A GIS-BASED METHODOLOGY FOR DROUGHT VULNERABILITY MODELLING: APPLICATION AT THE REGION OF EL HODNA, CENTRAL ALGERIA

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ABSTRACT

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Desert covers 80% of the Algerian territory, while the remaining area is covered by Mediterranean forests and arid climate steppe that are characterized by severe vulnerability to different stresses such as drought, especially with the increase of nefarious human impact and the overuse of natural resources. The objective of this study is to analyse and assess drought vulnerability in the area of El Hodna in central Algeria. The methodology was based on the use of GIS tools and multi-criteria analysis (Analytical hierarchy process) to develop a model of vulnerability mapping. The results showed that 35.67% of the study area was very vulnerable, 32.77% in fragile situation, 19.72% are potentially vulnerable, and only 11.83% of the surface is not affected. The drought-vulnerability map provides a basis from which it will be possible to prevent and prepare for a drought response.

INTRODUCTION

Drought is one of the most complex and least understood natural hazards that affects large numbers of people and results in significant economic, social and environmental impacts (Wilhite, 2005). Drought aggravates the stress on natural resources (soil and water reserves), and jeopardizes food security and water supplies. It does not have a universal definition, but it can be said that it is a deficit of water availability comparing to a normal period (Layelmam, 2008). Drought evolves slowly, it does not present an instantaneous danger. Rainfall deficit may

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occur after a few days, weeks, months or even years which makes it is a very difficult hazard to monitor (Yasef and Saltani, 2009). The impacts of drought are observed over large area compared to other natural hazards such as floods, tropical storms, and earthquakes, which makes it particularly challenging to quantify the impact (Wilhite, 2005). This phenomenon is increased by the nefarious human effect on the environment, like deforestation, gas emissions, livestock pressure, overgrazing and the overuse of natural resources (Safar Zitoun, 2006). Concerns about global drought and its impacts have become more pronounced in recent years (Dai, 2011), particularly in arid and semi-arid regions. Climatic disturbances are a major cause of the vulnerability in these ecosystems, vulnerability definition is the degree of a system's susceptibility to climate change and the inability to cope with adverse effects (Houghton et al., 2001). Drought is monitored and quantified using developed indices to depict this phenomenon in different applications (Dracup et al., 1980; Wilhite and Glantz, 1985). These indices are important to monitor drought's duration, frequency and spatial extent to provide decision makers with useful information needed to prepare for a response (WMO, 2016).

Algeria is situated in a transition zone between temperate and subtropical climates. Over the last twenty years, Algeria has experienced severe and persistent periods of drought, characterized by a large precipitation deficit that affected the whole country (Bensaid, 2006). The problem of Algerian steppe's vulnerability made the project of several studies (Nichane and Khelil, 2014; Medjereb and Henia, 2011; Bensaid, 2006, Nadjraoui, 2011). The present study seeks to identify the spatial extent of drought vulnerability in an arid region situated in central Algeria, by developing a GIS model with integrating meteorological, remotely sensed and socioeconomic indices and parameters that will form sub-criteria whose mapping is the first step to build this model, the second step is to map criteria layers of climate, soil, vegetation quality and socio-economic pressure, the final step is to use multicriteria analysis to map criteria layer and aggregate them to have the final vulnerability map.

MATERIALS AND METHODS

Study area

The study area is situated in the steppes of central Algeria, in El Hodna region, (4°90'4°351' N and 35°87'. 35°17' E). It extends over 6 sub-divisions of the state of M'sila: Maadhid, M'tarfa, M'sila, Souamaa, Ouled madhi and M'cif, (Figure1) spanning the area of 1261.20 km², including the salt pan named "Chott El Hodna" (400 m a.s.l). This study area has a transitory climate position between the sub humid climate of the North, and the dry climate of the Algerian south. According to the classification of Köppen, the climate of this zone is classified as an arid climate with cold winter (Urlike et al., 1993).

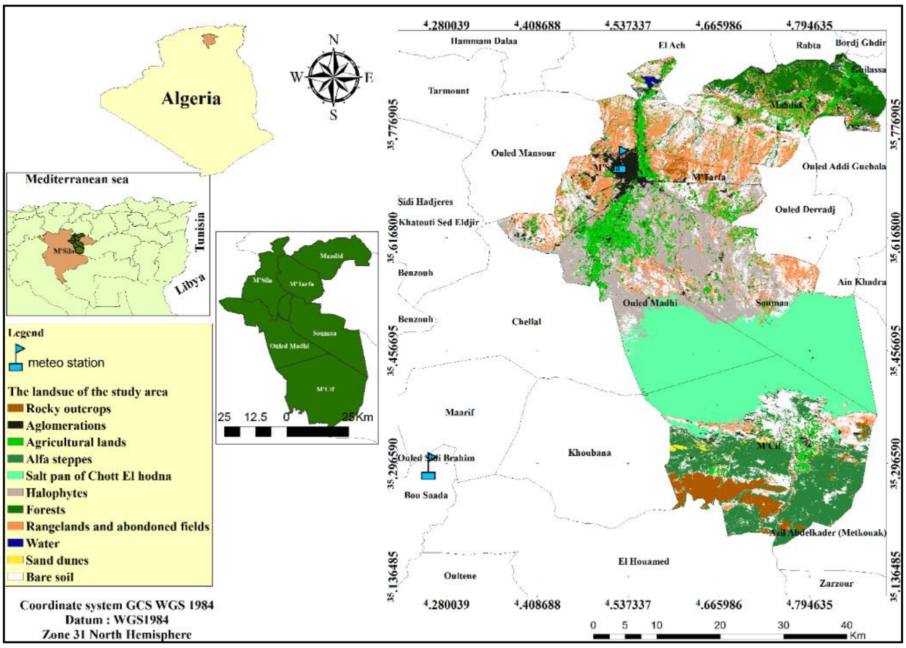

Figure 1. Geographic location and land use of the study area.

Data collection

We used a series of satellite images of the OLI sensor (Operational land imager) of the satellite Landsat 8 (Path: 135, Row: 95) of 30-meter resolution freely accessible and received from the United States Geological Survey "USGS" of the year 2016 on different dates: 09/03/2016, 15/07/2016/, 17/09/2016 and 20/11/2016, atmospherically corrected.

Also, climatic data that was obtained from the meteorological stations of M'sila and Bousaada, corrected and spatially extrapolated according to the topography of the study area (altitude and direction), by calculating the altitude difference (Xd) between meteorological station and the sampling points from the study area, then dividing this difference by a pluviosity increasing coefficient (A) according to direction as follows:

$$A_{North} = (Xd/100) \times 40$$

$$A_{South} = (Xd/100) \times 20$$

Then calculating a correction coefficient (C):

$$C = A + P/P$$

Where A is a pluviosity increasing coefficient, P is the total annual rainfall.

The precipitation values of the sampling points at the study area are obtained after dividing monthly rainfall amounts by the correction coefficient (C).

The socioeconomic study required data extracted from road, water network and urbanism maps, and also population and livestock statistics, provided by forests conservation direction, agricultural and rural development direction of M'sila province of each municipal subdivision (M'sila, Maadid, M'tarfa, Ouled madhi, Souamaa and M'cif).

Data analysis

In order to map drought vulnerability conditions, we developed a spatial model of vulnerability based on computed indices that utilize satellite imagery, meteorological series and socioeconomic data (population and livestock density, roads and hydrographic network maps). Then criteria map to assess climate, soil, vegetation cover quality and socioeconomic pressure were conducted.

Calculating remote sensing indices

Remote sensing technological development has facilitated the need to customize indices for specific climatic and hydrologic conditions. Drought can cause soil and vegetation degradation that is detectable using remote sensing data (Tucker, 1979). Satellite data can be complemental to meteorological observation. We used a series of remote sensing indices (table.1) and estimated land surface temperature as a basis of assessing drought in the study area. Indices are calculated for each date separately then, it is necessary to compute the annual average of each index and of land surface temperature.

TABLE 1

Calculated Remote Sensing Indices

Indices	*Equations*	*Author*
Redness index	$\mathrm{RI} = ((\mathrm{R} - \mathrm{G})) \,/\, ((\mathrm{R} + \mathrm{G}))$ (1)	Escadafal and Heute (1991).
Brightness index	$\mathrm{BI} = \sqrt{\mathrm{NIR}^2 + \mathrm{R}^2}$ (2)	Escadafal et al. (1994).
Normalized differenced vegetation index	$\mathrm{NDVI} = ((\mathrm{NIR} - \mathrm{R})) \,/\, ((\mathrm{NIR} + \mathrm{R}))$ (3)	Rouse et al. (1973)
Green Vegetation ratio	$\mathrm{GRVI} = \mathrm{NIR} \,/\, \mathrm{G}$ (4)	Sripada (2006)
Leaf area index	$LAI = 3.618 \times \mathrm{EVI} - 0.118$ (5)	Boegh et al , (2002)
Modified Simple Ratio	$\mathrm{MSR} = ((\mathrm{PIR/R}) - 1) \,/\, (\sqrt{((\mathrm{PIR/R}))} + 1)$ (6)	Chen (1996)
Normalized multiband drought index	$NMDI = (NIR - 5SWIR1)/NIR + (SWIR1 + SWIR2)$ (7)	Wang and Qu (2007).

Where: R: red band, G: Green band, NIR: Near Infrared band, $SWIR1$: short wave infrared 1, $SWIR2$: Short wave infrared 2, EVI is the enhanced vegetation index, we used the formula proposed by Huete, et al (2002):

$$EVI = 2.5[(\mathrm{NIR} - \mathrm{RED})/(NIR + 6 \times RED - 7.5Blue + 1)] \quad (8)$$

Land surface temperature

We used a method based on normalized and standardized vegetation index (NDVI) thresholds, by converting digital numbers of thermal bands into radiance and then converting spectral radiance into brightness temperature (9) using the thermal constants provided in the metadata file:

$$BT = \frac{k2}{\ln\left(\frac{k1}{l}+1\right)} \quad (9)$$

Where: BT is brightness temperature, $l =$ Top of Atmosphere spectral radiance $TOA\ \left({Watts}/{m^2 \times srad \times \mu m}\right)$, $k1 = 1321.08\ (Band\ 10), 1201.14\ (Band 11)$, $k2 = 777.89\ (Band\ 10), 480{,}980\ (Band 11)$ (Constant band-specific thermal conversion from the metadata of the thermal band).

The land surface temperature is calculated using the equation:

$$LST = BT/1 + w * BT/p * \ln(e) \quad (10)$$

Where: BT is brightness temperature, w is wavelength of emitted radiance (11.5 μm), $P = \frac{h \times c}{s}$ $(1.438 \times 10^{-2}\ mk)$, h is plank's constant $(6.626 \times 10^{-34}\ Js)$, s is Boltzmann constant $(1.38 \times 10^{-23}\ Jk)$, c is the velocity of light $(2.998 \times 10^{8}\ m/s)$, $P = 143.80$, e is the land surface emissivity :

$$\mathrm{e} = 0.004\mathrm{PV} + 0.986 \quad (11)$$

PV the vegetation proportion: $$PV = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (12)$$

Calculating meteorological indices

Evapotranspiration (ETR)

The equation used in computing annual potential evapotranspiration for the year 2016 is the one proposed by Turc (1961) (13) and (14)

$$ETR = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \quad (13)$$

Where P: rain in mm per year and L stands for the potential evaporation of the atmosphere

$$L = 300 + 25T + 0.05T^3 \quad (14)$$

$Where\ T$: temperature average over 1 year.

Ratio to normal

This index is expressed mathematically as a percentage as follows:

$$RN = \frac{P_i}{P_m} \times 100 \quad (15)$$

$Where\ P_i$: Annual precipitation, Pm: Average precipitation

A year is classified as dry if rainfall is below normal; that is to say, when the RN is less than 100% (Rognon, 1997).

Standardized Precipitation Index

This index was developed by McKee et., al (1993). It is a statistical indicator used to characterize local or regional droughts. It gives an easy and flexible way to monitor drought at a different scale ranging from near normal (0.99) to extreme drought condition (< -2.0)

$$SPI = \frac{Pi - Pm}{\sigma} \quad (16)$$

Where: P_i : Precipitation of year i, P_m : Average precipitation, σ : Standard deviation.

Socioeconomic pressure evaluation

Human interventions such as overgrazing or land use changing can damage irreversibly the recovering vegetation (Clark, 1996), one of these interferences is when shepherds in these areas set fires to eradicate the vegetation and encourage the growth of grass to overgraze later (Kosmas et al., 1999). Human activity is more intense around road network, agglomerations, industrial zones and agricultural lands which raise the demands on water supplies.

The socioeconomic pressure evaluation is based on computing the following Euclidean distances: distance of agglomerations (DA), distance of agricultural land (DAL), distance of hydrographic networks and water resources (DHN) and calculating the density of population (DP) and livestock (DL).

Creating thematic layers

The criteria used in this model are similar to those used in MEDALUS (1999) (Mediterranean Desertification and land use) for mapping environmentally sensitive areas to desertification (ESA), the methodology is based on the use of MEDALUS's criteria (Figure 2) of climate, vegetation, soil criteria in addition of the use of socio-economic pressure, but using remotely sensed, meteorological and socioeconomic drought related indices and parameters presented previously.

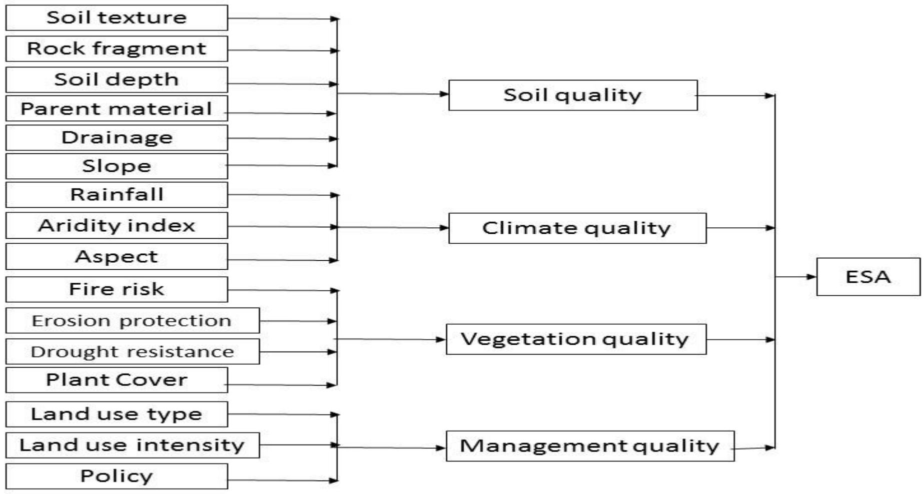

Figure 2. Environmentally sensitive areas to desertification mapping parameters. (MEDALUS, 1999)

Parameters and indices will form spatial sub-criteria to map climate, soil, vegetation quality and socioeconomic pressure using the following geometric equations.

$$Climate\ criterion = (SPI \times RN \times ETP \times ASPECT)^{1/4} \quad (17)$$

$$Soil\ criterion = (BI \times RI \times NMDI \times LST \times Field\ capacity)^{1/5} \quad (18)$$

$$Vegetaion\ criterion = (NDVI \times GRVI \times MSR \times LAI)^{1/4} \quad (19)$$

$$Anthropic\ pressure\ criterion = (DA \times DAL \times DHN \times DP \times DL)^{1/5} \quad (20)$$

After calculating each indice and parameter, every layer was reclassified according to value intervals, by resorting to land management and natural hazards expertise, scores that variate between 1 and 7 were assigned to each class of values, where score 1 is given for a favorable class and 7 to an unfavorable one (Figure3), each layer is a criterion that will be used later in our assessment using multi-criteria analysis and geographic information system (GIS).

	Indices (sub-criteria	Values	assigned scores
Climate quality criterion	SPI	0.99 ; 1.6	1
		-1 ; 0.99	3
		-1 ; -1.5	5
		-1.5 ; -1.7	7
	ETP	50-100 mm/ month	1
		100-150 mm/month	3
		150-250 mm/month	5
	Exposition	Nord - Est	1
		Sud -Est	2
		Nord- Ouest	3
		Sud -Ouest	4
	RN	100 ≥	1
		< 100	3
Soil quality criterion	LST	< 20ºC	3
		20 ºC -30 ºC	5
		30ºC<	7
	BI	40 ; 90	1
		90 ; 180	3
		180<	5
	RI	< 0	1
		0 ; 0.50	3
		0.50<	5
	NMDI	<0,6	3
		0.6 ; 0.70	5
		0.7 ; 1	7
Vegetation quality criterion	NDVI	0.70 ; 0,968	3
		0.474 ; 0.70	5
		-0,019 ; 0,474	7
	GRVI	0,971 ; 11,8	1
		11,8 ; 15,0	3
		15,0 ; 22,79	5
	MSR	-0,019 ; 3,43	1
		3,43 ;4,50	3
		4,50 ; 6,890	5
	LAI	2,50 ; 3,42	3
		1.83 ; 2.50	5
		-0,16 ; 1,83	7
Socioeconomic pressure citerion	DG	20 km <	3
		10 ; 20 km	5
		5 ; 10 km	7
	DAL	20 km <	3
		10 ;20 km	5
		5 ;10 km	7
	DHN	5 ; 10 km	1
		10 ; 20 km	3
		20 km < km	5
	DP	0.50- 0.90 ha/km²	1.5
		0.90 – 5 ha/km²	2.5
		5 – 12 ha /km²	3
	DL	5 – 20 t/h	1
		20- 60t/h	2
		60-20t/h	3

Figure 3. Criteria and sub criteria assigned scores.

Multicritaria analysis: Analytical hierarchy process (AHP)

Multi-criteria decision-making method is a branch of a general class of operations research models that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Wang et al.,2010).

This method was developed by Thomas Saaty in the 1970s and is based on mathematics and psychology (Saaty, 1980). It is used in the field of managerial decision-making. In summary, a decision-maker must "weigh" several options before deciding on one of them taking into account a series of criteria that he considers more or less essential to be respected (Cissokho, 2011).

The first step is to form a series of comparison by pair of these criteria according to their relative importance and their influence in drought hazard, we need a scale of numbers that indicate how many times more important or dominant one element is over another element, values of this scale rage from 1 to 9 (Saaty, 1980). For example, entering 3 in the climate -soil position means that climate factors are three times more important and influencing drought vulnerability in the study area than soil factors, and entering 1 in climate- socioeconomic stress position means that both factors are equally important (Table 2).

TABLE 2

Assigned Weight according to Saaty Scale

Criterion	*Climate*	*Socioeconomic stress*	*Soil*	*Vegetation*
Climate	1	1	3	7
Socioeconomic pressure	1	1	3	3
Soil	1/3	1/3	1	3
vegetation	1/7	1/3	1/3	1

The second step is to calculate the eigenvector (Vp) by calculating the geometric mean in every line of the previous table, the obtained values determine the weights to accord to each criterion whose sum must be equal to 1 (Table.3).

TABLE 3

Weighting Coefficients

Criteria	**Weight**
Climate	0,42198427
Socioeconomic	0,35055569
Soil	0,15256618
Vegetation	0,07489386
Sum	1

After calculating the weights, the decision map is built using a weighed sum aggregation; by multiplying each standardized criterion layer by its coefficient of respective weighting (Bouzekri and Benmessaoud, 2016). The organizational chart in (Figure 4) resumes the methodology followed in this study.

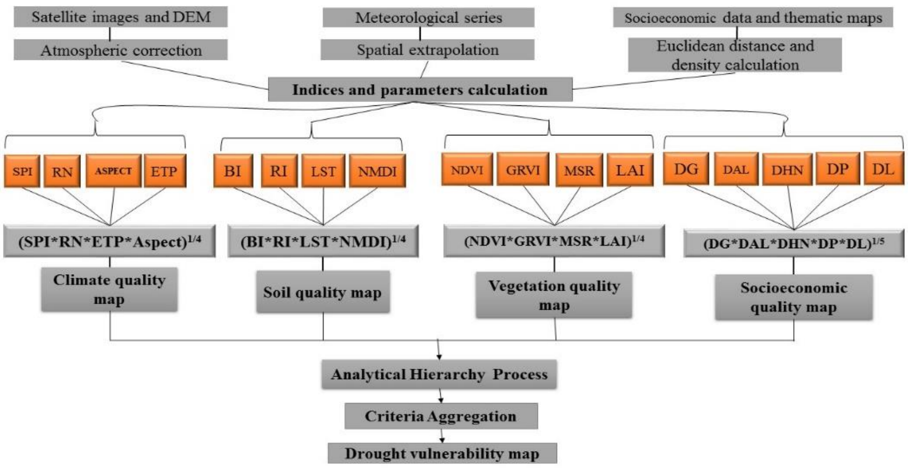

Figure 4. Methodology organizational chart.

RESULTS

Criteria maps

Climate quality criterion map

The areas of a highly suitable climate quality form approximately 17.30 % of the study area, which are located in the north, especially on the Maadhid Mountains, and agricultural lands in M'sila and M'tarfa. Suitable and medium quality areas (41.31%) are located on the plains of lower altitude with southern aspect. The unsuitable quality areas (41.39%) are located on the salt pane of El Hodna and peripheries where the altitude average is 400 m a.s.l and surrounding lands of low altitude and rainfall rates are mainly lower than

220mm (Figure 5).

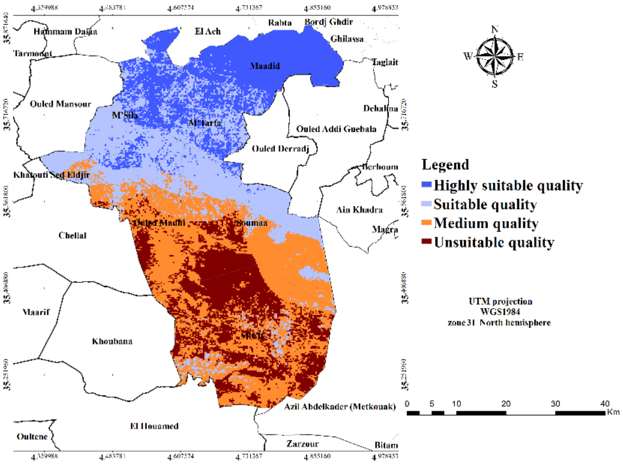

Figure 5. Climate quality criterion map.

Soil quality criterion map

The areas of highly suitable soil quality that form approximately 2.79%, are mostly located on agricultural lands and also on mountainous areas in Maadhid. The areas of suitable quality form 41.89% on the peripheries of agricultural lands, while the class of medium (37.17%) and unsuitable soil quality (17.60%) is located mainly in the southern zone whose soil is bare and sandy (Figure 6).

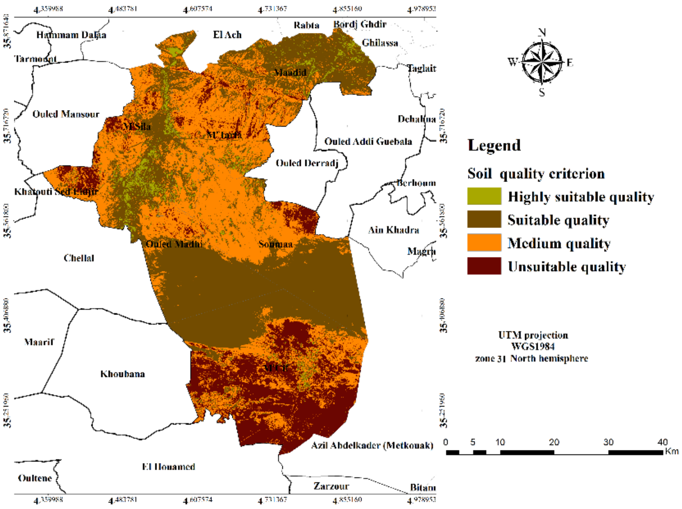

Figure 6. Soil quality criterion map.

Vegetation quality criterion map

Vegetation of a highly suitable quality forms approximately 13.21%% of the study area and is located on agricultural lands cultivated mainly with rainfed cereals and on the mountainous areas dominated by green oak stands, and forests of Aleppo pine. The suitable quality areas represent 23.25 % of the total study area and are located on the peripheries of agricultural lands, steppes and the abandoned fields. Medium-quality vegetation is located on lands covered by Halophytes and spontaneous vegetation and forms 11.69% of the study area. The unsuitable quality class of vegetation occupies the whole of the Chott El Hodna and the surrounding land where the soil is either bare and sandy or covered by Halophytes and grazing steppes and forms 51.83% (Figure 7).

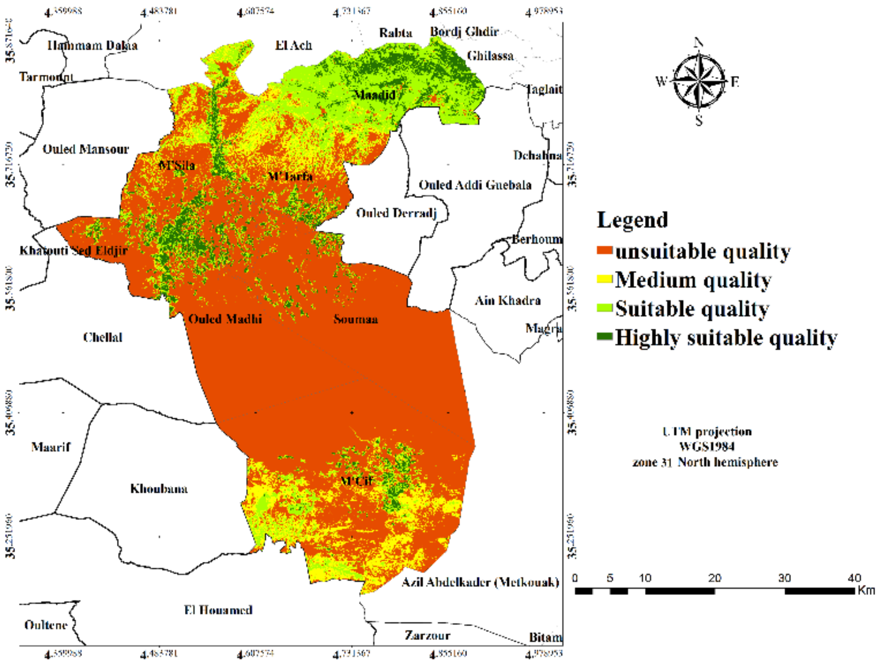

Figure 7. Vegetation criterion map.

Socioeconomic pressure quality criterion map

Elevated density of population and livestock require continuous availability of water resources, and agricultural goods. The degree of pressure decreases away from agglomeration and agricultural lands. Areas with very high socioeconomic pressure account for 39.89 % of the total area, high-pressure areas make 26,10 %, medium pressure form 23.17 % and low pressure form 10.73% of the total area generally on the mountainous region of Maadhid and also on the salt pan of Chott El hodna distant of agglomerations and road network (Figure 8).

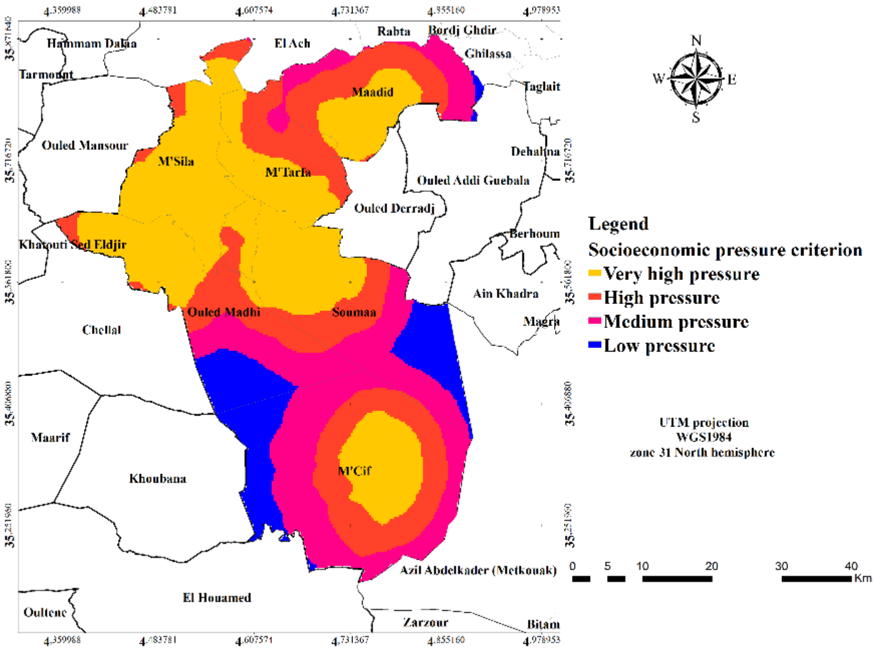

Figure 8. Socioeconomic quality pressure criterion map.

Drought Vulnerability Mapping

The situations of drought vulnerability are spatially delimited according to pixel values. The zones with a non-affected situation have a low pixel value, whereas the zones with a critical situation have a high pixel value (Figure 9).

The non-affected area occupies nearly 11.83% of the study area, located in the north on the Maadhid mountains (1293m- 1859m) and surrounding area, Djebel Meharga mountain (629 m to 892m a. s. l) in the south. Potential affected areas are almost 19.72 % and are mainly located on the mountainside of the Maadhid region in the North of the study area, where the altitudes are around 700 m a. s. l, and precipitation rates between 250 and 280 mm per year, also on the agricultural lands of M'sila and M’tarfa plains.

Fragile areas that form 32.77% are located on the peripheries of agricultural lands and on steppes where vegetation coverage is sparse and livestock density leads to soil degradation. The precipitation rate is 200 to 230 mm per year.

Highly vulnerable areas form nearly 35.67 % and are located in the central and southern part on an altitude that varies between 192 and 200 mm. The rainfall average is lower than 200 mm per year with sparse vegetation mainly preserved for grazing.

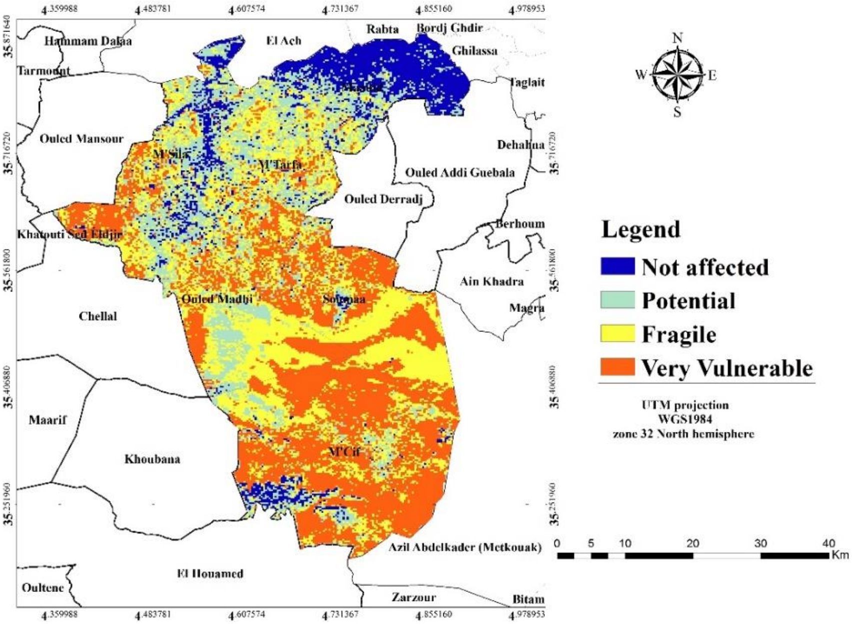

Figure 9. Drought vulnerability map.

DISCUSSION

In our country, management and conservation of the environment in Arid and semi-arid lands are based generally on thematic maps, field missions and classic methods, these operations take long durations of time, and absorb high disbursement especially in large areas (Bensaid, 2006), Drought is still quit an unstudied hazard, studies were conducted on a regional scale such as Yasef and Saltani (2009) (Sahara and Sahel observatory), or by reviewing climatic indices. The methodology presented in the article developed from a desertification sensitivity model MEDALUS (1999) aims to facilitate the task for planners and researchers in mapping drought vulnerability in arid lands.

Bensaid (2006) and Bouzekri (2015), have conducted similar studies in others regions of Algerian arid steppes in the region of Naama and the Aures respectively they found that grazing steppes are more affected by natural hazards such as desertification, sand invasion and wind erosion, in the case of our study agricultural lands are also potentially vulnerable besides steppes and rangelands. The climate factor takes a major part in identifying vulnerable areas to drought, precipitation series during the last decades show a significant decrease in rainfall rates. Medjerab and Henia (2011) conducted a study on drought variation in the occidental steppes of Algeria by computing climatic indices and found that the rainfall rates are tending to scarcity, rainfall decrease in combination with socioeconomic pressure leaded to a degradation of lands and of vegetation cover, transforming larges steppes into bare soils and making these areas more vulnerable.

The non-affected areas having the privilege of higher rainfall rates, are also distant from human and livestock pressure, and road network, where the vegetation cover is denser (forests) and the soil is more humid or ustic moisture regime, with a Northern less exposed to drought aspect (Figure 10).

The potentially vulnerable areas are located on altitudes around 700 m a. s. l, with southern aspect and precipitation rates between 250 and 280 mm per year, also on the agricultural lands of M'sila and M’tarfa plain (Figure 11) where irrigated agricultural lands exigently require permanent water supplies which puts more pressure on natural resources, rainfed agriculture can be proposed as a solution to minimize the pressure in these areas, also resorting to drip irrigation can limit the overuse of ground water.

Fragile areas mostly of low rainfall rates, surround agricultural lands covered by rangelands and abandoned fields (Figure 12) characterized by sparse vegetation and steppes, these areas are under a sever human stress through overgrazing and the increase of agglomeration surfaces, these regions are traversed by high roads and agglomerations such as the city of M’sila (approximately 800,000 inhabitant).

The highly vulnerable areas are occupied by the salt pan of El Hodna and surrounding lands (Figure 13) that are covered by Halophytes and sparse vegetation basically steppes alfa (*Stippa tenacissima*) or occupied by bare and sandy soil and rocky outcrops.

After building the vulnerability final map, field missions were performed to validate the results and to verify model’s adequacy as well as to identify and propose appropriate management plans of drought mitigation. Several management plans may be considered for application in this area to alleviate the impact of drought, such as planting trees around farms and agricultural lands to form natural barriers against wind erosion and sand storms, also by planting shrubs, and turf to limit soil evaporation and moisture lost. Drought mitigation is strongly related to water resources preservation (dams, reservoirs, underground water), and collecting precipitation water for immediate or eventual use in irrigation or domestic activities.

Land reclamation is required to minimize salt amount in soil due to irrigation using saline water, by disposing the accumulated salt on the surface, and improving the chemical and biological soil properties through leaching, drainage operations with adding amendments and calcium supplies to reduce salt concentration in depths allow plants’ roots to grow. It is important to select salt-tolerant crops at the beginning of reclamation.

This methodology facilitates the task for researchers, decision-makers and users concerned about the impacts of climate change and drought prediction, it provides necessary information on the spatial extent of drought vulnerability in an ecosystem, considering climatic, edaphic, ecological and socio-economic aspects. However, the use of this methodology may be limited in case of the lack of data, in particular climatic data and the satellite images required to compute meteorological and satellite images.

Figure 10. Not affected area region of Maadhid mountains.

Figure 11. Agricultural lands of the region of M'sila.

Figure 12. Rangelands and abondoned fields.

Figure 13. A side of the salt pan Chott of El hodna.

CONCLUSION

The use of multi-criteria analysis and the geographic information system GIS tool allowed us to develop a methodology for assessing drought vulnerability, taking into account climatic, socio-economic, and edaphic and vegetation cover factors. We first obtained four quality maps of climate, soil, vegetation and socio-economic pressure, then a multi-criteria analysis with the use of the analytical hierarchy process (AHP) allowed the weighing of these four quality maps that will be aggregated using weighed sum aggregation to obtain the final drought vulnerability map. Four vulnerability classes emerged, the most critical class occupies more than 35 % of the study area due to its climate, soil conditions and vegetation cover degradation, as well as the increasing of anthropic pressure. These results show the importance of limiting the destructive effects of the drought phenomenon and the special care that must be given to the environment conservation and management plans such as dune fixation, windbreaks, and reforestation must have place in the region of El Hodna.

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