Science of the Total Environment 592 (2017) 262–276

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Observational evidence on the effects of mega-fires on the frequency of hydrogeomorphic hazards. The case of the Peloponnese fires of 2007 in Greece

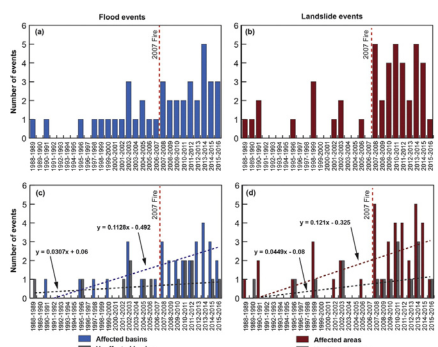
Diakakis M. [a,*], Nikolopoulos E.I. [b], Mavroulis S. [a], Vassilakis E. [a], Korakaki E. [c]

[a] Faculty of Geology and Geoenvironment, National & Kapodistrian University of Athens, Panepistimioupoli, Zografou GR15784, Greece
[b] Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA
[c] WWF Greece, 21 Lembessi St., 117 43 Athens, Greece

HIGHLIGHTS

- The mega fire of 2007 in Greece and its effects of hydrogeomorphic events are studied.
- The frequency of such events over the period 1989–2016 is examined.
- Results show an increase in floods by 3.3 times and mass movement events by 5.6.
- Increase in frequency of such events is steeper in affected areas than unaffected.
- Increases are found even in months that record a decrease in extreme rainfall.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 January 2017
Received in revised form 7 March 2017
Accepted 8 March 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Forest fires
Megafires
Floods
Landslides
Geomorphology
Hydrogeomorphic

ABSTRACT

Even though rare, mega-fires raging during very dry and windy conditions, record catastrophic impacts on infrastructure, the environment and human life, as well as extremely high suppression and rehabilitation costs. Apart from the direct consequences, mega-fires induce long-term effects in the geomorphological and hydrological processes, influencing environmental factors that in turn can affect the occurrence of other natural hazards, such as floods and mass movement phenomena. This work focuses on the forest fire of 2007 in Peloponnese, Greece that to date corresponds to the largest fire in the country's record that burnt 1773 km^2, causing 78 fatalities and very significant damages in property and infrastructure. Specifically, this work examines the occurrence of flood and mass movement phenomena, before and after this mega-fire and analyses different influencing factors to investigate the degree to which the 2007 fire and/or other parameters have affected their frequency.
Observational evidence based on several data sources collected during the period 1989–2016 show that the 2007 fire has contributed to an increase of average flood and mass movement events frequency by approximately 3.3 and 5.6 times respectively. Fire affected areas record a substantial increase in the occurrence of both phenomena, presenting a noticeably stronger increase compared to neighbouring areas that have not been affected. Examination of the monthly occurrence of events showed an increase even in months of the year were rainfall intensity presented decreasing trends. Although no major land use changes has been identified and chlorophyll is shown to recover 2 years after the fire incident, differences on the type of vegetation as tall forest has been substituted

* Corresponding author.
E-mail address: diakakism@geol.uoa.gr (M. Diakakis).

http://dx.doi.org/10.1016/j.scitotenv.2017.03.070

with lower vegetation are considered significant drivers for the observed increase in flood and mass movement frequency in the fire affected areas.

1. Introduction

Although forest fires are an integral part of Mediterranean forest ecosystems (Arianoutsou, 1998; Naveh, 1994; Pausas and Vallejo, 1999) they constitute one of the most threatening natural hazard, as human presence expands into forested land. Modern societies are profoundly affected by fire disasters, inducing significant economic losses (Calkin et al., 2005; Crompton et al., 2010) and an important number of human casualties (Blanchi et al., 2014; Diakakis et al., 2016; Haynes et al., 2010; Mangan, 2007) as well as various adverse effects on hydrologic and geomorphologic processes (Lavee et al., 1995; Neary and Leonard, 2016; Shakesby and Doerr, 2006; Shakesby, 2011).

Fires have been found, among other effects, to directly influence rock weathering rates (Allison and Bristow, 1999; Allison and Goudie, 1994; Goudie et al., 1992; Dorn, 2003), reduce interception and storage capacity of the surface layer through removal of litter (Diaz-Fierros et al., 1994), change the chemical structure and hydrological properties of soil due to extreme heating (Giovannini et al., 1988; Scott et al., 1998) and affects its water repellency (DeBano, 2000; Doerr et al., 2004, 2005; Vieira et al., 2015). Due to these impacts, forest fires induce a series of indirect hydrological and geomorphological effects that can last up to several years (Shakesby and Doerr, 2006). These effects include reduction of infiltration (Wondzell and King, 2003), increase in annual runoff volumes (Lavabre et al., 1993; Helvey, 1980), increase of overland flow (Cerda and Doerr, 2005; Scott et al., 1998) and increase in erosion rates (Cerda and Doerr, 2005), especially due to the influence of ash that intensifies splash erosion and runoff rates (Bodí et al., 2014; Jordán et al., 2016). These effects lead directly to alteration of hydrological response of burned catchments (Scott, 1993) that usually manifest as increasing peak flows and reduced concentration times during storm events (Moody and Martin, 2001; Smith et al., 2011). In terms of geomorphological response, forest fires lead to a temporary intensification of erosion rates (Vega and Diaz-Fierros, 1987; White and Wells, 1982; Shakesby and Doerr, 2006) and occurrence of mass movement processes including debris flows and shallow landslides (Campbell, 1975; Cannon and Reneau, 2000; Cannon and Gartner, 2005; Cannon et al., 1998, 2001; Dragovich and Morris, 2002; Meyer et al., 2001; Swanson, 1981; Wells et al., 1979).

The duration of fire's impact on the hydrogeomorphic behaviour of an area vary considerably. Previous works have shown that this period commences immediately after the fire (Shakesby and Doerr, 2006) and lasts from a few months up to several years as vegetation recovers (Brown, 1972; Mayor et al., 2007; Morris and Moses, 1987; Prosser and Williams, 1998; Shakesby et al., 1994; Shakesby and Doerr, 2006). In fact, fire-induced increased water repellency, intensified by vegetation removal and the role of ash (Shakesby and Doerr, 2006; Jordán et al., 2016) is a key process regarding the increased runoff volumes and has been reported to last from months up to 6 years (DeBano et al., 1976; Dyrness, 1976; Doerr et al., 2000; Ebel et al., 2016). Prosser and Williams (1998) reported a period of 7 years until resistance to erosion returns to pre-fire levels. Legleiter et al. (2003) and DeBano et al. (1996) indicate that the period of disturbance can last up to 13 or 14 years respectively. Wittenberg and Inbar (2009) and Keesstra et al. (2017) state that the window of disturbance can be lengthened and the "baseflow" level of sediment yield was raised with each successive forest fire. Shakesby (2011) suggests that under circumstances there could be a permanent increase of 'background' sediment yield, indicating a more enduring footprint of the fire in geomorphological processes. González-De Vega et al. (2016) found correlation between fire severity and the recovery time for tall vegetation (pine forests), which indicates different duration of disturbance in parts of the burnt area (Vieira et al., 2016).

Even though the influence of forest fires in hydrologic and geomorphic processes is well established, and the increase in peak runoff as well as in the occurrence of debris flows is recorded (Bart, 2016; Mahat et al., 2016; Riley et al., 2013; Van Eck et al., 2016; Wondzell and King, 2003), there is limited documentation on the quantification of changes on the frequency of flood and mass movement events, before and after a fire. Candela et al. (2005) identified probability increases of 5-year and 10-year floods of approximately 1.5 times, by comparing simulated flood frequency curves between pre- and post-fire conditions. Nalbantis and Lymperopoulos (2012) calculated the same figures at approximately 3.5 and 2.5 respectively. Laurance (2007) suggested that removing of a 10% of existing forest cover could lead to an increase in flood frequency between 4%–28%. However, all the above works estimate changes on the basis of simulated results. Observational evidence of changes in flood and mass movement frequency of occurrence before and after a fire incidence are virtually absent from existing literature.

Among all forest fires the damages and the costs induced by mega-fires are by far the most extensive and serious, defining them as disasters of an entirely different scale in terms of impacts than the rest of the incidents (Williams et al., 2011). Mega-fires expand during extremely dry, hot and windy weather conditions and are fuelled by dense vegetation and unmanaged forest fuels (Williams et al., 2011). Most of the times mega-fires overwhelm the most advanced firefighting systems and organizations with consequences reaching beyond damages to property and infrastructure requiring a large commitment of financial and other resources (Omi, 2005). Recent mega-fires caused long lasting indeterminable impacts on the environment and local or even regional economies and societies (Ferreira-Leite et al., 2015; Williams et al., 2011). In addition, there is evidence of their growing frequency since 1990 (Ferreira-Leite et al., 2015) suggesting that within a changing climate it is likely that we will be dealing with such events more frequently.

Within the context of impact of fire on hydrogeomorphic response, the effects of mega-fires on hydrogeomorphology and the occurrence of related disasters is scarcely quantified, especially using long-term observational evidence. Quantifying these effects at a regional scale is particularly important for understanding and estimating the potential extend of the impact of future forest fires, not only in terms of alterations in hydrogeomorphic processes but also in terms of decision making for civil pretection (e.g. selection of post-fire protection measures and risk mitigation efforts).

This study is in line with this objective and presents an observation-based analysis regarding the regional impact of a mega-fire on the frequency of occurrence of hydrogeomorphic hazards. Particularly, this work builds upon the development and analysis of a complete catalogue of flood and mass movement events in the period 1989–2016 in the western part of Peloponnese in Greece, an area that was affected by a mega-fire in 2007, specifically aims to:

i. Identify possible changes, patterns or trends in the frequency of flood and mass movement events before and after the fire incident.
ii. Examine possible influencing factors (drivers) of the above changes
iii. Estimate quantitative (e.g. magnitude) and qualitative (spatial distribution, seasonality) characteristics of changes in occurrence.

2. Materials and methods

2.1. The 2007 mega-fire in Peloponnese

In 2007, Greece experienced the most catastrophic forest fire event and its worst fire season in recorded history (Koutsias et al., 2012; Xanthopoulos, 1998). Following a deep drought and at least two heatwaves in the course of a summer with very adverse weather conditions (Founda and Giannakopoulos, 2009), a fire that started in August 24 in Peloponnese, approximately 200 km west of Greece's capital Athens (Fig. 1), eventually burnt 1773 km^2 (WWF Greece, 2007) of agricultural and forested land (Koutsias et al., 2012). Due to the fire, 78 lives were perished (Diakakis et al., 2016) in a period of 7 days at the end of August. Extreme weather conditions and concentrated fuels (Koutsias et al., 2012) along with high winds, high temperature and low humidity (Founda and Giannakopoulos, 2009) contributed to almost explosive fire growth in Ileia, a province situated in west Peloponnese. Although the majority of acres burned were public lands, 67 villages were affected and over 71 houses were destroyed just in the small villages of Makistos and Artemida in Ileia alone (Xanthopoulos et al., 2009) while indirect damages were recorded as well (e.g. transportation (Karamichas, 2007; Mitsakis et al., 2014)). Grass, evergreen shrubs, and pine forests were the dominant fuels in the area. Hundreds of homes, along with warehouses, businesses and stables were destroyed in total, while high fire severity was identified at locations (Veraverbeke et al., 2010, 2011). At least $US 5.5 million were expended to suppress this fire (Williams et al., 2011). The fire extended mostly in western Peloponnese (Fig. 1), where three major pieces of land (Fig. 1b) of total area 1213.1 km^2 were burnt.

2.2. Data

The study used different sources to collect flood and mass movement events data for the study area between 1989 and 2016. Data on flood event occurrence were collected from 4 databases with nationwide coverage (Table 1). To ensure completeness of record, scientific publications and press archives were examined as supplementary sources (Table 1). Information collected included location, exact dates, flooded river name, basin name, section of the river that flooded, towns, villages and administrational entities that suffered damages.

Data on mass movement events occurrence in the study area were collected from scientific publications and databases, individual landslide studies from the relevant national authority (Institute of Geology and Mineral Explorations) and press archives (Table 2). Information collected included location, exact dates and time, trigger, mass movement type, pictures and location maps. For the purposes of this work only rain-induced mass movement events were examined.

One of the most important drivers of hydrogeomorphic processes is rainfall. Thus collection of rainfall information for the region of interest was of paramount importance for this study. Unfortunately, the area under study is poorly covered by ground stations that have a record that is consistent and sufficiently long for this investigation. Examination of available rain gauges located in the local airports of the area revealed that data were inconsistent (had a lot of gaps) and in many cases reported unrealistically extreme values, suggesting a poor quality of the available observations. The only alternative for obtaining rainfall information for the area was from satellite-based rainfall products. Currently, a large number of satellite-rainfall products exist and selection of the most appropriate product can be a challenging task on its own,

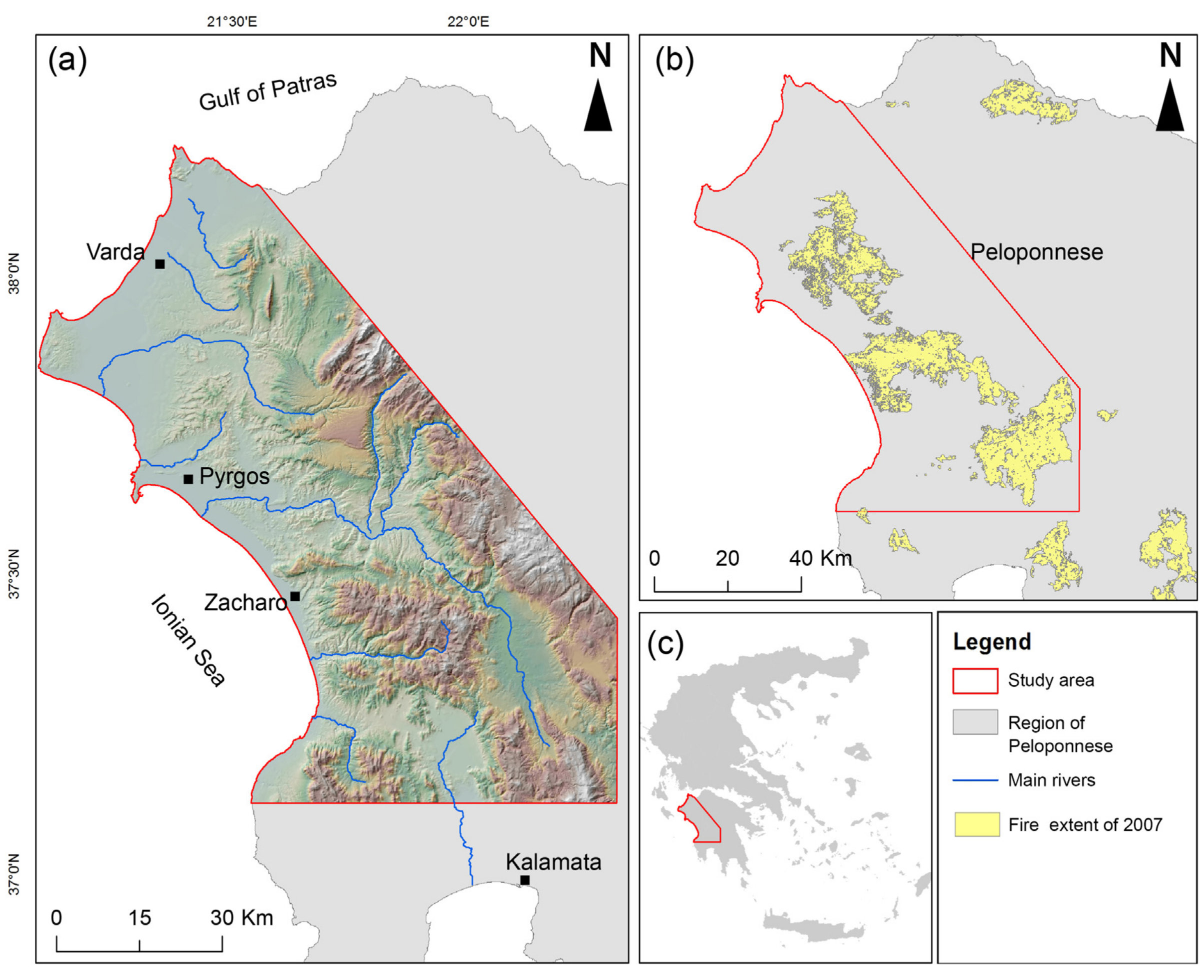


Fig. 1. Location map of study area and fire extent.

Table 1
Sources of data on past flood events in the study area.

Source type	Details	Coverage
Databases	Flood Database (Diakakis et al., 2012)	1880–2010
	Flood Event Registration Database (Special Secretariat for Water, 2012)	1896–2011
	Earthquake Rehabilitation Service Archive - Floods (Earthquake Rehabilitation Center, 2016a)	1994–2016
	Database of high-impact weather events in Greece (Papagiannaki et al., 2013)	2001–2011
Scientific publications	Diakakis et al. (2011)	1880–2010
	Papagiannaki et al. (2013)	2001–2011
Press archive	National Newspapers (Kathimerini, Ta Nea, Rizospastis, Ethnos, Eleftherotypia)	1994–2016
	Local Newspapers (Amaliada News, Hleia Live, Ilia oikonomia, Eleftheria, Patris)	2010–2016

given the strong regional dependence in the performance of each product (Derin et al., 2016).

In this work we selected to derive rainfall information from the US NASA (National Aeronautics and Space Administration) Tropical Rainfall Measurement Mission Multi-satellite Precipitation Analysis (TMPA) 3B42 version 7 (hereinafter 3B42V7) product (Huffman et al., 2007). Our selection was based on the following main reasons: i) 3B42V7 is one of the products most widely used by the hydrologic community, ii) it is a gauge-adjusted product and many evaluation studies (see for example Mei et al., 2014 among many others) have ranked it among the top performing products, and iii) results from recent evaluation studies involving the area of Greece (Nastos et al., 2016; Feidas, 2010; Katsanos et al., 2004) have shown good agreement of 3B42 (and 3B42-related products) with available reference data. Based on these reasons we decided to adopt the rainfall estimates obtained from 3B42V7 and use them as the reference rainfall information throughout this analysis. Rainfall estimates from 3B42V7 are available at 0.25° (spatial) and 3 h (temporal) resolution and the available record analyzed span from Jan 1998 to June 2016.

Geospatial data regarding relief, geomorphology, geology and vegetation for the 2007 fire extent were collected from several sources either in digital (GIS compatible) or analogue format. The scale of the original analogue maps, which were also digitised for GIS importing was generally 1:50.000 except in some cases where 1:5000 maps were used (i.e. flood and mass movement event mapping, river network mapping). Additionally, a series of freely distributed remote sensing images for the time period 2000–2016 was obtained from USGS/EROS image database. A total of 15 Landsat scenes for the path 184 and row 034, with minimal cloud cover during summer period were co-registered in a common projection system for the generation of a multi-temporal change detection dataset. No information for the years 2011 and 2013 was included in this 17-year multi-temporal analysis due to low quality of data during the summer period. Satellite images from Landsat 5 and 7 ETM+ sensors were included in this dataset and in many cases data acquired from Landsat 7 ETM+ were used despite the problem of the failure of the scan line corrector (SLC) during 2003 (Maxwell, 2004) (Table 3). The latter did not become an important issue as only the areas without the NODATA-stripes were used for the extraction of vegetation change detection some years before and after the 2007 mega-fire incident (Howard and Lacasse, 2004).

Table 2
Sources of data on past mass movement events in the study area.

Source type	Details	Coverage
Databases	Mass movements database (Lekkas et al., 2007)	1989–2007
	Database of high-impact weather events in Greece (Papagiannaki et al., 2013)	2001–2011
	Earthquake Rehabilitation Service Archive - Landslides (Earthquake Rehabilitation Center, 2016b)	1996–2016
Scientific publications	Lainas et al. (2015)	1956–2011
	Depountis et al. (2010)	1950–2011
	Korobilis (2001)	1998–2001
Individual mass movement event studies	Antonopoulos (2003a, 2003b), Bellas (1991, 1999, 2003), Konstantopoulou (2008), Koutsouveli (2003), Nikolaou and Kokkinakis (1991), Tzitziras (2002, 2003a, 2003b)	1988–2015
Press archive	National Newspapers (Kathimerini, Ta Nea, Rizospastis, Ethnos, Eleftherotypia)	1994–2016
	Local Newspapers (Amaliada News, Hleia Live, Ilia oikonomia, Eleftheria, Patris)	2010–2016

Geospatial landcover data were collected from CORINE 1990, 2000, 2006, 2012 land cover system of European Environment Agency (European Environment Agency, 2016). Landcover classes were grouped in 4 major categories, based on the CORINE system's major divisions (Table 4).

2.3. Methodology

In this section, we describe the methodological approach followed in order to analyse the changes in frequency of occurrence of flood and mass movement events between the period before and after the 2007 fire, as well as investigate the attribution of these changes to potential changes in rainfall, land cover and relevant infrastructure, which we have considered the main drivers for changes in the hydrogeomorphic response at regional scale.

2.3.1. Flood and mass movement event evolution

Based on the data described previously, the catalogue of flood and mass movement events was split into two periods, before and after the 2007 fire, for comparative analysis. Specifically, the periods of analysis span from: (i) September 1st, 1988 – August 31st, 2007 (pre-fire), (ii) September 1st, 2007 – August 31st, 2016 (post-fire).

Given that the 2007 fire occurred at the end of August, the two segments were selected in a way that effects of the first rainy season on September 2007, would be drawn up (aggregated) in the post-fire period. Similarly, to calculate the yearly number of events, this work considered the number of floods or mass movement events between 1st of September and 31st of August of each year.

In an effort to examine possible influences of older or newer forest fires in the hydrogeomorphic response, we also studied the fire history of the area based on an "Annual Burned Area" data from the Tsagkari et al. (2011). The record covers the period 1982–2015 and is dominated by relatively small numbers of burned areas ranging from 0.23 km^2 to 42 km^2 on an annual basis. Apart from 2007, only 3 years (1985, 1989 and 1998) were an exception to this range with 83 km^2, 50 km^2 and 156 km^2 respectively. Thus the rest of the period records annual extents of at least an order of magnitude (or more) lower than the fire of 2007 while the latest year with a noteworthy record is 9 years older. This absence of large fires in the area is considered one of the factors that lead to the accumulation of fuels that affected the magnitude and the behaviour of fire in 2007 (Koutsias et al., 2012; Xanthopoulos, 2013) and is known to affect the occurrence of large fires in the region (Meyn et al., 2007; Xystrakis et al., 2014; San-Miguel-Ayanz et al., 2012; Moreira et al., 2012; San-Miguel-Ayanz et al., 2013). Based on the above record, it is safe to assume that any fire-induced observed changes in flood/mass movement events in the affected area in the post 2007 period are attributed to the 2007 fire incident. In addition, it is safe to assume that the local fire history itself influenced the vulnerability of the area to fire.

The temporal trends of annual occurrence of flood and mass movement events were examined using least square linear regression in affected and unaffected hydrological basins to explore and compare the trends with and without the influence of the 2007 fire. Affected (unaffected) basins were identified as those that included (did not include) part of the burned area. The nonparametric Wilcoxon rank sum test

Table 3
List of remote sensing data used for the 17-year vegetation change detection in this study.

Acquisition date (dd-mm-yy)	Satellite sensor	Acquisition date (dd-mm-yy)	Satellite SENSOR
12-06-00	Landsat 7 ETM+	18-06-08	Landsat 7 ETM+ (SLC-off)
02-08-01	Landsat 7 ETM+	15-07-09	Landsat 5
26-06-02	Landsat 5	20-09-10	Landsat 5
16-08-03	Landsat 5	13-06-12	Landsat 7 ETM+ (SLC-off)
09-07-04	Landsat 7 ETM+ (SLC-off)	05-07-14	Landsat 7 ETM+ (SLC-off)
28-07-05	Landsat 7 ETM+ (SLC-off)	08-07-15	Landsat 7 ETM+ (SLC-off)
16-08-06	Landsat 7 ETM+ (SLC-off)	10-07-16	Landsat 7 ETM+ (SLC-off)
04-09-07	Landsat 7 ETM+ (SLC-off)		

(Hollander et al., 2013) was used to test the statistical significance (at 5% significance level) of differences in frequency of the events between the pre- and post-fire period.

Seasonal variation in the occurrence of flood and mass movement events was also examined. The number of events per month is reported for the available data period and seasonality of events as well as potential differences before and after the fire are discussed.

2.3.2. Examination of rainfall intensity changes

Analysis of changes in rainfall intensity regime in the study region, during pre- and post-fire period is examined based on the 3B42V7 satellite-rainfall product described previously. Our analysis is based on the period 1998–2016, which corresponds to the available record for the 3B42V7 satellite-rainfall product. Rainfall estimates at a spatial resolution of 0.25° can be considered quite coarse if the objective is to estimate localized characteristics of rainfall. However the objective of this study is not focused on the accurate estimation of local properties of the triggering rainfall but rather on the investigation of changes in rainfall regime at regional scale, which we assume that can be derived adequately at the 0.25° scale. In fact, recent work (Nikolopoulos et al., 2015; Marra et al., 2014) have shown that even with rain gauges, estimation of mass movement triggering properties can be severely biased due to the fact that rain gauges are usually placed far away from the location that the hazard occurred (e.g. landslide initiation point). Furthermore, Marra et al. (submitted) have shown that the degree of discrepancy in estimating debris flow triggering rainfall is almost equivalent between coarse-resolution rainfall (e.g. satellite estimates) and rain gauges placed few (~5) km away from initiation point; suggesting that even with in-situ rainfall observations available we may still be dealing with the same level of error as in the case of coarse remote sensing rainfall estimates.

While other studies exist on the examination of trends and variability of rainfall over the whole Greece (Kambezidis et al., 2010; Markonis et al., 2016) results that could assist our investigation could not be drawn directly from those studies mainly because of the following reasons:

i. Past studies are based on rain gauges and as previously discussed, our study area is poorly covered, which is one of the main reason we decided to utilize satellite-rainfall data.
ii. Previous studies examined characteristic values and temporal scales of rainfall (e.g. annual daily maxima, mean annual or monthly total) that are not necessarily informative about the rainfall intensity regime (e.g. in terms of temporal scale) that is relevant to triggering rainfall of the hazards under study. As a justification on the last statement we refer to the work of Alpert et al. (2002) who examined the paradoxical increase of extreme daily rainfall in Mediterranean in spite of the overall decrease in total rainfall.

Therefore we decided to carry out an analysis on rainfall regime that it is more relevant to the scope of the current study. For this reason, we selected as critical rainfall property the 95th percentile of 24 h rainfall accumulation (hereinafter noted as R_{95}) and examined its annual trend and distribution differences for each month separately. Our selection, regarding the rainfall property to be examined, was based on the rational that flood and mass movement events in the area are primarily associated with the higher spectrum rainfall values (hence the selection of the 95th percentile) and at the same time the 24 h scale is considered a representative proxy of the triggering rainfall in the area (Lainas et al., 2015; Diakakis, 2012). The 24 h rainfall accumulation values are calculated from the original 3 h 3B42V7 estimates, for each 0.25° pixel covering the area of study. The values are then grouped by month and year and from the distribution of values in each month-year group the R_{95} is determined. The temporal trend of the R_{95} is examined separately for each month and each satellite pixel by considering the slope value of a least square linear regression with respect to the year of observation. Additionally, the Wilcoxon rank sum test is used to examine differences in the distribution of the R_{95} values between the pre- and post-fire period. The null hypothesis examined for this test is that pre- and post-fire distributions are different.

2.3.3. Examination of land cover and vegetation changes

The extent of land cover changes, which is a known major influencing factor of water-related processes (Niehoff et al., 2002) was also examined for the study area and period analyzed. Previous works show that land cover changes may influence flood-triggering processes through an increase in impermeable surfaces accompanying an extension of urban areas (Hollis, 1975) or a deforestation process (Bradshaw et al., 2007), influencing in essence local hydrology (Carlson and Arthur, 2000). In addition, land cover changes have been documented to influence mass movement generation through changes in vegetation, influencing in slope stability (e.g. development of road networks, terracing) and affecting water content of geologic formations (Beguería, 2006; Zhou et al., 2002;Tasser et al., 2003). In this context, CORINE land cover classes were grouped in four major categories (Table 4) to explore possible substantial shifts in land cover distribution percentages. Comparison was carried out between four CORINE editions, namely of 1990, 2000, 2006 and 2012. In addition, different classes of natural vegetation (tall forest, shrubs etc.), were examined for changes.

Table 4
Grouping of land cover classes.

Category name	Details
Artificial surfaces	Continuous and discontinuous urban fabric, industrial and commercial units, road and railway networks, port and airport areas mine and construction sites and sport facilities.
Agricultural land	Non-irrigated arable land, Permanently irrigated land, Rice fields, Vineyards, Fruit trees and berry plantations, Olive groves, Pastures, Complex cultivation patterns, Land principally occupied by agriculture, with significant areas of natural vegetation
Forested land	Broad-leaved forest, Coniferous forest, Mixed forest, Natural grasslands, Sclerophyllous vegetation, Transitional woodland-shrub, Beaches, dunes, sands, Bare rocks, Sparsely vegetated areas, Burnt areas
Waterbodies	Wetlands and waterbodies Inland marshes, Salt marshes, Salines, Water courses, Coastal lagoons, Sea and ocean

Our methodology included multi-temporal change detection techniques by using medium spatial resolution remote sensing data (Table 3). Vegetation changes throughout the period of 2000–2016 were measured indirectly after the processing and interpretation of the available remote sensing data. The acquired satellite images were radiometrically, atmospherically and geometrically corrected according to the most widely acceptable procedures (Chavez and Mackinnon, 1994; Kaufman and Sendra, 1988; Liang et al., 1997; Song et al., 2001). More specifically, for every single geometrically and atmospherically corrected satellite image, the normalised difference vegetation index (NDVI) was calculated by using the red and infrared spectral bands (Tucker, 1979). Therefore, the extracted NDVI index images for each time period were comparable spatially as well as quantitatively. As a result, a new 15-channel dataset was generated after stacking each years' NDVI calculation. Taking under consideration the 2007 burnt area as well as the NODATA stripes of the Landsat 7 ETM + sensor failure after 2003, a number of ten sampling points were selected and at each point location, we calculated and compared the NDVI value. The sampling points were randomly selected from all points that satisfied the following rules:

- location inside the perimeter of the 2007 burnt area
- high NDVI values during 2006 (about one year before the fire)
- exclusion of nodata stripes due to Landsat 7 ETM+ malfunction

2.3.4. Examination of infrastructure changes

The study examined also public archives (i.e. the Notices and Assignments of Projects Database (Technical Chamber of Greece, 2017), the General Secretariat of Public Works Database (Ministry of Infrastructure and Transport (2017), Projects of the National Strategic Reference Framework Database (Ministry of Economy and Development, 2017), the Major management issues of water resources Western Peloponnese Water District Report (Ministry of Environment and Public Works, 2017), and finally the Transparency Program initiative (Ministry of Administrative Reconstruction, 2017) which record all public tenders, contracts and completion of works for transparency purposes) to obtain information regarding infrastructure works carried out between 1988 and 2016 in the study area, that could influence the flood or mass movement occurrence, such as hydraulic works, flood-protection works, major road network construction or other construction projects.

3. Results

3.1. Changes in the frequency of floods and mass movement events

Examination of the temporal evolution of flood and landslide events showed a noteworthy difference between the periods before and after the 2007 fire. In the case of floods, we identified 16 events in the period September 1988 to August 2007 (pre-fire), indicating an average frequency of 0.84 events/year. During the period September 2007 to August 2016 (post-fire), 25 flood events occurred in the same area, with an average frequency of 2.77 events/year (Table 5 and Fig. 2a) indicating that the average annual frequency of floods in the region has increased by approximately 3.3 times after the 2007 fire. In the case of rainfall-induced mass movement events, 12 (16) events were identified in the pre-fire (post-fire) period, indicating an average frequency of 0.63 (3.56) events/year. In this case, the relative increase

Table 5
Brief list of flood events in the study area (1988–2016).

Date	Location(s)	Date	Location(s)
22 Oct. 2015	Varda, Limnochori, Sagaiika, Kalamaki, Lakkopetra, Nissi, Manolada, Nea Manolada, Kourtesi	22 Nov. 2008	Andritsaina
08 Oct. 2015	Amaliada	01 Jul. 2008	Olympia
21 Sep. 2015	Pyrgos	17 Nov. 2007	Dafni, Leontari, Tourkoleka, Potamia
06 Mar. 2015	Diavolitsi, Zevgolatio, Kallirois, Valyra	26 Sep. 2007	Varvasaina
31 Jan. 2015	Markisia	20 Oct. 2006	Andania, Filia
18 Dec. 2014	Myrsini, Lechaina, Kourtesi, Vartholomio, Kalyvia	May 2006	Kourtesi
04 Mar. 2014	Oichalia, Zevgolatio, Magoula, Solaki	06 Mar. 2005	Prassidaki
02 Dec. 2013	Tholo, Lepreo, Pyrgos, Kakovato, Anilio, Figaleia, Faskomilia, Zacharo, Agrili	22 Feb. 2005	Kagkadi, Sageika Kapeleto
22 Nov. 2013	Pyrgos	27 Oct. 2003	Ilia
13 Nov. 2013	Pyrgos, Syntriada, Keraia	27 Aug. 2003	Pyrgos, Pelopio, Amaliada
10 Oct. 2013	Peristeri, Sochias, Geraki	31 Jan. 2003	Alfeios, Pineias, Oleni, Neochori, Fouskari, Zacharo, Kalyvakia, Makrysia
18–21 Jan. 2013	Makrisia, Kalyvakia, Phrixa, Trypiti, Kallithea, Dafnoula, Alfeios	06 Nov 2002	Pyrgos, N. Manolada
15 Sep. 2012	Gastouni, Amaliada	05 Nov. 2001	Lechaina
05 Feb. 2012	Pyrgos, Varvasaina, Lanthi, Arvaniti, Irakleia, Koliri	31 Jan. 2001	Central Ilia
22. Dec. 2011	Pyrgos, Peristeri, Dafni, Agios Dimitrios	12 Nov. 1999	Kalo Pedi, Lepreo, Friskas
17 Oct. 2011	Varda, Lechaina Amaliada, Vartholomio	22 Nov. 1998	Central Ilia
27 Oct. 2010	Vartholomio, Glyfa, Lygia, Arkoudi	15 Dec 1997	Border with Messinia
25 Sep. 2010	Pyrgos, Lapato	30 May 1996	Central Ilia
17–19 Oct. 2009	Koroivo, Roupaki, Lechaina, Kapeleto, Marathias, Zacharo, Sagaiika, Limnochori	29 Oct. 1990	Vartholomio
03 Oct. 2009	Zacharo, Amaliada, Andritsaina	Autumn 1988	Central Ilia
08 Jan. 2009	Amaliada		

in frequency of occurrence was equal to 5.6 times (Tables 6, 7 and Fig. 2b).

Mass movement occurrence in the post-fire period, showed a decline, with a high frequency regime immediately after the fire giving its place to a lower frequency regime in the more recent years (Fig. 2b), which nevertheless still exceeded (in absolute numbers) the pre-fire frequency. This sharp increase immediately after the fire is attributed to fire-induced phenomena related to: altered soil properties (e.g. water repellency shown by Vieira et al., 2016), creation of loose debris, slope stability changes due to root zones disturbance from the fire and increased runoff due to altered hydraulic properties (Shakesby and Doerr, 2006); and is followed by an apparent decline because the influence is gradually decreasing as time passes mainly due to the recovery of vegetation.

Examination of the statistical significance of difference in distribution of occurrences was carried out using the Wilcoxon rank sum test, where the null hypothesis assumes that no shift exists in the distribution of data (before and after the fire). Results for both flood and mass movement occurrences showed that the change was significant (i.e. null hypothesis is rejected) at the 5% significance level for the fire-affected areas while it was not significant for the unaffected areas.

Comparison between the affected and unaffected hydrological basins showed a different response between the two groups regarding the occurrence of both flood and mass movement events. Even though the unaffected basins record a marginal increase in flood occurrence (Fig. 2c) with a slope of 0.03, the affected basins show a significant rise with a slope of 0.1128. Both slopes were found to be statistically significant at the 6% level (p-values 0.06 and $5 * 10^{-6}$ respectively). The average frequency of flood events in the affected basins has more than quintupled from 0.47 events/year (or 9 events in 19 years) to 2.55 events/year (or 23 events in 9 years). For the unaffected basins the respective numbers were calculated at 0.368 events/year for the pre-fire and 0.778 events/year for the post-fire period. In the case of mass movement events, comparison between the fire-affected areas with the unaffected ones, showed a similar pattern. The area burned by the 2007 fire records an increase in mass movement numbers with a slope almost 3 times higher than the slope of the unaffected area (0.121 against 0.045 respectively) (Fig. 2d). Both slopes were found to be statistically significant at the 6% level (p-value 0.02 for the unaffected and 0.001 for the affected areas). The distribution of flood and mass movement events in the pre- and post-fire period can be seen in Fig. 3.

3.2. Seasonal distribution of flood and mass movement phenomena

Examination of the monthly occurrence of flood and mass movement events exhibited distinct differences between pre- and post-fire periods (Fig. 4), verifying our general expectations based on several past works on post-fire hydrogeomorphic response (Vieira et al., 2016; Vieira et al., 2015; Shakesby, 2011; Mayor et al., 2007; Shakesby and Doerr, 2006). Flood occurrence in fire-affected basins (Fig. 4a) shows an apparent increase after the fire (August 2007) and the degree of increase differs for different months. For example, the frequency of flood events in January and October, after 2007, is noticeably higher than in the pre-fire period with the most remarkable example of

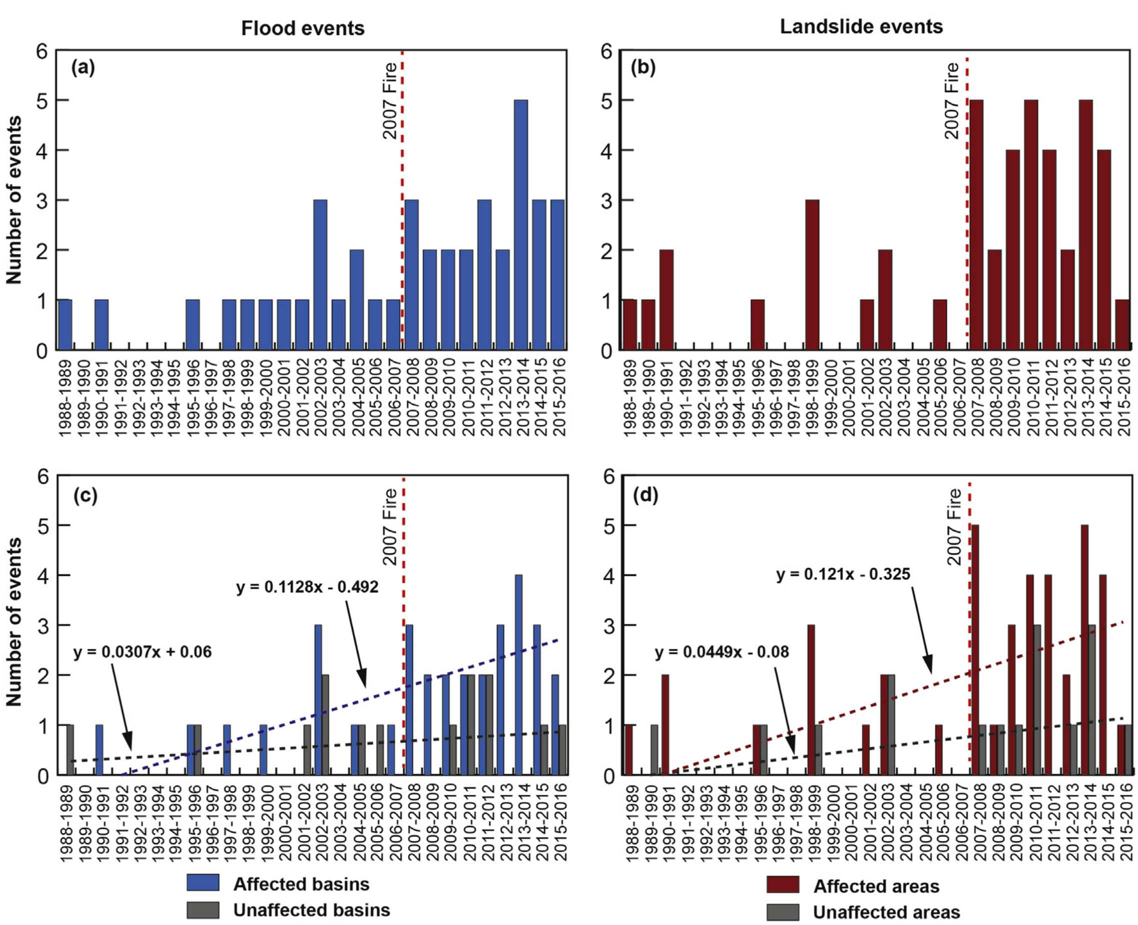


Fig. 2. Number of flood (a) and mass movement events (b) in the study area against time, along with the respective trends in the pre- and post-fire period and the temporal evolution of flood phenomena (c) in affected and not affected basins and of mass movement events in affected and unaffected areas (f).

Table 6
Brief list of rainfall-induced mass movement events in the study area (1988–2016).

Date	Location(s)	Date	Location(s)
20 Jan. 2016	Petralona – Perivolia	11 Nov 2009	Ilia
31 Jan 2015	Flokas	23 Apr 2009	Milioti – Aristomeni
01 Feb 2015	Agia Anna – Goumero	Sep 2009	Milioti – Aristomeni
06 Mar 2015	Vasta Megalopolis	05 Feb 2009	Platiana – Mparakitika
10 Mar. 2014	Analipsi Ilidas	17 Oct. 2009	Ithomi Messinia
02 Mar 2014	Pyrgos - Oinoi road	18 Mar. 2008	Ilia
03 Oct 2014	Chimadio	Jan 2008	Olympia
30 Jan. 2014	Kafkania Ilia	8–17 Dec. 2007	Ilia
07 Feb. 2014	Chouni Ilidas	20–24 Oct. 2007	Lepreo
19 Jan. 2013	Olympia	18 Nov. 2007	Zacharo
28 Feb. 2013	Revmatia – Malthi	Feb 2006	Peristeri Amaliada
02 Dec. 2013	Filiatra – Plati	04 Feb 2003	Skillounteia area
05 Feb. 2012	Moni Kremastis	28 Jan 2003	Pineia
06 Jan 2012	Ilia	Jan 2002	Doriza – Arachamites
20 Jan. 2011	Petralona – Perivolia	Mar 1999	Kalo Pedi
29–30 Jan. 2011	Andritsaina – Megalopoli road	5 Feb 1999	Kalathas Pineias
05 Feb. 2011	Platiana	22 Nov 1998	Moni Kremastis
13 Dec. 2011	Olympia	25 Sep 1995	Latzoio – Neraida Road
31 Dec. 2011	Divris – Tripotama road	Feb 1991	Neraida
23–26 Nov. 2010	75th – 90th km National Road 111	17 Dec 1990	Lagkadia
12 Oct. 2010	Ilia	11–17 Apr 1990	Central Ilia
6–15 Feb. 2010	Krestena - Kallithea	1–6 May 1989	Ilia

September for which no flood was recorded in the pre-fire period while flooding started to occur immediately after the fire and kept occurring in a rather regular interval (1 event every 2–3 years) ever since. Results for unaffected basins (Fig. 4b) do not follow the same pattern and the lower number (relative to fire-affected basins) of flood occurrences is scattered between the pre- and post-fire period, with perhaps the only exception of October where there is an apparent increase in flood occurrence after year 2008.

Occurrence of mass movement events follows a similar pattern with that of floods, showing again a monthly clustering of occurrence in the fire-affected basins and post-fire period (Fig. 4c) while similar pattern is not apparent for the not-affected basins (Fig. 4d). Again it is interesting to note that prior to 2007, the fall season was associated with very few mass movement occurrences, while a great number of events occurred at the fire-affected basins during post-fire period. An important note for results in Fig. 4c,d is that the month of occurrence for some of the mass movement records was uncertain and thus was not included in the results shown in Fig. 4. However, the vast majority of these events (23 out of total 27) occurred in the post-fire period and fire-affected basins thus excluding them could only affect the total monthly occurrence (and pattern) of events after 2007 (showing in Fig. 4c).

Overall, seasonality of floods and mass movement events is dominated by the fall and winter season, corresponding to the rainy season, but while mass movement events occur predominantly in the winter season, flood occurrence is higher in the fall season, which indicates potential differences in the characteristics (e.g. intensity/duration) of triggering rainfall and/or hydrologic conditions for the two different hazards. For example, floods in the area are primarily of flash flood type (typical for Mediterranean basins), which are usually attributed to short duration, high intensity storms that mostly prevail during early fall season. According to Neary et al. (2003), Robichaud et al. (2000) and Shakesby and Doerr (2006) increases in peak discharges in post fire periods tend to be more pronounced in the case of such storms especially in steep, severely burnt catchments, which is the case in the study area. On the other hand, the predominance of mass movements in the winter season may be attributed to higher antecedent soil wetness, as this season records higher rainfall totals.

3.3. Changes in rainfall intensity regime

The primary objective of the rainfall analysis in this section is to investigate potential changes in high rainfall regime between pre- and post-fire period. To differentiate this study from other studies that focus on the estimation of rainfall triggering properties for flood and mass movement events, it is important to note that while using rainfall information at coarse resolution (i.e. 0.25°) is expected to have an impact on the representation of highly localized rainfall intensities (i.e. impact the estimation of actual triggering rainfall amount), we however consider that satellite rainfall estimates can still be used to provide useful information on the relative change (not the absolute magnitude) of rainfall regime between the two periods.

Results are reported in Fig. 5 where positive (negative) slopes correspond to increasing (decreasing) trend of R_{95} values. The monthly separation was used to be able to connect changes in rainfall with the corresponding changes in occurrence (for floods and mass movements) identified in previous section. Note that results are reported only for months in fall and winter season since those are the dominant seasons of occurrence of floods and mass movements in the area according to the analysis in previous section. In addition, results for the Wilcoxon rank sum test are also reported for each pixel denoting whether the difference in distribution is statistically significant (null hypothesis cannot be rejected) or not (null hypothesis is rejected) at the 5% significance level.

The results summarized in Fig. 5 indicate a number of findings regarding overall trends and differences in rainfall regime before and after the fire. It is evident that the overall trend of R_{95} values exhibits considerable monthly variability in terms of both magnitude (i.e. value of slope) and direction (i.e. positive or negative). Regression slopes vary also in space and the degree of spatial variability differs for different months. The existence of no or negative trend (i.e. slope ≤ 0) suggests that observed increase in the frequency of rainfall-induced hazards in the area cannot be attributed to corresponding increase in rainfall. But while there may be individual cases (e.g. November or December) that it is relatively clear to identify such a pattern (i.e. increase in flood occurrence combined with negative slope values in R_{95}), in other cases we are dealing with a mixture of trends, which does not allow for a clear interpretation. However, analysis using the Wilcoxon rank sum test presents very consistent (in both space and time) results regarding the statistical significance of the difference in rainfall regime before and after the fire. In the vast majority of cases

Table 7
Changes in the average frequency of flood and mass movement events between the pre- and post-2007 fire period.

	Average frequency in pre-2007 fire period (in events/year)	Average frequency in post-2007 fire period (in events/year)	Change (%)
Floods	0.842	2.778	+229.8
Mass movement	0.632	3.556	+462.9

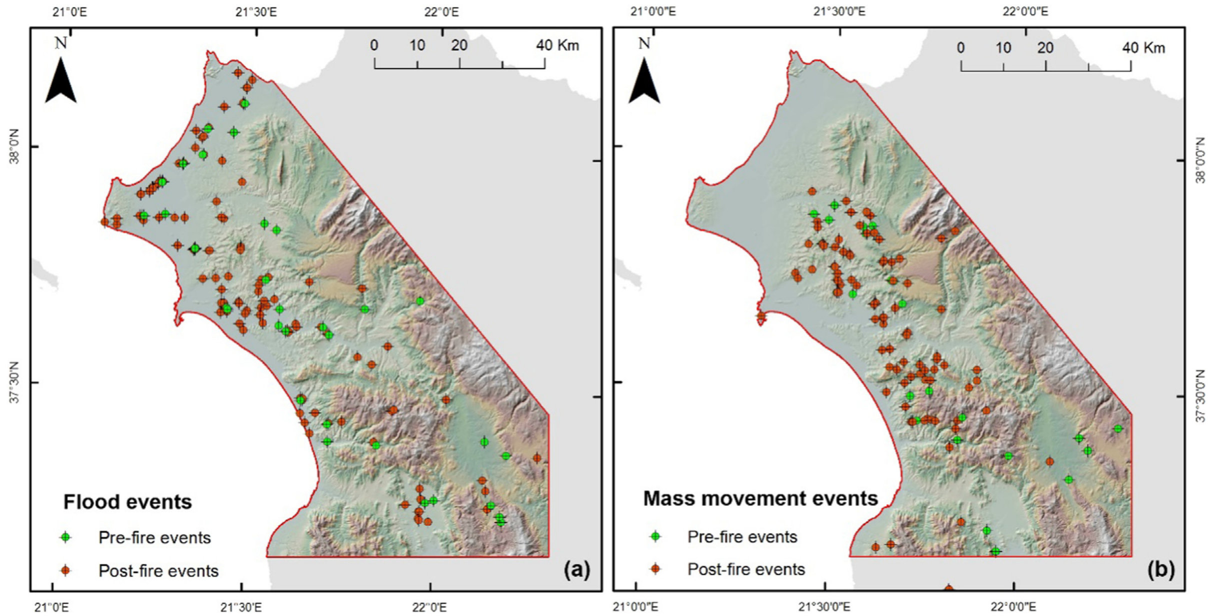


Fig. 3. Maps of (a) flood events and (b) rainfall-induced mass movement events in the study area (1988–2016).

examined, the null hypothesis (i.e. no shift in rainfall distribution before and after the fire) cannot be rejected. Contrasting these results with corresponding results on frequency changes in flood/mass movement events (Section 3.1) we can conclude that the observed and statistically significant changes in hazard frequency cannot be attributed to changes in rainfall regime.

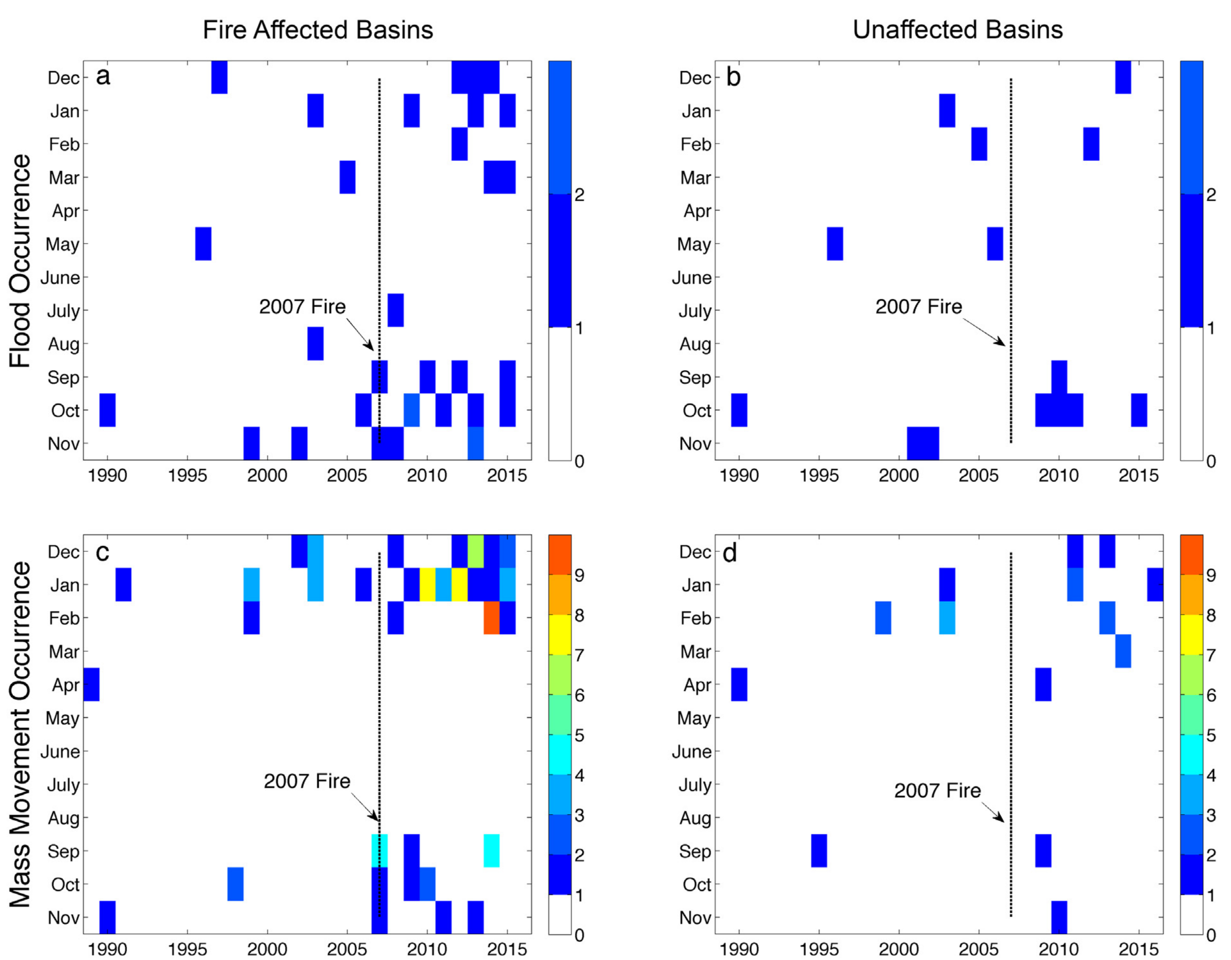


Fig. 4. Monthly occurrence of floods (top) and mass movement events (bottom) for fire affected (left) and not affected (right) basins. The color scale corresponds to number of events occurred within a given month/year and vertical dash line is used to separate pre- and post-fire years.

3.4. Changes in land use

Only minor changes were identified in the major land cover categories (Fig. 6a). Comparison for the period 1990-to-2012 indicates that there was only negligible increase in artificial surfaces and that forest land and agricultural land retained their percentages after the 2007 fire (Table 8). However, examination of land cover within the forest land cover group (Fig. 6) shows that tall forest extent records a decline after 2006 by >3%. On the contrary, shrubland shows an increase by almost the same percentage, while sclerophyllous vegetation retains the same figures. This indicates that low vegetation increases its percentage from 21.1% to 25.3% within forested lands, whereas tall forests

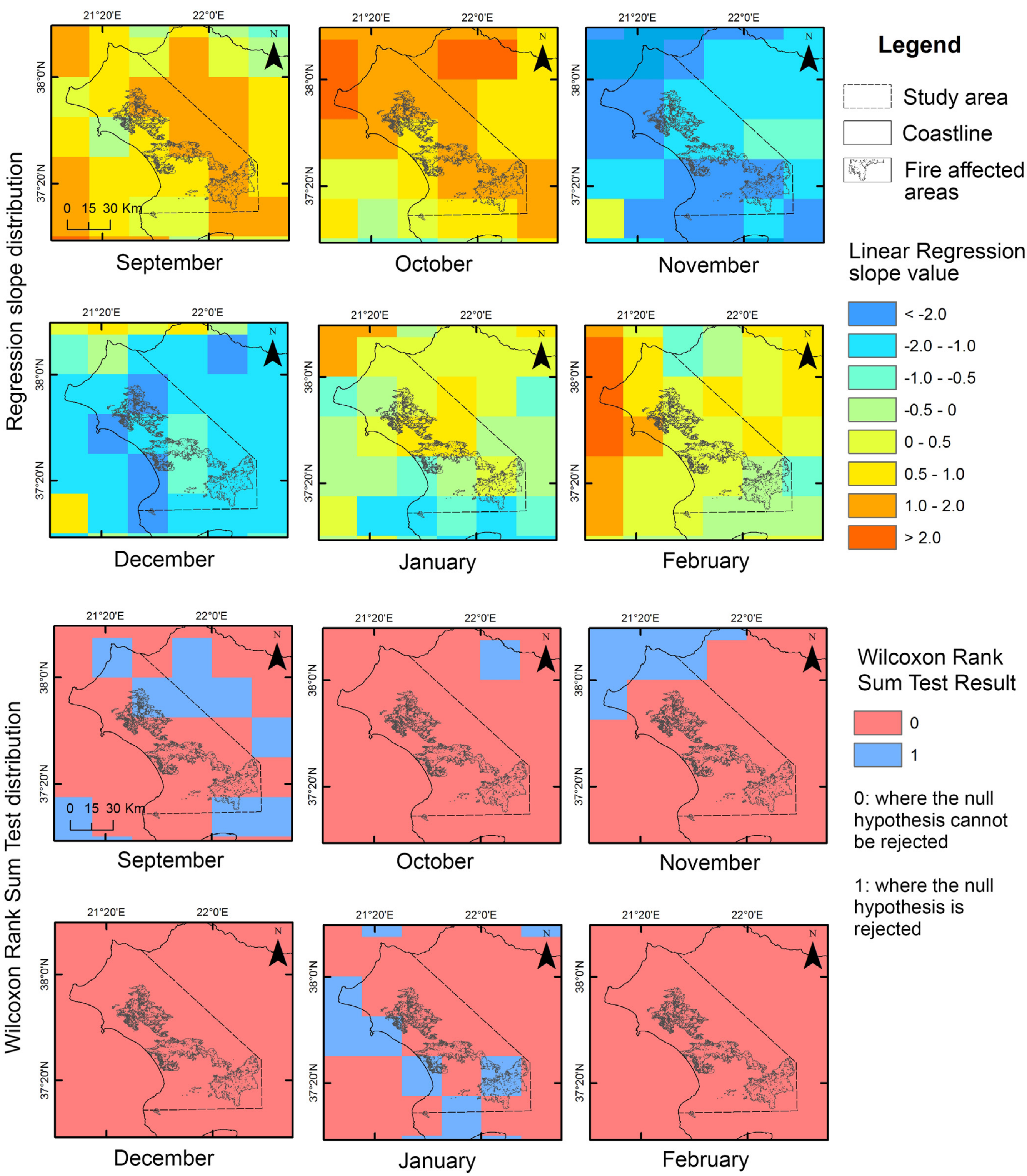


Fig. 5. Maps showing results for a) linear regression slopes and b) Wilcoxon rank sum test for the 95th percentile of 24 h rainfall accumulation. Results are shown for each 0.25°pixel (corresponding to 3B42 resolution) over the study area and for each month in fall and winter season. Note that slopes were calculated for the whole available record (1998–2016) and Wilcoxon rank sum test was calculated for the pre- and post-fire periods.

experience a decrease. This is attributed to a slower regeneration of tall trees against shrubs after the 2007 fire.

In general, the graph (Fig. 6) shows that there is no long-term, land cover regime change (either man-made or fire-induced) such as the increase of impermeable surfaces, or extensive penetration of agricultural land into forest. Characteristically, artificial surfaces (urban areas, roads etc.) were found to increase only by a total of 0.6% between 1990 and 2012, 5/6 of which was already recorded before the 2007 fire. Overall, results from Fig. 6 show that throughout most of the study period (1990–2012), percentages of the major land cover types have remained stable (apart from negligible changes), therefore observed changes in the hydrological or geomorphological processes in the area cannot be explained by land cover changes.

The temporal variation of the NDVI values at the 10 examined locations was quite impressive (Fig. 7) revealing an abrupt decrease of NDVI, based on the image acquired one month after the fire (September 2007), that was followed by an equally steep increase within the first two years after the fire (June 2008 and July 2009) for most of the locations examined. While this is a clear and rather remarkable indication of a rapid vegetation recovery rate in terms of NDVI just 1–2 years after the fire, it is important to note that it does not imply complete recovery of vegetation characteristics (e.g. vegetation height, root zone system etc.) which correspond to important control factors in hydrogeomorphic response of an area. However, it shows that the local ecosystem recuperates relatively quickly and it is resistant to forest fires. This is in agreement with the findings in mass movement occurrence in the post-fire period, which starts with a sharp increase and continuous with a negative trend, as the ecosystem gradually recovers.

4. Discussion

In general, the study shows a clear increase in the occurrence of floods and mass movement events, illustrating a significantly different regime between the pre- and post-fire periods and clear differences between affected and unaffected areas.

Examination of rainfall's temporal variability in the study area, (as one of the major influencing factors of flood and mass movement triggering), provides convincing evidence that changes in rainfall regime cannot explain the observed changes in the frequency of occurrence of flood and mass movement events. Although in some cases a mixture of trends is documented, a careful look shows that in specific months of the year (e.g. November and December) even though there is a decline in high rainfall (R_{95}) magnitude, there is still an increase in flood and mass movement occurrence. Furthermore, in cases where there is an overall positive trend in rainfall intensity (e.g. for October) common for fire affected and unaffected areas, occurrence of floods and mass movement events is much higher for fire affected areas providing a clear indication that a major control on their occurrence is attributed to the alterations of the landscape. On one hand, floods are influenced by the increase in overland flow affected by the lack of vegetation (i.e. reduced rainfall interception) and ash cover in burnt areas (i.e. reduced infiltration), which results significant increase in peak discharges especially in catchments experiencing short duration high intensity rainfall (Robichaud et al., 2000; Shakesby and Doerr, 2006). On the other hand, mass movements are influenced by increased rock weathering due to fire, changes in the hydrological properties of soil and its structure, increased erosion due to removal of roots, destruction of litter layer and increased rain splash phenomena (Shakesby and Doerr, 2006).

Analysis of land use changes showed that there were no substantial changes with respect to the major groups of land use. Artificial surfaces, agricultural and natural vegetation land have retained the same percentages since 1990 in the study area, leading to the conclusion that man-made development (e.g. increase of impermeable built areas) was not a factor in the increase of flood and mass movement occurrence. In addition, examination of vegetation through NDVI index showed that the study area returned to the previous levels of chlorophyll relatively quickly, after only two years. However, analysis of forested land through CORINE system showed that tall forests experienced a sharp decrease after the 2007 fire, accompanied by a respective increase in shrubland. This evidence leads to the conclusion that tall and deep-rooted trees were substituted by low vegetation with rooting system reaching only shallow depths. This is an important difference in vegetation that affects both mechanical and hydrological properties of soils and can potentially influence slope stability (Hümann et al., 2011; Reubens et al., 2007; Ziemer, 1981) as well as flood triggering (Shakesby and Doerr, 2006).

In the course of this research, the study identified only erosion control works at certain locations within the burnt area, following the 2007 fire, carried out mainly as slope treatment (ploughing, contouring, log erosion barriers development) and channel treatment (debris removing and small log check dams and rock check dams development) arrangements along with channel maintenance (Technical Chamber of Greece, 2017; Ministry of Environment and Public Works, 2017).

Examination of results for the 9 years of the post-fire period indicated also different trends between floods and mass movement events. Floods presented an increase throughout the post-fire period, whereas mass movement showed a sharp increase after 2007 and then recorded a decline, with frequency heading towards pre-fire levels. Assuming there is a period (window) of disturbance after a forest fire, as documented by previous works (Mayor et al., 2007; Prosser and Williams, 1998; Shakesby and Doerr, 2006; Wittenberg and Inbar, 2009), in this case evidence suggest that this period (window) is closer to ending for mass movement events compared to floods in the study area. This may suggest that the time length of the effect of fire on processes related

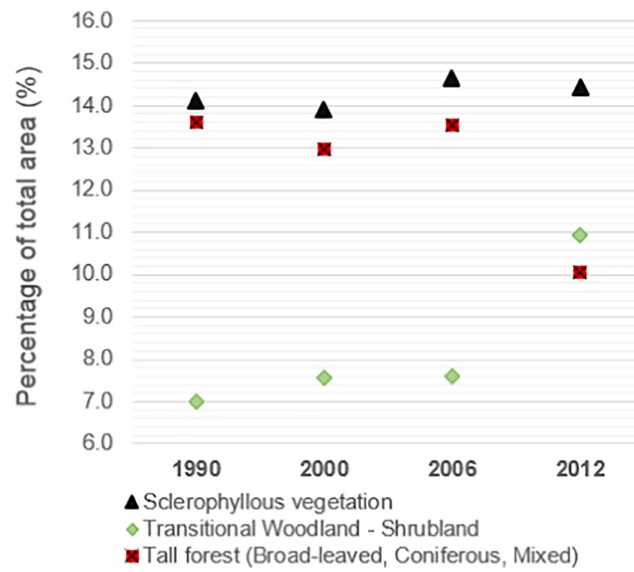


Fig. 6. Fluctuations of the extent of tall forests, sclerophyllous vegetation and shrubland, as percentage of the total study area in four separate years (namely: 1990, 2000, 2006 and 2012). Please note that 0.5% corresponds to approximately 30 km^2.

Table 8
Fluctuations of the extent of major CORINE land cover groups.

Land use category	Year			
	1990	2000	2006	2012
Agricultural land	56.1	55.9	55.5	55.3
Forested land	41.4	41.2	41.6	41.7
Artificial surfaces	1.1	1.5	1.6	1.7
Wetlands and waterbodies	1.4	1.4	1.4	1.4

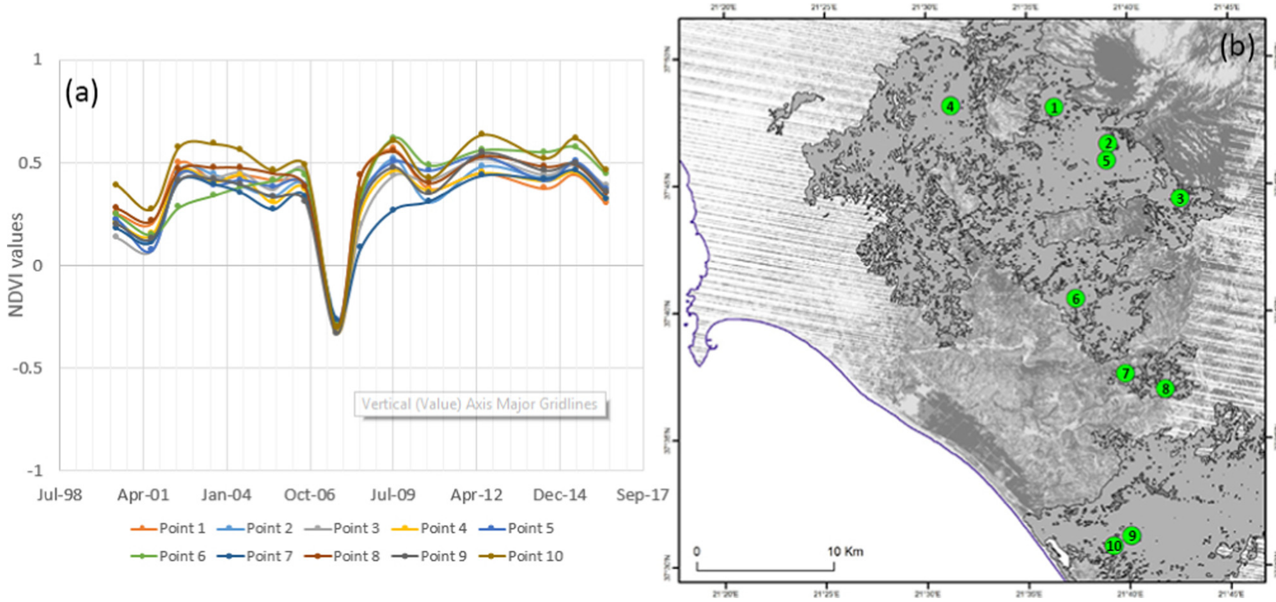


Fig. 7. Temporal fluctuation of NDVI values extracted from Landsat imagery for 10 randomly distributed locations.

to flood generation (e.g. interception, infiltration) and mass movements (e.g. soil erosion) can be different. Although specific data are not available, differences can be possibly attributed to variations in the regeneration of vegetation (documented in the area by Poirazidis et al., 2012), connected with the spatial variations fire severity (Veraverbeke et al., 2011). In specific, given that erosion phenomena are more sensitive to burn severity than runoff (Vieira et al., 2015), the gradual recovery of vegetation, especially in lower burn severity areas could influence the movement of earth material (i.e. the more sensitive factor out of the two) to a higher degree than runoff and therefore affect the mass movement triggering more. However, evidence on this subject cannot considered conclusive and further studies are necessary to investigate this hypothesis. Nevertheless, regarding the duration of fire effects, considering both groups of phenomena, evidence suggest that this window of disturbance has not been closed yet, 9 years after the fire, a period longer than most of the documented cases (Shakesby and Doerr, 2006). The length of this window, although no specific data are presently available can be attributed to the high fire severity (as described by Vieira et al., 2015, Vieira et al., 2016) of 2007 event, but not to the fire recurrence (as described by Wittenberg and Inbar, 2009) due to the lack of important previous fires in the area.

5. Conclusions

The principal conclusions from this work can be summarized as follows:

- the frequency of floods and mass movement events was tripled and quintupled respectively in the post-fire period relative to the pre-fire period.
- Changes in the frequency of both floods and mass movements exhibited considerable dependence on the month of occurrence for fire affected basins only.
- Changes in rainfall intensity regime cannot explain the statistically significant differences in pre- and post-fire frequency of floods and mass movement events.
- No considerable trend or change was found in the land use/cover extent and type in the area.
- The fire incident created a tremendous disturbance in the vegetation of affected areas that required approximately 2 years to recover (in terms of NDVI). However, the differences in the actual vegetation type and characteristics (height, root architecture etc.) are expected to be associated with a much longer duration of disturbance and thus recovering period.

Overall, the findings of this work provide clear indications that the mega-fire of 2007 was the main agent of the observed changes in the frequency of hydrogeomorphic hazards during the post-fire period in the area. To a large extent, this does not come as a surprise given the previous findings in the literature on the effects of fire on hydrogeomorphic response (Shakesby and Doerr, 2006; Vieira et al., 2016). However, quantification of the change in frequency of floods and mass movement events has not been previously reported for this particular fire event or fire events of similar scale. The quantification of the increase in frequency provides important information on the assessment of the impact of the fire incident that can be used as a reference for comparison with similar studies in other regions and/or for evaluating potential flood and mass movement risk in fire affected areas. We acknowledge the fact that lack of long-term in-situ monitoring stations (e.g. for rainfall observations) can be considered a limitation of this study but it is important to highlight and remind the reader that the satellite-rainfall estimates were used in this study for examining changes in rainfall regime before and after the fire incident, i.e. for a relative comparison between rainfall in the two periods, and not for providing accurate estimates of local rainfall amounts that triggered floods and mass movements. Pre finally, we wish to emphasize that the area of study as well as many areas in Eastern Mediterranean (where forest fire is a common hazard) suffer from the absence of local observational networks. Therefore we consider that the methodology presented, which uses remote sensing as the basis for observations of environmental variables (rainfall and vegetation index), can potentially be considered as a methodological framework that can be applied for similar analysis in other data-poor regions. Future efforts will be focused on a basin-specific analysis, including hydrological and geomorphological modelling to further investigate the impact of fire characteristics (e.g. percentage of burned area, fire severity) on the magnitude of floods and mass movements.

Acknowledgments

The authors would like to thank the two anonymous reviewers for their constructive comments that helped us improve this manuscript.

References

Allison, R.J., Bristow, G.E., 1999. The effects of fire on rock weathering: some further considerations of laboratory experimental simulation. Earth Surf. Process. Landf. 24, 707–713.

Allison, R.J., Goudie, A.S., 1994. The effect of fire on rock weathering: an experimental study. In: Robinson, D.A., Williams, R.B.G. (Eds.), Rock Weathering and Landform Evolution. Wiley, Chichester, pp. 41–56.

Alpert, P., T., BenGai, Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., Manes, A., 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophys. Res. Lett. 29 (11).

Antonopoulos, M., 2003a. Geological-Geotechnical Reconnaissance Report of Landslide Phenomena Along the Road Network Lalas-Ancient Olympia in Foloi Municipality of Elis Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).

Antonopoulos, M., 2003b. Geological-Geotechnical Reconnaissance Report of Landslide Phenomena in the Rodina Municipal District in Zacharo Municipality of Elis Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).

Arianoutsou, M., 1998. Aspects of demography in post-fire Mediterranean plant communities of Greece. Landscape Disturbance and Biodiversity in Mediterranean-Type Ecosystems. Springer, Berlin Heidelberg, pp. 273–295.

Bart, R.R., 2016. A regional estimate of postfire streamflow change in California. Water Resour. Res. 52 (2), 1465–1478.

Beguería, S., 2006. Changes in land cover and shallow landslide activity: a case study in the Spanish Pyrenees. Geomorphology 74 (1), 196–206.

Bellas, M., 1991. Geotechnical Reconnaissance Report of Landslide Phenomena in Neraida Village of Elis Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).

Bellas, M., 1999. Geotechnical Reconnaissance Report of Landslide Phenomena in Villages of Elis Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).

Bellas, M., 2003. Geotechnical Reconnaissance Report of Landslide Phenomena in Villages of Pineia Municipality in Elis Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).

Blanchi, R., Leonard, J., Haynes, K., Opie, K., James, M., de Oliveira, F.D., 2014. Environmental circumstances surrounding bushfire fatalities in Australia 1900–2011. Environ. Sci. Pol. 37, 192–203.

Bodí, M.B., Martin, D.A., Balfour, V.N., Santín, C., Doerr, S.H., Pereira, P., Cerdà, A., Mataix-Solera, J., 2014. Wildland fire ash: production, composition and eco-hydro-geomorphic effects. Earth Sci. Rev. 130, 103–127.

Bradshaw, C.J., Sodhi, N.S., PEH, K.S.H., Brook, B.W., 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. Glob. Chang. Biol. 13 (11), 2379–2395.

Brown, J.A.H., 1972. Hydrologic effects of a bushfire in a catchment in south-eastern New South Wales. J. Hydrol. 15 (1), 77–96.

Calkin, D.E., Gebert, K.M., Jones, J.G., Neilson, R.P., 2005. Forest Service large fire area burned and suppression expenditure trends, 1970–2002. J. Forest. 103 (4), 179–183.

Campbell, R.H., 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. US Geol. Surv. Prof. Pap. 851.

Candela, A., Aronica, G., Santoro, M., 2005. Effects of Forest fires on flood frequency curves in a Mediterranean catchment. Hydrol. Sci. J. 50 (2).

Cannon, S.H., Gartner, J.E., 2005. Wildfire-related debris flow from a hazards perspective. In: Hungr, O., Jacob, M. (Eds.), Debris Flows and Debris Avalanches - the State of the Art. Springer-Praxis Books in Geophysical Sciences, New York, pp. 321–344.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188.

Cannon, S.H., Powers, P.S., Savage, W.Z., 1998. Fire-related hyperconcentrated debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. Environ. Geol. 35, 210–218.

Cannon, S.H., Reneau, S.L., 2000. Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico. Earth Surf. Process. Landf. 25, 1103–1121.

Carlson, T.N., Arthur, S.T., 2000. The impact of land use—land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. Glob. Planet. Chang. 25 (1), 49–65.

Cerda, A., Doerr, S.H., 2005. Long-term soil erosion changes under simulated rainfall for different vegetation types following a wildfire in eastern Spain. Int. J. Wildland Fire 14, 423–437.

Chavez, P.S., Mackinnon, D.J., 1994. Automatic detection of vegetation changes in the southwestern United States using remotely sensed images. Photogramm. Eng. Remote Sens. 571–582.

Crompton, R.P., McAneney, J., Chen, K., Pielke, R.A., Haynes, K., 2010. Influence of location, population, and climate on building damage and fatalities due to Australian bushfire: 1925–2009. Weather Clim. Soc. 2, 300–310.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. J. Hydrol. 231-232, 195–206.

DeBano, L.F., Savage, S.M., Hamilton, D.A., 1976. The transfer of heat and hydrophobic substances during burning. Soil Sci. Soc. Am. J. 40 (5), 779–782.

DeBano, L.F., Ffolliott, P.F., Baker Jr., M.B., 1996. Fire severity effects on water resources. vol. 289. In: Ffolliott, P.F., DeBano, L.F., Baker Jr., M.B., Gottfried, G.J., Solis-Gorza, G. (Eds.), (Tech coords) Effects of Fire on Madrean Province Ecosystems—A Symposium Proceedings, General Technical Report RM. United States Department of Agriculture, Forest Service Rocky Mountain Forest and Range Experimental Station, Fort Collins, CO, pp. 77–84.

Depountis, N., Lainas, S., Pyrgakis, D., Sabatakakis, N., Koukis, G., 2010. Engineering Geological and geotechnical investigation of landslide events in wildfire affected areas of Ilia Prefecture, Western Greece. Proceedings of the 12th International Congress of the Geological Society of Greece, Patras, Greece. Bulletin of the Geological Society of Greece. 3, pp. 1138–1148.

Derin, Y., Anagnostou, Emm, Berne, A., Borga, M., Boudevillain, B., Buytaert, W., Chang, C.-H., Delrieu, G., Hong, Y., Hsu, Y.-C., Lavado-Casimiro, W., ManZ, B., Moges, S., Nikolopoulos, E., Sahlu, D., Salerno, F., Rodríguez-Sánchez, J.-P., Vergara, H.J., Yilmaz, K.K., 2016. Multi-regional satellite precipitation products evaluation over complex terrain. J. Hydrol. http://dx.doi.org/10.1175/JHM-D-15-0197.1.

Diakakis, M., 2012. Rainfall thresholds for flood triggering. The case of Marathonas in Greece. Nat. Hazards 60 (3), 789–800.

Diakakis, M., Deligiannakis, G., Mavroulis, S., 2011. Flooding in Peloponnese, Greece: a contribution to flood hazard assessment. In: Lambrakis, N., Stournaras, G., Katsanou, K. (Eds.), Advances in the Research of Aquatic Environment. Springer, Berlin Heidelberg, pp. 199–206.

Diakakis, M., Mavroulis, S., Deligiannakis, G., 2012. Floods in Greece, a statistical and spatial approach. Nat. Hazards 62 (2), 485–500.

Diakakis, M., Xathopoulos, G., Gregos, L., 2016. Analysis of forest fire fatalities in Greece: 1977–2013. Int. J. Wildland Fire 25 (7), 797–809.

Diaz-Fierros, F.V., Benito, E., Soto, B., 1994. Action of forest fires on vegetation cover and soil erodibility. In: Sala, M., Rubio, J.L. (Eds.), Soil Erosion and Degradation as a Consequence of Forest Fires, Geoforma Ediciones, pp. 163–176 (Logroño, Spain).

Doerr, S.H., Blake, W.H., Humphreys, G.S., Shakesby, R.A., Stagnitti, F., Vuurens, S.H., Wallbrink, P., 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. Int. J. Wildland Fire 13, 157–163.

Doerr, S.H., Douglas, P., Evans, R., Morley, C.P., Mullinger, N., Bryant, R., Shakesby, R.A., 2005. Effects of heating and postheating equilibration times on soil water repellency. Aust. J. Soil Res. 43, 261–267.

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency, its characteristics, causes and hydro-geomorphological consequences. Earth-Sci. Rev. 51, 33–65.

Dorn, R.I., 2003. Boulder weathering and erosion associated with a wildfire, Sierra Ancha Mountains, Arizona. Geomorphology 55, 155–171.

Dragovich, D., Morris, R., 2002. Fire intensity, slope wash and biotransfer of sediment in eucalypt forest, Australia. Earth Surf. Process. Landf. 27, 1309–1319.

Dyrness, C.T., 1976. Effect of Wildfire on Soil Wettability in the High Cascades of Oregon. Pacific Northwest Forest and Range Experiment Station, Portland, Or.

Earthquake Rehabilitation Center, 2016a. Disaster delimitations - Floods, Earthquake Rehabilitation Center (YAS). Ministry of Public Works (Available at: http://www.yas.gr. Accessed 10 October 2016).

Earthquake Rehabilitation Center, 2016b. Disaster delimitations - Landslides, Earthquake Rehabilitation Center (YAS). Ministry of Public Works (Available at: http://www.yas.gr. Accessed 10 October 2016).

Ebel, B.A., Rengers, F.K., Tucker, G.E., 2016. Observed and simulated hydrologic response for a first-order catchment during extreme rainfall 3 years after wildfire disturbance. Water Resour. Res. 52. http://dx.doi.org/10.1002/2016WR019110.

European Environment Agency, 2016. List of CORINE Reports. http://www.eea.europa.eu/publications/COR0-landcover/page001.html.

Feidas, H., 2010. Validation of satellite rainfall products over Greece. Theor. Appl. Climatol. 99 (1–2), 193–216.

Ferreira-Leite, F., Bento-Gonçalves, A., Vieira, A., da Vinha, L., 2015. Mega-fires Around the World: A Literature Review. Wildland Fires. A Worldwide Reality. Nova Publishers, New York.

Founda, D., Giannakopoulos, C., 2009. The exceptionally hot summer of 2007 in Athens, Greece - a typical summer in the future climate? Glob. Planet. Chang. 67 (3), 227–236.

Giovannini, G., Lucchesi, S., Giachetti, M., 1988. Effects of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci. 146, 255–261.

González-De Vega, S., De las Heras, J., Moya, D., 2016. Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: responses of Aleppo pine forests in the short, mid and long term. Sci. Total Environ. 573, 1171–1177.

Goudie, A.S., Allison, R.J., McLaren, S.J., 1992. The relations between modulus of elasticity and temperature in the context of the experimental simulation of rock weathering by fire. Earth Surf. Process. Landf. 17, 605–615.

Haynes, K., Handmer, J., McAneney, J., Tibbits, A., Coates, L., 2010. Australian bushfire fatalities 1900–2008: exploring trends in relation to the 'Prepare, stay and defend or leave. Policy 13 (3), 185–194.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. Water Resour. Bull. 16, 627–634.

Hollander, M., Wolfe, D.A., Chicken, E., 2013. Nonparametric Statistical Methods. John Wiley & Sons.

Hollis, G.E., 1975. The effect of urbanization on floods of different recurrence interval. Water Resour. Res. 11 (3), 431–435.

Howard, S.M., Lacasse, J.M., 2004. An evaluation of gap-filled Landsat SLC-off imagery for wildland fire burn severity mapping. Photogramm. Eng. Remote Sens. 70, 877–880.

Huffman, G.J., Bolvin, D.T., Nelkin, E.J., Wolff, D.B., Adler, R.F., Gu, G., Hong, Y., Bowman, K.P., Stocker, E.F., 2007. The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. J. Hydrol. 8:38–55. http://dx.doi.org/10.1175/JHM560.1.

Hümann, M., Schüler, G., Müller, C., Schneider, R., Johst, M., Caspari, T., 2011. Identification of runoff processes - the impact of different forest types and soil properties on runoff formation and floods. J. Hydrol. 409 (3), 637–649.

Jordán, A., Zavala, L.M., Granged, A.J., Gordillo-Rivero, Á.J., García-Moreno, J., Pereira, P., Alanís, N., 2016. Wettability of ash conditions splash erosion and runoff rates in the post-fire. Sci. Total Environ. 572, 1261–1268.

Kambezidis, H.D., Larissi, I.K., Nastos, P.T., Paliatsos, A.G., 2010. Spatial variability and trends of the rain intensity over Greece. Adv. Geosci. 26, 65–69.

Karamichas, J., 2007. The impact of the summer 2007 forest fires in Greece: Recent environmental mobilizations, cyber-activism and electoral performance. S. Eur. Soc. Polit. 12 (4), 521–533.

Katsanos, D., Lagouvardos, K., Kotroni, V., Huffmann, G.J., 2004. Statistical evaluation of MPA-RT high-resolution precipitation estimates from satellite platforms over the

central and eastern Mediterranean. Geophys. Res. Lett. 31 (6), L06116. http://dx.doi.org/10.1029/2003GL019142.
Kaufman, Y.J., Sendra, C., 1988. Algorithm for automatic atmospheric corrections to visible and near-ir satellite imagery. Int. J. Remote Sens. 9 (8), 1357–1381.
Keesstra, S., Wittenberg, L., Maroulis, J., Sambalino, F., Malkinson, D., Cerdà, A., Pereira, P., 2017. The influence of fire history, plant species and post-fire management on soil water repellency in a Mediterranean catchment: the Mount Carmel range, Israel. Catena 149, 857–866.
Konstantopoulou, G., 2008. Geological-geotechnical Reconnaissance Report of Landslide Phenomena in the Surroundings of the International Olympic Academy in Ancient Olympia. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Korobilis, G., 2001. Construction of digital maps for mapping risk erosion due to natural disasters (fires) in the wider Olympia area - proposals for ecological upgrade of the area. (MSc Thesis). Post-graduate Studies Programme on "Geography and Environment". Department of Geology and Geo-Environment, National and Kapodistrian University of Athens.
Koutsias, N., Arianoutsou, M., Kallimanis, A.S., Mallinis, G., Halley, J.M., Dimopoulos, P., 2012. Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather. Agric. For. Meteorol. 156, 41–53.
Koutsouveli, A., 2003. Geotechnical Reconnaissance Report of Landslide Phenomena in Ithomi Municipality of Messinia Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Lainas, S., Sabatakakis, N., Koukis, G., 2015. Rainfall thresholds for possible landslide initiation in wildfire-affected areas of western Greece. Bull. Eng. Geol. Environ. 75 (3), 883–896.
Laurance, W.F., 2007. Environmental science: forests and floods. Nature 449 (7161), 409–410.
Lavabre, J., Torres, D.S., Cernesson, F., 1993. Changes in the hydrological response of a small Mediterranean basin a year after a wildfire. J. Hydrol. 142 (1–4), 273–299.
Lavee, H., Kutiel, P., Segev, M., Benyamini, Y., 1995. Effect of surface roughness on runoff and erosion in a Mediterranean ecosystem: the role of fire. Geomorphology 11, 227–234.
Legleiter, C.J., Lawrence, R.L., Fonstad, M.A., Marcus, W.A., Aspinall, R., 2003. Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: a spatially explicit analysis. Geomorphology 54 (3), 119–136.
Lekkas, E., Papanikolaou, D., Migiros, G., Lozios, S., Fountoulis, I., Kranis, H., Papanikolaou, I., Antoniou, V., Logos, E., Theocharis, D., Ladas, I., Gouliotis, L., Mavroulis, S., Dalianis, V., 2007. Special Integrated Project for Management of Geodynamic Natural Hazards - Proposals for Spatial Planning in the Affected Settlements of Elis Prefecture. Applied Research Program, Faculty of Dynamic Tectonic Applied Geology, Department of Geology and Geo-Environment, National and Kapodistrian University of Athens.
Liang, S., Fallah-Adl, H., Kalluri, S., JáJá, J., Kaufman, Y.J., Townshend, J.R.G., 1997. An operational atmospheric correction algorithm for Landsat Thematic Mapper imagery over the land. J. Geophys. Res. Atmos. 102 (D14), 17173–17186.
Mahat, V., Silins, U., Anderson, A., 2016. Effects of wildfire on the catchment hydrology in southwest Alberta. Catena 147, 51–60.
Mangan, R.J., 2007. Wildland Firefighter Fatalities in the United States: 1990–2006. National Wildfire Coordinating Group, Safety and Health Working Team. 841. National Interagency Fire Center PMS, Boise, ID.
Markonis, Y., Batelis, S.C., Dimakos, Y., Moschou, E., Koutsoyiannis, D., 2016. Temporal and spatial variability of rainfall over Greece. Theor. Appl. Climatol. 1-16.
Marra, F., Nikolopoulos, E.I., Creutin, J.D., Borga, M., 2014. Radar rainfall estimation for the identification of debris-flow occurrence thresholds. J. Hydrol. 519, 1607–1619.
Marra, F., Destro, E., Nikolopoulos, E.I., Zoccatelli, D., Creutin, J.D., Guzzetti, F., Borga, M., 2017. Effect of rainfall spatial aggregation on the identification of debris flow occurrence thresholds. Geophys. Res. Lett. (submitted).
Maxwell, S., 2004. Filling Landsat ETM+ SLC-off gaps using a segmentation model approach. Photogramm. Eng. Rem. S. 70, 1109–1112.
Mayor, A.G., Bautista, S., Llovet, J., Bellot, J., 2007. Post-fire hydrological and erosional responses of a Mediterranean landscpe: Seven years of catchment-scale dynamics. Catena 71 (1), 68–75.
Mei, Y., Anagnostou, E.N., Nikolopoulos, E.I., Borga, M., 2014. Error analysis of satellite precipitation products in mountainous basins. J. Hydrometeorol. 15 (5), 1778–1793.
Meyer, G.A., Pierce, J.L., Wood, S.H., Jull, A.J.T., 2001. Fire, storms, and erosional events in the Idaho batholith. Hydrol. Process. 15, 3025–3038.
Meyn, A., White, P.S., Buhk, C., Jentsch, A., 2007. Environmental drivers of large, infrequent wildfires: the emerging conceptual model. Prog. Phys. Geogr. 31, 287–312.
Ministry of Administrative Reconstruction, 2017. The Transparency Program Initiative Database. https://diavgeia.gov.gr (last assessed January 25, 2017).
Ministry of Economy and Development, 2017. Projects of the National Strategic Reference Framework. https://www.espa.gr/el/Pages/BestPractices.aspx (last assessed January 20, 2017).
Ministry of Environment and Public Works, 2017. Major management issues of water resources Western Peloponnese Water District (EL01). Water Resources Management Plan of the Western Peloponnese Water District http://www.ypeka.gr/LinkClick.aspx?fileticket=kLjNIGpiDvM%3D&tabid=924&language=el-GR (last assessed January 25, 2017).
Ministry of Infrastructure and Transport, 2017. General Secretariat of Public Works Database. http://www.ggde.gr (last assessed January 20, 2017).
Mitsakis, E., Stamos, I., Diakakis, M., Salanova Grau, J.P., 2014. Impacts of high intensity storms on urban transportation: applying traffic low control methodologies for quantifying the effects. Int. J. Environ. Sci. Technol. http://dx.doi.org/10.1007/s13762-014-0573-4.
Moody, J.A., Martin, D.A., 2001. Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. Hydrol. Process. 15, 2981–2993.
Moreira, F., Arianoutsou, M., Corona, P., De las Heras, J., 2012. Post-Fire Management and Restoration of Southern European Forests. Springer-Verlag, p. 329 (ISBN 978-94-007-2207-1).
Morris, S.E., Moses, T.A., 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. Ann. Assoc. Am. Geogr. 77 (2), 245–254.
Nalbantis, I., Lymperopoulos, S., 2012. Assessment of flood frequency after forest fires in small ungauged basins based on uncertain measurements. Hydrol. Sci. J. 57 (1), 52–72.
Nastos, P.T., Kapsomenakis, J., Philandras, K.M., 2016. Evaluation of the TRMM 3B43 gridded precipitation estimates over Greece. Atmos. Res. 169, 497–514.
Naveh, Z., 1994. The role of fire and its management in the conservation of Mediterranean ecosystems and landscapes. The Role of Fire in Mediterranean-type Ecosystems. Springer, New York, pp. 163–185.
Neary, D.G., Gottfried, G.J., Ffolliott, P.F., 2003. Post-wildfire watershed flood responses. Second International Fire Ecology and Fire Management Congress, Orlando, Florida, 16–20 November 2003, Paper 1B7.
Neary, D.G., Leonard, J., 2016. Wildland fire: impacts on forest, woodland and grassland ecological processes. Wildland Fires: A Worldwide Reality, pp. 35–112.
Niehoff, D., Fritsch, U., Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. J. Hydrol. 267 (1), 80–93.
Nikolaou, N., Kokkinakis, I., 1991. Geotechnical Reconnaissance Report of Landslide Phenomena in Lagadia Municipality of Arcadia Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Nikolopoulos, E.I., Borga, M., Creutin, J.D., Marra, F., 2015. Estimation of debris flow triggering rainfall: influence of rain gauge density and interpolation methods. Geomorphology 243, 40–50.
Omi, P.N., 2005. Forest Fires: A Reference Handbook. ABC-CLIO.
Papagiannaki, K., Lagouvardos, K., Kotroni, V., 2013. A database of high-impact weather events in Greece: a descriptive impact analysis for the period 2001–2011. Nat. Hazards Earth Syst. Sci. 13 (3), 727–736.
Pausas, J.G., Vallejo, V.R., 1999. The role of fire in European Mediterranean ecosystems. Remote Sensing of Large Wildfires. Springer, Berlin Heidelberg, pp. 3–16.
Poirazidis, K.S., Zografou, K., Kordopatis, P., Kalivas, D.P., Arianoutsou, M., Kazanis, D., Korakaki, E., 2012. A GIS-based integrated approach predicts accurately post-fire Aleppo pine regeneration at regional scale. Ann. For. Sci. 69 (4), 519–529.
Prosser, I.P., Williams, L., 1998. The effect of wildfire on runoff and erosion in native Eucalyptus forest. Hydrol. Process. 12 (2), 251–265.
Reubens, B., Poesen, J., Danjon, F., Geudens, G., Muys, B., 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. Trees 21 (4), 385–402.
Riley, K.L., Bendick, R., Hyde, K.D., Gabet, E.J., 2013. Frequency-magnitude distribution of debris flows compiled from global data, and comparison with post-fire debris flows in the western US. Geomorphology 191, 118–128.
Robichaud, P.R., Beyers, J.L., Neary, D.G., 2000. Evaluating the Effectiveness of Postfire Rehabilitation Treatments. General Technical Report RMRS-GTR-63, September 2000. United States Department of Agriculture, Forest Service Rocky Mountain Research Station.
San-Miguel-Ayanz, J., Moreno, J.M., Camia, A., 2013. Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For. Ecol. Manag. 294, 11–22.
Camia, A., 2012. Land cover change and fire regime in the European Mediterranean region. In: San-Miguel-Ayanz, J., Rodrigues, M., Santos de Oliveira, S., Kemper Pacheco, C., Moreira, F., Duguy, B., Moreira, F., Arianoustsou, M., Corona, P., de las Heras, J. (Eds.), Post-fire Mangement and Restoration of Southern European Forests – Managing Forest Ecosystems. 2012. Springer, Berlin, Heidelberg, pp. 21–43.
Scott, D.F., 1993. The hydrological effects of fire in South African mountain catchments. J. Hydrol. 150, 409–432.
Scott, D.F., Versfeld, D.B., Lesch, W., 1998. Erosion and sediment yield in relation to afforestation and fire in the mountains of the Western Cape Province, South Africa. S. Afr. Geogr. J. 80, 52–59.
Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Sci. Rev. 105, 71–100.
Shakesby, R.A., Coelho, C.D.O., Ferreira, A.D., Terry, J.P., Walsh, R.P.D., 1994. Fire, post-burn land management practice and soil erosion response curves in eucalyptus and pine forests, north-central Portugal. Soil Erosion and Degradation as a Consequence of Forest Fires, pp. 111–132.
Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. Earth-Sci. Rev. 74, 269–307.
Smith, H.G., Sheridan, G.J., Lane, P.N., Nyman, P., Haydon, S., 2011. Wildfire effects on water quality in forest catchments: a review with implications for water supply. J. Hydrol. 396 (1), 170–192.
Song, C., Woodcock, C.E., Seto, K.C., Lenney, M.P., Macomber, S.A., 2001. Classification and change detection using Landsat TM data: when and how to correct atmospheric effects? Remote Sens. Environ. 75, 230–244.
Special Secretariat for Water, 2012. Flood event registration database. Special Secretariat for Water. Ministry of Environment and Energy, Greece.
Swanson, F.J., 1981. Fire and geomorphic processes. In: Mooney, H.A., Bonnicksen, T.M., Christiansen, N.L., Lotan, J.E., Reiners, W.A. (Eds.), Fire Regime and Ecosystem Properties, United States Department of Agriculture, Forest Service, General Technical Report WO. 26. United States Government Planning Office, Washington, DC, pp. 401–421.
Tasser, E., Mader, M., Tappeiner, U., 2003. Effects of land use in alpine grasslands on the probability of landslides. Basic Appl. Ecol. 4 (3), 271–280.
Technical Chamber of Greece, 2017. Notices and Assignments of Projects Database. http://portal.tee.gr/portal/page/portal/tptee/SERVICES_INFORM_TPTEE/prokhrixeis_meleton (last assessed January 30, 2017).
Tsagkari, K., Karetsos, G., Proutsos, N., 2011. Spatiotemporal investigation on forest fires in Greece. WWF Hellas - N.AG.RE.F (IMFE & FPT).
Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150.
Tzitziras, A., 2002. Geotechnical Reconnaissance Report of Landslide Phenomena in the Municipal Road Doriza – Arachamites. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Tzitziras, A., 2003a. Geological-geotechnical Reconnaissance Report of landslide Phenomena in Makryssi, Rapsomati and Plaka Villages in Megalopolis Municipality of Arcadia

Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Tzitziras, A., 2003b. Geological-geotechnical Reconnaissance Report of Landslide Phenomena in Leontari, Akovos and Kambochori Villages and in Segments of the Country Road Goutala-Akovos-Leptini in Falaisia Municipality of Arcadia Prefecture. Unpublished Report. Institute of Geological and Mineral Exploration, Athens, Greece (In Greek).
Van Eck, C.M., Nunes, J.P., Vieira, D., Keesstra, S., Keizer, J.J., 2016. Physically-based modelling of the post-fire runoff response of a forest catchment in Central Portugal: using field versus remote sensing based estimates of vegetation recovery. Land Degrad. Dev. 27 (5), 1535–1544.
Vega, J.A., Diaz-Fierros, F., 1987. Wildfire effects on soil erosion. Ecol. Mediterr. 13 (4), 119–125.
Veraverbeke, S., Lhermitte, S., Verstraeten, W.W., Goossens, R., 2010. The temporal dimension of differenced Normalized Burn Ratio (dNBR) fire/burn severity studies: the case of the large 2007 Peloponnese wildfires in Greece. Remote Sens. Environ. 114 (11), 2548–2563.
Veraverbeke, S., Lhermitte, S., Verstraeten, W.W., Goossens, R., 2011. A time-integrated MODIS burn severity assessment using the multi-temporal differenced Normalized Burn Ratio (dNBR MT). Int. J. Appl. Earth Obs. Geoinf. 13 (1), 52–58.
Vieira, D.C.S., Fernández, C., Vega, J.A., Keizer, J.J., 2015. Does soil burn severity affect the post-fire runoff and interrill erosion response? A review based on meta-analysis of field rainfall simulation data. J. Hydrol. 523, 452–464.
Vieira, D.C.S., Malvar, M.C., Fernández, C., Serpa, D., Keizer, J.J., 2016. Annual runoff and erosion in a recently burn Mediterranean forest–the effects of plowing and time-since-fire. Geomorphology 270, 172–183.
Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Fredriksen, R.L., Franklin, E.C., Froelich, R.C., Dunn, P.H., 1979. Effects of Fire on Soil: A State-of-Knowledge. General Technical Report WO. 7. United States Department of Agriculture, Forest Service.
White, W.D., Wells, S.G., 1982. Forest-fire devegetation and drainage basin adjustments in mountainous terrain. In: Rhodes, D.D., Williams, G.P. (Eds.), Adjustments of the Fluvial System. Proceedings of the 10th Geomorphology Symposium. Binghamton. Allen and Unwin, New York, pp. 199–223.
Williams, J.E., Albright, D.O., Hoffmann, A.A., Eritsov, A.N., Moore, P.F., Mendes de Morais, J.C., Leonard, M., San Miguel-Ayanz, J., Xanthopoulos, G., Van Lierop, P., 2011. Findings and implications from a coarse-scale global assessment of recent selected mega-fires. International Wildland Fire Conference, South Africa.
Wittenberg, L.E.A., Inbar, M., 2009. The role of fire disturbance on runoff and erosion processes–a long-term approach, Mt. Carmel case study, Israel. Geogr. Res. 47 (1), 46–56.
Wondzell, S.M., King, J.G., 2003. Post-fire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecol. Manag. 178, 75–87.
World Wildlife Fund (WWF) Greece, 2007. Environmental Performance of the Devastating Fires of August 2007 in Peloponnese. Report (37 pp).
Xanthopoulos, G., 1998. Forest fires in Greece: past, present and future. Wildland Fires: A Worldwide Reality, pp. 141–152.
Xanthopoulos, G., 2013. Forest fire related deaths in Greece: confirming what we already know. p. 339. Book of Abstracts of the “IV International Wildland Fire Conference”, May 13–17, 2004, Seville, Spain (Full paper on the CD accompanying the book of abstracts).
Xanthopoulos, G., Viegas, D.X., Caballero, D., 2009. The Fatal Fire Entrapment of Artemida (Greece) 2007. Recent Forest Fire Related Accidents in Europe. European Joint Research Centre, Luxembourg, pp. 65–75 (Scientific and Technical Reports).
Xystrakis, F., Kallimanis, A.S., Dimopoulos, P., Halley, J.M., Koutsias, N., 2014. Precipitation dominates fire occurrence in Greece (1900–2010): its dual role in fuel build-up and dryness. Nat. Hazards Earth Syst. Sci. 14 (1), 21–32.
Zhou, C.H., Lee, C.F., Li, J., Xu, Z.W., 2002. On the spatial relationship between landslides and causative factors on Lantau Island, Hong Kong. Geomorphology 43 (3), 197–207.
Ziemer, R.R., 1981. The role of vegetation in the stability of forested slopes. XVII IUFRO World Congress, Japan 1981, Division 1.