A GIS-BASED FLASH FLOOD RUNOFF MODEL USING HIGH RESOLUTION DEM AND METEOROLOGICAL DATA

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ABSTRACT

Natural hazards are historically a substantial threat to the progress and development of human communities. Floods hold a dominant position among these specific phenomena due to their frequent occurrence as well as their large spatial spread. Certainly, the aforementioned facts become more visible under the light of the assessment of the dramatic effects brought about by their occurrence. Consequently, the need to deal with the impact of floods on human communities with an effective way leads to a systematic involvement of the international scientific community on the subject of "Management of Natural Hazards".

The present study describes an attempt to model surface runoff in a typical ungauged basin, which is directly related to catastrophic flood events, by creating a system based on GIS technology. The main object was to construct a direct unit hydrograph for an excess rainfall by estimating the stream flow response at the outlet of a watershed. Specifically, the methodology was based on the creation of a spatial database in GIS environment and on data editing. Moreover, rainfall time-series data came from Hellenic National Meteorological Service and they were processed in order to calculate flow time and the runoff volume. Apart from the meteorological data, background data such as topography, drainage network, land cover and geological data were also collected. A high resolution DEM was of great importance in order to achieve the final result. The study area is the sub-basin of Archaia Olympia (Kladeos sub-basin) in Greece, and the examined event occurred on February 5th, 2012.

INTRODUCTION

Floods are one of the most common types of natural disasters that can be caused by many different naturally-occurring events such as thunderstorms, hurricanes, tidal waves and melting ice or snow. Floods can have several positive and negative effects on the environment. One of the negative effects is the great extent of damage that can be cause to man-made structures. The occurrence of this catastrophic phenomenon is directly related to population pressures which is the climate change and the environmental impact of human activity.

In Greece, flood events occur mostly in small - to medium-sized catchments drained by ephemeral water courses. Usually, disasters, in these flash flood prone basins, are mainly caused by high-intensity rainfall falling over a short period of time. Several regions in Greece suffer from frequent and extreme flood that is a phenomenon generally caused by intense rainstorms (1).

The majority of drainage basins in Greece are relatively small with steep slopes, configured by a torrent with braided main channel morphology. These systems become particularly active during extreme flood events and this may be a source of significant damage to human infrastructure. Despite the importance of these floods, the hydrological analysis of catchments in Greece has been especially difficult due to the lack of precipitation and discharge gauges. Generally, floods in the Mediterranean area are linked to storming events, but there are additional factors that can intensify flooding such as the pattern of the drainage network, the morphology of the catchment and the human interventions (2).

It has been shown that a catchment's morphometric variables control its hydrologic response. Understanding a basin's response to extreme rainfall based on geomorphological indices can be valuable when studying flood hazard in catchments (1).

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One of the most prevalent ways to assess this runoff that is generated by rainfall is the unit hydrograph introduced by Sherman in 1932. This theory has played a prominent role in runoff routing computation for several decades and assumes that the basin response to rainfall input is linear and time invariant. Moreover, the unit hydrograph combined with the excess rainfall, can give the discharge at the basin's outlet. In the recent years, the use of Geographic Information System (GIS) facilitates the estimation of the runoff from watersheds, and this is the reason why it has gained increasing attention. Development of GIS software allowed rapid and accurate calculation of geometric basin parameters and improved results in hydrograph derivation methods that required spatial analysis (3). Melesse and Graham (2004) (4), unlike previous approaches (5,6,7) proposed a routing model that is related with the travel time. This model can develop a direct hydrograph for each spatially distributed rainfall event without relying on developing a spatially lumped unit hydrograph. The sum of travel times of cells along a flow path is the travel time from each grid cell to the watershed outlet. The direct runoff flow was defined by the sum of the volumetric flow rates from all contributing cells at each respective travel time (4).

The model is based on raster data structures. Grids such as elevation, land use, soil type, are used to describe spatially distributed soil parameters. Moreover, hydrologic features of each grid, like slope, flow accumulation, flow direction and flow length, can be calculated using standard function included in GIS (4).

Several previous studies have tried to establish methodologies that have been developed for instantaneous unit hydrographs derivation based on morphometric parameters (among others 1,3, 5,6,7,8).

The object of the study is to present the impact of a severe flood event occurred on February 5th, 2012, in Ilias prefecture and to model surface runoff by creating a system based on GIS technology. Particularly, a unit hydrograph is constructed for the excess rainfall by estimating the stream flow response at the outlet of the Olympia sub-basin (Kladeos sub-basin), which is included in Alfios River basin, located in western Peloponnese.

METHODS

Study Area

The Alfios River is the longest river in the Peloponnese and the ninth longest river in Greece. It drains an area of almost 2,575 km^2 and the drainage basin is elongated along an almost S-W trending axis. The main channel follows an S-W flow direction for about 110 km in Western Peloponnese. It discharges at Kiparissiakos Gulf in Ionian Sea and its source is near the village Dorizas. Its catchment encompasses different types of terrain, including steep mountain slopes, narrow valleys and bedrock canyons. The main channel (seventh order branch by Strahler) traverses a wide, flat valley (9).

This study focuses to Olympia's sub-basin, which is included in Alfios basin area (Figure 1). The selected sub-basin as it was proven from the assessment of this flood disaster was affected the most. Olympia's sub-basin is elongated for about 103.7 km. It drains an area of 32.28 km^2 and its maximum height reaches 618 metres in the northern part. Moreover, the area consists of Neogene sediments. More specifically, the bulk consists of Pleistocene deposits, whereas in areas with the densest flow alluvial deposits are found. The majority of the study area is rural except for some central parts with forests and the southern part in which the city of Archaia Olympia is located and thus it can be characterized as urban. The greatest percentage of the sub-basin's area presents an altitude of 30 to 200 metres (47%). The 32% of sub-basin's area has an altitude of 200 to 400 metres and the 21% area presents an altitude over 400 metres. Most steep slopes can be found in the northern region where the highest altitudes are located.

The geology of the selected sub-basin follows the deposition of the Neogene sediments. The entire area was subject to intense uplift, and further movement along existing faults. During this period alluvial erosion was concentrated along tectonic boundaries and deeply incised the Neogene sediments, creating the deep and wide river valleys (9,10). The less resistant Neogene sediments are prone to mass movement, including landslides and creep. These processes tend to normalize the relief created by the deep incision of the earlier periods by lowering the higher points and smoothing the steepness of the cliffs and can provide important sediment sources for subsequent fluvial transport. They also cause major problems for the stability of settlements in combination with the high seismicity of the area (9,10,11). This process tends to reinforce catastrophic flood phenomena.

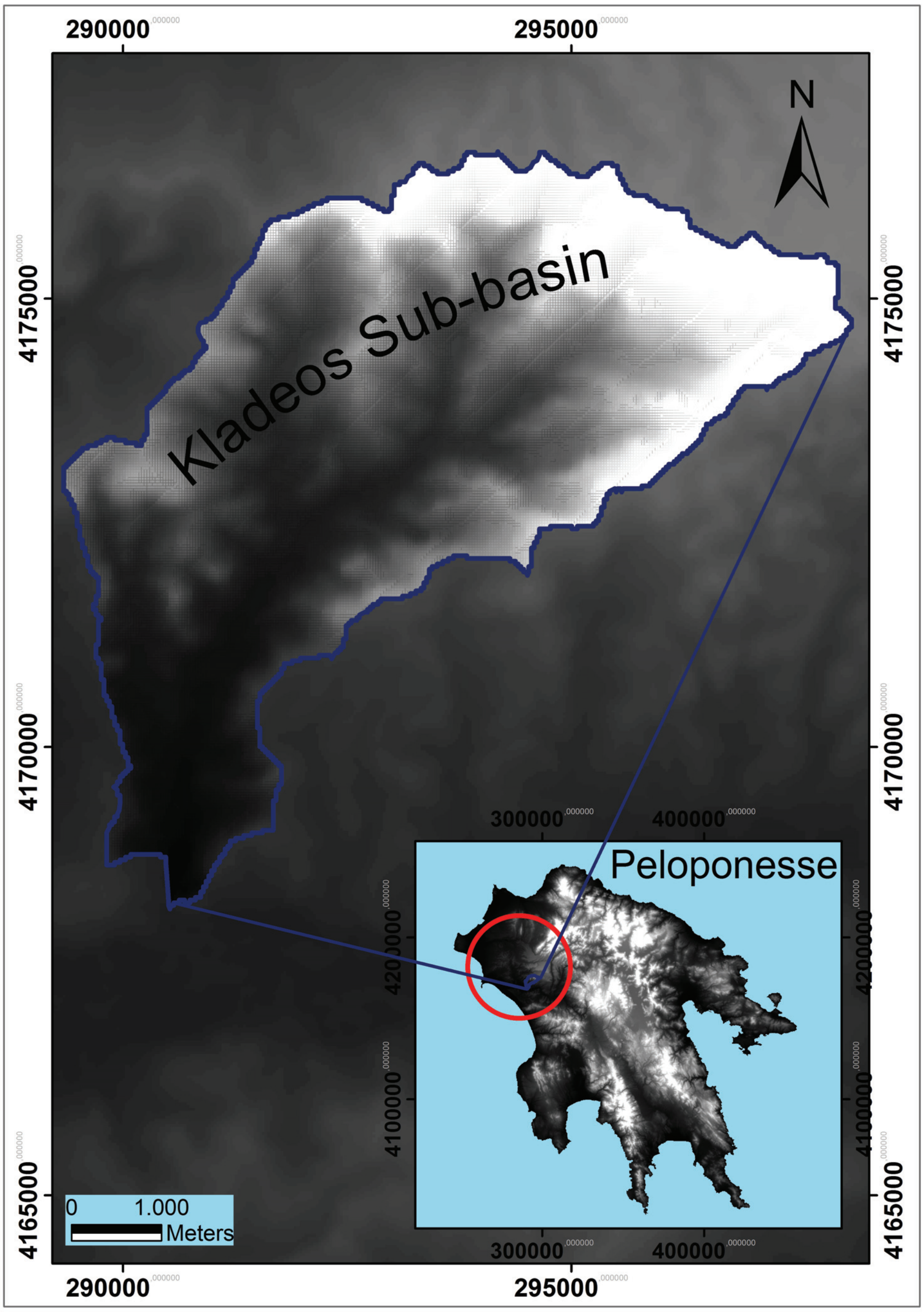

Figure 1: Study Area (coordinates in Greek grid).

Northwest Peloponnesus experiences a typical Mediterranean climate. The average annual rainfall over the area is around 821.9 mm, and it is very close to the average annual rainfall over the country, which is 821.3 mm. Rainfall, is distributed relatively unevenly with about 75% of it occurring between the months of October and March. The average temperature is around 17ºC but during summer, it ranges from 35.8 ºC to 45.8 ºC. The average relative annual humidity is near 68.7%, which is considered normal (9,2,12)

The Event

On the 5th of February, 2012, the Western Peloponnese was struck by one of the most extreme storms that had ever occurred in the meteorological history of the prefecture of Ilias.

Specifically, on Saturday 4th in February 2012, a low barometer moved rapidly from Italy to the east, causing heavy storms in the northern Ionian and Epirus at midday and the western Central mainland as well as the central and southern Ionian Sea in the afternoon. At night, it affected the northwestern prefecture of Ilia where it had rapid transit (Figure 2). On Saturday midnight, it started to affect the cities of Pyrgos and Archaia Olympia, where it literally "stuck" for more than eight hours.

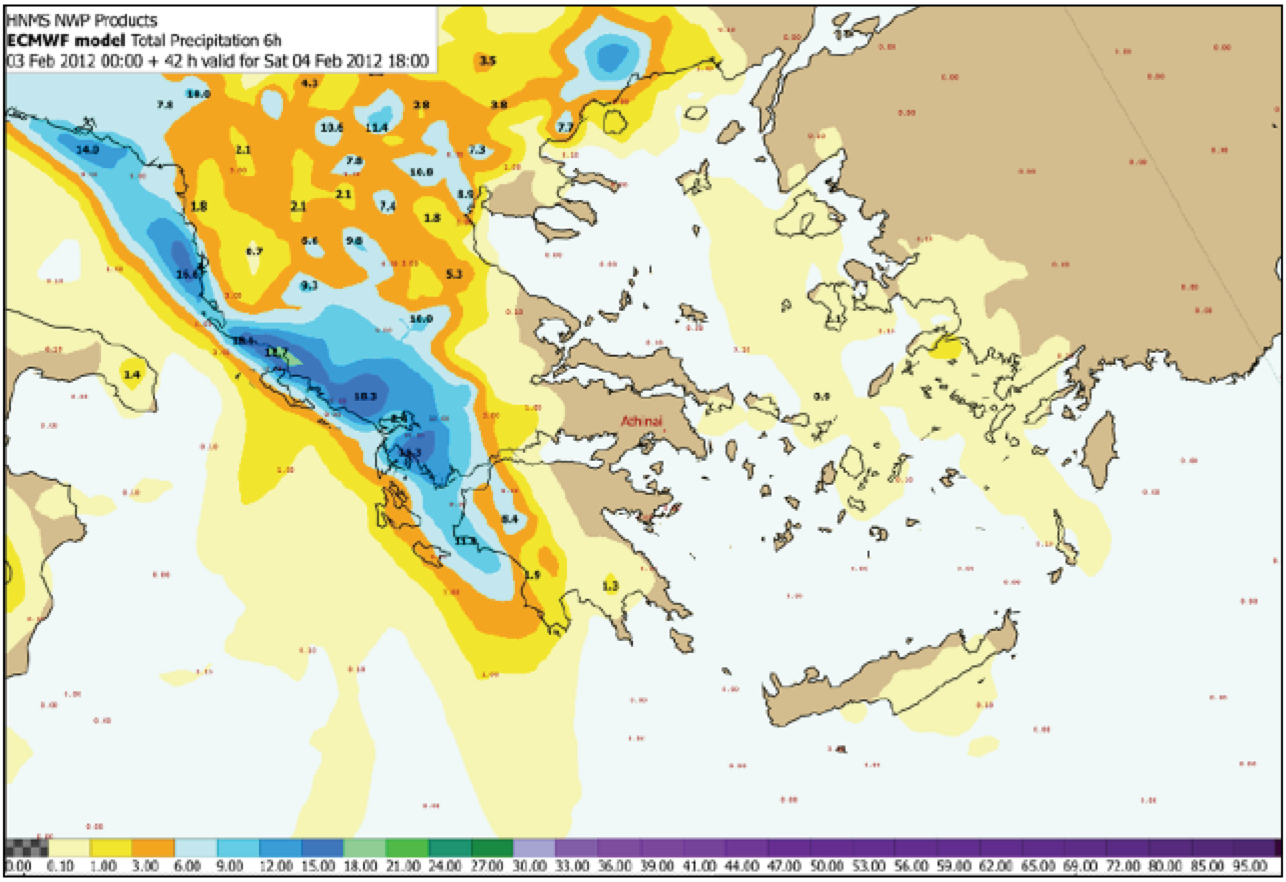

Figure 2: Weather forecast map (3-4 February 2012).

In the study area, 151.4 mm of water were recorded in about eight hours from 00:30 to 8:20 from which 106,5 mm (70% of total precipitation) were recorded in the first 3.5 hours. The long storm, accompanied with hail caused a lot of problems in the municipalities of Pyrgos and Archaia Olympia as the size of the losses from floods and landslides was big. Moreover, there was huge damage to infrastructure networks, rural crops, livestock and properties of the local population. However, the most dramatic consequence was the loss of a human life (9).

METHODS AND DATA

The topography of the land surface is one of the most fundamental geophysical measurements of the Earth, and it is a dominant controlling factor in virtually all physical processes that occur on the land surface. Consequently, topographic information was the most important data used at the current study. This information came from ASTER GLOBAL DEM (Figure 3) which is a joint product developed and made available to the public by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It is generated from data collected from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a spaceborne earth observing optical instrument. Its high spatial resolution which is 30 metres, contributes to the extraction of a great quality of spatial information. As a result, particular geomorphological and morphological characteristics such as slope map, flow direction, flow accumulation and flow length layers as well as hydrological basins and the drainage network were estimated for the study area. ArcGIS version 9.3 and especially spatial analysis extension contributed to this procedure.

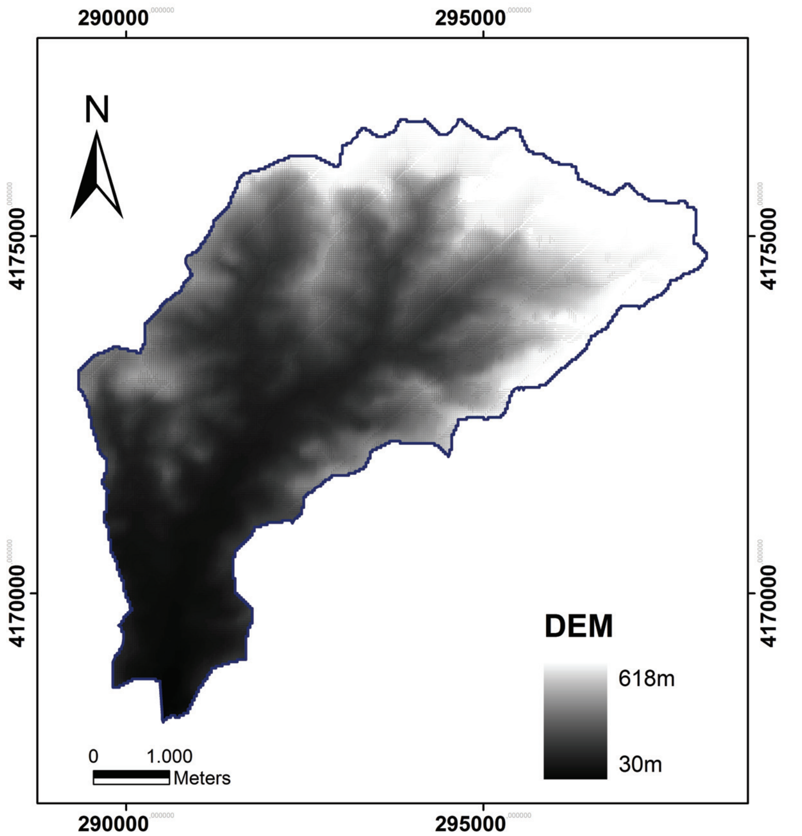

Figure 3: ASTER GLOBAL DEM (coordinates in Greek grid).

Another layer that was important for the study purpose was the land cover map. This map was derived from the CORINE program of the European Union and includes information on land cover for Greece in 2000. Although its scale, which is 1:100,000 is quite small compared with the DEM resolution, it can be defined as suitable for the analysis of hydrologic basins for this kind of scale.

Finally, geological data were also used for the study's purposes. They have been collected from Water Resources Master Management Plan (according to Water Framework Directive 2000/60) by the Ministry of Development.

All these derived maps were used for the construction of the runoff model for the flood event that was described previously. Consequently, the collection of the meteorological data, which have been provided from Hellenic National Meteorological Service, was an important part of the study. These data refer to Archaia Olympia's station which is the nearest station to the selected basin.

All the basic steps that were needed for the study are illustrated in Figure 4. The most important steps in order to simulate the real rainfall event were the calculation of the travel-time layer which indicates the time needed for the water to reach the outlet of the basin, as well as the extraction of the isochrone map which are lines of equal travel time to the outlet of basin. Subsequently, a routing model which combines all the above maps was created in GIS environment.

The estimation of the direct runoff at the outlet of the catchment was produced by assuming that the extreme rainfall event was a phenomenon with a spatially homogeneous distribution. This phenomenon lasted 8 hours and during this time the amount of water that ended to Olympia's basin was 151.4 mm.

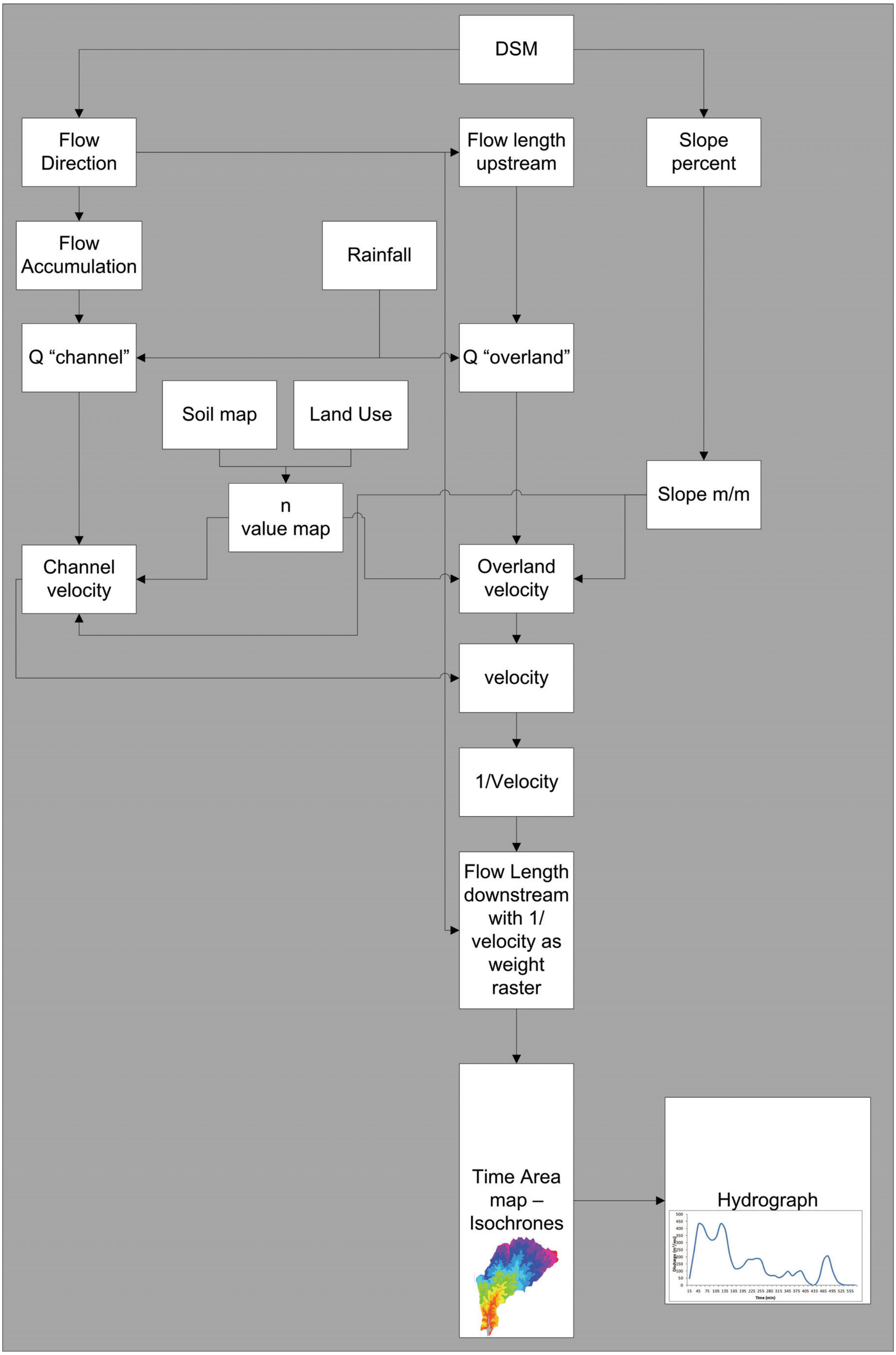

Figure 4: Methodological approach.

Using flow accumulation layer and rainfall, a new grid layer of discharge can be estimated from the formula:

$$Q = \frac{\text{amount of rainfall} \times \text{flow accumulation} \times (\text{cell size})^2}{\text{duration of rainfall}}$$

Combining the soil data map and the land use data map, a new grid map can be created based on Manning's *n* coefficient. Using the available data of Manning's *n* coefficient for each soil type and for each land use a general Manning's *n* coefficient for each area can be determined.

The value of Manning's coefficient was determined from the values published in the literature for the appropriate combination of land cover and geology[1]. Specifically, due to the fact that the geology of the study area only consists of Neogene sediments, the value of n for the geology was considered the same throughout the study area and was 0,035. Land use data, which came from Corine 2000, were firstly grouped into three categories: discontinuous urban fabric, agriculture and forest areas. In order to calculate the n value for each category some assumptions had to be made. The *n* value for urban data was estimated 0.013 which is the same with the *n* value of cement, mortar and unplanted areas. Agriculture areas appear in most cases in the literature to have a value about 0.035. Finally, forest areas appear to have a value that reaches 0.092. It has to be mentioned that these are the normal values from the *n* table that is given in the literature. The final layer of the *n* value for the selected basin was based upon the combination of the *n* value of geology and the *n* values of land cover. Particularly, the mean value of both *n* values was calculated with an exception in urban data where geology was not taken into account and the value remained 0.013 (Figure 5).

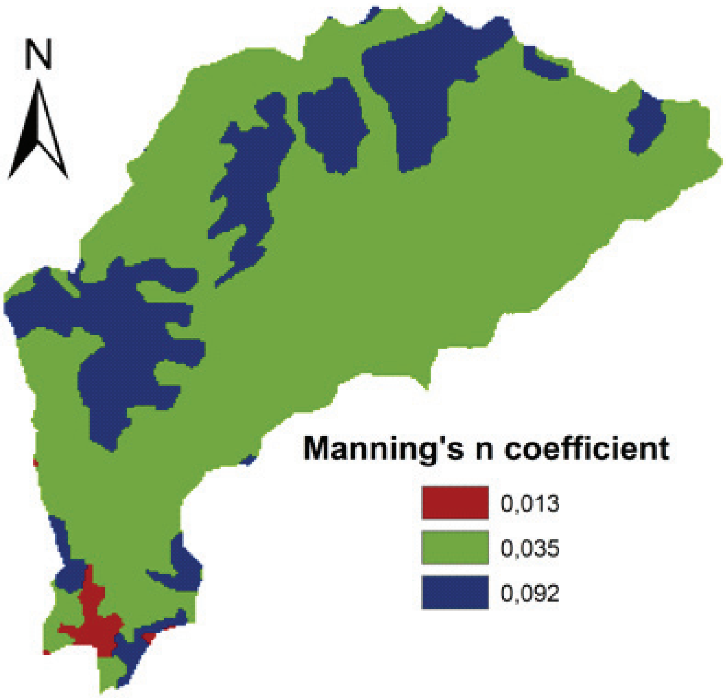

Figure 5: Manning's n coefficient.

For the needs of this work two types of velocity were considered. The first one was for channel flow and the second one for the overland flow. These two types are described mathematically below.

The channel flow travel velocity (V_c) can be estimated according to the combination of Manning's equation with the continuity equation by using the following formula:

[1] http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm (last date accessed: 16 April 2013)

$$V_C = KS_0^{3/8}Q^{1/4}n^{-3/4}$$

Where, S_0 is the surface slope (m/m), Q is the cumulative discharge (m^3/s) and n is the Manning's roughness coefficient. K is a coefficient that is determined after the calibration of the model (in the above equation the coefficient K is assumed to be equal to 1) and corrects the simulation errors of S_0 and n (3).

Likewise, the overland flow velocity (V_O) can be estimated according to the next formula:

$$V_O = S_0^{3/10}\ell^{2/5}i_e^{2/5}n^{-3/5}$$

Where S_0 is the surface slope (m/m), ℓ is the length of the slope (m), i_e is the vertical net incoming flux (m/s) and n is the Manning's roughness coefficient (3).

The next step is the combination of the above velocities (channel & overland velocity). The final product of the above mentioned combination is a GRID file which carries all the information about the channel and overland flow velocity.

Since V ($V_O + V_C$) was calculated for each cell off the basin (using a conditional function in ArcGIS), the travel time in each cell was computed from cell velocity and the travel distance (flow Length) as:

$$T_C = \frac{FL}{V}$$

The final step in order to create isochrones map, is the classification of the travel-time layer. This final map leads to the calculation of runoff volume per time and per isochrone area, and it was the one that contributed to the construction of the unit hydrograph.

RESULTS

The application of the routing model within GIS environment and the hydrological analysis concluded to the travel-time layer (Figure 6). This layer indicates that the water which is nearest to the outlet needs less time to runoff. Particularly, the most remote point in the basin needs 1.278 seconds to reach the outlet.

In addition, the flow-time layer was classified in order to produce an isochrones map (Figure 7). This map is separated in 4 intervals, which depict areas of equal travel time. The defined interval is 300 seconds (5 minutes). The total area of each isochrones was calculated. This result was then used to estimate the volume of water that fell every hour in each isochronous. After this procedure, the values of the Pulses were defined. For example, Pulse 1 represents the volume of water following the first 5 minutes in the first isochronous. Pulse 2 represents the volume of water that fell the next 5 minutes in the first isochronous and the first 5 minutes in the second isochronous etc. It was found that 99 Pulses were needed until the water runoff. These calculations were the final step for the creation of the hydrograph.

The shape of the hydrograph produced is typical of a flash flood. The diagram shows that the basin's response to the precipitation was very quick. The peak of the discharge (432.90 m^3/sec) was noted on February 5^{th}, 2012 at about 02:25 am, almost 2 hours after the beginning of the rainfall. It is quite interesting that 52.6% of the total precipitation occurred during this time period. Moreover, the diagram proves that each time a peak in precipitation occurs, after a while a peak in discharge occurs, too. This is happening due to the fact, as mentioned previously, that the basin is torrential and permits quick runoff response. Figure 8 presents the discharge and the precipitation of the rainfall in relation to the time parameter.

The analysis of the model-derived hydrograph for the Olympia's sub-basin shows that the response of the basin to intense rainfall was immediate.

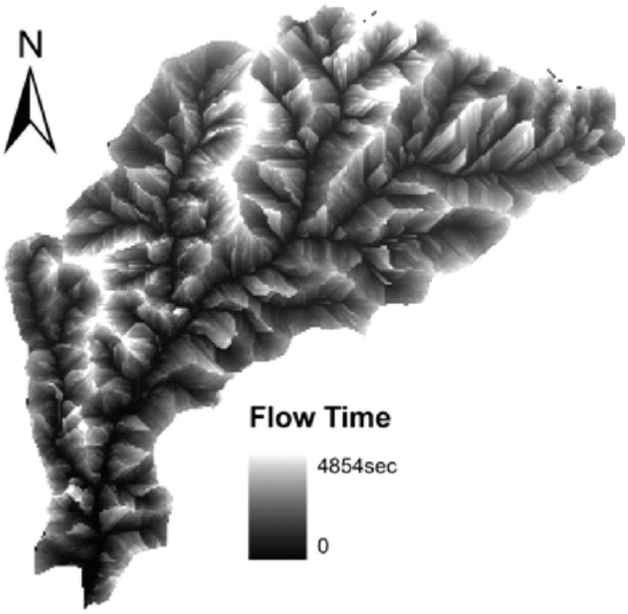

Figure 6: Travel-Time Area.

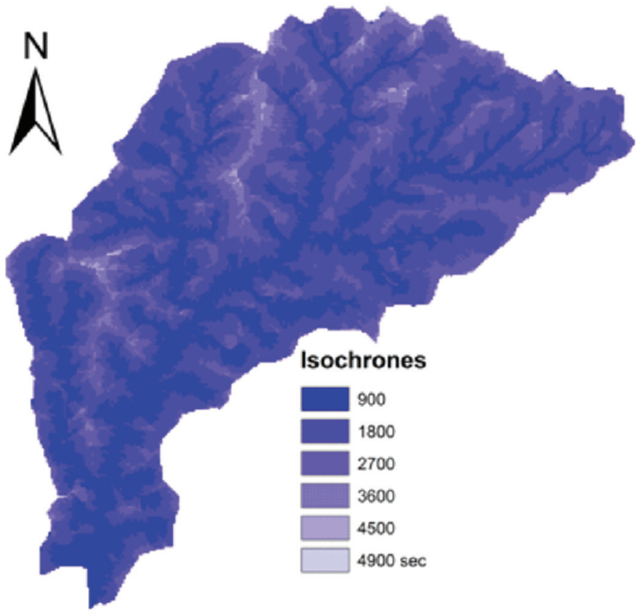

Figure 7: Isochrones Map.

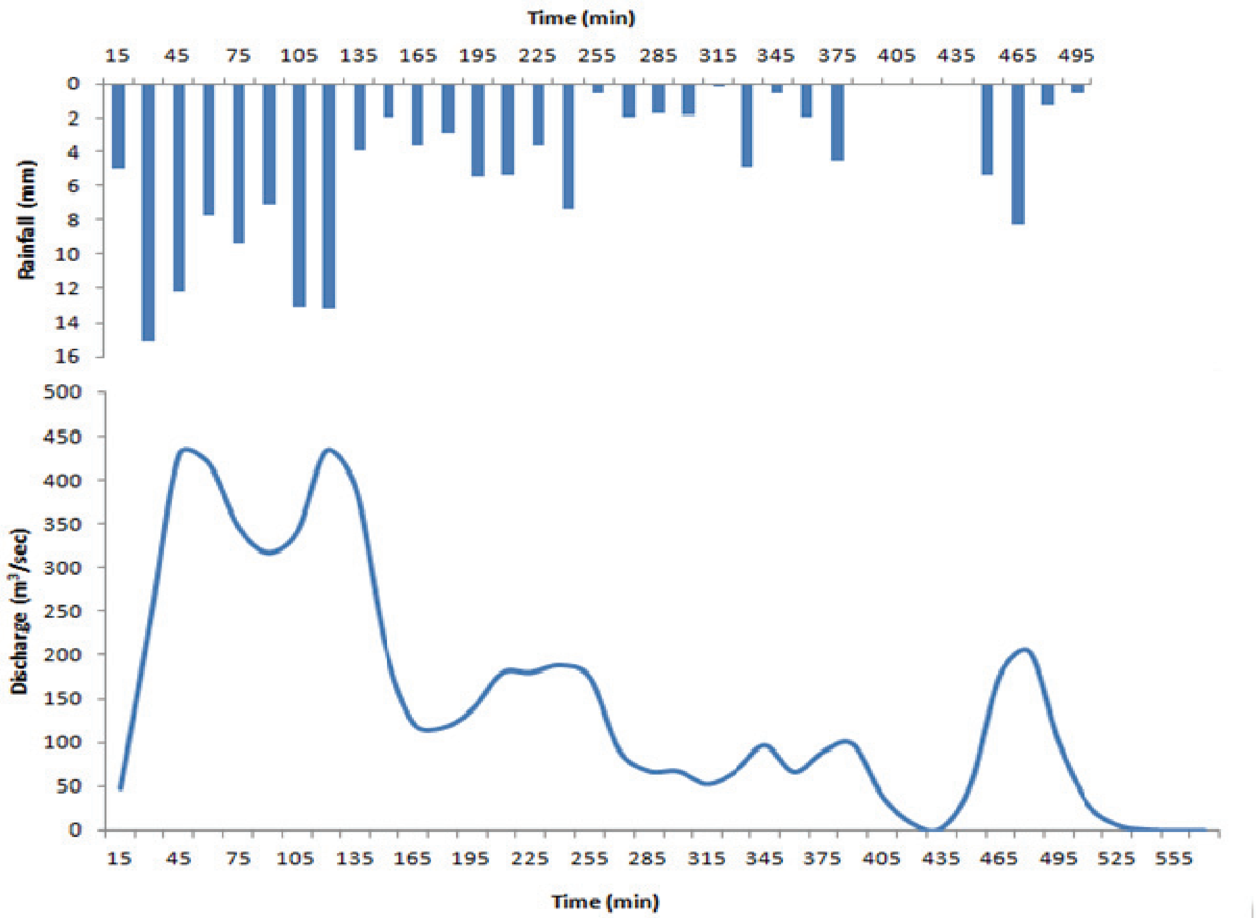

Figure 8: Discharge and precipitation versus time:

CONCLUSIONS

This study presents the process of modelling surface runoff, which is directly related to a catastrophic flood event. The approach developed for this analysis has a simple structure and can easily be performed in a GIS environment. It uses only DEM, land cover, soil type, and rainfall data, which are becoming more and more available and most parameters that are needed for this method can be derived from these data. The time-area method provides a unit hydrograph, which requires spatially constant excess rainfall data, ignoring the spatial variation of precipitation. This model is illustrated through a unit hydrograph which presents information about the maximum value of discharge and the peak time of the event.

The present analysis can be useful for several reasons. Initially, it may be used in order to predict areas, which are vulnerable to intense flood events. Consequently, such models could contribute to the economic and environmental protection of a potentially affected area. Finally, these models can be used as tools for the construction of artificial dams (i.e., containment barriers) and halting water projects in general. For all the above-mentioned reasons, Rainfall-Runoff models are integrated systems of assessing possible impacts for severe flood events.

The procedure presented in this study, i.e., the GIS-based distributed unit hydrograph, is a model which gives satisfactory results and it uses only two kinds of data as initial input data. These are a DEM grid and a roughness grid. Having these data and a rainfall phenomenon, it is very easy to follow the steps described in this current paper, in order to estimate the peak discharge and the critical time to reach this discharge.

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