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RAINFALL-RUNOFF SIMULATION IN AN EXPERIMENTAL BASIN USING GIS METHODS

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A GIS-based rainfall-runoff model was developed to simulate the runoff discharge at the outlet of a 15.18 km² gauged steep watershed that is located at the prefecture of Attica, Greece. The model's core is the time-area routing technique, which shares the assumptions of the unit hydrograph theory. This technique accounts for translation, does not account for watershed storage effects and is applicable mainly to small to midsized watersheds. GIS was used to develop the watershed cumulative travel time map that was divided into isochrones in order to generate the time-area histogram. Basic maps were the rasters of digital elevation model and landuse that were processed to derive the rasters of slope, flow direction, flow accumulation and roughness coefficient. The model was calibrated and validated using the observed rainfall-runoff data from thirty storm events. Two simulated hydrographs were calculated for each storm event, using the watershed time-area histogram and two temporal distributions of excess rainfall, estimated by the SCS and the Phi-Index methods. The simulated values of peak flow rate and time to peak were compared with the observed values, via statistical methods. A sensitivity analysis indicated the effect of various parameters on the simulated hydrographs.

INTRODUCTION

The rainfall-runoff relationship in watersheds has long been at the center of hydrologic research. The runoff volume, peak flow rate and time to peak are important parameters for the accurate design of flood control structures, the delimitation of flood plains etc. Because only a few rivers are gaged and the period of record is often short for safe estimation of the above parameters, many parametric models have been developed in order to connect the discharge with the rainfall data and the watershed characteristics. The contribution of geographic information systems (GIS) to hydrologic modeling is significant. GIS supports hydrologic analysis and modeling by describing the physical environment through which water flows, performs basic geospatial data-management tasks and spatial data processing, provides characteristic properties of watersheds and river reaches for hydrologic modeling, displays data, delineates watersheds and represents channel shapes based on digital elevation models (Maidment, 2002). The ESRI's ArcGIS Desktop-ArcInfo 8.1 software was used in this study. ArcInfo Workstation-Grid provided the necessary functions to analyze the digital elevation model and to obtain hydrologic features. Raster-based calculations were conducted in ArcMap, using the extension of Spatial Analyst (McCoy and Johnston, 2001). The resolution of the digital elevation model and the produced rasters was 20 m.

The model relies on the time-area routing technique to derive the discharge hydrograph due to a given excess rainfall hyetograph. This technique is believed to work best for small to midsized watersheds, where translation dominates the runoff processes. Furthermore, it does not account for watershed storage effects and shares the assumptions of the unit hydrograph theory. This means that a unique time-invariant transfer function is applied for watershed runoff hydrograph calculations regardless of the excess rainfall input (Saghafian et al., 2002). The watershed cumulative travel time map is divided into sub-areas separated by isochrones, which are lines of equal travel time to the outlet and are used to generate the time-area histogram. This histogram represents the portion of the watershed area that contributes to runoff during a specific period of time and is a prerequisite for the computation of the simulated hydrographs. The other prerequisite is a given excess rainfall hyetograph.

In this study, the SCS and the Phi-index methods were used for the estimation of the temporal distribution of excess rainfall. These temporal distributions combined with the time-area histogram resulted in two simulated hydrographs for each storm event. The simulated hydrographs were compared with the observed ones based on the statistics of relative error and average relative error in the peak flow rate and time to peak flow rate.

The objectives of this study were:

§ The development of a GIS-based rainfall-runoff model that relies on the watershed time-area histogram to derive the discharge hydrograph due to a given excess rainfall hyetograph

§ The determination of the most appropriate estimation method of excess rainfall, through the comparison between the simulated and the observed hydrographs

§ The determination of the effect of basic parameters on the resulting simulated hydrographs, through sensitivity analysis.

STUDY AREA

The watershed is located on the eastern side of the Penteli mountain, at the prefecture of Attica, Greece (Figure 1). The geometrical shape is oblong in the north-south direction. Concerning the

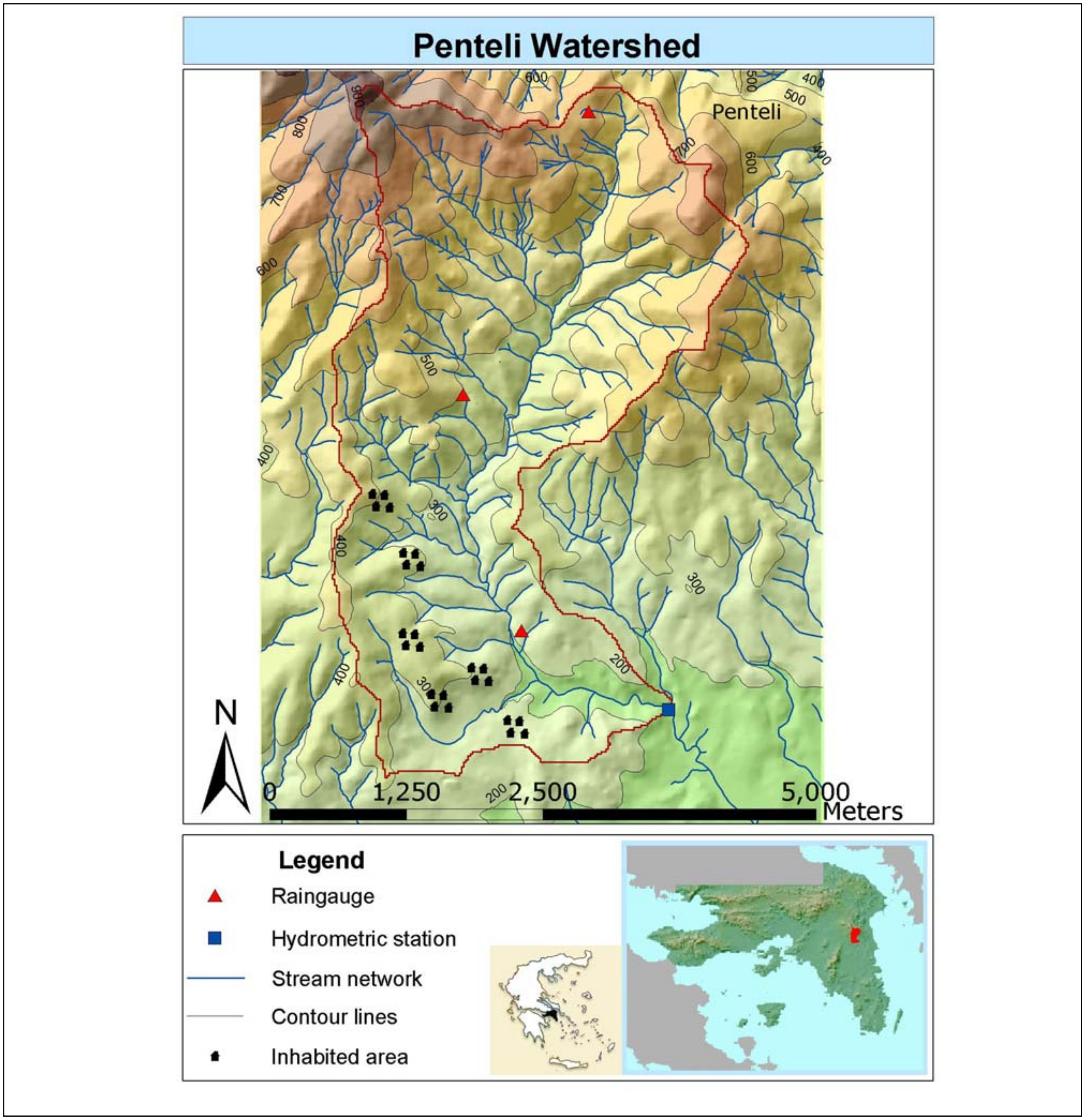

Figure 1. The study area

topographic characteristics, the drainage area is 15.18 km^2, the perimeter is 21.1 km, the average altitude is 430 m (146 m and 950 m is the minimum and maximum altitude respectively). The average slope of the terrain is 12 degrees (21.2%) and the maximum is 38.45 degrees (79.4%). The northern part of the watershed is characterized by steep slopes and rocky areas, in the place of which a forest existed in the past. The southern part presents slightly gentler slopes and is sparsely populated (Drafi). The Drafi settlement constitutes about 29% of the total area and the rest is covered by sparse vegetation, consisting mainly of bushes.

A raingauge network and a hydrometric station were installed and are operating within the watershed boundaries. The raingauge network consists of three gauges that record at ten-minute intervals the rainfall volume since October 2003. The gauges are properly installed at 220, 400 and 620 m altitude in order to give the complete picture of rainfall for the entire watershed. The hydrometric station, which is located at the watershed outlet (146 m altitude), consists of a stage recorder for the water level at ten-minute intervals since January 2003. Frequent discharge measurements are taken via a current flow meter for the compilation of the stage-discharge curve.

The length of the main channel is 7456 m and the density of the channel network is 3.72 km/km^2, which implies very good drainage. The baseflow reaches a minimum value in August and a maximum in February.

Regarding the soil characteristics, the southern part of the watershed is covered by Neogene formations with high proportion of clay. The northern part consists mainly of Schist formations with an upper erodible layer of low permeability. There is also a small percentage of marbles with good water capacity, owing to the numerous fissures that have been extended by the karstic activity.

The climate at the prefecture of Attica is Mediterranean with a mean annual precipitation of 400 mm, and most of the rainfall events occur between October and March.

DATA ANALYSIS

Selection of the rainfall-runoff events

Thirty rainfall-runoff events were selected between January 2003 and November 2004, based on the following criteria:

§ a minimum rainfall volume of 4 mm

§ the events during which snowmelt contributed to runoff were excluded

§ the event was considered to be over when there was at least a six hour period without rainfall

The watershed surface rainfall was calculated using the Thiessen polygon method and the analysis time step was 30 minutes.

Baseflow separation

The logarithmic method was used to separate the observed hydrographs into direct runoff and baseflow and the logarithms of discharge were calculated and plotted. The points of inflection indicate the starting point of direct runoff on the rising limb of the hydrograph and the ending point of direct runoff on the falling limb of the hydrograph. Finally, the total direct runoff volume was calculated in each rainfall event.

Estimation of the temporal distribution of excess rainfall

The excess rainfall temporal distribution in each storm event was estimated using two methods, the SCS and the Phi-index. A prerequisite for these calculations was the total excess rainfall volume in each storm event, that was derived from the previous baseflow separation.

The SCS rainfall-runoff relationship is given by the following equation:

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

where:

P is the total rainfall volume (mm)

Pe is the total excess rainfall volume (mm)

Ia is the initial abstraction (mm)

S is the total volume of the watershed storage (mm)

The above relationship is used when the event total rainfall volume (P) is greater than the volume of the initial abstraction (Ia). In the opposite case, the excess rainfall volume is equal to zero. The initial abstraction Ia consists mainly of interception, infiltration and surface storage, all of which occur before runoff begins. S is mainly the infiltration occurring after runoff begins and is controlled by the rate of infiltration at the soil surface (SCS National Engineering Handbook, 1972).

The steps that were followed for the estimation of the SCS excess rainfall temporal distribution in each of the thirty storm events, were the following:

§ First, the total excess rainfall volume (Pe) was calculated based on the separation of the observed hydrograph into direct runoff and baseflow. The next step was the calculation of the initial abstraction (Ia), which is equal to the accumulated rainfall from the beginning of the storm to the time when direct runoff started

§ Then, the total volume of watershed storage (S) was calculated using Equation (1)

§ Finally, on a thirty-minute time step, the rainfall values were accumulated and tabulated. Then, at each time step, the accumulated excess rainfall value was calculated using Equation (1). The increment of excess rainfall in a time step is the difference between the accumulated excess rainfall at the end of that time step and the accumulated excess rainfall at the beginning of that time step.

The Phi-index method assumes that the losses are distributed uniformly during the storm event, resulting in the overestimation of the starting excess rainfall intensity and in the underestimation of the ending excess rainfall intensity (Mimikou and Baltas, 2002). The sum of the rainfall volume, below the Phi-index line, represents the losses and above the line represents the total excess rainfall volume.

MODEL DEVELOPMENT

The model algorithm consists of four basic components. The time-area histogram is calculated via the first three components and the simulated hydrograph is calculated at the watershed outlet in the final component. The flow chart for the calculation of the time-area histogram is shown in Figure 2.

In the first component, topographic and hydrologic properties of the watershed are extracted from the digital elevation model (DEM). The DEM of the watershed was generated from the digitized elevation contours of (1:5000 scale) topographic maps, the digitized channel network and topographic points of known altitude. These three coverages are necessary in the interpolation technique of TOPOGRID, which is available in ARC (Arc/Info Workstation). TOPOGRID imposes constraints on the interpolation process that result in connected drainage structure and correct representation of ridges and streams. The generated DEM contained sinks that could result in an erroneous flow direction grid, thus, the GRID command FILL was used to create the depressionless DEM, which comprises the base for the determination of the watershed decimal slope grid using the Spatial Analyst extension. Next, the FLOWDIRECTION function, operating on the depressionless DEM, determined the direction of flow by finding the direction of steepest

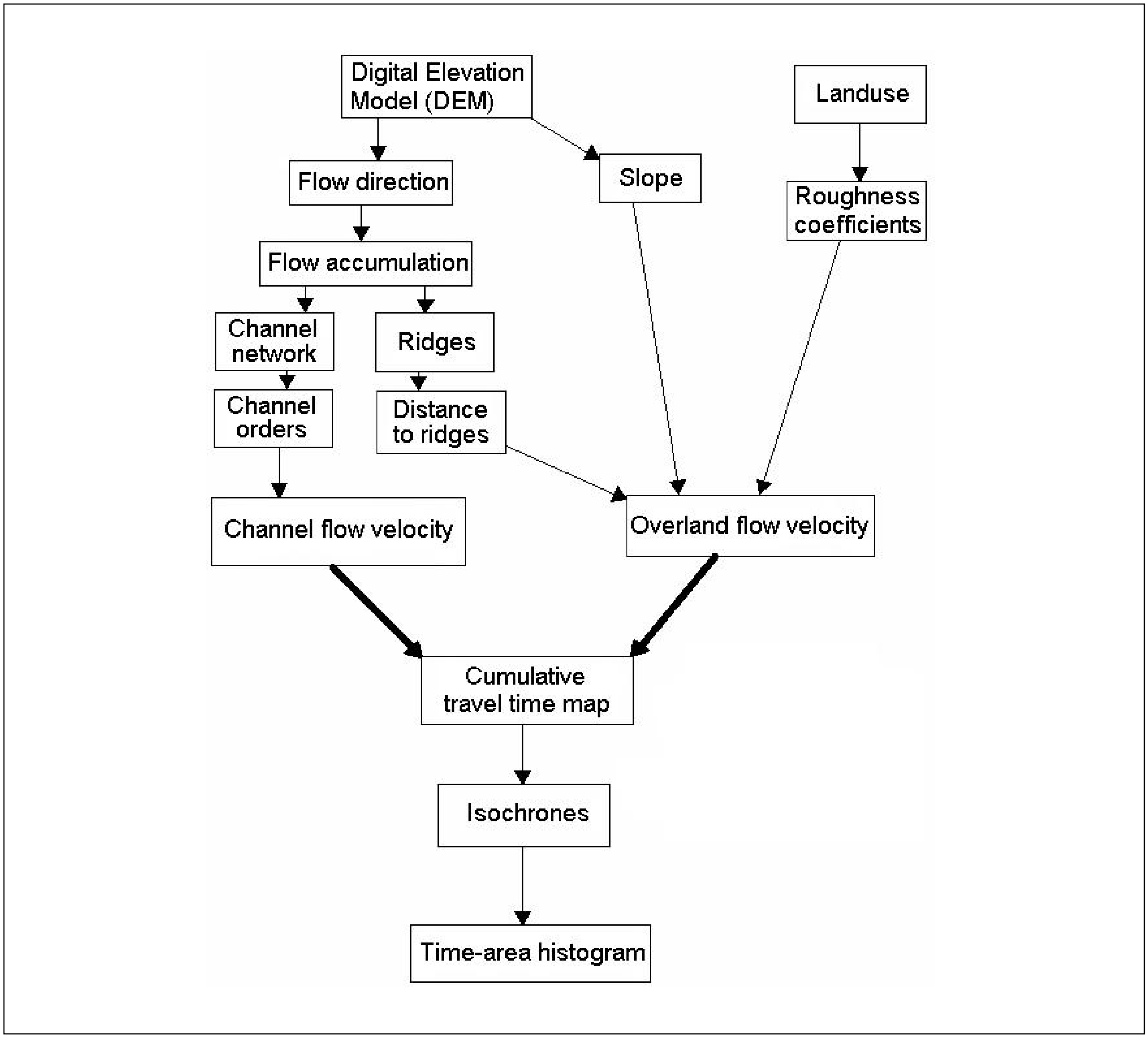

Figure 2. The flow chart.

descent from each cell in the grid. The FLOWACCUMULATION function, based on the flow direction grid, calculated the number of upstream cells that flow into each cell.

The channel network was delineated by applying a threshold value to the flow accumulation grid using the GRID function CON. Cells with a flow accumulation less than the threshold value were considered cells of overland flow and cells with a flow accumulation equal or greater than the threshold value were considered cells of the channel network. In this study, the threshold value was 50 cells or 20000 m^2. Supposing that the area that contributes to runoff is semicircular, the 20000 m^2 area corresponds to an overland flow length of 112 m. This is consistent with the recommendation of Huggins and Burney (1982) that the overland flow can only exist for the first 100 meters along the flow path before the runoff concentrates into small rills (Kilgore, 1997; Al-Smadi, 1998).

Once created, there was almost a perfect match between the digitized and the GIS-derived channel network. The Strahler method of the STREAMORDER function was used to classify the channels in orders. Finally, the ridges of the sub-watersheds were identified, based on the fact that the cells with a zero flow accumulation are local topographic highs.

The flow velocities are determined in the second component. The surface runoff is classified into overland flow and channel flow. The overland flow is observed on the watershed cells that are not part of the channel network and was calculated based on the combination of kinematic wave theory with Manning's equation. The overland flow is simulated with the flow in a wide orthogonal channel and the kinematic wave theory can be applied since steep slopes characterize the watershed. The raster of the overland flow velocity was calculated by the following equation (Kilgore, 1997; Al-Smadi, 1998):

$$V_o = \frac{(i_e x)^{0.4} S_o^{\ 0.3}}{n^{0.6}} \tag{2}$$

where:

V_o is overland flow velocity (m/s)

x is distance along the flow plane (m)

S_o is decimal slope

n is Manning's roughness coefficient

i_e is excess rainfall intensity (m/s)

The distance (x) along the flow plane was considered to be the distance of each grid cell from the closest ridge cell and it was calculated in Spatial Analyst. The roughness coefficient grid was based on the watershed's landuse map and the values derived from literature tables (Arcement and Schneider, 1984). The excess rainfall intensity (i_e) is one of the model's parameters and resulted from the calibration process.

The channel flow velocity constitutes the second of the model parameters and also resulted from the calibration process. The discharge measurements at the watershed outlet were used for the comparison between the calibrated value and the measured average flow velocity of the main channel.

The time-area histogram is determined in the third component. This histogram shows the portion of the watershed area that drains to the outlet during each time interval and is used for the computation of the simulated hydrograph in each rainfall event. The cumulative travel time of any grid cell results from the sum of each cell's travel time along the optimal flow path that a raindrop follows from the time it reaches the cell's surface until the watershed outlet. According to Saghafian et al., (2000), the cumulative travel time reflects the time required for a kinematic wave to travel from any cell to the outlet under equilibrium conditions. The cumulative travel time grid was calculated using the GRID function FLOWLENGTH. The function's inputs are the flow direction grid and the inverse of the final flow velocity grid, which is equal to the sum of the overland and the channel flow velocity grids. The watershed isochrones were developed on a thirty minute time step via the classification of the cumulative travel time grid. Finally, the time-area histogram was generated by measuring the incremental areas between the adjacent isochrones.

The computation of the simulated hydrograph takes place in the fourth component. Each simulated hydrograph resulted from the application of the temporal distribution of excess rainfall to the time-area histogram. More specifically, the excess rainfall intensity of the first thirty-minute period of time was multiplied by the values (area) of the time-area histogram, resulting in a flood hydrograph. The same was performed for the rest of the excess rainfall time intervals. Each flood hydrograph was temporally (30 minutes) displaced from the next. The final simulated hydrograph was calculated according to the superposition principle from the horizontal sum of the ordinates of the incremental flood hydrographs that were developed for each excess rainfall time interval.

Description of the model calibration

The model parameters are: (i) excess rainfall intensity, which is included in the overland flow velocity equation and (ii) the channel flow velocity. Five rainfall-runoff events were selected for the calibration of the above parameters, based on the following criteria: intense, short duration rainfall event, typical bell-shaped hydrograph. Many tests were conducted with various combinations of the parameters' values, in order to get simulated hydrographs that approached (in terms of shape, peak flow rate and time to peak), as close as possible to the observed hydrographs. After the calibration, the model was validated using the remaining rainfall-runoff events.

RESULTS

The model calibration resulted in the determination of the following parameters:

The excess rainfall intensity was set 10^{-6} m/s (or 0.6mm/10min). Applying this value to the overland flow velocity equation, the distribution of the resulting overland flow velocity grid was calculated, as shown in Table 1.

Regarding the channel flow velocity, different values were applied to channels of different order. The applied values gradually decreased from the fourth-order main channel till the first-order channels. The final applied values are shown in Table 2.

Discharge measurements that were made at the watershed outlet at the duration of two storm events with peak flow rate greater than 1 m^3/s, showed that the maximum channel flow velocity during each event's peak flow rate was 1.1 m/s. This value was calculated by dividing the peak flow rate (m^3/s) by the cross-section (m^2). The cross-section, where the discharge measurements took place, is wider than the typical V-pattern cross-sections of the main channel, implying that the channel flow velocity may be much higher in another cross-section.

The developed isochrones (Figure 3) follow the dendritic pattern of the channel network, since the channels and the areas close to them drain to the outlet faster, compared to other areas, because of their higher flow velocities. According to the isochrones, the watershed time of concentration is practically 2.5 hours. This value confirms the time of concentration that is calculated based on the observed rainfall-runoff events. Two simulated hydrographs were calculated for each of the thirty rainfall events, using the time-area histogram (Figure 4) of the watershed and the temporal distributions of excess rainfall, estimated by the SCS and the Phi-index methods.

Table 1. Area-overland flow velocity distribution.

% of the total watershed area	Overland flow velocity (m/s)
6.03	0.016-0.040
39.71	0.040-0.060
27.16	0.060-0.080
16.16	0.080-0.100
10.93	0.100-0.176

Table 2. Applied values of channel flow velocity.

Channel order	Channel flow velocity (m/s)
1st	0.8
2nd	1.0
3rd	1.2
4th	1.4

One of the five rainfall-runoff events that were selected for the parameters' calibration is shown in Figure 5, while in Figure 6 a rainfall-runoff event that was used for the validation of the resulting parameters is depicted.

The SCS simulated hydrographs successfully approached in shape, peak flow rate and time to peak flow rate, the observed hydrographs, in the majority of the rainfall events, even in the case of long duration rainfall events that were characterized by different peak discharges. This indicates that the watershed time-area histogram was successfully developed and that the SCS excess rainfall estimation method worked very well. In some long duration rainfall events, the simulated falling limb of the hydrograph presented a steeper slope related to the corresponding limb of the observed hydrograph and the simulated runoff ended before the observed. This is due to the fact that after the end of the rainfall, a large amount of water that has been stored on the watershed's surface, mainly in the channel network, now drains to the outlet, increasing the hydrograph's base duration.

A peak flow rate and a time to peak flow rate analysis followed, where the estimated values of peak flow rate and time to peak flow rate, were compared with the corresponding observed values. The statistics of relative error and average relative error were used for this purpose.

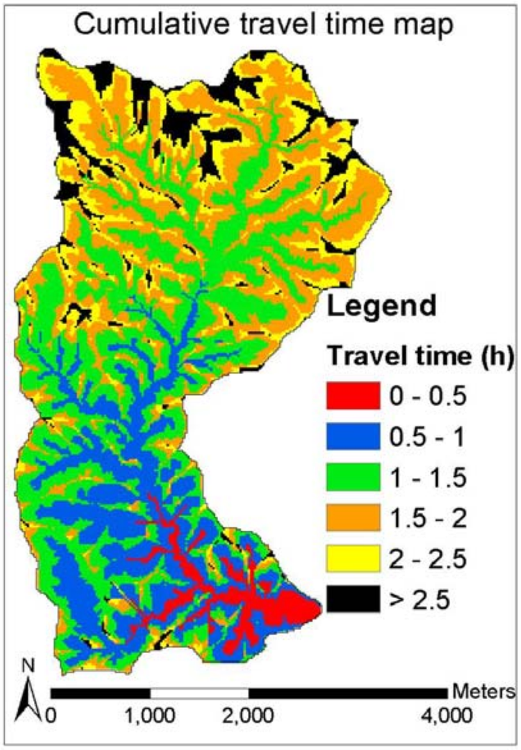

Figure 3. Cumulative travel time map.

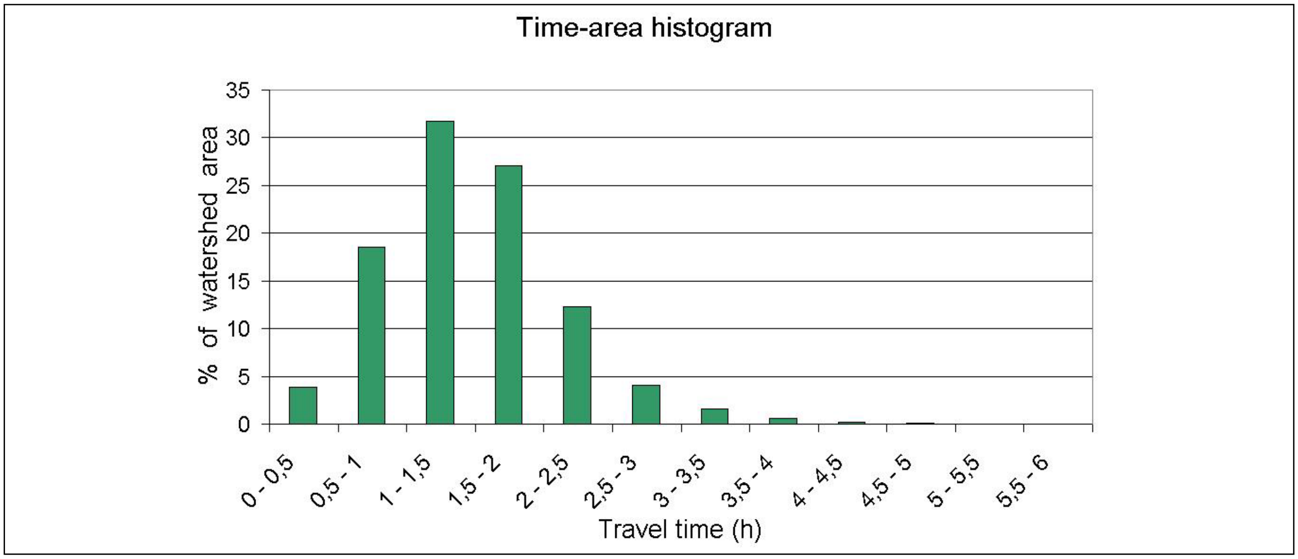

Figure 4. Time-area histogram.

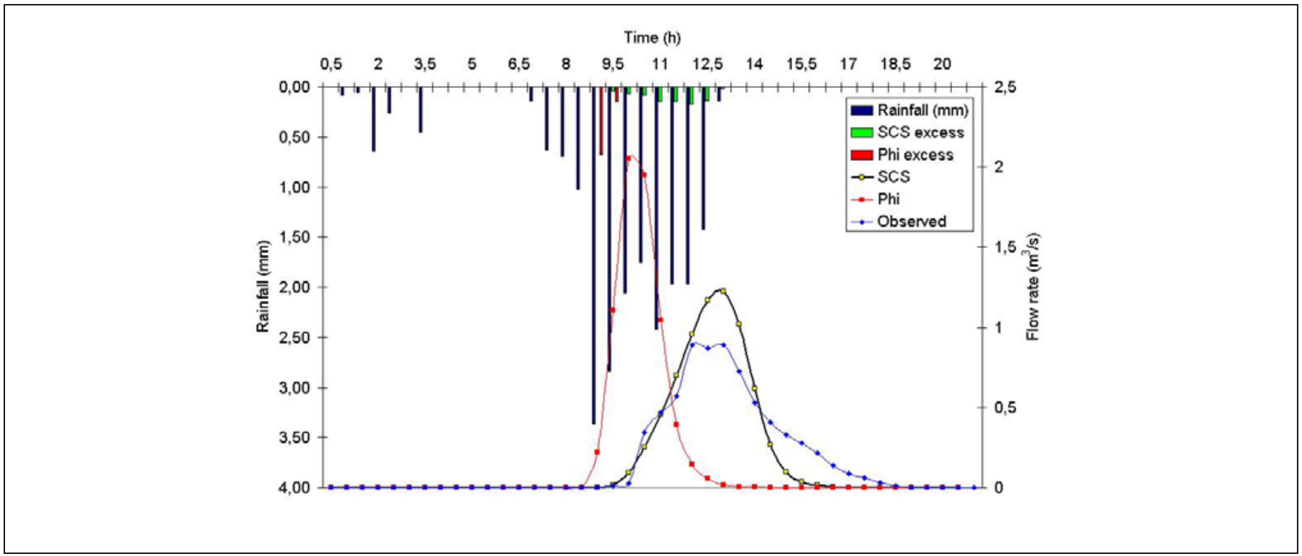

Figure 5. Rainfall event 25/12/2003.

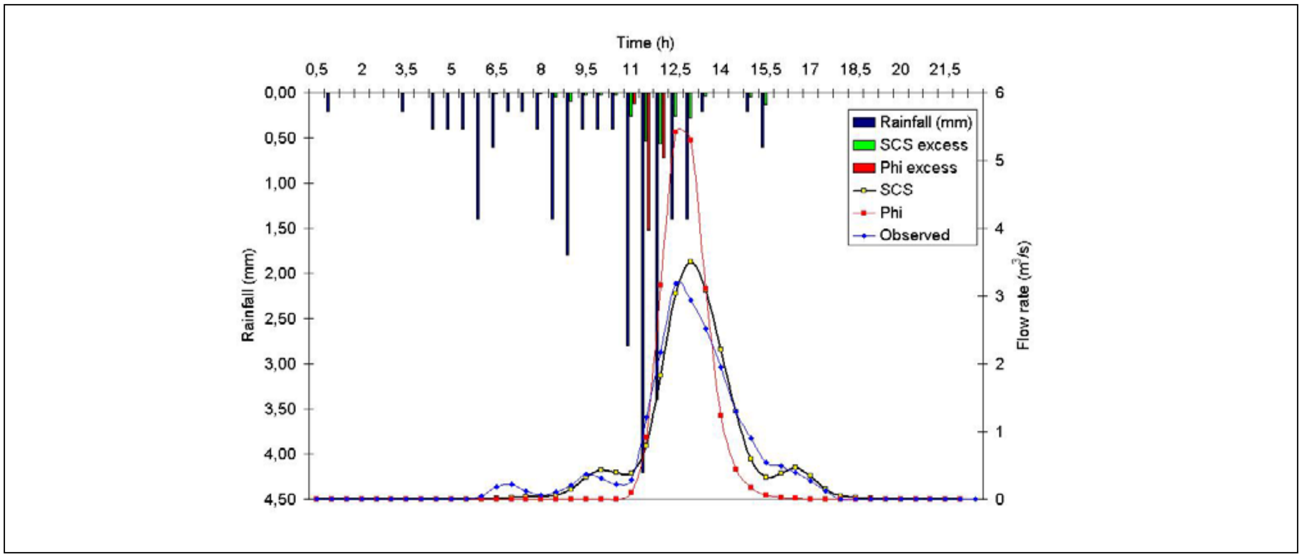

Figure 6. Rainfall event 02/02/2003.

Regarding the peak flow rate analysis (Figure 7), the estimated values of the SCS method closely approached the observed values, in both small and large rainfall events. On the other hand, the estimated values of the Phi-index method were much greater than the observed values. The Phi-index method had relatively good estimates in short-duration rainfall events. However, in long duration events, the simulated hydrographs had by far higher peak flow rates compared to the observed hydrographs, since the rainfall intensity was not temporally uniform. More specifically, there were time periods of great rainfall intensity during which the Phi-index method distributed the total of the event's excess rainfall volume. This resulted in very high peak flow rate in the simulated hydrograph. The average relative error in the peak flow rate was 0.213 for the SCS method versus 0.951 for the Phi-index method. The categories of absolute relative error are shown in Table 3.

The time to peak flow rate is equal to the period of time from the beginning of the storm to the time when peak flow rate occurred. The analysis showed that the estimates of the SCS method were good (Figure 8). The absolute relative error was lower than 0.1 in 70% of the simulated hydrographs (Table 4). The corresponding percentage was 36.7 % for the Phi-index simulated hydrographs, in 50% of which the time to peak was underestimated. The average relative error for the SCS method was 0.108 versus 0.178 for the Phi-index method.

Further analysis based on the rainfall volume was performed. The rainfall events were classified according to their rainfall volume and for each category, the average relative error in the peak flow rate and time to peak flow rate were calculated for both of the excess rainfall estimation methods (Table 5). The analysis showed an increase in the average relative error in the peak and time to peak flow rate, as the rainfall volume increases. This increase was greater for the Phi-index estimation method.

A sensitivity analysis was performed in order to evaluate the effect of various parameters on the simulated hydrograph. The parameters that were analyzed were: (i) overland flow velocity, (ii) channel flow velocity, (iii) analysis time step. The overland flow velocity has a great impact on the peak flow rate and the shape of the resulting hydrograph. Doubling the overland flow velocity, the resulting hydrograph had 27% increased peak flow rate and a much shorter falling limb. The channel flow velocity affects both the peak and time to peak flow rate. Increasing the velocities of the first, second, third and fourth order channels 100%, 66%, 50% and 40%, respectively, the time to peak flow rate decreased 40% and the peak flow rate increased 23.3%. Two time steps of thirty and sixty minutes were used in the time step analysis. Increasing the time step, there was little change in the peak flow rate, but the time to peak flow rate increased 33.3%, implying that the results are more accurate when a short analysis time step is used.

CONCLUSIONS

The proposed model is based on the time-area technique, which shares the assumptions of the unit hydrograph theory. A single time-area histogram was developed and used for the computation of the simulated hydrograph in each rainfall event. The input of these computations was the temporal distribution of excess rainfall estimated by the SCS and Phi-index methods. Evaluating the model results, it is concluded that:

§ The model performed well for the majority of the observed hydrographs implying that the time-area histogram, which constitutes the model's core, was successfully developed. The time-area technique does not account for watershed storage effects and this was noticed in some long-

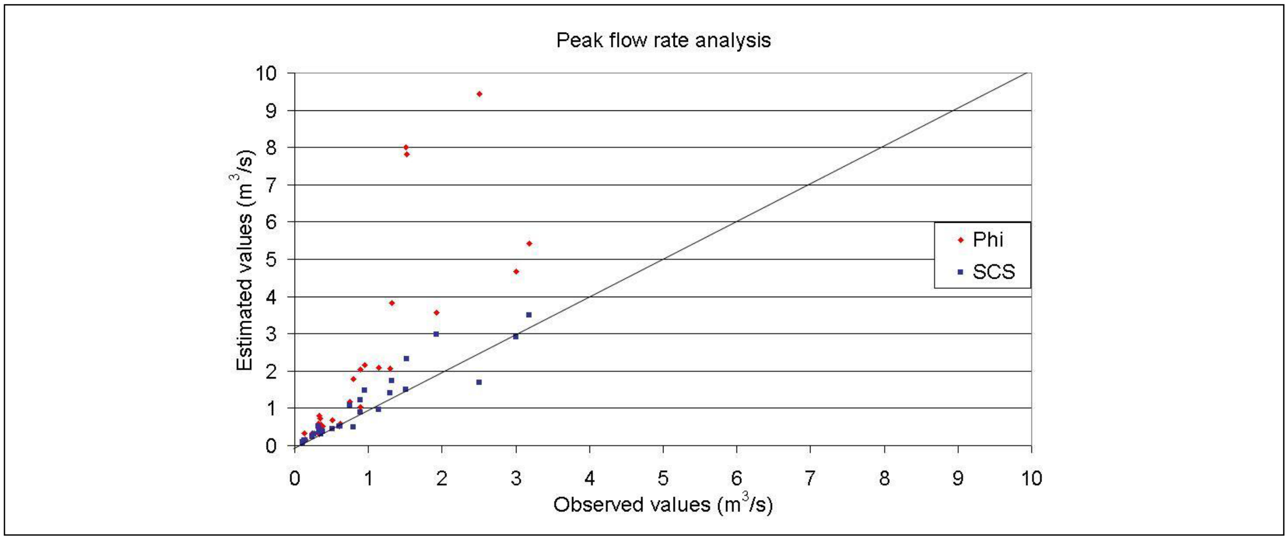

Figure 7. Estimated versus observed peak flow rate.

Table 3. Absolute relative error in the peak flow rate.

Absolute Relative Error (R.E) in the **peak flow rate**	% of the SCS simulated hydrographs	% of the Phi-index simulated hydrographs
R.E. < 0.1	30.0	13.30
0.1 < R.E. < 0.2	30.0	13.30
0.2 < R.E. < 0.3	6.7	3.33
0.3 < R.E. < 0.4	16.7	10.00
R.E. > 0.4	16.7	60.00

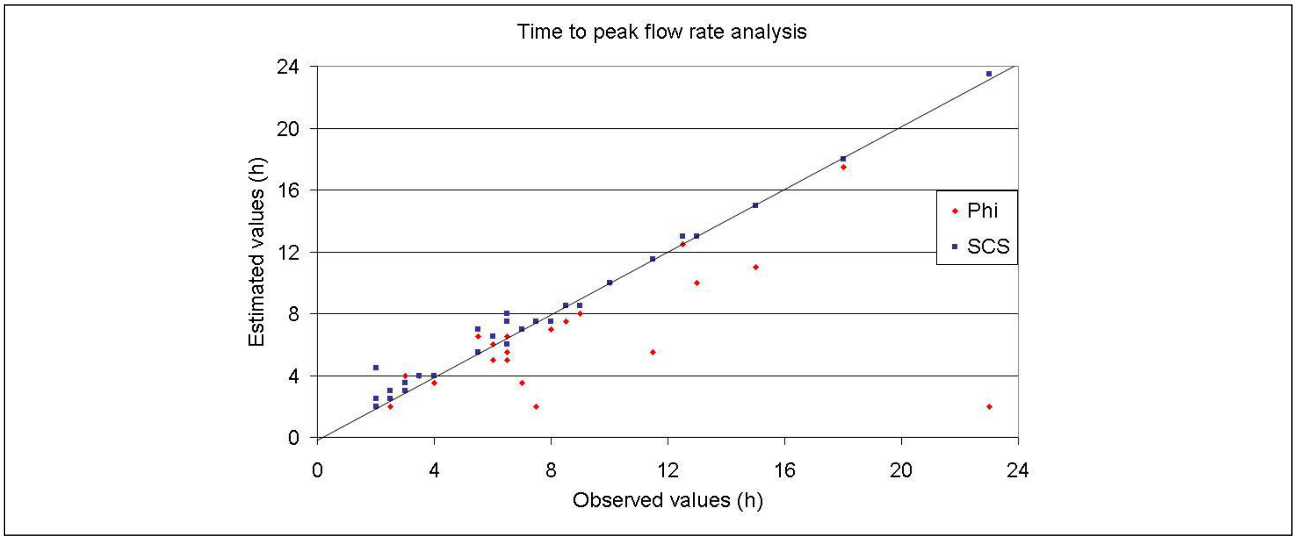

Figure 8. Estimated versus observed time to peak flow rate.

duration rainfall events, where the simulated runoff ended before the observed

§ The estimation of the temporal distribution of excess rainfall is fundamental for the simulated hydrograph. The SCS method estimated with a good approximation the temporal distribution of excess rainfall, resulting in simulated hydrographs that closely approached

Table 4. Absolute relative error in the time to peak flow rate.

Absolute Relative Error (R.E) in the time to peak flow rate	% of the SCS simulated hydrographs	% of the Phi-index simulated hydrographs
R.E. < 0.1	70.0	36.7
0.1 < R.E. < 0.2	16.7	36.7
0.2 < R.E. < 0.3	13.3	26.6

Table 5. Rainfall volume analysis.

	Average relative error (Peak flow rate)		**Average relative error** (Time to peak flow rate)	
Rainfall volume (mm)	**SCS**	**Phi-index**	**SCS**	**Phi-index**
4 < P < 10	0.168	0.251	0.075	0.135
10 < P < 30	0.202	0.771	0.082	0.190
P >30	0.314	2.537	0.222	0.222

observed peak flow rate and time to peak. This was seen in both large and small storm events. The Phi-index method did not provide a good estimation of the temporal distribution of excess rainfall in most of the high volume and long-duration rainfall events, because of the great variations in rainfall intensity.

§ According to the sensitivity analysis, the overland flow velocity significantly affects the simulated peak flow rate. The channel flow velocity has major influence on the time to peak flow rate and less on the peak flow rate. A short analysis time step leads to more accurate simulated hydrographs, especially as regards the time to peak flow rate

§ The model could be further improved by taking into account other approaches for the spatial distribution of excess rainfall and the storage of the watershed.

REFERENCES

Al-Smadi, M. 1998. Incorporating spatial and temporal variation of watershed response in a Gis-based hydrologic model, MS thesis, Faculty of the Virginia Polytechnic Institute and State University, Blacksburg.

Arcement, G.J.Jr., and V.R. Schneider. 1984. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains, United States Geological Survey Water-supply Paper 2339, Metric Version.

Huggins, L.F., and J.R. Burney. 1982. Surface runoff, storage and routing in Hydrologic Modeling of Small Watersheds, eds. C.T. Haan, H.P. Johnson, D.L. Brakensiek, ch. 5, 169-225. St. Joseph, Mich.: ASAE.

Kilgore, J.L. 1997. Development and evaluation of a Gis-based spatially distributed unit hydrograph model. MS thesis, Biological Systems Engineering Dept., Faculty of the Virginia Polytechnic Institute and State University, Blacksburg.

Maidment, D. 2002. ArcHydro-Gis for Water Resources, ESRI Press, Redlands California.

McCoy, J., and K. Johnston. 2001. Using ArcGis Spatial Analyst, GIS by ESRI.

Mimikou, M., and E. Baltas. 2002. Technical Hydrology, Faculty of Civil Engineering, Sector of Water Resources, Hydraulic and Marine Structures, National Technical University of Athens.

Saghafian B., P. Julien, and H. Rajaie. 2000. A spatial travel-time method for watershed routing, 4th International conference on integrating Gis and Environmental Modeling (GIS/EM4), Canada, September 2-8, 2000.

Saghafian B., P. Julien, and H. Rajaie. 2002. Runoff hydrograph simulation based on time variable isochrone technique, Journal of Hydrology 261 (2002) 193-203.

SCS National Engineering Handbook. 1972. Estimation of direct runoff from storm rainfall by Victor Mockus. Section 4, Hydrology.

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