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Satellite-based Drought Estimation in Thessaly

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Abstract: Drought is the phenomenon, which is characterized by abnormally dry weather usually initiated when the average rainfall for a region drops far below the normal amount for a long period of time. Higher than normal temperatures usually occur during drought periods. The severity of drought depends upon the degree of moisture deficiency, the duration, and the size of the affected area. Drought results to a large number of impacts that affect the social, environmental, and economic standards of living, and in this way its assessment is very critical for the decision makers. There are several indices that asses how much precipitation for a given period of time has deviated from historically recorded norms. Although none of the major indices is inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses. The conventional drought indices provide information on a specified area where the measurement is taken. With the new information technology tools provided by remotely sensed data and Geographical Information Systems (GIS) spatial drought monitoring in an extended region is possible. In this research two satellite- derived indices are used for drought assessment in Thessaly water district from 1981 to 2001, namely Reconnaissance Drought Index (RDI) for hydrometeorological drought and Vegetation Health Index (VHI) for agricultural drought. The results delineate the drought conditions in Thessaly through RDI and VHI mapping. The two indices adequately delineate drought features and can be used complementarily, since they describe different types of drought.

Key words: Drought Indices, RDI, Remote Sensing, TCI, VCI, VHI.

1. INTRODUCTION

Droughts are natural phenomena that occur throughout history. Droughts are associated with a shortage of water resources over a large geographical area, which extends for a significant period of time (Rossi, 2000). There is not a universally accepted definition of drought as it depends on a wide variety of climatological parameters, with significant spatial variability (Loukas *et al.,* 2002; Dalezios *et al*., 1991). Drought occurs in both high and low rainfall areas and virtually all climate regimes. The main drought characteristics are type, severity, frequency, duration, and areal extent.

For drought assessment several studies have been carried out, which mainly estimate the precipitation shortage and the water supply deficit (Keyantash and Dracup, 2002). These studies have focused on the development of drought indices for drought identification and quantification. During the 20th century, numerous drought indices based on several variables were developed (e.g., Heim, 2002; du Pissani *et al*., 1998). Although temperature or evapotranspiration are generally included in drought index calculation, precipitation is the most important parameter (Oladipo, 1985; Guttman, 1998; Keyantash and Dracup, 2002).

Over the last decades with the development of remote sensing, spatial drought monitoring and assessment becomes possible. Remote sensing is an important tool for the detection of the spatial and temporal drought distribution at different scales. Satellite data can significantly contribute to monitor drought. Special emphasis is given to agricultural drought, as the reflected radiation recorded by satellite sensors provides an indication of the vegetation conditions, type and density (Domenikiotis *et al*., 2004a). Steven and Jaggard (1995) classified the application of remote sensing to agriculture into three categories: a) land classification, b) mapping and monitoring of crop production and c) identification of stress in crops and vegetation. In most cases, vegetation stress is identified and monitored by the use of vegetation indices. A number of satellite drought-monitoring indices are developed based on Advanced Very High Resolution Radiometer (AVHRR) of NOAA (National Oceanic and Atmospheric Administration) polar-orbiting satellite series, MODIS (Moderate Resolution Imaging Spectroradiometer) and other satellite data. These indices are normally radiometric measures of vegetation condition and dynamics, exploiting the unique spectral signatures of canopy elements, particularly in the red and near-infrared (NIR) portions of the spectrum (e.g., Huete *et al*., 1997; 2002). One of the remotely sensed drought indices, which is used for the assessment of agricultural drought is the Vegetation Health Index (VHI) (Kogan, 2002). VHI is a combination of the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI) derived by a long time series of Normalized Difference Vegetation Index (NDVI) and Channel 4 images from NOAA/AVHRR sensor. In Greece, VCI and TCI have been used for the detection of agricultural drought (Domenikiotis *et al*., 2002; Tsiros *et al*., 2004). Also, VCI has been succefully used in Greece for early cotton yield and assessment (Domenikiotis *et al*., 2004a; 2004b; 2005).

Reconnaissance Drought Index (RDI) is a new index, which is used for hydrometeorological drought estimation (Tsakiris and Vangelis, 2005). RDI is a physically based and general index and can be used in a variety of climatic conditions. This index can be calculated for any time period (1-, 3-, 6-, 9- and 12-months) and it is suitable for comparisons with other drought indices (Kanellou, 2008a). For instance, the annual RDI may be directly compared with the Aridity Index in the areas under study (Tsakiris and Vangelis, 2005). Moreover, RDI provides additional information for the water deficit in an area as it is based not only on precipitation, but also on potential evapotranspiration.

In the current study, RDI and VHI are used for the estimation of hydrometeorological and agricultural drought in the Thessaly water district, respectively. The major innovation is that the RDI is estimated based on Land Surface Temperature (LST), which is derived from satellite data instead of conventional data. Furthermore, for potential evapotranspiration Blaney-Criddle method is used in the RDI computation instead of Thornthwaite method, which was originally employed. The annual satellite-derived RDI is compared with annual conventional RDI over the meteorological station of Larissa. Finally, monthly satellite-derived RDI and monthly VHI maps are jointly used as they represent complementary spatial information and features of the drought phenomenon.

2. STUDY AREA AND DATA SET

The area under study covers the Thessaly water district, Central Greece (Figure 1). Thessaly is geographically the central section of the mainland of Greece. Thessaly's major part is mainly flatland surrounded by high mountains. Thessaly is the major agricultural area of the country. The climate of Thessaly is typical continental; the winters are cold and the summers are hot and dry and the temperature varies significantly between the two seasons. One of the characteristics of the climate of the plain of Thessaly is the frequent summer rainstorms. These frequent rains amplify the fertility of the plain, often called the "breadbasket of Greece" (Mariolopoulos, 1938). Moreover, moderate and severe drought events are very often in the region as it is shown in previous research (Dalezios *et al*., 2000). These phenomena affect very notably the agricultural activities in this region and this is the main reason for selecting Thessaly for this study.

For the VHI estimation, the data consist of images of Channels 1, 2, 4 and 5 of NOAA satellite. A time series of ten-day NDVI extracted from Channels 1 and 2, as well as Brightness Temperature (BT) images from Channels 4 and 5, for 20 consecutive hydrological years (October 1981 - September 2001), was obtained (NOAA/NASA Pathfinder program). The images cover the entire Thessaly with a spatial resolution of 8x8 km^2. An example of NDVI and BT images, which are used in the methodological procedure are shown in Figures 2 and 3, respectively.

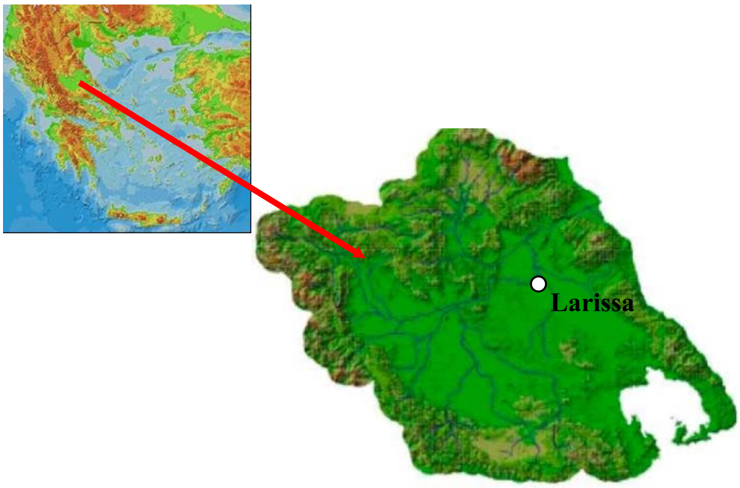

Figure 1. Thessaly water district

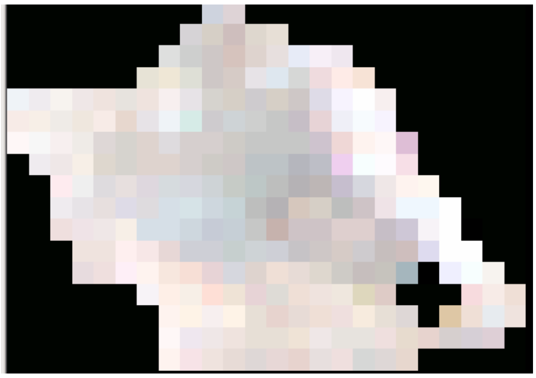

Figure 2. NDVI image for Thessaly water district 1st decadal of September 1981.

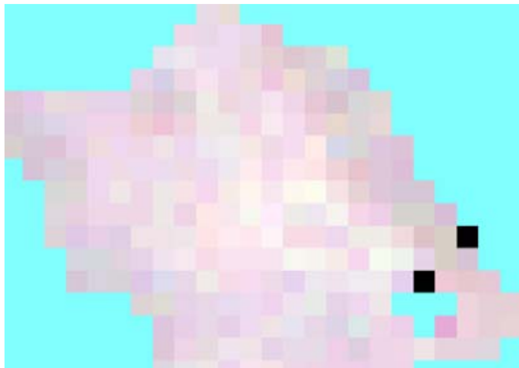

Figure 3. BT satellite image for Thessaly water district. for the for the 1st decadal of September 1981.

For the RDI estimation the following data is additionally utilized:

- 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, Ispra, Italy.
- Crop coefficients maps extracted by Corine Hellas 2000 for each month of the year.
- Monthly maps of daytime sunshine duration for 39.39^o Middle North Latitude of Thessaly.

3. METHODOLOGICAL GEOINFORMATIC APPROACH

In the current study, the methodological procedure is divided into two stages. In the first stage, RDI is used to estimate hydrometeorological drought, calculated on a monthly and annual basis using satellite data, whereas in the second stage agricultural drought is estimated in the area using the monthly VHI. A description of the employed drought indices as well as the methodological procedure for the spatial drought estimation in the Thessaly water district is briefly presented below.

3. 1. Satellite-derived Reconnaissance Drought Index (RDI)

The hydrometeorological drought conditions in Thessaly water district are estimated with the use of RDI, which depends on monthly precipitation and monthly potential evapotranspiration. In its first approach, RDI is calculated based on Thornthwaite potential evapotranspiration (Tsakiris and Vangelis, 2005). Its application with conventional data, in four areas in Greece, is described by

Kanellou *et al.*, 2008b. In this paper, Blaney-Criddle (Blaney and Criddle, 1950) potential evapotranspiration is used for the RDI extraction. The calculation of the index starts with the estimation of a_k coefficient (Tsakiris *et al.*, 2007), as it is given by the equation:

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

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=1. RDI_n is the Normalised RDI, which is given by:

$$RDI_n(k) = \frac{a_k}{\bar{a}_k} - 1 \quad (2)$$

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

$$RDI_{st}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k} \quad (3)$$

where y_k is the ln a_k, $\bar{y}_k$ is its arithmetic mean and $\hat{\sigma}_k$ is its standard deviation. The drought categories based on RDI are shown in Table 1.

Table 1. Drought categories based on RDI (Tsakiris and Vangelis, 2005).

Drought Categories	RDI Values
Extremely Wet	>2.00
Very Wet	1.50 to 1.99
Moderately Wet	1.00 to 1.49
Near Normal	-0.99 to 0.99
Moderately Dry	-1.00 to -1.49
Severely Dry	-1.50 to -1.99
Extremely Dry	<-2.00

3.2. Vegetation Health Index (VHI)

An agricultural drought index, VHI, is selected to monitor agricultural drought conditions in the study area. VHI is a combination of VCI and TCI. VCI is based on NDVI, which is obtained by combining the Channels 1 and 2 (Ch1, Ch2), visible and near infrared of NOAA/AVHRR respectively. The NDVI is given by the equation:

$$NDVI = \frac{Ch2 - Ch1}{Ch2 + Ch1} \quad (4)$$

where Ch_1 and Ch_2 are the radiances of the first two channels of NOAA/AVHRR.

NDVI is a quick and efficient way for the estimation of vivid vegetation. NDVI is indicative of the level of photosynthetic activity in the vegetation monitored (FEWS, 1996), reflecting whether the vegetation is stressed or not. After a stressed condition, significant reduction in NDVI of the field is expected and values corresponding to complete lack of chlorophyll elements are sometimes anticipated.

Maximum amount of vegetation is developed in years with optimal weather conditions, since such conditions result to optimum development due to efficient use of ecosystem resources (e.g., increase in the rate of soil nutrition uptake). Conversely, minimum vegetation amount develops in years with extremely unfavorable weather (mostly dry and hot), which suppresses vegetation growth directly as well as through a reduction in the rate of ecosystem resources use (e.g. lack of water in drought years reduces considerably the amount of soil nutrient uptake). Therefore, the absolute maximum and minimum of NDVI and BT, calculated for several years, contains the extreme weather events (drought and wet conditions). The resulted maximum and minimum values can be used as criteria for quantifying the potential of geographic areas (Kogan, 1995a; Kogan, 1997). This can be expressed by the vegetation condition index (VCI) and the temperature condition index (TCI), which are given by the equations (5) and (6) respectively:

$$VCI = 100 * \frac{NDVI\text{-}NDVI_{min}}{NDVI_{max}\text{-}NDVI_{min}} \tag{5}$$

$$TCI = 100 * \frac{BT_{max} - BT}{BT_{max}\text{-}BT_{min}} \tag{6}$$

where NDVI, NDVImax and NDVImin are the smoothed ten-day normalized difference vegetation index, BT, BTmax and BTmin are the smoothed ten-day radiant temperature, its multi-year maximum and its multi-year minimum, respectively, for each pixel, in a given area.

VCI and TCI vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions. Thus, higher VCI values represent unstressed vegetation. Thermal stresses, which have direct impact on vegetation's health can be monitored with the use of TCI (Kogan, 1995a; 2001; 2002). Kogan (2001) proposed, for agricultural drought mapping, the Vegetation Health Index (VHI), which represents overall vegetation. VHI is expressed by the following equation:

$$VHI = 0.5 * (VCI) + 0.5 * (TCI) \tag{7}$$

The five classes of VHI that represent agricultural drought (Kogan 2001; Bhuiyan *et al*., 2006) are shown in Table 2. In VHI computation, an equal weight has been assumed for both VCI and TCI, since moisture and temperature contribution during the vegetation cycle is currently not known (Kogan, 2001).

Table 2: VHI drought classification schemes (Kogan, 2001)

VHI VALUES	Agricultural drought classes
<10	Extreme drought
<20	Severe drought
<30	Moderate drought
<40	Mild drought
>40	No drought

3.3. Geoinformatic approach

RDI uses precipitation and potential evapotranspiration. The 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 (e.g. California, Mediterranean region) 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 (8):

$$ET_m = k * [0.46T+8.16]*p \qquad (8)$$

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 and land use.

Maps of mean monthly crop coefficients for each vegetation type and land use in 500 x 500 m^2 pixel size (Figures 4 and 5), as well as maps of daytime sunshine duration (p) for each monthly value for the Thessaly water district (39,39^o North Latitude) are extracted in a GIS environment (ArcMap 9.1. software) (Kanellou *et al*., 2006).

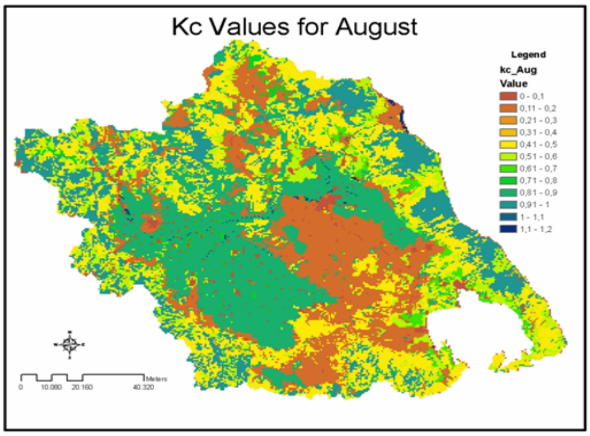

Figure 4. Crop coefficient map for August.

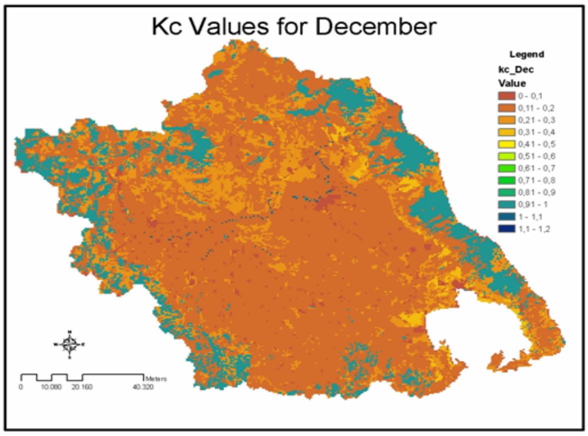

Figure 5. Crop coefficient map for December.

Also, 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 (Figure 6). The empirical relationship between LST and air temperature (Tair) is given by:

$$Tair = 0,6143 * LST + 7,3674 \qquad (R^2 \approx 0.82) \qquad (9)$$

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) using the software Erdas Imagine 8.7 version. In Figure 7, the monthly potential evapotranspiration is estimated using the Blaney-Criddle method for June of 1982. Finally, the Blaney-Criddle monthly potential evapotranspiration for the hydrological years 1981 to 2001 combined with precipitation maps (Figure 8) of Thessaly for the same time period are used for the RDI estimation. In this study, RDI is calculated on a monthly and annual basis.

VHI is based on NDVI and BT satellite images. The maps of NDVI are composited over a ten-day period and integrated on a monthly time scale. The composite values are derived from the daily NDVI images, where for each pixel the maximum value, that has the largest difference between radiance of near-infrared and visible, is saved. This process produces the Maximum Value Composite (MVC) images. For the BT images from Channels 4 and 5 the monthly values are derived by the mean of the daily images per pixel. Images with cloud coverage have been replaced by monthly climatic values, derived from the images of the time series, which presented no blunders.

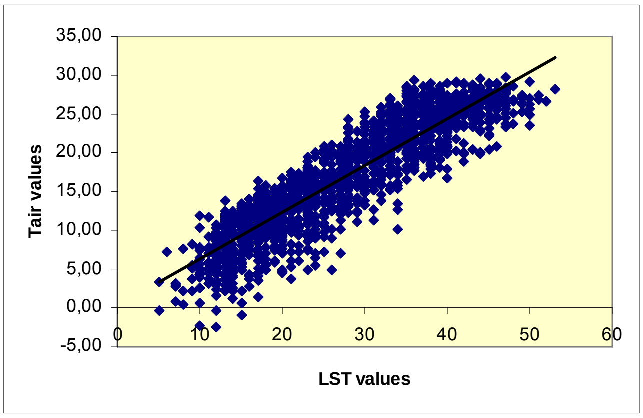

Figure 6. LST and ground based air temperature regression.

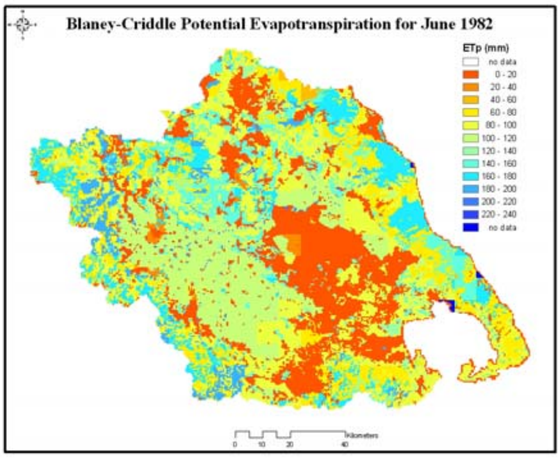

Figure 7. Blaney-Criddle potential evapotranspiration for June 1982.

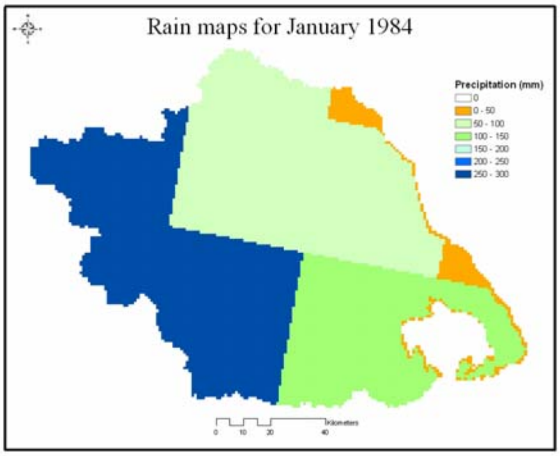

Figure 8. Precipitation map at 50 x 50 km^2 spatial analysis for January 1984.

For the impact assessment of the weather condition on vegetation, it is necessary to filter out the non weather effects. Kogan (1990) proposed spatial filtering to eliminate the portion of noise incorporated into NDVI and BT images. Filtering along with the MVC can significantly reduce the noise from residual clouds, fluctuating transparency of the atmosphere, target/sensor geometry and satellite orbital drift (Goward *et al*., 1991). Other noise can be related to processing, data errors, or simple random noise (Kogan, 1995b). Such fluctuations must be removed before NDVI and BT images are used for monitoring. This can be achieved with a "4253 compound twice" filter applied to remove the noise of the NDVI and BT series (Van Dijk, 1987). In the current study, the "4253 compound twice" median filter was applied only at the NDVI images. The BT series presented continuous spatial fluctuations. Thus, a "selective" spatial filter (statistical mean) with an adaptive window size (3x3, 5x5, 7x7 etc. according to image needs) (Tsiros *et al*., 2008) was applied for smoothing Channel 4 and Channel 5 BTs. "Selective" means that the filter was applied only to those pixels, which presented errors. From the BT images, Land Surface Temperature (LST) for the same time series of satellite data is extracted. Finally, VHI maps for the Thessaly water district are calculated as a combination of TCI and VCI. TCI was also computed using LST instead of Channel 4 (Brightness Temperature) data.

4. RESULTS AND DISCUSSION

The results refer to RDI and VHI drought maps for Thessaly water district from 1981 to 2001. As already mentioned, RDI is calculated both on monthly and annual time step. In Figure 9 annual conventional and satellite-derived RDI of Larissa station is presented for the whole data set.

Examples of annual satellite-derived RDI maps for the 1984-85 and 1991-92 hydrological years are presented in Figures 10 and 11, respectively. Monthly satellite-derived RDI is compared with monthly VHI maps for selected months of 1984-85 hydrological year.

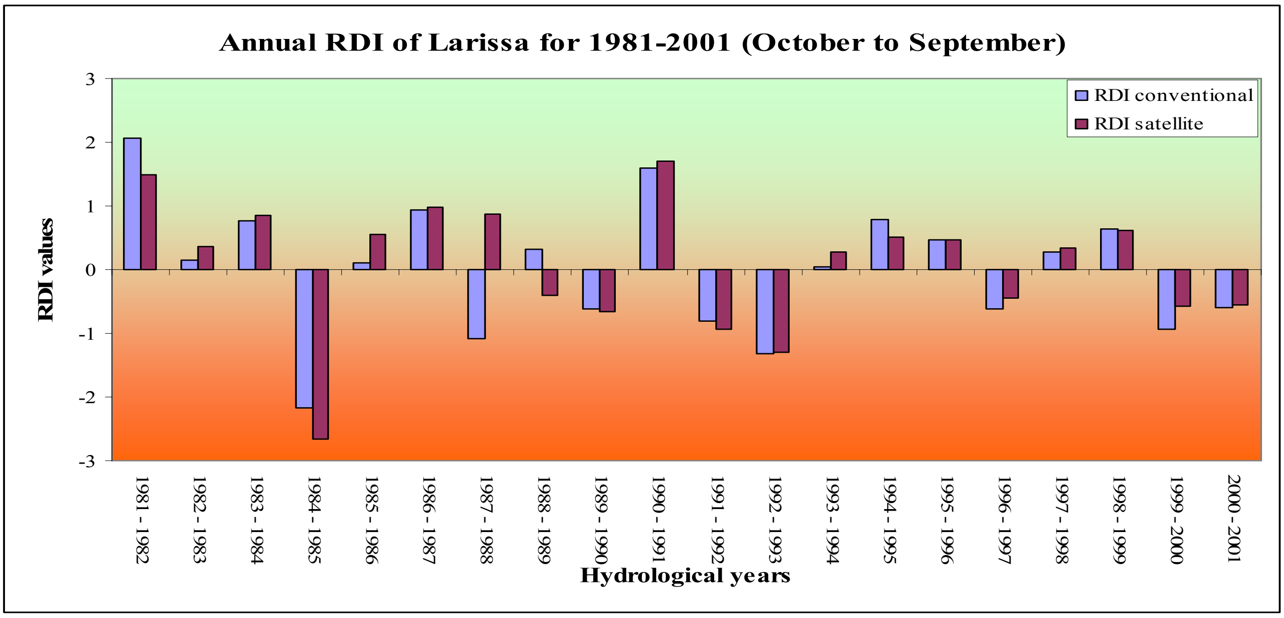

Figure 9: Conventional RDI values for the hydrological years (October to September) of the whole data set 1981-2001 for the Larissa station.

The comparison of annual conventional RDI and satellite-derived RDI over Larissa station (Figure 9) shows that the two indices result into the same drought categories for the same periods. This fact indicates the reliability of the satellite-derived RDI estimation. There is an exception in the hydrological year of 1987-88, but the values are in the near normal category, although with opposite signs. The hydrological year 1984-85 seems to be one of the driest years of the last decades with conventional RDI = -2.2 and satellite-derived RDI = -2.65, respectively. The same analysis is also presented in Table 3, where the two RDI methods are classified into drought severity categories (negative RDI values) for the corresponding hydrological years. Table 3 also signifies the coincidence of the two RDI methods.

Table 3: Conventional and satellite-derived RDI negative values classification from 1981 to 2001.

Near normal		**Moderate drought**		**Severe drought**		**Extreme drought**	
Convention. RDI	Satellite-derived RDI	Convention. RDI	Satellite-derived RDI	Convention. RDI	Satellite-derived RDI	Convention. RDI	Satellite-derived RDI
1987-1988	1987-1988	1992-1993	1992-1993			1984-1985	1984-1985
1988-1989	1988-1989	1999-2000	1999-2000	-	-		
1989-1990	1989-1990						
1991-1992	1991-1992						
1996-1997	1996-1997						
2000-2001	2000-2001						

**Convention: Conventional*

Furthermore, a comparison of annual satellite-derived RDI is attempted between hydrological years 1984-85 (drought) and 1991-92 (near normal) (Figures 10 and 11), respectively. Extreme drought, according to satellite-derived RDI, is shown in the central and northeastern Thessaly in 1984-85 (Figure 10), as well as in the southeastern part of Thessaly for the 1991-92 hydrological year (Figure 11). However, southwestern Thessaly in 1984-85 as well as the central and the northern part are classified as wet or normal. This is mainly due to the blocky of 50 x 50 km^2 maps of the RDI, which is caused by monthly precipitation maps (Figure 8) provided by the JRC, EC (Ispra, Italy).

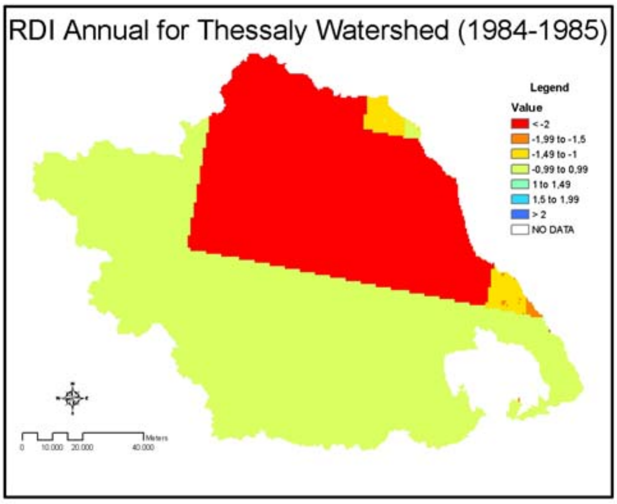

Figure 10: RDI map for the hydrological year 1984-85.

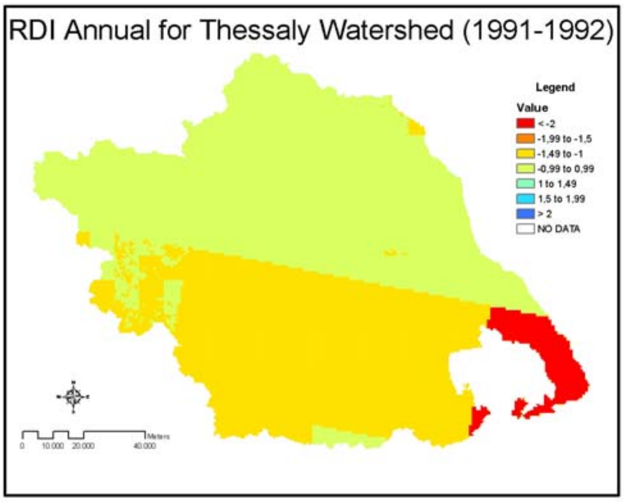

Figure 11: RDI map for the hydrological year 1991-92.

Furthermore, different time steps (1-, 3-, 6-, 9-months), are used for the estimation of conventional and remotely sensed RDI. In Figures 12 and 13 monthly RDI and monthly VHI maps for April, May and June of 1985 are presented, respectively. In Figure 12a, April 1985 shows normal conditions over Thessaly according to RDI values. Extremely drought conditions are shown in southern Thessaly for May 1985, whereas the southeastern area is classified as moderate drought (Figure 12b). Finally, in Figure 12c, extreme drought values are presented for southern-southwestern areas of Thessaly for June 1985 as well as severe drought conditions for southern Thessaly.

VHI map for April 1985 (Figures 13a) classifies the study area as wet. For May 1985, VHI results into mild and moderate drought in western Thessaly and near normal in the rest of the study area (Figure 13b). Moderate drought in northwestern Thessaly and extreme drought in southeastern study area are shown in the VHI image of June 1985 (Figure 13c). Examining the TCI values for June 1985, it seems that temperature plays more significant role in the estimation of VHI than the VCI component (eq. (7)).

Finally, a comparison for RDI and VHI is attempted for June 1985 (Figure 12c and 13c). RDI monitors the hydrometeorological drought and depends on potential evapotranspiration of the cultivations and thus it is directly affected by the high values of temperature during the summer period. Similarly, VHI estimates the agricultural drought and thus it depends on vegetation conditions and consequently it is affected by irrigated cultivations. The results show that, although RDI and VHI estimate different types of drought, both of them offer information about the onset and the end of the phenomenon from the monthly images. Both methods show a sequence of drought escalation in terms of severity from April 1985 through June 1985, although they represent different types of the phenomenon. This fact justifies the potential complementary use of both indices.

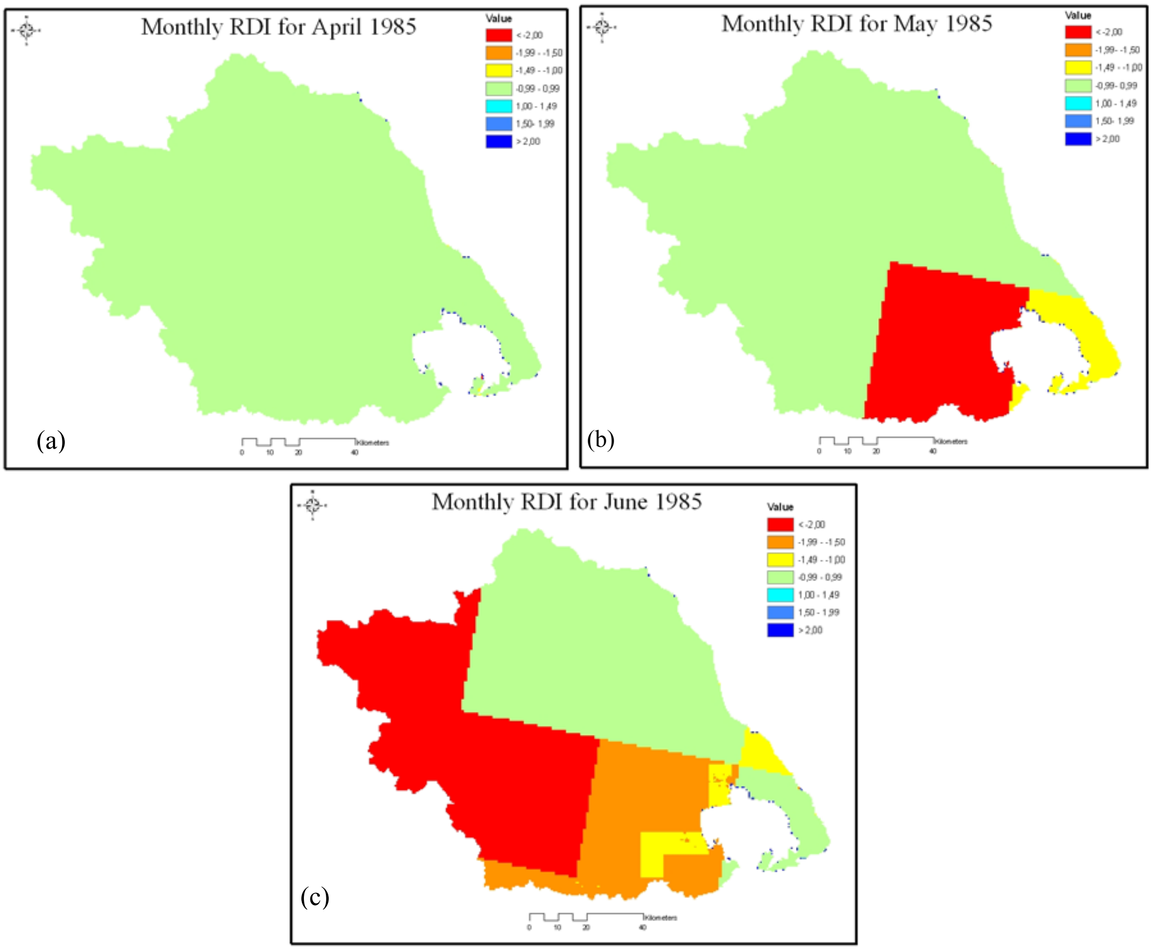

Figure 12: Satellite- derived monthly RDI maps: a. April, b. May and c. June of the hydrological year 1984-85.

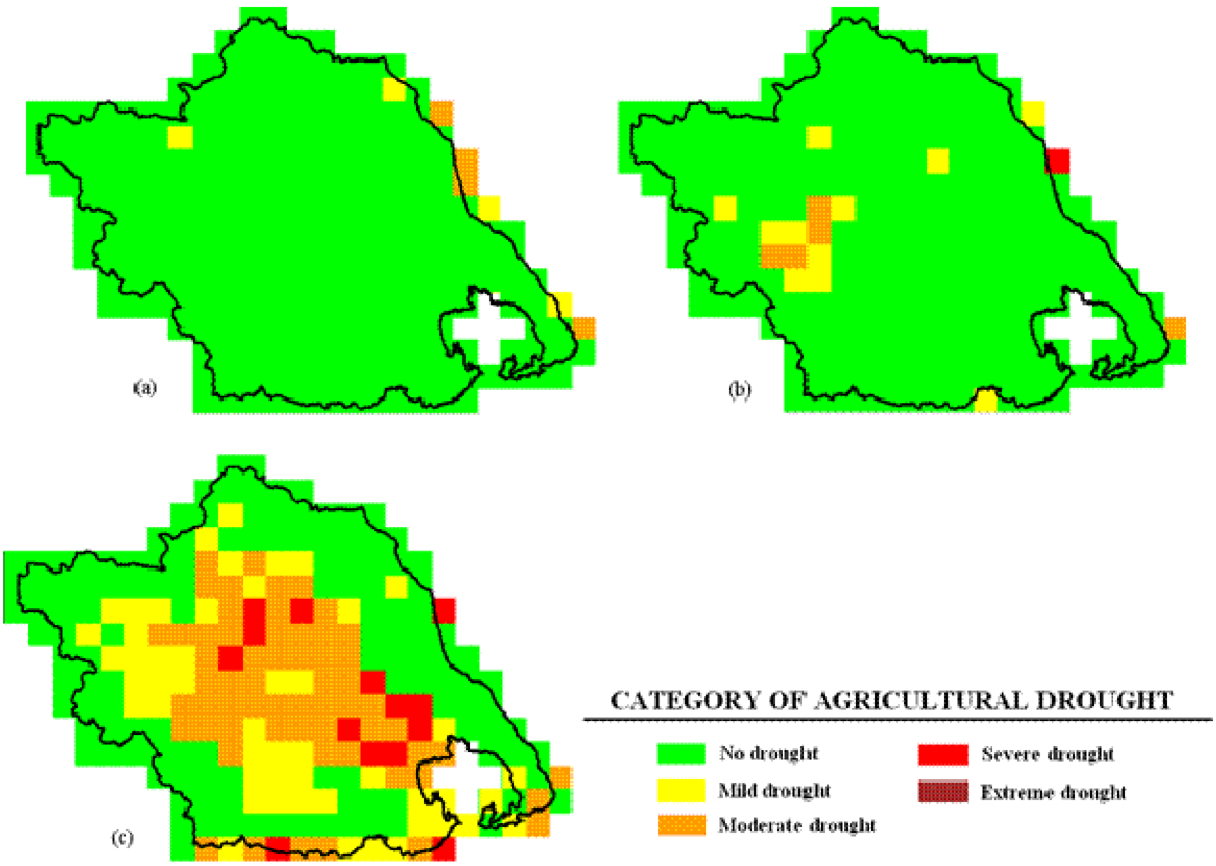

Figure 13: Monthly VHI maps for a. April, b. May and c. June, of the hydrological year 1984-85.

5. CONCLUSIONS

In this paper, two drought indices, namely RDI and VHI, are applied in Thessaly water district based on remote sensing and GIS techniques. RDI monitors the hydrometeorological drought, whereas VHI delineates the agricultural drought. The RDI is estimated on annual and monthly basis and VHI only on a monthly basis. The data set covers a period of 20 hydrological years, from October 1981 to September 2001. Initially, a comparison between annual conventional and satellite-derived RDI is attempted over the meteorological station of Larissa. The two RDI methods show similar results and indicate the reliability of the satellite-derived RDI estimation. Annual remotely sensed RDI maps are extracted for the whole study area and for each hydrological year of the data set, classifying drought severity in Thessaly. Finally, different time steps (1-, 3-, 6-, 9-months), are used for the estimation of conventional and remotely sensed RDI. The monthly satellite-derived RDI maps are compared with monthly VHI maps. The results show that, mostly, in central, northwestern and southeastern parts of Thessaly the drought episodes are very often. The two satellite-derived indices show different spatial variability and severity of drought phenomenon, since they represent different types of drought, although they show a coincidence in the temporal variation of drought. The results also show that both of the methods offer information about the onset and the end of the drought from the monthly images and thus, they can be used complementarily.

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