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THE IMPACT OF FOREST FIRES ON THE VULNERABILITY OF PERI-URBAN CATCHMENTS TO FLOOD EVENTS (THE CASE OF THE EASTERN ATTICA REGION)

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ABSTRACT

Floods are natural disasters that pose a direct threat to human life and often cause significant economic loss. River floods are caused by heavy and/or prolonged rainfall, causing rivers and streams to overflow and sometimes also burst dams or levees. Forest fires increase the risk factor to which humans and properties are exposed during flood events, by intensifying and accelerating the peak volume of the overflow water. Wildfires alter significantly the geomorphological characteristics of a river basin, thus affecting both directly and indirectly its hydrological behavior. A forest fire, followed by a rainfall event, may cause a significant flood downstream. This paper presents a hydrological analysis of the eastern Attica region, which is performed both prior to and after forest fire events, in order to assess the change in the consequent flood risk. The study area is the eastern part of the greater Athens area in Attica (Greece). This is a peri-urban area experiencing rapid urban growth, and its hydrometeorological conditions are being monitored though a dense hydro-meteorological network for the past 10 years. A fire model is set up to simulate the characteristics of the development of three hypothetical fire events of low, medium and high severity accordingly. The parameters that affect fire intensity and rate of spread (e.g. topographic factors such as slope steepness, elevation, aspect, and configuration of land) are taken into consideration and the temporal and spatial distribution of a forest fire is studied. Of additional interest in this study is the fact that a recent forest fire event devastated a significant part of its northern, mountainous area and the consequences of this event are further examined. A detailed simulation of the three hypothetical fire scenarios and the real fire event is performed and the outcomes of the analysis are used as an input in a rainfall – runoff model that allows for an enhanced hydrological study of the affected area. Land use changes and geomorphological and hydrological alterations as a result of the fire event are taken into consideration during a post-fire hydrological analysis, which eventually demonstrates the impact of fire on the hydrological response of the study area. This impact is assessed by means of application of a methodological framework for the estimation of post-fire values for three hydrological parameters (CN, initial abstraction and lag time) and the paper concludes that the fire impact has rendered the downstream areas more prone to floods.

KEYWORDS: Forest fires, floods, fire modeling, rainfall-runoff modeling, Hydrological Observatory of Athens, eastern Attica.

INTRODUCTION

Mediterranean countries, including Greece, experience frequent wildfire events, especially during the summer. This has led to increased awareness of the scientific community, which systematically investigates not only the effects of forest fires on ecosystems, but also on human lives and properties. In addition, over the past few years, extensive research has been made on the effects of wildfires on the hydrological response of river basins and the erosion/sedimentation process at the burnt areas.

The fire effects on hydrological behavior of river basins can be classified into direct and indirect effects. Direct effects are related to the destruction of the vegetation cover, the reduction of interception and evapotranspiration, while indirect effects are related to changes in the physical, chemical and hydraulic soil properties. Specifically, the indirect effects include the destruction of the organic matter, the reduction in soil porosity and infiltration capacity and the formation of a hydrophobic soil coating. This coating is formed because of the coating of soil particles with organic substances (DeBano, 2000) and the consequent reduced affinity between soil and water increases significantly the burnt areas runoff.

The consequences of direct and indirect effects are the increase of surface runoff, erosion and peak discharge rates. Increase in the flood frequency and alteration in the shape of the flood hydrographs has also been reported. Several studies are focusing on the effects of forest fires on the hydrological response of river basins (Imeson *et al.*, 1992, Lavabre *et al.*, 1993, Inbar *et al.*, 1998, Benavides-Solorio and MacDonald, 2001, McLin *et al.*, 2001, Rulli and Rosso, 2007, Pierson *et al.*, 2008), pointing out the increased vulnerability of downstream areas to floods due to burnt land upstream.

Moreover, according to the European Flood Directive (Directive 2007/60/EC), published on 26/11/2007, which intends to reduce the risks and adverse consequences of floods in European Union and is a complement to EU legislation for integrated water resources management (Directive 2000/60/EC), it is very important to develop an integrated framework for assessing the change in the hydrological response of watersheds. In order to address effectively the requirements of the Directive and draw accurate flood maps, the accurate estimation and quantification of changes in the hydrological response of watersheds following a wildfire event is necessary.

The purpose of this study is to investigate the changes in the hydrological response of a river basin following a wildfire event and develop a methodological framework that will support the redefinition of the hydrological parameters after the wildfire event.

STUDY AREA

The area selected for the current research is the Rafina catchment, located in the greater southeast Mesogeia region in the eastern Attica, Greece. This area covers 127.17 km^2 and geographically extends east of the Ymittos mountain to the coastline of Evoikos Gulf.

During the last 30 years the study area has been under rapid urban development and in many cases this urban expansion remains unplanned. Based on demographic data for the eastern Attica region a significant increase in the population of the area at the main settlements has been recorded. The increase in Pikermi community is estimated at 419% from 1971 to 2007, while the increase in the population of Drafi and Rafina communities, for the period between 1971 and 2001, is estimated at 79% and 38% respectively. Furthermore, large scale public works are being constructed in the area especially during the last decade and this has contributed to a significant increase in the private building activity. These works include inter alia the construction of the new national airport of Athens in Spata, the construction of major roads, such as the Attiki highway, which connect the southeast Attiki area with the rest of the Prefecture and the business centre of Athens, and the developing Rafina port.

However, the urbanization which caused a radical land use change from rural to urban is not the only factor that has affected the variety of land uses in the study area. During the last 15 years the northern part of the area has experienced large scale forest fires, including the ones of 1995, 1998 and 2009, which apart form the ecological degradation of the region, resulted in the progressive conversion of large forest areas to burnt land.

As a result of the extensive wildfires and according to scientific studies (Marinos *et al.*, 1995) the affected area is at a great extent vulnerable to erosion. Additionally, the destruction of the forest land in its northern part has altered the geomorphological characteristics of the area making its downstream parts particularly prone to floods (Karymbalis *et al.*, 2005). The unprecedented urban development and the fact that the existing hydraulic works in the area are inadequate to release floods (Giakoumakis, 2000), also contribute to the increased vulnerability of the study area during flood events.

It should also be noted that the study area has been monitored during the last 10 years for academic and research purposes by the Laboratory of Hydrology and Water Resources Management of the National Technical University of Athens and numerous studies have been made in the area so far (Papathanasiou *et al.*, 2009). Hydrometeorological stations, raingauges and streamflow gauges of the Hydrological Observatory of Athens (HOA), operated by the Laboratory, are installed and cover the study area adequately. The existing reliable pre-fire and post-fire (regarding the 2009 fire event) data records of the Observatory enhance the current study.

All the above mentioned issues clearly demonstrate the vulnerability of the area during flood events and indicate the necessity to systematically monitor the hydrological response of the area.

METHODOLOGY

Fire modeling

The fire model that was selected for the simulation of fire scenarios is the Geographic Fire Management Information System (G.FMIS), a model developed by Pangaiasys Ltd. (Source: www.g-fmis.com). G.FMIS is a decision support system, which organizes and refines forest-fire management by exploiting the capabilities of the Geographic Information Systems (GIS) and the scientific knowledge on fire behavior. It is a complicated fire management system widely used in Mediterranean regions, since it provides fuel models that simulate well the conditions of Mediterranean ecosystems (MEDIGRID project). For this reason G.FMIS is considered as appropriate for forest fire simulations in Greece, and this has led the Greek Fire Service to widely use it.

In the current research, the G.FMIS was applied in order to simulate three scenarios of forest fire. The scenarios were chosen to represent fire events of low, medium and high severity, as resulting from different initial conditions of wind and fuel moisture, thus affecting in a different way the catchment. For each scenario, the model produced a spatial scenario output. These spatial scenario outputs which were then used in the hydrological analysis depicted the affected land after each hypothetical fire event, containing information related to the rate of fire spread, the flame length and the fireline intensity.

Furthermore, the burnt area after a real fire event, which occurred in the study area in August 2009, as provided from satellite (Source: Laboratory of mineralogy and geology, Agricultural University of Athens) has been digitized and used in the hydrological analysis, as well. It should be mentioned that the real fire event represented an intermediate situation between the simulated medium and the high severity forest fires.

Hydrological analysis

The semi-distributed hydrological model HEC-HMS has been used to assess the hydrological response of the catchment for the different scenarios. Six rainfall events, 3 pre-fire and 3 post-fire ones, as recorded from the raingauges of the Hydrological Observatory of Athens, were selected for the setting up of the model. The characteristics of the rainfall events are presented in Table 1.

Table 1. The characteristics of the selected rainfall events

Rainfall events	Total Rainfall Depth [in mm]	Mean Rainfall Intensity [in mm*h^{-1}]
17/11/2008	41.0	8.0
12/12/2008	33.6	7.5
8/2/2009	24.3	4.5
6/12/2009	17.6	3.3
11/12/2009	34.0	6.0
17/10/2010	39.0	6.0

The stream flow that was observed after the three events was used for the calibration of the model, while the observed flow following the other three rainfall events was used for its validation. For the simulation, the catchment was divided into five sub-basins, presented in Figure 1. A comparison between the simulated and observed flow at the outlet of sub-basin 1 for the event recorded at 12/12/2008 is presented in Fig. 2.

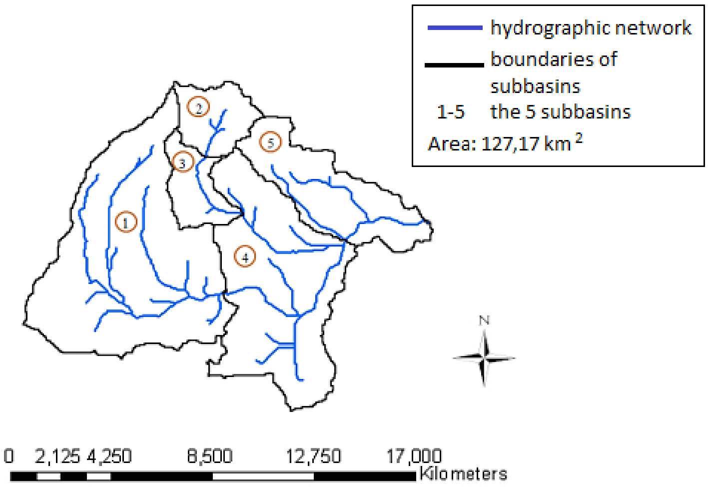

Figure 1. The 5 sub-basins of the study area, as defined in the HEC-HMS model

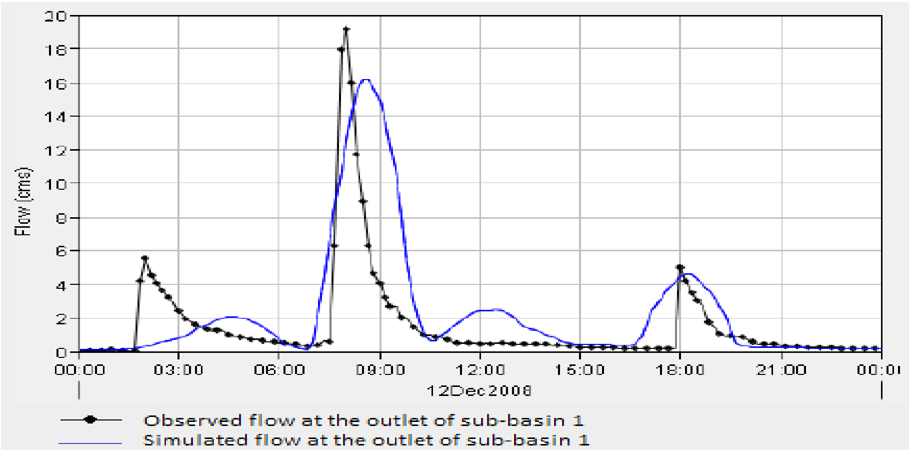

Figure 2. Simulated and observed flow at the outlet of sub-basin 1 for the event of 12/12/2008

The methodologies selected for the simulation with the HEC-HMS model included the Soil Conservation Service (SCS) loss method, the Snyder unit hydrograph transform method, the Recession method for the calculation of the baseflow and the Muskingum routing method. More information on the values of the parameters required for the application of these methodologies can be found in Kasella A. (2011).

Each sub-basin has different pre-fire and post-fire values of three hydrological parameters that were chosen to be studied. These parameters are the curve number, the initial abstraction and the lag time. The methodology developed to assess the changes in their values is described below.

The values of the curve numbers were defined in proportion with the land uses and hydrology soil group, in accordance with the results of a relevant study (Goodrich *et al.*, 2005). In particular, Goodrich developed a linear correlation between the percentage of land cover affected by fire and the curve number for each hydrological soil group (A, B, C and D). The values chosen correspond to 0% of land cover according to Goodrich (100% affected), based on the assumption that the Mediterranean vegetation cover has been entirely destructed after the fire effect.

As far as the values of the initial abstraction (I_a) are concerned, a recent research made for sub-basins 2 and 3 of the study area concluded that the SCS empirical equation (Eq.1) which correlates Ia with total storage, S, overestimates the initial abstraction and leads to a delayed start of the excess rainfall and the simulated runoff (Baltas *et al.*, 2007). This overestimation was attributed to the uneven spatial distribution of land uses in that area.

$$Ia = 0.2 \cdot S \qquad \text{(Eq.1)}$$

For that reason, the value of $I_\alpha \cdot S^{-1}$ for each one of the 5 sub-basins, was not taken as equal to 0.2, but it was estimated according to the calibration of the hydrological model HEC-HMS with pre-fire data records and the corresponding values are presented in the following Table.

Table 2. The area and the values of $I_\alpha \cdot S^{-1}$ for each one of the 5 sub-basins

Sub-basin	Area [in km^2]	$I_\alpha \cdot S^{-1}$
1	53.6	0.03
2	7.1	0.037
3	19.5	0.01
4	39.0	0.02
5	8.0	0.05

In similar studies, the post-fire lag time is reduced at about 40% compared to the pre-fire one (Elliott *et al.*, 2004, Cydzik and Hogue, 2009). In the current research a 40% reduction in lag time was attributed to the totally burnt areas, while the lag time in the partially burnt areas was reduced proportionally to the percentage of the burnt land after each fire.

Following the hydrological analysis, the values and the range of peak discharges after the six rainfall events that were used for the setting up of the model were associated with the percentage of the burnt area after each fire. The results are presented in the following section.

RESULTS

The application of the Geographic Fire Management Information System (G.FMIS) resulted in the production of three GIS spatial scenario outputs, which depicted the burnt area after each one of three fire scenarios of increasing severity in terms of increased wind speed and reduced initial humidity. The affected areas in each case are presented in Figure 3 (left). The burnt area as derived from digitized satellite image is presented in Figure 3 (right). The burnt area (both in km^2 and as a percentage) in each case is presented in Table 3.

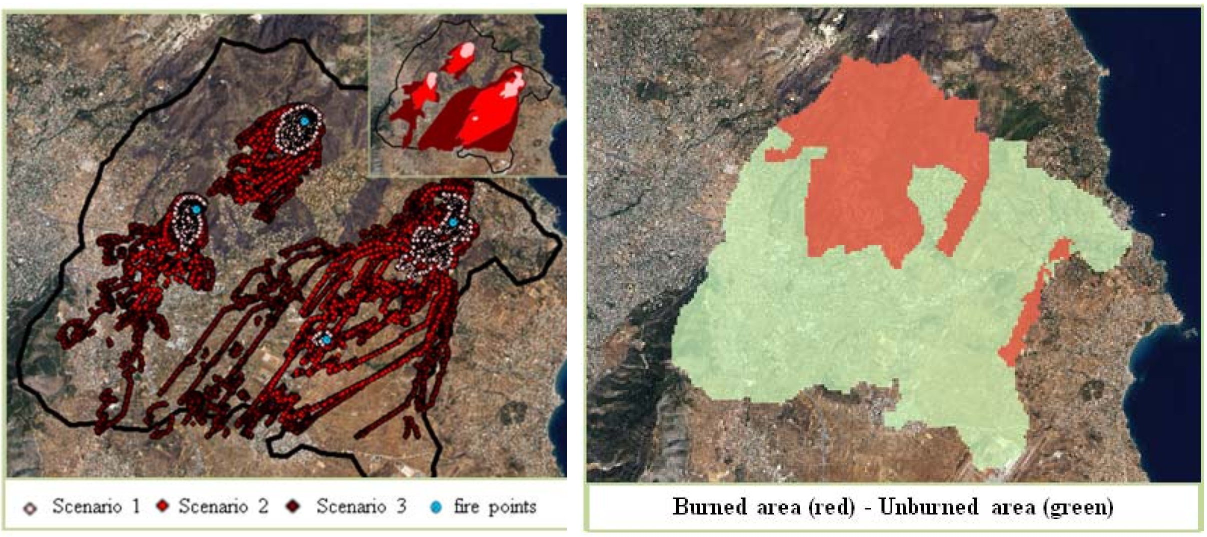

Figure 3. Fire simulation using the G.FMIS (left) and the real fire event of 2009 (right)

Table 3. The burnt area (in km^2 and as a percentage) for the three fire scenarios and the fire event of 2009

Fires	Burnt area [in km^2]	Burnt area (%)
1st scenario	5.09	4.0
2nd scenario	29.25	23.0
3rd scenario	62.31	49.0
Fire 2009	35.10	27.6

Concerning the results of the G.FMIS, it is obvious that the burnt area grows proportionally to the speed of the wind, while its relation to the humidity of fuels is inversely proportional. Moreover, an uneven expansion of the fire in different parts of the watershed, as well as unevenness in the shape of the burnt areas is also observed. The final percentage of the burnt area for the scenarios 1, 2, 3 comes up to 4.0%, 23.0% and 49.0% respectively. Based on the digitization of satellite image of the burnt area after the real fire of 2009, the fire affected 27.6% of the total watershed. The event affected 20.2% of forest lands, while the percentages of the affected urban and cultivable area come up to 5.0% and 2.4% respectively.

The hydrological analysis performed focused on the selection of the values of the CN, the initial abstraction and the lag time, after the three fire scenarios and the real fire event, according to the methodology described above, and these values were compared to the corresponding pre-fire values. This analysis was performed for all 5 sub-basins of Figure 1, while the results are shown in Figure 4.

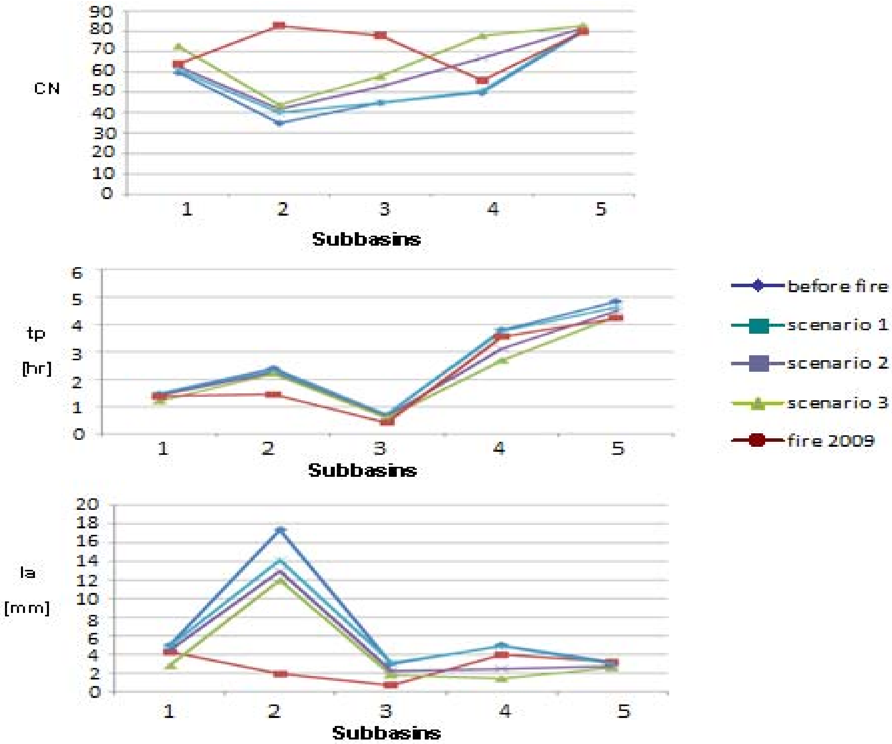

Figure 4. The values of the three hydrological parameters (CN, I_α, t_p) for each fire (three scenarios and fire 2009) and according to recorded pre-fire data, for each sub-basin

Comparing the values of the three parameters after each fire with estimated pre-fire ones, it is obvious that the values of the CN change proportionately to the surface of the area affected by each fire. More specifically, the sub-basins 2 and 3 show a significant difference in the value of CN after the fire of 2009, with percentage changes 137% and 73% respectively. Remarkable changes in CN are observed in the sub-basin 4 in the second and third fire scenarios, with percentage changes 34% and 56% respectively. The sub-basin 1 has the slightest deviations in the values of CN and this can be attributed to the fact that the affected area was extremely limited in all fire scenarios. Additionally, the value of initial abstraction is significantly reduced in the cases where a significant increase in CN was estimated. The lag time reaches its lower values for the real fire event and the sub-basins 2 and 3, since these areas were practically entirely destroyed by the fire.

The values of the CN, the initial abstraction and the lag time were estimated for all sub-basins and for all fire scenarios and were imported in the calibrated hydrological model HEC-HMS. Hydrological analysis was performed for six rainfall events which have the same characteristics as the recorded events presented in Table 1 and the model produced the corresponding hydrographs at the outputs of each sub-basin for all rainfall events and all fire scenarios.

The peak discharges of the hydrographs for all six rainfall events were then compared with the percentages of burnt area for all fire events (the 3 hypothetical and the real one) at the output of the sub-basin 5, in order to identify a relation between these two parameters. In all cases, a linear correlation between the percentage of the burnt area and the peak discharge was observed, with a high correlation coefficient (varying between 0.95 and 0.98) for all the events. The results are presented below.

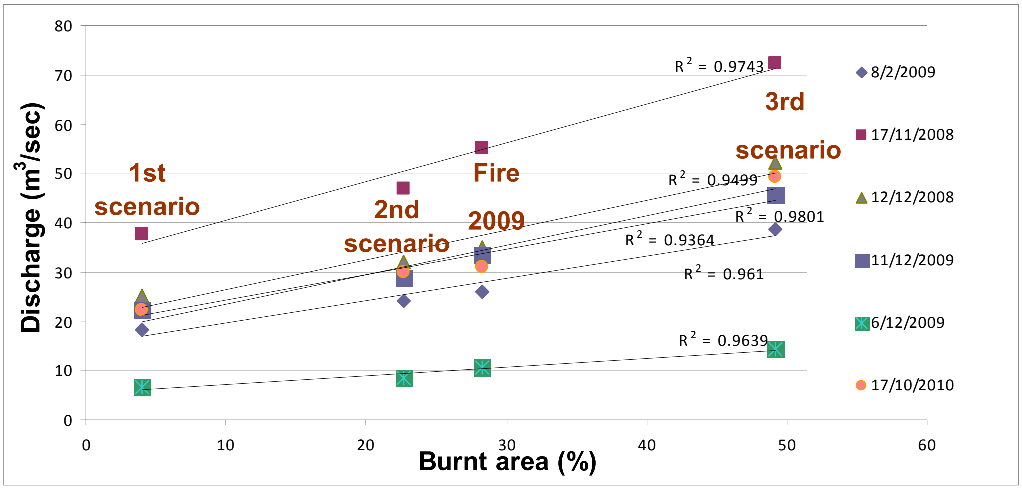

Figure 5. The correlation between the percentage of burnt area and the peak discharges.

Finally, the peak discharge prior to the fire and the corresponding discharge after each fire scenario were calculated for the six rainfall events. The range of the discharge (3 values prior to the fire and 3 after the fire) was then correlated with the percentage of the burnt area and the results are illustrated in Figure 6.

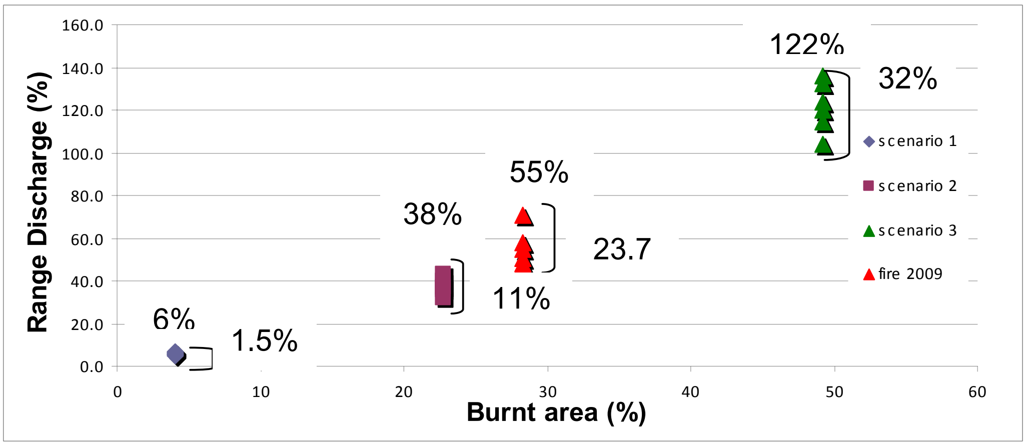

Figure 6. The correlation between the percentage of burnt area and the range of the peak discharges

In Figure 6 for each scenario the percentage deviation in peak discharges is calculated and all of them are averaged to find the range discharge. For the first scenario the mean value of the peak discharge is about 6%, while for the second, third scenario and the real fire of 2009, the variation is estimated at about 38%, 122% and 55% respectively. Moreover the range of variation was also calculated for each case. As it can be seen in Figure 6 it rises up to 1.5% for the first scenario, in the second it reaches 11%, while it increases up to 32% and up to 23.7% for the third scenario and the real fire of 2009.

CONCLUSIONS

As far as the results of the fire model G.FMIS are concerned, the following conclusions can be drawn. The wind effect was proven to be a more dominant factor than the fuel humidity in terms of defining the severity of a fire scenario. In all scenarios, the fire expanded unevenly in the watershed and this can be attributed to the existence of a wide variety of land uses, i.e. fuels, in the area. The main reason for the unevenness in the shape of the burnt areas is that the model has restrictions concerning its application in urban areas. More specifically the existence of several peri-urban cells in the study area hinders the even distribution of fire.

Changes in CN values after the fire scenarios and the real event demonstrate the proportional relation between the CN value and the extent of the burnt area. The CN values for the sub-basins 2 and 3 for the real fire event differ from the values derived from the other scenarios due to the extent of the burnt area which can be seen on the digitized satellite image (Figure 3). In other words, the sub-basins 2 and 3 were practically totally burnt during the 2009 fire, while in the hypothetical fire events they were not much affected, and as a result a high CN number has been attributed to them. Similarly the sub-basins 2 and 3 have a significant low initial abstraction value since this parameter is inversely proportional related to the percentage of the burnt area.

The significant influence of fire on the hydrological response of a river basin was observed through the comparison of the percentage of the burnt area with the peak discharge of the basin. As expected, for all six pre-fire and post-fire rainfall events, increased surface of the burnt area resulted in increased peak discharge in the sub-basins' outputs but the research also identified a linear correlation between these two parameters, with a correlation coefficient varying from 0.95 to 0.98.

As the percentage of the burnt area increases, the mean discharge deviation for each scenario and the range of peak discharge deviation before and after the fire increase as well. The range of the peak discharge values for each scenario, which was calculated as the mean deviation of the peak discharge values before and after each fire scenario for all rainfall events, increases proportionally to the burnt area. Moreover, a linear correlation was observed between the percentage of the burnt area and the range of the peak discharge deviation prior to and after the fire.

Another conclusion that can be drawn from this study is that the effect of rainfall intensity on the amount of discharge is more significant than the effect of total rainfall depth, especially when the increased rainfall intensity is observed after the fire event. More specifically, the comparison between the discharge of events with similar rainfall depths shows that events with higher intensity result in higher discharge, which is significant in case of post-fire events. This conclusion can be drawn by comparing for example the rainfall events of 17/11/2008 (pre-fire) and 17/10/2010 (post-fire) which have about the same total rainfall depth, but the post—fire event has slightly higher intensity. In this case, the post-fire event results in significantly increased discharge.

The post-fire hydrological analysis of river basins with equal characteristics to the Rafina river basin, in terms of total surface, topographic characteristics, hydrometeorological conditions etc, is of particular interest. Such studies could verify the effectiveness of the proposed methodology, regarding the reliable redefinition of the selected hydrological parameters after a fire event, and allow for its application to similar catchments that have experienced similar wildfires.

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Additional information for the Geographic Fire Management Information System (G.FMIS) is provided in the website www.g-fmis.com (last visited 15/03/2012).