Drought Vulnerability in Croatia

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Summary

Drought is the most frequent hazard causing the highest economic losses among all hydro-meteorological events in Croatia, especially in the agricultural sector. Climate assessment according to aridity index shows that susceptibility to desertification is present in the warm part of the year and mostly pronounced in the Adriatic region and eastern lowland. Evidence of higher frequencies of extreme droughts in the last decade has been noted. These were the motivations to study the drought risk assessment in Croatia and to develop a vulnerability map. This map is a complex combination of the geomorphologic and climatological inputs (maps) that are presumed to be natural factors which modify the amount of moisture in the soil. The first version of the vulnerability map developed from the slope map, solar irradiation and coefficient of the variation of precipitation is updated by inclusion of optional parameters: soil types and land cover classes. The recommended procedure in the framework of Drought Management Centre for Southeastern Europe is modified and adopted in this study. The obtained results for Croatia show the areas most sensitive to drought to be on the southern Adriatic coast and over the eastern continental lowland.

Key words

drought, aridity index, drought vulnerability map

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Introduction

The major part of the last 32 years (1981-2012) of economic losses due to natural hazards in Croatia has been associated with meteorological and hydrological events (MF, 2013). The greatest damage has been documented in agriculture, infrastructure, buildings and movable property. Drought causes highest economic losses (44%) among all hydro-meteorological events (Figure 1). The relationship between different natural hazards in particular years during the long-term period is rather variable concerning the frequency of appearance and damage magnitude. The cost and type of damage differs from year to year. The highest losses due to drought impacts in Croatia during the 1981-2012 period were recorded over eight years. Their participation in the total reported annual damage was between 68% and 90%. These cases of drought-related damage were associated with losses exceeding USD 200 Mill and annual GDP between 0.63% and 3.97%.

The first climatological information on dryness (or wetness) of the country on an annual scale can be obtained from rainfall amounts and number of dry (rainy) days. Significant spatial differences in average precipitation amounts and frequency between the continental, mountainous and coastal areas are apparent—precipitation increases from 300 mm recorded in 100 days per year on the outlying islands of the southern Adriatic to slightly over 3,000–3,500 mm recorded in 170 days in the mountainous region (Gajić-Čapka et al., 2008). This indicates the presence of 53–73% of days per year that lack precipitation, and raises the issue of regional occurrence of dry days during the year, as well as the characteristics of related sequences. Climatological features of mean and maximum dry spell durations, as well as the frequency of long dry spells (>20 days), which are particularly important in practice, are discussed in Cindrić et al. (2010). The spatio-temporal distribution affirms the three prevalent climatological regions with regard to dry spells: the coastal region, which exhibits the longest dry spells, the highlands with the shortest dry spells throughout all seasons and the mainland with the longest dry spells during the winter months. Cindrić et al. (2010) identified the prevailing positive trend of both mean and maximal durations during winter and spring seasons, and the prevailing negative trend in autumn for all thresholds. This issue is consistent with the IPCC report (Meehl et al., 2007) that predicts an increase in precipitation intensity for the middle latitudes, with longer periods between rainfall events.

Compared to other hydro-meteorological events, such as floods, drought affects wide areas over long periods of time; it develops very slowly and is often not recognized until human activities or the environment are affected (see references in Vicente-Serrano, 2006). The threat of drought to countries' economies and societies has started various projects the purpose of which is to create a basis for mitigation of and adaptation to drought.

The Republic of Croatia signed the UN Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification (UNCCD). The Croatian Government established the National Committee to Combat Desertification with the basic task of monitoring of and participation in the preparation and implementation of a National Action Programme. In 2003, the Committee started to work on the preparation of a project under the title "National Action Programme to Mitigate the Effects of Drought and Combat Land Degradation", which was adopted in 2007 (MZOPUG, 2007).

In this paper, the drought threat in Croatia is assessed using the aridity index. Spatial characteristics of drought are further analysed by construction of drought vulnerability map for Croatia according to the modified procedure recommended in the framework of Drought Management Centre for Southeastern Europe (DMCSEE project, http://www.dmcsee.eu/). The input maps are presented and discussed followed by the three versions of the vulnerability map: the first one dependent on climatological inputs only, the second one modified by soil type and the final one based on the necessary and two optional parameters of soil type and land cover class.

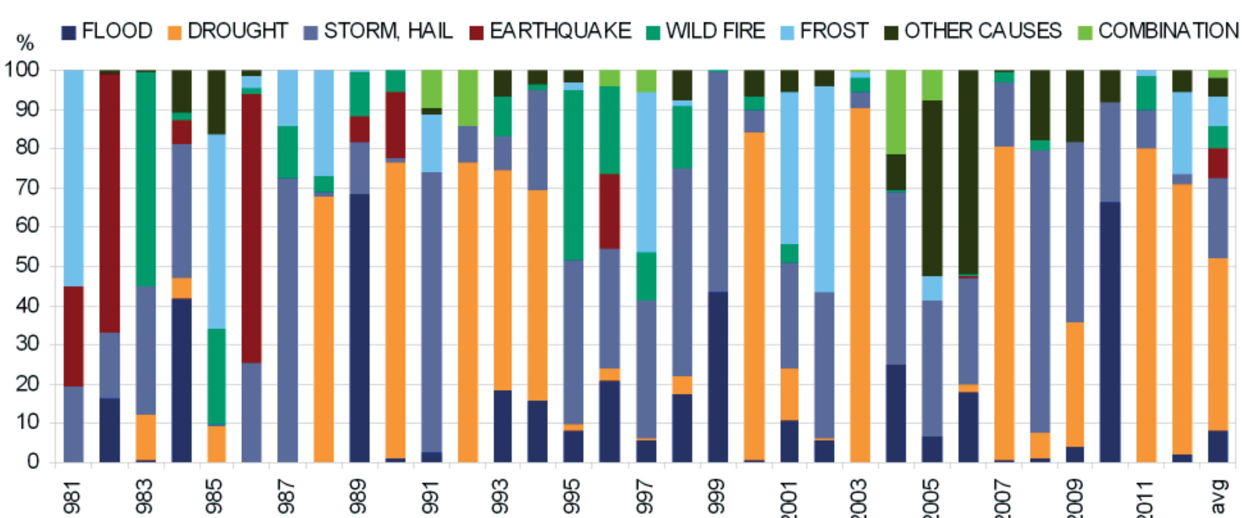

Figure 1. Economic losses (in percentages) due to natural hazards in Croatia during the 1981-2012 period and average losses throughout the period (avg-last column)

Data and methods

To assess the drought vulnerability of Croatia, two approaches were implemented. The aridity index, showing average monthly and annual precipitation deficit, was analysed. Consequently, the drought vulnerability map was developed showing the average susceptibility to drought due to morphological, climatic and pedological characteristics of the Croatian territory.

Aridity index

Evaporation that takes place directly from the soil (evaporation) and through plants (transpiration), is reaching higher values at higher temperatures, during stronger winds and less humidity. Potential evapotranspiration can be calculated if these three climatological parameters are known. However, actual evaporation, i.e. evapotranspiration, can be equal to or less than the potential evaporation. When rainfall is greater than potential evapotranspiration, it can compensate for the loss of water due to evaporation, and the surplus of water soaks the soil. When precipitation cannot restore water deficiency due to evaporation, soil water storage reduces. A long-lasting water shortage can cause a drought and serious damage to agriculture and water management. The precipitation deficit in terms of the P/PET ratio is then a useful aridity index. Lower values of this ratio correspond to drier areas.

Table 1. Aridity index (P/PET) classes

Hyper-arid zone	P/PET<0.05	desertification threat
Arid zone	0.05≤P/PET<0.20	
Semi-arid zone	0.20≤P/PET<0.50	
Dry-subhumid zone	0.50≤P/PET<0.65	
Humid zone	0.65≤P/PET	no desertification threat

Colour codes show the categories due to susceptibility to desertification.

Potential evapotranspiration, as one of the water balance components, is calculated using the Eagleman formula (Eagleman, 1967) modified by Pandžić (1985), taking into account the air flow. Besides the meteorological parameters (monthly values of mean air temperature, precipitation and mean relative humidity), the pedological characteristics of the sites have also been included in the calculation. The presumption was that, at the beginning of the calculation period (January 1961), the soil was saturated at its maximum capacity.

Atmospheric conditions which cause a considerable water deficit determine a desert climate, or a climate with a tendency to desertification. According to the United Nations Convention to Combat Desertification (UNCCD) definition and criteria accepted by UNEP/GEMS (1992), the next scheme shows the threat of desertification due to climate conditions, according to the bioclimatic aridity index (Table 1).

This categorization was applied to the average monthly and annual aridity index for 22 meteorological stations covering the different climate regions of Croatia in the 1961-2000 period in order to analyse and compare two 30-year periods, 1961-1990 and 1971-2000.

Drought vulnerability map for Croatia

Following the recommended procedure within the DMCSEE project, the map of vulnerability to drought for Croatia is prepared using the maps of necessary parameters: slope, irradiation, and precipitation, as well as available optional parameters: soil type and land cover. The derived maps are classified into five classes from 0.2 to 1.0, according to criteria in Table 3. Class maps are then aggregated (summed) and classified into five categories of vulnerability to drought: not vulnerable, slightly vulnerable, moderately vulnerable, vulnerable and strongly vulnerable.

Table 2. Annual course of aridity index (P/PET). Period: 1971-2000

Station	Reg.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Osijek	P1	3.73	2.00	1.24	0.93	0.64	0.71	0.49	0.50	0.63	1.22	2.95	3.77	0.88
Donji Miholjac	P1	3.43	1.76	1.13	0.86	0.58	0.60	0.42	0.46	0.52	1.07	2.64	3.80	0.78
Slavonski Brod	P2	4.27	2.17	1.39	1.10	0.87	0.81	0.75	0.62	0.91	1.74	3.45	4.42	1.14
Varaždin	P4	2.79	2.10	1.50	1.15	0.83	0.88	0.72	0.79	1.18	1.98	3.50	3.87	1.19
Đurđevac	P3	2.93	2.40	1.41	1.17	0.82	0.81	0.66	0.68	1.01	1.73	3.65	4.25	1.15
Koprivnica	P3	3.21	2.53	1.45	1.23	0.86	0.82	0.71	0.71	1.13	1.98	3.82	4.60	1.22
Zgb-Maksimir	P3	3.07	1.95	1.56	1.09	0.87	0.89	0.62	0.81	1.19	2.08	3.64	4.00	1.20
Sisak	P3	3.77	2.40	1.57	1.27	0.94	0.87	0.64	0.71	1.22	2.03	4.33	4.86	1.26
Karlovac	G1	6.10	3.63	2.64	1.91	1.28	1.16	0.93	1.02	1.78	3.15	6.11	7.55	1.85
Ogulin	G1	5.65	4.81	3.11	2.40	1.43	1.28	0.92	1.06	2.01	3.72	6.76	7.94	2.18
Parg	G2	9.23	7.60	5.86	4.55	2.65	2.36	1.38	1.70	3.55	7.45	11.89	11.64	3.85
Gospić	G2	9.27	7.07	4.13	3.03	1.89	1.25	0.63	0.95	2.64	4.76	9.72	12.91	2.66
Pazin	J1	3.41	2.58	2.14	1.80	0.99	0.86	0.46	0.74	1.27	2.38	3.88	3.88	1.39
Pula	J1	1.94	1.44	1.09	0.86	0.48	0.37	0.18	0.33	0.57	1.06	1.87	1.80	0.67
Rijeka	J1	3.58	2.54	2.13	1.68	0.98	0.85	0.38	0.55	1.27	2.62	3.57	4.00	1.40
Senj	J1	1.15	1.12	0.91	0.80	0.52	0.40	0.18	0.28	0.67	1.04	1.88	1.82	0.65
Zadar	J2	1.59	1.29	1.08	0.90	0.56	0.33	0.15	0.25	0.74	1.08	1.61	1.86	0.69
Knin	J2	2.53	1.94	1.50	1.35	0.86	0.56	0.23	0.34	0.92	1.56	2.55	3.19	0.96
Šibenik	J2	1.18	0.95	0.81	0.66	0.33	0.24	0.10	0.16	0.41	0.67	1.19	1.28	0.46
Split Marjan	J3	1.14	0.87	0.73	0.54	0.34	0.19	0.08	0.15	0.32	0.57	1.10	1.28	0.41
Hvar	J3	1.19	0.92	0.89	0.57	0.34	0.18	0.11	0.19	0.36	0.63	1.12	1.30	0.47
Dubrovnik	J3	1.51	1.44	1.21	0.97	0.51	0.23	0.12	0.31	0.46	0.88	1.53	1.67	0.67

Colour codes showing the categories due to susceptibility to desertification are according to Table 1. Regions (Reg.): P-Pannonian, G- mountainous, J- maritime region.

Table 3. Proportion of the necessary and optional parameter classes related to the vulnerability (Vlb.) classes over the territory of Croatia (expressed in km²)

Vlb.	Slope		Irradiation		Coeff. of variation		World soil		Land cover	
class	Limits [°]	Area [km²]	Limits [kWh/m²]	Area [km²]	Limits	Area [km²]	Type	Area [km²]	Code	Area [km²]
0.2	0–5	32325.6	1164.9-1259.0	18609.2	0.08-0.16	21582.5	-	-	223,243,311,312,313,324	31879.2
0.4	5–12	14482.4	1259.0-1353.1	22763.5	0.16-0.24	33802.6	LV	24923.5	221	289.0
0.6	12–20	6699.3	1353.1-1447.2	6526.7	0.24-0.32	1130.2	CM	13508.0	242,321,322,323,333	14803.6
0.8	20–35	2875.2	1447.2-1541.3	7485.7	0.32-0.40	37.6	PH	1824.6	222	95.5
1.0	35–90	172.2	1541.3-1635.4	1169.6	0.40-0.48	1.9	LP	16298.8	211,212	3797.0

Soil classes: LV - Luvisol, CM - Cambisol, PH - Phaeozem, LP – Leptosol. Land cover code according to Table 4. Dominant Vlb. class is shaded for all maps.

Slope

The slope map presents the slope angle calculated from the digital elevation model (SRTM DEM of 100 m resolution). Calculated angles range from 0° on the flat terrain to 74° in some river canyons and on mountain slopes, though the slopes predominantly belong to the lowest category classes of 0.2 and 0.4 (Figure 2 a and Table 3). Steeper slopes are more likely to lose water and to become dryer.

Solar irradiation

The potential incoming solar irradiation (PISR) map for the vegetation period is calculated using the RSAGA rsaga.pisr module (Brenning, 2011). This algorithm is implementation of the Saga GIS Potential Incoming Solar Radiation module (Conrad, 2010) for R statistical computing and visualisation framework (www.r-project.org). PISR was calculated for one year with four hours' temporal resolution and clear sky conditions. Maximum values are predicted for the southern slopes while minima are associated with the northern slopes (map is not shown). The obtained range of values is larger (126.7 kWh/m2 –1552.6 kWh/m2), compared to the irradiation map from the observations (Table 3 and Figure 2 b) due to a number of pixels in shadows with very low irradiation values (<500 kWH/m2). This small-scale spatial information could not be deduced from the irradiation map derived from the observations. The problem that arises from the proposed methodology has to do with the characteristics of Croatian climate. Namely, the irradiation on the territory of Croatia depends significantly on the cloudiness regime that was not included in the PISR calculation. Thus, the available Croatian solar irradiation map for the 1961–1980 period (Perčec Tadić, 2004; Perčec Tadić, 2008) was used. The irradiation is increasing from the north to the south and is larger on the coast than inland (Figure 2 b). The values are lower on mountain tops due to an increased cloudiness during summer. This is contrary to the distribution of potential irradiation which shows maximum values on mountain summits. It could not be expected that the vulnerability to drought in the vegetation period, due to solar radiation, would be the highest on the mountain tops. Most of the territory belongs to the lowest category classes of 0.2 and 0.4 (Table 3).

Precipitation

Vulnerability to drought over a certain region depends not only on the precipitation amount but also on its regular appearance. If some years have significantly lower precipitation than the average, larger inter-annual variability appears and the droughts will present a stronger threat to the area. This can be analysed taking into account the coefficient of variation of annual precipitation, that is the ratio of standard deviation and precipitation.

Average annual precipitation (map not shown) in Croatia for the 1971–2000 period ranges from about 3900 mm on the summits of the southern Velebit mountain located along the northern Croatian Adriatic coast to about 300 mm on the outlying islands in mid-Adriatic. Quite dry areas are also the eastern lowland (Slavonia), the middle and southern Adriatic islands and the coastal flat zone of the western Istrian peninsula and middle Adriatic coast. The mountainous hinterland (Gorski Kotar) of the Kvarner Bay in the northern Adriatic and of the southern Dalmatia as well as the southern Velebit mountain are the areas with the highest precipitation amounts in the country.

This precipitation map was created in the regression kriging framework, as described in Perčec Tadić (2010). Average annual precipitation data from the 1971–2000 period, collected on 562 meteorological stations have been used in the geostatistical analysis. The correlation with the climatic factors such as altitude, weighted distance to the sea, latitude and longitude has been established and the residuals (differences of observation and regression prediction) were modelled for the spatial correlation. A final prediction of the average annual precipitation was calculated as a raster map at a 1-km resolution. This map was resampled to a 100-m resolution for the estimation of the drought vulnerability map.

Standard deviation of precipitation for the 1971–2000 period (map not shown) was calculated using the same method as for precipitation (and solar irradiation), that is, regression kriging. Values of standard deviation range from 99 mm to as high as 455 mm. The lowest values are recorded over the western continental part of the country, eastern continental lowland and some coastal areas (western Istria in the northern Adriatic and the plain of Ravni Kotari beyond the mid- Adriatic coast). Standard deviation is the highest in mountain areas.

Coefficient of variation (Figure 2 c) is defined as the ratio of standard deviation and precipitation. Higher values are correlated with higher vulnerability to drought. The most sensitive areas are found on the southern coast. Coefficient of variation ranges from 8% to 48% of the average annual precipitation amount. With the proposed classification procedure of five equidistant classes, the resulting category map is dominated by the lowest category classes of 0.2 and 0.4 (Table3).

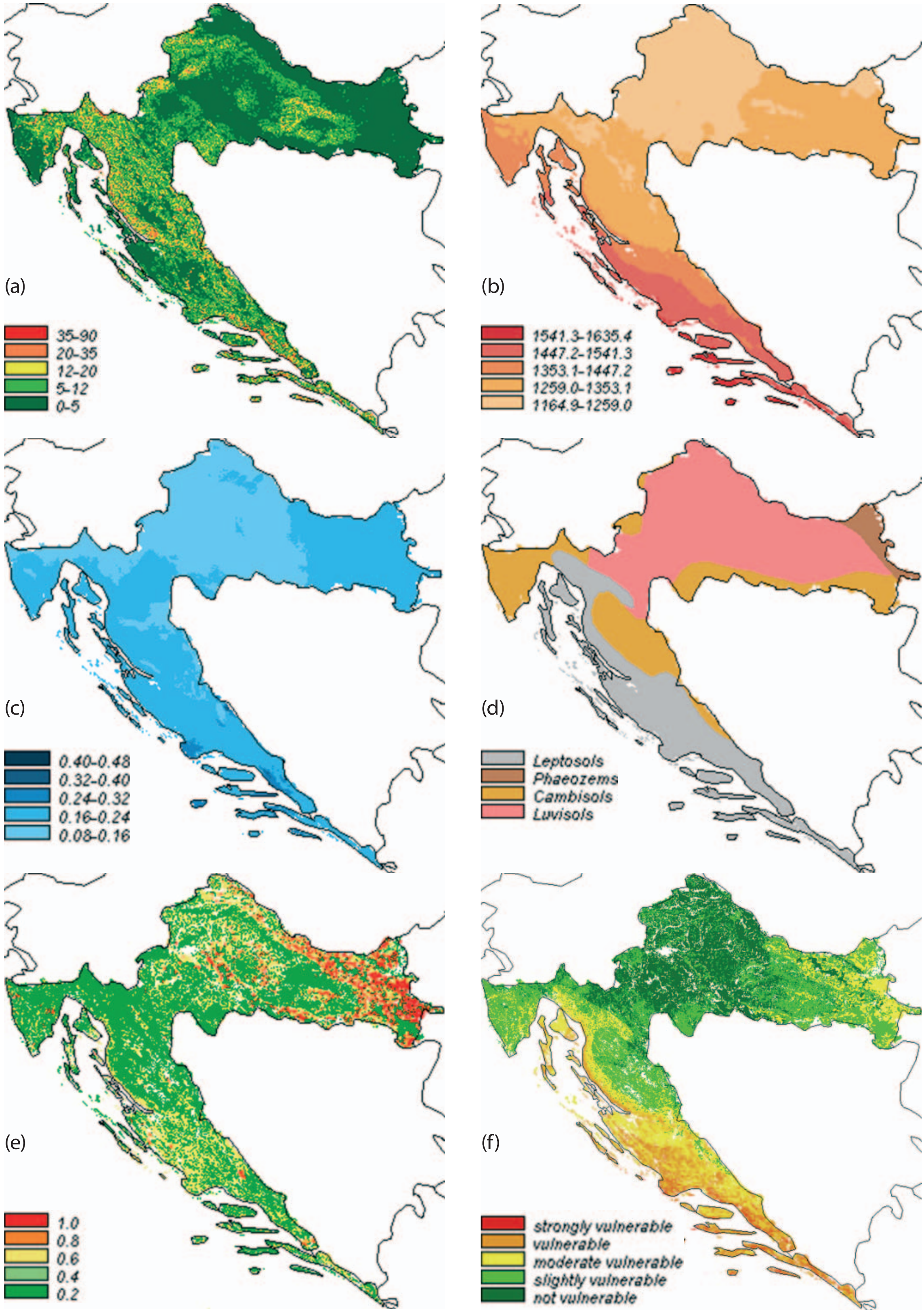

Figure 2. Input maps of (a) Slope [°], (b) Annual solar irradiation [$kWhm^{-2}$], (c) Coefficient of variation of precipitation, (d) Soil classes and (e) Land cover. (f) Drought vulnerability map, V3

Soil class

The Map of World Soil Resources (WRB, 2003) is available from the FAO web page at a scale of 1:25.000.000 as a World Soil Resources Coverage (WSRC, 2003). There are 32 soil classes for the world and, at this scale, four of them can be found in Croatia. Widespread are Luvisols (class 0.4), followed by Leptosols (class 1.0) and Cambisols (class 0.6), while the rarest are Phaeozems (class 0.8) (Table 3).

Luvisols (LV) are the most common soil in flat or gently sloping land in cool temperate (Central Europe) and warm regions (e.g. Mediterranean) with distinct dry and wet seasons. Most Luvisols are fertile soils and suitable for a wide range of agricultural uses. These are characterized by a clay-rich subsoil (IUSS Working Group WRB, 2006); Hence, they are resilient to drought. Luvisols dominate the continental part of Croatia, accompanied by some Cambisols and Phaeozems (Figure 2 d).

Cambisols (CM) generally make good agricultural land and are used intensively. Cambisols with high base saturation in the temperate zone are among the most productive soils on earth. In Croatia, they dominate the Istrian peninsula, Lika region and the area of Sava river bed. Due to WSRC generalisations, it can be argued that, in the northern part of the mountainous district of Gorski Kotar, WSRC Cambisols are misclassified as Leptosols (Bakšić et al., 2008), whereas on the Medvednica mountain in NW Croatia, beside Luvisols, Cambisols are also present (Pernar et al., 2009).

Pheaeozems (PH) are more common in America and Asia. In Europe, mostly discontinuous areas are found in Central Europe, notably the Danube area of Hungary and adjacent countries like Croatia. Wind and water erosions are serious hazards. There can be periods in which the soil dries out (IUSS Working Group WRB, 2006).

Leptosols (LP) are the world's most extensive soils (IUSS Working Group WRB, 2006). These are very shallow soils over continuous rocks, extremely gravelly and/or stony, and consequently the most susceptible to drought. They predominate on the Croatian coast, with the exception of the Istrian peninsula

Land cover

Land cover classes for the part of the Croatian territory covered with vegetation have been analysed from the Corine Land Cover raster data (CLC, 2006). The area of 50,864.3 km2 (89.9%) of the Croatian territory is covered with some kind of vegetation (Table 4). The largest part of the Croatian land (56.4%) is mostly covered with forest and transitional woodland-shrub or occupied by agriculture with significant areas of natural vegetation belonging to the lowest class of 0.2 (Figure 2 e). These types of vegetation are not so vulnerable to drought. Vineyards occupy 0.5% of the area and are slightly more sensitive to drought. Complex cultivation patterns, natural grasslands and sclerophyllous vegetation are the second most widespread land cover type and occupy 26.2% of the territory. They belong to the 0.6 vulnerability class. Fruit trees and berry plantations are quite sensitive to drought but grow on only 0.2% of the land. Most sensitive to drought is arable land (6.7%) which in Croatia, unfortunately, is mostly non-irrigated (6.5%), according to the CLC 2006 data.

When available, the CLC 2006 data were compared against the national sources. According to the CBS (2011), forests occupy

Table 4. Description of the vulnerability classes (Vlb. class) for the land cover map

Vlb. class	Description	Code	Area [%]
0.2	Olive groves, Land principally occupied by agriculture, with significant areas of natural vegetation, Broad-leaved forest, Coniferous forest, Mixed forest, Transitional woodland-shrub	223, 243, 311, 312, 313, 324	56.4
0.4	Vineyards	221	0.5
0.6	Complex cultivation patterns, Natural grasslands, Moors and heathland, Sclerophyllous vegetation, Sparsely vegetated areas	242, 321, 322, 323, 333	26.2
0.8	Fruit trees and berry plantations	222	0.2
1.0	Non-irrigated arable land, Permanently irrigated land	211, 212	6.7
	Without vegetation, water area		10.1

39.5% of the territory. According to the National Agricultural Census Report (CBS, 2003), Croatia has 0.5% of vineyards, 0.6% of orchards, 14.2% arable land and gardens and only 0.2% of irrigated arable land.

Results

Aridity index

The climate assessment in Croatia, according to the aridity index, shows, on average, the prevailing precipitation deficit in the warm part of the year throughout the country, with the exception of the mountainous region (Table 2). In the Pannonian region, there is no precipitation deficit on the annual scale; the deficit rather occurs on a monthly basis. The precipitation deficit decreases going from the east to the west. Moreover, the duration of deficit is shorter in the western and northwest regions (from May to August) than in the eastern and central mainland (from April to September). In the mountainous region, there is more precipitation than is necessary for water evaporation. However, the precipitation deficit occurs in the pre-mountainous area only during July. The deficit is mostly pronounced in the Adriatic region. In the mid-Adriatic region, the precipitation deficit usually lasts from April (May) to September, while in the southern region, the deficit is present from February to October. The mean annual precipitation restores only 50% of the evaporating water.

According to the P/PET categorization (Table 1), the average annual climatic conditions in Croatia are not favourable to desertification (P/PET<0.05). On the annual scale, the semi-arid zone is present on the mid-Dalmatian coast and Dalmatian islands (Table 2). However, in the warm half of the year, there is a susceptibility to desertification in the eastern Croatia (Slavonia) and the coastal region. The eastern Slavonia finds itself in the dry sub-humid zone from May to September, including the warmest month of July. The semi-arid characteristic of the precipitation deficit appeared in its northern part. In contrast to the average conditions in the reference 1961-1990 period (not shown), in the recent 30-year period of 1971-2000, precipitation deficit characteristics of a dry sub-humid zone were recorded on mainland

Table 5. Proportion of drought vulnerability classes over the territory of Croatia (expressed in km2 and percents of land area) for three versions of the vulnerability map

Vulnerability class	V1		V2		V3		
	Limits	Area [km^2]	Limits	Area [km^2]	Limits	Area [km^2]	Area [%]
NV	0.6-1.0	33015.3	1.00-1.52	24744.9	1.2-1.8	15891.7	28.1
SlV	1.0-1.4	12445.1	1.52-2.04	16016.1	1.8-2.4	16678.3	29.5
MV	1.4-1.8	7852.8	2.04-2.56	9095.5	2.4-3.0	11925.1	21.1
V	1.8-2.2	2784.3	2.56-3.08	6241.7	3.0-3.6	5797.2	10.3
StV	2.2-2.6	457.3	3.08-3.60	456.5	3.6-4.2	571.9	1.0

Drought vulnerability classes: NV - not vulnerable, SlV - slightly vulnerable, MV - moderately vulnerable, V - vulnerable and StV - strongly vulnerable. Dominant Vlb. class is shaded for all maps.

locations (Zagreb and Sisak), and even in the mountainous location of Gospić. The vulnerability to desertification is most pronounced on the Adriatic coast and islands. The semi-arid zone occurs on the west coast of Istria, Primorje and northern Dalmatia in the summer (JJA), and the length of the semi-arid period extends from May to September in the southern Adriatic. The characteristics of an arid zone, in terms of rainfall deficit, can be perceived in the warmest month of July along the coast and from June to August in the central Dalmatia.

Drought vulnerability map

The first version of the drought vulnerability map (not shown) is calculated from the category maps of slope, irradiation and the coefficient of variation of precipitation. It is dominated by the lowest vulnerability classes (Table 5, V1) of "not vulnerable" and "slightly vulnerable" since the lowest class categories of 0.2 and 0.4 are the most common on the category maps of slope, coefficient of variation of precipitation and solar irradiation.

Inclusion of soil information raises drought vulnerability most evidently along the coast and the Dinaric mountains as well as in the very eastern lowland of Slavonia (map not shown) (Table 5, V2). Since the coastal zone is dominated by Leptosols (class 1.0, Table 2), excessive internal drainage and the shallowness of Leptosols can cause a drought even in a humid environment (IUSS Working Group WRB, 2006). The continental part of the country is mostly "not vulnerable", according to this version of the vulnerability map. Only dryer (east of Croatia) or steeper mainland (Slavonian mountains) can be "slightly vulnerable". "Slightly vulnerable" are also the Istrian peninsula and the mountainous Lika region, where only some smaller parts belong to the classes of "not vulnerable" or "moderately vulnerable". Along the coast, vulnerability rises southwards from "moderately vulnerable" and "vulnerable" on the northern Adriatic coast and over the nearby Velebit mountain to the predominant "vulnerable" class on the southern Adriatic coast. "Strongly vulnerable" to drought are some steeper slopes with higher irradiation and/or higher precipitation variability.

This vulnerability map was modified further by the inclusion of the land cover map in the analysis. Consequently, a final version of the drought vulnerability map (Figure 2 f) is calculated from the category maps of slope, irradiation, coefficient of variation of precipitation, soil classes and land cover classes for the areas with vegetation only. The vulnerability increased mainly on the cultivated land, natural grassland and arable land, and decreased predominantly in the forests and olive groves, which are adapted to the dryness.

According to the final vulnerability map (Table 5, V3), 28.1% of the Croatian territory is not vulnerable to drought. Slightly vulnerable is 29.5% of the area, and 21.1% is moderately vulnerable. Vulnerable to drought is 10.3% and only 1% of the territory is strongly vulnerable. The 10% of the land without vegetation or water bodies has not been classified.

The easternmost inland part of Croatia is considered "moderately vulnerable" to drought. This area is largely associated with arable land or complex cultivation patterns. Forests in this area belong to the "not vulnerable" and "slightly vulnerable" classes. In the north-west inland area, the woods are principally "not vulnerable", while the arable land and cultivated areas are "slightly vulnerable" to drought. "Slightly vulnerable" are also the Istria and Lika regions where only some smaller parts are classified "not vulnerable" (mixed forests) or "moderately vulnerable" (cultivated land or pastures). On the northern Adriatic coast, the vulnerability rises to "moderately vulnerable" (forests) and "vulnerable" (cultivated areas, sparse vegetation or shrub). On the mid-Adriatic coast, "moderately vulnerable" to drought are primarily transitional woodlands, while grassland and cultivated areas are "vulnerable". Some smaller areas can be "strongly vulnerable" to drought.

Discussion and conclusions

For the purpose of sustainable adaptation to the detected climate change, namely the frequent droughts in Croatia, drought risk assessment emerges as one of the priorities. The present study accomplishes the first step towards this goal giving insight into the drought-prone regions of Croatia.

In a globally changing climate, the region of Croatia belongs to the transitional area between northern Europe with an increase in average precipitation and a drying Mediterranean. Annual precipitation trends during the recent 50-year period (1961-2010) are found to be mainly negative throughout the main part of Croatia, thus reflecting the characteristics of the Mediterranean regime (Gajić-Čapka et al., 2013). The eastern lowland, belonging to the very southern part of the Pannonian Plain, exhibits positive, thought insignificant, annual precipitation trends, more like those of central Europe. The most pronounced seasonal trends are associated with summer, with a significant decrease in the mountainous region and on the coast. For spring, significant downward trends are found in the mountainous region and on the Istrian peninsula, while for autumn, significant upward trends are recorded in the eastern lowland. The decrease is mainly associated with an increase in frequency of dry days and decrease in frequency of moderately wet and very wet days. A comparison between two climate periods, 1961-1990 and 1971-2000, shows evidence of warming throughout Croatia (MZOPUG, 2007) that, together with a generally prevailing downward trend in precipitation (MZOPUG, 2007; Gajić-Čapka et al., 2013), results in climatic conditions more favourable to drought.

In this context of climatic change, the droughts are expected to become more frequent, intense and to last longer. This has been supported by a comparison of the aridity index for the two 30-year periods. The later period shows precipitation deficit characteristics of a dry sub-humid zone in mainland and even mountainous locations, and in some places an extended period with a precipitation deficit, compared to the earlier period. Precipitation deficit of the later period in the warm part of the year dominates the whole country, except the mountainous region. The deficit is mostly pronounced in the Adriatic region and the deficit period is longer in the southern Adriatic (Table 2).

Following this analysis is the calculation of the drought vulnerability map (Figure 2 f) as an attempt to summarize the complex interactions of terrain, soil, land cover and climatological properties of the region in only one parameter that would describe the sensitivity of a region to drought. The vulnerability map was calculated from climatological, morphological and land cover characteristics, while it could also include such information as irrigation and groundwater level. The map detected the relative preferences of the Croatian territory to drought due to steep slopes, large precipitation variability, increased irradiation, soil types not able to retain water or cultivated with plants less resilient to drought. Despite the promising and encouraging results, there remains the issue of interpretation of class values on this map. A major concern is how to set the limiting values for the vulnerability classes. The choice of equal intervals for classes on the input maps as on the vulnerability map is not an ideal one due to the fact that the distribution of values for the maps can be skewed. This enables the tails of the distribution to predominate in more than one vulnerability class. Further research should focus on defining the actual limits for the vulnerability classes that should be established as the result of correlation analysis between natural drought parameters and consequences (for example, economic losses in agriculture and electricity production by hydropower). Solution of the key to these relations could allow for an expert decision on how to treat a land that belongs to a certain vulnerability class and how to compare drought vulnerability maps from different countries.

References

Bakšić D., Pernar N., Vukelić J., Baričević D. (2008). Properties of cambisol in beech-fir forests of Velebit and Gorski Kotar. Period. Biol., Vol 110, No 2: 119-125

Brenning A. (2011). Package 'RSAGA', http://cran.r-project.org/web/packages/RSAGA/index.html

CBS (2003). Agricultural Census 2003. Croatian Bureau of Statistics

CBS (2011). Croatia in Figures 2011. Croatian Bureau of Statistics

Cindrić K., Pasarić Z., Gajić-Čapka M. (2010). Spatial and temporal analysis of dry spells in Croatia. Theor. Appl. Climatol. Vol 102 (1-2): 171-184

CLC (2006). Corine Land Cover 2006 raster data - version 15 http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1/

Conrad O. (2010). Modul for the Potencial Solar Radiation in SAGA GIS http://www.saga-gis.org

Eagleman J.R. (1967) Pan evaporation, potential and actual evapotranspiration. J. Appl. Meteorol. 6: 482-488

Gajić-Čapka M., Cindrić K., Mihajlović D. (2008). Precipitation. In: Klimatski atlas Hrvatske / Climate Atlas of Croatia 1961–1990., 1971–2000. Zaninović K. (ed) Meteorological and Hydrological Service of Croatia , Zagreb, 43-59

Gajić-Čapka M., Cindrić K., Pasarić Z (2013). Trends in indices of precipitation extremes in Croatia, 1961–2010. Theor. Appl. Climatol. Submitted.

IUSS Working Group WRB (2006). World reference base for soil resources 2006. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome

Meehl G.A., Stocker TF., Collins WD., Friedlingstein P., Gaye AT., Gregory JM., Kitoh A., Knutti R., Murphy JM., Noda A., Raper SCB., Watterson IG., Weaver AJ., Zhao Z-C. (2007). Global climate projections. In: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt KB., Tignor M., Miller HL. (eds) Climate Change: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

MF (2013). Economic losses from natural hazards in Croatia during the period 1981–2012. Državno povjerenstvo za procjenu štete od elementarnih nepogoda, Ministarstvo financija. Unpublished.

MZOPUG (2007). National Action Programme to Mitigate the Effects of Drought and Combat Land Degradation (in Croatian). Kisić I., Vihovanec M., (coordinators), Ministry of Environmental Protection, Physical Planning and Construction (MZOPUG), Zagreb. Unpublished. http://klima.hr/razno.php?id=projekti&param=nap

Pandžić K. (1985). Bilanca vode na istočnom primorju Jadrana, Rasprave, 20: 21-29

Perčec Tadić M. (2004). Digitalna karta srednje godišnje sume globalnog Sunčeva zračenja i model proračuna globalnog Sunčeva zračenja na nagnute, različito orijentirane plohe. Hrvatski meteorološki časopis. 39: 41-50

Perčec Tadić M. (2008). Solar radiation. In: Klimatski atlas Hrvatske / Climate Atlas of Croatia 1961–1990., 1971–2000. Zaninović K. (ed) Meteorological and Hydrological Service of Croatia , Zagreb, 75-79

Perčec Tadić M. (2010). Gridded Croatian climatology for 1961-1990. Theor. Appl. Climatol. 102 (1-2): 87-103

Pernar N., Vukelić J., Bakšić D., Baričević D., Perković I., Miko S., Vrbek B. (2009). Soil properties in beech-fir forests on Mt. Medvednica (NW Croatia). Periodicum biologorum. 111 (4): 427–434

UNEP/GEMS (1992) Global reassessment of desertification

Vicente-Serrano SM. (2006). Spatial and temporal analysis of droughts in the Iberian Peninsula (1910-2000). Hydrological Sciences Journal, 52 (1): 83-97

WRB (2003). Map of World Soil Resources 1:25 000 000 http://www.fao.org/ag/agl/agll/wrb/soilres.stm

WSRC (2003). World Soil Resources Coverage ftp://ftp.fao.org/agl/agll/faomwsr/wsrll.zip

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