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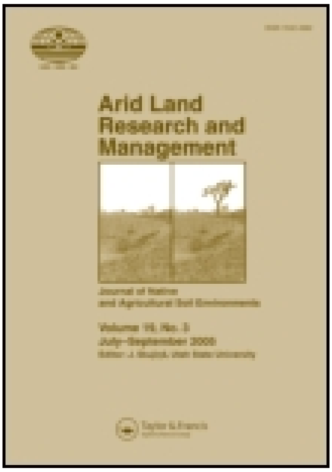

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Aridity Variability in the Last Five Decades in the Dobrogea Region, Romania

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Aridity Variability in the Last Five Decades in the Dobrogea Region, Romania

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The present study constitutes a climatic approach of aridity trend analysis in the south-eastern part of Romania (Dobrogea region), over the past five decades. The analysis is based on a series of investigations on the temporal trends of certain climatic parameters that play a key role in a territory's climatic variability, such as temperature, precipitation, and potential evapotranspiration. In this respect, a series of aridity index trends (De Martonne Index, UNEP Index, and Water Deficit Index), recorded between 1961 and 2009, was analyzed, using climatic parameters provided by eight weather stations in the Dobrogea region. While the results showed that the last five decades were generally characterized by an upward climatic aridity trend (increasing temperatures and potential evapotranspiration in all considered instances), there are certain regional differences due to precipitation regime variations (higher rainfall values were recorded at four weather stations). In terms of maximum aridity conditions, the study reveals that the most critical aridity index values were reported in 1990, 2000, 2001, 2003, and 2008, especially at the weather stations located in the northern part of the Dobrogea region. The situation is slightly different in the central-southern part, where the results indicated an aridity trend decline coupled with an increase of annual precipitation amounts, especially between 1995 and 2009.

Keywords aridity, aridity indices, climatic parameters, Dobrogea, variability

Introduction

Global climate change is now a fact endorsed by most scientists, and a phenomenon that is affecting extensive areas at a global scale. It is estimated that approximately 35% (around 50 million km^2) of the globe's land surface is affected by arid and semi-arid climate conditions (Ziadat et al., 2012). These conditions have been amplified over the course of the past century by major large scale climatic changes. Over the past 150 years, the mean global temperature, which is a primary index for climatic changes (Nasef, 2012), increased by almost 0.8°C compared to the preindustrial era. However, the phenomenon was accelerated over the past four

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decades at an estimated average decadal rate of 0.16°C (Solomon et al., 2010). The anthropic causes are mainly linked to fossil fuel burning and large scale deforestations (Houghton et al., 2001), which led to a CO_2 concentration increase from approximately 280 ppm in 1800 to 369 ppm in 2000 (Crueger et al., 2008).

According to the IPCC Fourth Assessment Report (chapter 11), the scenarios regarding climatic changes indicate a high probability that the entire globe will be affected by climate warming by the end of the twenty-first century (temperature increases coupled with precipitation decline), with certain regional rainfall regime variations.

While annual mean temperature rises will occur on all continents and islands, the scenarios also predict annual precipitation amount increases at a continental level. The most representative examples are northern Europe, eastern Africa, northern North America (Canada), southern South America (southern Argentina), and certain Asian regions (areas from the north, east, and south-east) (IPCC, 2007). In the other regions, extensive areas will be affected by significant rainfall decreases; however, there are regions for which no clear trends could be estimated.

The negative effects of climate change have become increasingly apparent over recent decades, and currently have a significant impact on both natural and anthropic systems (Vespremeanu-Stroe and Tătui, 2011; Abbaspour et al., 2012; Chuai et al., 2012; Croitoru et al., 2013a; Peptenatu, Sîrodoev, and Prăvălie, 2013; Nandintsetseg and Shinoda, 2014; Nazaripour and Mansouri Daneshvar, 2014; Scasta and Rector, 2014). At planetary scale, some of the most important consequences of global warming are the so-called tipping elements, which generate accelerated long-term negative effects. Relevant examples include decreased reflectance of solar radiation due to glacier melting and methane release associated with permafrost melting (both accelerating global warming). The Arctic is among Earth's most vulnerable regions, when considering these positive feedback type mechanisms (Nilsson et al., 2010; Steffen et al., 2011; Carstensen and Weydmann, 2012; Lenton, 2012; Wadhams, 2012).

The European region is presently facing an apparent mean annual temperatures rise, as well as a decrease of annual rainfall quantities especially in the central, eastern and southern parts of the continent, of which the Mediterranean area is the most heavily affected (García-Ruiz et al., 2011). Therefore, different studies based on the temporal analysis of drought and aridity indices found that Europe's southern region recorded an increase in climatic aridity over recent decades (Vicente-Serrano et al., 2004; Piccarreta, Capolongo, and Boenzi, 2004; Livada and Assimakopoulos, 2007; Sousa et al., 2011). Moreover, upward trends of climate aridity due to lower rainfall rates and rising temperatures (and, implicitly, to rising potential evapotranspiration) were also observed in other European areas: in the east and southeast (Lloyd-Hughes and Saunders, 2002; Paltineanu et al., 2007a; Koleva and Alexandrov, 2008; Croitoru, et al., 2013a).

It is estimated that, by the end of the twenty-first century, it is likely that climate aridity and the expansion of dry and arid lands will intensify especially in the Mediterranean region (principally in the central and southern areas of the Iberian, Italian, Hellenic, and Turkish peninsulas, in north Africa and the islands of Corsica, Sardinia and Sicily), but also in the adjacent regions, including the central southeastern part of Europe, where Romania is located (Gao and Giorgi, 2008).

Romania is one of the states that were affected by global warming and in which the general temperature increase and rainfall rate decrease augmented most notably throughout the twentieth century (García-Ruiz et al., 2011). Dobrogea is currently one of Romania's regions most heavily affected by climatic aridity (Paltineanu et al., 2007a; 2007b; Croitoru et al., 2013b), in addition to other representative sectors such as Bărăgan (the eastern part of the Romanian Plain) (Paltineanu et al., 2009) and southern Oltenia (the western part of the Romanian Plain) (Prăvălie, 2013; Prăvălie, Peptenatu, and Sîrodoev, 2013).

The purpose of the present study is to identify the temporal characteristics of climatic aridity trends in Dobrogea region over the past five decades by using representative aridity indices. As opposed to previous studies on aridity trends in this region and in other areas outside the Romanian Carpathians (Croitoru et al., 2013b), this study focuses on a detailed interannual analysis of climate aridity characteristics (while highlighting critical oscillations of semi-arid and arid years), using three representative indices: De Martonne index, UNEP index, and Water Deficit Index. At the same time, the study entails a systemic approach based on the statistical analysis of the interannual oscillations revealed by the aforementioned aridity indices between 1961 and 2009.

Study Area and Its Climatic Aridity Characteristics

The study area, the Dobrogea region, covers 15570 km^2 (Posea, Bugă, and Dobre 2005) and has the following boundaries: the Danube to the west and north, the Black Sea to the east, and the Bulgarian border to the south (Figure 1). It is known to be the region with the most visible climatic aridity traits in the country, due to certain specific peculiarities such as the highest temperatures (the 11°C annual isotherm, except for the northern high lands) and the lowest precipitation amounts countrywide. According to the data provided by the eight weather stations for the 1961–2009 period, average multiannual temperatures range from 10.8°C to 11.8°C, while the average multiannual precipitation values fall between 257.5 and 535 mm (Table 1).

One of the main causes of climatic aridity is the high influence of Eurasian continental anticyclones, which generate a rainfall deficit and warm dry air masses during the summer (Bogdan, 2005). Another major cause is linked to the thermal barrier role the Black Sea plays, due to the thermal inversion phenomena caused by evaporation processes that determine descending airflows which cause cloud system dissipation in the coastal area (Bogdan, 1989). Other important causes are related to the location of the study area at the extremity of oceanic influences on Romanian territory (potential sources of precipitation), but also to local wind peculiarities, characterized by high intensity (especially in the north), which are responsible for local aridity, drought and dryness phenomena (Bogdan, 2005). At the same time, considering that wind is largely responsible for the evapotranspiration process (Bandoc and Golumbeanu, 2010; Bandoc, 2012), its intensity, generally high throughout the year, causes a significant acceleration of the process, thus leading to an escalating climatic aridity in the Dobrogea region.

According to the Global Aridity Index (or UNEP aridity index) (Trabucco and Zomer, 2009), a global scale high resolution spatial database (thirty arc seconds or ~1 km at the equator), the most arid regions in Romania are northern Dobrogea and the adjacent areas in the north-west and north-east (Figure 1b, c). This aridity index, developed by the Consortium for Spatial Information (CSI), part of the Consultative Group for International Agriculture Research (CGIAR), was estimated at global level based on the precipitation and potential evapotranspiration ratio (P/PET, resulting the UNEP aridity index), using spatial data of the two climatic parameters, computed as mean values between 1950 and 2000 (Trabucco and Zomer, 2009).

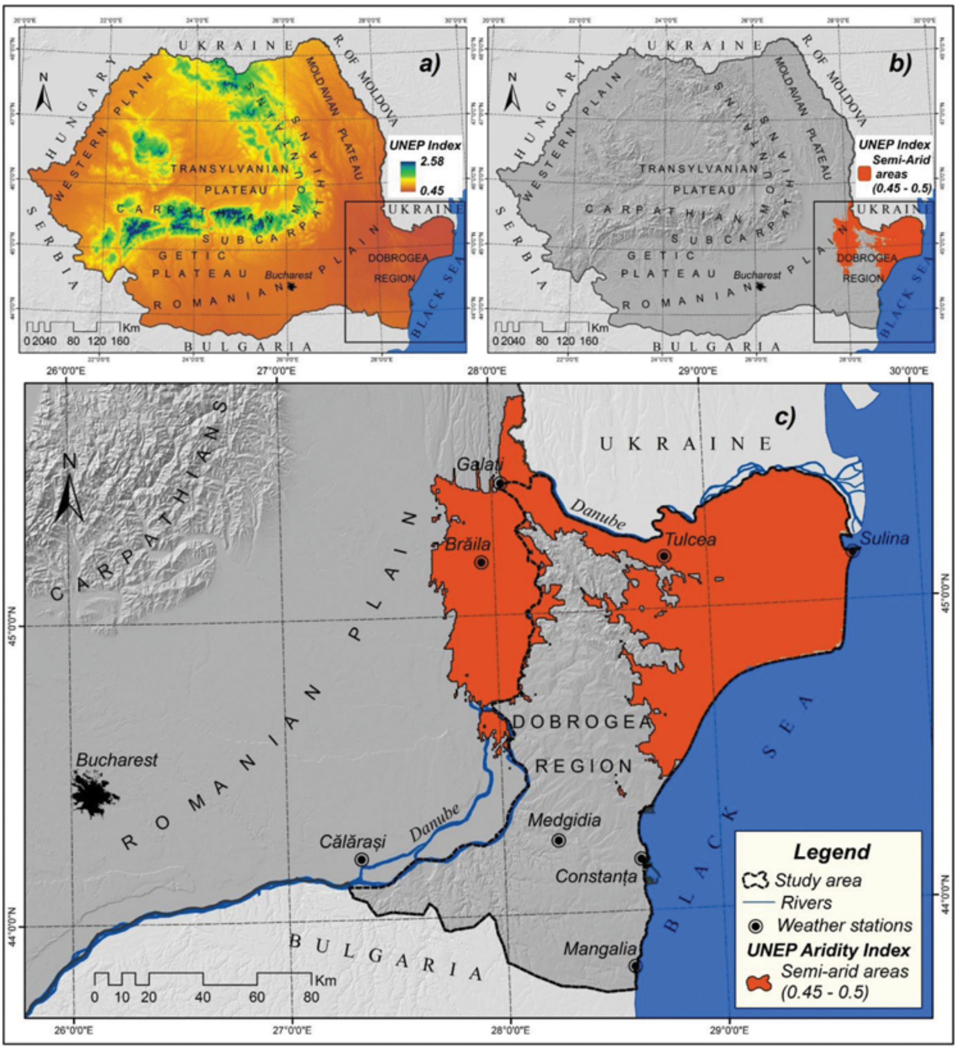


Figure 1. Location of the study area in Romania; spatial representation of the UNEP Aridity Index (mm/mm) in Romania (a) and semi-arid areas in northern Dobrogea and adjacent territories (b, c) (data processed after Trabucco and Zomer, 2009).

According to the spatialized values of the UNEP aridity index, Dobrogea is the region with the highest aridity degree in Romania, as the values of this aridity index fall in the 0.2–0.5 (mm/mm) interval, which indicates a semi-arid climate (as in Romania the minimum values reach 0.45 mm/mm, semi-arid areas are located between 0.45 and 0.5 mm/mm).

Materials and Methods

In order to quantify the climatic aridity trends, climatic data series provided by eight weather stations were analyzed for the 1961–2009 period. The available data consisted of temperature and precipitation recordings from Brăila, Galaţi, Tulcea, and Sulina weather stations—relevant to the northern parts of Dobrogea—as well

Table 1. Geographic coordinates and mean multiannual temperatures and rainfall values (1961–2009) at the eight weather stations (geographic coordinates after Croitoru et al., 2013b)

Meteorological stations	Latitude	Longitude	Altitude (m)	Temperature (°C)	Rainfall (mm)
Galaţi	45°28′23″	28°01′56″	70.4	10.8	487.2
Brăila	45°12′24″	27°55′11″	15.0	10.8	449.1
Tulcea	45°11′26″	28°49′26″	5.0	11.2	460.5
Sulina	45°08′00″	29°45′00″	3.0	11.6	257.5
Călăraşi	44°12′52″	27°20′18″	19.9	11.8	535.0
Medgidia	44°14′35″	28°15′05″	70.7	11.2	452.9
Constanţa	44°12′49″	28°38′41″	13.0	11.8	424.0
Mangalia	43°48′58″	28°35′14″	7.2	11.6	425.9

as from Călăraşi, Medgidia, Constanţa and Mangalia, which covered the central-southern regions (Figure 1). Even though not all stations are located in the Dobrogea region (Brăila and Călăraşi weather stations), due to the fact that they are situated in its immediate vicinity, the information they provide is considered to be relevant for the study area. While the recordings are provided by ECA&D (European Climate Assessment and Dataset), in the case of the Brăila station the sources are Vişinescu et al. (2003) for the 1961–2002 period and the National Meteorology Administration (2012), for the years 2003–09. The National Meteorology Administration is also the data source for the Medgidia (1965–2000) and Mangalia (1965–2008) weather stations; the missing data were obtained through linear regression based on the shared data series with the Constanţa station (with an uninterrupted set of data), as all three stations are positioned in relatively similar geographical conditions).

The regression was applied to both temperature (*r* correlation coefficient values were very high, above 0.92) and precipitation (as this parameter is characterized by a greater variability, the *r* correlation coefficient values were lower especially during the summer season, and in certain cases they even went below 0.8). A linear regression data extension was also applied to the Călăraşi station recordings (due to the lack of data in the ECA&D database over recent years), but only for the 2006–09 period and only for temperature (the *r* correlation coefficient for the common period had particularly high values, close to 1).

In order to estimate potential evapotranspiration values, needed for obtaining two of the three aridity indices, the Thornthwaite methodology (Thornthwaite, 1948) was used, which is a typical method for Romanian territory (Paltineanu et al., 2007a). Therefore, the potential evapotranspiration was estimated using the following formula (The climate of Romania, 2008):

$$ETP = 16 * \left(\frac{10t}{I}\right)^{a} F(\lambda)$$

where: t is the average monthly temperature (°C); I is the annual thermal index computed using the formula $I = \sum_{n=1}^{12} \mathrm{i_n}, \mathrm{i_n} = \left(\frac{\mathrm{t}}{5}\right)^{1.514}$; $a = 6.75 * 10^{-7} * I^3 - 7.71 * 10^{-5} * I^2 + 1.79 * 10^{-2} * I + 0.49$; and $F(\lambda)$ is the adjustment factor depending on latitude and month of the year.

Annual temperature, precipitation, and potential evapotranspiration recordings were processed in order to obtain the following synthetic climatic aridity indices: De Martonne Index, UNEP, and Water Deficit Index. The De Martonne Index (*I ar-DM*) uses the temperature-precipitation relationship (De Martonne, 1926): $I\ ar\text{-}DM = P/(T + 10)$, where P and T are precipitation (mm) and temperatures (°C). The UNEP aridity index (*Iar-P/PET*), initially advanced in 1979 as the UNESCO index (resulting from the precipitation/potential evapotranspiration ratio computed with the Penman method) (UNESCO, 1979), was proposed in 1992 by the United Nations Environment Program. It is computed using the formula $Iar\text{-}P/\mathrm{PET} = P/\mathrm{PET}$, where P is the precipitation (mm) and PET the potential evapotranspiration (mm), obtained using Thornthwaite's methodology (UNEP, 1992).

The Water Deficit Index, computed as the subtraction between rainfall and potential evapotranspiration, synthetically emphasizes the atmospheric humidity balance and is a good indicator of a territory's climatic aridity (Bussay et al., 2012).

Finally, the statistical significance of the linear trends for all three aridity indices was verified by applying Mann-Kendall's statistical significance test (Salmi et al., 2002), one of the most widely used statistical tests for climatic data trend analysis (Shifteh Some'e, Ezani, and Tabari, 2012a).

In order to identify to what extent the values determined for the three indices (De Martonne, UNEP Index, and Water Deficit Index) exhibit disturbances with respect to their own values, the Durbin Watson test was applied.

The hypotheses usually considered in the Durbin–Watson test are: H_0: $\rho = 0$ (the errors are not autocorrelated) and H_1: $\rho \neq 0$ (the errors are autocorrelated), and ρ is the autocorrelation coefficient (Montgomery, Peck, and Vining, 2001). The test statistics is:

$$\mathrm{DW} = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^2},$$

where $e_i = y_i - \hat{y}_i$ and y_i and $\hat{y}_i$ are, respectively, the observed and predicted value of the response variable for individual i.

The theoretical values of the Durbin–Watson test are computed and tabulated according to significance thresholds, sample size and model parameter count. The tables determine two critical values: the lower (d_L) and upper (d_U) limits. Based on these critical values, the following intervals, which lead to the decision of either rejecting or accepting the null hypothesis, are determined: if $\mathrm{DW} < d_L$ reject H_0: $\rho = 0$; if $\mathrm{DW} > d_U$ do not reject H_0: $\rho = 0$; if $d_L < \mathrm{DW} < d_U$ $_U$ test is inconclusive.

Results and Discussion

Upon analysis of the results prompted by the three aridity indices, a significant variability of interannual climatic aridity was observed. The De Martonne aridity index values had significant oscillations over the analyzed period (1961–2009) - the most critical values were recorded at the Sulina meteorological station in 2003 (5.2 mm/°C), 2001 (6 mm/°C) and 2000 (6.1 mm/°C) (Figure 2d), and all of them correspond to the <10 mm/°C interval, which is associated to arid areas, according to De Martonne's classification (De Martonne, 1926).

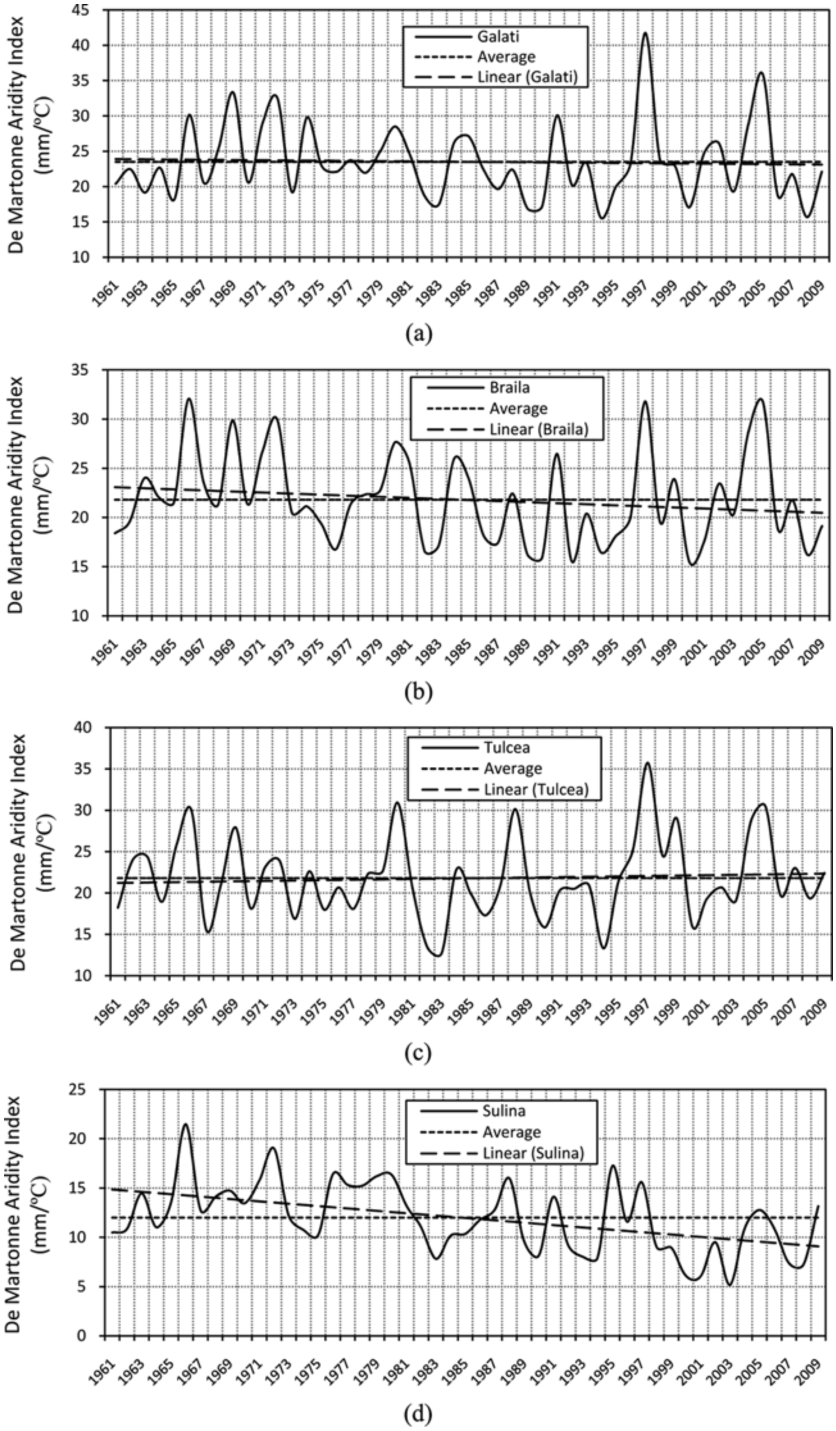


Figure 2. Interannual variation of the De Martonne aridity index at Galaţi (a), Brăila (b), Tulcea (c), Sulina (d), Călăraşi (e), Medgidia (f), Constanţa (g), and Mangalia (h) weather stations.

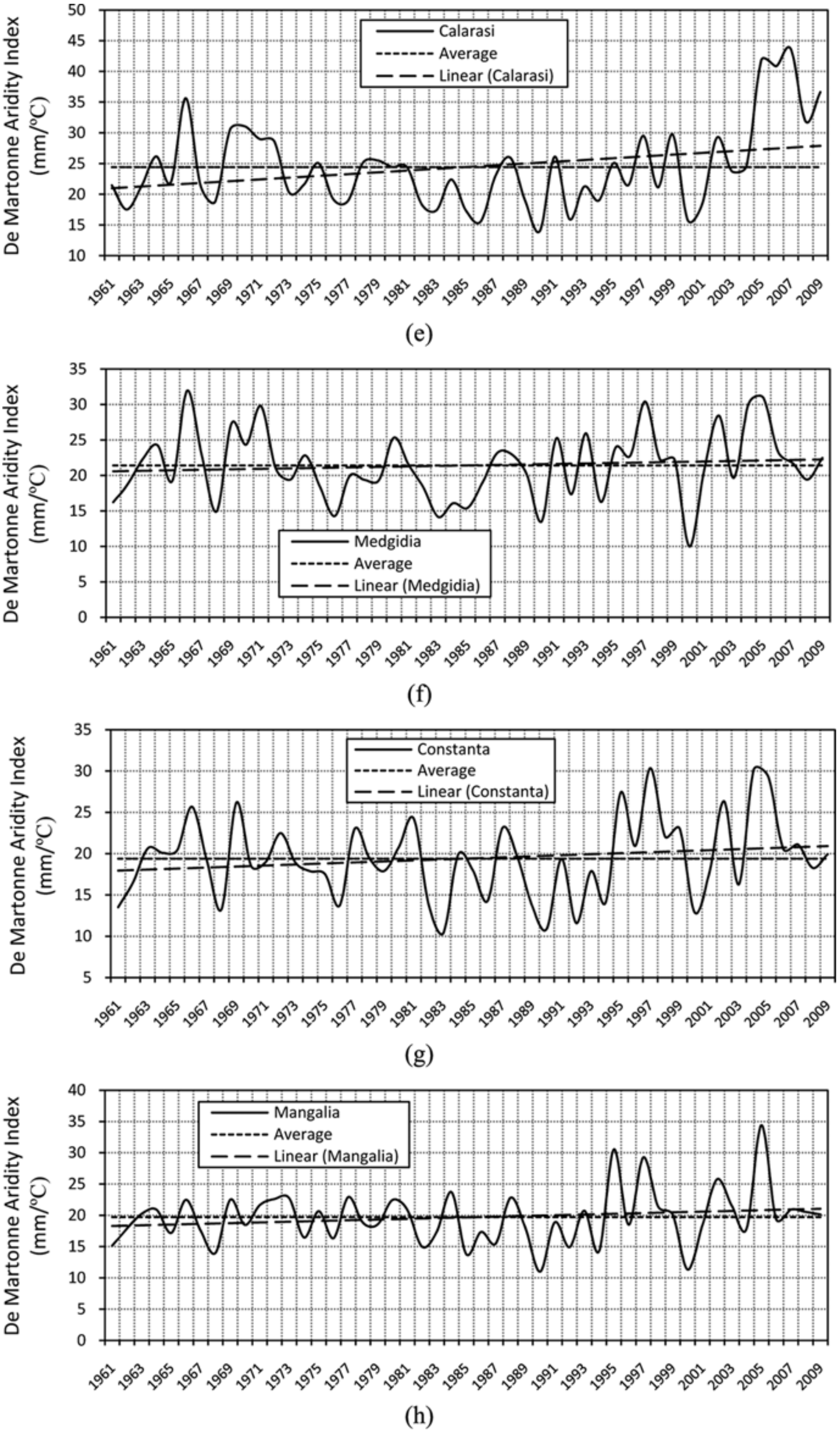


Figure 2. Continued.

It is noteworthy to point out that, in the analyzed period, there are 11 years with values under the mentioned threshold (between 1983 and 2008), which stands out when compared to the other analyzed stations. In fact, it is the only station where such values were recorded, and they result in the most marked De Martonne index downward trend out of the eight stations (Figure 2d).

Sulina is the only station where the mean value of the De Martonne's index between 1961 and 2009 (12 mm/°C) corresponds to the 10–15 interval (semi-arid interval), which not only confirms interannual oscillations, but also the stability of a local climate with semi-arid features (the Danube Delta region).

While similar decreasing trends in De Martonne index values can also be seen at the Brăila and Galaţi stations, they are less obvious (Figure 2a, b), and the critical index values correspond to the 15–20 mm/°C interval, which indicates a dry steppe climate. Semi-arid interval values (10–15 mm/°C) were also frequently recorded at the weather stations located in Tulcea (in the years 1982, 1983, and 1994), Călăraşi (1990), Medgidia (1968, 1976, 1983, 1990, and 2000), Constanţa (over a ten-year period, with the most critical values of 10.4 mm/°C in 1983 and 10.9 mm/°C in 1990) and Mangalia (six years, with the most critical values of 11 mm/°C in 1990 and 11.3 mm/°C in 2000) (Figure 2c, e–h). A slight increasing trend can be noticed in the data provided by these stations, of which the most easily noticeable is the one in Călăraşi. This is due to annual rainfall amounts intensification, especially over the last decade, even though upward mean annual temperature trends were found in all eight data sets.

The UNEP aridity index also has important oscillations for the 1961–2009 period, but with certain significant peculiarities for each weather station. The most critical values were observed at the Sulina weather station, with maximum values recorded in 2003 (0.16 mm/mm), 2001 (0.18 mm/mm), and 2000 (0.19 mm/mm) (Figure 3d): according to UNEP's classification (UNEP, 1992), these years correspond to the arid interval (0.05–0.2 mm/mm).

For the same station, 77.5% (38 years) of the entire data set had oscillations that correspond to the 0.2–0.5 mm/mm interval, associated to a semi-arid climate. Therefore, for Sulina as well, a stability of the semi-arid climate can be observed; this station also represents the distinctive case in which the mean value of the UNEP index in the 1961–2009 period (0.4 mm/mm) corresponds to the 0.2–0.5 mm/mm interval.

While the same decreasing trends of the UNEP index which appeared at Sulina were found at the Galaţi and Braila weather stations, the trend slope is less obvious in these two cases (Figure 3a, b, Table 2). In these instances, although the mean multiannual UNEP index does not fall within the semi-arid interval (0.7 mm/mm at both stations), there are certain interannual values with significant oscillations that indicate a semi-arid climate (1994 and 2008, with 0.48 mm/mm in Galaţi; and 1990, 1992, and 2000 with values of 0.49 mm/mm, 0.48 mm/mm, and 0.47 mm/mm, respectively, in Brăila).

Whereas trend analyses for Tulcea, Călăraşi, Medgidia, Constanţa and Mangalia generally reveal upward trends (Călăraşi had the highest trend slope) (Figure 3c, e–h, Table 2), even in these instances there are certain pronounced interannual oscillations (between 0.2–0.5 mm/mm), with semi-arid characteristics (1967, 1982, 1983, and 1994 for the Tulcea station; 1986, 1990, 1992, and 2000 for the Călărasi station; 1968, 1976, 1983, 1985, 1990, and 2000 for the Medgidia station; a total of 11 years for the Constanţa station; and a total of nine years for the Mangalia station).

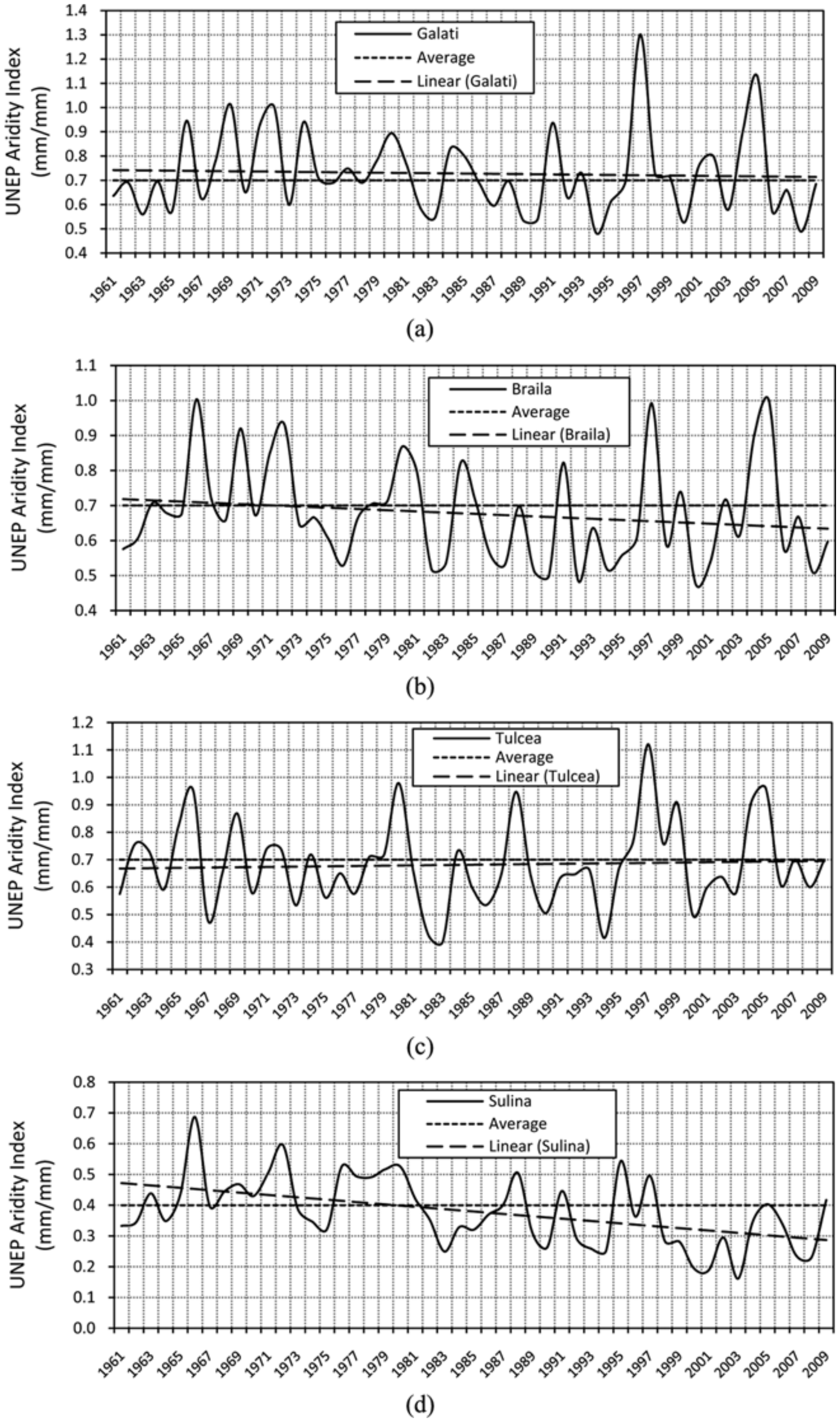
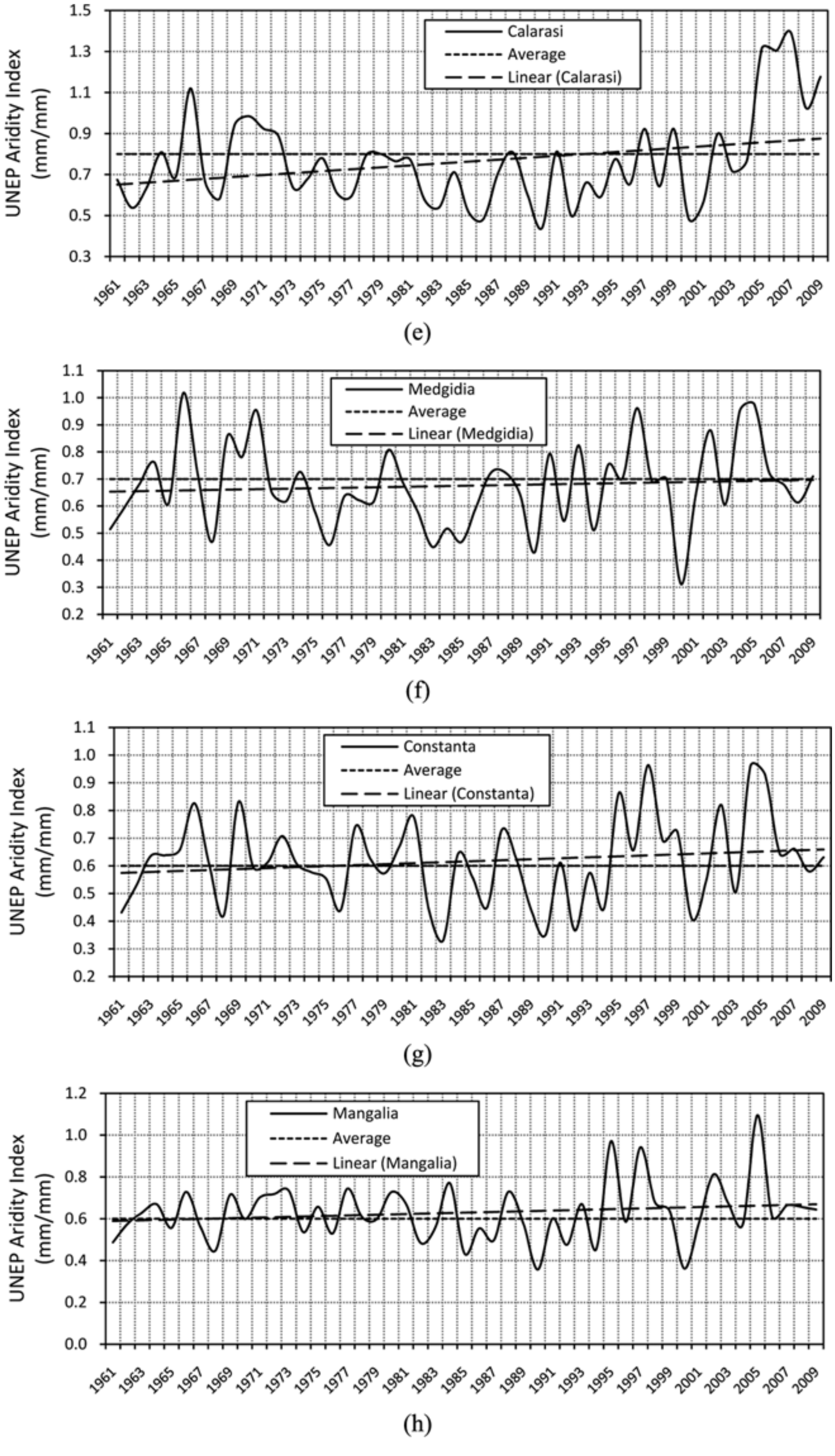


Figure 3. Interannual variation of the UNEP aridity index at Galaţi (a), Brăila (b), Tulcea (c), Sulina (d), Călărasi (e), Medgidia (f), Constanţa (g), and Mangalia (h) weather stations.



(e)

(f)

(g)

(h)

Figure 3. Continued.

Table 2. Annual trend characteristics (resulting from the Mann-Kendall test and Sen's slope method) of the three aridity indices, and of temperature, precipitation, and potential evapotranspiration (PET) at Galaţi (G), Brăila (B), Tulcea (T), Sulina (S), Călăraşi (Cl), Medgidia (Me), Constanţa (Ct), and Mangalia (Ma) weather stations (WS)

	De Martonne Index		UNEP Index		WDI		Temperature		PET		Rainfall	
WS	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope
G	−0.63	−0.032	−0.75	−0.001	−0.99	−1.002	2.85^{**}	0.027	3.23^{**}	1.01	−0.09	−0.161
B	−1.53	−0.062	−1.53	−0.002	-1.80^{+}	−1.739	2.1^{*}	0.019	2.58^{**}	0.703	−0.95	−0.822
T	0.16	0.009	0.04	0.000	−0.04	−0.056	2.28^{*}	0.015	3.04^{**}	0.637	0.53	0.568
S	-3.32^{***}	−0.121	-3.32^{***}	−0.004	-3.37^{***}	−3.216	2.24^{*}	0.02	2.58^{**}	0.701	-3.15^{**}	−2.322
Cl	1.15	0.078	1.03	0.002	0.82	1.670	3.40^{***}	0.025	3.09^{**}	0.675	1.47	2.212
Me	0.80	0.035	0.70	0.001	0.35	0.381	2.63^{**}	0.024	3.09^{**}	0.895	1.42	1.441
Ct	0.97	0.039	0.87	0.001	0.39	0.471	3.25^{**}	0.025	3.61^{***}	1.037	1.42	1.433
Ma	0.85	0.034	0.73	0.001	0.44	0.334	2.79^{**}	0.023	3.30^{***}	0.859	1.22	1.082

Note: "+," "*," "**," and "***" indicate significance at $\alpha = 0.1$, 0.05, 0.01, and 0.001 level, respectively; the values without these symbols indicate lack of statistical significance.

The Water Deficit Index, another synthetic indicator of climatic aridity, shows noticeable interannual variations, similarly to the other two analyzed aridity indices. In this third instance as well, the critical values were recorded at the Sulina station, where the climatic water deficit (or Water Deficit Index) reached extremely high values of −573.1, −579.8 and −568.9 mm in 2000, 2001, and 2003, respectively (Figure 4d). Although this index can be computed in a fairly simple manner and can, at the same time, be particularly suggestive for climatic water balance assessments, it generally does not have a clear scale of climatic classification. However, considering that the same years (2000, 2001, and 2003) were characterized as climatically arid by the De Martonne and UNEP aridity indices, an approximate delimitation of an arid climate for values lower than −550 mm can be estimated by extrapolation.

Using the aforementioned principle, for this index, a delimitation of a semi-arid interval for values lower than −350 mm s (approximately) can be advanced, which corresponds to the −350 mm– (−550) mm interval. Thus, 75% (37- years) of the total of 49 analyzed years at the Sulina station correspond to this interval (Figure 4d). Similar to the previous case, Galaţi, Brăila, and Tulcea also had downward trends, with the lowest values (correspond to the semi-arid interval) observed in 1994 (−373.8 mm) and 2008 (−368.8 mm) (Figure 4a); 1990 (−351.5 mm) and 2000 (−372.6 mm) (Figure 4b); and 1983 (−408 mm) and 1994 (−420.6 mm), respectively (Figure 4c).

Călăraşi, Medgidia, Constanţa, and Mangalia stations are characterized by slightly increasing trends (therefore, climatic water deficit decrease), with a trend slope maximum value recorded at the Călăraşi station (Figure 4e, Table 2). However, at the same stations, semi-arid oscillations were found as well: the most representative examples are 1990 and 2000 (at the Călăraşi, Medgidia, and Mangalia), and 1983 and 1990 (Constanţa station) (Figure 4c, e–h).

With regard to the analysis of trends and their statistical significance, the results show certain particularities from one case to another. Before applying the Mann-Kendall method, the Durbin-Watson test was applied in order to detect data series autocorrelation. For a 0.05 significance level, for a total of 49 analyzed values and one regressor as $dL = 1.50$ and $dU = 1.59$, results showed that autocorrelation was not confirmed at any of the eight stations (neither by the three aridity indices, nor by the individual analysis of climatic parameters, namely temperature, precipitation and potential evapotranspiration). Therefore, given that no serial correlation instances were found, applying correction methods such as Trend Free Pre-Whitening (Shifteh Some'e, Ezani, and Tabari, 2012b; Abghari, Tabari, and Hosseinzadeh Talaee, 2013; Tabari and Hosseinzadah Talaee, 2013) was no longer deemed necessary.

The statistical significance analysis of the linear trends of all three aridity indices using the Mann-Kendall statistical test revealed that the trends are statistically significant only for Sulina (with a high statistical significance threshold, $\alpha = 0.001$, for all three aridity indices) and Brăila (only for the Water Deficit Index, and with a lower statistical significance threshold of $\alpha = 0.1$) (Table 2). In terms of trend magnitude, the results obtained through the Sen's slope method showed high, statistically significant values for these two stations. Considering the Water Deficit Index (as it is easier to interpret), it can be noticed that its values increased by −3.2 mm/year at Sulina station and by −1.7 mm/year at Brăila station, while throughout the entire period WDI increasing rates reached −157.6 mm per 49 years (Sulina) and

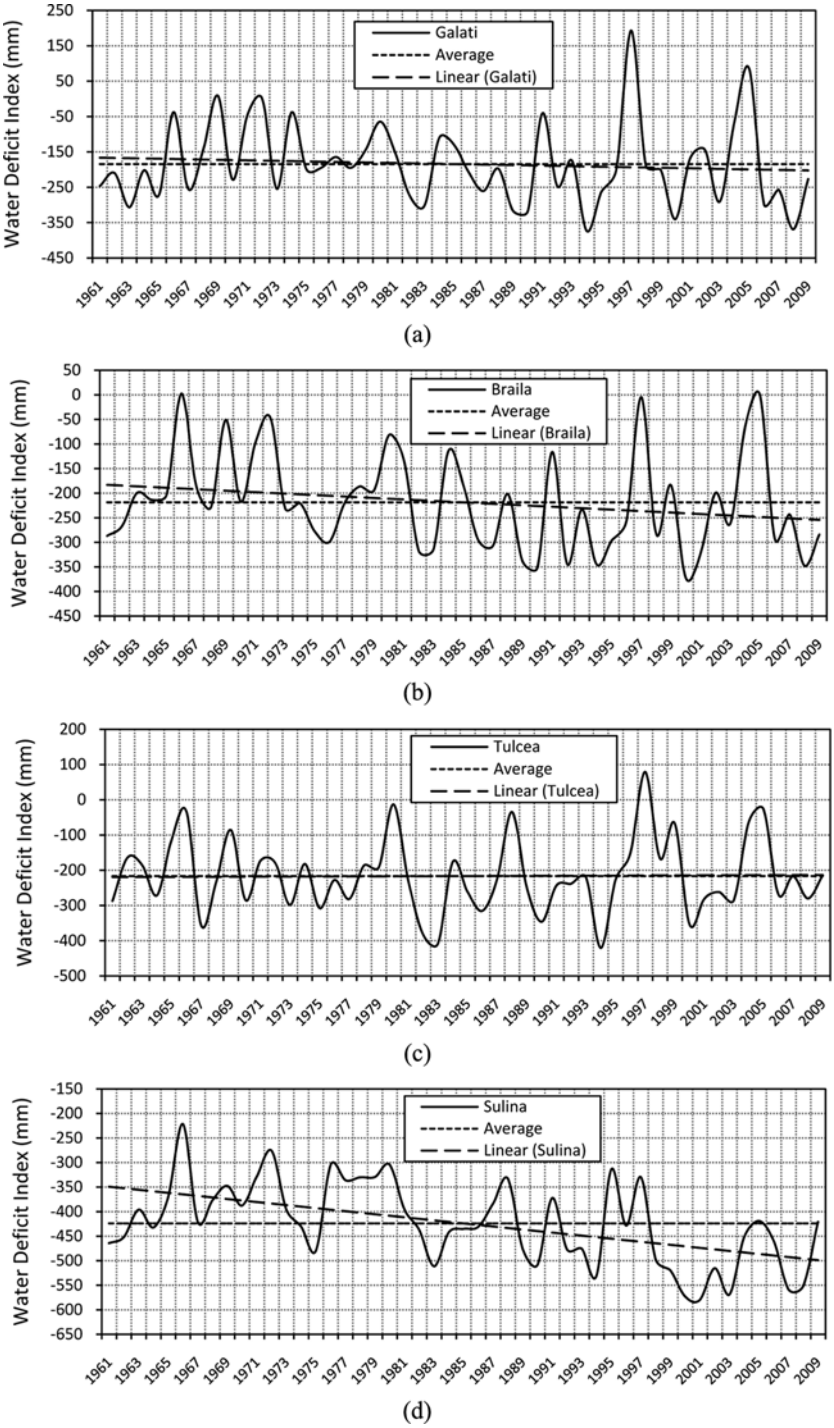
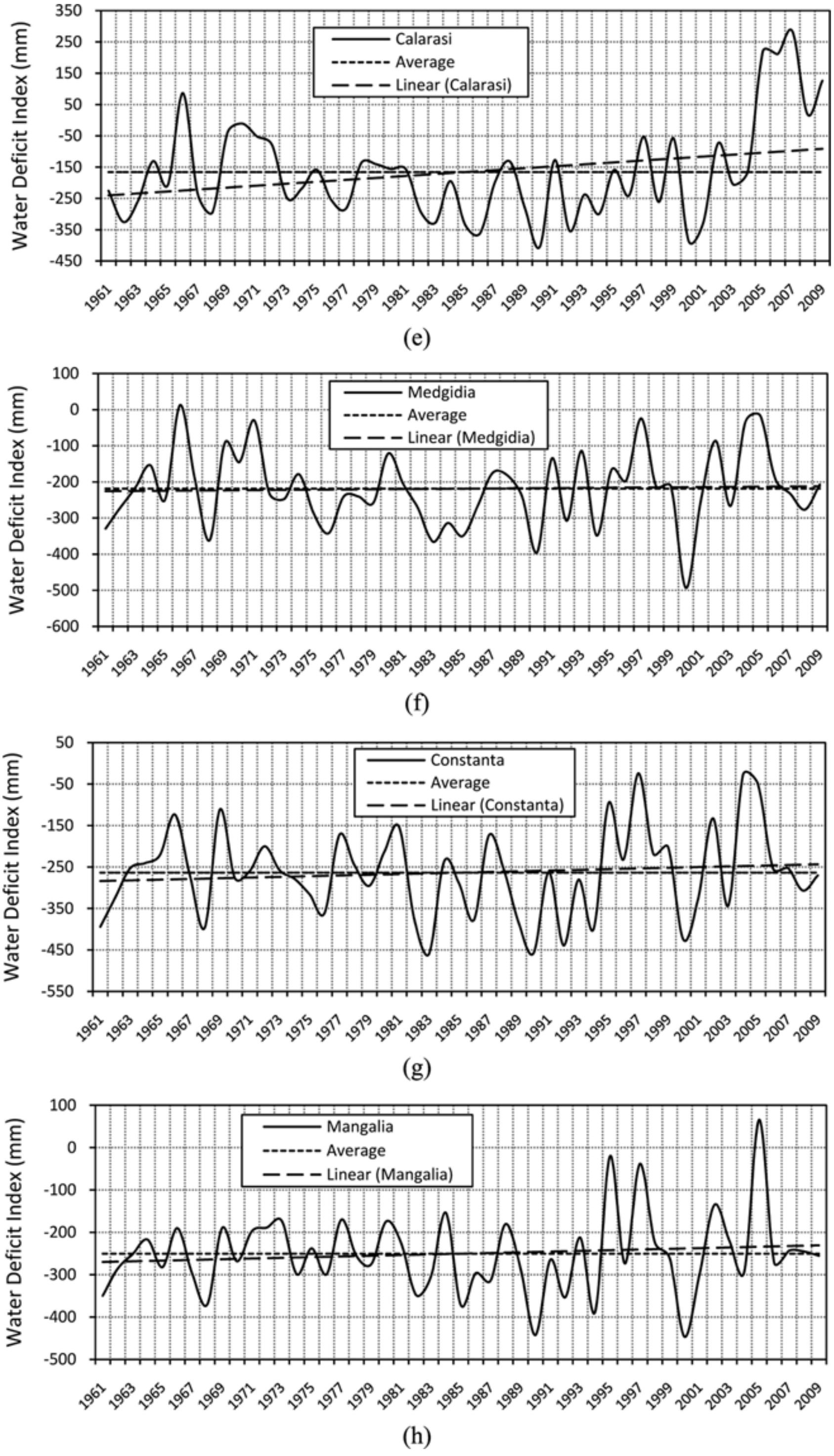


Figure 4. Interannual variation of the Water Deficit Index values at Galaţi (a), Brăila (b), Tulcea (c), Sulina (d), Călărasi (e), Medgidia (f), Constanţa (g), and Mangalia (h) weather stations.



(e)

(f)

(g)

(h)

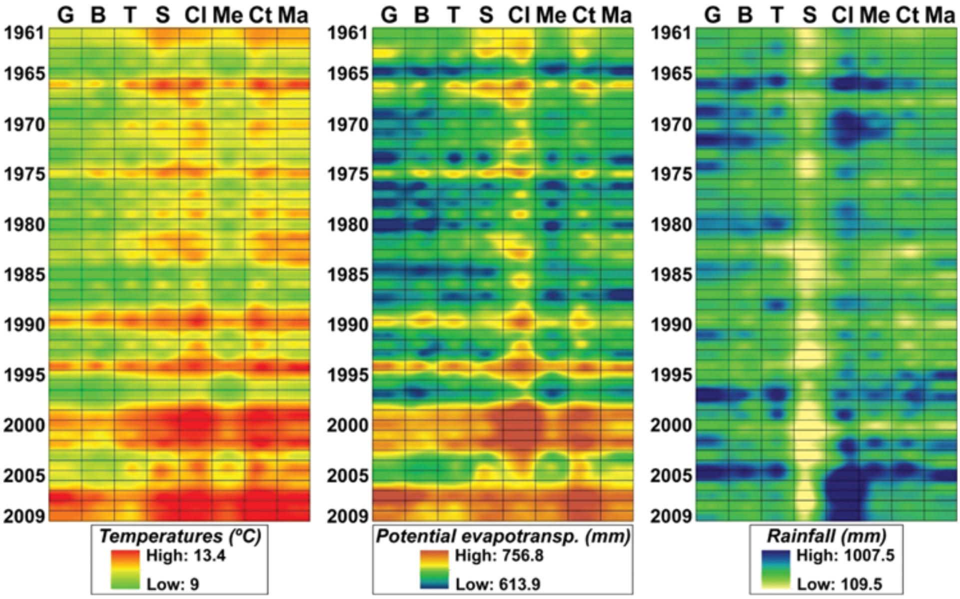
Figure 4. Continued.

−85.2 mm per 49 years (Brăila). Statistically, the trends are not significant for the other weather stations (Table 2). It is important to underline that such a situation is due to changes (increases) in the rainfall regime (in most cases, but with lack of statistical significance) (Table 2), which mainly occurred over the last decade (although, before the year 2000, the annual rainfall amounts decreased at most of the eight weather stations) (Figure 5c), which determined an attenuation of aridity index trends.

However, it is noteworthy that a separate analysis of climatic parameters used in the aridity indices calculation showed that the mean annual temperature had statistically significant increasing trends at all stations (Figure 5a, Table 2). Therefore, Sen's slope values recorded at the eight weather stations indicate a variation of positive rates ranging from 0.015 to 0.027°C (with a peak value recorded at the Galaţi station) when considering the annual warming rate (Table 2), or from 0.7 to 1.3°C, when considering the rate over 49 years. A similar situation can be noticed for potential evapotranspiration, a parameter which had statistically significant increasing trends at all stations (Figure 5b, Table 2). In this instance, increase rates (Sen's slope) fall between 0.6–1 mm/year (with a peak value at Constanţa), or between 31.2–50.8 mm per 49 years.

With regard to precipitation, as trends lack statistical significance (except for Sulina station) (Table 2), its dynamics are uncertain. Thus, the potential evapotranspiration parameter, along with temperature, provides the premises of climatic aridity increases in Dobrogea region, at least from a thermal stress point of view.

This paper also presents a systemic approach based on a statistical analysis of interannual variability of aridity indices, computed for the 1961–2009 time frame, using specific indicators (Wilks, 1995) (Table 3).



(a) (b) (c)

Figure 5. Interannual variation of the mean annual temperatures (a) and annual potential evapotranspiration (b) and precipitation (c) amounts, at Galaţi (G), Brăila (B), Tulcea (T), Sulina (S), Călăraţi (Cl), Medgidia (Me), Constanţa (Ct), and Mangalia (Ma) weather stations.

Table 3. Descriptive statistics for De Martonne, UNEP and WDI aridity indices (in the 1961–2009 period), at Galaţi (G), Brăila (B), Tulcea (T), Sulina (S), Călăraşi (Cl), Medgidia (Me), Constanţa (Ct), and Mangalia (Ma) weather stations

	G	*B*	*T*	*S*	*Cl*	*Me*	*Ct*	*Ma*
Coefficient of Variation								
De Martonne index	0.23	0.21	0.23	0.30	0.28	0.23	0.25	4.43
UNEP index	0.23	0.21	0.23	0.30	0.29	0.23	0.25	0.22
Water Deficit Index	0.63	0.46	0.49	0.20	0.95	0.48	0.41	0.38
Skewness								
De Martonne index	1.12	0.71	0.61	0.30	1.06	0.19	0.32	0.89
UNEP index	1.15	0.77	0.65	0.32	1.10	0.22	0.34	0.88
Water Deficit Index	0.98	0.67	0.56	0.08	1.06	0.12	0.27	0.82
Kurtosis								
De Martonne index	1.67	−0.26	0.40	−0.12	0.91	0.05	−0.12	2.15
UNEP index	1.65	−0.21	0.43	−0.10	1.00	0.03	−0.10	2.07
Water Deficit Index	1.27	−0.32	0.33	−0.50	0.98	0.23	−0.13	2.16

The variation coefficient was computed in order to identify the data series homogeneity. The resulting values indicate that, for all the stations in the study area, the De Martonne and the UNEP aridity indices show high homogeneity, while in the case of the Water Deficit Index, homogeneity levels are lower.

The skewness was computed in order to identify empirical distribution deviation against a symmetrical distribution around the average value, in the analysis of the data series distribution for the De Martonne Index, UNEP Index, and the Water Deficit Index. The use of this statistical indicator leads to the conclusion that skewness values are positive for all stations, which means that aridity index values have a left pitch, a negative skewness where the mean value of the series is lower than the module. This indicates the presence of numerous right extreme values.

The kurtosis was computed in order to show the flattening degree of the aridity indices for the 1961–2009 period. Thus, the following cases can be identified: firstly, at Brăila, Sulina, and Constanţa, the aridity index distributions have a platykurtic configuration, which translates into a lower probability of having extreme values, as opposed to a normal distribution; secondly, at Galaţi, Tulcea, Călăraşi, Medgidia, and Mangalia, the aridity index distributions have a leptokurtic configuration, which implies a higher probability of having extreme values.

Therefore, the De Martonne and UNEP indices best characterize the aridity evolution in the study area, given the fact that the data series obtained by applying the calculation formulas are homogeneous and the average value is relevant for the entire analyzed period.

Thus, upon analysis of the interannual variations of all three aridity indices, significant semi-arid oscillations (arid oscillations as well, in certain cases) were noticed (1961–2009), with decidedly more pronounced values for the weather stations situated in the northern part of the analyzed area, therefore confirming the spatial variability of critical values (0.45–0.5 mm/mm) of the CGIAR aridity index (Figure 1b).

The identified semi-arid oscillations represent, above all, an important climatic restriction for the analyzed area, which is mainly characterized by intense thermal stress (with consequences on the intensification of the evapotranspiration process) with high and very high values of climatic water deficit. However, even if some of the precipitation amounts increase over the last two decades appeared most notably in the southern part of Dobrogea (oscillations that correspond to certain periods with intense cyclonic regime and active atmospheric fronts) (Tiscovschi et al., 2013), those amounts of precipitation did not have an interannual uniformity and the climatic water deficit was balanced to a considerable extent by an increasing potential of the evapotranspiration regime.

Therefore, the semi-arid oscillations determined an important impact upon some of the environmental components which are highly dependent on climatic variability. A relevant example can be found in the changes (decrease) of groundwater level in certain parts of Dobrogea region (Caraivan et al., 2011), as a result of the increasing potential evapotranspiration. This parameter is one of the climatic components that has the greatest influence on groundwater dynamics (Hübener et al., 2005). The relationship between these two environmental variables can be considered to have become stronger over the past two decades, especially due to the collapse of national and regional irrigation systems which occurred after 1990 (a political transition year in Romania) (Grumeza and Kleps, 2005), as these systems have an essential role in regulating the hydrologic balance and decreasing the influence of the potential evapotranspiration regime.

On Romanian territory, these circumstances were found principally in the southern part of Oltenia (the south-western part of Romania), where the increasing evapotranspiration regime of the last two decades caused a considerable decrease of the groundwater level, with an indirect influence on the decline of agricultural system productivity (Prăvălie, Peptenatu, and Sîrodoev, 2013).

Therefore, in the absence of irrigation systems over the past two decades, the change (decrease) in the productivity of agricultural systems in Dobrogea region is one of the major negative consequences of the aridity phenomenon, as well as other related phenomena such as climatic droughts (Lungu et al., 2010; Panaitescu, Lungu, and Niţă, 2012; Prăvălie, Sîrodoev, and Peptenatu, 2014b).

According to the interannual aridity characteristics analysis for the study area, a large-scale rehabilitation of irrigation systems is necessary at this point. For example, in the case of the De Martonne index, the values below 30 mm/°C threshold need an additional humidity contribution from irrigations (Bussay et al., 2012); irrigations are necessary in the study area because the mean annual values of the index (for all eight stations) are notably lower than the mentioned threshold over the analyzed period (1961–2009).

The degradation (dryness) of forest ecosystems (most notably in the northwestern central part of Dobrogea), caused by thermal stress and potential evapotranspiration rises, represents another possible effect of climatic (thermal) aridity intensification in Dobrogea (Ungurean et al., 2012). Southern Oltenia can be a relevant example as well, as a targeted analysis, using remote sensing techniques, managed to highlight the relationship between climatic aridity conditions and vegetation withering in forest ecosystems (Prăvălie, Sîrodoev, and Peptenatu, 2014a; Prăvălie et al., 2014).

Limitations of the Study

It should be noted that certain shortcomings can be identified in the present study, mainly related to evapotranspiration estimations through the Thornthwaite method, due to the unavailability of detailed climatic parameters needed for estimating evapotranspiration values more accurately, such as the Penman-Monteith method, recommended by FAO (Food and Agriculture Organization of the United Nations) (Allen et al., 1998). Although the Thornthwaite methodology is used in countless specialized studies, its main limitations are related to the fact that, in addition to the temperature parameter, it does not take other important variables influencing the evapotranspiration process into account. Such a variable is wind speed, which, due to the high values it reaches in certain sectors of the study area, can have a substantial impact on the evapotranspiration process. Therefore, by considering air temperature alone, an important drawback of the Thornthwaite methodology resides in the underestimation of evapotranspiration values during summer and their overestimation during winter (Carrega, 1994). However, the methodology is considered to be advantageous due to the fact that it requires minimal data input and provides satisfactory results; additionally, it is considered to be representative for Romanian territories (Paltineanu et al., 2007a).

While other limitations of the study can be linked to linear regression estimations of missing temperature and precipitation data for the Călăraşi, Medgidia, and Mangalia weather stations, the data extension only covered a few years, and the *r* correlation coefficient of the common data series had high values (generally above 0.9), the linear regression thus being statistically viable.

Conclusions

According to the analysis of all three aridity indices in this study (De Martonne, UNEP, and Water Deficit Index), the northern part of Dobrogea is more heavily affected by semi-arid climatic conditions, when compared to the southern part. This is due to a relatively uniform evolution of climatic parameters (rising annual temperatures and potential evapotranspiration, and decreasing annual rainfall amounts) for the weather stations situated in the northern region (except for Tulcea, where the precipitation amounts had a slight upward trend), when compared to the Călăraşi, Medgidia, Constanţa, and Mangalia stations, where the precipitation increase was significantly higher. As a result, semi-arid oscillations of the aridity indices are attenuated at these four stations located in the central-southern part of the study area.

However, even in these circumstances, according to the individual climatic parameter analysis, the conclusion can be that the slightly upward trend of annual rainfall amounts is neither statistically significant (when compared to the opposite instance of temperature and potential evapotranspiration parameters), nor interannually uniform. Therefore, at least a "thermal" aridity trend is found in the entire Dobrogea region, due to the obvious increasing trends of mean annual temperatures and potential evapotranspiration values, statistically significant for high and very high thresholds at all eight analyzed stations.

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