Fuzzy Logic Approach to Complex Assessment of Drought Vulnerability

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Abstract. Drought is a common climate phenomenon for the territory of Bulgaria, which has a negative impact on agriculture and water resources. Taking into account the undetermined character of drought in regard to drought occurrence, severity and impact the present study proposes a fuzzy logic approach to complex drought vulnerability assessment. The assessment is based on multifactorial analysis integrating climatic (precipitation and air temperature) and non-climatic (distance from the water objects, aspects and soil types) factors for drought occurrence as well as anthropogenic factors (land use types) in order to determine drought susceptibility and vulnerability. In this study, the fuzzy logic model is designed as a three-level hierarchical system with four inputs and one output. Each level of the hierarchical system is consisted of one fuzzy logical subsystem with two inputs. The results of the simulations performed with developed fuzzy logic system using actual data show the importance of climatic factors for drought susceptibility while drought vulnerability depends mainly of anthropogenic factors. The areas with the same susceptibility to drought may have different degrees of vulnerability depending on the type of land use and the number of people affected. The fuzzy logic model is useful for a comprehensive drought assessment, especially for areas for which available data are insufficient.

Keywords: Fuzzy logic approach · Drought susceptibility · Drought vulnerability · Multifactorial analysis

1 Introduction

Drought is a consequence of reduced precipitation over a long period of time. It often occurs in conjunction with several meteorological elements such as high temperatures, strong winds and low relative humidity, which makes this phenomenon very pronounced. In addition, anthropogenic activity, deforestation, urbanization and various types of land use can exacerbate the negative effects of drought. A trend towards a significant increase in the areas in Europe affected by water scarcity has been established. Between 1976 and 2006, the number of regions and people in the EU affected by drought increased by almost 20%. One of the largest droughts was observed in 2003, when more than 100 million people and a third of the EU's territory were affected. The economic losses from

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the drought in Europe in 2003 exceeded $ 13 trillion [1]. The results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) show a decrease of precipitation in Southern Europe, including Bulgaria with about 10–20% during the period 2081–2100 in comparison to 1986–2005 [2]. According to the climate models, an increase in drought and prolonged dry periods combined with high temperatures are expected [3–5]. Considering RCP8.5 emission scenario Spinoni et al. [6] point out that severe and extreme droughts will increase in Europe and over southern Europe the extend of spring and summer drought will be observed.

Drought differs from aridity, low flow, water scarcity and desertification [7]. Aridity is permanent characteristic of the climate in some areas with very low annual rainfall, while drought is a temporary phenomenon. On the other side, water scarcity is a temporary water imbalance that occurs as a result of drought or anthropogenic activities. Due to various causes and consequences, different types of droughts are analyzed in the scientific publications [8–12].

- Meteorological (atmospheric) drought depends on the amount of rainfall. Defined as the period, generally from months to years, in which the inflow of moisture to an area drops below the normal level under given humid climatic conditions. The atmospheric conditions associated with a deficit of precipitation are different for the individual regions, therefore the meteorological drought have to be defined according to the specifics of the respective region. In addition to the absence or little rainfall meteorological droughts are often characterized by - high temperature and low air humidity. The reason is the high atmospheric pressure and the advection of warm and dry air masses.
- Agricultural drought is associated with the deficit of soil moisture (mostly in the root zone). It is a period when soil moisture is insufficient to meet the water needs of plants and to carry out normal agricultural management.
- Hydrological drought is characterized by a decrease in river flow and usually occurs with a delay compared to meteorological and agricultural drought. Since river basins are interconnected by hydrological systems, a hydrological drought may cover a larger area than that originally covered by a meteorological drought.
- Socioeconomic drought is associated with the effects of water scarcity, which affect socio-economic systems. This type of drought occurs when the demand for an economic commodity exceeds the supply as a result of a shortage of water due to the weather.
- Ecological drought is defined by Crausbay et al. [13] as "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems."

Common to all types of drought is the lack of precipitation [14]. From a meteorological point of view, drought is associated with periods of varying lengths with water shortages. The main measure for drought is the insufficient amount of precipitation for a specific activity (i.e. crop growth, irrigation water supply, water level in dams), [15].

Many publication analyze various aspect of drought phenomena in Bulgaria: drought in 90-es and hydrological and economic impact [16]; drought study based on various precipitation indices [11], soil drought [15], theoretical review of methods for drought investigation [17], study drought based on SPI and precipitation anomalies [18], agricultural drought [19–21], wetlands-drought relation [22]. On the other side drought hazard, vulnerability and risk are important topics which are not well investigated in Bulgaria.

The overall objective of the present research is to enlarge the knowledge about drought assessment and to support decision making by presenting a tool for drought assessment in respect to drought susceptibility and vulnerability. In this regard, the specific aim is to propose a fuzzy logic approach to complex drought assessment in selected area regarding to the multiple monitored factors. In order to achieve the aim of study the following tasks are solved: 1) assessment of drought susceptibility based on drought triggering factors, and 2) integration of the results of drought susceptibility analysis with anthropogenic factors and develop a fuzzy logic model for complex drought assessment. The northwest region of Bulgaria (NUTS 2 - Severozapaden) is selected as a case-study area. Considering data availability and fact that the area is mainly agricultural the fuzzy logic model development is directed to the agricultural drought assessment.

2 Factors for Drought Occurrence and Manifestation

Precipitation is the main factor causing droughts, but there are also a number of other climatic factors that increase intensity of dry events (e.g. high temperature or low relative humidity, strong wind, moisture deficit, sunshine, atmospheric pressure, climate peculiarities). In addition to the climatic factors for drought occurrence, the duration of the dry periods, as well as the altitude, the topography, the land use and the extent of the affected areas also influence. The combined action of different climatic factors leads to the manifestation of different types of drought. For example, precipitation in combination with insignificant snow cover and high temperatures is a factor for the manifestation of hydrological drought, while for the agricultural drought occurrence the leading factors are air temperature and wind speed, not precipitation, especially in areas where irrigated agriculture is possible. Due to the fact that soil moisture, sunshine duration and solar radiation are the parameters that are measured in a limited number of stations or are not measured regularly and the data do not cover large areas, most often drought assessment is made based on the precipitation as a source of soil moisture. On the other side extreme high temperature can cause flash drought [23]. Because air temperature and precipitation are the most often measured elements and for which there is a good database the combination of both factors – temperature and precipitation is most often examined in the agricultural drought assessment.

The combined study of air temperature and precipitation makes it possible to assess the dry and rainy periods in terms of conditions for the development of cultivated plants. At above-average rainfall and below-average temperatures, there is the lowest stress for plants. The most stressful conditions are associated with high temperatures and low rainfall. At high temperatures and high precipitation, as well as at temperatures below average, combined with precipitation below average, moderate stress is noted.

The negative effect of drought is determined by its duration, intensity, spatial extent and the number of people affected. Despite of technological development climatic factors, soil types, hydrological peculiarities still have a significant contribution to the negative effects of drought. The risk associated with drought is determined by two factors: 1) the degree of exposure of the area to drought, the possibility of droughts of varying severity and 2) how vulnerable people, infrastructure, economic assets are at risk. Vulnerability to drought is determined by socio-economic factors such as demographic characteristics of the population, technological development, water use, land use, economic and cultural development, and country policy. These factors change over time, and this leads to different consequences of drought events, even when they have the same intensity, duration and spatial extend.

The intensity and consequences of drought depend on the time of occurrence (season, delay of the rainy season, precipitation in connection with the phases of development of major crops). Therefore, each dry year has unique characteristics and consequences. The drought is a complex phenomenon that has a negative effect on various sectors, therefore the assessment of drought risk has to be done on the basis of multi-criteria analysis, including not only meteorological and hydrological parameters but also social and economic aspects.

3 Study Area and Data

The study area is the territory of the northwestern administrative region in Bulgaria – NUTS 2 (Severozapaden) which includes five administrative districts (NUTS 3): Vidin, Montana, Vratsa, Pleven and Lovech. Most of the studied area is a part of the Danube plain located between Balkan Mountains on the south and the Danube River on the north. The relief is flat and hilly, and in the southern and southwestern parts – mountainous (see Fig. 1). The climate is temperate continental and is formed under the influence of predominant air advection from the northwest and north [24].

Agriculture is among the main economic sectors in the northwestern region and in a significant part of the territory the natural vegetation has been replaced by cultivated plants, which increases the vulnerability of the region to drought. Analyzing eight socio-economic indicators as regional GDP, unemployment rate, employment in high-tech sectors, research and development expenditure, motorways network, population density, life expectancy at birth and people at risk of poverty or social exclusion, Dokov and Stamenkov [25] have pointed out that NUTS 2 - Severozapaden is among the least developed Danube-adjacent regions. The low level of socio-economic development is crucial for the lower capacity of the region to adapt to climate change and brings to the greater vulnerability to adverse climatic events, including drought.

In order to achieve the aim of the study the following type of data were used:

- Climatic data – monthly air temperature and precipitation from selected meteorological stations located at the investigated area, and
- Geographic information: some basic data such as Balkan national borders, borders of Bulgaria's NUTS 2 regions, urban areas, hillshade layer (based on STRM elevation data), and some more specific data - rivers, water areas, soils, and Digital Terrain Model (DTM). All basic data layers were used for preparing the maps in addition to the processed specific data used for the assessment of drought susceptibility.

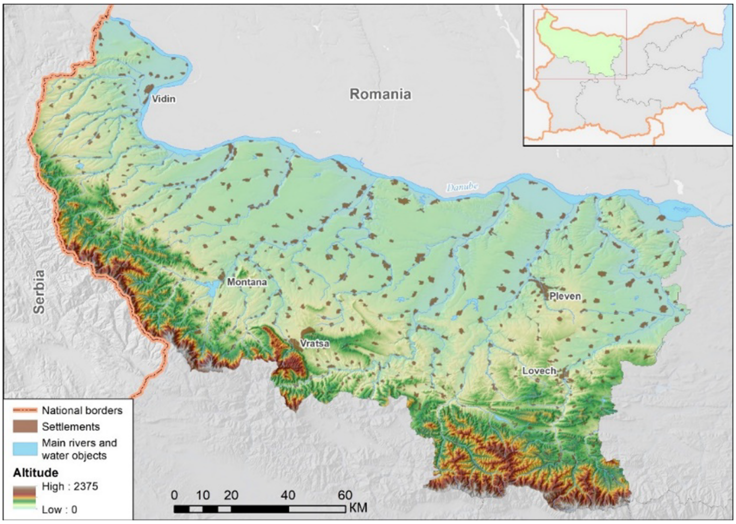

Fig. 1. Study area – NUTS 2 region Severozapad

4 Essence of the Fuzzy Logic Approach

This study proposes a fuzzy logic approach to complex drought assessment that integrates various natural and anthropogenic land factors. Due to the indeterminate nature of drought, the fuzzy logic has been described in several publications as a successful tool to study the drought occurrence, manifestation, impact, hazard, susceptibility and vulnerability [26–29].

The present approach is based on the factor analysis which is recommended for a complex assessment of drought vulnerability [30, 31]. The approach includes two main stages. The purpose of the first stage is to identify the factors influencing drought occurrence and manifestation. Based on the expert knowledge and the peculiarities of the studied area, the factors are grouped into two groups: 1) related to natural forces and 2) indicators of anthropogenic activity. The group of natural factors is divided into two groups: climatic (precipitation and air temperature) and non-climatic factors (distance from rivers, aspect and soil types). In this study, the land use and land cover data from CORINE Land cover are used as indicators of the anthropogenic activity.

The purpose of the second stage is to develop a fuzzy logic model for complex assessment of drought vulnerability based on the identified groups of factors. Here, the fuzzy logic model is designed as a three-level hierarchical system with four inputs and one output. Each level of the hierarchical system is consisted of one fuzzy logical subsystem with two inputs. The fuzzy logic system output gives a drought vulnerability assessment in certain area regarding to the multiple monitored factors.

A scheme of the three-level hierarchical fuzzy system for complex assessment of drought vulnerability is presented on Fig. 2.

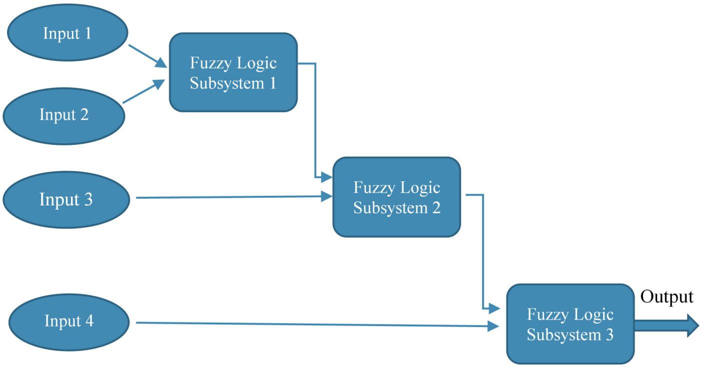

Fig. 2. Three-level hierarchical fuzzy system with four inputs

The following four variables are defined as system inputs on the basis of expert knowledge and the identified factors influencing the drought: Input 1 "Precipitation" (% of climate normal), Input 2 "Air temperature" (according to the percentile distribution), Input 3 "Non-climatic factors for drought" and Input 4 "Anthropogenic factors". In the designed model, two intermediate linguistic variables are defined: Intermediate variable 1 "Climatic factors for drought" and Intermediate variable 2 "Natural factors for drought". The fuzzy logic system output is defined as the linguistic variable "Drought vulnerability degree".

In the proposed fuzzy logic model, the all input linguistic variables, corresponding to the defined four inputs, two intermediate variables and system output are described by five membership functions, as follow: 1) "*Very low* (*VL*)", 2) "*Low* (*L*)", 3) "*Moderate* (*M*)", 4) "*High* (*H*)", and 5) "*Very high* (*VH*)". The all linguistic variables are assessed in the given intervals using trapezoidal membership functions as shown in corresponding tables (from Table 1, Table 2, Table 3, Table 4 and Table 5).

Table 1. Numeral values of membership functions and susceptibility levels of the *Input 1*

Precipitation, P (% of climate normal)/determined values/	Trapezoidal membership functions	Drought conditions	Susceptibility level
$95 \leq P$	[93, 97, 100, 100]	Normal	VL
$85 \leq P < 95$	[83, 87, 93, 97]	Mild dry	L
$75 \leq P < 85$	[70, 77, 83, 87]	Moderate dry	M
$50 \leq P < 75$	[45, 55, 70, 77]	Very dry	H
$P < 50$	[0, 0, 45, 55]	Extremely dry	VH

Table 2. Numeral values of membership functions and susceptibility levels of the *Input 2*

Air temperature, *T* (percentiles)/determined values/	Trapezoidal membership functions	Drought conditions	Susceptibility level
$T \leq 10^{-\text{th}}$	[0, 0, 5, 15]	Extreme low	VL
$10^{\text{th}} \leq T < 30^{\text{th}}$	[5, 15, 25, 35]	Low	L
$30^{\text{th}} \leq T < 70^{\text{th}}$	[25, 35, 65, 75]	Near normal	M
$70^{\text{th}} \leq \text{T} < 90^{\text{th}}$	[65, 75, 85, 95]	High	H
$90^{\text{th}} \leq T$	[85, 95, 100, 100]	Extreme high	VH

Table 3. Numeral values of membership functions and susceptibility levels of the *Input 3* and *Input 4*

Input 3 Non-climatic factors for drought	*Input 4* Anthropogenic factors	Susceptibility level
[0, 0, 0.5, 0.6]	[0, 0, 5.5, 7.5]	VL
[0.5, 0.6, 0.90, 1.0]	[5.5, 7.5, 11, 15]	L
[0.90, 1.0, 1.25, 1.35]	[11, 15, 21. 27]	M
[1.25, 1.35, 1.6, 1.70]	[21, 27, 33, 37]	H
[1.6, 1.70, 2, 2]	[33, 37, 42, 42]	VH

Table 4. Numeral values of membership functions and susceptibility levels of the *Intermediate variable 1* and *Intermediate variable 2*

Intermediate variable 1 Climatic factors for drought	*Intermediate variable 2* Natural factors for drought	Susceptibility level
[0, 0, 0.8, 1.1]	[0, 0, 1.3, 1.7,]	VL
[0.8, 1.1, 1.45, 1.75]	[1.3, 1.7, 2.3, 2.7]	L
[1.45, 1.75, 2.1, 2.4]	[2.3, 2.7, 3.3, 3.7]	M
[2.1, 2.4, 2.75, 3.05]	[3.3, 3.7, 4.3, 4.7]	H
[2.75, 3.05, 3.5, 3.5]	[4.3, 4.7, 5, 5]	VH

Table 5. Numeral values of membership functions/susceptibility levels of the *System Output*

Membership functions of *System Output*	*Drought vulnerability degree*
[0, 0, 1.5, 2.5]	*Very low,* VL
[1.5, 2.5, 3.5, 4.5]	*Low,* L
[3.5, 4.5, 5.5, 6.5]	*Moderate,* M
[5.5, 6.5, 7.5, 8.5]	*High,* H
[7.5, 8.5, 10, 10]	*Very high,* VH

The inputs of the first fuzzy logic subsystem are Input 1 "*Precipitation*" and Input 2 "*Air temperature*", and the output variable is the Intermediate variable 1 "*Climatic factors for drought*". The first intermediate variable gives information for drought susceptibility of the territory according to the precipitation and air temperature. The threshold for classifying precipitation data into five levels was determined based on the precipitation anomaly (the deviation of the precipitation totals as a percentage of the multi-year average value – climatic normal). Whereas air temperature data was grouped according to the percentile distribution. Drought susceptibility levels according to the climatic factors is given in corresponding tables (Tables 1, 2, 4).

The inputs of the second fuzzy logic subsystem are Intermediate variable 1 "*Climatic factors for drought*" and Input 3 "*Non-climatic factors for drought*", and the output variable is the Intermediate variable 2 "*Natural factors for drought*" (Tables 3 and 4).

Here, as "*Non-climatic factors for drought*" are considered the distance to the rivers, aspect and soil type. The distance from the rivers (water objects) determines the possibilities and costs for water supply and provision of water for the irrigation. The territory is classified into five susceptibility levels according to the distance from the rivers and taking into account the peculiarities of the investigated area [32]. For this component of complex assessment of drought we used three data layers from the geodatabase developed within the project "Integrated water management in the Republic of Bulgaria" financed by the Japanese government through the Japanese International Cooperation Agency (more known in Bulgaria as JICA geodatabase) – rivers, water objects and Danube riverbed (polygon data layer). All three layers were used to calculate the distance to main water objects (see Fig. 3). After having the distance calculated, the output data layer was reclassified based on the peculiarity of the territory using the following classes according to drought susceptibility: 0–500 m - 1 (very low); 500–1000 m - 2 (low); 1000–2500 m - 3 (moderate); 2500–5000 m - 4 (high); >5000 m - 5 (very high).

The aspect (NW-N-NE, NE-E-SE, SW-W-NW, flat territory, SE-S-SW) affects sunshine duration and quantity of solar radiation. Drought can be observed more often on sunny slopes (with Southern exposure) and most rarely on shady slopes (Northern exposure). For the analysis of the aspect as a component of the drought assessment, a raster data for the elevation were geoprocessed. The input DTM has resolution of 30 m. Based on this layer, we generated the aspect layer. After that, the new layer was reclassified according to drought susceptibility using the following classes: NW, N, NE – 1 (very low); NE, E, SE – 2 (low); SW, W, NW – 3 (moderate); flat territory – 4 (high); SE, S, SW – 5 (very high). (see Fig. 4).

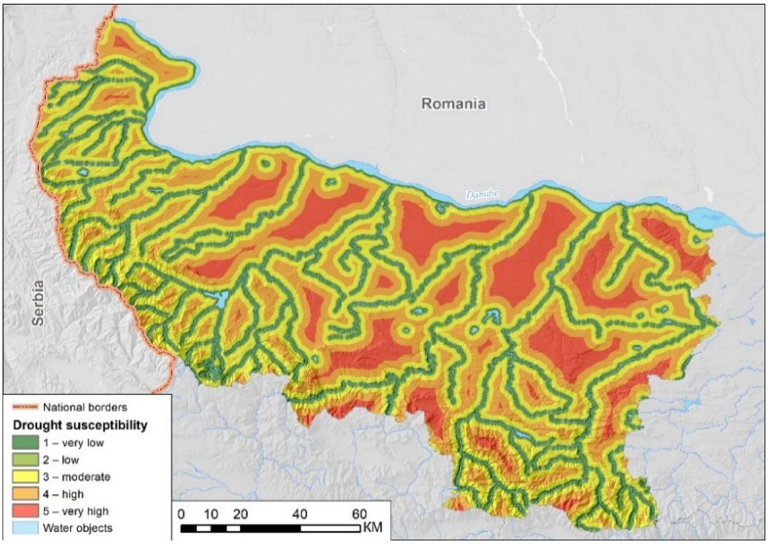

Fig. 3. Drought susceptibility according to the distance from the rivers /water objects

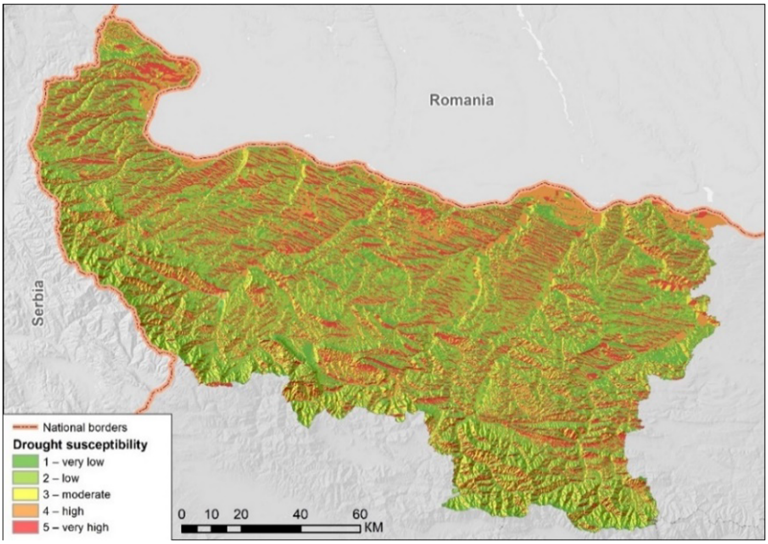

Fig. 4. Drought susceptibility according to the aspect

The soil types are grouped according to mechanical composition - the most susceptible to drought are sandy soils, and the least susceptible - clay, alluvial and boggy soils, (see Fig. 5). For this part of our research, we used another feature class from the geodatabase of JICA – the layer Soils. At the beginning of the data processing the layer had to be converted from vector to raster layer. After that, the different types of soils in this layer were regrouped according to their mechanical composition and reclassified from 1 (least susceptible – clay, alluvial and boggy soils) to 5 (very highly susceptible – sandy soils).

The territorial distribution of each non-climatic indicator was presented on a separate map (from Fig. 3, Fig. 4 and Fig. 5). The composite map of drought susceptibility based on considered non-climatic factors was produced by the combination of the three components in ArcGIS using weighted overlay. The following weights ware used: distance from water objects – 45%; aspect – 35% and soil types – 20%. The output raster data layer has 5 classes of drought susceptibility from 1 (Very low) to 5 (Very high).

In particular, the results from the composite map is used as Input 3 "*Non-climatic factors for drought*" of the second fuzzy logic subsystem.

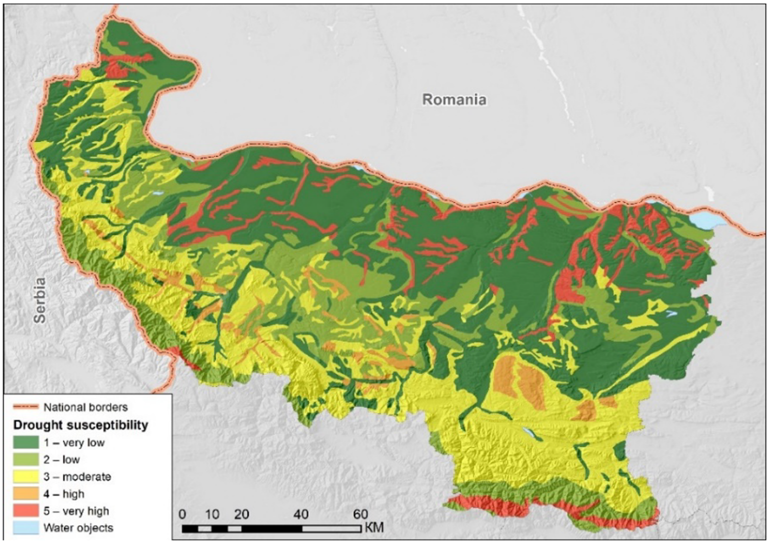

Fig. 5. Drought susceptibility according to the soil types

The inputs of the third fuzzy logic subsystem are Intermediate variable 2 "*Natural factors for drought*" and Input 4 "*Anthropogenic factors*".

The analysis of the anthropogenic factor gives us a tool to assess vulnerability of the study area to drought. As an indicator for anthropogenic activity different types of land use and land cover was evaluated as well as urban areas which give the information about the people affected by drought. Based on the expert knowledge we grouped selected land use types in five drought vulnerability classes. Each of the selected land use types is assigned a weight according to the Analytic Hierarchy Process method followed by Saaty [33], Nikolova and Zlateva [34], 2018 (Table 6). Most vulnerable are urban areas where the population density is highest.

Table 6. Anthropogenic factors indicators and weights

	Urban areas	Rain-fed agriculture	Irrigated fields	Natural areas	Pastures	Total	Weight %
Urban areas	1.00	2.00	2.50	3.00	3.50	12.0	40
Rain-fed	0.50	1.00	2.25	2.50	2.75	9.0	30
Irrigated fields	0.40	0.44	1.00	1.50	2.00	5.3	18
Natural areas	0.33	0.40	0.67	1.00	2.25	2.4	8
Pastures	0.29	0.36	0.50	0.44	1	1.6	5
Total						30.3	100

The inference rules in the three fuzzy logic subsystem are defined as "If - then" - clause. The number of rules in the knowledge base for each of the fuzzy logic subsystems is 25. Some of the inference rules are defined as follow:

FLS1: Drought susceptibility assessment according to climatic factors

If *Precipitation* is VL and *Air temperature* is H then *Climatic factors for drought* is M;
If *Precipitation* is M and *Air temperature* is VH then *Climatic factors for drought* is H;
If *Precipitation* is H and *Air temperature* is M then *Climatic factors for drought* is H.

FLS2: Drought susceptibility assessment according to natural factors

If *Climatic factors for drought* is VL and *Non-climatic factors for drought* is H then *Natural factors for drought* is L;
If *Climatic factors for drought* is L and *Non-climatic factors for drought* is H then *Natural factors for drought* is M;
If *Climatic factors for drought s* is VH and *Non-climatic factors for drought* is VL then *Natural factors for drought* is H.

FLS3: Drought vulnerability assessment according natural and anthropogenic factors (Complex assessment of drought vulnerability)

If *Natural factors for drought* is H and *Anthropogenic factors* is H then *Drought vulnerability degree* is VH;
If *Natural factors for drought* is L and *Anthropogenic factors* is H then *Drought vulnerability degree* is H;
If *Natural factors for drought* is VH and *Anthropogenic factors* is L then *Drought vulnerability degree* is M.

The fuzzy logic hierarchical system is designed in MATLAB computer environment using Fuzzy Logic Toolbox [35]. The three fuzzy logic are based on Mamdani's inference machines, max/min operations and center of gravity defuzzification [36].

The inference surfaces in 3D for the three fuzzy logic subsystems are shown on Figures 6, 7 and 8, respectively.

5 Results and Discussion

According to the results from the assessment of non-climatic factors for drought occurrence, presented by the composite map (see Fig. 9) most part of the investigated area has low or moderate degree of drought susceptibility. Low drought susceptibility is characteristic for 30.8% of the territory of Northwestern administrative region of Bulgaria (NUTS 2 – Severozapaden) and 42.7% of the territory have moderate drought susceptibility.

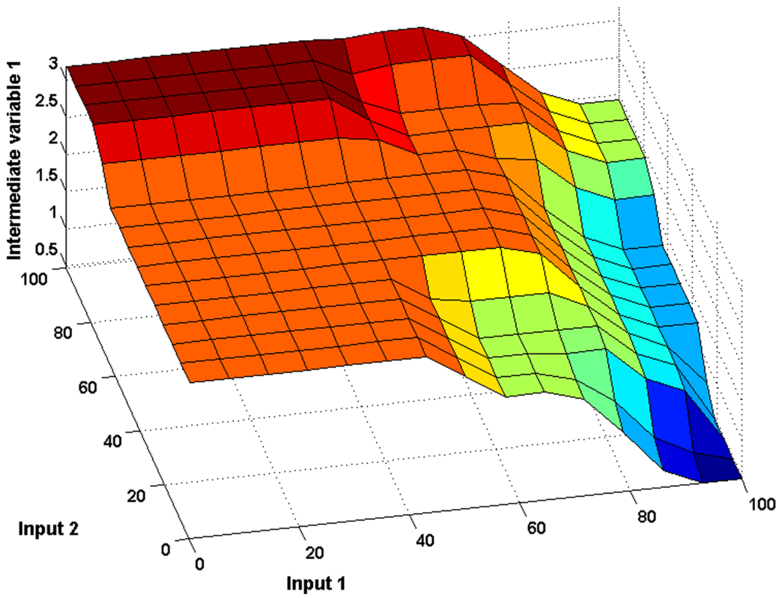

Fig. 6. Inference surfaces of the Fuzzy logic subsystem 1.

On the other side climatic factors are more important natural factor for drought occurrence than non-climatic and due to various values of air temperature and precipitation totals drought susceptibility of the given area can be different. Many simulations with developed fuzzy logic system have been performed using particular values of input variables to calculate the "Drought vulnerability degree" in investigated area. Some simulation results for the regions of two towns located in the investigated area (Vidin – northwestern part and Pleven – eastern part) are shown in Table 7. Vidin is located in the region with moderate drought susceptibility according to the non-climatic factors while for the region of Pleven low to moderate drought susceptibility is characteristic.

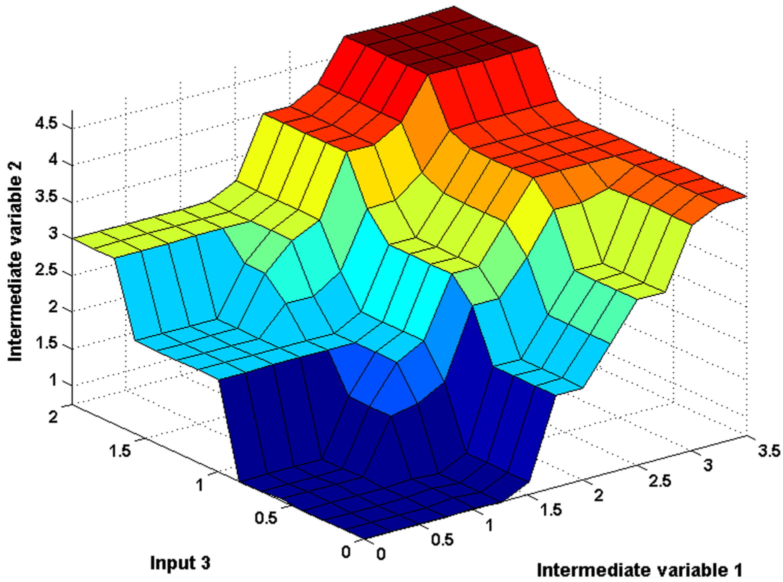

Fig. 7. Inference surfaces of the Fuzzy logic subsystem 2

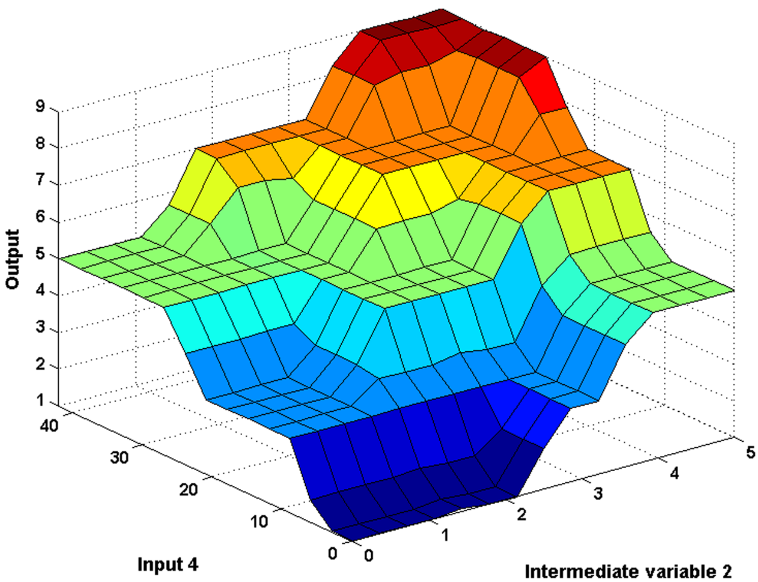

Fig. 8. Inference surfaces of the Fuzzy logic subsystem 3

Depending on the type of land use and how many people are affected, areas with the same susceptibility to drought may have different degrees of vulnerability.

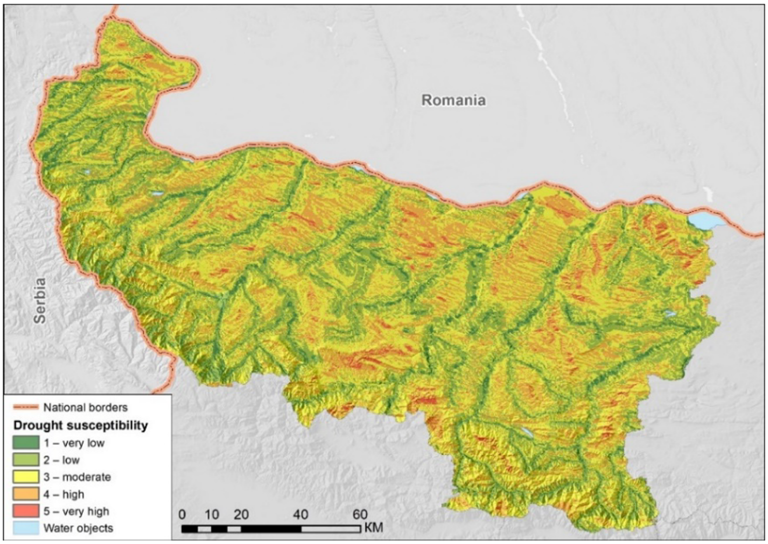

Fig. 9. Composite map – drought susceptibility according to the non-climatic factors for drought in Northwestern administrative district of Bulgaria (NUTS 2 – Severozapaden)

The results of the present analysis show the importance of the climatic and anthropogenic factor for drought susceptibility and vulnerability.

Table 7. Complex drought vulnerability assessment of the investigated area with particular values of the input variables (selected simulation results)

Input 1	Input 2	Intermediate variable 1	Input 3	Intermediate variable 2	Input 4	Output
Vidin						
121.2 VL	74 M - H	1.87 *M*	1.08 *M*	3 *M*	30–40 *H - VH*	7 *H*
51.8–52 H - VH	97 VH	3.16 *VH*	1.08 (*M*)	4 *H*	35.5–36.5 *H - VH*	8.14–8.69 *H - VH*
Pleven						
108.7 VL	13.1 VL - L	0.47 *VL*	0.97 *L - M*	1.54 *VL - L*	30–33 *H* 34–42 *H - VH*	5 M 5.61–6.18 *M - H*
69 H	13.3 VL - L	1.92 *M*	0.72–1.08 *L - M*	3 *M*	30–40 *H - VH*	7 *H*

When climatic factor (*Input 1 - Air temperature* and *Input2 - Precipitation*) determines very high susceptibility to drought (*Intermediate variable 1* = 3.16) and according to the non-climatic factors drought susceptibility is moderate (*Input 3* = 1.08) then overall susceptibility is high (*Intermediate variable 2* = 4). If anthropogenic factor shows high to very high susceptibility (35.5 ≤ *Input 4* ≤ 36.5) then complex drought assessment shows high to very high drought vulnerability degree (8.14 ≤ *Output* ≤ 8.69).

If climatic factor show very low drought susceptibility (*Intermediate variable 1* = 0.47) and non-climatic factor (*Input 3* = 0.97) indicate low to moderate susceptibility then drought susceptibility of the territory is very low to low (*Intermediate variable 2* = 1.54). When anthropogenic factor shows high vulnerability (*Input 4* = 30–33) then complex drought vulnerability is moderate (*Output 4* = 5). If the *Input 4* has a value between 34 and 42 it is shows high to very high vulnerability and the complex drought vulnerability is moderate to high (5.61 ≤ *Output 4* ≤ 6.18).

In the case that climatic factors determine moderate susceptibility to drought (*Intermediate variable 1* = 1.92) and non-climatic factors show low to moderate susceptibility (*Input 3* has values between 0.72 and 1.08) natural factors indicate moderate drought susceptibility (*Intermediate variable 2* = 3). When according to the anthropogenic factor (30 ≤ *Input 4* ≤ 40) drought vulnerability is high to very high then complex drought vulnerability is high (*Output* = 7).

6 Conclusion

The present study shows the importance of complex assessment of various factors (natural and anthropogenic) for drought occurrence and vulnerability. In general, the investigated area is low to moderate susceptible to drought. Nevertheless, the drought susceptibility and vulnerability also depend on peculiarities of air temperature and precipitation regimes as well as on anthropogenic factors as type of land use and concentration of the population. In particular, the most vulnerable to drought are the settlements and urban areas which are located far from the water bodies and especially when the climate parameters show high drought susceptibility.

A fuzzy logic model to complex drought assessment is developed by the comprehensive analysis of natural and anthropogenic factors. The results from the analysis prove the usefulness of the proposed fuzzy logic approach as a good tool for drought vulnerability assessment, especially for areas for which available data are insufficient.

The major beneficiaries of the proposed work will be scientific researchers working on the problems related to natural, economic and social dimensions of drought. Future work will focus on the expanding territorial scope of the presented research work in order to validate the model for different territories. The information about the adaptive capacity of the study areas will be included in further analyses, which will bring to better understanding of drought impact on various human activities.

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