



Flash flood occurrence and relation to the rainfall hazard in a highly urbanized area

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Flash flood occurrence and relation to the rainfall hazard in a highly urbanized area

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Abstract

The paper examines the flash flood events that occurred during a decade in the Attica prefecture, the most urbanized region of Greece, with the aim of assessing the local vulnerability to the flash flood hazard and the effect of rainfall upon the magnitude of the induced damages. The analysis incorporates rainfall records from a network of 28 surface meteorological stations and information on the spatial distribution of the flash flood events that is derived from the active database of damaging weather events maintained by the atmospheric modelling group of the National Observatory of Athens. The main findings concern the relation between the flash flood impact, as measured by the Fire Service operations in flooded properties, and precipitation in various time intervals, as well as the possibility to define rainfall intensity thresholds for flood triggering at a more local level. It is shown that the quality of the produced thresholds depends on the distribution and density of the rain gauges that cover each specified geographical area of the Attica region.

1 Introduction

Flooding caused by heavy rainfall is a weather-related hydrological hazard associated with significant economic losses, human fatalities and adverse effects to the society and the ecosystem. Even though floods do not appear with the catastrophic power of other natural hazards, such as the earthquakes, their overall impact on the society and economy is very serious. In Europe, numerous floods and flash-floods occur each year, accounting for 40% of the total economic damages due to natural hazards for the period 1989–2008 (CRED, 2009). The societal impact of flash floods varies and depends on the hazard intensity and the vulnerability of the affected area as measured by its topographic and demographic features, the quantity and quality of the materials exposed, the anthropogenic interventions and the effectiveness of the prevention measures taken by the local authorities (Tsakiris, 2014). Interestingly, extreme flash

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floods in the Mediterranean countries tend to be greater in magnitude compared to the inner continental countries (Gaume et al., 2009), while they occasionally produce catastrophic damages (Llasat et al., 2013; Lastoria et al., 2006). Furthermore, analysis of the spatial distribution of flood events in Mediterranean countries has shown that the urbanized environment increases vulnerability and flood risks (Llasat et al., 2009).

As the risk and consequently the societal impact of the weather hazard is a function of the hazard's magnitude and the local vulnerability (Špitalar et al., 2014), the assessment of damages caused by flash floods in urban areas integrates a variety of factors related to the weather and hydrological hazard and to urban specific characteristics. Compared to the damages that are caused by riverine or coastal flooding, damages in urban areas are much more dependent on anthropogenic and demographic factors that increase flood risk and are difficult to assess, such as the land development that limits water infiltration and increases runoff (Du et al., 2015; Kandilioti and Makropoulos, 2012) and population density that associates to the amount of people and property exposed to risk (Amaro et al., 2010; Llasat et al., 2009). Recently, Barbería et al. (2014) discussed rainfall intensity thresholds in conjunction with regional vulnerability indicators, namely the population density, which is directly linked to the type of urbanization and the land use (Llasat et al., 2009). The study of Barbería et al. investigates the correlation between several rainfall parameters and the number of requests received in the Meteorological Services related to insurance claims, which have been already proved to be a good indicator of social impact in the study of Amaro et al. (2010). The urban area discussed is the city of Barcelona and results for the period 2008–2011 show that there is a statistically significant correlation between short duration rainfall intensities and the requests related to insurance claims. The high value of this study is that it successfully introduces an alternative measure of the material damages, namely the number of insurance claims, compared to monetary measures such as the compensations paid by the implicated authorities and the insurance companies (Llasat et al., 2008; Lastoria et al., 2006; Jonkman, 2005), which

may constitute a better indicator of the impact intensity of the event, but are rather hard to find and often cover part of the overall damage.

As mentioned before, Barbería et al. (2014) also assess the rainfall intensity factor as an indicator of the flash-flood hazard. The authors suggest specific thresholds of precipitation and relate them with the impact intensity of the flash-flood events. In search of the flood triggering factors, other studies have also used the accumulated rainfall and/or the rainfall intensity as main indicators of the flash-flood occurrence and magnitude. Cannon et al. (2008) and Guzzetti et al. (2008) developed rainfall intensity-duration thresholds for the occurrence of debris flows, landslides and floods. This methodology was later adapted by Diakakis (2012) to examine the role of storm totals, peak and average rainfall intensity and moisture conditions in flood triggering in northeast Attica, in Greece, for the period 1993–2008. The author found significant correlation between peak storm intensity and flood triggering and presented rainfall thresholds above which flooding is highly probable. Bracken et al. (2008) studied a semi-arid area in south-east Spain and found that floods in the period 1997–2003 have been more highly related to the total rainfall than to the intensity of a storm, although intensity controls the nature and timing of the flood process.

Rainfall thresholds have been also proposed as indicators of early warning for flash floods. Martina et al. (2006) introduced a methodology for issuing flood warnings by directly comparing the quantitative precipitation forecast to a critical rainfall threshold value, incorporating initial soil moisture conditions as well as expected costs, without the need of real time meteorological and hydrological forecasting models. In Norbiato et al. (2009) flash flood warning methodologies are based on hydrological models, but they also integrate the flash flood guidance (FFG) method, that is the rainfall threshold approach in which the US National Weather Service relies for issuing warnings (Georgakakos, 2006). FFG refers to the volume of rain of a given duration necessary to cause minor flooding on small streams (Carpenter et al., 1999). Price et al. (2011a, b) recognised that flash floods are among the costliest natural hazards around the globe and used lightning data to better understand and predict flash floods

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in the Mediterranean. Over the highly urbanised area of Athens, flash flood forecasting has been explored based on an integrated hydro-meteorological system by Koussis et al. (2003) with promising results.

The present paper contributes to the research on the impact and triggering factors of flash floods in Greece and the Mediterranean, introducing an analysis of the flash-flood events that occurred during the 10-year period 2005–2014 in the Attica basin, the most urbanized and densely populated region of the country. The main targets are to detect systematically affected areas within Attica, define and assess flash flood hazard indicators and discern flash-flood patterns and possible rainfall thresholds related to the occurrence of flash-flood as well as to the magnitude of the adverse impact. The possibility to use the estimated rainfall thresholds to establish alert systems to warn communities of impending floods is also discussed.

For the analysis, the database of high-impact weather events developed by the atmospheric modelling group of the National Observatory of Athens has been used (Papagiannaki et al., 2013). The database provides information about all the high-impact weather events that occurred since 2001 and is systematically updated. Vulnerability indicators, namely population and topographic features of the location where damages took place, are also discussed. The number of operations, provided by the Fire Service, during flooding events, is also studied in correlation to the rainfall parameters, in search of a reliable impact indicator that is systematically and officially recorded.

2 Data collection

The target area of this study is the most urbanized and densely populated department of the prefecture of Attica that comprises the city of Athens, which is the capital of Greece, and the suburbs, which are subdivided in municipalities. In what concerns the frequency and magnitude of damages caused by weather-related hazards, Attica is by far the most affected region in the country (Papagiannaki et al., 2013; Diakakis

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et al., 2012), suffering particularly from flash floods, which cause at times serious damages. According to the latest report of the Hellenic Association of Insurance Companies (HAIC, 2015), the 13 most damaging flash flood events that occurred in Greece during the period 1993–2014 caused economic losses of about EUR 93 million, most of which correspond to claims for compensations in Attica. Vulnerability of the Attica prefecture to flash floods is highlighted in the study of Papagiannaki et al. (2013), which introduced the database of high-impact weather events that occurred in Greece since 2001, followed by the spatial and temporal distribution of the events for the period 2001–2011. A simplified version of the database is available on-line in the site of the atmospheric modelling group of the National Observatory of Athens (http://www.meteo.gr/weather_cases.asp). This database is systematically updated with every new weather event that generates damages in Greece and includes so far more than 300 cases which are classified according to their weather and impact intensity. According to the updated database, during the period 2001–2014, 91 flash flood events affected Attica, causing buildings, infrastructure and vehicle damages, large-scale transport disruption, flooded roads and in some cases human fatalities. The database, besides the weather and impact classification, also encloses detailed information for each weather event, namely their geographical distribution, the location and type of damages, meteorological data, as well as detailed references in the press. Thus, it has been used for the purposes of the present analysis, in order to define the flash flood events that occurred in the target area and the location of the respective damages.

From a geographical point of view, the target area – hereafter called Athens-Suburbs – depicted in Fig. 1, is located in the centre of the Attica region, at the central-east of the Greek mainland, bordering the south part of the Aegean Sea and surrounded by four mountains, Aigaleo and Parnitha at the west-northwest, Penteli and Hymettus at the east-southeast. Two rivers flow through the Athens plain. The large one, river Kifissos, is the main water-stream of Athens, follows a NNE–SSW flow direction and has produced serious flooding events in the past. Since 2002, it is systematically

monitored to prevent unpredictable overflows. The second and smaller river, Ilissos, is found in the east part and has been built to a great extent.

To address the vulnerability of the specific areas affected by flash floods within the Athens-Suburbs region, weather and impact indicators are both incorporated in the present analysis. Data on the meteorological parameters used in the analysis derive from 28 surface meteorological stations (Fig. 1) spread in the Athens-Suburbs region. The atmospheric modelling group of the National Observatory of Athens (NOA) operates 18 of these stations, while the rest are operated by the Laboratory of Hydrology and Water Resources Management of the National Technical University of Athens (NTUA) and are freely available to the public. The meteorological stations provide 10 min observations of various meteorological parameters such as temperature, pressure, humidity, wind velocity and direction, rain and rain intensity. Based on the availability of rain observations from the NOA and NTUA meteorological station networks in Athens, the present analysis is limited in the 10-year period 2005–2014, during which 48 flash flood events of various impact intensities affected the target area.

Data on actual financial losses due to flash floods, such as the monetary compensations paid by the implicated authorities and the insurance companies, were not available during this study. Therefore, following the concept of Barbería et al. (2014), the impact of each flash-flood event is assessed using the number of the Fire Service operations that took place due to citizens' calls for flooded properties. Daily data on the operations in flooded properties derive from the Statistical Department of the Greek Fire Service and concern the entire Attica region for the period 2003–2013. For the year 2014, the respective data have been found in press articles, thus they may deviate from the official ones, being underestimated only to a small degree. Even though the number of operations during an event concerns the entire region of Attica, the description of the events included in the database is extensive enough to reproduce with high certainty the map with the specific areas affected during each event. The data provided by the Fire Service are exhaustive and all the events with more than 10 daily

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flood event, as explained in Sect. 2, the descriptive information included in the NOA database of weather-related events has been used.

In the context of the present analysis, impact indicators are studied in conjunction with hazard parameters. Following the concept of the most recent and relevant articles (Barbería et al., 2014; Diakakis, 2012), precipitation parameters have been used in the analysis, namely the rain records in various time intervals. For each event, the maximum precipitation is calculated based on the observations of the representative rain gauges. Maximum precipitation in different time intervals is then correlated to the number of the Fire Service operations, in order to assess the effect of the rainfall intensity on the magnitude of the societal impact. The statistical dependence is measured with the Spearman's rank correlation coefficient, ρ , which does not assume normality of data. Also, distributions of the frequency of the operations by month and by rainfall level are presented to complement the discussion.

A methodological limitation is the fact that the number of the Fire Service operations per event, which is given as a total for the entire target area, cannot be distributed to the specific areas affected in each case. Thus, the local impact intensity cannot be measured by the number of operations. Instead, local vulnerability is assessed firstly based on the frequency of damaging flash flood events per area and secondly by the examination of the hazard intensity related to the flood occurrence in each specified area. To estimate possible rain thresholds related to flood triggering in each area, the methodology followed by Diakakis (2012) has been applied. The author developed rainfall intensity-duration thresholds for the occurrence of floods in Marathonas, Greece, and by plotting peak rainfall intensities of various time intervals against their respective durations and then defining rainfall intensity thresholds above which flooding is most likely to occur. Accordingly, in the present study, the graphs of peak rainfall intensities of various time intervals (10, 30, 60 min, 2, 3, 12 and 24 h) vs. duration have been plotted for each area, in order to investigate for possible rainfall thresholds, above which flooding is most likely to occur. For that, all the time series records of 10 min precipitation have been used. It should be noted that a rainfall event

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– independently of whether flooding occurred – is considered to start if more than 24 h without rain have proceeded. Also, the maximum accumulated rain in 10, 30, 60 min, 2, 3 h 12 and 24 h of each rainfall event is calculated as the maximum moving sum, through time steps of 10, 30, 60 min, 2, 3, 12 and 24 h respectively.

4 Urban flash flood analysis

During the period 2005–2014 48 flash flood events occurred in the Athens-Suburbs region and caused more than 3500 Fire Service operations in flooded properties. The maps in Fig. 3a, b highlight the spatial distribution of flash flood events in the Athens-Suburbs region and population density respectively. Both maps display the distribution at a municipality level due to the respective availability of population data. Comparison between the two maps leaves no doubt on the importance of the population distribution to the regional vulnerability. The municipality of Athens, which is the most densely populated area with around 17 000 inhabitants per km², was the most frequently affected area, with 20 events recorded during the study period. High population density is naturally related to intense urbanization which results to an increase in impervious surface and, consequently, in total runoff volumes. Besides that, the geographical location of Athens also contributes to the increased vulnerability to the rainfall hazard. Athens is located in the centre of the Attica basin, where runoffs from the higher sloped areas end.

4.1 Relation between hazard and impact indicators

Table 1 includes the areas affected by each flash flood, following the numbering of the specific areas shown in Fig. 2, the number of the Fire Service operations and the maximum precipitation in various time intervals per event. Most of the events affected as many as 6 areas and only 3 out of the 48 events were actually spread over a large part of the Athens-Suburbs region.

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in what concerns the mainland (Jansa et al., 2014; Lagouvardos and Kotroni, 2007; Kotroni et al., 1999; Lagouvardos et al., 1996). This is in accordance with previous analysis of historical floods in Greece, which concluded that autumn was the season with the richest flood record for the period 1880–2010 (Diakakis et al., 2012). The high impact of February flash floods is mostly owed to 1 event that occurred in 2013 and provoked more than 600 operations. Similarly, 1 event that occurred in October of 2014 caused 500 operations. Overall, the highest R24 record was 186 mm, observed during an event that caused 118 operations by the Fire Service and had a quite low R10 (3.2 mm in 10 min). Actually, the correlation between R24 and R10 is weak ($\rho = 0.32$, $\rho < 0.05$), while most of the high R10 values relate with R24 less than 70 mm.

Correlation between the number of operations and the maximum rainfall in the various time intervals have been investigated in order to detect the hazard parameter that best relates to the magnitude of the impact. As illustrated in Table 2, the number of operations is strongly correlated with the maximum rainfall in 24 h, R24, ($\rho = 0.61$), while the strength of correlation drops with the decrease in the time interval. The fact that R24 is the precipitation parameter that better represents the magnitude of the impact, at least when considering only the flooded properties, is reasonable since the calculation concerns the entire Athens-Suburbs region, which includes, though, areas of unique regional vulnerability that may respond differently in rainfall of the same intensity. These differences, however, tend to become smoother as the accumulation period increases and the various small-scale intensities are normalized.

The significance of the regional vulnerability can be further studied by focusing to specific areas of the Athens-Suburbs region. However, what is known with certainty is the number of operations per event as well as the areas the event affected, while the exact allocation of the operations is not known. Therefore, to minimize the uncertainty in the estimated results, we attempted to study separately only the city of Athens, focusing on the events that affected the centre, south and east of the municipality of Athens together. This is actually the most populated region in Attica and Greece, exhibiting also the highest frequency of damaging flash flood events, while the network of rain gauges

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is denser compared to the other areas examined. When correlation analysis focuses in these neighbouring areas together, the number of operations is strongly correlated with all the durations of accumulated precipitation (ρ 0.69–0.85), the R10 included. Correlation results are included in Table 2. It is obvious that analysis on a more local scale permits to better capture the effect of the volume of rainfall to the magnitude of impact and allows for consideration of short duration rainfall in the examination of the flash flood impact, as long as a sufficient network of rain gauges exists.

4.2 Rainfall intensity thresholds for flood triggering, at regional level

The results of the previous section raise the question whether rainfall intensity thresholds can be defined, above which flooding is probable or even certain for some areas, and whether short duration rain intensities can reliably indicate risk for flooding. For that, the entire time-series of precipitation records (not only of the flood events) for different accumulation durations have been used and the respective peak rainfall intensities are plotted, following the methodology introduced by Canon et al. (2008) and Diakakis (2012). Graphs of rainfall intensity vs. duration have been developed for each one of the areas specified in Fig. 2 and illustrate the peak rainfall intensities recorded by the most representative rain gauges of each area. Flash flood occurrence is highlighted with red colour. As it is expected, rainfall intensity is falling as accumulation duration is increasing. The goal is to distinguish, if possible, 2 clear thresholds (denoted by the black lines in Fig. 7) that divide the graph in three parts: (a) the lower one includes peak intensity values that did not lead to flooding throughout the studied period, (b) the middle part includes peak intensities that either did or did not lead to flooding; and (c) the upper part includes peak intensities that always led to flooding.

Results vary considerably depending on the area examined and the local vulnerability, as well as on the density, location and record length of the representative rain gauges. Graphs in which extremely low rainfall intensities are shown to correspond to flood occurrence indicate poor relation between the flooding event and one or more of the rain gauges that represent the studied area. One reason for this inconsistency

may be the long distance of the gauge from the flooded area, while it is even possible for a flash flood to be caused by the runoff of a distant intensive rainfall occurring in higher terrains around the affected area.

The distribution of the rainfall intensity values in the short durations varies a lot between areas, while as accumulation time increases peak intensities tend to be more similar. Obviously, areas with high frequency of flash flood events tend to give more explicable outcomes. These are mainly the areas around the centre of Athens (centre, east and south of Athens) and secondarily both Hymettus areas. In most of these cases quite clear thresholds can be defined particularly for the high probability for flooding. These graphs are also consistent regarding the distribution of the flash flood events concentration, which tends to increase as we move to higher rainfall intensity values. Contrariwise, areas such as Holargos and Glyfada are obviously not well represented by the existing rain gauges, since their graphs present a wide and inconsistent spread of peak intensities. Low representativity relates either with the small operation record of rain gauges or the local density of stations, in some cases too low to cover adequately the entire area. It is also possible that some areas demonstrate particular vulnerability in some places that are prone to flooding even for low rainfall intensity. To capture the specific local sensitivities to rainfall it is obvious that a denser network of rain gauges is required. This applies in areas Chalandri and Maroussi, while it is even more necessary for Acharnes, Penteli and Dionisos due to the topographic features of the mountainous areas.

The areas of Ampelokipoi and Athens Centre, opposite of what we would expect for the most intensively urbanized areas, present high rainfall intensity threshold above which flooding is likely to occur. Specifically, in the area of Ampelokipoi no damaging flash flood occurred for peak intensity less than 29 mm h^{-1} for 10 min duration or 9 mm h^{-1} for 1 h duration. Even though distribution of population has been found to be relevant to the frequency of flash flood events, it can only partly explain the flash flood thresholds. The threshold value, in other words the hazard intensity needed for a place to flood, may relate also with other factors, such as the drainage system effectiveness

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and the preparedness of the local authorities. Therefore, there is not one simple answer to what are the key drivers behind vulnerability of an area. For the highly urbanized areas like the centre of Athens there is land cover and population density on the one hand, while on the other hand, as discussed also by Brody et al. (2012), a more co-ordinated system of flood mitigation infrastructure due to greater resources may exist. Although the centre of Athens is not likely to flood if rainfall intensity is less than 22.8 mm h^{-1} for 10 min duration or 9.6 mm h^{-1} for 1 h duration, it floods for intensities, of 63.3 mm h^{-1} for 10 min duration or 24.4 mm h^{-1} for 1 h duration, that are lower than the respective intensities for which other areas flood, showing a lower resistance of the system. Low threshold values above which flooding is most probable, could indicate some limits in the existing infrastructure to cope with the growth of population and materials exposed and, in any case, confirm the necessity for additional protection measures and for the development of an effective warning system.

According to the European Environmental Agency (EEA, 2010), the improvement of forecasting and early warning systems is seen as the most effective way to mitigate the effects of flash floods. Early warning for flash floods is provided in Greece, based on the weather forecasts, and it is communicated via the media. However, the spatial scale of the numerical weather prediction models but also the uncertainty in the quantitative precipitation forecasts do not allow for the risk estimation at local level. For that reason, a dense network of automatic surface meteorological stations providing real-time 10 min accumulated rainfall and intensity observations, could constitute a Supplement tool for early warning. Standardization of regional rainfall thresholds in several time intervals could therefore be a very useful tool during a rainfall event. Evidently, what is required in order to produce reliable thresholds on a local level is a denser network of rain gauges as well as long-period data. According to the rain intensity-duration graphs produced in the present study, the rainfall thresholds for flood triggering for the areas around the Athens city and Hymettus, could be used for the needs of an early warning system, while for the other areas under examination a denser rain gauge network is required in order to obtain more robust results.

5 Concluding remarks

The objective of this study was to perform an analysis of the flash flood occurrence in an urbanized region, in an effort to identify triggering rainfall thresholds, as well as the effect of the rainfall hazard indicators to the magnitude of the induced impact, considering factors that influence the local vulnerability, such as the population distribution and the geographical features. A major contribution of this paper is that it provides extensive information on the flash flood events of a 10 year period, at the very local level of the most highly urbanized area of Greece, the urban part of the Attica prefecture. This information is considered particularly useful in the context of an integrated approach of the assessment and management of flood risks (EEA, 2010). Moreover, the synthesis of flash flood impact data and complete rainfall records allows the investigation of local rainfall thresholds related to the occurrence of damaging flooding.

Almost all the damaging flash flood events in the target area that occurred during the period 2005–2014 were associated with maximum accumulated rainfall more than 20 mm in 24 h and 3 mm in 10 min. However, the flash flood impact intensity, as measured by the number of fire service operations per event, increases significantly above the level of 60 mm in 24 h and 10 mm in 10 min. It is interesting that Barbería et al. (2014) in their study for the role of factors related to the social impact of heavy rain events in the city of Barcelona, examined the maximum 24 h rainfall paying special attention to the rainfall between 40 and 60 mm and the rainfall exceeding 60 mm especially for the areas with high population density. These thresholds have been found significant in what concerns the magnitude of the flash flood impact in an urban environment. They also found good correlation of the maximum rainfall recorded in short time intervals (10 and 30 min) with the impact indicators. In the present study, rainfall in short time intervals has been proved a good indicator of the induced impact only when the analysis is performed on a more local scale and provided that a sufficient network of rain gauges exists in the examined area.

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The most robust results in what concerns the rainfall intensity thresholds have been produced for the centre of Athens, the area that mostly suffers from damaging flash flood events. The respective rain gauges have been found representative of the area and the estimated thresholds indicate that the city centre manages to resist to very low rainfall intensities, but its resistance has a certain limit, above which flooding seems to be the most probable scenario.

Consideration of the local particularities led to conclusions regarding the rainfall hazard at a local level and the implication of urbanization to the coping capacity. The analysis showed that reliability of these thresholds depends a lot on the representativity of the existing rain gauge network in terms of density, location and record length. The ongoing expansion of the network operated by the National Observatory of Athens ensures the future collection of long-term data which will enhance the accuracy of defined rainfall thresholds associated with flooding and will permit to further assess changes in the local vulnerability.

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Table 1. Areas affected, impact and rainfall (at various accumulation durations) per flash flood event.

Date	Areas ^a	Operations	R10 ^b	R30 ^b	R60 ^b	R12 ^b	R24 ^b
3 Jul 2005	7, 8, 9, 10	35	11.6	25.6	33.4	35.6	35.6
22 Sep 2005	1, 2, 4, 7, 8, 9	168	13.4	28.8	37.6	53.0	55.2
17 Nov 2005	7, 8	73	8.0	16.4	19.8	76.8	82.0
24 Nov 2005	4, 7, 8, 10, 12	245	15.8	44.2	65.4	105.4	122.8
28 Dec 2005	4, 12	31	4.2	8.4	9.4	15.4	17.2
5 Feb 2006	1, 7, 8	23	10.6	22.2	29.6	52.0	52.0
11 Mar 2006	4	11	7.6	22.2	24.8	30.2	35.0
18 Sep 2006	1, 4, 5, 12	24	11.4	23.6	28.0	28.2	28.2
20 Sep 2006	1, 3, 4, 11	11	2.2	5.4	7.6	13.0	13.0
21 Sep 2006	1, 4, 5, 6, 12	55	12.4	29.8	34.0	34.2	34.2
10 Oct 2006	14	85	13.6	23.2	30.6	82.9	132.9
30 Oct 2006	11, 12, 13, 15	32	3.0	8.4	15.4	94.2	110.8
24 May 2007	15	130	20.6	41.8	55.6	71.6	72.2
21 Oct 2007	1, 3, 5	80	11.4	20.4	23.6	46.2	46.4
17 Nov 2008	2, 9	24	7.0	16.8	25.4	42.6	42.6
12 Dec 2008	1, 2, 3, 8, 9	27	9.4	15.6	16.6	21.0	23.2
4 Jul 2009	4, 5, 12	42	9.4	18.8	25.4	28.8	28.8
31 Aug 2009	15	20	15.2	27.8	28.8	29.0	29.0
25 Oct 2009	13	25	5.2	8.4	11.4	27.0	33.6
3 Nov 2009	12	18	4.6	9.6	14.4	20.4	22.4
15 Dec 2009	15	24	6.6	14.4	19.6	37.4	37.4
3 Jul 2010	1, 6, 7	25	18.4	33.4	38.4	39.2	39.2
26 Jul 2010	11, 13	16	11.0	23.8	29.4	45.6	45.6
27 Oct 2010	1-7, 9, 11, 12	52	16.4	28.4	30.8	36.0	36.0
12 Nov 2010	6, 7, 8	16	11.0	15.2	16.2	28.0	32.0
3 Feb 2011	7, 8, 10	210	3.4	9.4	18.0	88.0	99.6
24 Feb 2011	6, 11	54	2.6	5.6	7.4	29.8	41.0
12 Jun 2011	1, 2, 3	26	9.6	24.6	32.4	36.4	36.4
14 Jun 2011	15	37	11.0	22.8	33.8	35.2	35.2
10 Oct 2011	3	35	2.6	5.8	8.4	23.0	28.8
6 Feb 2012	1, 2, 3, 7, 9	70	12.2	25.2	39.2	65.2	72.0
18 Apr 2012	2, 8	10	5.0	10.2	18.6	32.6	32.6
30 Nov 2012	13, 14	30	20.8	34.8	39.2	54.0	55.2
18 Dec 2012	1, 2, 8, 9	36	16.0	25.0	29.4	31.0	43.8
29 Dec 2012	6, 14	118	3.2	4.8	8.4	161.6	186.2
16 Jan 2013	2, 15	17	6.8	15.4	24.4	39.6	40.0
22 Feb 2013	1-9, 11, 12, 15	632	15.6	35.0	46.4	95.4	97.6
12 Jun 2013	11, 12	26	19.6	31.8	42.6	50.4	50.8
11 Nov 2013	1, 2, 3	90	10.0	23.0	39.0	53.2	53.2
20 Nov 2013	10	22	4.8	12.4	14.8	27.4	27.4
24 Nov 2013	1, 2, 3	12	8.0	12.6	19.6	26.8	26.8
25 Jan 2014	1, 2, 3, 6, 7	100	16.4	34.6	35.6	37.6	42.0
28 Jan 2014	1, 2, 4	20	10.0	17.2	31.2	56.4	62.2
19 Jul 2014	3, 7, 8, 10	50	16.6	41.2	51.6	55.4	55.4
7 Sep 2014	13	25	12.0	31.6	46.6	50.6	50.8
15 Sep 2014	11, 12	20	15.6	27.6	28.6	28.6	28.8
16 Sep 2014	1, 7, 14	60	10.2	24.6	26.4	28.4	28.8
24 Oct 2014	1-4, 9, 12, 15	500	14.0	35.6	43.6	71.8	74.0

^a For numbering see Fig. 2.

^b Maximum precipitation per event in various time intervals: 10, 30, 60 min, 12, 24 h.

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Table 2. Correlation (Spearman's rank coefficient, ρ) between the number of the Fire Service operations and the maximum rainfall in various time intervals.

Maximum rainfall (time interval)	R24 (24 h)	R12 (12 h)	R60 (60 min)	R30 (30 min)	R10 (10 min)
Operations					
Athens-Suburbs	0.61 (***)	0.58 (***)	0.40 (**)	0.37 (**)	0.31 (*)
Athens city	0.85 (**)	0.85 (**)	0.85 (**)	0.83 (**)	0.69 (*)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

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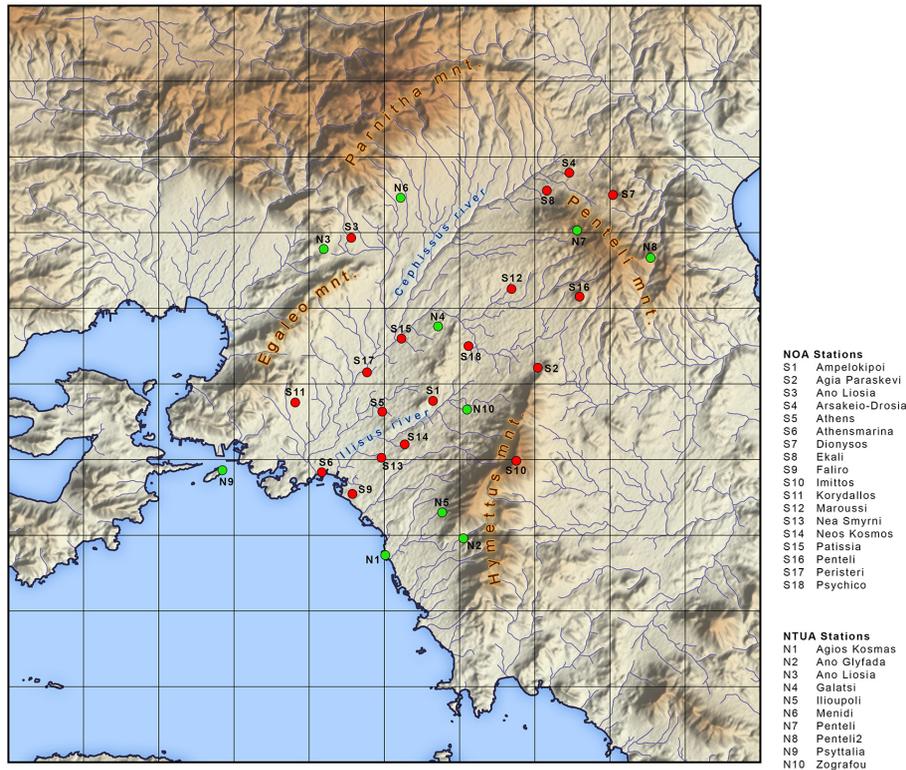


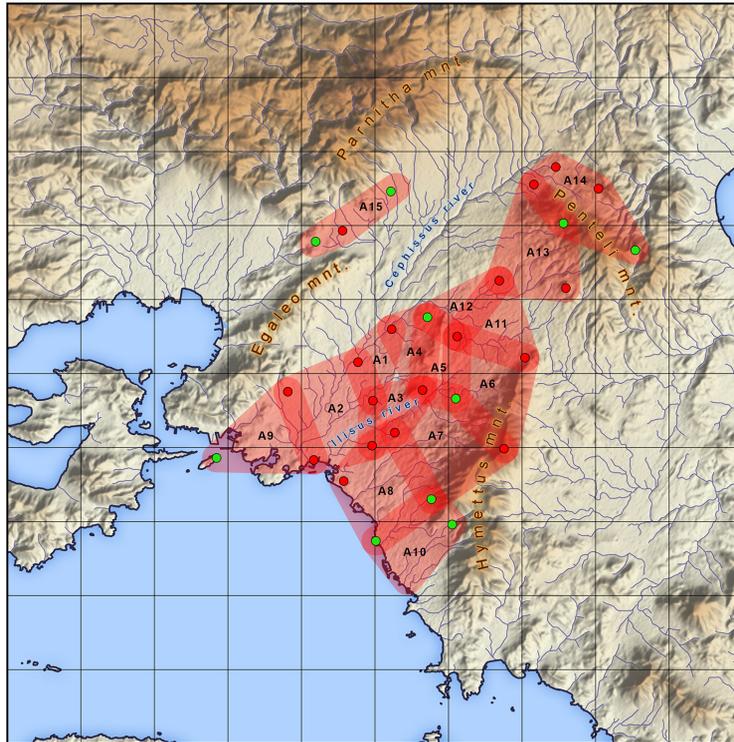
Figure 1. Map of target area and locations of surface meteorological stations.

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- A1 ATHENS (center)
- A2 ATHENS (south)
- A3 ATHENS (east)
- A4 ATHENS (north)
- A5 AMPELOKIPOI
- A6 HOLARGOS
- A7 HYMETTUS
- A8 HYMETTUS (south)
- A9 PIRAEUS
- A10 GLYFADA
- A11 CHALANDRI
- A12 MAROUSSI
- A13 PENTELI
- A14 DIONISOS
- A15 ACHARNES

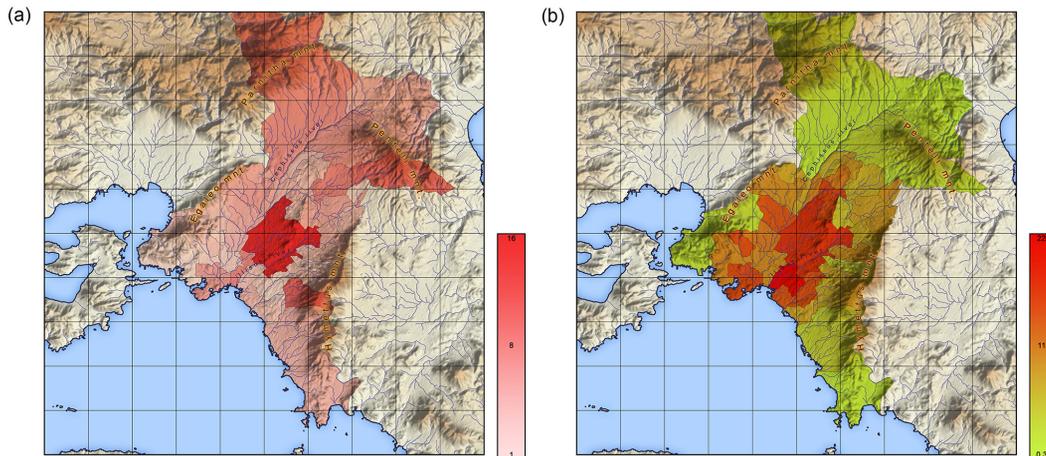
Figure 2. Division of Athens-Suburbs region in 15 specific areas. The representative rain gauges in each area are also shown with red (NOA stations) and green (NTUA stations) bullets.

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**Figure 3.** (a) Spatial distribution of flash flood events. (b) Population density.

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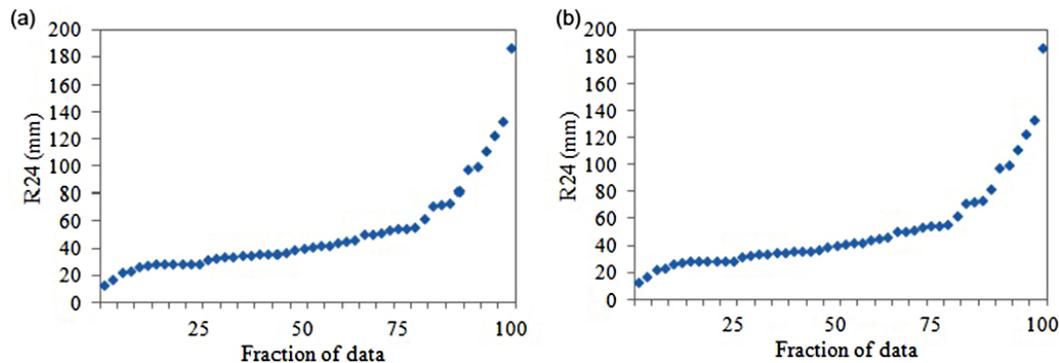


Figure 4. Quantile distribution plots for **(a)** R24 and **(b)** R10 observations.

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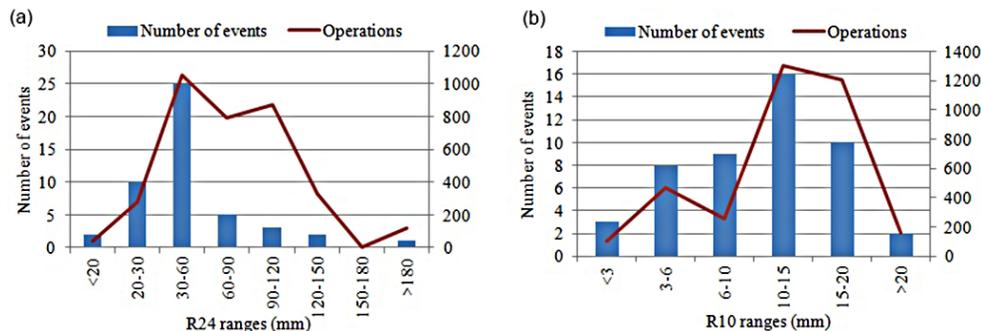


Figure 5. Number of events and Fire Service operations for various ranges of **(a)** 24 h (R24) and **(b)** 10 min (R10) accumulated rainfall.

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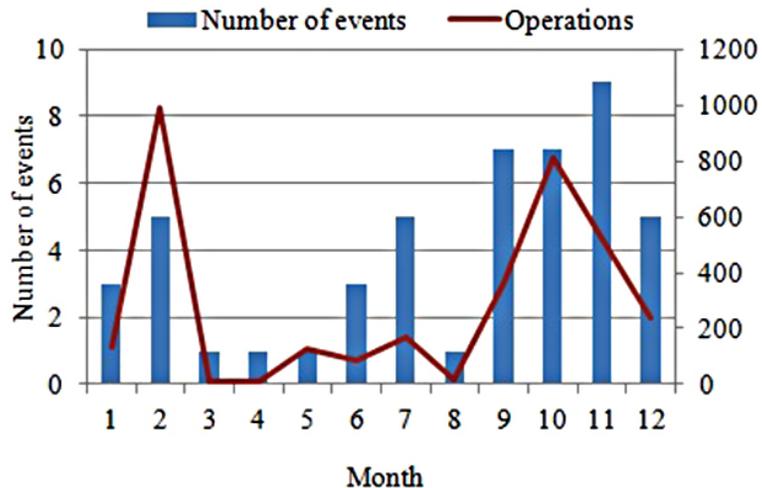
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**Figure 6.** Monthly distribution of the number of flood events and Fire Service operations.

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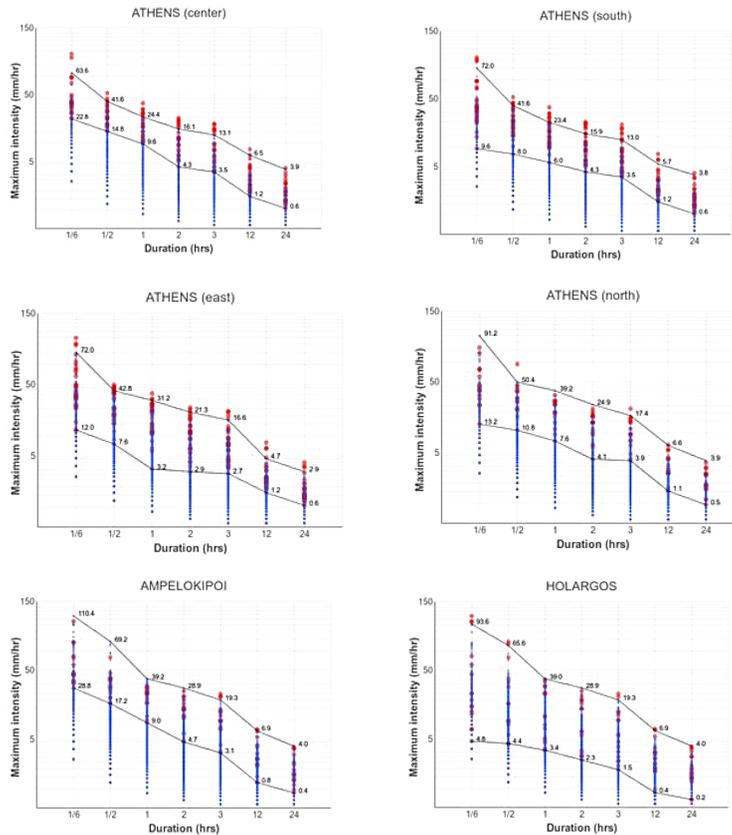


Figure 7.

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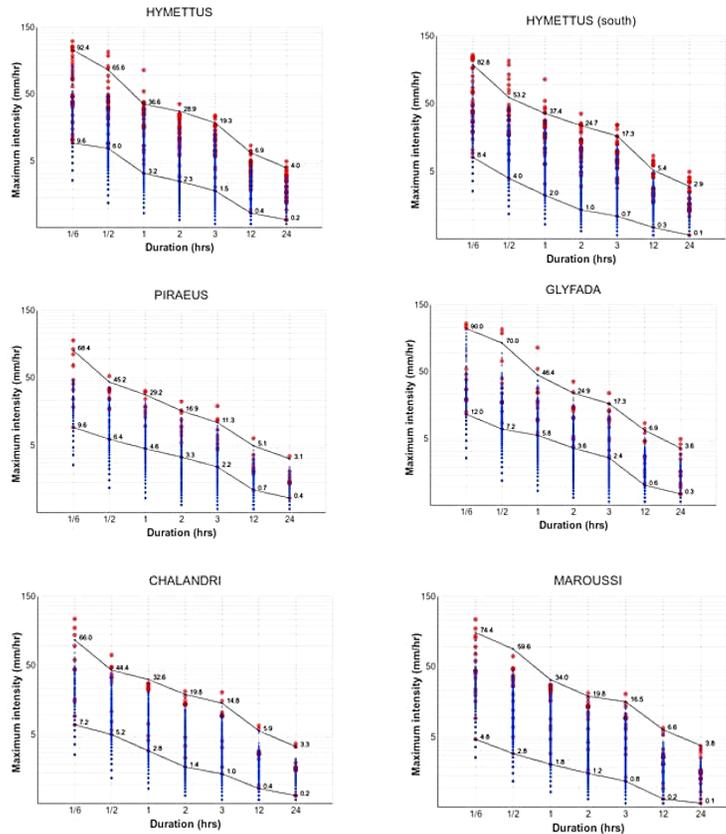


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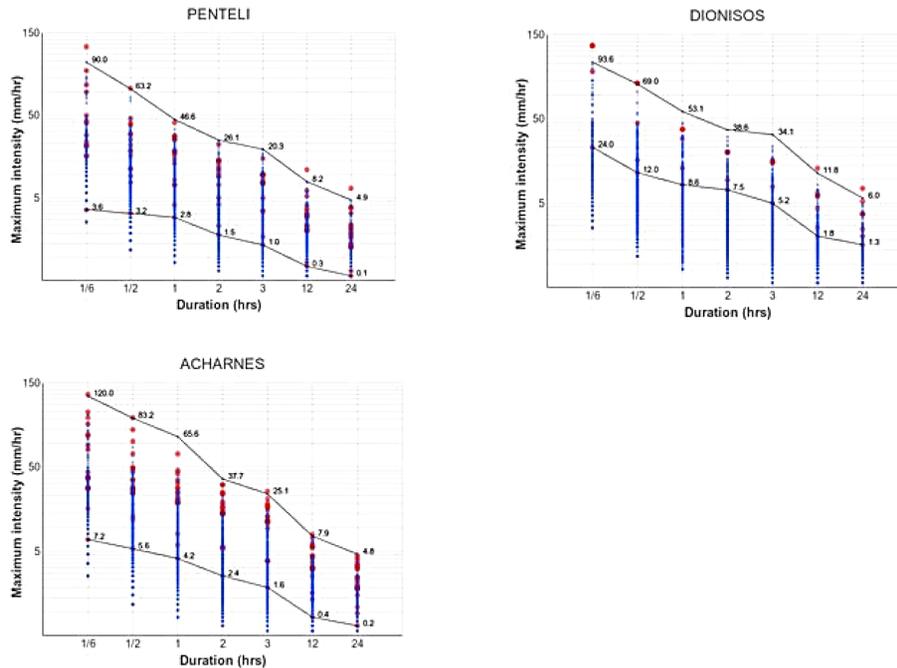


Figure 7. Peak rainfall intensities vs. duration graphs, at each specific area shown in Fig. 2. Peak intensities for each area derive from the rainfall data recorded by all the representative rain gauges shown in Fig. 2.

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