Journal of Spatial Hydrology

Volume 6 Article 7

2006

Rainfall-Runoff Modeling for an Experimental Watershed of Western Greece Using Extended Time-Area Method and GIS

Journal of Spatial Hydrology
Vol.6, No.1 Spring 2006

Rainfall-Runoff Modeling for an Experimental Watershed of Western Greece Using Extended Time-Area Method and GIS

Athanassios Bourletsikas[1], Evangelos Baltas[2] and Maria Mimikou[3]

Abstract

In this study, an effort was made to simulate the transformation of rainfall into runoff, in a small experimental mountainous-forested watershed in western Greece. The main objective was the production of flood hydrographs by calculating average flow velocities (inside and outside the stream network). The usefulness of the flow velocities lies in using them in other ungauged small-forested watersheds that have similar geomorphological and hydrological characteristics. The meteorological and hydrological data of four storm events were obtained from the corresponding stations that are located near and at the outlet of the watershed, respectively. Geographic Information Systems (GIS) technology was used for the obtainment of the spatially distributed watershed characteristics. The resolution of the digital elevation model and the produced rasters was 50X50 m^2. By integrating all information, a simplified model was developed, which is based on the Time – Area (TA) rainfall – runoff flow routing technique. The first results were satisfactory, especially the simulation of the ascending curve of the simulated flood hydrographs.

Key words: Rainfall-runoff modeling, Forested watershed, Time-area method, Flow velocity, GIS, Greece.

INTRODUCTION

A hydrological model is a mathematical simulation of the complex hydrological cycle. The rainfall – runoff mathematical simulation is necessary for the understanding of the interaction between the climatic, terrestrial, topographic and hydrological elements of a watershed. A number of mathematical models has been developed for the investigation of these physical processes. Additionally, many researchers proposed a variety of surface runoff models that usually interact with Geographic Information Systems (GIS) (DeVantier and Feldman 1993, Olivera and Maidment 1996, Jain et al. 1997, Gorokhovich et al. 2000, Saghafian et al. 2000, Melesse et al. 2003). GIS technology is a very useful platform that is used for the production of digital elevation models (DEMs), the division of the watershed into grid-cells, in order to characterize its terrain. Furthermore, it is also used for the preparation of the appropriate input files for the models.

One of the tools that hydrologists often use for the rainfall-runoff simulation is the Time-Area (TA) method. The TA diagram is a graph that shows the cumulative drainage area that contributes to runoff during time and is derived from the sum of the incremental sub-areas of the watershed. These sub-areas are delineated by contours of equal travel time (isochrones).
Many researchers estimated the travel time by calculating the flow velocity with the kinematic wave theory (Saghafian and Julien 1995, Wang and Hjelmfelt 1998, Ajward and Muzik 2000, Wong 2003).On the contrary, other researchers (Maidment 1993, Maidment et al. 1996, Ashour 2000) allegated that the average (constant) flow velocity can be used for the

[1] National Agriculture Research Foundation (N.AG.RE.F), Institute of Mediterranean Forest Ecosystems and Technology of Forest Products, Terma Alkmanos, 115 28, Ilissia, Athens, Greece. [2] Aristotle University of Thessaloniki, Department of Agriculture, Lab of General and Agricultural Hydraulics and land reclamation, 54006, Thessaloniki, Greece. [3] National Technical University of Athens, Iroon Polytechniou 5, Zografos 15780, Greece.
Corresponding author e-mail: baltas@agro.auth.gr

estimation of the travel time of the surface runoff and therefore, for the determination of the flood hydrograph. In this case, the hydraulics of the flow system are not taken into account. Actually, two different average flow velocities are estimated; the first concerns the velocity inside the stream network (channel flow) and the second the velocity of the rest of the watershed's cells (overland flow).

The study and investigation into the flow velocities that result from the application of a model, are of great importance. According to some researchers, the magnitude of the solid transport depends on the flow velocities and the slope of the watercourse (Fox and Bryan 1999, Grunwald and Norton 2000). Additionally, Kolsky and Butler (2000) report that the total transport capacity depends on the size of the sediment transport.

The objective of this study was the development of a simplified hydrological flow routing model in a small experimental mountainous-forested watershed of western Greece. The model is based on an extension of the Time-Area (TA) concept and uses GIS tools for the manipulation of spatial data. This method has not been applied on other watersheds in Greece. The results of this study might be used in other ungauged small-forested watersheds that have similar geomorphological and hydrological characteristics.

The applied method can be described as an evolution of Clark's original methodology (Clark 1945) to spatially distributed runoff (Kull and Feldman 1998), by ignoring the storage effects on the deeper soil layers. According to Ponce (1989, chap. 10), the results of the application in small and mid-sized watersheds are very satisfactory. This is due to the fact that a constant, time-fixed transport process is applied for the calculation of the discharge, independently of the time distribution of rainfall (Saghafian et al. 2002).

METHODOLOGY

Study Area

The study area is located in the prefecture of Etoloakarnania, western Greece. (Figure 1). The drainage area of the watershed is 1.23 km^2, the average altitude is 529.6 m a.s.l. and varies from 366.3 m to 632.9 m. The mean ground slope is 13.53% (minimum ground slope = 0.35% and maximum ground slope = 33.67%). The length of the main stream is 1,373.18 m and the density of the stream network is 0.28 km/km^2. The software package that was utilised in the processing of geographic and meteorological information was GIS ArcMap (ESRI 1999). This GIS environment is integrated with the National Data Bank of Hydrological and Meteorological Information (NDBHMI). NDBHNI is a database system of crucial importance to the country's water resources, as it contains raw and processed hydrometeorological and hydrological data for the whole of Greece (NDBHMI 2000).

This watershed is a small-forested one that contributes to the flow of Acheloos River. The area is covered by pure stands of *Quercus ilex* or mixed stands of evergreen broadleaved species such as *Arbutus sp., Phyllirea sp., Erica sp., Fraxinus sp.*, etc. The dominant soil parent material in the region is the flysch (impermeable and very easily corroded formation) of the zone of central western Greece. The flysch belongs to the category of mechanical sedimentary rocks and consists of alternating layers of clay and shale sediments.

The climate of the area is the classic Mediterranean with mild winters and dry summers. The meteorological and hydrological data were taken from the corresponding stations that are located near the watershed and at the outlet, respectively (Figure 1). More specifically, the amount of precipitation in each selected event was obtained from three non-recording raingauges operating near the watershed. The temporal distribution of the rainfall was taken from the recording raingauge, which is part of the complete meteorological station. According to the available meteorological data, the mean annual precipitation for the years 1973 – 2001 is 989 mm, while the mean annual temperature for the same period is 15.1 ^{o}C. Most of the precipitation (>95%) falls in the form of rainfall and more than 75% of it falls from October to March (Vouzaras, 1999).

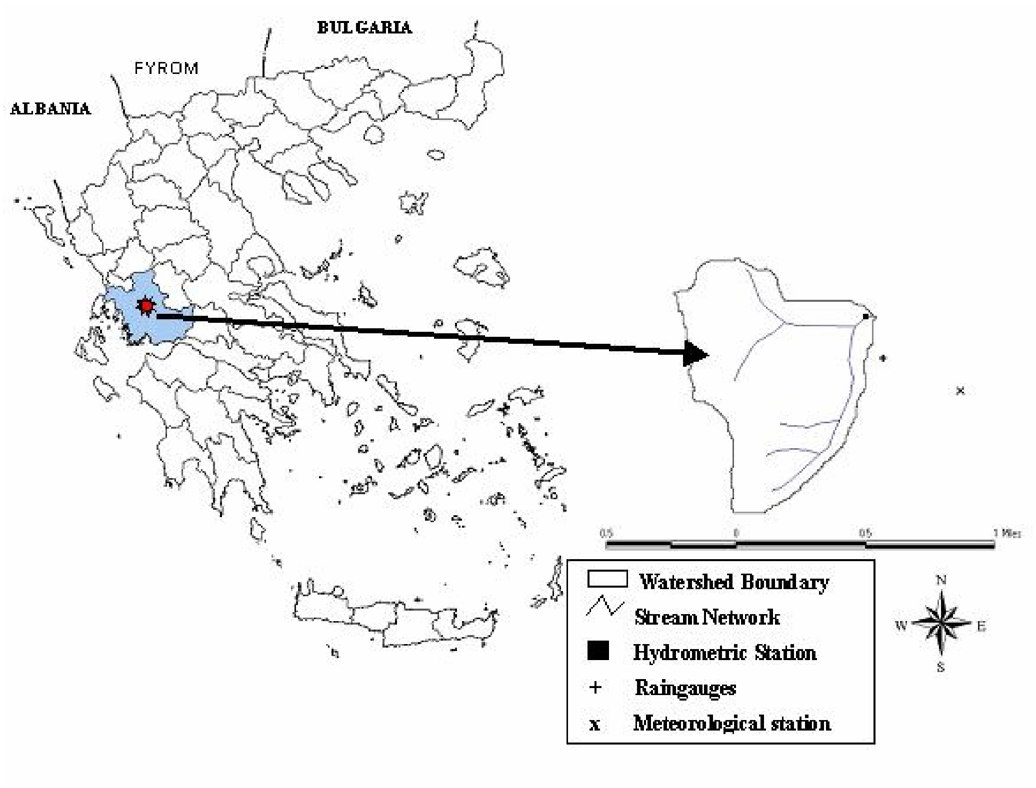

Figure 1. Map of Greece with the location of the experimental watershed.

Selection of Rainfall Events

In order to meet the aim of this work, four rainfall events were selected, based on the following criteria:

- The necessary data for each rainfall event (rainfall volume, temporal distribution and hydrograph) should be available and reliable.
- Each rainfall-runoff event occurred in the wet season (winter).

Hydrological Analysis

<u>Estimation of Hydrological Losses and Baseflow</u>

The four rainfall events were analyzed on a 15 min time-step. At this point, it is of interest to note that from the available hydrological and meteorological data, it was extremely difficult to quantify the hydrological losses separately (interception, transpiration, infiltration). So, the effective rainfall (h_e) of each event was calculated by subtracting the total losses quantified with the SCS method (SCS 1972) from the total amount of rainfall. Table 1 shows the characteristics of the selected rainfall events along with the parameters S (Potential Maximum

Retention) and CN (runoff curve number) calculated by the use of the equations (1) and (2), as follows:

$$S(mm) = 5h + 10h_e - \sqrt{h_e(h_e + 1.25h)} \qquad (1)$$

where: h is the measured rainfall and

$$S(mm) = 254(\frac{100}{CN} - 1) \qquad (2)$$

The h_e was already known from the measurement of the direct runoff (flood hydrographs – Table 2).

In order to derive each flood hydrograph, the direct runoff was calculated by subtracting the baseflow from the total runoff (Table 2). The baseflow separation was carried out by using the Hewlett and Hibbert (1967) empirical equation:

Constant Separation Slope = 0.00055*A (m^3/s)/h (3)

where: A is the total area of the watershed in km^2.

This equation gives the slope of the base flow line and corresponds in the best way, to the real hydrological behavior of a mountainous small-forested watershed. Table 2 also shows the characteristics of the runoff that resulted from the analysis of the recorded data.

Table 1. Characteristics of the selected rainfall events

Rainfall Event	**Date**	**Start Time**	**Ending Time**	**Duration (h)**	**Rainfall (mm)**	**Losses (mm)**	**Effective rainfall (mm)**	**S**	**CN**
1	**4/2/98**	16:30	4:15 5/2/98	11.75	56.2	36.2	20.0	56.2	81.9
2	**1/12/98**	13:00	21:30	8.5	48.5	39.5	9.0	82.3	75.5
3	**21/12/98**	0:15	8:15 22/12/98	32	105.4	73.2	32.2	122.6	67.4
4	**9/1/01**	2:00	4:15	2.25	35.5	29.3	6.2	62.5	80.3

Table 2. Characteristics of the corresponding total flood hydrographs

Rainfall Event	Date and Start Time	Duration (h)	Date and Time to Peak	Peak Runoff (m^3/s)	Total runoff (mm)	Direct runoff (mm)	Base flow (mm)	Runoff coefficient
1	4/2/1998 20:30	48.75	5/2/1998 7:45	0.8526	26.9	20.0	6.9	0.36
2	1/12/1998 16:15	23.5	22:30	0.5222	10.4	9.0	1.4	0.18
3	21/12/1998 9:15	45.25	22/12/1998 2:30	1.3952	36.8	32.2	4.6	0.30
4	9/1/2001 3:00	23.25	4:45	0.5410	7.9	6.2	1.7	0.17

Rainfall-Runoff Modeling

A time-area method utilises a convolution of the effective rainfall hyetograph with the service of a time-area diagram. This diagram represents the progressive area contributions within a watershed as the time increases. Two different average flow velocities (inside and outside the stream network) had to be calculated for the production of the time-area diagram. The procedure for this production consists of the following three phases:

In the first phase, the ESRI's ArcGIS Desktop-ArcInfo 8.1 software was used. ArcInfo Workstation-Grid provided the necessary functions for the process of the digital elevation model (DEM file) and the obtainment of the hydrologic features. Raster-based calculations were conducted in ArcMap using the extension of Spatial Analyst. Two more important files were also created:

(a) The Flow Direction file was derived from the DEM file. It is a raster, in which each grid-cell shows the direction that water follows and

(b) The Flow Accumulation file resulted from the previous (Flow Direction) file. It is a raster that shows the grid-cells with the largest accumulation of water (stream channels), as well as the cells with null stocking of water (divides).

In fact, two series of files (a total of 6 files) were created:

(a) The dimensions of each cell was (10X10) m^2 in the first series (a total of 12,368 grid-cells for the whole watershed) and

(b) In the second series of files, the dimensions of each cell were (50X50) m^2 (493 grid-cells in total).

(c)

Thus, with the contribution of GIS technology, spatial terrain, as well as, hydrological characteristics (ground slope, flow direction and flow accumulation) were determined for the calculation of the watershed's travel time map (Figure 2).

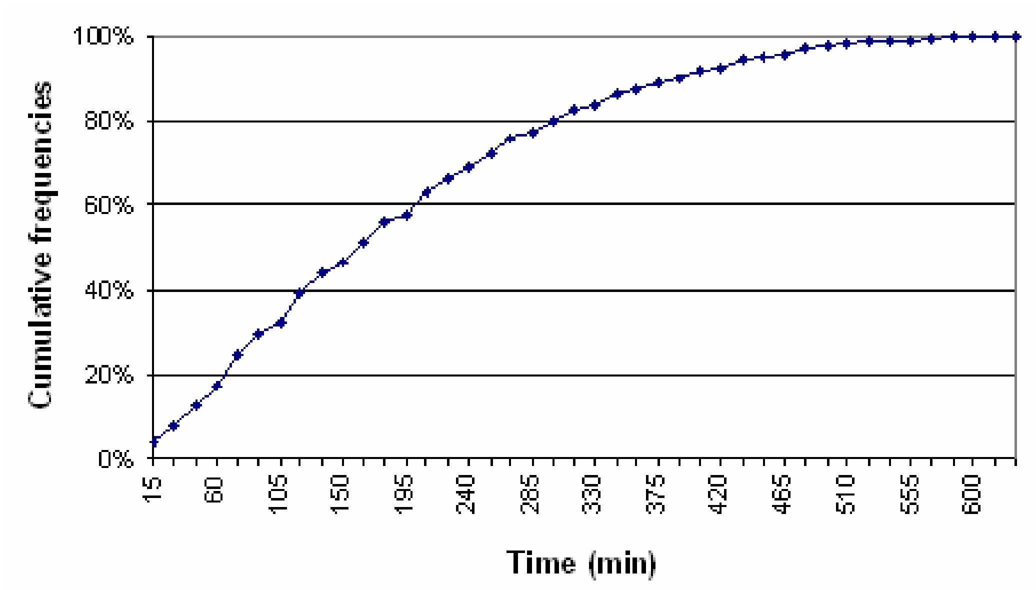

Figure 2. Cumulative frequencies in time of the number of grid-cells contributing to runoff.

In the second phase, the path that a raindrop follows was drawn from the center of each 50X50 m^2 grid-cell to the outlet, with the use of the tools of hydrological analysis that were included in the software. These tools take into consideration the flow direction and accumulation using the corresponding files from the first series of files (10X10 m^2) so that the water's direction and accumulation would be realistic as much as possible (Zang and Montgomery 1994). Next, two distances were measured for each one of the 493 grid-cells. One distance concerned the path of the channel flow and the second concerned the path of the overland flow. This segregation was essential because the resistances (frictions) to the surface flow, and by extension, to the water velocity inside and outside the stream network are by far different. In our case, where the watershed in its overwhelming percentage (>90%) is forested, the flow velocities outside the stream channels are much lower.

Finally, in the third phase, a pair of flow velocities applied on each grid-cell and the travel time was calculated by the following equation:

$$t_i = \frac{D_{in}^i}{V_{in}^i} + \frac{D_{out}^i}{V_{out}^i} \qquad (4)$$

where: i = 1–493, is the number of the grid-cell,

V_{in} and V_{out} are the velocities (m/s) that were applied inside and outside the stream network respectively,

D_{in} and D_{out} are the distances (m) that a raindrop covers inside and outside the stream network, respectively, from the center of each cell to the outlet and

t is the travel time (s) of direct runoff.

Taking into account that the hydrological data were analyzed on a 15 min time step, the travel time in each cell was calculated and then each cell was classified into time-groups of 15 min (0'-15 ', 15'-30 ', and so on). Next, a time area diagram was developed for each one of the combinations of the applied pair of velocities. Convolution of the time-area diagram led to the watershed flood hydrographs. These flood hydrographs had to be compared with the measured one, for the selection of the best pair of flow velocities that represented the model's solution.

RESULTS AND DISCUSSION

Characteristics of Rainfall Events and Flood Hydrographs

Table 1 presents the characteristics of the four selected rainfall events. A variety of duration and magnitude was considered for the obtainment of the most reliable results. The four selected rainfall events ranged from 2.25 to 32 h (duration), from 35.5 to 105.4 mm (rainfall) and from 6.2 to 32.2 mm (effective rainfall).

Table 2 presents the characteristics of the corresponding total flood hydrographs. In two out of the four rainfall events (4/2/98 and 21/12/98) the duration, the peak runoff and the runoff coefficient were similar. The same remark stands for the other two rainfall events. This is owed to the different soil moisture conditions. With respect to the runoff coefficient, it is noted that it was estimated as a fraction of the flood runoff (Table 2) to the rainfall (Table 1).

Grid-cells versus Flow Velocities

Figure 2 shows the cumulative frequencies in time of the number of grid-cells contributing to runoff for the four selected rainfall events. As it is shown, the farthest grid-cell needs 615 min to contribute to runoff at the outlet. Although the time of reaction is different for each grid-cell, the total of 493 grid-cells participate in the surface runoff and the curve's distribution is crescive. Three minor attenuations can be observed in the curve's slope due to the small area of the watershed.

The chosen pair of velocities was the following:
Average flow velocity inside the stream network, V_{in} = 1 m/s
Average flow velocity outside the stream network, V_{out} = 0.02 m/s

During the calibration process of the pair of flow velocities, it was clear that when the applied average flow velocities were decreasing, the peak of the calculated flood hydrograph was also decreasing and its descending curve sector had a lower slope than the corresponding measured. This finding is very important for the vegetation management in mountainous forested watersheds and especially for flood prediction simulations. In addition, an important result drawn from the analysis of the calculated flood hydrographs is some delay in the time to peak that two of them presented. This delay is due to the fact that the method does not calculate the infiltration and the interception, which have higher values at the beginning of the rainfall event and lower values, later on. However, in a study of watershed draining, the average velocity that was applied for the calculation of travel time, leads to less conservative design (Wong 2003).

Figure 3 shows an outline of the experimental watershed divided into 50 X 50 m^2 grid-cells. Each grid-cell depicts the calculated cumulative travel time to the outlet of the watershed (in seconds). From the analysis of these cumulative times, it is concluded that the mean percentage of time that a drop of direct runoff in each grid-cell needs inside the stream network, until it reaches the outlet of the watershed, is only 13.2% of the total travel time.

				16807	14877	11702	9592																	
			18457	15957	13457	10597	8097	6302	2426															
			19267	16892	13802	9842	7342	4842	878	5043	6168	10244												
			20117	17398	14898	12398	9848	7258	3563	2692	4801	8259												
	25605	23105	19920	16640	14140	11640	9140	6690	3845	1875	4364	7114												
2826	25415	22005	19740	17240	14740	12240	9740	7240	4740	804	3784	4229	4263	25102										
	26024	23524	21024	18524	16024	13524	10724	8524	6024	3304	729	2901	4659	24246	21746	19246	16746	14246	11746	9246	6746	4088		
	27319	24819	22319	19819	17319	14664	12034	9841	7311	4756	3865	665	2410	3745	3915	3965	5651	6817	6352	5104	4659	2780	769	0
	28434	25904	23406	22929	20429	17929	15429	12929	10429	7929	5389	2934	576	526	476	426	376	326	276	3292	1634	1874	4339	2109
	29181	26681	27966	22442	19942	17442	14942	12602	9507	7007	4507	667	8196	5886	2926	8998	6388	10543	8303	5768	3298	1678	5844	4129
		26198	23698	21198	18698	16488	8626	6126	3626	768	3943	11853	10268	7418	5428	10827	7972	11700	6909	4409	1909	1359	5200	6585
		20248	16136	13636	11136	8566	6381	3881	1346	7343	6443	14353	12768	9918	8783	14214	11714	9214	6714	3815	1300	2732	4692	
		21328	16158	13658	9799	7299	4799	2399	1791	9923	8943	17718	13433	19899	17399	14899	12399	9817	7132	4497	1653	2080	6247	
		17844	15344	12844	10829	6649	4007	876	4281	12423	16733	26049	23549	20869	18554	15839	12844	8961	6461	3946	2071	2332	4832	
		16904	14404	11904	8846	6346	3846	1722	6781	15433	29609	27109	24504	22004	19474	14996	12386	10086	7347	4702	1587	2649	4749	
		15396	12475	9975	7365	4945	2445	4119	6557	32994	30494	27994	25494	22929	18826	15941	12669	10169	7669	5194	2379	1082	3582	
			13025	11220	8448	5948	3979	7044	7639	31251	28506	25461	22961	20456	17851	15631	12442	9442	6942	4442	1942	2662	4222	
			12040	12098	9263	7484	6364	6379	34711	30221	27456	24956	22456	19956	17456	14301	11801	9301	6801	4301	1801	2485		
					11489	9949	9484	9939	33561	31061	28561	26061	23496	20040	17770	15380	12835	7715	5889	3389	660	3304		
						12504	13414	37196	34696	32196	29696	26265	23765	21305	18860	15870	9929	7429	4880	2380	2587	4202		
							19347	16847	14347	11847	9347	6847	4492	6370	4215	10890	8480	5498	3198	753	2943			
							20647	18147	15647	12422	14448	11948	9448	7053	1042	992	942	892	842	2170	4448			
							25113	22241	19741	18258	15013	12513	10013	7373	5108	10545	7844	5246	2746	2241				
							23476	21201	18701	16201	13501	15381	12881	10326	8261	6601	6226	3726	916	3909				
							23246	20066	17566	15066	12566	10066	7566	10151	7651	4131	2111	997	2699					
							12905	10475	7975	6029	3529	3906	3300	3115	4841	3216	1076	3277						
							14824	12324	9824	7049	18076	15576	13076	10576	6761	1153	3518							
							27956	25456	22881	20381	17881	15381	12881	10381	5064	3664								
							14822	12706	10236	9252	6752	4252	1752	8894	7499									
							14227	11727	9227	6076	3551	3055	12504	11204										
							14676	12176	9676	7176	6845	16414												
							18125	15775	13055	10555	9875													

Figure 3. The experimental watershed divided into 50 X 50 m^2 grid-cells and the travel time that a drop of direct runoff needs to reach the outlet of the atershed from the center of each grid-cell (in s).

Simulation Results

The rainfall – runoff simulation is depicted in Figure 4. More specifically, Figure 4 shows the hyetographs of the four examined rainfall events, divided into effective rainfall and rainfall losses and their corresponding flood hydrographs (measured and calculated). The pair of applied velocities presents a satisfactory relationship with the flood hydrograph that was measured at the outlet of the watershed. Table 3 presents the calculated correlations, bias and standard error of estimate in order to evaluate the effectiveness of the model used for runoff computation. In the first column, the presented correlations refer up to the peak of the measured flood hydrographs, while in the second one the reported correlations refer to the entire flood hydrographs.

Table 3. Statistical analysis of the simulation results for the selected rainfall events

Rainfall Event	Date	Measured Peak Correlation	Total Correlation	Bias (m^3)	Standard Error of the Estimate (m^3/s)
1	4/2/1998	0.534	0.367	-7.745	0.291
2	1/12/1998	0.827	0.748	-0.876	0.121
3	21/12/1998	0.879	0.847	4.226	0.219
4	9/1/2001	0.882	0.879	-1.223	0.073

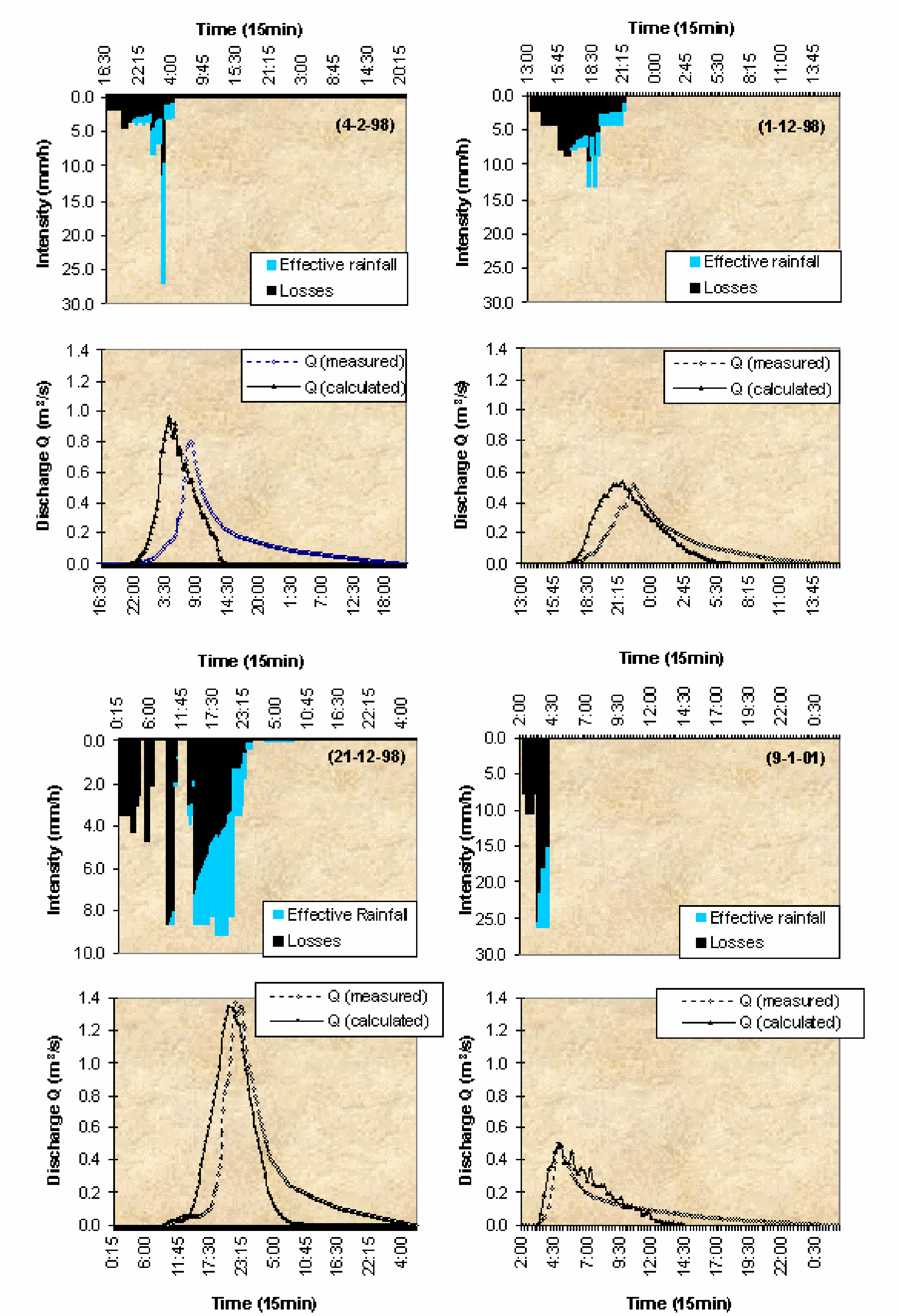

Figure 4. Hyetographs divided into effective rainfall and rainfall losses and the flood hydrographs (measured and calculated) of the selected rainfall events.

Some differences that appeared are due to the fact that this particular method calculates the base duration of each rainfall event, regardless of the excess rainfall input (Saghafian et al. 2002). Therefore, it is necessary to overcome the difficulties that may appear in the calculation of the base duration of the flood hydrograph. These difficulties are created by the complexity of the interactions between the hydrologic parameters (topography, flow resistance within soil, soil type) and the parameters of infiltration and spatial-temporal distribution of rainfall. In addition, the form of the descending curve's sector depends almost exclusively on the characteristics of the stream channels watercourse, which the method does not take into account (Mimikou and Baltas 2002). Thus, while the produced flood hydrographs present the bell-shaped form that are supposed to have and simultaneously simulate relatively well the ascendant sector, nevertheless, the calculated flood hydrographs descend enough faster than the corresponding measured, because of their particular base duration.

CONCLUSIONS

The conclusions resulting from this research work are concentrated on the following:

- The developed model that was based on the time area (TA) rainfall – runoff analysis and applied in a small-forested watershed gave satisfactory results especially for the ascendant curve of the simulated flood hydrographs. However, a combination of the model's application with the determination of the transportation of sediment would improve its application.
- The ratio of the flow velocity outside the stream channel to that inside the stream channel was 1:50.
- The mean percentage of time that a drop of direct runoff in each grid-cell needs inside the stream channel, till it reaches the outlet of the watershed, is only 13.2% of the total travel time.

REFERENCES

Ajward, M.H., and Muzik, I. (2000) A Spatially Varied Unit Hydrograph Model, Journal of Environmental Hydrology, 8, paper 7, pp. 8.

Ashour, R.A. (2000) Description of a simplified GIS-based surface water model for an arid catchment in Jordan. Proceedings of 20th Annual International ESRI User Conference, held in San Diengo, CA, USA, on June 26-30. San Diego: ESRI.

Clark, C. O. (1945). Storage and the unit hydrograph, Transactions of American Society of Civil Engineering, 110, 1419-1446.

DeVantier, B.A, and Feldman, A.D. (1993) Review of GIS Applications in Hydrologic Modelling, Journal of Water Resources Planning and Management, 119(2), 246-261.

Environmental Systems Research Institute 2000. Using ArcMap. ESRI: Redlands, CA, USA.

Fox, M.D., and Bryan, R.B. (1999) The relationship of soil loss by interrill erosion to slope gradient, Catena, 38, 211-222.

Gorokhovich, Y., Khanbilvardi, R., Janus, L., Goldsmith, V., and Stern, D. (2000) Spatially distributed modeling of stream flow during storm events, Journal of the American Water Resources Association, 36(3), 523-539.

Grunwald, S., and Norton, L.D. (2000) Calibration and validation of a non-point source pollution model, Agricultural Water Management, 45, 17-39.

Hewlett, J. D., and Hibbert, A. R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In: Forest Hydrology, edited by W.E.Sopper and H.L.Lull, pp. 275-290. Oxford: Pergamon.

Jain, S.K., Chowdhary, H., Seth, S.M., and Nema, R. (1997) Flood estimation using GIUH based on a conceptual rainfall-runoff model and GIS, ITC Journal, 1997-1, 20-25.

Kolsky, P.J., and Butler, D. (2000) Solids size distribution and transport capacity in an Indian drain, Technical note, Urban Water, 2, 357-362.

Kull, D.W., and Feldman, A.D. (1998) Evolution of Clark's Unit Graph Method to Spatially Distributed Runoff, Journal of Hydrologic Engineering, 3(1), 9-19.

Maidment, D.R. (1993) Developing a spatially distributed unit hydrograph by using a GIS. Proceedings of the International Conference on Application of GIS in Hydrology and Water Resources Management held in Vienna, Austria, No 211, pp 181-192. Vienna: IAHS.

Maidment, D.R., Olivera, F., Calver, A., Eatherall, A., and Fraczek, W. (1996) Unit hydrograph derived from a spatially distributed velocity field, Hydrological Processes, 10(6), 831-844.

Melesse, A.M., Graham, W.D., and Jordan, J.D. (2003) Spatially distributed mapping and modeling: GIS-based storm runoff response and hydrograph analysis: Part 2, Journal of Spatial Hydrology, 3(2), pp. 28.

Mimikou, M.A., and Baltas, E.A. 2002. Technical Hydrology (in Greek). Athens: National Technical University.

National Data Bank of Hydrological and Meteorological Information (2000) NDBHMI, Information Pamphlet, http://ndbhmi.chi.civil.ntua.gr/en/index.html

Olivera, F., and Maidment D.R. (1996) Runoff Computation Using Spatially Distributed Terrain Parameters. Proceedings of the ASCE-North American Water and Environment Congress held in Anaheim, California, USA, on June 22-28 1996. Anaheim: ASCE.

Ponce, V. M. (1989) Engineering Hydrology. Englewood Cliffs: Prentice-Hall, N.J. 07632.

Saghafian, B., and Julien, P.Y. (1995) Time to equilibrium for spatially variable watersheds, Journal of Hydrology, 172, 231-245.

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

Saghafian, B., Van Lieshout, A.M., Pajaei, H.M. (2000) Distributed catchment simulation using a raster GIS, International Journal of Applied Earth Observation and Geoinformation, 2(3/4), 199-203.

Soil Conservation Service (1972). U.S.D.A., National Engineering Handbook, section 4, Hydrology. Washington D.C.: GPO.

Vouzaras, A. (1999) A forest treatment applied to mature evergreen sclerophyllous forests of western Greece increases water yield and serves multiple purposes. Proceedings of the International Occasional Symposium of the European Grassland Federation held in Thessaloniki, Greece, on May 27-29 1999, Volume 4: 317-322.

Wang, M., and Hjelmfelt, A.T. (1998) DEM Based Overland Flow Routing Model, Journal of Hydrologic Engineering, 3(1), pp. 8.

Wong, S.W.T. (2003) Comparison of celerity-based with velocity-based time-of-concentration of overland plane and time-of-travel in channel with upstream inflow, Advances in Water Resources, 26, 1171-1175.

Zang, W., and Montgomery, D.R. (1994). Digital elevation model grid size, landscape representation, and hydrologic simulations. Water Resources Research, 30(4): 1019-1028.