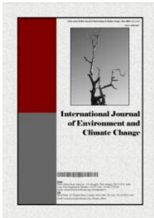

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# A GIS Based Methodology to Obtain the Hydrological Response to Storm Events of Small Coastal Basins, Prone to Flash Flooding

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***Author's contribution***

*The sole author designed, analyzed, interpreted and prepared the manuscript.*

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## ABSTRACT

The present study aims to investigate the hydrological response of small coastal watersheds to storm events. Areas around the Mediterranean Sea are usually characterized by streams with intermittent flows and flash floods are common. Firstly, we analyze the geomorphological, soil and land cover characteristics of the watershed in order to estimate their effect on surface runoff. Furthermore, the rainfall characteristics of an extreme event that caused flash flooding in the past are analyzed. By combining these factors, we are able to predict the response of this basin to severe storm events. The study area is located in the island of Samos, in Eastern Greece, where flash flood events are usual and pose a risk to areas located around rivers. In this area runoff is intermittent, occurring mainly during storm events and there is a lack of discharge or other instrumental measurements. By applying the SCS-CN method we estimate the response of two of the largest watersheds in Samos Island, through the construction of a Synthetic Unit Hydrograph (SUH). Firstly, we examined the record of historic floods in the area, selecting a large flash flood event (November 2001) and then obtained the daily rainfall data, which are used by the SCS method for the calculations. We applied the SCS methodology in order to estimate various parameters (e.g. lag time, time of concentration, maximum discharge), which also required the calculation of the Curve Number (CN) for each watershed. During this event (136 mm rainfall), we

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calculated a direct runoff (excess rainfall) of 44%-48% for these watersheds. This methodology can be particularly useful in simulating the hydrological response of small Mediterranean watersheds and to introduce better strategies for the management of the whole drainage basin.

*Keywords: G.I.S; Hydrology; flash floods; curve number; geomorphology; SCS-CN.*

## 1. INTRODUCTION

One of the most frequent natural disaster around the world is flooding, which occurs when water (from the sea, rivers, or lakes) covers a part of the land that is normally dry. Common types of floods are river floods, flash floods and coastal floods [1] and this research focuses on flash floods, mostly occurring during storm events, in small ungauged watersheds (<1000 km$^2$). In the southern part of Europe, where small mountainous watersheds are prevalent [2], flash flood events occur repeatedly and cause significant damages in infrastructure and/or loss of life [3]. These areas usually demonstrate complex geomorphological patterns and short response times, to rainfall, of a few hours, thus the accurate prediction of a flash flood event is a difficult task, that is yet to be solved by science [4].

While torrential rainfall remains the main reason behind the occurrence of flash floods, several other factors affect the response of small drainage basins to rainfall, i.e.: (a) lithology, (b) geomorphology, (c) land use and (d) the characteristics of precipitation [5]. Lithological and soil properties, in combination with vegetation define the infiltration capacity of the ground during a storm event; the later acting also as a retarding factor to surface runoff. The geomorphology of the drainage basin affects the time of concentration and the lag time of a watershed which plays a significant role in the estimation of its' flash flood potential [6],[7]. The duration and intensity of the precipitation determines the amount of excess rainfall and as a result determines the direct flow of water.

An accurate method for estimating peak discharge and runoff volume in ungauged catchments can improve management plans of a watershed regarding its' water resources through various ways: ecosystem equilibrium, stormwater management, water quality, flash flood risk mitigation [8].The use of the unit hydrograph for estimating storm runoff [9] was the first tool that proved effective in the determination of the complete shape of the hydrograph, in addition to peak discharge that is very important for the determination of flood risk. This method is still used in hydrologic analysis, but the lack of actual data (discharge and/or precipitation), in many areas around the world, gave birth to the synthetic unit hydrograph (SUH). Through the SUH the runoff characteristics of a watershed can be approximated based on widely available data that describe the watershed [10-15]. One of the most common SUH methods is the SCS method, which is based on the geomorphological characteristics of the watershed (topography, flow length), in addition to soil hydrological behavior, antecedent moisture conditions and the precipitation during a storm event.

The aim of this study is to investigate the hydrological response of small coastal watersheds to extreme storm events, where flash flood events are frequent, typically in areas with a Mediterranean climate that have a rich history of flash flooding.

The aim of this study is to understand the hydrologic behavior of flash flood prone drainage basins in small coastal watersheds in areas characterized by a temperate Mediterranean climate through G.I.S. analysis of the hydrological characteristics of these watersheds. Through the analysis of various data (geomorphological variables, land use/land cover, soil hydrological behavior, rainfall characteristics and antecedent moisture conditions) through GIS tools and the SCS method we estimate the hydrological response of two watersheds in Samos island, Greece.

### 1.1 Study Area

In the eastern part of the Mediterranean Sea, between Greece and Turkey, there are numerous islands, most of which belong to Greece. Samos Island, one of the largest islands in this area, is located in the eastern part of the Aegean Sea (between longitudes 26° 33' 36"E and 27° 3' 36"E and latitudes 37° 48' 36"N and 37° 38' 24"N). The geomorphology of the island is characterized by two main mountainous areas (Ambelos Mt. in the central part and Kerketeas Mt. in the western part) and two geomorphological depressions, in its' central part. Lithology varies greatly in this area and consists mainly of marbles, schists, Neogene and Quaternary depositions [16-18]. The climate of Samos is characterized by dry summers and mild wet winters, with an average precipitation of ~676 mm/year [19] and an average annual temperature of ~19°C. Small watersheds are typical in the mountainous areas, while larger watersheds are found along the two Neogene basins of the islands. The rivers are ephemeral: during summer they are completely dry in most of their drainage length, but during storm events water discharge increases rapidly, eroding the banks of the rivers and transferring a large volume of sediments to the outlet. Morphology is steep (~37% average slope) but in the central part there are large flat areas with well-developed river network [20].

Rivers 'Fourniotiko' and 'Megalo Rema' are situated in the NW part of the island, near the town of Karlovasi, draining two of the largest watersheds of the island (~ 46 $Km^2$ and 25 $Km^2$ respectively). 'Fourniotiko' river originates from the mountain "Ambelos" which has a maximum altitude of 1063m, mainly consisting of schists and having a thick forest cover in most of its part. On the contrary, 'Megalo Rema' drains the western cliffs of Kerketeas mountain (~1400m), which has very steep slopes, consists mainly of marbles and vegetation is scarce. On the lower parts of these two rivers, flood plains are formed, which are heavily affected by human interventions. Flood events have occurred in the past in this area causing large damages in the city of Karlovasi and nearby infrastructure. The largest flood events, in the recent history of the area, took place on November 2001, when the island was declared in a state of emergency. We apply the SCS-CN for this specific flood occurrence to estimate the hydrologic response of both watersheds to this extreme storm event.

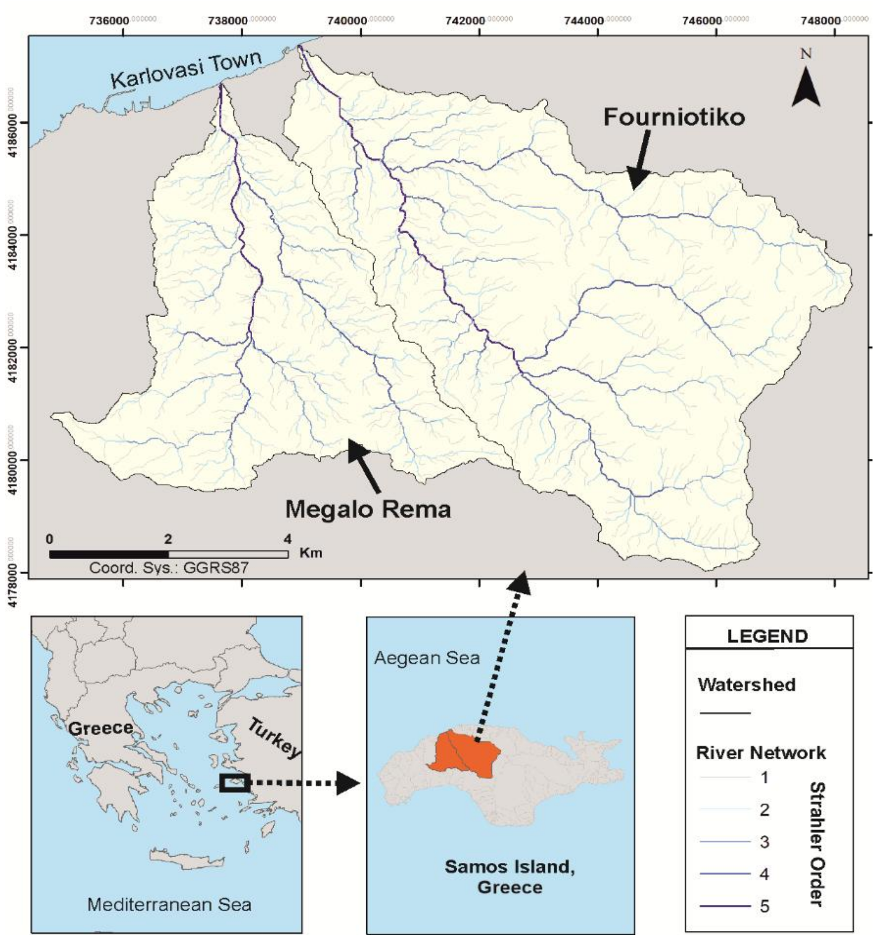


**Fig. 1. The island of Samos, Greece and the drainage basins of rivers (a) 'Fourniotiko' and (b) 'Megalo Rema' in NW Samos. The river network was classified in 5 classes [21]**

## 2. METHODOLOGY

### 2.1 Materials

To estimate the hydrological response of the two watersheds to an extreme rainfall event a series of data were collected and analyzed through G.I.S. techniques. To describe the geomorphological conditions of the study area a detailed Digital Elevation Model (DEM) was used, having a grid resolution of 5 m × 5 m (Kotinas, 2020). The DEM was processed through ARCGIS PRO and SAGA GIS software (creating a slope map, a flow direction map and flow accumulation map for the study area) to calculate the catchment area and the river network in the two watersheds. The main topographic variables (e.g. slope, catchment area, river network, hydraulic length and average slope of the watershed) were obtained through G.I.S for each watershed and the stream order information was assigned to various parts of the river network, after applying the ordering system developed by Strahler [21]. To determine the hydrologic soil group in the study area we used the 'HYSOGs250m' dataset [22], which separates soils in four main categories depending on their runoff potential (groups HSG-A to HSG-D). For the land use the latest version of Corine Land Cover dataset was acquired (CLC2018; [23], which has a spatial accuracy of around 100m and separates land uses to 44 groups. Daily rainfall data were collected from the Hellenic National Meteorological Service, from the 1st November 2001 to 6th December 2001, including the extreme storm event of the 29th of November 2001, where precipitation exceeded 135 mm during 24 hours in the station that is located in the international airport of Samos, and there are reports that it exceeded 350mm in mountainous areas.

### 2.2 Methods

In the study area we apply the SCS method [24] to estimate total runoff based on the watershed and rainfall characteristics. This method includes a series of steps that need to be carried out, by analyzing the data that were collected. Firstly, we analyze the available rainfall data to calculate the total rainfall during the storm event, and also the 5-day antecedent moisture conditions. The AMC prior to a storm event is divided into three levels: dry (AMC-I), average (AMC-II), and wet (AMC-III). This adjustment of the CN is based on the five-day antecedent moisture conditions (total rainfall for 5 days before the main storm event), improves the accuracy of the SCS method and is calculated based on specific tables that are part of the SCS method [24], [25].

#### 2.2.1 SCS Method: Direct runoff

A general form of the SCS-CN model is expressed through the equation [24]:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{1}$$

where Q is direct runoff (mm), P is total precipitation for the storm event (mm), $I_a$ is initial abstraction (mm) and S is the potential retention of the watershed (mm).

The initial abstraction represents the delay between the start of precipitation and the observation of surface runoff, i.e. there is an initial abstract of rainfall for which no runoff is observed (Ia). Initial abstraction is always less than the potential retention of the watershed (storage or evapotranspiration) and can be expressed as:

$$I_a = \lambda S \tag{2}$$

where $0 \leq \lambda \leq 0.3$ is the initial abstraction coefficient (dimensionless; [26] with a usual (empirical) value of:

$$\lambda = 0.2 \tag{3}$$

As a result, through the integration of equations (1), (2) and (3) direct runoff (or excess rainfall) can be calculated through the equation:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{4}$$

To calculate the potential maximum retention the SCS method uses an empirical equation which is based on the curve number (CN):

$$S = \frac{1000}{CN} - 10 \tag{5}$$

#### 2.2.2 SCS Method: Curve number

The Curve Number (CN) depends on the soil type, land cover/land use, hydrological conditions, and antecedent moisture condition (AMC) and was calculated through G.I.S., after assigning to each grid cell, through the spatial analysis of the available data, values for the hydrologic soil group and land cover. By using bibliographical data [24] we assign a value to each cell, representing the Curve Number and then we adjust the calculated CN for the Andescendent Moisture Conditions. Finally, through G.I.S. we obtain a weighted curve number for the whole watershed (also known as the composite curve number), representing the AMC-II conditions. To adjust the CN for other (dry or wet) conditions we apply the formulas:

$CN(I) = \frac{4.2CN(II)}{10-0.058CN(II)}$ or $CN(III) = \frac{23CN(II)}{10+0.13CN(II)}$

### 2.2.3 SCS-CN: Main variables of the UH

Through the SCS method the basic characteristics of a unit hydrograph can be calculated which can be used to estimate the hydrological response of the watershed to an extreme storm event.

Time of concentration ($T_c$) of a watershed is the time it takes for water to travel from the hydrologically most distant point of the watershed to the outlet, and is correlated to lag time ($T_L$) through the following equation:

$$T_c = 5/3T_L \tag{6}$$

The lag time ($T_L$) expresses the difference in time (hours) between the center of the total volume of rainfall excess to peak discharge and can be estimated empirically by using the composite curve number that was calculated through G.I.S. [27], taking into account also the hydraulic length of the watershed (L: m) the average slope of the watershed (Y: m/m):

$$t_L = \frac{L^{0.8}(2540-22.86CN)^{0.7}}{14104CN^{0.7}Y^{0.5}} \tag{7}$$

Peak discharge of the watershed (measured in the outlet), per one cm of excess rainfall, can be estimated through the application of the empirical equation [27], that combines the area of the watershed (A: $km^2$) and the time to peak discharge ($T_p$):

$$Q_p = 2.08\frac{A}{T_p} \tag{8}$$

Time to peak ($T_p$) represents the time it takes (hours), after surface runoff initiates, for water discharge to reach its maximum value and can be calculated using the duration of rainfall excess in hours (SCS recommends $T_R = 0.1333T_C$) and $T_L$:

$$T_p = \frac{T_R}{2} + T_L \tag{9}$$

The duration of the flood event can be estimated through the calculation of the time of base of the unit hydrograph, i.e. the time that surface runoff can be observed in the study area and is the sum of $T_p$ and $T_L$. It can be estimated as:

$$T_b = 2.67T_p \tag{10}$$

## 3. RESULTS AND DISCUSSION

The daily data were imported to MATLAB and a time series graph was constructed. Firstly, we analyzed through MATLAB the daily rainfall data, starting from the 1st of November 2001 and ending in the first week of December. We observe that during November, the evolution of the time series is characterized by repeated peaks. Average rainfall for November was ~15 mm, while total monthly rainfall was more than 440 mm (more than 70% of the yearly precipitation in this area). On the 29th of November, an extreme event of 136 mm total rainfall occurred (Fig. 2), causing flash floods in many watersheds around the island. By analyzing the 5-days preceding the storm event we calculate that the total precipitation during this period was 26.4 mm (AMC-II conditions).

As described in the methodology through G.I.S. we calculated the Curve Number for each grid cell of the study area (Fig. 3) and then we calculated the composite CN(II) number for each watershed: (a) 73.1 for ‘Fourniotiko’ and (b) 75.6 for ‘Megalo Rema’. Soil group of type HSG-C (less than 50% sand, 20-40% clay, high runoff potential) for the whole area, after examining the hydrologic soil group dataset (Ross,2018) in a G.I.S. environment. As expected, the forest – covered watershed of Fourniotiko river demonstrates lower CN values indicating higher infiltration potential and lower discharge of surface water.

The hydraulic length and the average slope of the watersheds were calculated through SAGA GIS: (a) the watershed of ‘Fourniotiko’ has a hydraulic length of ~ 13 km and an average slope of 0.38 m/m and (b) the watershed of ‘Megalo Rema’ a hydraulic length of 9.3 km and an average slope of 0.30 m/m.

After the analysis of the rainfall data, the calculation of the composite CN for each watershed and the calculation of the hydraulic length and slope we proceed calculate the basic characteristics of the unit hydrograph according to the SCS method (equations 1 to 10). The results of our analysis are presented in Table 1 for each watershed.

We observe that 'Fourniotiko' river watershed is predicted to have longer lag time (1.2 hours), time of concetration (2.1 hours), duration of rainfall excess (0.28 hours), time to peak (1.4 hours) and base time (3.8 hours) than 'Megalo Rema' watershed which demonstrates relatively lower times. Peak discharge per 1cm of effective rainfall is significantly higher in the case of 'Fourniotiko' river (66.8 $m^3$/s), while 'Megalo Rema' has a peak discharge of ~ 44 $m^3$/s. All of these differences can be mainly attributed to the larger area that is drained by 'Fourniotiko river'. Direct runoff (or effective rainfall) is higher in the case of 'Megalo Rema', mainly due to its land cover properties, and therefore peak discharge is high when compared to the total area that is drained by this particular river network.

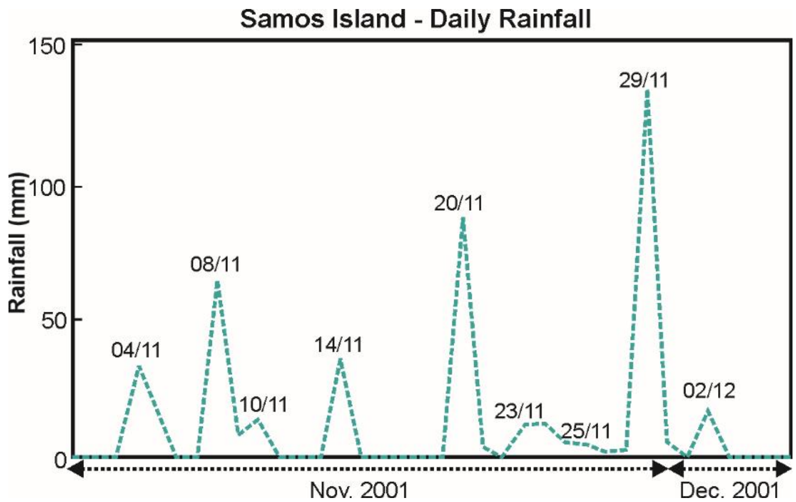


**Fig. 2. Daily Rainfall on Samos Island preceding and following the extreme event of 29th November 2001**

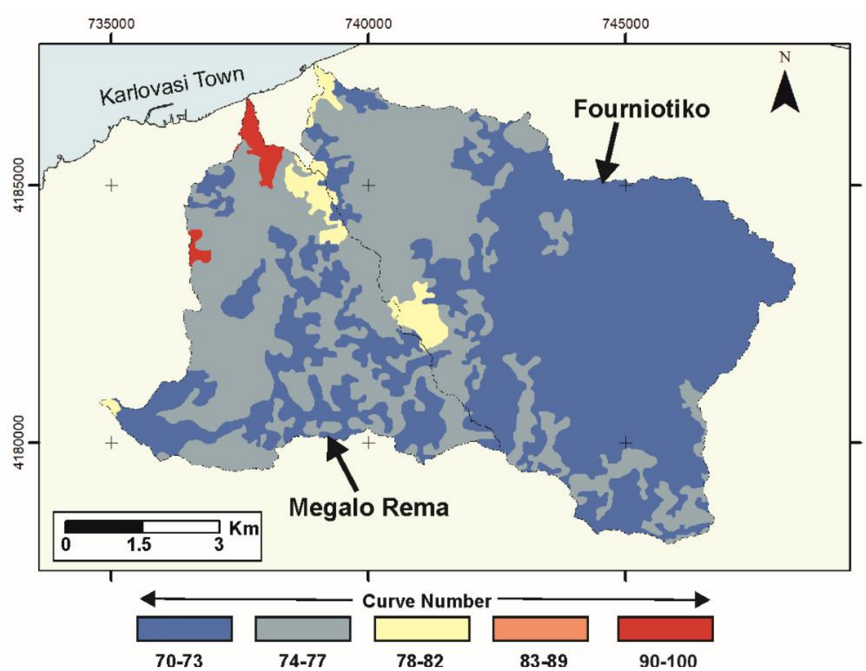


**Fig. 3. Daily Rainfall on Samos Island preceding and following the extreme event of 29th November 2001**

**Table 1. Hydrological Response of the two watersheds to a storm event**

| Parameter | Fourniotiko | Megalo Rema |
|---|---|---|
| Hydraulic length (km) | 13.06 | 9.3 |
| Slope (m/m) | 0.38 | 0.30 |
| Composite CN (II) | 73.09 | 75.57 |
| Potential maximum Retention: S | 3.68 | 3.23 |
| Direct Runoff: Q (mm) | 59.9 | 65.5 |
| Lag time: $T_L$ | 1.28 | 1.02 |
| Time of Concentration: $T_c$ | 2.14 | 1.70 |
| Duration of Rainfall Excess: $T_R$ | 0.28 | 0.23 |
| Time to peak: $T_p$ | 1.43 | 1.17 |
| Base time: $T_{base}$ | 3.82 | 3.13 |
| Peak discharge: $Q_p$ ($m^3$/s) | 66.82 | 44.03 |

## 4. CONCLUSIONS

The spatial and time distribution of rainfall in combination with the drainage basin characteristics control the hydrological response of a watershed to rainfall.

During an extreme storm event like that of the year 2001, where Antecedent Moisture Conditions are moderate, a significant amount of total rainfall is expressed as direct runoff (or excess rainfall). In the case of ‘Imvrasos’ river ~44% of the total rainfall (59.9 mm) is expressed is direct flow while in the case of ‘Megalo Rema’, where infiltration rate is lower, ~48% of total rainfall flows directly though river channels. If AMC were wet, then this percentage would be significantly higher (e.g. for the case of ‘Imvrasos’ river ~70%), resulting in higher peak discharge and an increased flash flood risk.

The peak flow for ‘Imvrasos’ river is calculated to be more than 66 $m^3$/s per 1 cm of effective rainfall, which is observed about 1.5 hours after the peak of the storm event. The time of concentration is about 2.1 hours. For the case of ‘Megalo Rema’ peak flow is estimated to ~44 $m^3$/s per 1 cm of effective rainfall, which is observed about 1.2 hours after the peak of the storm event and the time of concentration is about 1.7 hours. Excess rainfall is ~ 10% higher (more than 65 mm) in the case of ‘Megalo Rema’, and as a result the difference of total discharge between the two watersheds is expected to be relatively low, especially if we consider the area difference and the peak discharge rate.

The watershed of ‘Megalo Rema’ demonstrates significantly shorter hydrograph variables: flood risk is expected to be higher than in the case of ‘Imvrasos’ even during less intense storm events of shorter duration, but both watersheds demonstrate an extremely high potential of flash flooding during storm events that have the characteristics of the storm event of the year 2001. This study provides a dynamic tool, that can be easily adjusted for different rainfall characteristics predicting the response of these watersheds to storm rainfall events and can provide a useful way of predicting flash flood potential in small coastal watersheds. Based on this tool better strategies for the management of the drainage basin can be implemented, focusing mainly to land uses and main channel peak discharge capacity.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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