Spatiotemporal classification of drought severity

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Abstract. The growing number and effectiveness of earth observation satellite systems, along with the increasing reliability of remote sensing methodologies and techniques, present a wide range of new capabilities in monitoring and assessing droughts. In this paper, several drought features are analyzed and assessed by using remotely sensed Reconnaissance Drought Index (RDI). The developed methodology is applied to the region of Thessaly in Central Greece, which is the major agricultural area in the country. In particular, severity, areal extent, duration, onset and end time are analyzed from monthly RDI images over the period 1981-2001. The results show an increase in the areal extent of drought during each episode and that droughts are classified in two classes, namely mild to moderate and severe to extreme, respectively, lasting about one hydrological year. The onset of severe to extreme droughts coincides with the beginning of the hydrological year, whereas the onset of mild to moderate droughts is in spring.

Keywords: RDI, Remote Sensing, drought features

1 Introduction

Drought is one of the major natural hazards with significant impact to environment, agriculture, economy and society. There is a great variety of sectors affected by drought and its spatiotemporal variability (Heim, 2002). The basic cause of drought is the lack of precipitation events over a period of time in a region. Droughts occur in both high and low rainfall areas and virtually all climate regimes. There are several definitions and types of drought as a hazard, namely meteorological, agricultural, hydrological drought, as well as socioeconomic impacts, which are based on the temporal and spatial scale of the selected approach. Drought impacts are very critical affecting societies more than any other natural disaster (Keyantash and Dracup, 2002). However it is difficult to determine the effects of drought as it constitutes a complicated phenomenon evolving gradually in any single region. Monitoring and assessing drought conditions is usually performed through drought indicators and indices.

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The quantification of drought is not an easy task. It is common practice that several indicators can be synthesized into a single indicator in quantitative terms, called a drought index. There are several widely used drought indices using conventional and/or remote sensing data (Kanellou et al., 2008). Historically, drought quantification methods are based on conventional hydrometeorological data, such as precipitation and temperature, which are limited, often inaccurate and unavailable in near real-time (Thenkabail et al, 2004). On the other hand, satellite-based data are consistently available and can be used to detect several features (Kanellou et al., 2008). In fact, over the last decades, remote sensing has gradually become an important tool for the detection of the spatial and temporal distribution and characteristics of drought at different scales. Thus, the growing number and effectiveness of earth observation satellite systems, along with the increasing reliability of remote sensing methods and techniques, present a wide range of new capabilities in monitoring and assessing droughts.

Remotely sensed drought features and characteristics have recently become key parameters in any drought preparedness and mitigation plan in the framework of drought risk management (Rossi, 2000). In particular, in order to assess and monitor drought episodes and to alleviate the impacts of droughts it is necessary to detect several drought features such as severity, duration, periodicity, areal extent, onset and end time and to link drought variability to climate and its variability (Loukas et al., 2002). It is clear that there is a need for proper quantification of drought impacts. Thus monitoring of drought development is of critical importance in economically and environmentally sensitive regions. In this paper, the remote sensing potential in terms of data and methods is explored in order to quantify drought and classify drought severity based on several drought features by using RDI.

RDI provides information for the water deficit in a region as it is based not only on precipitation, but also on potential evapotranspiration. In the computation of RDI the innovation consists of employing Blaney-Criddle method for potential evapotranspiration instead of Thornthwaite method, since it is more appropriate for the Mediterranean region with dry and hot summers (Blaney and Criddle, 1950). Several drought features and characteristics are analyzed from monthly remotely sensed RDI images for the period 1981-2001 for Thessaly, Greece. Specifically, areal extent and severity during drought episodes signify the spatiotemporal variability of droughts in Thessaly. The paper is organized as follows: in section 2 remote sensing in drought assessment is described; in section 3 classification of drought severity is presented; in section 4 the methodology is developed and section 5 delineates the analysis and discussion of results.

2 Remote Sensing in Drought Assessment

In this section the remote sensing potential in drought assessment is presented along with drought indices based on remote sensing.

2.1 Remote Sensing Potential

The application and utility of remote sensing to drought assessment is growing rapidly, mainly due to the increasing number of pertinent satellite systems and their capabilities as well as to the International Decade for Natural Disaster Reduction and impacts of climatic variability and/or change. Remote sensing methodologies and techniques can be employed in several aspects of drought, such as vulnerability and damage assessment and warning. Exposure to drought can be controlled as well as an effort can be undertaken to alleviate the effects of drought. There are three steps which outline the elements of drought monitoring and, in general hazard monitoring and management, and are briefly described as follows: prevention which involves activities designed to provide permanent protection from hazards such as hazard and land cover mapping and vulnerability assessment; preparedness, which involves activities designed to minimize loss of life and damage including hazard warning; and relief, which involves assistance and/or intervention during or after hazard. The possible contribution of remote sensing could be focused on relief and, possibly, preparedness or warning although in many cases remote sensing can make a valuable contribution to disaster prevention, where frequency of observation is not such a prohibitive limitation.

A major consideration for development of remote sensing for drought assessment and disaster reduction is the extent to which operational users can rely on a continued supply of data. There are two types of remote sensing systems for drought assessment, namely meteorological and environmental (or resource) satellites. Meteorological satellites are usually operational, since there is a commitment to continually provide data. Besides weather forecasting, meteorological satellites have found application in several other important hazard applications mainly due to the high frequency of coverage and moderate resolution. The two meteorological satellites, namely METEOSAT and NOAA/AVHRR, can contribute to operational monitoring and assessment of drought. In addition, environmental satellites such as LANDSAT, SPOT and recently Ikonos, WV2 with high to very high resolution, but low frequency of coverage, can contribute to land-use classification and qualitative features of drought and less to quantitative assessments.

Monitoring the extent of drought is best achieved in near arid areas by the extent of vegetation. This can be done by multispectral visible imagery from polar orbiting satellites. In particular, the Normalized Difference Vegetation Index (NDVI) of the visible channels (Ch1 and Ch2) of NOAA/VHRR is effectively used (Kogan, 2002). The technique can be calibrated against biomass and give good guidance on extending drought affected areas. Soil moisture can be directly measured in the microwave region and interpretation of Synthetic Aperture Radar (SAR) data may provide some information on soil moisture.

2.2. Remotely Sensed Drought Indices

If drought is considered as a phenomenon, it is certainly an atmospheric phenomenon. However, if drought is considered as a hazard, there is a tendency to classify drought types into three categories, namely meteorological or climatological, agricultural and hydrological drought and to include as a fourth class the socioeconomic impacts of drought (Keyantash and Dracup, 2002). Table 1 shows a list of satellite-based drought indices for the quantification of drought.

Table 1. Satellite-based Drought Indices

1. Normalized Difference Vegetation Index
2. Deviation $_{NDVI}$ index
3. Enhanced Vegetation Index
4. Vegetation Condition Index
5. Monthly Vegetation Condition Index
6. Temperature Condition Index
7. Vegetation Health Index
8. Normalised Difference Temperature Index
9. Crop Water Stress Index
10. Drought Severity Index
11. Temperature - Vegetation Dryness Index
12. Normalized Difference Water Index
13. Reconnaissance Drought Index

In this paper, RDI is used based on remote sensing. The Reconnaissance Drought Index (RDI) is a new index, which is used for hydrorneteorological drought estimation (Tsakiris and Vangelis, 2005). RDI is a physically-based and general index and can be used in a variety of climatic conditions. Moreover, RDI provides information for the water deficit in an area as it is based not only on precipitation, but also on potential evapotranspiration. In order to assess and monitor drought, it is necessary to detect several drought features. Moreover, remote sensing data and methods can delineate the spatial and temporal variability of several drought features in quantitative terms.

3 Classification of Drought Severity

The classification of drought severity is achieved through the combination of several drought features using remote sensing data. A brief summary of the study area and description of drought features follows.

3.1 Study Area

The region of Thessaly overtakes the central - Eastern department of continental Greece and overtakes a total areal extent of 14036 Km2 (10.6% of total extent of the country). The 36.0% of ground are in a plain, the 17.1% semi-mountain, while the 44.9% is mountainous. High mountains surround the plain of Thessaly, which constitutes the bigger plain of the country that divides westwards to Eastern from the river Pinios that is the third bigger river of country. Pinios River is springing the western slopes of Pindos Mountains and outflows, after 216 km, in the Aegean Sea. Its main tributaries are Titarisios, Enipeas, Kalentzis and Litheos. Surface and groundwater resources are jointly used to cover rural, urban and industrial needs, whilst on the same time they are essential to the preservation of the wetland developed in the area. The main watershed in Thessaly water district is the Pinios basin which covers 9500 km2. Thessaly is one of the thirteen hydrological districts of the country and it is located in Central Greece (Figure 1). Thessaly plain is a drought-prone area, which is also the main agricultural region of Greece.

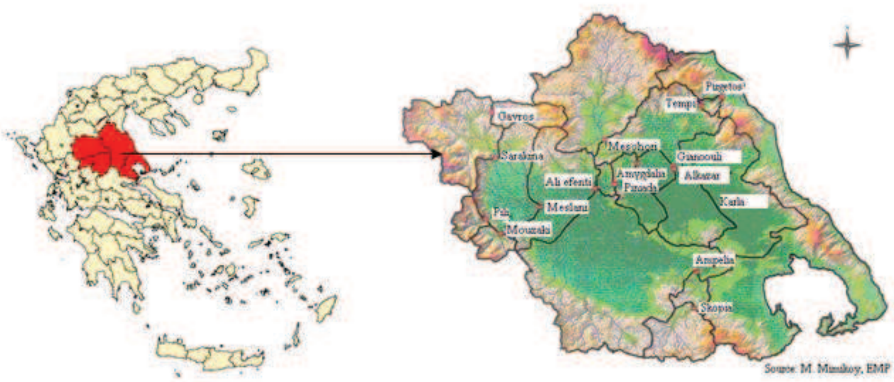


Fig.1. Location and geographical map of Thessaly region.

At the western side of Thessaly the climate is continental; the winters are cold and the summers are hot and the temperature difference between the two seasons is large. At the eastern side of Thessaly the climate is typical Mediterranean. Summers in Thessaly are usually very hot and dry, and in July and August temperatures can reach 40^{o} C. Mean annual precipitation over the whole Thessaly region is about 700mm and it is distributed unevenly in space and time. The mean annual precipitation varies from about 400mm at the central plain area to more than 1850mm at the western mountain peaks.

3.2 Drought Features

The major drought features are defined as follows:

Severity: severity or intensity of drought consists of the classification and escalation of the phenomenon from mild to moderate, severe and extreme. The severity is usually determined through drought indicators and indices, which include the above mentioned classes.

Duration: duration of a drought episode is the time interval from the start and end time usually in months. Since drought is a complex phenomenon and hazard the assessment of start and end time is a complicated issue.
Onset: the beginning of drought is determined by the appearance of drought episode. The beginning of droughts is assessed through indicators or indices reaching certain threshold value.
End time: end time of drought episode signifies the termination of drought based again on threshold values of indicators or indices.
***Areal extent*:** areal extent of drought is considered the spatial coverage of the phenomenon as it is quantified in classes by indicators or indices. Areal extent varies in time and remote sensing has contributed significantly in the delineation of this parameter.

Table 2. Drought categories based on RDI, VHI and PDSI

Drought Categories	RDI Values	VHI values	PDSI Values
Incipient dry spell	-	-	-0.5 to -0.99
Mild drought	0 to -0.99	<40.0	-1.0 to -1.99
Moderately Dry	-1.00 to -1.49	<30.0	-2.0 to -2.99
Severely Dry	-1.50 to -1.99	<20.0	-3.0 to -3.99
Extremely Dry	<-2.00	<10.0	< -4.0

4 Methodology

The methodology covers the estimation of RDI based on remote sensing data and techniques. Specifically, the methodology follows the described steps, which include prepossessing of satellite data, calculation of air temperature, estimation of potential evapotranspiration with the use of satellite data, rain map extraction and remotely sensed estimation of RDI. A brief description follows.

4.1 Data base and Prepossessing of satellite data

For the RDI estimation the following data is used:
- Daily precipitation of Thessaly water district in 50 x 50 km^2 spatial analysis derived by ground measurements provided by the .Joint Research Center (JRC) of EC, lspra, ltaly.
- Crop coefficients maps extracted by Corine Hellas 2000 for each month of the

year.

➢ Monthly maps of daytime sunshine duration for 39.39° Middle North Latitude of Thessaly.

➢ A time series of ten-day Brightness temperature (BT) images extracted from Channels 4 and 5 of NOAA/AVHRR for 20 consecutive hydrological years (October 1981 - September 2001) 8x8 km^2 provided by NOAA. The variables which are extracted from satellite data are Brightness Temperature (BT) and Normalized Difference Vegetation Index (NDVI) on monthly time step. Next step is the geometric and atmospheric correction of all images with the use of software Erdas Imagine.

4.2 Calculation of air temperature

Air temperature maps are derived from LST satellite images based on regression analysis between LST values and ground measurements of air temperature from meteorological station of Larissa, which is located in the region. LST is calculated with the use of BT and NDVI images on a pixel basis (Kanellou et al., 2008). The derived empirical relationship between LST and air temperature (Tair) is given by:

$$T_{air} = 0.6143 - LST + 7.3674 \quad R^2 \approx 0.82 \tag{1}$$

4.3 Estimation of potential evapotranspiration with the use of satellite data

The RDI uses precipitation and potential evapotranspiration. In this paper potential evapotranspiration is estimated with the use of Blaney-Criddle method. This method is selected as it is appropriate for subtropical climates with dry and hot summers such as Mediterranean region, since it has been applied in California, instead of Thornthwaite method, which is more appropriate for climates with wet and hot summers (e.g. East U.S.A). Blaney and Criddle (1950) estimated the monthly potential evapotranspiration (ET_m) in mm, by the equation (2):

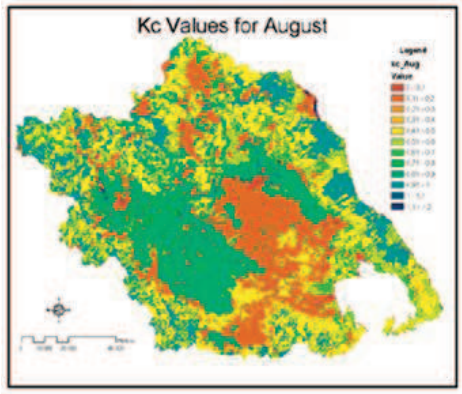
$$ET_m = k * \left[0.46T + 8.16\right] * p \tag{2}$$

where T is the mean monthly air temperature, p is the monthly daytime sunshine duration, which depends on the latitude of the area, and k is the crop coefficient, different for each cultivation, vegetation type, season and land use.

Maps of mean monthly crop coefficients for each vegetation type and land use in 500x 500 m^2 pixel size, as well as maps of daytime sunshine duration (p) for each monthly value for the Thessaly water district (39,39° North Latitude) are extracted in a GIS environment (ArcMap 9 .1. software) (Kanellou et al., 2008).

The monthly crop coefficient and the maps of daytime sunshine duration are combined with the air temperature maps for the whole data set in order to extract

Blaney-Criddle potential evapotranspiration for each month in the time series (1981-2001).



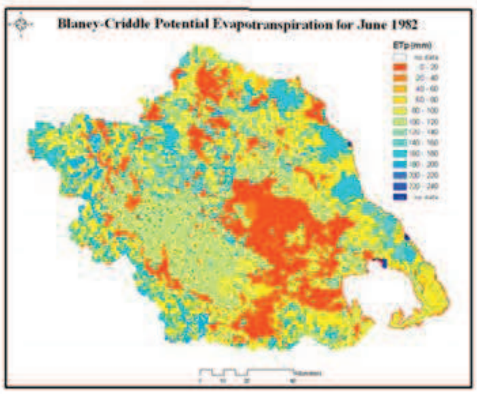


Fig. 2. Crop coefficient map (August).

Fig. 3. Blaney-Criddle ETp for June 1982.

4.4 Rain map extraction

For the estimation of RDI it is required to estimate monthly areal precipitation. Rain maps over Thessaly on a monthly basis are provided by JRC, ISPRA. These data cover Greece from 1975 to 2005 per 50x50 km^2. From daily values of all time series the monthly cumulative rain of each hydrological year from 1975 to 2005 is calculated. Then rain maps produced every month using linear interpolation.

4.5 Remotely sensed estimation of RDI

Estimation of RDI is achieved with the use of models in software Erdas Imagine, in which are used monthly temperature maps, crop coefficient (Kc) maps, sunlight maps (p), potential evapotranspitration Blaney- Criddle (ETp) maps and rain maps (P). In this study, RDI is calculated on a monthly and annual basis

The calculation of the index starts with the estimation of a_k coefficient (Tsakiris and Vangelis, 2005), as it is given by the equation:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \quad (3)$$

where P_j and PET_j are the precipitation and potential evapotranspiration, respectively, of the j-th month of the hydrological year. The hydrological year for the Mediterranean region starts in October, hence for October k=l.

RDI_n is the Normalised RDI, which is given by:

$$RDI_n(k) = \frac{a_k}{\overline{a_k}} - 1 \quad \textbf{(4)}$$

The Standardised RDI *(RDI_{st})* is given by:

$$RDI_{st}(k) = \frac{y_k - \overline{y_k}}{\hat{\sigma}_k} \quad \textbf{(5)}$$

where y_k is the ln a_k, $\overline{y_k}$ is its arithmetic mean and $\hat{\sigma}_k$ is its standard deviation.

5 Results and Discussion

The results include quantification of drought through RDI estimation on a monthly basis (1981-2001) using remote sensing data, as well as extraction of several drought features. The analysis results are presented in tables 3 and 4 and figures 4 and 5. In particular, Table 3 presents the drought periods, their duration along with the start and end times based on RDI monthly estimates. This table indicates that during the 20-year period there are eight drought episodes lasting one hydrological year, with minor exceptions. Moreover, Table 4 presents the areal extent of the monthly RDI values including all the drought classes in terms of number of pixels for each drought episode.

From Tables 3 and 4 it can be stated that the eight drought episodes are classified in two severity classes, namely mild to moderate drought (five cases) and severe to extreme drought (three cases). The next step consists of plotting the values, which are less than -2.0 of Table 4 in two separate figures, one for the mild class and another for the extreme class, respectively, along with a fitted curve for each plot.

Table 3. Duration of drought episodes (in months in Thessaly)

Drougth Years	Start	End	Duration
Oct 1984 - Oct 1985	Oct 1984	Oct 1985	13
Oct 1987 - Oct 1988	Oct 1987	Oct 1988	13
Sep 1989 - Oct 1990	Sep 1989	Oct 1990	13

Oct 1991 - Sep 1992	Oct 1991	Sep 1992	12
Oct 1992 -Oct 1993	Oct 1992	Oct 1993	13
Oct 1996 - Sep 1997	Oct 1996	Sep 1997	12
Oct 1999 - Sep 2000	Oct 1999	Sep 2000	12
Oct 2000 - Sep 2001	Oct 2000	Sep 2001	12

Table 4. Monthly Areal Extent of Drought years for the period 1981-2001. The values are in number of pixels (each pixel= 8x8 km^2)

Years **Month**	**1984-1985**	**1987-1988**	**1989-1990**	**1991-1992**	**1992-1993**	**1996-1997**	**1999-2000**	**2000-2001**
Oct	207.704	0.039	75.214	81.906	111.175	2.589	25.984	16.675
Nov	84.984	0.234	167.91	163.812	128.343	207.769	8.398	207.691
Dec	95.527	66.21	23.019	205.765	203.183	45.351	74.156	205.273
Jan	82.093	86.312	207.714	207.648	199.039	72.425	199.3	40.957
Feb	2.441	0.238	207.789	207.496	45.347	199.359	22.148	164.46
Mar	0.265	0.218	207.789	203.925	199.718	201.363	207.417	207.617
Apr	167.148	127.707	159.589	0.222	206.437	0.41	203.73	4.847
May	125.921	196.152	2.089	12.472	0.105	207.753	185.269	14.039
Jun	205.144	59.792	161.484	8.48	114.875	16.73	12.289	133.984
Jul	128.741	60.468	40.132	8.386	201.535	146.554	171.257	0.089
Aug	114.992	130.746	0.25	203.839	191.9609	0.128	193.574	49.066
Sep	123.332	83.679	77.0234	204.066	81.285	203.824	75.566	199.304
Total	**1338.27**	**811.8**	**1330.007**	**1508.023**	**1683.007**	**1304.261**	**1379.093**	**1244.007**

The results are shown in Figures 4 (extreme class) and 5 (mild class), respectively. It is interesting to notice that in Figure 4 the fitted curve starts at the beginning of the hydrological year with at least 50 pixels and the areal extent is also increasing throughout the year. On the other hand, in Figure 5 the fitted curve starts in spring with even less than five pixels and the areal extent is also increasing throughout the year, but not reaching high values. It is, thus, evidence in Thessaly that droughts can be classified in two classes, namely mild to moderate and severe to extreme, respectively, and that the former starts in spring, whereas the latter starts in October. This finding can certainly be used for prognostic assessment purposes. It simply requires more cases for verification.

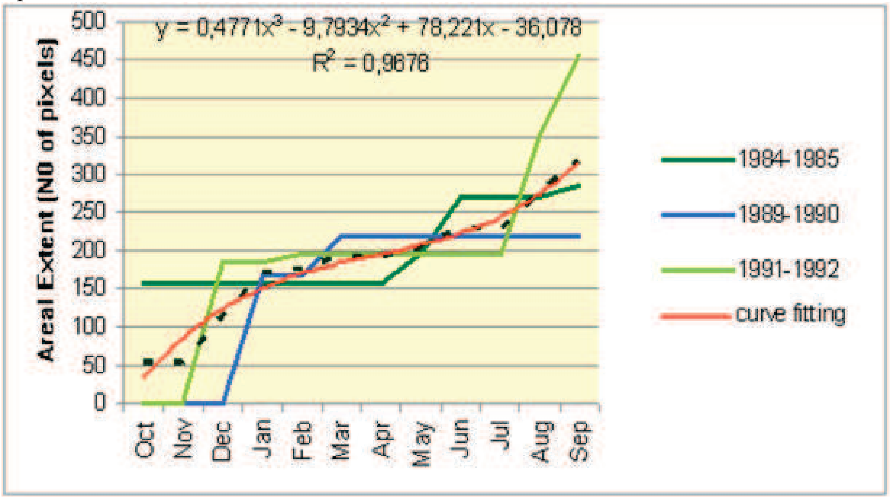


Fig. 4. Cumulative Areal Extent (Number of pixels 8X8 km^2) of extreme drought (<-2.0) during drought episodes based on remotely sensed RDI

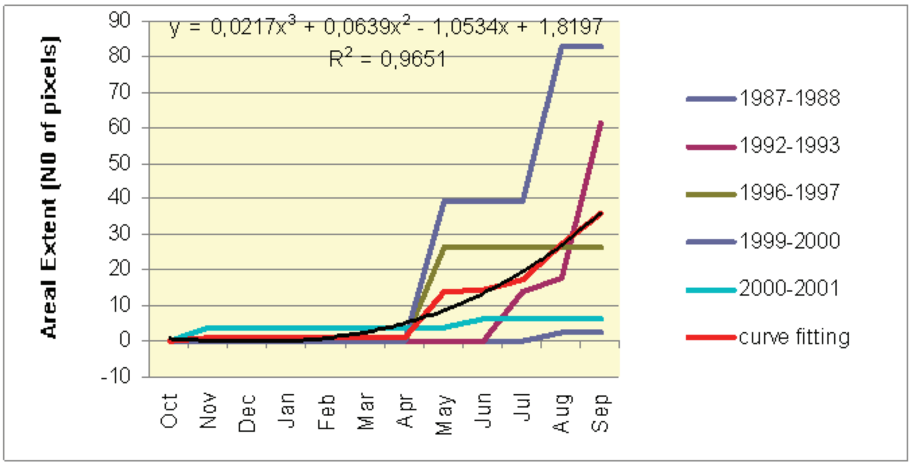


Fig. 5. Cumulative Areal Extent (Number of pixels 8X8 km^2) of mild drought (<-2.0) during drought episodes based on remotely sensed RDI

6 Conclusions

In this paper drought quantification is conducted through the estimation of remotely sensed monthly RDI (1981-2001) in Thessaly, central Greece. Moreover, the remote sensing potential is explored by assessing several drought features towards drought severity classification. The results are encouraging since drought episodes are classified in two distinct classes with prognostic ability for each class.

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