



This discussion paper is/has been under review for the journal Natural Hazards and Earth System Sciences (NHESS). Please refer to the corresponding final paper in NHESS if available.

# Risk identification of agricultural drought for sustainable agroecosystems

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Received: 28 February 2014 – Accepted: 4 March 2014 – Published: 30 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

**NHESSD**

2, 3097–3135, 2014

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## Abstract

Drought is considered as one of the major natural hazards with significant impact to agriculture, environment, society and economy. Droughts affect sustainability of agriculture and may result in environmental degradation of a region, which is one of the

5 factors contributing to the vulnerability of agriculture. This paper addresses agrometeorological or agricultural drought within the risk management framework. Risk management consists of risk assessment, as well as a feedback on the adopted risk reduction measures. And risk assessment comprises three distinct steps, namely risk identification, risk estimation and risk evaluation. This paper deals with risk identification of

10 agricultural drought, which involves drought quantification and monitoring, as well as statistical inference. For the quantitative assessment of agricultural drought, as well as the computation of spatiotemporal features, one of the most reliable and widely used indices is applied, namely the Vegetation Health Index (VHI). The computation of VHI is based on satellite data of temperature and the Normalized Difference Vegetation

15 Index (NDVI). The spatiotemporal features of drought, which are extracted from VHI are: areal extent, onset and end time, duration and severity. In this paper, a 20 year (1981–2001) time series of NOAA/AVHRR satellite data is used, where monthly images of VHI are extracted. Application is implemented in Thessaly, which is the major agricultural drought-prone region of Greece, characterized by vulnerable agriculture.

20 The results show that agricultural drought appears every year during the warm season in the region. The severity of drought is increasing from mild to extreme throughout the warm season with peaks appearing in the summer. Similarly, the areal extent of drought is also increasing during the warm season, whereas the number of extreme drought pixels is much less than those of mild to moderate drought throughout the

25 warm season. Finally, the areas with diachronic drought persistence can be located. Drought early warning is developed using empirical functional relationships of severity and areal extent. In particular, two second-order polynomials are fitted, one for low and the other for high severity drought classes, respectively. The two fitted curves offer a

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forecasting tool on a monthly basis from May to October. The results of this drought risk identification effort are considered quite satisfactory offering a prognostic potential. The adopted remote sensing data and methods have proven very effective in delineating spatial variability and features in drought quantification and monitoring.

## 5 1 Introduction

Agriculture faces many challenges over the coming years, such as international competition and further liberalization of trade policy. Moreover, agricultural production is highly dependent on climate, and is adversely affected by anthropogenic climate change and increasing climate variability leading to increases in climate extremes (Sivakumar et al.,

10 2005). Under a changing climate, the role of agriculture as provider of environmental and ecosystem services will further gain importance. On the other hand, natural disasters play a major role in agricultural development and the economic cost associated with all natural disasters has increased significantly (Salinger et al., 2005). Current scientific projections point, among others, to changes in climate extremes, such as heat-waves, heavy rainfall and droughts, in many areas including Southern Europe. In fact, 15 the entire Mediterranean basin is characterized as vulnerable area affecting agriculture due to the combined effect of reduced precipitation and temperature increases in areas already coping with water scarcity. Agricultural production risks could become an issue in Southern Europe as mainly droughts and heatwaves are likely to increase the incidence of crop failure. As yield variability increases the food supply is at increasing 20 risk.

Environmental degradation is one of the major factors contributing to the vulnerability of agriculture, because it directly magnifies the risk of natural disasters. Vulnerability of agriculture can be reduced through adaptation measures and tools to increasing climate variability (EU, 2007). In order to ensure sustainability in agricultural production, 25 a better understanding of the natural disasters that impact agriculture, in particular droughts, is essential. Drought is considered as one of the major natural hazards with

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such feedback, which constitutes a serious deficiency in the reduction of environmental hazards at the present time.

There is an increasing trend for the use of remote sensing in drought assessment mainly due to the growing number and efficiency of earth observation satellite systems, along with the increasing reliability of remote sensing methods (Dalezios et al., 2012a). Specifically, remote sensing data and methods can be employed in several aspects of drought, such as vulnerability and damage assessment and warning. Remote sensing contribution can be focused on relief and, possibly, preparedness or warning (Foot, 1993), although, in many cases remote sensing can also contribute to disaster prevention, where frequency of observation is not such a prohibitive limitation. This is why a major consideration for remote sensing use in drought assessment and disaster reduction is the extent to which operational users can rely on a continued supply of data (McVicar and Jupp, 1998; Thenkabail et al., 2004). Indeed, satellite systems provide temporally and spatially continuous data over the globe and, thus, they are potentially better and relatively inexpensive tools for regional applications, such as monitoring vegetation conditions, agricultural drought and crop yield assessment than conventional weather data (Domenikiotis et al., 2004). For these types of applications, appropriate remote sensing systems are those that provide low spatial and high temporal resolution data, since daily coverage and data acquisition are necessary. The series of geosynchronous, polar-orbiting meteorological satellites NOAA/AVHRR fulfill the above requirements and there are already long series of databases.

In addition, remote sensing is a useful tool to analyse the vegetation dynamics on local, regional or global scales (Kogan, 2001), to assess the vegetative stress and to determine the impact of climate on vegetation (Wang et al., 2003). Satellite-derived vegetation indices have been extensively used for identifying periods of vegetative stress in crops, which represents an indication of agricultural drought, or generally vegetation (Dalezios et al., 2012b; Kogan, 2001; Domenikiotis et al., 2002). Specifically, the NOAA/AVHRR derived NDVI has been used in drought detection and mapping (Kogan, 1995; Tucker and Choudhuri, 1987). NDVI is a quick and efficient way for the estimation

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of vivid vegetation. Furthermore, NDVI is indicative of the level of photosynthetic activity in vegetation and during vegetative stress periods results in significant reduction in NDVI values, corresponding occasionally to complete lack of chlorophyll elements.

Agricultural drought is described in terms of crop failure and exists when soil moisture is depleted so that crop yield is reduced considerably. Indeed, crop growth and yield are largely dependent on water availability (Heim, 2002). This paper deals with the quantitative risk assessment of agricultural drought affecting agriculture and its sustainability. For clarification purposes, in this paper, the term agricultural drought is used, which is already an established term in international literature. The objective of the paper consists of considering and analyzing the risk identification component of agricultural drought within the risk management framework. Risk identification of agricultural drought involves drought quantification, monitoring including early warning, as well as statistical inference. For the quantitative assessment of agricultural drought, as well as the computation of spatiotemporal features, one of the most reliable and widely used indices is applied, namely the Vegetation Health Index (VHI). The VHI is a combination of the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI) derived from NOAA/AVHRR satellite data (Kogan, 2001). In Greece, VCI and TCI, as well as the adjusted VHI, have proven to be useful tools for the detection of agricultural drought and for monitoring agricultural crops (Dalezios et al., 2012b; Domenikiotis et al., 2002; Tsilos et al., 2004). The paper is organized as follows: in Sect. 2, drought types are defined and the concept of drought risk assessment is presented. In Sect. 3, the risk identification methodology of agricultural drought is developed including drought quantification, monitoring, drought features along with the remote sensing potential, as well as the study area and database. Finally, in Sect. 4 results are analyzed and discussed.

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## 2 Conceptualizing drought and drought risk

Droughts are part of nature's climate variability. Droughts originate from a deficiency of precipitation over an extended period of time resulting in a water shortage for some activity, group or environmental sector. Droughts differ from other environmental hazards due to several unique characteristics, such as its slow onset often characterized as a creeping phenomenon, the absence of a precise and universal definition leading to inaction, and its non-structural impacts, which can be local or regional and can last for a long time or a very short time (Wu and Wilhite, 2004). Moreover, the impacts of droughts on agriculture may be severe and are neither immediate nor easily measured.

5 All these make assessment and response difficult and mitigation actions less obvious resulting into slow progress on drought preparedness.

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### 2.1 Drought types and definitions

By considering drought as a hazard, there is a tendency to define and classify droughts into different types. Definitions of drought can be categorized into two types: conceptual and operational (Univ. Hawai, 2003). Conceptual definitions are general and help

15 the public to understand the concept of drought. Operational definitions help in identifying the duration and severity of drought and are more useful in recognizing and planning for drought. Three operational definitions are presented, namely meteorological or climatological, agrometeorological or agricultural and hydrological drought. With

20 the exception of meteorological drought, the other types of drought, such as agricultural and hydrological, emphasize on the human or social aspects of drought, in terms of the interaction between the natural characteristics of meteorological drought and human activities that depend on precipitation, to provide adequate water supplies to meet societal and environmental demands.

25 *Meteorological* drought is a region-specific natural event, due to the regional nature of atmospheric phenomena, resulting from multiple causes. It is defined as the degree of dryness specified by deficiencies of precipitation and the dry period dura-

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tion. *Agricultural* drought refers to the agricultural impacts resulting from deficiencies in the water availability for agricultural use. Indeed, agricultural drought is defined by the availability of soil water to support crop and forage growth and there is no direct relationship between precipitation and infiltration of precipitation into the soil. Indeed, 5 infiltration depends on antecedent moisture conditions, soil type, slope and precipitation intensity. Soils with low water holding capacity are typical of drought-prone areas, which are more vulnerable to agricultural drought. *Hydrological* drought is normally defined by the departure of surface and subsurface water from some average conditions over a long time period resulting from meteorological drought. Like agricultural 10 drought, there is not a direct relationship between precipitation amounts and the status of surface and subsurface water supplies. There is also significant time lag between departures of precipitation and the appearance of these deficiencies in surface and subsurface components of the hydrological system (Sivakumar et al., 2010). All these 15 drought types along with the temporal sequence of procedures are shown schematically in Fig. 1 (from NDMC, Univ. of Nebraska, 2004). Finally, *socioeconomic* drought refers to the gap between supply and demand of economic goods brought on by the three other types of drought described before, such as water, food, raw materials, transportation, hydroelectric power, as a result of a weather-related shortfall in water supply. Socioeconomic drought is different from other types of drought, since its occurrence 20 depends on the spatiotemporal processes of supply and demand.

Droughts result into several significant impacts, which can be defined as direct and indirect. Direct drought impacts include reduced cropland, forest and rangeland productivity, reduced water levels, increased fire hazards, livestock and wildlife mortality rates, as well as damage to wildlife and fish habitat. The consequences of these direct 25 impacts are considered as indirect impacts. Moreover, drought impacts can also be classified by the affected sector, leading to environmental, economic or social types of impact. Specifically, environmental impacts refer to the losses resulted as a direct consequence of drought or indirectly, such as wildfire damage to plant and animal species. Similarly, many economic impacts affect agriculture and related sectors. Finally, so-

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data and methods in order to quantify agricultural drought and assess several drought features and characteristics.

## 2.2 Drought risk concepts

It is significant and very useful to address and clarify basic terms of risk analysis. At first, *hazard* is an inescapable part of life. Indeed, hazard is best viewed as a naturally occurring or human-induced process or event, with the potential to create loss, i.e., a general source of future danger. On the other hand, *risk* is sometimes taken as synonymous with hazard, but risk has the additional implication of the chance of a particular hazard actually occurring. In fact, risk is the actual exposure of something of human value to a hazard and is often regarded as the product of probability and loss. Based on the above, hazard (or cause) may be defined as “a potential threat to humans and their welfare” and risk (or consequence) as “the probability of a hazard occurring and creating loss” (Smith, 2001). Unlike hazard and risk, a *disaster* is an actual happening, rather than a potential threat, thus, a disaster may be defined as “the realization of hazard”. The term environmental hazard has the advantage of including a wide variety of hazard types ranging from “natural” (geophysical) events, through “technological” (man-made) events to “social” (human behavior) events.

The concept of *vulnerability*, like hazard and risk, indicates a possible future state. It implies a measure of risk combined with a relative inability to cope with the resulting stress. Vulnerability can be assessed by the adverse reaction of a system, or part of a system to the occurrence of a hazardous event (Salinger et al., eds, 2005). UNISDR (2005) reached the following definition: “the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards”. Most approaches to reduce system-scale vulnerability can be viewed as expressions of either resilience or reliability. Moreover, vulnerability refers to the characteristics of populations, activities and the environment that make the population susceptible to the effects of a drought, and is measured by the ability to anticipate, to deal with, to resist and recover from drought. Vulnerability

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assessment provides a framework for identifying or predicting the underlying causes of drought impacts. As drought hazard is a potential threat, it is important to assess the risk associated with the drought hazard based on an assumed exposure and coping capacity of the system. Thus, vulnerability of the system with regards to the hazard implies the lack of the system's capacity to cope with the hazard and its consequences. The vulnerability of a system towards drought can be decomposed into the vulnerability of each element of the system. Indeed, vulnerability is dependent on several factors, such as the state of the system, the magnitude of the phenomenon, the social factor and the exposure of an element or a system to a certain hazard and is expressed as a function of the above factors or variables.

Besides physical protection, a synthesis of anti-hazard measures starts being considered, including land use management, better planning for response and recovery and emergency warnings. The recent (2012) special report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) from the IPCC (Intergovernmental Panel for Climate Change) focuses on the relationship between climate change and extreme weather and climate events, the impacts of such events, and the strategies to manage the associated risks (IPCC, 2012). Understanding of extreme events and disasters is a pre-requisite for the development of adaptation strategies in the context of climate change and risk reduction within the disaster risk management framework. Extreme events and disasters, such as droughts, are expected to have greater impacts on sectors with closer links to climate, such as agriculture and food security.

For the calculation of risk for each drought episode, the impacts and implications on the system have to be estimated. Specifically, if water shortage and impact assessment addressed jointly, this leads to the estimation of vulnerability and risk. Indeed, agricultural drought can be directly associated to these impacts. In order to reduce the drought risk, vulnerability of the affected system can be reduced by improving its conditions, by decreasing the magnitude of the water shortage and its consequences and by improving the public capacity. In fact, the vulnerability reduction of a system is

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the most important step for reducing the drought risk. This can be achieved by a well structured preparedness plan, which has to be developed with the participation also of stakeholders and long before any expected drought episodes. Risk can be computed as a functional relationship of hazard and vulnerability, shown in Fig. 2. Furthermore,

5 Fig. 3 presents a list of the components of drought risk management framework, which include risk assessment and risk governance.

The subject of risk analysis, as already mentioned, involves risk management and risk assessment in order to investigate and better understand the problem of drought hazard with the objective to develop pro-active measures and procedures before a crisis. In turn, it is stated that risk management covers the risk assessment component either quantitatively or qualitatively, along with risk governance, which involves a feedback by all the affected parties. Moreover, quantitative risk assessment consists of three components, namely risk identification, risk estimation and risk evaluation (Smith, 2001). Specifically, risk identification involves hazard quantification and their interaction, event monitoring and hazard modeling, statistical inference, as well as the development of a database, which is based on recorded historical environmental data of the study area, where historical information on drought and its effect is analyzed. Similarly, risk estimation involves the risk of such events, i.e., event probabilities, as well as magnitude-duration-frequency and areal extent relationships for hazard assessment. Finally, risk evaluation includes environmental impact assessment, cost-benefit analysis of adaptation options for the development of mitigation measures.

### 3 Risk identification of agricultural drought

This section covers the development of risk identification for agricultural drought, which is a component of drought risk assessment within the risk management framework.

25 As already mentioned, drought risk identification involves quantification and modeling of agricultural drought, drought monitoring including early warning, statistical inference and the development of a database. At first, the study area is described showing the

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need for vulnerability assessment, which affects agriculture and its sustainability. Then the database is presented, which consists of satellite and conventional data and is based on recorded historical environmental data of the study area. For the quantification of agricultural drought, one of the most reliable and widely used indices is applied, 5 namely the Vegetation Health Index (VHI). The spatiotemporal features of drought are then described, which are extracted from VHI, and are the areal extent, onset and end time, duration and severity of drought. For monitoring of agricultural drought, empirical models are developed also based on satellite data, which relate drought severity to areal extent based on VHI values during the growing season, and provide a prognostic 10 ability for potential drought occurrence during the warm season.

### 3.1 Study area and database

#### 3.1.1 Study area

Thessaly is located in the central part of Greece and has a total area of 14 036 km<sup>2</sup>, which roughly represents 10.6 % of the whole country. Moreover, in Thessaly 36 % of the land is flat, 17.1 % is semi-mountainous, whereas the remaining 44.9 % is mountainous. The region of Thessaly is characterized by a highly variable landscape and the terrain is such that high mountains surround the plain, which is the largest in the country (Fig. 4). The plain of Thessaly is crossed by Pinios river. Thessaly water district is divided into three watersheds, where the main one is the Pinios watershed with 15 9500 km<sup>2</sup> in size, Lake Karla watershed with 1050 km<sup>2</sup> in size, and the remaining basins and subbasins cover an area of 2827 km<sup>2</sup>. The main part of the Pinios watershed includes a mountainous terrain with altitudes higher than 2000 m, as in Olympus (north) and Pindos (west), agricultural plains (the Thessalic plain) and urban areas with mean 20 elevation of 285 m.

The climate of the east part of Thessaly is a typical Mediterranean climate. In the west part of Thessaly, the climate is considered continental with cold winters, hot summers and large seasonal temperature range. Indeed, summers are usually hot and dry 25

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with temperatures occasionally reaching 40 °C in July and August. Mean annual precipitation over Thessaly is about 700 mm, unevenly distributed in space and time, varying from about 400 mm at the central plain to more than 1850 mm at the western mountain peaks. The mountain areas receive significant amounts of snow during winter months.

5 At the Thessalic plain, around Larissa and Karla watersheds, the mean annual precipitation has been reduced over the last thirty years about 20 % (Dalezios, 2011) and ranges between 250 to 500 mm.

The Thessalic plain constitutes the main agricultural area of the country, with cotton being still the major crop, however, wheat, sugar beets, maize, barley, horticulture, 10 fruits, olive trees and recently energy crops are also cultivated in the region. Since rainfall is, in general, rare from June to August, the resulted water deficit is replaced by irrigation in order to satisfy agricultural water needs. At the present time, in practical terms, the annual water availability is about 1023 million m<sup>3</sup>, consisting of surface (623 million m<sup>3</sup>) and groundwater (400 million m<sup>3</sup>), whereas the annual water 15 needs amount to 1836 million m<sup>3</sup>. There is, thus, an annual water deficit of 813 million m<sup>3</sup>. Part of it (about 600 million m<sup>3</sup>) is expected to be covered from Acheloos dam, which is under construction. Moreover, the amount of water used for irrigation purposes accounts for about 96 % of the total water consumption. The irrigated areas have significantly increased over the last decades and are expected to further increase in Thessaly, thus, the future water needs are also expected to increase despite 20 scheduled crop restructuring programs. Thessaly is characterized by vulnerable agriculture, since extreme hydrometeorological events, such as floods, hail and droughts are quite common in the catchment, but also due to the existing water deficit for agriculture. Thessaly is considered as one of the most important agricultural regions in the 25 country and drought episodes could have environmental and socioeconomic impacts. Droughts occur mainly due to reduced precipitation causing lack of soil moisture, increased evapotranspiration, increased vegetative stress, runoff reduction, decrease in streamflow levels in rivers, lakes and dams, lowering of the groundwater table, thus resulting in water deficit for agriculture. The subject of this paper is agricultural drought

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and several drought features are explored through remote sensing and analysed and presented in subsequent sections.

### 3.1.2 Database

For the VHI estimation the following data are utilized. A time series of 10 day Brightness Temperature (BT) images extracted from Channels 4 and 5 for 20 consecutive hydrological years (October 1981–September 2001) with resolution 8 km × 8 km provided by NOAA. Similarly, a time series of 10 day Normalized Difference Vegetation Index (NDVI) extracted from Channels 1 and 2 for 20 consecutive hydrological years (October 1981–September 2001) with resolution 8 km × 8 km provided by NOAA.

A database is developed for drought risk analysis and expected to be used in several components within the risk management framework. This database is based on recorded historical environmental data of the study area and consisting of the following components. Digital information is collected on environmental factors, such as geology, geomorphology, soil, topography, agronomy, land use, land cover, GIS and similar topics, which are used in susceptibility assessment. Information is also collected on triggering factors leading to drought, such as meteorological and hydrological parameters, e.g. rainfall and temperature, which are used in drought assessment. Also a drought inventory is developed based on recorded historical drought episodes affecting agriculture. This drought inventory is used in susceptibility and hazard assessments. Finally, the exposed elements at risk are identified and recorded, such as crops, production, environmental degradation, farms, soil and similar aspects, which are used in exposure analysis and vulnerability assessment.

## 3.2 Quantification of agricultural drought

The estimation of VHI from remotely sensed data on a monthly basis follows certain steps. At first, preprocessing of satellite images is implemented, which includes geometric and atmospheric correction of all images, as well as certain filters for smoothing

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the data, which constitute an innovation of the procedure resulting in the improvement of VHI's performance (Domenikiotis et al., 2002). Then, the computation of the VHI is implemented and monthly VHI images of Thessaly are produced on a pixel basis. A brief description of the developed methodology follows.

### 5 3.2.1 Preprocessing of satellite data

All satellite data are obtained on-line from NASA archives. NDVI maps are ten-day maximum value composite (MVC) images produced from the original CH1 and CH2 images, visible and near infrared, respectively, of NOAA/AVHRR. Similarly, CH4 and CH5 images are converted to BT images using the equation provided by the info file 10 of the data set. Using the ten-day images, NDVI and BT images are composed over a monthly period using the MVC and the mean pixel value, respectively. Missing data due to cloud cover or sensor's technical problems are filled up using monthly climatic values from time series of images with no blunders. Before using NDVI and BT images, fluctuations induced by noise must be removed. The combination of filtering and the 15 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, 1995). In the present study, a "4253 compound twice" median filter (Van Dijk et al., 1987) is applied to NDVI images, whereas a "conditional" statistical mean spatial 20 filter (window size ranging from  $3 \times 3$  to  $7 \times 7$ , according to image needs) has been used for smoothing the BT series (Tsiros et al., 2009). The BT series presented continuous spatial fluctuations, and thus, a spatial filter (statistical mean) has been preferred for smoothing channel 4 and channel 5 BTs. The term "conditional" means that the filter is applied only to the pixels that present errors.

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### 3.2.2 Computation of VHI

The computation of VHI is based on satellite data of temperature and the Normalized Difference Vegetation Index (NDVI). The VHI is a combination of the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI), both derived from

5 NOAA/AVHRR satellite data (Kogan, 2001). VCI and TCI, as well as VHI, as properly adjusted, have been successfully applied to Greece for the detection of agricultural drought and for monitoring agricultural crops (Dalezios et al., 2012b; Domenikotis et al., 2002; Tsilos et al., 2004). A description of both VCI and TCI is presented followed by the computation of VHI.

10 *Vegetation Condition Index (VCI)*. The VCI is based on NDVI and is an extension of NDVI. VCI scales the NDVI response of one image to the range of NDVI responses and this way quantifies the potential of regional responses (Kogan, 1995, 1997). VCI is related to the long-term minimum and maximum NDVI (Kogan, 1990) and is expressed by the following equation:

$$15 \quad VCI = 100 \cdot \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (1)$$

where NDVI,  $NDVI_{max}$  and  $NDVI_{min}$  are the smoothed ten-day normalized difference vegetation index, its multi-year maximum and its multi-year minimum, respectively, for each pixel, in a given area. VCI values vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions. Maximum amount of vegetation is developed in

20 years with optimal weather conditions. Conversely, minimum vegetation amount develops in years with extremely unfavourable weather (mostly dry and hot). Thus, higher VCI values represent healthy and unstressed vegetation. VCI separates the short-term weather signal in the NDVI data from the long-term ecological signal (Kogan, 1997). VCI has excellent ability to detect drought and to measure the time of its onset and its 25 severity, duration and impact on vegetation. The drought-monitoring VCI algorithm was developed and tested in several areas of the world with different environmental and economic resource (Kogan, 1995; Domenikotis et al., 2002).

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5 *Temperature Condition Index (TCI)*. TCI is based on the same concept as VCI. Similarly, maximum amount of vegetation is developed in years with optimal weather conditions, whereas minimum vegetation amount develops in years with extremely unfavourable weather (mostly dry and hot). Therefore, the absolute maximum and minimum of BT, calculated for several years, contains the extreme weather events (drought and no drought conditions). The resulted maximum and minimum values can be used as criteria for quantifying the environmental potential of a region (Kogan, 1995, 1997). TCI is expressed by the following equation:

$$TCI = 100 \cdot \frac{BT_{\max} - BT}{BT_{\max} - BT_{\min}} \quad (2)$$

10 where  $BT$ ,  $BT_{\max}$  and  $BT_{\min}$  are the smoothed ten-day radiant temperature, its multi-year maximum and its multi-year minimum, respectively, for each pixel, in a given area. As VCI, TCI varies from zero, for extremely unfavourable conditions, to 100, for optimal conditions, and higher TCI values represent healthy and unstressed vegetation.

15 *Computation of VHI*. Kogan (2001) proposed the Vegetation Health Index (VHI), which represents overall vegetation health and used it for drought mapping and crop yield assessment. The five classes of VHI that represent agricultural drought, as well as no drought conditions (Bhuiyan et al., 2006), are illustrated in Table 2. Specifically, from Table 2 it is evident that drought severity is decreasing with increasing VHI values, i.e. class 1 refers to extreme drought with VHI values less than 10, whereas for 20 VHI values greater than 40 there is no drought. VHI is expressed by the equation:

$$VHI = 0.5 \cdot (VCI) + 0.5 \cdot (TCI) \quad (3)$$

25 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. VCI and TCI vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions.

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VCI and TCI characterize the moisture and thermal conditions of vegetation, respectively (Kogan, 1995, 2001; Bhuiyan et al., 2006). Thermal conditions are especially important when moisture shortage is accompanied by high temperature, increasing the severity of agricultural drought and having direct impact to vegetations health. In many parts of the world, TCI along with VCI have proven to be useful tools for the detection of agricultural drought (Kogan, 2001; Bhuiyan et al., 2006; Tsilos et al., 2004).

### 3.3 Agricultural drought features

As already mentioned, in order to assess and monitor drought, it is necessary to detect several drought features. Indeed, remote sensing data and methods can delineate the spatial and temporal variability of several drought features in quantitative terms (Dalezios et al., 2012a). A description of some key features follows. *Severity*: severity or intensity of drought is defined as escalation of the phenomenon into classes from mild, 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 defined as the time interval from the start and end time usually in months. Since drought is a complex phenomenon, the assessment of start and end time is a complicated technical subject. *Onset*: the beginning of a drought is determined by the occurrence of a drought episode. The beginning of a drought is assessed through indicators or indices reaching certain threshold value. *End time*: end time of a 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 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 by counting the number of pixels in each class.

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## 4 Analysis and discussion of results

The results consist of quantification of drought through VHI estimation on a monthly basis for a period of 20 years (1981–2001) using satellite data. The analysis of results, besides quantification, also involves extraction of several drought features from VHI images, which lead to useful inferences. Moreover, the analysis of results includes evaluation and validation of the remotely sensed fitted monthly VHI series, in order to assess its accuracy and prognostic potential.

The results are presented in Table 3 (categories 1 & 2) and 4 (categories 3 & 4) and Figs. 5–8. At first, it should be mentioned that there is an on-going research effort on droughts in the study area of Thessaly. In a recent study on hydrological drought using the Reconnaissance Drought Index (RDI) based on satellite and conventional data (Dalezios et al., 2012a), there are eight detected drought periods lasting 12 months each within the same 20 year study period. However, in this paper, which deals with agricultural drought using VHI, and for the same period, drought occurs every year during the warm season, namely from April till October. This is shown in Table 3, which presents the cumulative areal extent of monthly VHI values throughout the warm season in number of pixels per severity class for the 20 year period. The above findings indicate that it would be advisable to jointly consider, at a later stage, the two different types of drought by merging RDI and VHI values, respectively, on a pixel basis for a holistic delineation of drought in the study area.

As already mentioned, the quantification of agricultural drought by using VHI has resulted into Table 3. However, the initial four VHI severity classes of the analysis are merged into two in Table 3, namely extreme (class 1) and severe (class 2) drought into one class, and moderate (class 3) and mild (class 4) drought into another class (Table 4) respectively. The reason for merging classes is the small number of pixels in each class in order to develop a sizeable dataset for fitting models. Table 3 and 4 also show the monthly total and the average for the merged classes. The majority of pixels is accumulated between mild to moderate drought severity classes indicating

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a significant decrease in the number of pixels from mild to extreme drought classes for all the months. Similarly, from Tables 3 and 4 it is noticed that the total areal extent in Thessaly for all the years ranges in the same order of magnitude. Moreover, there is no significant increase in the areal extent from class 1 to class 4. Table 3 and 4 also show the same increasing trend throughout each warm season. Furthermore, Table 3 indicates that there are years with very small areal extent at the beginning of the warm season reaching smaller total areal extent at the end of the warm season than other years with larger areal extent at the beginning reaching equally larger total areal extent at the end of the warm season.

Figure 5 shows the histogram of the cumulative average monthly areal extent of the first two merged severity classes, namely extreme (class 1) and severe (class 2). Similarly, Fig. 6 shows the histogram of the other two merged severity classes, namely moderate (class 3) and mild (class 4) class. Figures 5 and 6 also indicate that most of the pixels are accumulated between mild to moderate severity classes with the peaks of severity and areal extent, respectively, appearing mainly towards the end of the summer. Moreover, Fig. 7 shows the plotting of Figs. 5 and 6 in one graph. Indeed, Fig. 7 presents the cumulative monthly areal extent curves of the two merged classes, which correspond to the four VHI severity classes of agricultural drought. Furthermore, curve fitting is conducted for each of these curves resulting in the following polynomials, namely Eq. (4) for high severity areal extent drought and Eq. (5) for low severity areal extent drought, respectively, both with high coefficient of determination.

$$y = 0.0905x^2 + 4.3574x \quad (R^2 = 0.9168) \quad (4)$$

$$y = -3.7413x^3 + 34.977x^2 - 6.8352x \quad (R^2 = 0.9998) \quad (5)$$

It is worth noticing that the two curves of Fig. 7, namely the cumulative monthly areal extent curve of high severity classes (Eq. 4) and the corresponding curve of low severity classes (Eq. 5), respectively, delineate the range of values that agricultural drought may show every year during the warm season. Specifically, the curve of high severity classes (Eq. 4) shows on the average 0.3 pixels in May with maximum 3 pixels,

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whereas in October the curve shows an average of 24 pixels with maximum 71 pixels. Similarly, the curve of low severity classes shows an average of 25 pixels in May with maximum 84 pixels, whereas in October the curve shows an average of 391 pixels with maximum 568 pixels. Indeed, at the beginning of the warm season in May, the low

5 severity drought may start with average 25 pixels and may extend to 391 pixels in October, on the average. On the other hand, the high severity drought starts in May with average 0.3 pixels reaching in October 24 pixels, on the average. These findings sig-

nify the possibility of using the fitted curves for monitoring and assessing drought in any region by implementing the described methodology in the previous section, where the

10 actual VHI values may be different for different regions. In particular, for the study area of Thessaly, if at the beginning of the warm season in May there are close to 25 pixels or close to zero pixels, this indicates that a low severity or a high severity drought, respec-

tively, may be expected during the warm season. Thus, the fitted curves of Fig. 7, along with the corresponding Eqs. (4) and (5), respectively, can be used for first-guess 15 drought prognostic and monitoring assessment leading to early warning systems. It is possible that by increasing the number of years in the satellite database may lead to more reliable drought prognostic potential and early warnings.

Finally, for illustrative purposes, Fig. 8 presents VHI drought severity mapping of Thessaly for six months, namely from April to September 1985 (Kanellou et al., 2009a).

20 In this Fig. 8, it is evident that drought starts occurring in May with increasing severity and areal extent throughout the warm season with the maximum occurring in September, as expected. This Fig. 8 also shows the spatial variability of drought severity and extent within Thessaly, as well as delineating the areas of drought persistence.

## 5 Conclusions

25 In this paper, VHI is developed based on remote sensing and GIS data and techniques. VHI monitors agricultural drought and is estimated on a monthly basis. The data set covers a period of 20 hydrological years, from October 1981 to September 2001. The

study area is the region of Thessaly, in central Greece, which is a drought-prone agricultural region characterized by vulnerable agriculture. The results indicate that drought occurs every year during the warm season starting in May with increasing severity and areal extent throughout the warm season with the maximum occurring in September,

5 The results also show that, mostly, in central, northwest and southeast parts of Thessaly (Fig. 8) drought occurrence persists. Drought quantification of the remotely sensed fitted VHI estimation is assessed indicating a very high coefficient determination.

It is clear that remote sensing has indicated some new capabilities in assessing and monitoring the spatiotemporal variability of drought. Several drought features are

10 analysed from the monthly VHI images, namely severity, duration, areal extent, onset and end time. The majority of pixels is accumulated between mild to moderate drought severity classes indicating a significant decrease in the number of pixels from mild to extreme drought classes for all the months. Similarly, from Table 3 it is noticed that the total areal extent in Thessaly for all the years ranges in the same order of magnitude.

15 Moreover, there is no significant increase in the areal extent from class 1 to class 4. Table 3 and 4 also show the same increasing trend throughout each warm season. There is also an increase in the areal extent of drought during each drought period with the maximum occurring usually in the summer. Finally, the fitted curves of Fig. 7 along with the corresponding Eqs. (4) and (5), respectively, can be used for first-guess 20 drought prognostic and monitoring assessment leading to early warning systems.

*Acknowledgements.* This research was funded by Pleiades, Smart and Hydrosense EC projects. The satellite data was provided by NOAA. Software ERDAS Imagine 8.7 is used in the analysis.

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**Table 1.** Conventional and satellite data-based Drought Indices (from Kanellou et al., 2009).

Conventional Drought Indices	Satellite data-based Drought Indices
1. Percent of normal.	1. Normalized Difference Vegetation Index.
2. Discrete and cumulative precipitation anomalies.	2. Deviation NDVI index.
3. Rainfall deciles.	3. Enhanced Vegetation Index.
4. Drought Area Index.	4. Vegetation Condition Index.
5. Rainfall Anomaly Index.	5. Monthly Vegetation Condition Index.
6. Standardized Precipitation Index.	6. Temperature Condition Index.
7. Effective Drought Index.	7. Vegetation Health Index.
8. Palmer Drought Indices.	8. Normalised Difference Temperature Index.
9. Crop Moisture Index.	9. Crop Water Stress Index.
10. Bhalme-Mooley Drought Index.	10. Drought Severity Index.
11. Surface Water Supply Index.	11. Temperature–Vegetation Dryness Index.
12. Reclamation Drought Index.	12. Normalized Difference Water Index.
13. Total water deficit.	
14. Cumulative streamflow anomaly.	
15. Computed soil moisture.	
16. Soil Moisture Anomaly Index.	
17. Agro-Hydro Potential.	
18. Drought Indices derived from flow data.	
19. Standardised Water-Level Index.	
20. Reconnaissance Drought Index	

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**Table 2.** VHI drought classification scheme (Kogan, 2001).

VHI Values	Vegetative Drought Class	Drought Classes Numbers
< 10	Extreme drought	1
< 20	Severe drought	2
< 30	Moderate drought	3
< 40	Mild drought	4
> 40	No drought	



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**Table 3.** Cumulative Areal Extent (number of pixels) of Monthly Drought VHI values (sum of severity classes 1 and 2).

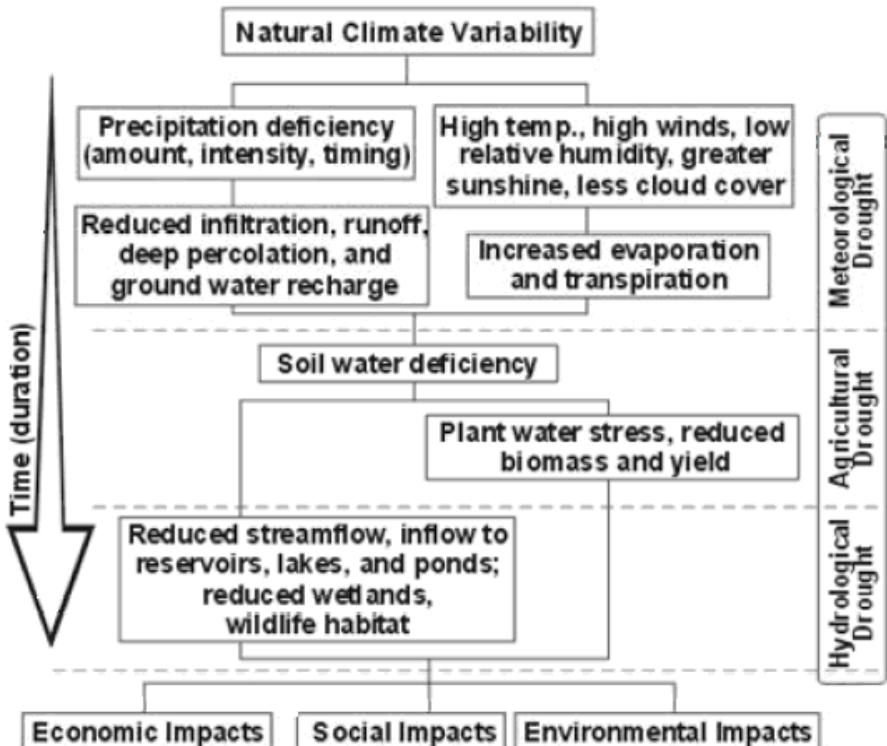
Cummulative:	May	Jun	Jul	Aug	Sep	Oct	SUM
1981	0	0	19	38	65	66	188
1982	0	1	14	28	31	31	105
1983	0	9	10	13	17	17	66
1984	0	1	6	10	10	10	37
1985	0	12	30	58	71	71	242
1986	0	3	13	25	33	33	107
1987	0	0	7	8	17	17	49
1988	0	10	24	36	40	40	150
1989	1	19	36	43	53	53	205
1990	3	39	57	69	69	69	306
1991	0	0	1	2	2	2	7
1992	0	2	3	5	5	5	20
1993	0	1	2	10	10	10	33
1994	0	0	0	0	0	0	0
1995	0	0	17	20	20	20	77
1996	1	13	18	19	19	19	89
1997	0	0	2	2	3	3	10
1998	0	2	3	11	12	12	40
1999	0	6	6	7	7	7	33
2000	1	2	12	17	18	18	68
2001	0	7	15	15	15		52
	6	127	295	436	517	503	
Average	0.2857143	6.047619	14.047619	20.761905	24.619048	23.952381	
SD	0.7171372	9.265399	13.843685	18.683963	22.44655	23.010924	
Min	0	0	0	0	0	0	
Max	3	39	57	69	71	71	

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Cummulative:	May	Jun	Jul	Aug	Sep	Oct	SUM
1981	0	0	123	252	343	418	1136
1982	8	74	193	321	416	431	1443
1983	36	142	228	331	433	464	1634
1984	6	72	173	266	308	332	1157
1985	23	134	240	361	494	568	1820
1986	45	139	249	350	471	513	1767
1987	9	71	204	287	405	418	1394
1988	19	108	243	359	467	541	1737
1989	18	107	211	315	408	474	1533
1990	84	169	298	422	511	561	2045
1991	0	38	129	203	266	306	942
1992	16	103	174	265	323	374	1255
1993	12	94	173	260	310	352	1201
1994	9	60	101	154	213	236	773
1995	4	44	146	215	278	318	1005
1996	49	148	237	309	338	347	1428
1997	27	124	228	291	358	379	1407
1998	25	106	196	284	336	365	1312
1999	40	145	227	305	357	376	1450
2000	43	129	243	337	421	431	1604
2001	45	141	229	299	345		1059
	518	2148	4245	6186	7801	8204	
Average	24.666667	102.28571	202.14286	294.57143	371.47619	390.66667	
SD	21	43	49	60	79	89	
Min	0						
Max	84	169	298	422	511	568	



**Fig. 1.** Drought types and temporal sequential procedure (from US National Drought Center, University of Nebraska).

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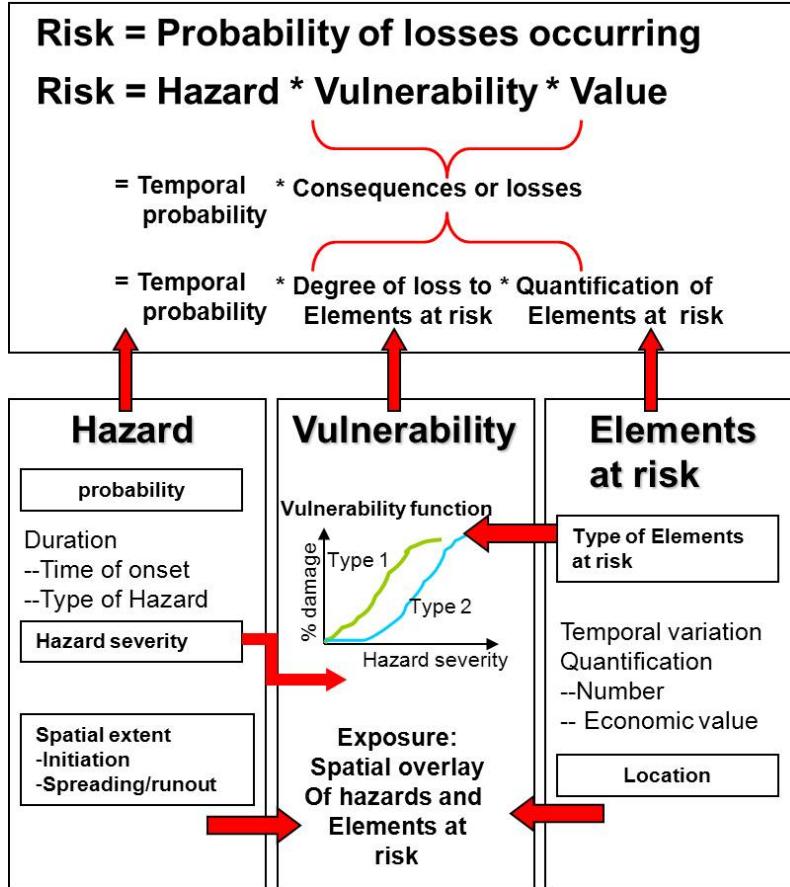
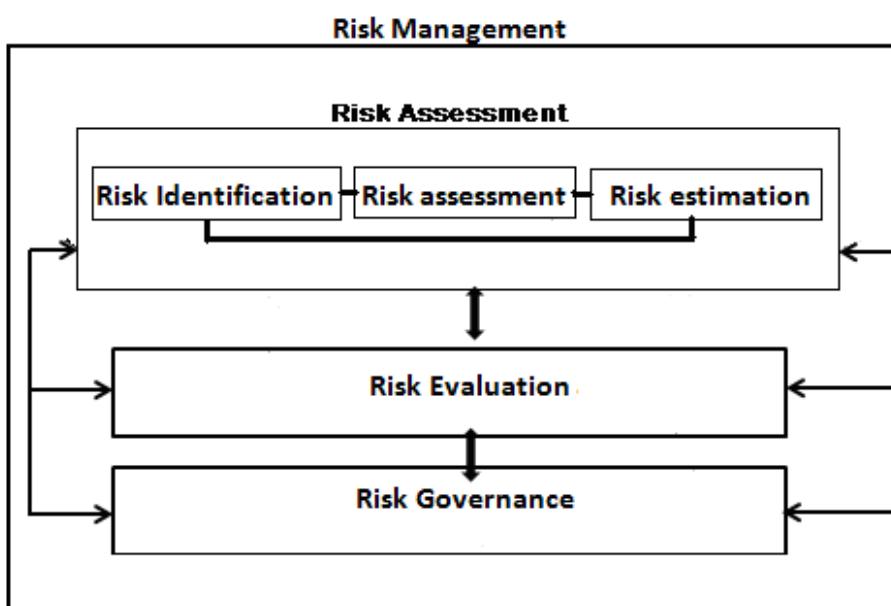


Fig. 2. Definition of Risk Concept.



**Fig. 3.** Components of Drought Risk Management.

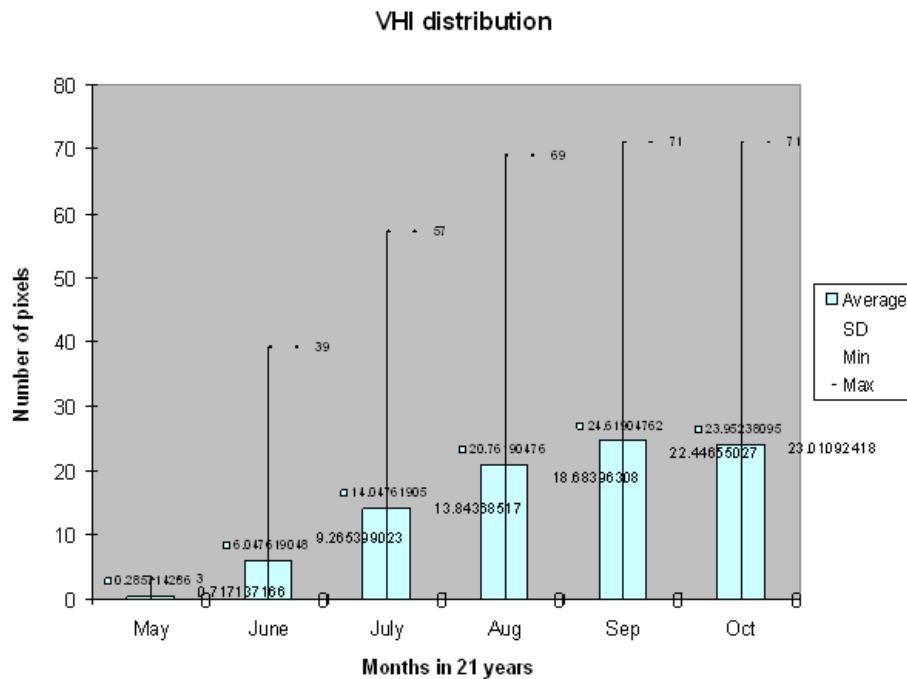


**Fig. 4.** Geophysical map of Thessaly region.

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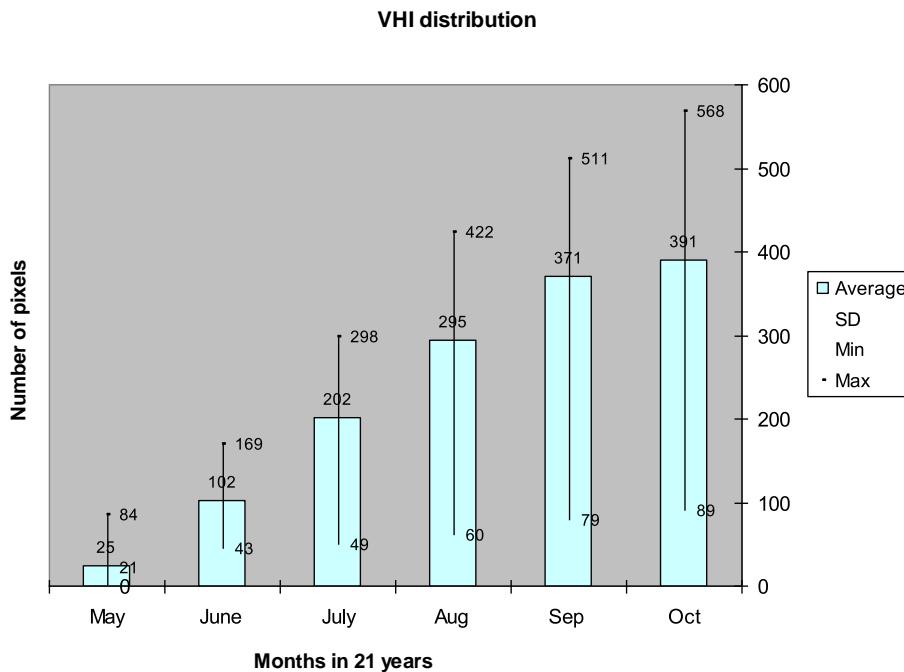
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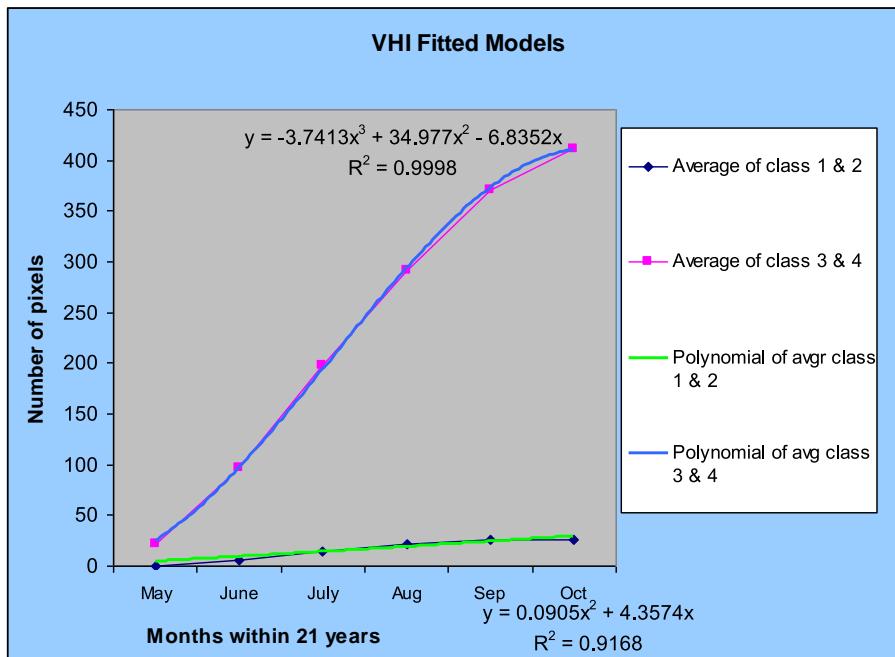
**Fig. 5.** Histogram of Cumulative Areal Extent (number of pixels) of Average Monthly Drought VHI values (sum of severity classes 1 and 2).

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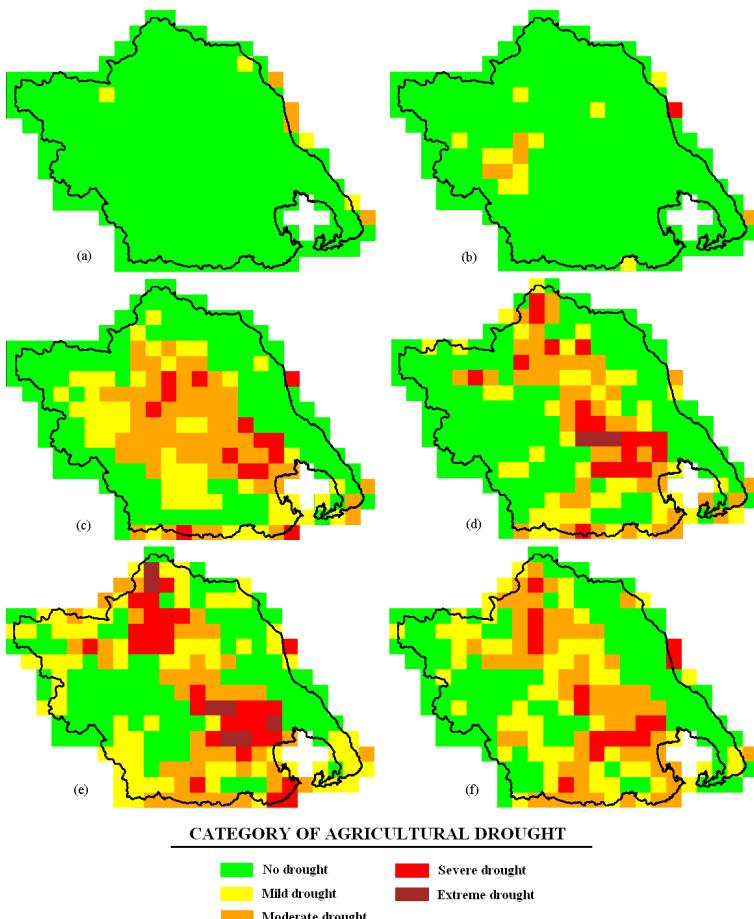
**Fig. 6.** Histogram of Cumulative Areal Extent (number of pixels) of Average Monthly Drought VHI values (sum of severity classes 3 and 4).

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**Fig. 7.** Fitted models of Cumulative Areal Extent (number of pixels) of Average Monthly Drought VHI values for the two sums of severity classes.

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**Fig. 8.** VHI map of Thessaly for six months (April–September 1985) (from Kanellou et al., 2009) (a) April 1985, (b) May 1985, (c) June 1985, (d) July 1985, (e) August 1985, (f) September 1985.

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