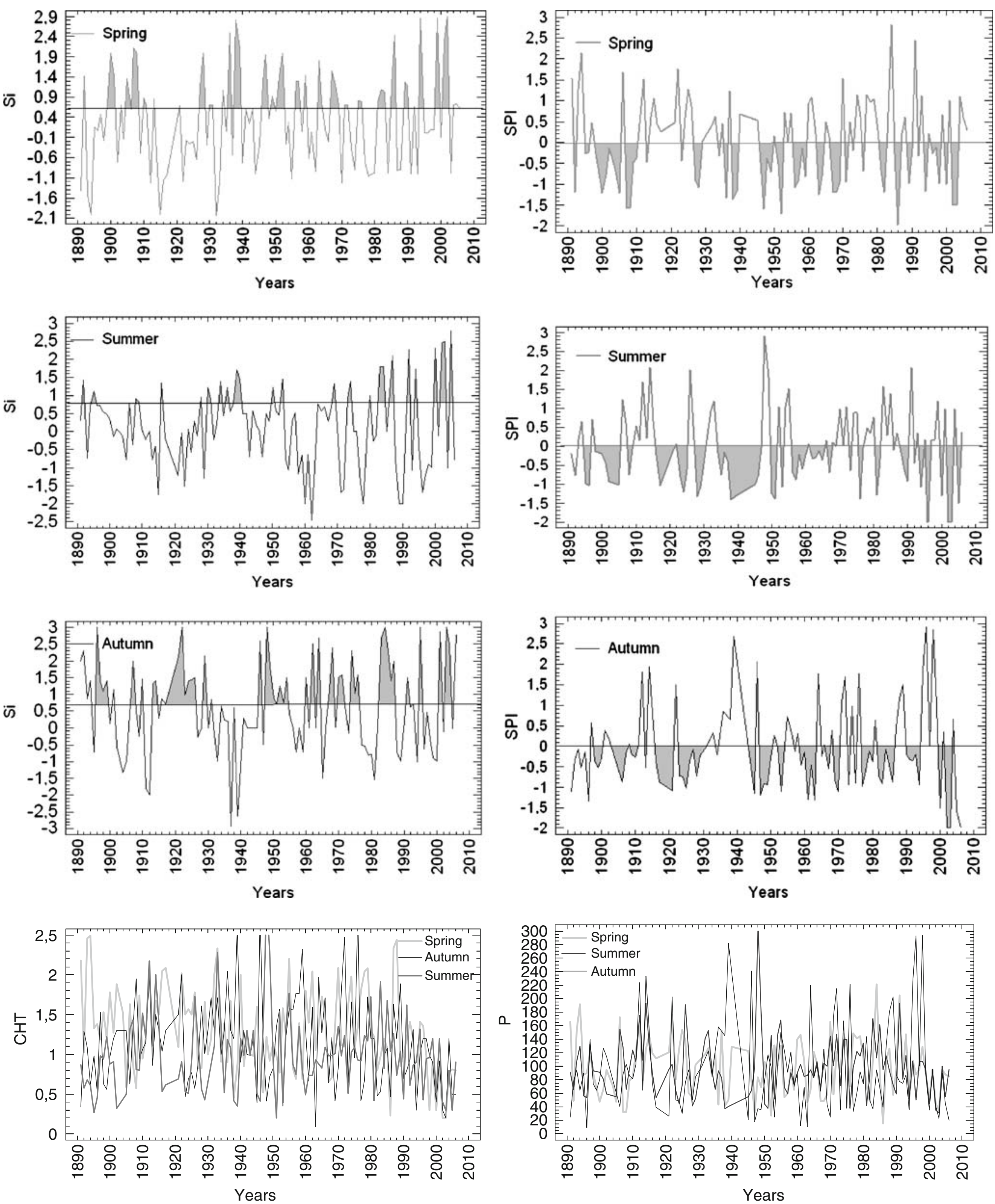

Fig. 1 Evolution of the regional severity indices values representative of the Chisinau meteorological station for the 126-year time series. They are described by the time distribution for individual seasons of the set of meteorological and agrometeorological indices (Si, SPI, P and CHT) proposed in identification severity drought. The linear trend of drought expressed by the indices P (with level of significant p=0.02) and CHT (p=0.05) have a negative trend. It must be noted that the negative value of SPI (p=0.05) and the positive value of Si (p=0.036) have increased

country, dryness is more frequent than in the north. The studied phenomenon was noticed in 116 months (70 periods). The maximum duration of the phenomenon was of six consecutive months of dryness occurred in 1945, 1961, 1963, 1967, 1990, 1994 and 2003. Judging by the frequency and intensity of drought, the south of the republic is a special place where, during the period of 61 years, there were 38 years of drought. The sum of drought months constitutes 116 (2.1 months/year) and 72 periods. The dryness phenomenon was noticed in 150 months (2.5 months/year) and 72 periods. It is worth mentioning, that consequently, with a greater frequency of drought in the south of Moldova, drought periods of long duration have been noticed. The territorial distribution of the named phenomena depends on the temperature and precipitation variation, because a great variability from the north to the south has been observed, both as a frequency (1–2 or more periods of dryness and drought in a year may occur) and also as duration (several consecutive months).

3.3 Periods without precipitation (PWP) as criteria for determining a dry spell length

The periods without precipitations (PWP) are common for the climate of Moldova. In the drought years, the average number of the PWP of various lengths is about 5–7. The computations show that, during the warm season (April–October, the average number of days without precipitations is 18 in the north and 23 in the south. More frequent are the PWP in the south of the country, with their number varying from the north to the south from 2–4 respectively. Depending on the year, the number of these periods varies from 1

Table 5 Example of specifying the PWP in the south (Comrat) of the country

Years	The number of periods	Total days	Maximum consecutive dry days	Duration, day	
				Beginning	Ending
1945	4	133	52	8 August	29 September
1946	6	147	43	22 July	3 September
1947	4	147	62	31 August	31 October
1948	3	129	57	26 July	21 September
1949	3	128	71	22 August	31 October
1950	3	84	56	22 August	17 October
1951	4	97	40	21 September	31 October
1952	3	106	68	27 July	3 October
1953	4	141	66	26 August	31 October
1954	1	37	37	1 September	7 October
1956	3	72	42	19 September	31 October
1957	6	112	26	5 October	31 October
1960	6	144	33	29 June	1 August
1961	5	103	41	19 August	28 September
1962	5	141	48	4 May	20 June
1963	3	136	69	24 August	30 September
1965	6	128	25	15 September	9 October
1966	3	54	23	19 April	11 May
1967	4	112	37	25 April	31 May
1968	2	50	30	1 April	30 April
1969	5	94	24	7 September	1 October
1970	5	71	49	5 September	23 October
1973	3	68	32	19 September	20 October
1975	4	81	23	15 September	7 October
1976	5	60	17	18 June	14 July
1981	4	129	29	15 May	12 June
1982	2	92	40	4 May	10 June
1983	4	81	30	15 August	13 September
1985	3	97	27	4 September	1 October
1986	5	123	47	15 April	31 May
1990	7	90	30	26 April	25 May
1992	5	150	41	2 April	13 May
1994	5	128	34	1 September	5 October
1996	7	102	43	2 April	15 May
1999	5	79	26	11 September	7 October
Mean	4.2/year	104.2/year	40.5/year		

to 8, and the maximum duration of the PWP reaches 69–90 consecutive days depending on the geographical region. In Moldova, the periods of 20 days without precipitations are predominant and their frequency is 65–74%. The lack of precipitations for 20 days has negative effects on the crops, since starting with the 10th day without precipitations the relative humidity of the air diminishes and high temperatures become constant, which produces a hydrothermic stress for the plants. According to the cumulative distribution, the frequency of the periods with duration of 30 days is 16–32%, and the periods of over 60–70 days occur rather seldom (1–2%). A negative effect on corn cultures also occurs during a period of around 20 days, especially when that takes place between April–June. It is in this interval when 40% of the periods of such duration without precipitation occurs in the centre and the south of the country. In the whole territory during the drought years there are recorded, on the average, four periods without precipitation of a duration of 29 days in the north, 35 days in the centre of the country and 41 days in the south (Table 5).

3.4 Temporal and spatial analysis of droughts

The register of droughts makes it possible to obtain extensive information concerning both the intensity and the intervals of their manifestation. It shows that the manifestation of dryness and drought has a random character, which follows a Poisson-type distribution. The statistics was based on the data from the droughts register and the elaborated climograms that allowed us to produce a new statistical series, which was then analysed according to the Poisson model. The Poisson distribution is used to model the number of drought and dryness events occurring within a given time interval:

$$f(n;\lambda) = \frac{\lambda^n \times \exp(-\lambda)}{n!} \quad (3)$$

If the expected number of occurrences in a year is λ, then $f(n;\lambda)$ is the probability of how many occurrences of drought there will be. To assess how well a given distribution describes the data, it is possible to compare the empirical cumulative probability distribution with the corresponding theoretical cumulative probability distribution. The statistical series thus obtained was tested by the criteria of χ^2 (Pearson criterion) and Kolmogorov–Smirnov goodness-of-fit test, in order to emphasize the homogeneity and accuracy of the data for three agroclimatic regions (north, centre and south). For the respective evaluation of the time distribution of dryness according to Poisson's law and its parameters, according to the known rules, the experimental histograms of the distribution of intervals between them were drawn, and the correlation degree between the empirical and theoretical data was thus established (Table 6). According to Pearson's test $\left(\chi_e^2\right)$, the phenomenon obeys the same rule when the empirical data are smaller than the theoretical ones. Chi-square is calculated by finding the difference between each empirical and theoretical frequency for each possible outcome, squaring them, dividing by theoretical frequency, and taking the sum of the results:

$$\chi_e^2 = \sum_{\mathrm{i}}^{k} \left[\left(P_{\mathrm{e,i}} - P_{\mathrm{T,i}}\right)^2 \Big/ P_{\mathrm{T}} \right],$$

where $P_{\mathrm{e,i}}$ is an empirical frequency, $P_{\mathrm{T,i}}$ is a theoretical frequency, i, and k is the number of possible outcomes of each event.

As the results in Table 6 show, the average time intervals between dryness events decreases towards the south. In the first agroclimatic region (north) the number of dryness events is 26 with an average time interval of 2.04 years; by contrast, in the central and southern regions, the number of dryness events increases from 32 to 33 cases with an average time interval of 1.65 and 1.39 years.

Examination of the distributions of the mild intensity droughts has shown that, in the third agroclimatic region, their number diminished and droughts of moderate intensity occur more frequently. In the first agroclimatic region—evaluated as the most humid—five cases of moderate intensity drought were recorded in the warm period, with an average time interval of 11 years between them (Table 7). In the second agroclimatic region, the number of similar droughts increased to 12 but the average time interval was 6 years. Throughout the whole period of study, there were about nine moderate intensity droughts in the south of Moldova with an average interval of 4 years. However, unlike in the first two regions where, during the warm season there were two and nine severe droughts respectively, in the third region their number becomes 11 with

Table 6 Values of the distribution of the time intervals between dryness events identified by the climograms

Agroclimatic region	The number of dryness events, n	The average of time interval between dryness events (year), X	The density function of dryness, (λ, 1/year)	Pearson criterion χ^2	
				Empirical	Theoretical (α=0.05)
I (north)	26	2.04	0.49	2.57	3.84
II (central)	32	1.65	0.60	5.38	5.99
III (south)	38	1.39	0.72	5.67	5.99

Table 7 Values of the distribution of the time intervals between the drought tests by the Kolmogorov–Smirnov for every agroclimatic region (warm period) in Moldova. *I* northern agroclimatic region, *II* central agroclimatic region, *III* southern agroclimatic region

Drought categories	The number of droughts, *n*			The average of time interval between droughts (year), *X*			The density function of drought (λ, 1/year)			The maximum of time interval between droughts (year) with $F(\tau)=0.95$		
	I	II	III	I	II	III	I	II	III	I	II	III
Mild	13	16	6	4	3	9	0.31	0.19	1.50	9	10	10
Moderate	5	12	9	11	6	4	2.20	0.50	0.44	12	16	9
Severe	2	9	11	27	6	5	13.50	0.66	0.45	19	9	6
Extreme	0	0	0	0	0	0	0.00	0.00	0.00	0	0	0

an average interval of 5 years. Thus, according to Poisson's law, an increased frequency of the moderate and severe droughts has been noticed together with considerable diminishing of the intervals between them. Moreover, quite frequently the droughts extended over 2–3 successive years.

3.5 Spatial distribution of droughts

The estimate of the territories affected by drought was made for every season for the first time, as well as for the whole vegetation period of each drought year (Table 8). The drought noticed on the surface of up to 10% of the territory of Moldova is estimated to be a local one. The droughts that cover 11–30% of the territory are related to widespread droughts. But the droughts that cover a territory of 31–50% are considered very widespread and over 50% are classified as catastrophic, as the last one brought great damage to the national economy (Potop 2003). The surface affected by drought was estimated in percentage, which considered the total number of stations as 100% with an indicator of drought being CHT≤0.8. The Surfer software was used with the interpolation method (to radial basis function interpolation) by the function multiquadric. The kernel basis functions are analogous to variograms in kriging. The kernel basis functions define the optimal set of weight to apply to the data points when interpolating a grid node: $B(h) = \sqrt{h^2 + R^2}$, were h^2 is the anisotropically rescaled relative distance from the point to the node; R^2 is the smoothing factor.

The local droughts are characteristic of the southern areas, while the widespread ones have been observed in the southern and south-eastern parts of the republic. According to the degree of intensity, mild and moderate droughts have been included (Fig. 2). The very widespread droughts cover a large territory of up to 50% of the area and are frequent in the southern, south-eastern and central parts of Moldova. In the above-mentioned territory droughts of severe intensity were manifested in the south of the republic, while in the rest of the area mostly droughts of a moderate and mild degree of intensity have been noticed. The catastrophic droughts cover the whole territory except the very north of the republic. A catastrophic drought was registered in 1994. During the spring of that year, the drought covered 87% of the territory of Moldova and was of a severe intensity degree and/or extreme intensity degree. In the summer, the development of the hydrothermal conditions in the area of drought affected 40% of the territory. The degree of the intensity was completely different from the other seasons, the greater part of the territory experienced mild and/or moderate drought and only a small part of the territory suffered from severe drought.

4 Conclusion

This study describes the dryness and drought episodes in Moldova from 18 weather stations and from Chisinau Observatory, with daily and monthly rainfalls and temperature measurements obtained during periods of 62 and 126 years, respectively. Four meteorological and agrometeorological indices are applied to ascertain a year or season as a drought period. Attempts are made to quantify the time evolution of these indices and the length and frequency of drought periods. The drought episodes are quite common; an accurate analysis of the spatial distribution of several indices of dryness and drought is extremely important for agriculture. This is particularly so in Moldova where the majority of the agricultural areas is situated in the zones with insufficient humidity conditions. This is because agriculture is highly sensitive to this phenomenon and it is the main branch of economy in many countries, especially those that are in economic transition. In the Republic of Moldova, for example, agriculture accounted for 24.5% of the national income and employed about half of the population in 2000.

The combined application of four indices, among them the well known SPI, is an interesting strategy, which can be used to determine if a particular season or year suffers from a dryness or drought event. In this study, we propose new criteria for the Si index, to be used together with the standardized precipitation index (SPI), which is well known around the world, plus CHT and P indices, which are already used in Moldova. The Si index exhibits significant advantages over the other indices by including the values of

Table 8 Estimation of the territories affected by drought in Moldova in the 1945–2006 period on the basis of data from 15 meteorological stations and 7 precipitation stations; "-" marks the absence of drought in that year

Years	Spring		Summer		Autumn	
	Surface affected, (%)	Type of droughts	Surface affected, (%)	Type of droughts	Surface affected, (%)	Type of droughts
1945	-	-	60	Catastrophic	40	Very widespread
1946	100	Catastrophic	33	Very widespread	-	-
1947	39	Very widespread	-	-	60	Catastrophic
1948	-	-	-	-	60	
1949	60	Catastrophic	-	-	20	Widespread
1950	33	Very widespread	-	-	20	Widespread
1951	60	Catastrophic	40	Very widespread	-	-
1952	20	Widespread	20	Very widespread	-	-
1953	-	-	40	Very widespread	60	Catastrophic
1954	-	-	73	Catastrophic	25	Widespread
1956	7	Local	13	Widespread	20	Widespread
1957	7	lLcal	27	Widespread	-	-
1958	13	Widespread	-	-	-	-
1959	-	-	13	Widespread	13	Widespread
1960	-	-	53	Catastrophic	13	Widespread
1961	-	-	27	Widespread	47	Very widespread
1962	-	-	20	Widespread	40	Very widespread
1963	40	Very widespread	7	Local	93	Catastrophic
1964	13	Widespread	7	Local	7	Local
1965	-	-	47	Very widespread	80	Catastrophic
1966	47	Very widespread	7	Local	60	Catastrophic
1967	60	Catastrophic	40	Very widespread	93	Catastrophic
1968	93	Catastrophic	7	Local	-	-
1969	7	Local	47	Very widespread	73	Catastrophic
1970	-	-	-	-	93	Catastrophic
1971	26	Widespread	20	Widespread	-	-
1973	20	Widespread	53	Catastrophic	87	Catastrophic
1975	-	-	7	Local	87	Catastrophic
1976	27	Widespread	20	Widespread	7	Local
1981	7	Local	53	Catastrophic	-	-
1982	60	Catastrophic	-	-	93	Catastrophic
1983	20	Widespread	13	Widespread	93	Catastrophic
1985	27	Widespread	-	-	73	Catastrophic
1986	100	Catastrophic	13	Widespread	100	Catastrophic
1987	13	Widespread	7	Local	40	Very widespread
1989	40	Very widespread	-	-	-	-
1990	7	Local	67	Catastrophic	60	Catastrophic
1992	27	Widespread	60	Catastrophic	40	Very widespread
1993	-	-	26	Widespread	7	Local
1994	87	Catastrophic	40	Very widespread	100	Catastrophic
1995	13	Widespread	26	Widespread	-	-
1996	13	Widespread	40	Very widespread	-	-
2000	90	Catastrophic	19	Widespread	70	Catastrophic
2003	10	Local	100	Catastrophic	-	-

temperatures and precipitation in the form of normalized observations, thus permitting the objective comparison of the trends displayed by various observation stations during different months. Although it seems that in the majority of cases Si responds similarly to the SPI and the CHT, it is concluded that the Si (just as SPI) is more sensitive and suitable in cases where the environment is changing.

The index PWP (with precipitation less then 0.1 mm/day) and Walter-Lieth climograms were used for the determination of the dry spell distribution in Moldova. The climogram method has permitted a study of the monthly length of the dryness and drought episodes across the country.

The register of the droughts for spring, summer and autumn have been identified and elaborated. We are proposing a new

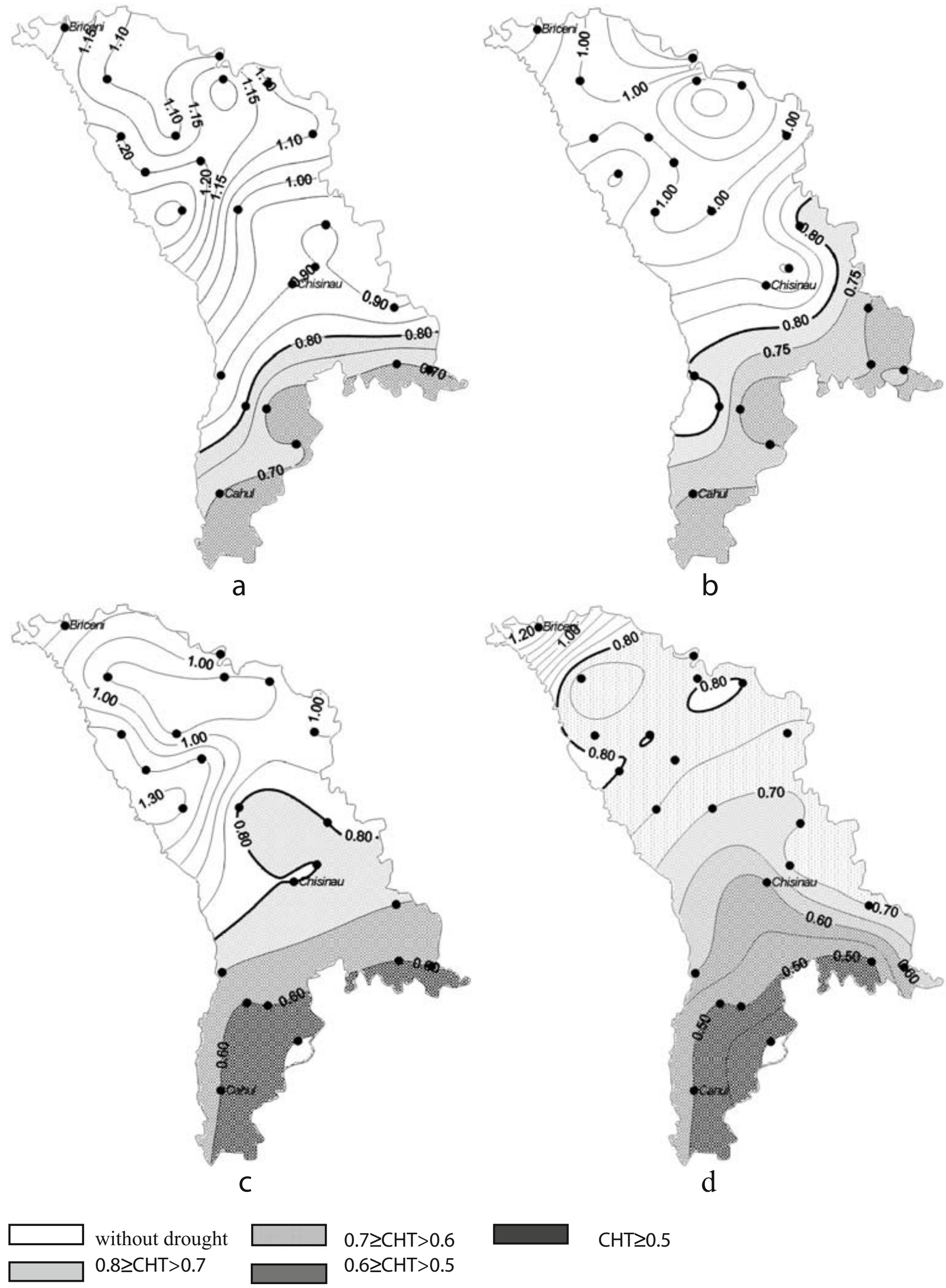

Fig. 2 Areas affected with local drought (**a**), widespread drought (**b**), very widespread drought (**c**) and catastrophic drought (**d**). The *points* on the maps represent meteorological stations (including 15 meteorological stations and 7 precipitation stations). The 0.80 isoline demonstrates the limit of the extent of drought by the radial basis function spatial interpolation. The *white colour* indicates the territory without drought events

methodology for the creation of the register of droughts. It is a known fact that a single index on its own is not able to identify all the drought years in a given region. Thereby it is recommended to evaluate a complex of several indices which complement one another; in this way, for instance, a combination of several indices will determine severity drought.

An analysis of extreme drought events shows the CHT provides a better spatial distribution than the SPI and Si. By contrast, SPI is the best informative index in identification of mild and moderate droughts for all seasons. On the other hand, the Si and P are better indices for identification of severe magnitude droughts. However, the P index is less informative in the determination of summer drought, because in Moldova the amount of the monthly precipitations is not distributed uniformly.

In Moldova, we have reported a general increase in the severity of droughts. This increase is reflected by the progressive decrease in the value of P, CHT and also SPI. The linear trend of drought expressed by the indices P (with significant p=0.02) and CHT (p=0.05) have a negative trend. It must be noted that the negative value of SPI (p=0.05) and the positive value of Si (p=0.036) have increased. As a result of the analysis of drought catalogue for a period of over 100 years, an increase in the tendencies of frequency and intensities of the studied phenomena after the 1980s was discovered. The longest drought periods were noticed at the beginning of the 1950s–1960s, reaching their highest points in the decades of 1981–1990 and 1991–2001 with the lowest points in the 1970s. Similarly, during the last 20 years, in 11 cases (1986, 1990, 1992, 1994, 1996, 1998, 2000, 2002, 2003, 2005, 2006) of drought, nine were registered as being of a severe intensity degree and/or extreme intensity degree. In 1990, 1992, 2003, a drought season occurred during the entire vegetation period.

Such climatic features such as dryness and drought are regional particularities caused to a certain extent by the physical-geographical position of the country and consequences of the warming of the global climate. If we compare data for the whole period of more than a century, we will see that droughts have occurred once every 3 years, and, after the 1980s, their frequency has already increased to once every 2 years.

The spatial distribution of droughts was analysed using CHT, confirming previous features of the regions affected by drought. This coefficient is the most sensitive index that can be used in the identification of a drought event at regional scale. As a summary of the resulting drought classification by the territory covered, we could say that it is typical for the territory of Moldova to pass through very widespread (31–50%) or catastrophic droughts (over 50%) during the spring seasons; while in the summer season the widespread (11–30%) and very widespread droughts are more frequent. However, during the autumn season, the very widespread and catastrophic droughts have an important frequency, covering almost the whole territory of Moldova.

It has been noticed that over 35% of the area belongs to the high-risk region (in the south and south-west of the country), where moderate droughts occur once every 3 years. Interestingly, most regions predisposed to drought are located in the principal agricultural production areas used for cereal crops.

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