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Using aridity indices to describe some climate and soil features in Eastern Europe: a Romanian case study

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With 8 Figures

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Summary

As a result of climatic change associated with global warming, aridity is an increasing problem in many parts of the world, including south-eastern and southern regions of Romania. This paper clarifies the concept of aridity, and discusses related concepts including indices of aridity, and their influence on some landscape and soil features including climatic water deficit (WD) and the depth to soil carbonates (DC). As used here, WD is calculated as the difference between precipitation sum (P) and the Penman-Monteith reference evapotranspiration sum ($ET_{o\text{-}PM}$) over certain periods. Another three well-known aridity indices are also considered: De Martonne's index ($I_{ar\text{-}DM}$), Thornthwaite's index ($I_{ar\text{-}TH}$), the UNESCO (1979) $P/ET_{o\text{-}PM}$ ratio index ($I_{ar\text{-}P/ETo\text{-}PM}$). WD is as high as -450 mm during the growing season in the most arid, south-eastern and southern regions of Romania, especially in the Dobrogea and Baragan areas. In other regions of Romania, including most of the plains and plateaus where agriculture is an important branch of the economy, WD reaches -100 to -300 mm during the growing season. The above aridity indices were spatially interpolated for specific periods by kriging, to generate relatively homogeneous areas. WD can also be seen as an aridity index which has the advantage of a more accurate quantification of the water supply needed for a reference crop, e.g. grass under standardised conditions, for various geographical regions. WD is significantly correlated with the other aridity indexes and with DC. This paper also examines the risk of aridity spreading, and suggests improvements to the water management system for agriculture in Romania.

1. Introduction

Water is a limiting factor for the world's economy because of its decreasing quality and changes in distribution. With global warming, an increase in aridity is predicted for some areas in some model scenarios which estimated that drought would persist in critical agricultural regions in Europe, especially in the southern regions, as well as in eastern North America. It is projected that these regions will suffer from increased dryness, heat, water shortages, and reduced production (Schwartz and Randall, 2003). Other scenarios evaluating the impact of global changes in Romania showed that aridity would increase especially during the crop growing season in the southern parts of Romania (Marica and Busuioc, 2004). Consequently, knowledge of aridity is needed to explain landscape characteristics and the rational utilisation of water resources in many regions. Aridity has been defined in various ways, often using factors based on temperature and precipitation. Aridity indices include De Martonne's aridity index ($I_{ar\text{-}DM}$) which is the ratio between the mean annual precipitation (P) and temperature (T) plus 10 °C (De Martonne, 1926), and the Thornthwaite index ($I_{ar\text{-}TH}$), (Thornthwaite, 1948). Other aridity terms have taken reference evapotranspiration (ET_o) and P into consideration, either as the difference ($P - ET_o$) giving the climatic water deficit (WD), or as the P/ET_o ratio (UNESCO aridity index, 1979, $I_{ar\text{-}P/ETo}$). All these terms have some value in evaluating water resources of regions and for devising practical measures to control drought through irrigation.

In Romania, Cernescu (1961), Berbecel et al. (1970), Botzan (1972), Donciu and Gogorici (1973), Apetroaiei (1977), Canarache (1990) and Paltineanu et al. (2000a, b) among others, have reported data on arid or drought-affected areas, including soil moisture dynamics, water-crop response and irrigation water requirements (IWRs) for various regions of Romania. Teaci (1980) has also published a method of rating land based on soil chemical and physical properties, climate characteristics and relief.

The most widely used method of calculating ET_o in Romania has been that of Thornthwaite (1948). Cernescu (1961) produced an aridity map of Romania based on De Martonne's aridity index and, together with Florea et al. (1968), considered the connection between depth to soil carbonates (DC) and De Martonne's aridity index.

The purpose of this paper is to: i) explain and update the spatial distribution of aridity in Romania in relation to its landscape using the climatic water deficit (WD) concept, ii) show how WD relates to other aridity indices, iii) link WD to other soil characteristics, such as DC, iv) use kriging to show the spatial variability of the aridity indices already mentioned, and thereby improve water management for agriculture in Romanian watersheds.

2. Methods

2.1 Meteorological parameters

Mean monthly and annual weather statistics were calculated for 192 weather stations in various relief regions of Romania. The period of investigation was about one century, mainly from 1900 to 2000. The data set used in this paper consisted of mean monthly data for temperature and precipitation, as well as for other climatic parameters needed in calculating the FAO recommended Penman-Monteith reference evapotranspiration ($ET_{o\text{-}PM}$): sunshine hours, air humidity, as well as wind speed at 10 m or 2 m height.

The quality of the data set was assessed to be reliable because they were recorded in the national network, and standard quality control methods were applied to the data.

Unfortunately, not all stations had records for the same number of years (*Clima RSR, 1966). According to a study of Paltineanu et al. (2006), short-term series of weather data in this country were generally less than about 40–50 years in length, when both the means and standard deviations calculated for increasing periods became relatively steady for the climatic parameters.

If data from short-term stations were significantly correlated with those for long-term stations from the same geographical region, they were extended accordingly to create a more uniform record in space and time. In order to extend a short time-series using the regression analysis method, the coefficient of determination (R^2) of the linear regression equations ($y = a + bx$) obtained had to be higher than 0.7 in most situations, and coefficient b of the equations was in the range of (0.7–1.3) as recommended by Allen et al. (1998, p. 230) to ensure acceptable data homogeneity.

2.2 Aridity indices

Three well-known aridity indices were used to describe aridity conditions in Romania in the present paper.

$I_{ar\text{-}DM}$ was calculated after De Martonne's relationship (De Martonne, 1926):

$$I_{ar\text{-}DM} = P/(T + 10) \qquad (1)$$

where P and T are the mean annual precipitation (mm) and mean annual temperature (°C), respectively.

There was no standard method for calculating ET_o until the late 20th century when the Penman-Monteith method (Monteith, 1965; Jensen et al., 1990; Allen et al., 1998) achieved international recognition. It was used to calculate, with mean annual precipitation (P), WD by difference:

$$WD = P - ET_{o\text{-}PM} \qquad (2)$$

where P is the precipitation sum (mm) and $ET_{o\text{-}PM}$ is the Penman-Monteith reference evapotranspiration (mm), which was calculated using the combined equation (Monteith, 1965; Smith, 1992) based on monthly data of mean temperature, sunshine duration, air humidity and wind speed at 2 m height:

$$ET_{o\text{-}PM} = (0.408\Delta(Rn\text{-}G) + 900\gamma\, U(e_a - e_d) /(T + 273))/(\Delta + \gamma(1 + 0.34U)) \quad (3)$$

where Rn is the net radiation at the grass surface (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), T is average temperature (°C), U is wind speed at 2 m height (m s^{-1}), $(e_a - e_d)$ is the vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa C^{-1}), γ is the psychrometric constant (kPa C^{-1}). The other terms needed to calculate $ET_{o\text{-}PM}$ were taken from Jensen et al. (1990) and Allen et al. (1998).

UNESCO (1979) $I_{ar\text{-}P/ETo\text{-}PM}$ was then calculated as:

$$I_{ar\text{-}P/ETo\text{-}PM} = P/ET_{o\text{-}PM} \quad (4)$$

where ET_o-Penman from UNESCO (1979) was replaced by $ET_{o\text{-}PM}$.

$I_{ar\text{-}TH}$ was calculated from Thornthwaite's formula (1948), as the percentage ratio between the sum of the monthly climatic water deficits $[\Sigma(P - ET_{o\text{-}PM})]$, and the sum of $ET_{o\text{-}PM}$ monthly values through the growing season (April–October). Use of $ET_{o\text{-}PM}$ rather than $ET_{o\text{-}TH}$ is recommended by Jensen et al. (1990) and Allen et al. (1998), and $I_{ar\text{-}TH}$ was calculated as follows:

$$I_{ar\text{-}TH} = [\Sigma(P - ET_{o\text{-}PM})/\Sigma ET_{o\text{-}PM}] \times 100 \quad (5)$$

When P exceeded $ET_{o\text{-}PM}$, $I_{ar\text{-}TH}$ was considered to be zero.

Correlation between WD, $I_{ar\text{-}TH}$, $I_{ar\text{-}DM}$ and $I_{ar\text{-}P/ETo\text{-}PM}$ data were calculated using the least squares method. In order to assess the significance of R (the correlation coefficient or correlation ratio) for both linear and non-linear regression equations, respectively, the t-test was calculated and utilised in comparisons with tabulated values at the desired significance level, using a two-sided t-test and $(n - 2)$ degrees of freedom (Aïvazian, 1970):

$$t = R\ \mathrm{sqrt}(n - 2)/\mathrm{sqrt}(1 - R^2) \quad (6)$$

where n is the number of points used in the calculation.

Spatial interpolation between $I_{ar\text{-}DM}$, WD, $I_{ar\text{-}TH}$ and $I_{ar\text{-}P/ETo\text{-}PM}$ values was achieved by applying the kriging method (Cressie, 1990; Deutsch and Journel, 1992), using SURFER (Surface Mapping System, Golden Software Inc. 2002). The quality of the interpolation achieved depends on the number and density of weather stations, the representation of relief, accuracy of the data collected and computed, etc. Gridding from the Surfer Program was made by using an interpolation density of 200 gridding lines on both latitude and longitude. To perform this, the point-kriging type with no-drift and ordinary kriging options were used in this study. The resulting isolines were designed to have a higher density in the arid regions which were the main subject of this study and a lower density in the mountains. Due to the altitudinal and latitudinal zonation, the climatic parameters of the main mountain peaks which had no weather stations were assimilated with the parameters of the neighbouring mountain peaks of similar altitude where weather stations existed. There were only altitudinal and latitudinal data available for some mountain locations, even if the climatic parameters gradients were highest; in such cases the climatic data were estimated by using multiple regression equations as a function of altitude and latitude as previously reported by Canarache (2004). Consequently, they were also included in the gridding procedure of the kriging interpolation. This resulted in plotting relatively homogeneous areas for the above indices. So, climatic data interpolation was more precisely performed for the plains and hilly regions not exceeding an altitude of 800 m which was the main objective of this paper. In turn, for the mountain regions from the range of 800–2500 m the maps have mainly to be seen as a rough guide.

2.3 Depth to carbonate

Soil carbonate was determined and DC measured in 200 representative soil profiles, which were dug to a 2.5 m depth unless solid rock was met. The parent materials of the soils were loess, loess-like deposits, loams and loamy clays, which prevail in the major plains of Romania. Extreme soil textures such as sand and stony soils possessing high water permeability were avoided, they form only small areas in the arid regions. The relief of the sampled areas had flat plains and gently-sloping hilly areas with slopes not exceeding 3–4%.

The relationship and R^2 between DC and WD were calculated as before by regression in the Excel program using the least squares method.

3. Results and discussions

3.1 De Martonne's aridity index ($I_{ar\text{-}DM}$)

In Romania, the spatial distribution of $I_{ar\text{-}DM}$ shows high variability, with the lowest values (15–20 mm °C^{-1}) in the most arid regions of south-eastern areas near the Black Sea coast (Fig. 1).

These areas were included in the *BS dry semi-arid – steppe* climate category of Köppen's classification (Köppen, 1931). The Köppen Climate Classification System is the most widely used system for classifying the world's climates. Its categories are based on the annual and monthly averages of temperature and precipitation. The Köppen system recognises five major climatic types and each type is designated by a capital letter.

On a worldwide basis, values of 15–20 mm °C^{-1} characterise semi-arid regions, but in a temperate climates they are distinctly arid. The agricultural regions of southern and central parts of the Romanian Danube Plain, the eastern part of the Moldova Plateau, much of the Western Romanian Plain (Tisa Plain) and the western part of the Transylvania Plateau have values of 20–30 mm °C^{-1} $I_{ar\text{-}DM}$. They are considered sub-humid regions after De Martonne's classification. Other hilly regions of about 250–700 m in height mainly show $I_{ar\text{-}DM}$ values between 30 and 45 mm °C^{-1}, which characterises them as humid. An even more humid region was found in other hilly areas 800–1000 m in height, near the Carpathian Mountains, where $I_{ar\text{-}DM}$ ranges between 45 and 60 mm °C^{-1}. The highest values (60–160 mm °C^{-1}) occur in upland regions, such as the Carpathian Mountains and high plateau areas between an altitude of 1000 and 2500 m. The distribution of $I_{ar\text{-}DM}$ values therefore shows altitudinal zoning around the Carpathian Mountains.

3.2 The annual climatic water deficit (WD)

The spatial distribution of WD (Fig. 2) suggests that the most arid region of this country is the

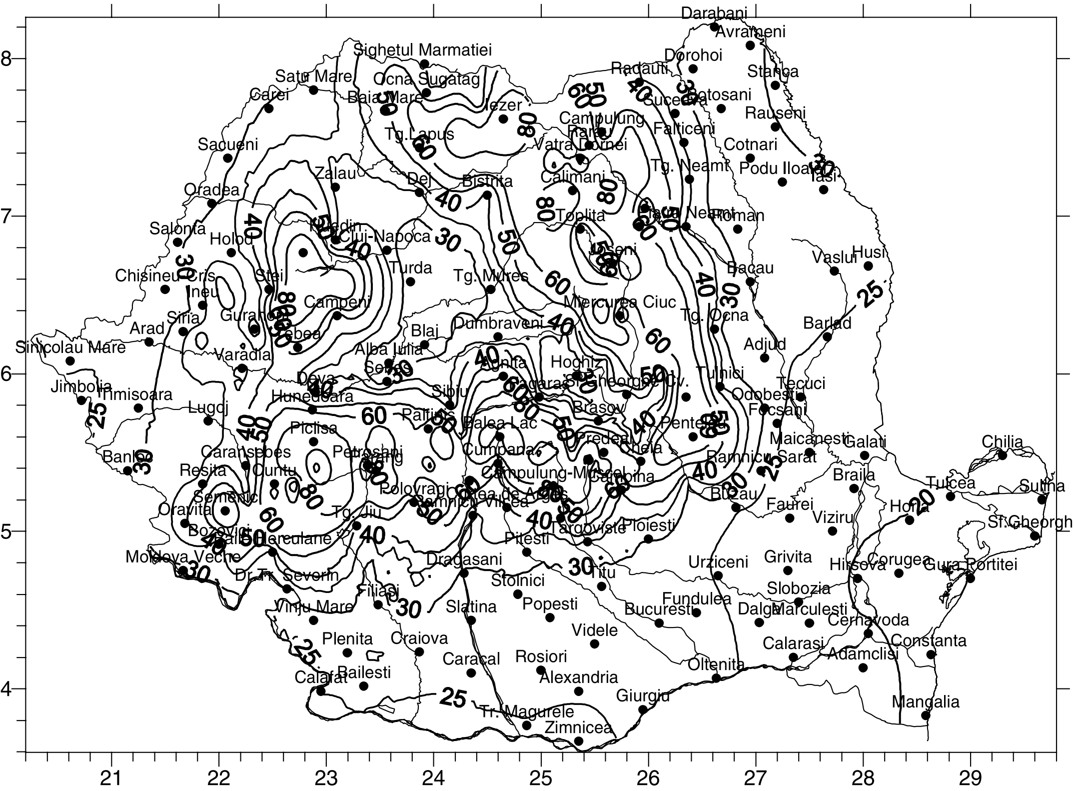

Fig. 1. Spatial distribution of De Martonne's aridity index ($I_{ar\text{-}DM}$, mm °C^{-1}) in Romania

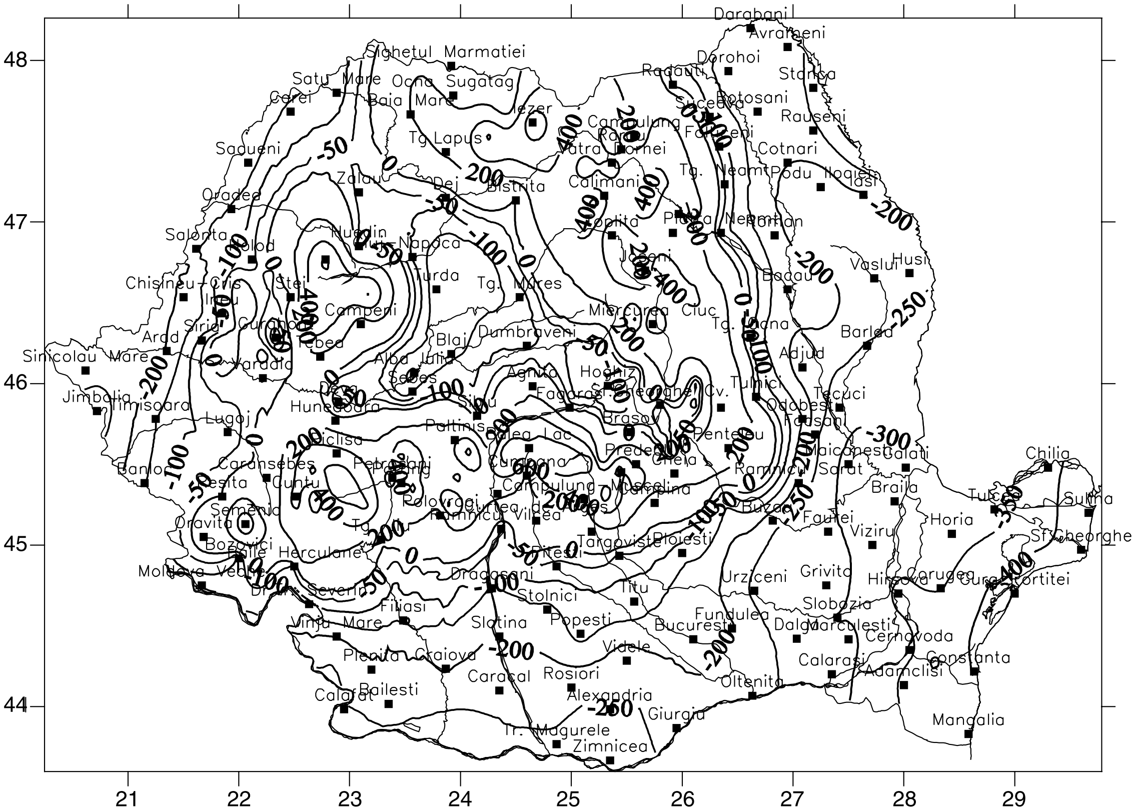

Fig. 2. Spatial distribution of the annual climatic water deficit (WD, mm) in Romania

Black Sea coast where WD reaches as much as −400 mm.

The western part of the Dobrogea region and the eastern part of the Romanian Plain (Baragan) have WD values between −300 and −400 mm, making these regions the second most arid part of the country.

The southern part of the Romanian Danube Plain is crossed by the −200 mm WD isoline which then turns northwards so that the eastern part of the plane has WD values between −200 and −300 mm. Similar WD values occur in the southern and central parts of the Moldova Plateau, from where they decrease northwards to −200 mm and even to −100 mm. These most arid regions of the country have a specific agriculture, in which cereals are associated with vineyards and some thermophile fruit tree species such as apricot and peach. Even if rain-fed agriculture is still practiced in these regions, high yields cannot be obtained without the application of irrigation.

The 40 and 50 mm °C^{-1} $I_{\text{ar-DM}}$ isolines of Fig. 2 pass through the middle and high hilly regions, especially through the platforms and Pre-Carpathian areas. The 40 mm °C^{-1} $I_{\text{ar-DM}}$ isoline corresponds approximately with equilibrium between annual P and $ET_{\text{o-PM}}$ values, as annual WD here is practically nil. From these locations towards the high mountain peaks, $I_{\text{ar-DM}}$ values always increase and exceed 100 mm °C^{-1} in the alpine climate regions of the Carpathian Mountains, reaching as high as 160 mm °C^{-1} and even more on peaks about 2500 m high.

In the Tisa Plain the −200 mm WD isoline passes near to the town of Timisoara, and most of this plain has WD values as high as −200 mm. The −100 mm WD isoline passes through the central part of the Romanian Plain and around the Pre-Carpathian regions towards the Moldova Plateau. In Transylvania, the same WD isoline separates the lowest parts of the Transylvania Plateau from upper parts of neighbouring hilly or mountain regions.

The WD isoline with special importance for agriculture is the 0 mm WD isoline, which crosses the southern side of the Getic Platform and follows closely the Pre-Carpathian regions of Moldova towards the northern border of the country. In Transylvania, it defines the geograph-

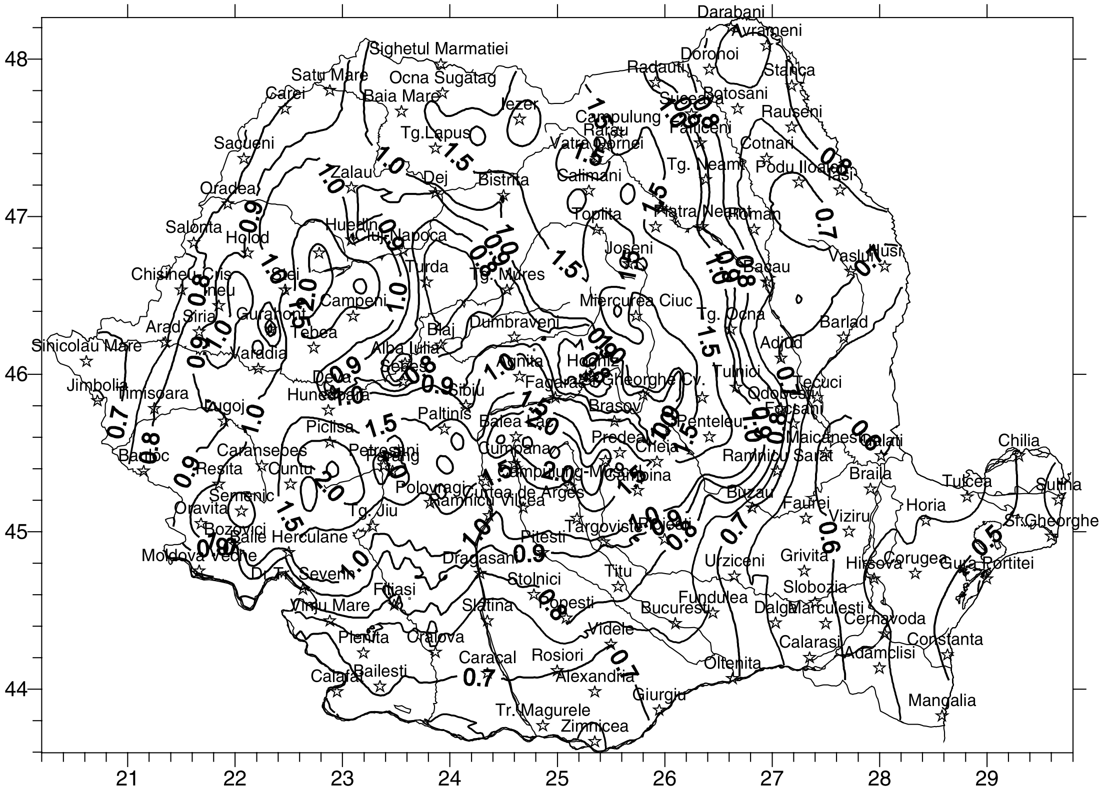

Fig. 3. Spatial distribution of the UNESCO (1979) annual $I_{\text{ar-P/ETo-PM}}$ aridity index (mm mm^{-1}) in Romania

ical limits of the Transylvannia Plateau and Carpathian Mountains (Fig. 2). At locations with higher altitude values only positive WD values occur (i.e. excess water), where P exceeds $ET_{\text{o-PM}}$ and runoff, infiltration and internal drainage prevail. On the highest peaks of the Carpathian Mountains the excess water increases to as much as +650 to +750 mm and results in large temporary and permanent outflows.

3.3 The UNESCO (1979) $I_{ar\text{-}P/ETo\text{-}PM}$ aridity index

The spatial distribution of the $I_{\text{ar-P/ETo-PM}}$ is shown in Fig. 3. The 0 mm WD isoline (Fig. 2) corresponds with the 1.0 mm mm^{-1} $I_{\text{ar-P/ETo-PM}}$ isoline (Fig. 3).

According to this index, the most arid south-eastern regions of Romania with $I_{\text{ar-P/ETo-PM}}$ values of 0.45–0.50 mm mm^{-1} are close to the Black Sea coast, and the 0.2–0.5 mm mm^{-1} $I_{\text{ar-P/ETo-PM}}$ climatic class shows a semi-arid climate (UNESCO, 1979). However, the $I_{\text{ar-P/ETo-PM}}$ in the most intensive agricultural territories is 0.5–0.8 mm mm^{-1}, and after UNESCO (1979) these regions are classed as humid. However, the UNESCO (1979) classification took into consideration the Penman ET_o and not the Penman-Monteith ET_o (PM – ET_o) as in this study.

Because Penman ET_o values are usually higher than PM – ET_o values in this country (Paltineanu and Chitu, 2001), the limits of classification of the arid climates described in UNESCO (1979) would somewhat increase.

The upper hills and the Carpathian Mountains have isolines higher than 1.0 mm mm^{-1} $I_{\text{ar-P/ETo-PM}}$.

3.4 The Thornthwaite aridity index ($I_{ar\text{-}TH}$)

The spatial distribution of $I_{\text{ar-TH}}$ is shown in Fig. 4. Worldwide, values between 0 and 10% mm mm^{-1} characterise a semi-temperate climate, those in the 10–20% mm mm^{-1} interval have a temperate climate, those in the 20–40% mm mm^{-1} interval a semi-arid climate, and values greater than 40% mm mm^{-1} an arid climate.

In Romania, $I_{\text{ar-TH}}$ values representing severe aridity (higher than 40% mm mm^{-1}) occur in the southern half of the Romanian Plain, in Baragan

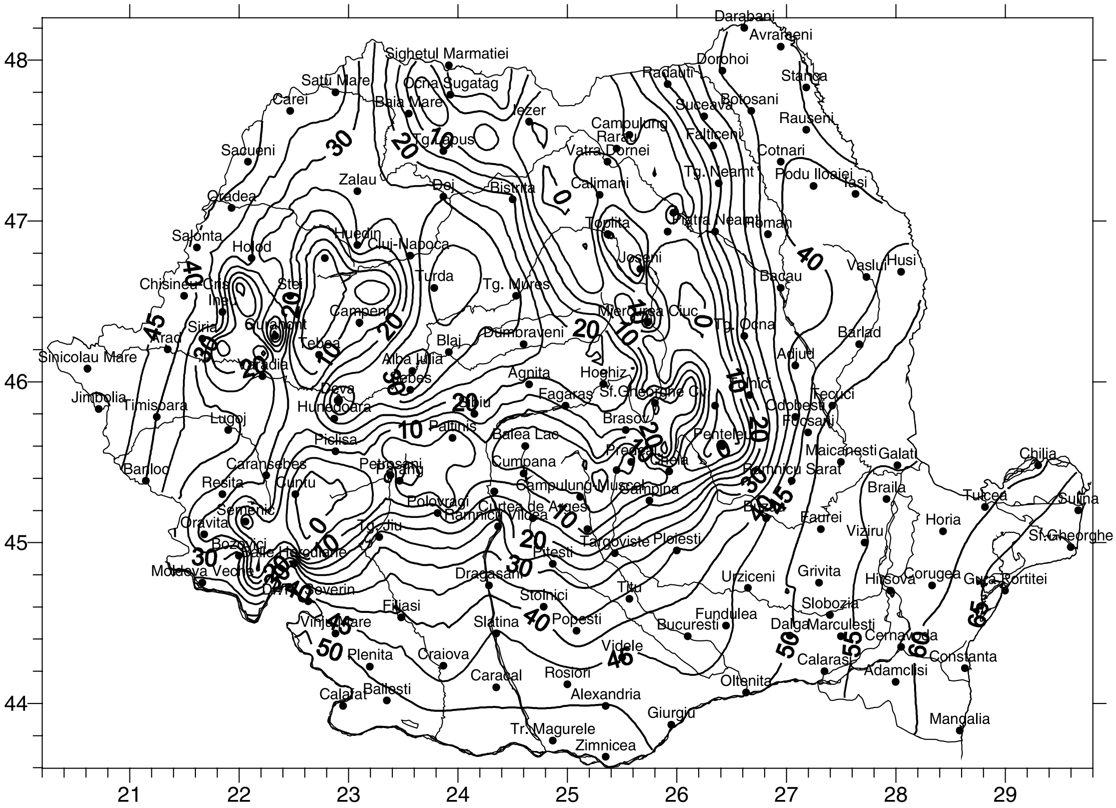

Fig. 4. Spatial distribution of $I_{ar\text{-}TH}$ (% mm mm^{-1}) calculated using $ET_{o\text{-}PM}$ for the crop growing season (April–October) in Romania

and Dobrogea, the southern part of the Moldova Plateau and the western extremity of the Tisa Plain (Fig. 4). $I_{ar\text{-}TH}$ exceeds 60% mm mm^{-1} in the eastern part of Dobrogea, indicating very severe aridity. Values of 0–10 mm mm^{-1} occur on the Carpathian Mountain peaks. Unlike $I_{ar\text{-}DM}$, $I_{ar\text{-}TH}$ measured the aridity as a percentage of the sum of $ET_{o\text{-}PM}$ for the growing season. This seemed more realistic than $I_{ar\text{-}DM}$. In the arid regions it was more meaningful in agronomic terms, but in regions with values greater than 40% mm mm^{-1} it needs to be more detailed.

3.5 Correlations between the aridity indicators

a) A third order regression equation was calculated between $I_{ar\text{-}DM}$ and WD calculated versus $ET_{o\text{-}PM}$ ($P - ET_{o\text{-}PM}$) (Fig. 5).

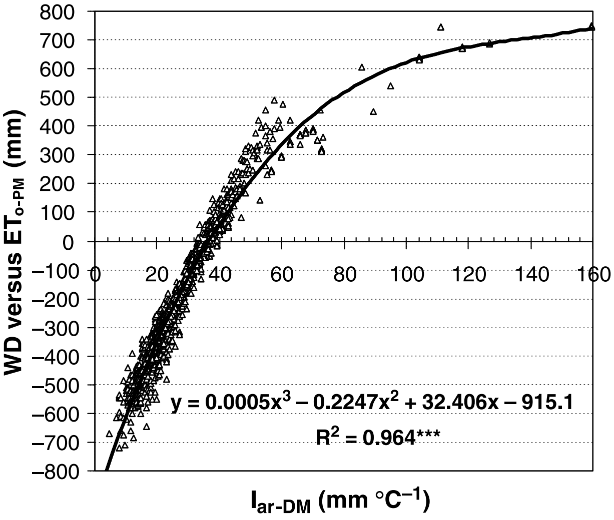

Fig. 5. Relationship between $I_{ar\text{-}DM}$ and WD calculated versus $ET_{o\text{-}PM}$ for various regions of Romania; note that here, and in subsequent Figs. 6–8, the symbol *** indicates highly significant (Probability < 0.001)

The correlation was highly significant and its determination coefficient was high ($R^2 = 0.964^{***}$). For $I_{ar\text{-}DM}$ values larger than 50 mm °C^{-1} the points scattering increased probably due to the lower density of weather stations, more variable natural conditions met in the high altitude regions and maybe due to the lower climatic data accuracy from some of these locations. However, R^2 for the entire $I_{ar\text{-}DM}$ range remains high.

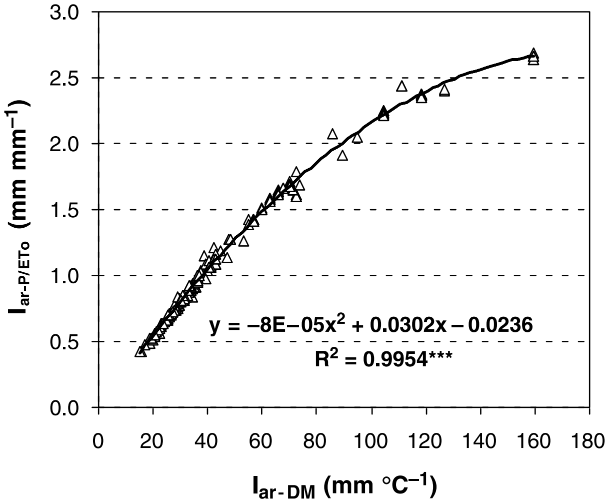

Fig. 6. Relationship between $I_{ar\text{-}DM}$ and $I_{ar\text{-}P/ETo\text{-}PM}$ for various regions of Romania

This correlation can be used to estimate WD values as a function of $I_{ar\text{-}DM}$ in regions lacking the weather data needed for calculating $ET_{o\text{-}PM}$. The intersection of the graph with the horizontal Ox axis (i.e., WD = 0 mm) resulted in $I_{ar\text{-}DM}$ values of about 37.0 mm °C^{-1}. As a result, this graph separates negative (real) WD values located below the WD = 0 horizontal axis from positive (excess water) WD values from the upper part of the graph.

b) The relationship between $I_{ar\text{-}DM}$ and the UNESCO (1979) $I_{ar\text{-}P/ETo\text{-}PM}$ is curvi-linear (Fig. 6).

The regression equation is highly significant, with R^2 exceeding 0.99. Canarache (2004) also found a similar correlation between $I_{ar\text{-}DM}$ and $I_{ar\text{-}P/ETo\text{-}PM}$ for the Romanian territory, and intersection with the $y = 1$ horizontal line gave the same $I_{ar\text{-}DM}$ figure of about 37 mm °C^{-1}. This emphasises the value of $I_{ar\text{-}DM}$ as an indicator of landscape aridity.

c) There is also a strong, curvi-linear, but inverse relationship between the calculated $I_{ar\text{-}DM}$ and $I_{ar\text{-}TH}$ values versus $ET_{o\text{-}PM}$ with a R^2 value greater than 0.97 (Fig. 7). There is also an approximate correspondence between the thresholds used in Thornthwaite's classification of $I_{ar\text{-}TH}$ and some values of $I_{ar\text{-}DM}$. Hereby, the 0 $I_{ar\text{-}TH}$ value is equivalent to about 67 $I_{ar\text{-}DM}$; the value of 10 for $I_{ar\text{-}TH}$ (the limit between semi-temperate and temperate climates) corresponds with a value of 45 $I_{ar\text{-}DM}$ which is in the humid class; the value of 20 for $I_{ar\text{-}TH}$ (the lower limit of the semi-arid range) is equivalent to 37 in De Martonne's classification, which is in the humid range, a value of 40 $I_{ar\text{-}TH}$, the limit between semi-arid and arid, is equivalent to 27 $I_{ar\text{-}DM}$.

However, De Martonne's (1926) classification seems now to require an increase in the number of classes, specifically for the humid classification (e.g. 30–45 and 46–60 mm °C^{-1}), and "over humid" classification (e.g. 60–100 and 101–160 mm °C^{-1}). These thresholds would be more useful in characterising moisture regimes in central and south-eastern parts of Europe. The value of 37 $I_{ar\text{-}DM}$ represents the equilibrium between the *source* and *consume* regimes, and supports the idea of dividing the $I_{ar\text{-}DM}$ humid range (30–60 mm °C^{-1}) into two classes: from 30 to 45 mm °C^{-1}, close to the value of 37, which could be called *balanced*, and 46–60 mm °C^{-1}, as *humid*.

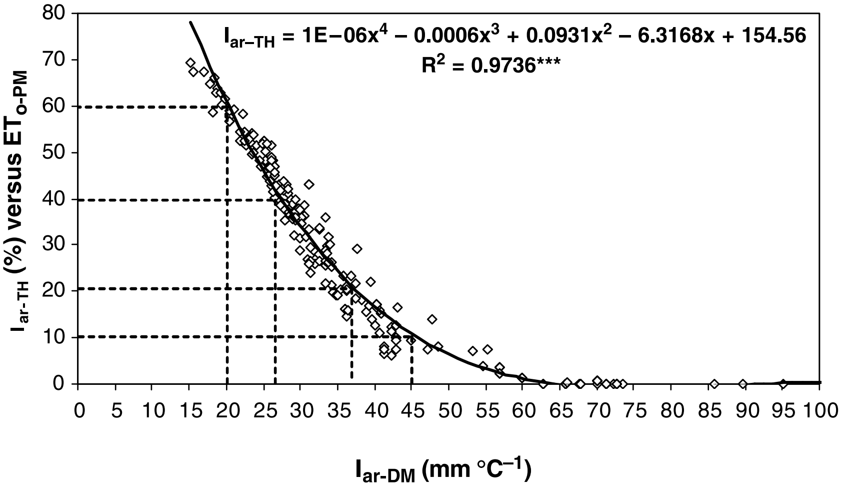

Fig. 7. Relationship between $I_{ar\text{-}DM}$ and $I_{ar\text{-}TH}$ calculated versus $ET_{o\text{-}PM}$ for the crop growing season in various regions of Romania

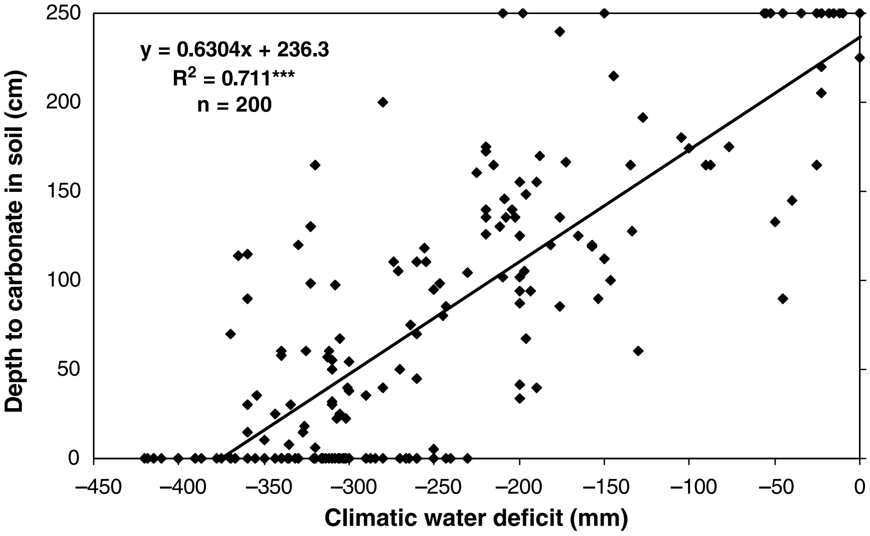

Fig. 8. Relationship between the depth to carbonate (DC) in soils and the annual climatic water deficit (WD) in Romania

d) For a given period, e.g. month, there is a functional theoretical relationship between $I_{ar\text{-}P/ETo\text{-}PM}$ and $I_{ar\text{-}TH}$, provided there was no water excess, as follows:

$$I_{ar\text{-}TH} = \Sigma(P - ET_{o\text{-}PM})/\Sigma ET_{o\text{-}PM} = \Sigma P/\Sigma ET_{o\text{-}PM} - 1 = I_{ar\text{-}P/ETo\text{-}PM} - 1 \quad (7)$$

3.6 WD in relation to some soil properties and landscape coverage considerations

Depth to carbonate (DC) within the main soil types was found to correlate positively, and highly significantly with WD (Fig. 8), even if R^2 was not high ($R^2 = 0.711$).

The regression equation was considered linear even if other equations, e.g. curvi-linear equations, resulted in a similar or small gain in the magnitude of R^2 values. The scatter of points on the graph is relatively high, probably due to other factors determining DC, such as land slope and aspect, soil permeability, land use, age of relief (e.g. river terraces or plains of various ages within a large area assumed to have uniform WD), etc. In spite of the high diversity of the natural conditions of the soils, it was essential that a direct significant relationship between DC and WD was found.

The soils of areas showing WDs between −250 and −425 mm had DC values less than about 50 cm deep, and included Kastanoziems according to the *Romanian system of soil taxonomy* (Florea and Munteanu, 2000), and also referred to as Calcaro-calcic Kastanoziems (FAO, ISRIC, 1998) and as Typical Calciustolls (Soil Taxonomy, 1999) and various chernozem types represented by Typical Chernozem (Calcic Chernozems, Entic Haplustolls, in the other two international soil classification systems above), Cambic Chernozem (Haplic Chernozems, Typical Haplustolls), Argic Chernozem (Luvic Chernozems, Udic Argiustolls), Typical Faeoziom (Haplic Phaeozioms, Entic Hapludolls). These soils have a mull-type humus and well developed soil structure (Florea et al., 1968).

Many different soil types have WD values between the extreme WD of the Kastanoziems and the 0 WD value which is approximately equivalent to a DC of 250 cm depth. This depth is generally the maximum depth dug in the soil profiles.

For WD values between −250 and −350 mm, the chernozems have the same mull type of humus but DC values increase from 0 cm to about 50–100 cm. With a further decrease in WD, from −250 to −150 mm, the soils are mainly cambisols (Typical Eutricambosol, Florea and Munteanu, 2000) and are referred to as Eutric Cambisols (FAO, ISRIC, 1998) and Typic Eutrocryepts (Soil Taxonomy, 1999), as well as Typical Districambosol (Distric cambisols, Typic Dystrudepts in the other two international soil classification systems above), and DC increase further to 100–150 cm. In the phaeozems (Typical Phaeozems, Haplic Phaeozioms, Entic Hapludolls, as well as Greyic Phaeozems, Greyi-luvic

Phaeozioms, Alfic argiustols, in the three classification systems discussed) with WD up to 0 mm, carbonates are leached to greater depths (more than 150 cm).

Unless situated on carbonate-rich parent materials, the soils of regions with positive WD values (excess water) are very deeply leached; in some luvisols (Typical Luvosol, Haplic Luvisols, Typic Hapludalfs as well as Albic Luvosol, Albic Luvisols, Glossic Hapludalfs, in the three systems) and planosols (Typical Planosol, Haplic Planosols, Albaquic Hapludalfs, in the three systems) carbonate is completely absent from the profile. The humus type of such soils is mor and the soil structure is weak. Clay has migrated into sub-soil horizons (Florea et al., 1968; Conea et al., 1980). Towards the mountains this trend continues with increasing climatic water excess and the climate is colder; the soils show migration in iron to form haplic podzols (Haplic Podzols in FAO, ISRIC, 1998; Typic Humicryods in Soil Taxonomy, 1999).

4. Discussion of aridity indices and their implication for the landscape

In the former aridity classification of Cernescu (1961), the $I_{ar\text{-}DM}$ values of 26–35 mm °C^{-1} found in the highest plains of these territories showed a balance between the annual P and reference ET_o. This was not confirmed in the present study, as the reference ET_o was not standardised at that time and the Thornthwaite ($ET_{o\text{-}TH}$) method was usually utilised to determine reference or potential evapotranspiration. The 30 mm °C^{-1} $I_{ar\text{-}DM}$ value of Cernescu (1961) corresponded to the annual WD isoline of −100 mm (Fig. 2).

The extent of natural vegetation and agricultural crops in the landscape depends mainly on WD, but also on relief, altitude, slope, aspect, soil permeability, land use, land surface age, water table depth, etc. The most arid regions of the country with −300 to −400 mm WD had a natural vegetation of steppe before this land was cultivated intensively, i.e. during the 19th century, and a mixed wild vegetation of steppe and forest occurred generally between the WD isolines of −200 and −300 mm before the same period, while between the 0 and −200 mm isolines oak-dominated forest existed (Florea et al., 1968). These authors reported that from 0 mm to about +200 mm WD there was mixed natural forest vegetation of broad-leaved or deciduous trees, and coniferous forests occurred in areas where WD exceeded +200 mm. The significance of this is that the wild vegetation above found proper climatic conditions to develop within the WD limits mentioned.

By comparison, the approach of aridity based on more than one factor (e.g. on climate, relief and soil data) was more complex and closer to reality. For instance, the real water deficit (RWD) was usually higher than WD on hillslopes due to runoff flowing into streams and rivers. Canarache and Dumitru (2000) and Canarache (2004) found that within the same geographical regions the climate aridity characterised by RWD was more severe in: a) soils possessing coarse texture such as those from the south-western extremity of the Romanian Danube Plain, b) naturally-compacted clay soils such as vertisols (Vertic Chernozem in FAO, ISRIC, 1998; Vertic Hapludolls in Soil Taxonomy, 1999) in the Getic Plateau and Gavanu-Burdea Plain (southern Romania), c) salt-affected soils such as from the Calmatui Valley (south-eastern Romania), and d) stony eroded soils on steep slopes in hilly and mountainous regions such as the central and eastern parts of Dobrogea. In contrast, the climatic aridity expressed by RWD was less severe in the deep, medium-textured and less compacted soils situated on flat plains or where the groundwater table was shallow (e.g. the Danube Flood Plain). However, this procedure needs a separate approach involving limits of the soil units in describing the spatial distribution, and is not the objective of the present paper.

As discussed so far, aridity has been characterised by various climatic factors, but additional indicators could also have been used for this purpose. Unlike drought indicators such as SPI (standardised precipitation index, McKee et al., 1993), WD has the advantage of a more accurate quantification of the water supply needed for a reference crop, e.g. grass under standardised conditions, for various geographical regions. SPI was developed in order to quantify the precipitation anomalies versus the average for multiple time scales: 3, 6, 9, 12 and 24 months, allowing a standardised comparison between various geographical regions. The real advantage of precipitation standardisation consists of the fact that SPI values represent the same occurrence probabilities, regardless of the period of year, location or climate. SPI could thus be assessed more usefully in association with WD, as droughts are usually more severe in arid regions or where the reference evapotranspiration exceeds precipitation. Aridity quantified by WD is closely related to crop evapotranspiration and irrigation needs by crop coefficients described by Doorenbos and Pruitt (1977), Jensen et al. (1990), Allen et al. (1998). Consequently, this paper has a practical aspect.

It should be emphasised that increasing aridity in Eastern Europe due to global warming is a significant future hazard. There could be a real threat of desertification in the most arid regions of southern Romania as reported Marica and Busuioc (2004). Based on the CROPWAT model (Smith, 1992) and climate change scenarios derived through a global climate model (HadCM3) they assessed the impacts of future climate changes and estimated significantly negative effects on the main water balance components and maize yield. In this respect, water availability for crops would decrease due to a combination of increased daily ET_o, higher soil moisture deficit and decrease in precipitation. For instance, the mean monthly temperature would increase by as much as 2.5 °C in August in the 2020s and 4.8 °C in the 2050s, whereas the daily ET_o would increase up to 8–16% during the same periods when irrigation water requirements would also increase by about 15–28% (Marica and Busuioc, 2004). Following this scenario, a drop in soil moisture content would lead to a reduction of the actual crop evapotranspiration by 16 and 24% for the 2020s and 2050s, respectively, despite an increase in the evaporative atmospheric demand.

Governments of countries with aridity problems should develop proper policies in areas of concern, e.g. by rehabilitating irrigation systems, use of strategic planning for all aspects of water requirements and applying a rational use of water resources based on risk management rather than crisis management.

Another strategy in agriculture would be the use of certain plant species and cultivars that are better adapted to water stress as, for example in the southern parts of Romania, the average yield reduction for maize due to the crop water stress for the next decades of this century could be as high as 60–70% due to higher temperatures that could shorten the growing season length, associated with water stress especially during the grain-filling stage (Marica and Busuioc, 2004).

5. Conclusions

The climatic water deficit (WD), calculated as the difference between precipitation and the Penman-Monteith reference evapotranspiration, is an important term with worldwide usefulness in characterising climate aridity; it can also be seen as an aridity index which has the advantage of a more accurate quantification of the water supply needed for a reference crop, e.g. grass under standardised conditions, for various geographical regions.

In Romania WD shows values as high as -350 to -450 mm during the growing season in the most arid, south-eastern and southern regions of Romania, especially in the Dobrogea and Baragan regions. For most of the plains and plateaus where agriculture is an important aspect of the economy, WD reached a total of -100 to -300 mm during the crop growing season; however, the deficit was usually higher on steep-slopes due to runoff flowing to streams and rivers.

WD was highly and significantly correlated with other aridity indices for Romania.

A direct, linear and highly significant relationship was found between depth to soil carbonate (DC) and the WD. This relationship could also apply to countries showing a similar range of climate.

Our results help explain the type of land cover in Romania and emphasise the increased risk of spreading aridity; on the other hand they could contribute to the development of a better water management system for agriculture.

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