PhD Cand. Kotinas V., Prof. Gournelos T.
National and Kapodistrian University of Athens
vkotinas@geol.uoa.gr

A GIS based Morphometric Analysis on Areas Prone to Flash Floods. An Example from the Island of Samos, Greece.

Abstract

Morphometric analysis is very important for the investigation of drainage basin of flood risk in areas where flash floods are frequent. Geographic Information Systems give us the ability to study and correlate the morphometric variables more accurately and efficiently, thus allowing the creation of better natural hazard maps, that can help decision makers to plan ahead and reduce the impact of these events. The correlation between morphometric parameters is examined by using statistical analysis and the results help us in estimating the flash flood risk. The aim of this paper is to analyze various morphometric characteristics in a small drainage basin related to flash flood events. The study area is located in the island of Samos, in Eastern Greece, where such flood events are usual and pose a risk to the nearby town of Karlovasi. For this purpose, the basin is divided into several sub-basins and a series of morphometric indexes are calculated and evaluated through statistical procedures and using fuzzy sets, in order to locate the sub basins that have the highest contribution to flash floods.
Keywords: Geomorphology, G.I.S, Hydrology, Flood Risk, Flash Floods.

Introduction

Flash flooding is one of the most common natural disasters in southern Europe causing extended damages and loss of human life (Gaume et al, 2009). Increase of population and infrastructure near rivers, in combination with more frequent extreme rainfall events, caused by climate change, makes flood events more intense and recurrent (Westra et al., 2014).
Drainage pattern, geometry and density of a river system are controlled by climate, lithology and topography (Frissel et al., 1986). A morphometric analysis is useful for the identification and further understanding of the features of a catchment with respect to floods. Detailed morphometric analysis gives information about basin evolution, which is a result of the three controlling factors and provides quantitative characteristics of a drainage network.
Morphometric parameters like drainage density, stream magnitude, relief ratio and stream slope are practical measures of flood potential in small (<150km^2) drainage basins (Patton & Baker, 1976; Costa, 1987). Drainage basins can be prioritized through morphometric analysis for their potential of flooding, in order to create better flood risk assessment and management plans.
The aim of this study is to understand the hydrologic behavior of a flash flood prone drainage basin in Samos Island, in Eastern Greece, through the use of G.I.S. The relative contribution to flood risk of individual sub-basins is identified, by carefully selecting and combining various morphometric parameters. This study can help local authorities and decision makers to improve their management plans on an area, where flash floods are frequent.

Study Area

Samos Island is one of the largest islands of Greece and is located on the Eastern border of Greece, very close to Turkey. It is elongated, with mountainous relief and two main geomorphological depressions in the central part of the island (Karlovasi and Mytilinii basin). The geology of Samos Island consists of a complicated substratum, with metamorphic rocks, a non metamorphic unit and neogene and quaternary depositions (Theodoropoulos, 1979; Papanikolaou, 1979; Mezger & Okrusch, 1985). The two neotectonic basins (depressions) of the island consist of marls, conglomerates, limestone and tuffs (Stamatakis, 1989). Recent sediments, which are mainly alluvial, overlay the pre-neogene and neogene formations. Climate is mild and wet in winter and dry in summer, with an average precipitation of 698,6 mm/year. The streams are ephemeral, and during most time of the year, they are dry in most of drainage length.

Flash flooding and erosion are common problems in large parts of the island. In the past we have treated the erosional problem of Samos using fuzzy sets (Gournelos et al, 2001) and probability models (Kotinas et al.,2015). Furthermore, coastal erosion problems have been investigated by Evelpidou et al. (2008).

The drainage basin of “Fourniotiko” stream (Fig.1) is situated in the NW part of the island, near the town of Karlovasi. It is the largest basin on the island covering an area of 46.5 Km^2 and located between 37^o 43’ to 37^o 48’N and 26^o 42’ to 26^o 48’ E. The river originates from the mountain “Ambelos” which is located in the central part of the island, has a maximum altitude of 1063m, mainly consists of schists and is covered by forest. It flows to the NW and its mouth is located near the town of Karlovasi. The river flood plain, is heavily affected by human intervention. Flood events are frequent in the area causing damages in the city of Karlovasi. One of the most recent flood events occurred in November 2001, when the island was declared in a state of emergency.

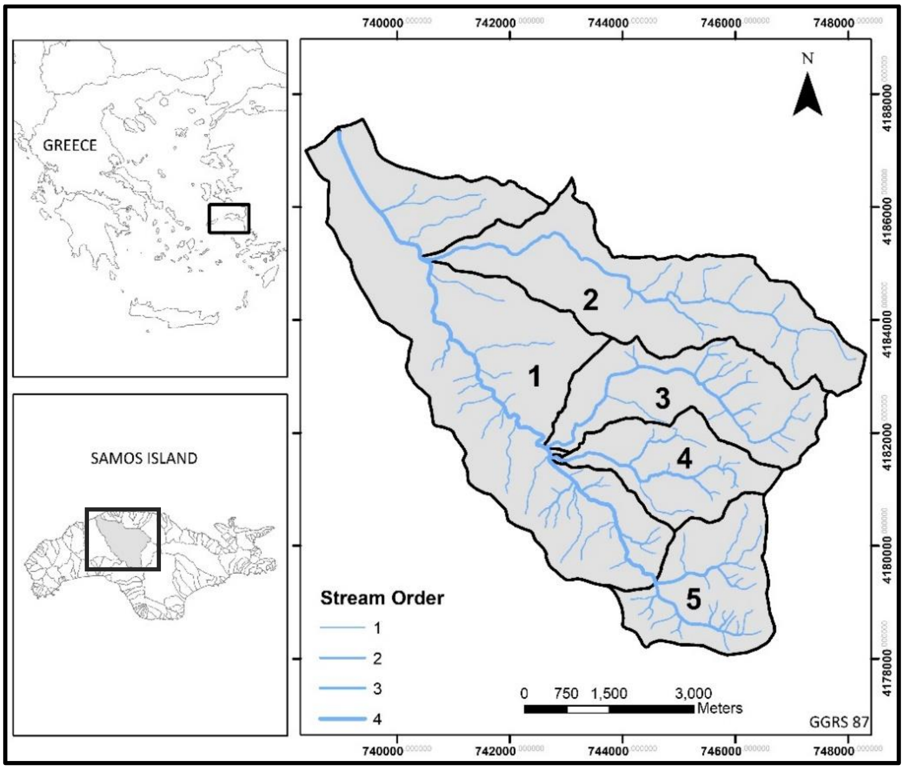

Figure 1. Study area including the drainage sub-basins and river network of “Fourniotiko”.

Data collection and Methodology.

In this paper Aster Global DEM (GDEM) of 30m resolution and topographic maps of 1:50.000 scale were used for the delineation of the river network and the drainage basin. Flow direction and flow accumulation grids, were produced and with the use of carefully selected pour points the sub-basins were created. The main basin was divided in 5 sub-basins, taking into account geometry and flow characteristics of the whole drainage basin. The topographic maps, were used mainly for cross-checking and correcting the GDEM. The following procedure was used for the morphometric analysis of the drainage basin:

- Import of topographic data and cross-checking using control points.
- Creation of a slope map, flow direction and flow accumulation map.
- Delineation of the river network and the drainage basin.
- Selection of pour points and creation of drainage sub-basins.
- Calculation of various morphometric parameters (Table 1) .

The most important *morphometric parameters* (Zavoianou, 1985) affecting the hydrological characteristics of the basin were processed with the use of statistical packages (SPSS) to identify *inter-correlations* between the variables and produce the correlation matrix.

Table 1. Methods to calculate morphometric parameters for the study area.

Parameter (Units)	***Method***	**Reference**
Drainage Order	$\boldsymbol{U}$: GIS (Fig.1)	Strahler (1952)
Drainage Area (km^2)	$\boldsymbol{A}$: GIS	
Basin Perimeter (km)	$\boldsymbol{P}$: GIS	
Nr. of streams in order u	$\boldsymbol{N_u}$: GIS	Strahler (1952)
Length of Streams in ord. u (km)	$\boldsymbol{L_u}$: GIS	Strahler (1952)
Basin Length (km)	$\boldsymbol{L_b}$: GIS	
Basin Maximum Altitude (m)	$\boldsymbol{H}$: GIS	
Basin Mean Altitude (m)	$\boldsymbol{H_m}$: GIS	
Basin Mean Slope (degrees)	$\boldsymbol{S}$: GIS	
Main Channel Length (km)	$\boldsymbol{L}$: GIS	
Bifurcation Ratio	$\boldsymbol{R_b} = N_u/N_u + 1$	Schumm(1956)
Stream Frequency	$\boldsymbol{F_s} = \Sigma N_u/A$	Horton(1932)
Drainage Density (km/km^2)	$\boldsymbol{D_d} = \Sigma L_u/A$	Horton(1932)
Drainage Texture	$\boldsymbol{T} = D_d \times F_s$	Smith(1950)
Length of Overland Flow (km)	$\boldsymbol{Lg} = A/2L_u$	Horton(1945)
Main Channel Slope (m/m)	$\boldsymbol{MCS} = H85 - H10/L85 - L10$	Dempster (1983)
Basin Relief (m)	$\boldsymbol{H} = Z - z$	Strahler (1952)
Relief Ratio (km/km)	$\boldsymbol{Rhl} = (H/1000)/L_b$	Schumm(1956)
Ruggedness Number	$\boldsymbol{R_n} = D_d \times (H/1000)$	Melton 1957
Elongation Ratio	$\boldsymbol{R_e} = (2/L_b) \times (A/\pi)^{0.5}$	Schumm (1956)
Circularity Ratio	$\boldsymbol{R_c} = (4\pi \times A)/P^2$	Miller (1953)
Form Factor	$\boldsymbol{R_f} = A/{L_b}^2$	Horton (1932)
Time of Concetration (min)	$\boldsymbol{T_c} = T_{channel} + T_{overland}$ $\boldsymbol{T_{ov}} = 1.44 \times \left(L_g \times N\right)^{0.467} \times S^{-0.235}$ $\boldsymbol{T_{ch}} = 0.0195 \times L^{0.770} S^{-0.385}$	Kerby (1959) Kirpich (1940)

Then the most important morphometric parameters were selected and treated as *fuzzy variables* (Gournelos et al., 2004). Values such as Low, Medium, High were assigned to the parameters for all drainage sub-basins and then proper *logical rules* were created for the transformation of input variables into the output (relative flood risk) such as:

If Stream Slope is High	&	Drainage Density is High	&	Relief Ratio is Medium-High	→	Relative Flood Risk is High

The spatial distribution of the output variable has been visualized with the help of G.I.S. tools into a map showing the relative contribution to flood risk of each sub-basin.

Results and Discussion

Drainage area is the most frequent used variable in the estimation of discharge. *Average basin slope* and *slope distribution* determine infiltration rate, runoff and time of concentration. Figure 2 represents distribution of ground slope for each sub-basin and shows that sub-basins 2-4 have relatively high values resulting in lower infiltration rate, shorter time of concetration and higher surface runoff.

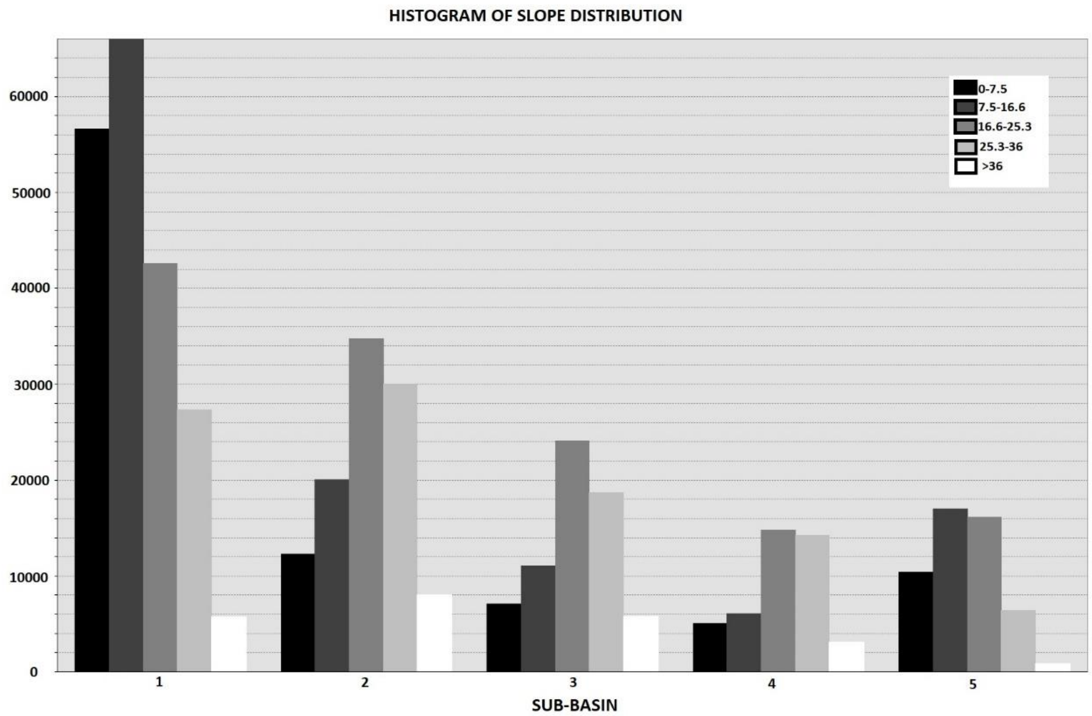

Figure 2. Slope Distribution of the sub-basins of “Fourniotiko” drainage basin

The rest of the basic morphometric parameters were calculated for the main basin and each sub-basin, including basin length, average and maximum altitude, average slope and other basic morphometric variables (Table 2). These variables are mainly used for the calculation of the derived morphometric parameters, but can also be used as a first indication of hydrologic behavior. Sub-basins 2-5 are more mountainous, and have higher average slopes and consequently a higher contribution to flash floods is expected

Table 2. Basic Morphometric parameters for the main basin and the sub-basins (parameters are defined in Table 1).

(Sub)-Basin	**A**	**P**	**N_1**	**N_2**	**N_3**	**N_4**	**N_{tot}**	**L_1**	**L_2**	**L_3**	**L_4**	**L_{tot}**	**L_b**	**H_{max}**	**H_μ**	**S**	**L**
1	19.9	30.5	31	6	0	1	38	20.5	2.3		11.2	34.1	9.8	800	269.6	14.4	11.7
2	10.5	20.5	11	2	1	0	14	7.0	3.5	5.3		15.7	2.4	912	594.1	15.5	2.6
3	6.7	14.4	18	6	1	0	25	6.5	3.6	4.7		14.8	8.1	1063	678.1	21.3	9.6
4	4.3	10.5	12	3	1	0	16	3.7	2.6	2.9		9.2	4.1	1010	680.5	22.2	4.6
5	5.1	10.3	23	7	2	0	32	8.7	2.2	2.8		13.7	5.1	1040	769.9	22.1	7
BASIN	46.5	33.5	95	24	5	1	125	46.5	14.2	15.6	11.2	87.5	11.8	1063	507.7	17.9	13.5

The derived morphometric give a better estimation of hydrologic behavior since most of them depend on other influencing variables like lithology. The derived parameters and their range of values in the study area, are listed in Table 3, and are the following:

- *Bifurcation Ratio (Rb)* is a dimensionless parameter related to the branching pattern of a drainage network. Lower bifurcation ratio means that there is higher chance of flooding since water tends to concentrate in one channel. Usual values ranging from 3 to 5(Strahler 1964) are observed in all the sub-basins.
- *Drainage Density (Dd)* depends on topography, infiltration capacity, climate and resistance of geological formations to erosion. It is highly correlated with maximum flood discharge (Horton 1945). Flood prone areas are expected to have high drainage density values, which leads to rapid concetration of flow (Paton and Baker 1976) as a result of low infiltration capacity, steep slopes and low vegetation cover. In our study values between 1.49 and 2.70 km/km^2 are observed, which are strongly related with stream frequency values.
- *Stream Frequency (F_s)* depends on the lithology of the basin and is an indication of the texture of a river network (Horton 1945). Values between 1.33 and 6.29 are observed in the study area indicating strong lithological differences between the sub-basins.
- The *drainage texture (T)* is related to lithology and relief of a basin. High T-value represents higher relief. Smith (1950) categorized the drainage texture in five classes from very course (<2) to very fine (>8). Values ranging from 1.99 (very course) to 16.97 (very fine) were observed.
- *Length of Overland Flow (Lg)* is the maximum length of surface flow generated by rain before entering a definite stream channel (Horton 1945). It is affected mainly by infiltration, and is critical for time of concetration calculation. Lengths between 190 meters and 330 meters were calculated.
- *Main channel slope (MCS)* is highly correlated with maximum flood discharge [Horton, 1945]. For this study the slope between 10% and 85% of stream length was calculated, that is more representative for water flow (Dempster, 1983) and values between 0.03 and 0.15 m/m were observed.
- Basin relief controls the stream gradient and influences the sediment transport and flood patterns and usually two indexes are used:
    1. *Relief ratio* [Schumm, 1956] is the ratio of basin relief to basin length and is used to compare relief between different basins. It indicates the rate of altitude decrease along the main channel and values between 0.08 and 0.20 m/m were identified.
    2. *Ruggedness number* [Melton 1957] combines drainage density with relief. Areas of high drainage density-low relief, are as rugged as areas with high relief-low drainage.

Areas with high ruggedness have a higher potential of flash flooding. Values between 1.27 and 1.89 were observed in the sub-basins.

- *Elongation ratio* is the ratio between the diameter of a circle that has the same area as the basin and the maximum length of the basin. An elongated basin is less efficient in the discharge of runoff, thus time of concetration increases and flood risk decreases. Values between 0 and 0.6 indicate an elongated basin. In our study area values range between 0.45 and 1.07, and most of the sub-basins have low values.
- *Circularity index* is used to determine basin shape, infiltration rate and time of concetration. The lithology, stream frequency and gradient of various orders determine the values of this index (Strahler 1964). Higher values indicate circular shape. Values between 0.27 and 0.61 were calculated.
- *Form Factor* has a direct relation with peak discharge and the inverse of axial length (Gregory & Walling 1973). High values indicate high peak flows of shorter duration. In our study area values between 0.16 and 0.89 were observed.
- *Time of concetration*, which is the time required for water to travel from the most hydraulic distant part of a basin to the outlet. It represents the time at which all the areas of the basin contribute runoff to the outlet, and can be used to determine the minimum storm duration required to have a flood event. Since we are working in small basins where overland flow is important for time of concetration, the Kirpich – Kerby method (Russel et al., 2005) was applied. Values between 40 and 105 minutes were observed in the sub-basins.

Table 3. Derived morphometric parameters for the main basin and the sub-basins

(Sub)-Basin	R_b avg	F_s	D_d	T	Lg	MCS	Rhl	R_n	R_e	R_c	R_f	t_c (min)
1		1.91	1.71	3.27	0.29	0.04	0.08	1.37	0.52	0.27	0.21	105.82
2	3.75	1.33	1.49	1.99	0.33	0.15	0.14	1.64	0.45	0.32	0.16	63.45
3	4.50	3.75	2.21	8.29	0.23	0.10	0.17	1.89	0.57	0.40	0.25	57.34
4	3.50	3.70	2.12	7.85	0.24	0.10	0.20	1.70	0.57	0.49	0.26	45.95
5	3.39	6.29	2.70	16.97	0.19	0.03	0.20	1.27	1.07	0.61	0.89	42.20
Basin	4.58	2.68	1.88	5.06	0.26	0.04	0.09	2.00	0.65	0.52	0.33	118.09

The correlation matrix between the most important morphometric parameters (Table 4) was calculated through the use of IBM SPSS Statistics software. By taking into account this matrix the parameters that are highly inter-correlated were identified. As a result, three principal morphometric parameters were selected for further processing (MCS, drainage density and Ruggedness number).

The values of these parameters have different units and range of values, and to be combined more effectively data has to be scaled. The available data were standardized using the formula:

$X - X_{min}/X_{max} - X_{min}$.

Then the standardized data were classified (Low, Medium, High) and after applying fuzzy rules through the use of Matlab numerical computing environment, the output variable was obtained, which is the degree of contribution to flash floods (Fig.3).

Table 4. Correlation matrix of the main morphometric variables

	A	H	S	L	Df	Dd	T	Lg	MCS	Rhl	Rn	Re	Rc	Rf
A	1.0	-0.5	-0.4	0.7	-0.4	-0.4	-0.4	0.3	-0.4	-0.8	0.5	-0.1	0.0	-0.2
H	-0.5	1.0	0.8	-0.5	0.7	0.7	0.7	-0.6	0.3	0.9	0.1	0.5	0.7	0.5
S	-0.4	0.8	1.0	-0.2	0.8	0.9	0.8	-0.9	-0.1	0.9	0.1	0.6	0.8	0.5
L	0.7	-0.5	-0.2	1.0	0.0	0.0	-0.1	-0.2	-0.7	-0.6	0.3	0.1	0.0	0.0
D_f	-0.4	0.7	0.8	0.0	1.0	1.0	1.0	-1.0	-0.5	0.7	-0.3	0.9	0.8	0.9
D_d	-0.4	0.7	0.9	0.0	1.0	1.0	1.0	-1.0	-0.5	0.7	-0.3	0.9	0.8	0.8
T	-0.4	0.7	0.8	-0.1	1.0	1.0	1.0	-0.9	-0.4	0.7	-0.4	0.9	0.8	0.9
Lg	0.3	-0.6	-0.9	-0.2	-1.0	-1.0	-0.9	1.0	0.5	-0.6	0.1	-0.8	-0.8	-0.8
MCS	-0.4	0.3	-0.1	-0.7	-0.5	-0.5	-0.4	0.5	1.0	0.2	0.3	-0.6	-0.4	-0.6
R_{hl}	-0.8	0.9	0.9	-0.6	0.7	0.7	0.7	-0.6	0.2	1.0	-0.2	0.5	0.6	0.5
R_n	0.5	0.1	0.1	0.3	-0.3	-0.3	-0.4	0.1	0.3	-0.2	1.0	-0.5	0.0	-0.5
R_e	-0.1	0.5	0.6	0.1	0.9	0.9	0.9	-0.8	-0.6	0.5	-0.5	1.0	0.8	1.0
R_c	0.0	0.7	0.8	0.0	0.8	0.8	0.8	-0.8	-0.4	0.6	0.0	0.8	1.0	0.8
R_f	-0.2	0.5	0.5	0.0	0.9	0.8	0.9	-0.8	-0.6	0.5	-0.5	1.0	0.8	1.0

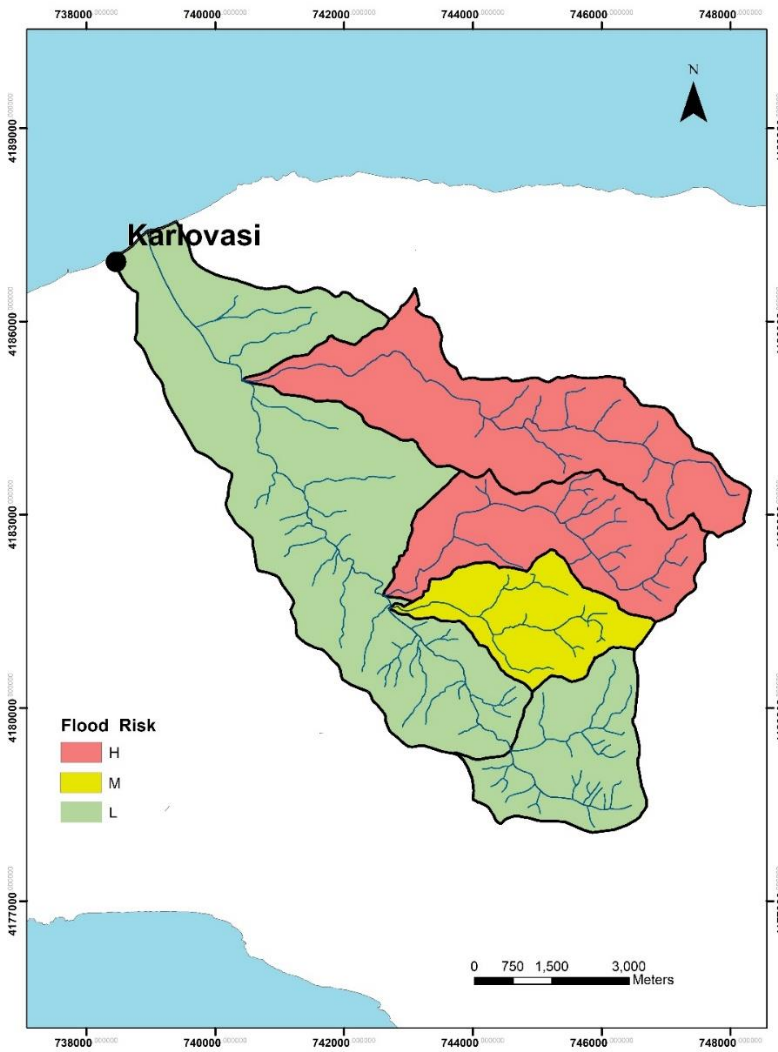

Figure 3. Map showing the degree of contribution to flash flood for each sub-basin of the drainage basin of “Fourniotiko” in Samos island.

Conclusions

The basin is classified as a 4th order basin, while most of the sub-basins are classified as 3rd order. First order streams are dominant, providing a sufficient superficial draining directly to the higher order stream. The bifurcation ratio reflects the mountainous or highly dissected nature of the terrain in most of the area. Stream frequency values indicate strong lithological differences between the drainage sub-basins.

The analysis and processing of morphometric parameters suggests that the 5 sub-basins of "Fourniotiko" stream, have different hydrological behavior during a flash flood event. By observing the produced map (Fig.3) we can conclude that sub-basins 2&3 have high degree of contribution to flash floods, while sub-basin 4 presents medium degree and finally the other basins present low degree of contribution. These results are compatible with the slope distribution (Fig.2) and the estimated time of concetration of each drainage sub-basin.

The analysis of morphometric variables show that the sub-basins with the highest degree of contribution to flash floods are controlled mainly by topographic parameters such as relief ratio and slope ground distribution. High drainage area and total length of streams also increase contribution to flash floods, but they are of secondary importance in the study area. These results can be helpful for local authorities and policy makers, which can improve drainage basin management and planning. Also the methodology with minor modifications can be applied to other drainage basins with similar characteristics.

Acknowledgement

This research was supported by "Papadakis" grant of NKUA, awarded to the main author for his PhD. Research.

References

Costa, J.E. (1987). Hydraulics and basin morphometry of the largest flash floods in the conterminous United States. Journal of Hydrol., 93, 313–338.

Dempster, G.R. (1983). Instructions for streamflow/basin characteristics file. U.S. Geological Survey National Water Data storage and retrieval system (WATSHORE), 4(2).

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaskovicova, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velascom, D., Viglione, A.(2009). A compilation of data on European flash floods. Journal of Hydrology, 367, 70-78.

Evelpidou, N., Vassilopoulos, A., Leonidopoulou, D., Poulos, S. (2008). An investigation of the coastal erosion causes in Samos Island, Eastern Aegean Sea. Journal of Landscape Ecology, 6, 295-310.

Frissel, C., Liss, W., Warren, C., Hurley, M. (1986). A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environ. Manag., 10, 199-214.

Gournelos, T., Evelpidou, N., Vassilopoulos, A. (2004). Developing an Erosion Risk Map Using Soft Computing Methods (Case Study at Sifnos Island). Natural Hazards, 31, 63-83.

Gournelos, T., Vassilopoulos, A., Evelpidou, N. (2001). An erosion risk study on Samos Island, based on fuzzy models, taking into consideration land use situation after the fire of July 2000. Greece: 7th International Conference on Env. Science & Technology Proceedings.

Gregory, K.J., Walling, D.E. (1973). Drainage basin form and process: a geomorphological approach. New York: Wiley.

Horton, R.E. (1932). Drainage-basin characteristics. EOS Trans. American Geophys. Union, 13, 350-361.

Horton, R.E. (1945). Erosional development of streams and their drainage basins: Quantitative Morphology, Bull Geological Society of America, 56, 275-361.

Kerby, W.S. (1959). Time of concetration for overland flow. Civil Engineering, 29(3), 174p.

Kirpich, Z.P. (1940). Time of concetration of small agricultural watersheds. Civil Engineering, 10(6), 362p.

Kotinas, V., Gournelos, T., Evelpidou, N., Vlachogiorgou, M. (2015). Spatial distribution of erosion and deposition zones as a result of surface runoff, based on a probability model. A case study in the island of Samos. Bulgaria: SGEM2015 Conference Proceedings.

Melton, M.A. (1957). An analysis of the relations among elements of climate, surface properties and geomorphology. New York, USA: Columbia University.

Mezger, K., Okrusch, M. (1985). Metamorphism of the Variated Sequence at Kallithea, Samos, Greece. TMPM Tschermaks Mineral. Und Petr. Mitt, 34, 67-82.

Miller, V.C. (1953). A quantitative geomorphic study of drainage basin characteristics in the Clinch mountain area, Virginia and Tennessee. Technical Report 3 of Project nr:389-042, New York: Columbia University.

Papanikolaou D. (1979). Unites tectoniques and phases de deformation dans l'ile de Samos, Mer Egee, Grece. Bull. Soc. Geol De France, 21 (6), 745-752.

Patton, P., Baker, V. (1976). Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls, Wat. Resources Res.,12, 941-952.

Roussel, M.C., Thompson, D.B., Fang, Xing, Cleveland, T.G., and Garcia, C.A. (2005). Time-parameter estimation for applicable Texas watersheds. Texas Department of Transportation Research Report 0–4696–2, Texas: Lamar University.

Schumm S.A. (1956). Evolution of Drainage Systems and slopes in bad lands at Perth, Amboy, New Jersey. Bulletin of the Geological Society of America, 67, 597-646.

Smith, K.G. (1950). Standards for grading texture of erosional topography. American Journ. Sci., 248, 655–668.

Stamatakis, M. (1989). Authigenic silicates and silica polymorphs in the Miocene saline-alkaline deposits of the Karlovassi basin, Samos Island, Greece. Economic Geology, 84, 788-798.

Strahler, A.N. (1964). Quantitative Geomorphology of drainage basin and channel networks. In: Chow, Handbook of Hydrology. USA: mcgraw Hill.

Strahler, A.N. (1952). Hypsometric analysis of erosional topography. Bulletin of the Geological Society of America, 63, 1117-1142.

Theodoropoulos, D. (1979). Geological map of Greece 1:50.000: Sheet Neon Karlovasi. Athens: IGME publication.

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G., Roberts, N.M. (2014). Future changes to the intensity and frequency of short duration extreme rainfall. Rev. Geophys.,52, 522–555.

Zavoianu, I. (1985). Developments in Water Science 20: Morphometry of drainage basins., New York: Elsevier.