

Pre post differenced runoff biology essay

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ABSTRACT: Wildfires change the way water infiltrates soils by reducing the amount of interception matter that protects soil and slow surface runoff. The wildfires at Northeast Attiki in August 2009 destroyed approximately a third of the study area covered by a mixed vegetation cover consisting of shrublands, pasture and pine forests. This study represents an effort to improve existing understanding and provide insight to the relationship between multiple geomorphic determinands and the hydrologic response the first few years following wildfires at semi-arid, shrubland-dominated catchments. The modelling framework of choice included the application of MIKE SHE, a physically based, hydrological model, in order to calculate catchments' surface runoff. Further, an extended list of 44 linear, areal and shape geomorphic determinands, derived using GIS or established mathematical equations for each catchment, was then tested along with meteorological parameters for correlation against mean monthly surface runoff before and after the wildfires, as well as differenced mean monthly surface runoff as a response to wildfires. The strongest (positive and negative) correlations were then used to identify simple and multiple linear regression model relationships. Backward multiple linear regression statistical analysis identified several models-equations that gave best prediction of surface runoff. This paper has shown that primarily burnt area but also channel initiation index were the main explanatory variables for the increase of mean monthly surface runoff as a response to wildfires. The extracted relationships may be used in semi-arid, shrubland dominated areas affected by wildfires that present similar land use, soil and geological characteristics. **KEYWORDS:** wildfires; surface runoff; MIKE SHE; hydrological

model; geomorphic; linear regression Background Hydrological responses such as overland flow are intimately interrelated with landscape surface and geomorphic characteristics. This means that hydrological response can change greatly when these characteristics are altered through environmental disturbances, such as drought or fire (Beeson et al., 2001). Wildfire constitutes a natural, essential, and ecologically significant disturbance process that impacts on the interconnections between physical, chemical, biological, biotic and abiotic components of terrestrial ecosystems or catchments (Rogers, 1996) and is frequently affected by human activities. Wildfires modify infiltration capacity of soil and decrease the amount of interception matter (such as canopy, litter, organic debris), that protects soil from raindrop impact (Moody and Martin, 2001; Ice et al., 2004). Since surface roughness is significantly reduced infiltration subsequently decreases (Arend, 1941; Anderson, 1949; Fuller et al., 1955) often resulting in sudden and dramatic increase in surface runoff velocities even as a response to a normal precipitation pattern, while higher peak flows may be observed at the catchments outlets (e. g. Hoyt and Troxell, 1934; Brown, 1972). The magnitude of the hydrological response during the period after a wildfire can be quantified as the change in process rates from pre-fire conditions (Swanson, 1981). The magnitude of the disturbance depends upon the sensitivity of the system, the precipitation regime, the severity, duration and areal extent of the burn, and the frequency of wildfires (Swanson, 1981; Ice et al., 2004). Mediterranean type ecosystems evolved under the influence of environmental stresses (such as summer drought) and natural hazards (such as wildfires). They are generally highly impacted by

humans, since the Mediterranean Basin was inhabited for thousands of years, and are thus characterized to a large degree as humans-made landscapes (Pérez et al., 2003). Over the last years, a growing body of literature has been concerned with wildfire impacts worldwide (Shakesby and Doerr, 2006). An increase in the number and size of fires has particularly been observed in the Mediterranean Basin (Moreno et al., 1998; Piñol et al., 1998), that was mainly attributed to land abandonment and afforestation of former agricultural land (Moreira et al., 2001; Pérez et al., 2003), the influence of climatic changes (Pausas et al., 2008; Pausas, 2004; Piñol et al., 1998), as well as the expansion of urbanized and agricultural areas at the expense of peri-urban and peri-agricultural land. As a result of above facts the Mediterranean landscape is more vulnerable to fuel accumulation, subsequently leading to increased fire occurrence (Loepfe et al., 2010; Vega-García and Chuvieco, 2006) and changes in the ecosystem structure with increased presence of invasive and highly inflammable shrubs like *Cistus* (Margaris, 1980). Most studies have identified the first one, two or three post-fire years as the critical period for high runoff (Wright and Bailey 1982; Veenhuis 2002), although, in semi-arid areas, such as Mediterranean shrublands much higher runoff rates are being noticed even five to ten years after the fire (Inbar et al., 1998; Robichaud, 2000; Mayor et al., 2007). In this study, surface runoff was assessed for the first three years following the fires while vegetation recovery within or extending over this period is not assessed herein. Hydrological models provide a framework to conceptualise and investigate the relationships between climate, human activities (e. g., land use changes in agriculture, urban areas, etc) and water resources

(Legesse et al., 2003) and are particularly useful for the assessment of scenarios for establishing management alternatives. In the past, numerical models have been applied to examine streamflow and groundwater response to a variety of management problems, such as land use changes (e. g. Hookey, 1987; Arnold and Allen, 1996; Salama et al., 1999) historical trends (e. g. Chen et al., 2007) and future climate change scenarios (e. g. Scibek and Allen, 2006; Scibek et al., 2007). Recent modelling efforts to predict forest fire hydrological effects are presented by e. g. Johansen et al. (2001), Moffet et al. (2007), Rosso et al. (2007), Hill et al. (2008) and Lane et al. (2010). In geomorphology, morphometry is dedicated to the quantification of morphology. Linear, areal and shape indices used in drainage basin morphometry relate to the quantification of catchment morphology. Morphometric (or geomorphic) characteristics of catchments provide a means for describing the hydrological behaviour of a catchment. Multivariate statistical approaches may be used to establish correlations between geomorphic determinands and hydrological key variables. Moreover, geomorphic parameters may provide information for hydrological modelling, especially in the stage of model calibration (Brodosy and Schmidt, 2002). Among the indices for catchments, the most well known include probably the compactness ratio index (Gravelius, 1914), the form factor (Horton, 1932), the basin circularity (Miller, 1953) and the basin elongation (Schumm, 1956). By capitalizing valuable pre-fires data, also using GIS and calibrating MIKE SHE, a semi-distributed, physically-based hydrological model, this paper aimed initially at calibrating the model for a three year pre-fires reference period defining the normal behaviour of seven semi-arid, shrubland-

dominated catchments and subsequently predicting the first three years hydrological response (total, annual and mean monthly runoff) of the catchments following 2009 wildfires. At the next stage multiple (44) geomorphic determinands were quantified for each catchment using GIS and mathematical equations from the geomorphology literature. At the third stage, a correlation analysis was carried out between geomorphic determinands, the extent of burnt land, meteorological parameters and the hydrological response (pre, post and differenced/increase of surface runoff). Models or equations for predicting surface runoff characteristics from catchment geomorphic characteristics are often derived using multiple regression which assumes the existence of linear relationships (Mazvimavi et al., 2005). Therefore, as a final step, simple and multiple linear regression analysis was carried out to examine and quantify the influence of various geomorphic determinands to hydrological parameters such as the increase of mean monthly and annual surface runoff that is taking place after a wildfire and establish potentially useful relationships for similar types of semi-arid areas. The results will illustrate aspects of the potential dynamics and interrelationships between catchments geomorphic characteristics, deforestation as a result of burnt land, meteorological characteristics and catchments surface water response to wildfires. The possibility of discovering useful relationships between hydrological consequences and various geomorphic determinands on seven different semi-arid catchments affected by wildfires, lends this study a special relevance. Furthermore, the hydrological regionalisation that is often carried out due to limited available hydrological data (also the case in the present study with a single flow

measuring station in a subcatchment) and involves the extension in space of flow characteristics (Simmers, 1984; Riggs, 1990) in order to explain the spatial variability of surface runoff, may be assisted by catchment geomorphic characteristics (Clarke, 1977; Vogel and Kroll, 1992).

Hydrological responses to wildfire depend upon the precipitation regime and may be viewed at different temporal scales. In this paper we have analysed the hydrological change aspects related to the changes in total, annual but also mean monthly runoff response. Effects on the frequency and magnitude of peak discharge events were not dealt within this study, as these are widely documented in the related literature (Shakesby and Doerr 2006).

Shakesby and Doerr (2006), in their review on wildfires as hydrological and geomorphic agent, identified research gaps such as in the field of past and potential future hydrological and geomorphic changes resulting from wildfires and concluded that past research focused mainly on post-fire conservation issues or prescribed fires rather than the hydrological impacts of wildfire. Furthermore, hydrological consequences of fire have been widely examined in forest ecosystems, but few studies have examined wildfire impacts on rangeland or shrubland hydrology (Pierson et al. 2001). To this extent, we believe that this study attempts to bridge some of these gaps in the specific literature field of research. Lavabre et al. (1993) mention that there are relatively few studies evaluating the effect on the hydrological response, whereas the ecological and biological impacts have been widely examined, merely reflecting the lack of good quality data in order to compare hydrological regimes before versus after a fire. Moreover, it seems that scientific interest in an area generally starts after the fire (Lavabre et

al., 1993). Further, while there is an extensive documentation on fire impacts in experimental studies with human-controlled small sites, the field of pre-post catchment-scale impact modelling is less developed. Finally, Shakesby and Doerr (2006) indicated that there is more emphasis in the literature on the impact of wildfire on soil erosion by water than on the timing and quantity of runoff and therefore erosion and sedimentation rates analyses were not examined herein.

Study AreaThe study area encompasses a 465 km² largely semi-mountainous low land, located east of Athens, and Ymittos, Penteli and Parnitha mountains, at the prefecture of Attica, Central Greece. The area was initially delineated to 10 catchments, namely: Kato Souli, Lower Marathon (subcatchment below Marathon reservoir), Upper Marathon (subcatchment above Marathon reservoir), Nea Makri, Grammatiko, Rafina, Vranas, Coastal Catchment 1, Coastal Catchment 2 and Coastal Catchment 3 (Figure 1). The study area is characterized by Mediterranean semi-arid climate with mild, wet winters and hot, dry summers, with mean annual temperature around 18 °C and relative humidity 62%. The mean annual precipitation depth for the three hydrological years studied (2006-2009) is 465 mm. Reference evapotranspiration rate is more than 1.5 times the rainfall depth. The low runoff rates and the natural relief do not lead to the formation of significant stream/river networks and river cross-sections, although the catchments' stream network is dense including fifth-order streams according to Strahler (1952) method,. The catchments are therefore drained by streams and ephemeral torrents with little or no water and dry stream beds during the summer, and quick surface runoff leading to localized floods, during storm precipitation events (Diakakis, 2011). The

study area presents a mean elevation of 204 m, highest altitude of 1330 m (Figure 1) and mean slope of 15%. The western part of the study area is semi-mountainous, characterized by steep slopes and rocky areas, in the place of which forest patches existed. The eastern part is more densely populated and characterized by gentler slopes. Lake Marathon, a small-size reservoir, serves as Athens's safety regulating water supply resource, and divides the Upper and Lower Marathon subcatchments. Figure 1: Study area with delineated catchments and Digital Elevation Model. Regional geology presents a complex structure, comprising of many different rock formations. A generalised hydrogeological map was used to distinguish four main geological-hydrogeological units. Flysch, schist, marls and other impermeable or low permeability rocks (up to 7% of the rainfall infiltrates locally, Zacharias et al. 2003) cover more than half (54%) of the study area. Alluvial deposits of moderate to high permeability comprise approximately one third (30%) of the total study area. Older deposits, characterised as of lower to moderate permeability (5-15% of the rainfall infiltrates), cover 9% of the area, while limestones and other carbonaceous rocks of high permeability cover ~7% of the study area and present high infiltration rates (up to 35% of the rainfall infiltrates locally, Zacharias et al. 2003). There are also two main faults extending in a southwest to northeast direction located at the northwest part of the study area. The study area is of great concern and significance in terms of water resources and environmental management. This is merely because a number of human and natural resources in the area are at risk, sometimes leading to water quality and management issues, such as the case of Marathon reservoir, used as Athens

supplementary water supply source. Also the dry arid conditions in the area result in higher risk for wildfires occurrence, as well as more frequent fires. At the same time human activities, such as the expansion of residential areas and particularly the Athens periurban zone, have increased the risk of large and high severity fires. Further, shrublands and coniferous forests in the area have higher potential post-fire runoff and erosion rates than densely vegetated wideleaf forests. In addition,. In recent years, the study area was affected by two wildfires in August 1995 and in August 2009. Before the first wildfire a large part of the central area was mainly covered by a dense pine forest that was almost totally destroyed. Before the second fire in August 2009 the study area had a mixed vegetation cover consisting of shrublands, pasture, and pine forest at the first stages of development (Soulis et al., 2010). Figure 2 presents the complex land uses mosaic before the 2009 wildfires and overlaid the surface extent of burnt land. The study area was dominated by shrublands that were covering one third of the total surface extent, and by agricultural and cultivated land that covered another third. A 20% was covered by coniferous forests and 12% by urban areas and bare land. In August 2009, the wildfires started near Gramatiko village at the north part of the study area and then moved southwards for 5 days leaving behind an area of 146 km² of low value burnt land (approximately one third of the study area). Apart from extended areas of low vegetation (shrubs) and invaluable coniferous forest, the fire damaged properties, infrastructure and agricultural productive fields. Figure 2: Land use map with land uses before 2009 wildfires and burnt areas (superimposed transparent red colour)Table 1 presents the surface extent for each catchment as well as the surface extent

of burnt land within each catchment, as a result of the wildfires. It is evident that burnt areas represent more than 60% within the corresponding catchments in Vranas, Lower Marathon and Grammatiko catchments, which were most affected by the wildfires. Burnt areas represent between 24-25% within the corresponding catchments, of Rafina and Kato Souli catchments, while smaller percentages of burnt areas were observed at Nea Makri (18%) and Upper Marathon (14%) catchments. Coastal Catchment 1, Coastal Catchment 2 and Coastal Catchment 3 are isolated small coastal catchments at the eastern part of the study area that were to a great extent unaffected by the wildfires (~0% burnt land) and are therefore not analysed herein.

Table 1. Surface extent of catchments and burnt land within each catchment

Catchment	within catchment (%)
Vranas	>60%
Lower Marathon	>60%
Grammatiko	>60%
Rafina	24-25%
Kato Souli	24-25%
Nea Makri	18%
Upper Marathon	14%
Coastal Catchment 1	~0%
Coastal Catchment 2	~0%
Coastal Catchment 3	~0%

As a result of the wildfires disaster having an impact on seven catchments with significant portions of natural vegetation burned, questions were raised about the extent that their natural hydrological processes would be affected. Method Hydrological model setup and calibration The modelling framework of choice in this study included the application of MIKE SHE, a physically based, hydrological model, in order to calculate catchments' surface runoff. MIKE SHE is a descendant of the Systeme Hydrologique Europeen, SHE, initially developed by Abbott et al. (1986). MIKE SHE is a physically based, deterministic, distributed hydrological model that has been widely applied in a variety of water resource and water quality problems under diverse climatological and hydrological conditions (Refsgaard, 1997). In this case study, a semi-distributed adaptation of MIKE SHE was defined to describe the processes of overland flow, evapotranspiration (parameters based on land uses

distribution), unsaturated vertical flow (two-layer soil column) and saturated subsurface flow (linear reservoirs approach), while analytical solutions are incorporated to describe interception (Rotter model) and evapotranspiration (Kristensen and Jensen (1975) model) (DHI, 2011). The modelling strategy was to construct a simple model with as few parameters subject to calibration as possible (Refsgaard, 1997). The model cell size selected was 100 m x 100 m, which allowed both for accurate representation of hydrological conditions and acceptable computational time. Precipitation, potential evapotranspiration and pumping time series were imported in MIKE SHE model to represent water inflows/outflows. Measurements of recorded precipitation, relative humidity, wind velocity, solar radiation, vapour pressure, and air temperature were available for three hydrological years, 2006-2009, from six precipitation and seven meteorological gauging stations in the study area. Missing data in precipitation and potential evapotranspiration timeseries were filled in using bilinear interpolation and correlation methods between nearby gauging stations, while the modified Penman-Monteith method was used to calculate daily potential evapotranspiration (Maidment, 1993). Groundwater abstraction timeseries were created based on water demands of municipalities in the area (data from Ministry of Development, 2006). Spatial distribution of precipitation and potential evapotranspiration was created in GIS software (ESRI ArcGIS) using Thiessen polygons for corresponding gauging stations. Spatial variation of geological and soil substrata was obtained through processing of hard-copy 1: 50000 maps produced by the Greek Institute of Geology and Mineral Exploration (IGME) and National Agricultural Research Foundation (Nakos,

1979). The spatial distribution of leaf area index (LAI), root depth (RD) and crop coefficient (Kc) was defined using the LULC map while their temporal variation was derived from literature previous studies (Vázquez and Feyen, 2003; Vázquez et al., 2008). The spatial distribution of overland parameters (e. g. slope, detention storage) was based on the results of the land cover mapping, while appropriate literature values of Manning number were assigned for the different overland flow zones. A simple two-layer unsaturated zone (UZ) model (soil root zone and zone down to the aquifer's top level) was used with the appropriate definition of soil types based on the area's digitised soil map. Soil water content parameter values at saturated conditions, field capacity, field wilting point and infiltration rate were used as calibration parameters for the experimental subcatchment water balance and for the observed hydrograph. The spatial distribution of saturated zone (SZ) was implemented using a digitised geological map of the area. A linear reservoir approach was followed for the saturated zone that involved a slow groundwater component in the baseflow linear reservoir and a relatively faster groundwater flow component in the interflow linear reservoirs. The model was calibrated for the hydrological period 2006-2009 with a calibrated-catchment approach and a manual trial-and-error procedure by altering the calibrated parameters, until the simulated monthly surface runoff at the outlet of Pikermi experimental subcatchment matched closely the observed values (water level gauge at the subcatchment outlet located within the catchment Rafina, Figure 1; NTUA, 2010). Previous studies and/or physical reasoning were used for the definition of the range of each calibration parameter in the model. A standard performance metric, Nash

and Sutcliffe (1970) coefficient of efficiency was selected as the main statistical criterion to evaluate the accuracy of both the magnitude and timing of predicted flows (e. g. Andersen et al., 2001; Beven, 2001; V? squez et al., 2002) and the overall model performance, defined as: (1) where O is the observed flow, \bar{O} is the mean observed flow, and P is the predicted flow. Multi-variable checks were carried out during the calibration procedure to ensure total and annual water balance components values were within the expected literature range for the specific area. Soil hydraulic conductivity, time constants for interflow and baseflow reservoirs and specific yield proved as the most sensitive calibration parameters. Due to lack of stream discharge measurements temporal validation of the model with a split sample test in order to evaluate the robustness of these behavioural sets under a range of hydrological conditions in the experimental subcatchment or any other catchment was not possible. It is hoped that measured data will become available the forthcoming years, so that the model gets validated and its performance improved. After the model was calibrated to a satisfactory level at the experimental subcatchment, the group of behavioural parameter sets i. e. hydrological, land use, soil and hydrogeological parameters was transferred to the ungauged catchments in the study area. The runoff response results were examined for each of the seven catchments and the initial model with land uses of the catchments before the wildfires was compared against the model with land uses of the catchments after the wildfires (including burnt land). For post-fire simulations we modified the spatial distribution of input parameters (LAI, R_d , K_c and Manning's n). Geomorphic, meteorological and hydrological parameters

evaluation of development of topography and drainage networks of the study area can provide some clues to understanding the geomorphic processes and hydrological characteristics of the study area (Bagyaraj and Gurugnanam, 2011), as well as the influence of geomorphic determinands to hydrological response to wildfires. The hydrological, dependent variables that were used in correlation and multiple linear regression analysis were the mean monthly surface runoff Pre, the mean monthly surface runoff Post and the increase of (differenced) mean monthly surface runoff Pre-Post. The meteorological, independent variable that was also used in correlation and multiple linear regression analysis was the mean annual precipitation. An extensive list of 44 geomorphic determinands was considered. The evaluated geomorphic determinands were grouped as linear, areal and shape (or relief) and were then measured and derived in GIS or evaluated with established mathematical equations (Table 1). The geomorphic determinands that were tested for correlation and multiple linear regression and their mathematical expressions are listed at Tables 2-4. The determinands considered for assessing the linear aspects include bifurcation ratio, basin length, and perimeter (Table 2). Table 2: Linear geomorphic determinands at catchment level

Parameter (Units)	Schumm, 1977
No. of stream segments of given order / No. of stream segments of next highest order	The determinands considered for the present study to understand the areal aspects include catchment area and burnt area, drainage density, stream frequency and texture ratio (Table 3).

Table 3: Areal geomorphic determinands of catchments

Parameter (Units)	N1 = Total No of first order streams	Horton, 1945
Total no. of stream segments of all orders / Perimeter	Ratio of number of streams in catchment	

to area of catchment Bassey, 2010 Shape or relief geomorphic aspects of the catchments play an important role in drainage development, surface and sub surface water flow, permeability, landforms development and erosion properties of the terrain. Shape or relief geomorphic determinands used in this study are listed in Table 4. Table 4: Shape or relief geomorphic determinands

Parameter (Units)	Description
Diameter of circle of same area as catchment / Basin length	where A_s = specific catchment area in units of $(m^2 m^{-1})$ = slope gradient (in degrees)
Used to identify the erosive effects of concentrated surface runoff. Predicts net erosion in areas of profile convexity and tangential concavity (flow acceleration and convergence zones) and net deposition in areas of profile concavity (zones of decreasing flow velocity).	
capacity stream-power index average, SPI LSW	where A_s = specific catchment area in units of $(m^2 m^{-1})$ = local slope gradient, measured in degrees
Derived from unit stream power theory and equivalent to the length-slope factor in the Revised Universal Soil Loss Equation in certain cases.	
initiation index average, CIT	where, A_s = specific catchment area $(m^2 m^{-1})$ = slope gradient (in degrees)
Variation of stream-power index used to predict the locations of headwaters of first-order streams (i. e., channel initiation).	

Results and Discussion Geomorphic determinands results A_s as mentioned above an extensive list of 44 linear, areal and shape (or relief) geomorphic determinands was considered. The evaluation of such determinands in GIS or using established mathematical equations led to useful preliminary or indicative results for the assessment of potential relationships between the geomorphic determinands and hydrological characteristics. A small discussion of the results of the most important geomorphic determinands

follows. Bifurcation ratio (R_b) is a very important linear geomorphic parameter that expresses the degree of ramification of the drainage network. The mean R_b (2.78) indicates that the drainage pattern is generally not influenced by geological structures (Strahler 1964), also signifying a high drainage density, low permeability of the terrain and indicating areas with uniform surficial materials where geology is reasonably homogeneous. Only in Lower Marathon catchment bifurcation ratio presents a relatively high value of 5.4 suggesting structural control in the area and low permeability, as well as regions of steeply dipping rock strata, where narrow strike valleys are confined between the ridges (Suresh, 2000). Waugh (1995) noted that the human significance of the bifurcation ratio is that as the ratio is reduced so the risk of flooding within the basin increases.

Moreover, long narrow basins with high bifurcations would be expected to have attenuated flood discharge periods, whereas rotund or moderately elongated basins such as the majority of the study area catchments with low bifurcation ratio would be expected to have sharply peaked flood discharges (Strahler, 1964). Compactness factor (C_c) of the basin is used to express the basin shape, which is indicated by the deviation of the basin area from a circle having an equal area (Gravelius, 1914). Average values for the seven catchments of compactness index of 1.57, circularity index of 0.43, elongation ratio of 0.67 and the shape factor of 0.41, reveal moderately elongated catchments with semi-mountainous relief (Havg: 259 m). Other shape (or relief) geomorphic determinands include the Stream Power Index (SPI) which is a measure of erosive power of flowing water (Wilson and Gallant, 2000). The sediment transport capacity index was derived from unit

stream power theory and is equivalent to the length-slope factor in the Revised Universal Soil Loss Equation in certain circumstances. The Channel Initiation Index (CIT) is used to predict the locations of headwaters of first-order streams (i. e., channel initiation) (Wilson and Gallant, 2000). Tangential and Cross-Sectional curvatures describe how water would converge or diverge as it flows over a point. Total and General curvature are general descriptions of how curved (convex or concave) the landscape is (Jenness, 2011). The thickness ratio is expressed as a ratio of the polygon area versus the area of its minimum bounding square taking a value of 1 for a square. The smaller the value is, the thinner the polygon is. In this study the average thickness ratio for the catchments was 0. 42 supporting a thin rather than rectangular shape of the catchments. The circularity ratio (R_c) (Miller 1953; Strahler 1964) of the present study has an average value of 0. 43 indicating moderate to low relief, and more or less elongated catchments. [12] described the basin of the circularity ratios range 0. 4 to 0. 5 which indicates strongly elongated and highly permeable homogenous geologic materials. According to Waugh (1995), shape of a basin has long been accepted that a circular basin is more likely to have a shorter lag time and a higher peak flow than an elongated basin. Chow (1964) had noted that strongly elongated basins have circularity ratios of between 0. 40 and 0. 50. Hydrological model calibration results Calibration results present satisfactory calibration of MIKE SHE model (Nash-Sutcliffe coefficient of 38% and MAE, RRMSE and BIAS of 0. 01, 0. 52 and 0. 005, respectively). Figure 3: Observed vs simulated mean monthly discharge for hydrological period 2006-2009 at Pikermi experimental subcatchment Hydrological model simulation results Figure 4

presents differenced simulated (Post-Pre) mean monthly surface runoff for the seven catchments. This parameter was calculated when subtracting mean monthly surface runoff on land uses before wildfires from mean monthly surface runoff as a response to the wildfires. Positive deviations show that monthly surface runoff is higher after introducing the land use change of wildfires to the model. Figure 4: Increase of simulated mean monthly surface runoff as a response to wildfires, QPost-QPreMIKE SHE water balance results show that annual surface runoff would increase by 51% on average as a result of the wildfires which is within the expected literature range of 0.09- to 21-fold (e. g. Hoyt and Troxell, 1934; Scott and Van Wyk, 1990; Badia et al., 2008). Correlation and simple linear regression analysis

The results of simple linear regression method for the parameters of increase of mean monthly surface runoff, total surface runoff before and after the wildfires, and burnt area (absolute surface extent) revealed the following strong relationships: $Q_{post-pre} = 0.030 + 0.011 \times BuA$ (1) Where, $Q_{post-pre}$: average increase of monthly surface runoff as a response to wildfires (hm³) BuA : Burnt area (km²) $Q_{totPost} = 1.32 \times Q_{totPre} + 2.58$ (2) Where, $Q_{totPost}$: Total surface runoff after the wildfires (hm³) Q_{totPre} : Total surface runoff before the wildfires (hm³)

Correlation and multiple linear regression analysis A correlation and multiple linear regression analysis was also carried out in order to investigate relationships between the average increase of (or differenced) monthly surface runoff (expressed in absolute values) before-after the wildfires and various geomorphic catchment determinands. The correlation results between the average increase of monthly surface runoff and geomorphic determinands presented a strong

positive correlation (defined above 0.7) for the determinands of burnt area, compactness ratio, bifurcation ratio, stream-power Index and channel initiation index (Table 6). The correlation of the specific geomorphic determinands with the increase of surface runoff as a response to wildfires indicates the accelerating influence these determinands have to mean monthly surface runoff. This means that if a catchment presents high values of these geomorphic determinands, then after the occurrence of wildfires it is likely that the catchment will also present large increase of mean monthly surface runoff. Furthermore, the increase of mean monthly surface runoff is clearly influenced by high values of specific geomorphic determinands, which are themselves directly related to sharply peaked flow discharges and soil erosion. Table 6. Strong statistical Pearson correlation between increase of mean monthly surface runoff as a response to wildfires and geomorphic determinands

Parameter	The correlation results between average monthly surface runoff before the wildfires and linear, areal and shape geomorphic determinands presented a strong positive correlation (defined above 0.7) for the geomorphic determinands of catchment area, mean elevation, perimeter, basin length, basin width average, basin width 2 and mean annual precipitation (Table 7 and Figures 7-9). The correlation results between average monthly surface runoff after the wildfires and linear, areal and shape geomorphic determinands presented a strong positive correlation (defined above 0.7) for the geomorphic determinands of catchment area, mean elevation, perimeter, basin length, basin width 2, compactness ratio and mean annual precipitation (Table 7 and Figures 7-9). The positive correlation of geomorphic determinands with the mean monthly surface
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runoff (either before or after the wildfires) indicates the accelerating influence these determinands have to mean monthly surface runoff. This means that if a catchment presents high values of these geomorphic determinands, then after the occurrence of wildfires it is likely that the catchment will also present high values of mean monthly surface runoff. Figure 7 Positive correlations between mean monthly surface runoff before the wildfires, after the wildfires and linear geomorphic parameters. Figure 8 Positive correlations between mean monthly surface runoff before the wildfires, after the wildfires and areal geomorphic determinands. Figure 9 Positive correlations between mean monthly surface runoff before the wildfires, after the wildfires and shape (or relief) geomorphic determinands. A strong negative correlation between average monthly surface runoff before the wildfires and geomorphic parameters were observed for thickness ratio, cross-sectional curvature, tangential curvature, sediment transport capacity index and basin circularity (Table 7 and Figures 10-11). A strong negative correlation between average monthly surface runoff after the wildfires and geomorphic parameters were observed for thickness ratio, basin circularity, cross-sectional curvature, tangential curvature and sediment transport capacity index (Table 7 and Figures 10-11). The negative correlation of geomorphic determinands with the mean monthly surface runoff (either before or after the wildfires) indicates the decelerating influence these determinands have to mean monthly surface runoff. This means that if a catchment presents high values of these geomorphic determinands, then after the occurrence of wildfires it is likely that the catchment will present low values of mean monthly surface runoff. Figure 10

Negative correlations between mean monthly surface runoff before the wildfires, after the wildfires and areal geomorphic determinands. Figure 11 Negative correlations between mean monthly surface runoff before the wildfires, after the wildfires and shape (or relief) geomorphic determinands. Correlation results showed that no significant difference between strong Pearson correlation coefficients of average monthly surface runoff before vs after the wildfires was evident for the linear and areal geomorphic determinands. However, a change of more than 10% of strong Pearson correlation coefficients for the mean monthly surface runoff before vs after the wildfires was found for the group of strongly correlated shape/relief geomorphic determinands of compactness ratio, stream power index, channel initiation index and basin circularity, indicating relative influence of specific determinands to the increase of mean monthly surface runoff as a response to wildfires. Table 7. Strong positive and negative statistical Pearson correlation between average monthly surface runoff before and after the wildfires and geomorphic determinands

Type of parameter

06 The strongest (positive and negative) correlations between the increase of mean monthly surface runoff as a response to the wildfires, and the geomorphic determinands were used to identify multiple linear regression model relationships. The backward multiple linear regression statistical analysis (with the statistical software package SPSS) identified a model-equation that gave the best prediction of the average increase of mean monthly surface runoff as a response to wildfires. The significance level for a variable to stay in a tested linear regression model was 0. 10. The equation below relates the increase of mean monthly surface runoff (as a response to wildfires) and the

determinands of burnt area (absolute values) and channel initiation index:

$Q_{\text{post-pre}} = 0.024 + 0.009 \times \text{BuA} + 0.025 \times \text{CIT}$ (3) Where, $Q_{\text{post-pre}}$:

average increase of monthly surface runoff as a response to wildfires

(hm^3) BuA: Burnt area (km^2) CIT: Channel initiation index At significance level

0.05 further elimination of the Channel initiation index parameter results in

the previously discussed simple linear regression equation (Equation 1

above) relating the increase of mean monthly surface runoff and burnt area.

The results of backward multiple linear regression for the tested models are

presented at Table 8. Table 8. Results of multiple linear regression analysis:

independent association of hydrological (increase of mean monthly surface

runoff) and geomorphic factors Model Additional statistical analysis to

investigate the relationships between average increase of monthly surface

runoff as a response to wildfires and the squares, as well as square roots, of

geomorphic determinands was also carried out but did not reveal

significantly different correlation coefficients and is therefore not discussed

herein. The strongest (positive and negative) correlations between mean

monthly surface runoff before the wildfires and the geomorphic

determinands were used to identify linear regression relationships. The

models obtained from the statistical analysis of backward multiple linear

regression (with statistics software package SPSS) relate the average

increase of monthly surface runoff before the wildfires and the geomorphic

determinands of thickness ratio, mean basin width and mean annual

precipitation. The significance level for a variable to stay in a tested linear

regression model was 0.10. $Q_{\text{pre}} = -51.3 + 0.004 \times \text{B1} + 0.099 \times \text{MAP}$

(4) At significance level 0.05 further elimination of the Mean basin width

parameter results in a simple linear regression model relating mean monthly surface runoff before the wildfires and mean annual precipitation (equation 5). $Q_{pre} = -50.6 + 0.133 \times MAP$ (5) Where, Q_{pre} : mean monthly surface runoff before the wildfires
B1: Basin width average (m)
MAP: Mean annual precipitation (mm)
The results of backward multiple linear regression for the tested models are presented at Table 9. Table 9. Results of multiple linear regression analysis: independent association of hydrological (mean monthly surface runoff before the wildfires), meteorological and geomorphic factors
Model
The strongest (positive and negative) correlations between mean monthly surface runoff after the wildfires and the geomorphic determinands were used to identify linear regression relationships. The model obtained from the statistical analysis of backward multiple linear regression (with statistics software package SPSS) relate the average increase of monthly surface runoff after the wildfires and the parameters of perimeter and mean annual precipitation. The significance level for a variable to stay in a tested linear regression model was 0.05. $Q_{post} = 45.0 + 0.46 \times P + 0.097 \times MAP$ (6) Where, Q_{post} : mean monthly surface runoff after the wildfires
P: Perimeter (km)
MAP: Mean annual precipitation (mm)
The results of backward multiple linear regression for the two tested models are presented at Table 10. Table 10. Results of multiple linear regression analysis: independent association of hydrological (mean monthly surface runoff after the wildfires), meteorological and geomorphic factors
Model
Such simple and multiple linear regression relationships may be used in semi-arid areas that present similar land use, soil and geological characteristics, i. e. with significant areas of shrublands and large extent of impermeable soils

and geological units (flysch, schists and marls). However, the regression equations should be applied with care and only to catchments with geomorphic characteristics within the ranges used in this study.

CONCLUSIONThe wildfires at Northeast Attiki in August 2009 destroyed most of the mixed vegetation cover, approximately one third of the study area, mainly consisting of shrublands, pasture and pine forests. Using valuable pre-fires data this paper aimed at analysing and predicting the first three years hydrological response (total, annual and mean monthly runoff) of seven semi-arid, shrubland dominated catchments to land use changes of deforestation at catchment scale, as a consequence of wildfires. The possibility of discovering useful relationships between hydrological consequences and various geomorphic determinands on seven different semi-arid catchments affected by wildfires, lends this study a special relevance. We believe that this effort attempts to bridge some gaps in the literature field of wildfires as hydrological and geomorphic agent and their impacts on semi-arid, shrubland-dominated hydrology. The modelling framework followed in this study involved the simulation of a hydrological model, MIKE SHE. In this case study, a semi-distributed adaptation of MIKE SHE with a linear reservoir approach for the saturated subsurface flow was followed. Calibration model results were satisfactory with a coefficient of efficiency although model performance can be improved further by increasing the flow gauging stations density in the study area and by reducing the uncertainties associated with precipitation gauges and rainfall data input to the model. Simulation of the model in the study area has shown that total (three years) and annual surface runoff would increase by 51% on

average as a result of the wildfires. Such runoff response is comparable with various similar cases of monitored sites where observed annual runoff after the wildfires would increase significantly from 0.09- to 21-fold (e. g. Moody and Martin, 2001; Badia et al., 2008). An extensive list of 44 linear, areal and shape geomorphic determinands was derived using GIS or established mathematical equations to assess potential relationships between any of these, burnt land, meteorological and hydrological characteristics (mean monthly surface runoff before, and after the wildfires and increase of mean monthly surface runoff as a response to wildfires). Values of specific geomorphic determinands indicate moderately elongated catchments with sharply peaked flood discharges. The correlation results between the average increase of monthly surface runoff and geomorphic determinands presented a strong positive correlation (defined above 0.7) for the determinands of burnt area, compactness ratio, bifurcation ratio, stream-power Index and channel initiation index. The increase of mean monthly surface runoff is clearly influenced by high values of specific geomorphic determinands, which are themselves directly related to sharply peaked flow discharges and soil erosion. The positive correlation of geomorphic determinands of catchment area, mean elevation, perimeter, basin length, basin width average, basin width 2, compactness ratio and mean annual precipitation with the mean monthly surface runoff (either before or after the wildfires) indicates the accelerating influence these determinands have to mean monthly surface runoff, in contrast to the decelerating influence of negatively correlated geomorphic determinands of thickness ratio, cross-sectional curvature, tangential curvature, sediment transport capacity

stream-power index and basin circularity. No significant difference between strong Pearson correlation coefficients of mean monthly surface runoff before vs after the wildfires was evident for linear and areal geomorphic determinands. However, a change of more than 10% of strong Pearson correlation coefficients for the mean monthly surface runoff before vs after the wildfires was found for the group of strongly correlated shape/relief geomorphic determinands of compactness ratio, stream power index, channel initiation index and basin circularity, indicating relative influence of specific determinands to the increase of mean monthly surface runoff as a response to wildfires. The strongest (positive and negative) correlations between mean monthly surface runoff before and after the wildfires, the increase of mean monthly surface runoff as a response to the wildfires and the extended set of geomorphic determinands were used to identify multiple linear regression model relationships. We conducted a backward multiple linear regression statistical analysis (with the statistical software package SPSS) that identified several models-equations giving the best prediction of hydrological parameters as a response to wildfires. Particularly, this paper has shown that burnt area and channel initiation index are the main explanatory variables for the increase of mean monthly surface runoff as a response to wildfires. It is concluded and anticipated that some of the simple and multiple linear regression relationships that were identified in this study may be used in semi-arid areas that present similar land use, soil and geological characteristics, i. e. with significant areas of shrublands and large extent of impermeable soils and geological units (flysch, schists and marls). However, the regression equations should be applied with care and only to

catchments with geomorphic characteristics within the ranges used in this study. Particularly, the aforementioned results and relationships could be of considerable use for researchers and land managers in the future in order to predict the magnitude of runoff after wildfires in other semi-arid catchments with similar land use, soil and geological characteristics, as the underlying processes will vary in rates and magnitude but are generally applicable to other burned areas. Furthermore, the modelling approach demonstrated here using the hydrological model MIKE SHE, correlation, simple and multiple statistical regression analysis indicates the possibilities and potential benefits of adopting such an integrated approach, while it provides a means of prioritizing catchment screening with respect to post-fire remediation and management. Extrapolating the conclusion, we believe that this combined modelling-regression methodology would be valuable to other semi-arid shrubland areas, while providing a simple way for a comprehensive assessment of post-fire hydrological response over large regions based on readily available meteorological and geomorphic information. In short, the present study can be thought of as a simultaneous modelling assessment of multiple semi-arid, shrubland-dominated catchments hydrologic response to wildfires using precipitation and catchment geomorphic parameters, the first few years following wildfires. The probability of wildfires as well their frequency and intensity are expected to increase in the forthcoming decades due to anticipated climate changes as well as land management practices. (Lenihan et al., 1998; Swetnam et al., 1999; Easterling et al., 2000). Wildfires can produce dramatic changes in hydrologic responses (e. g. surface runoff) posing risk to human life, infrastructure, and the environment (Beeson et al.,

2001) and therefore, it will be increasingly important to be able to assess rapidly and effectively pre-post wildfires changes and relationships in hydrology and to apply these assessments to evaluate such risks. As part of a future work it would be interesting to examine these relationships to another semi-arid area, with a larger group of catchments-samples.