Development of a simplified model for the estimation of hydrological components in areas of maquis vegetation in Greece

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Abstract: Gross rainfall, throughfall, stemflow and interception losses were measured and studied for seven years (1996 – 2002) in an evergreen schlyrophylous species (maquis) stand of eastern Mediterranean region and specifically of southern – western Greece. The monthly values were analysed and compared with the corresponding values of gross rainfall through the year. Throughfall, stemflow and interception losses were regressed, on a single rain event scale, against a number of meteorological variables. All the regression equations were found significant for at least 0.05 probability level. The models were tested with the data of 2003 by means of comparison of predicted and observed values of these components. All models yielded satisfactory estimates, especially from rainfall events greater than 10 mm.

Key-Words: - Rainfall, Throughfall, Stemflow, Interception Losses, Hydrological Modeling

1 Introduction

Rain that falls on a forest canopy is distributed into throughfall, stemflow and interception losses as it moves towards the forest floor. Interception losses contribute to a non-uniform wetting of the forest soil and evaporate more rapidly than transpiration in the same microclimates (Jackson, 1971; Lee, 1980). Stemflow is a spatially localized input point of precipitation and nutrients to the forest floor at the tree base (Herwitz, 1991; Levia and Herwitz, 2002). Measurements and investigation of the above hydrological components have been conducted in various types of forests. Such studies are also very important for the evergreen sclerophylous vegetation (maquis) of the Mediterranean region. The climatic conditions of the Mediterranean region and the human impact on vegetation have led to the development of the drought resistant evergreen sclerophylous vegetation.

This vegetation type occupies an area of at least 500,000 km^2 (Quezel, 1981) or 17.6% of the total area of Portugal, Spain, France, Italy, Maroco, Greece, Turkey and Israel and constitutes a narrow belt around the sea or it penetrates to some extent into the interior according to ecological and topographic characteristics. Similar types of vegetation also grow in other regions of the planet with Mediterranean climate and mainly in western California, southern Africa and southern Australia.

Maquis develops very dense stands, sheds their second year leaves at the beginning of summer and has a secondary growth during autumn, if precipitation and temperature are favorable. It also sprouts and grows very fast after clear felling, forest fires or heavy grazing. maquis in the Mediterranean region do not grow under undisturbed conditions because it has been severely affected by human activities during the turbulent long history of the area. So, its composition, canopy structure, density and extend of the growing area differ and appear in the form of a mosaic. An expansion of our knowledge on rainfall partitioning into its components as it moves through the canopy of maquis in eastern Mediterranean region would improve our general understanding of water balance analysis and provide a theoretical basis for the rational management of water, soil and vegetation in these important ecosystems.

The objective of this study was to develop simplified models to estimate throughfall, stemflow and interception losses at the event scale from gross rainfall and other meteorological variables without resorting to complex deterministic models. The rain event time scale was selected because it represents the quantity and duration of rainfall for hydrologic analysis (Llorens *et al.*, 1997). Such simplified models would be easily applicable even in mountainous areas because their variables are usually available from automatic meteorological stations that operate almost everywhere nowadays. Furthermore, the physical interpretation of the ways the various meteorological variables affect positively or negatively the mentioned hydrological components will contribute to modeling in a more sophisticated fashion in future studies.

2 Materials and Methods

2.1 Study Area

The study area is located in southern western Greece (38°50΄51΄΄N and 21°18΄20΄΄E), 225 km from Athens (Fig. 1). It lies in the headwaters of one of the small streams of the Acheloos River, which is the main one of western Greece. A plot of 0.27 ha was selected for biogeochemical and hydrological studies and being representative of the vegetation (maquis), soil, the parent rock and the topography of the wider area. The altitude of the plot is 360 m a.s.l. and the terain is hilly. The soil is Haplic Luvisol (FAO, 1988) and its parent material is flysch. The mean annual rainfall and the mean annual temperature (1973-2003) at the meteorological station of the area located 400 m from the plot and at an altitude of 350 m, are 1001 mm and 15.2 °C, respectively.

2.2 Measurements

Hydrological and meteorological measurements were carried out in the area during eight consecutive years to study atmospheric deposition and in this case the data are analyzed from a hydrological point of view. The main analysis was carried out for the first seven years and the data of the last year were used to test the relationships between throughfall, stemflow and interception losses with various meteorological variables derived from the first seven years data.

Gross rainfall was measured in a forest clearing located 80 m approximately from the center of the experimental plot and having the same altitude with it. Two non-recording raingauges and a recording raingauge were installed for the study of the distribution of rainfall in time. All the gauges were read on a weekly basis. The arithmetic mean of rainfall of them was estimated and considered as the “true” value of the plot. Throughfall was measured in a rectangular subplot (39 x 22 m) located inside the original plot of 0.27 ha, using ten collectors. The mean value of the ten collectors was considered as the throughfall value of the plot. Stemflow was measured on five trees located within the subplot of throughfall measurement (2 stems of *Quercus ilex*, 2 of *Arbutus unedo* and 1 of *Phillyrea latifolia*).

2.3 Data Analysis

Single rainfall events were chosen from weeks during which it rained only once. This was because the weekly-collected quantities of throughfall and stemflow by volumetric equipment could not be separated into events if more than one had occurred. The corresponding interception losses were determined as the difference between measured rainfall and measured throughfall plus stemflow. Multiple linear regression equations of throughfall, stemflow and interception losses (dependent variables) against a number of meteorological variables were calculated. The tested meteorological variables were the following:

- The magnitude of gross rainfall (mm) - GR
- The duration of gross rainfall (h) - D
- The weighted arithmetic mean of the wind speed (km/hr) - WS
- The weighted arithmetic mean intensity of rainfall (mm/hr) -WI
- The maximum intensity of rainfall (mm/hr) – Ml

Throughfall and interception losses were both used as dependent variables despite the fact that the second component can be predicted from the difference of gross rainfall and the sum of throughfall and stemflow. This was because this component can be predicted with a higher degree of accuracy by relating it directly to the various independent meteorological variables rather than to predict it from the mentioned difference (Jackson, 1975). Meteorological variables for the modeling of throughfall, stemflow and interception losses were extracted from the charts of recording instruments operating at the mentioned meteo station and from an automatic weather station installed at the same site in 2002.

The parameters WI and WS of each rain event were calculated by using the formulas 1 and 2, respectively:

$WI = (\Sigma\ i_j * d_j) / \Sigma d_j$ (1) and

$WS = (\Sigma\ ws_j * d_j) / \Sigma d_j$ (2),

Where:

i_j = constant intensity of rainfall (mm/h) taken from the distribution of rainfall in the analyzed single rain event

ws_j = constant wind speed (m/s) taken from the charts of the recording instruments or from the automatic weather station

d_j = corresponding duration (h) of the constant intensity or of the constant wind speed

j = 1 … n, the periods in which each single rain event was analyzed.

The developed models of throughfall, stemflow and interception losses were tested by means of comparison of the predicted (through the regression equations) and observed values of these components (paired-T test). The comparison was made between eight rain events occurred in 2003, corresponding to weekly time scale. The statistical analysis was carried out by the SPSS 11.0 statistical programme.

3 Results and Discussion

The monthly values of throughfall, stemflow and interception losses were analyzed for the understanding of their distribution throughout the year. Firstly, the mean monthly values of the seven years period of these components were estimated. Additionally, the percentages of these mean monthly values with regard to the corresponding mean monthly values of gross rainfall were also estimated (Fig. 2). As shown in Fig. 2, throughfall, stemflow and interception losses fluctuate through the year and range from 55.8% to 65.4%, from 3.9% to 8.3% and from 26.3% to 40.0% of the corresponding gross rainfall, respectively. The fluctuations of throughfall and interception losses are not high in comparison with those of stemflow and are attributed to small changes of the density of the foliage in the evergreen species and to different rainfall characteristics during winter and summer. More specifically, the negative trend of throughfall from January to April and from November to December is attributed to longer duration and to smaller intensities of rainfall in comparison with the summer months (Vouzaras, 1981). In contrast, the very clear positive trend of this component from May to June and from July to October is due to the senescence of the second year leaves of the evergreen species and to shorter duration and high intensities of rainfall, respectively.

Regarding the monthly percentage of stemflow throughout the year, it remains practically constant during the winter and in the summer it is approximately 40% smaller than that of the winter. The lower stemflow yield in summer with regard to winter may be attributed to higher evaporation losses from the canopy, to higher storage capacity of it and also to the dry conditions of the bark of the trees.

Concerning interception losses, it is mentioned that this component was calculated from the difference between gross rainfall and the sum of throughfall and stemflow. So the monthly distribution of interception losses through the year (Fig. 3) follows the opposite fluctuations of the sum of these two components.

The examination and explanation of the above fluctuations of monthly throughfall, stemflow and interception losses through the year are of particular hydrological importance. This is because future studies attempting to model these components in maquis vegetation must take into account that the volume of them varies as a function of the change of foliage density during May-June and the characteristics of rainfall within the year. Furthermore, understanding of the monthly fluctuations of these hydrological components is important and from an ecological point of view because they are the paths of the input nutrients of the forest soil.

3.1 Relationships among hydrological components and meteorological variables

For the establishment of simple relationships among throughfall, stemflow and interception losses of single rainfall events and the mentioned meteorological variables, 81 single rain events ranging from 0.3 to 66.8 mm were firstly selected. Throughfall and stemflow was observed in 70 and 35 of the events, respectively and their gross rainfall ranged from 1.8 to 66.8 and 8.9 to 66.8 mm.

The multiple regressions of the three hydrological components against the significant meteorological variables are presented in Table 1. The correlation of throughfall and interception losses were both very high (R^2 = 0.99 and 0.98 respectively), while a lower but still very high coefficient of determination was observed for stemflow (R^2 = 0.96). Table 1 shows that the three dependent variables correlate positively or negatively only with some of the five tested meteorological variables.

Table 1. Multiple regressions of throughfall, stemflow and interception losses against the five mentioned meteorological variables (GR, D, WS, WI and MI).

Dependent variable	**Model** [a]	**R^2**	**Std Error of the estimate (mm)**
Throughfall (mm)	$\mathbf{T} = 0.634*\mathbf{GR} - 0.075*\mathbf{D} - 0.062*\mathbf{WS} + 0.052*\mathbf{MI}$	0.99	1.16
Stemflow (mm)	$\mathbf{S} = 0.104*\mathbf{GR} - 0.029*\mathbf{D} - 0.019*\mathbf{WS} - 0.034*\mathbf{MI}$	0.96	0.34
Interception losses (mm)	$\mathbf{I} = 0.250*\mathbf{GR} + 0.115*\mathbf{D} + 0.077*\mathbf{WS}$	0.98	1.25

[a] All coefficients are statistically significant for at least $p<0.05$ in every model

So a physical explanation and interpretation of the way they correlate and why there is no correlation with the rest of the variables, could be useful for the prediction of them in more sophisticated models of future studies.

Firstly, throughfall, stemflow and interception losses of the present study correlate positively with the magnitude of gross rainfall and so the quantity of these components increases as gross rainfall increases. These results are in agreement with those of previous investigators (Rogerson, 1967; Llorens *et al.*, 1997; Kuraji *et al.*, 2001), who considered some of these components, as shown in Table 2. Of the three components, interception losses generally start at the beginninng of rainfall and when the canopy storage capacity is reached, throughfall and stemflow begin. However, the relationship between these hydrological components and gross rainfall may not always be as described above. This is because in some cases throughfall and stemflow initiate before the canopy storage capacity is reached. This occurs because some raindrops reach the surface of the ground through the gaps of the canopy from the very beginning of rainfall (Lee, 1980). Also stemflow may begin under windy (Crockford *et al.*, 1996) or calm conditions (Herwitz, 1987) when half of the bark of the branches and the trunk get wet. Furthemore, in the maquis vegetation of our experimental plot and after long dry periods during the summer, initiation of stemflow is observed almost with the start of rainfall due to water repellance of the leaves and the bark. The same phenomenon was also observed in the sclerophyll eucalyptus forests of Australia (Crockford *et al.*, 1991).

The above three hydrological components correlate also with the D. Actually throughfall correlates negatively with it. So the decrease of this component with the increase of the D could be attributed to lower intensities as the result of a longer duration and a constant quantity of rainfall. As throughfall decreases, larger quantities of rainfall are intercepted and evaporate from the canopy. This process is also supported by the positive correlation of our interception losses with the D. The results concerning interception losses and throughfall agree with those of previous investigators (Table 2).

With regard to stemflow, the negative correlation of it with the D could be attributed to the same reason with that of throughfall. This is in agreement with the results of Kuraji *et al.* (2001) and in disagreement with those of Levia (2004) – Table 2. The positive correlation of stemflow with the D found by the second investigator was due to the wetting of the tree crown by rainfall for a longer time and also to the wetting of the underside of the tree's steep branches by melting snow.

Concerning the WS, throughfall and stemflow correlate negatively and interception losses positively. The increase of interception losses with the increase of the wind speed could be caused by the higher evaporation losses of rain and the closure of the gaps among the branches and the dense foliage by the blowing wind. The increase of interception due to these reasons, contributes to the decrease of throughfall as the wind increases.

Table 2. Positive (+) or negative (-) correlations of interception losses, throughfall and stemflow with meteorological variables (GR, D, WS, WI, MI) in a number of studies around the world

S/N	Reference	Hydrological components														
		Interception losses					Throughfall					Stemflow				
		Meteorological variables														
		GR	D	WS	WI	MI	GR	D	WS	WI	MI	GR	D	WS	WI	MI
1	Baloutsos & Bourletsikas, 2006	+	+	+	No cor	No cor	+	-	-	No cor	+	+	-	-	No cor	-
2	Levia, 2004											No cor	+	+	-	
3	Kuraji *et al.*, 2001	+	+									+	-	+		
4	Xiao *et al.*, 2000	+	+	+		-			-	+		+		+	+	
5	Crockford & Richardson, 2000				-					+					-	
6	Llorens *et al.*, 1997	+			-					+						
7	Jackson, 1975				+											
8	Bultot *et al.*, 1972				-											
9	Rogerson 1967						+	-		+						

± Opposite correlation of the components in relation to the majority of the selected investigators

The negative correlation of stemflow of the maquis vegetation with the WS is also very important, since the negative correlation is against the findings of previous investigators e.g. Xiao *et al.* (2000), Kuraji *et al.* (2001) and Levia (2004) found a positive correlation. According to the first two, this was likely the result of the increased projected surface area of the tree crown under wind driven and consequently inclined rainfall conditions. On the other hand, Levia (2004) argued that the positive correlation of winter stemflow with the WS was connected to the efficient funneling of rainfall in leafless tree crowns when rainfall and windy conditions co-occur. In the present study the negative correlation of stemflow with the WS was attributed to the coverage of most of the length of the trunk and branches by smaller branches and dense foliage. So during co-occurrence of wind and rainfall, the surface of the trunks and the branches of the trees is not exposed to raindrops and stemflow decreases. This type of crown architecture of the maquis vegetation does not have a different effect on interception losses and throughfall. So, the quantity of stemflow does not depend on the same variables everywhere but must be the result of the specific tree species characteristics as well.

With regard to the MI, it is stressed that only throughfall and stemflow correlate positively and negatively with it, respectively. The increase of throughfall and the decrease of stemflow with the increase of the MI could be due to the falling of raindrops through the canopy without being intercepted and also without flowing down the bark of the branches and the trunk, respectively.

Finally, it is of interest to be added that in the present study no correlation was found between the three hydrological components and the WI (Table 2). This was because this variable was substituted by the duration and gross rainfall because the ratio of them equals approximately to the WI of rainfall. However, such a correlation was found between some of the three components and the WI by previous investigators (Bultot *et al.*, 1972; Jackson, 1975; Llorens *et al.*, 1997; Crockford and Richardson, 2000; Xiao *et al.*, 2000; Levia 2004). For the majority of them, interception losses correlated negatively, throughfal positively and stemflow negatively to the WI. However, some of them found a reversal correlation. For example, Jackson (1975) and Xiao *et al.* (2000) found positive correlations between interception losses and WI and stemflow and WI, respectively. The first of them attributed this correlation to higher evaporation of rainfall from the canopy when a large quantity of it is available and the second to the open grown trees.

3.2 Test of Models

The paired-T test conducted for the eight single rain events of the year 2003, showed that there was no significant difference between the observed and the derived values from the regression equations, which was of course desirable. The magnitude of these events ranged from 4.8 to 144.3 mm and for better presentation and discussion they were separated into two categories having smaller and greater magnitude of 10 mm (Fig. 3). This was decided because the relative measurement errors of gross rainfall and its components are usually larger in small than in high rain events.

The three models estimated throughfall and interception losses from the three small rain events ranging from –16.1% to 20.2% and from –21.4% to 39.2% of the measured values, respectively. These differences, although high in relative terms, are in reality small taking into account the small quantity of gross rainfall and the high probability of measuring it and its components with some error. Concerning the comparison of stemflow in the three small rain events, this was not possible because this component generally starts from rain events roughly higher than 10 mm.

With regard to the rest five rain events, the models estimated throughfall, stemflow and interception losses ranging from –4.8% to 6.8%, –24.1% to 21.3% and from –11.4% to 14.1% of the measured values, respectively. The smaller and the higher values between measured and estimated throughfall and interception losses were observed in rain events 8 and 4 (Fig. 3) and this supports the fact that the models give more satisfactory estimates from rain events of relatively great magnitude. In contrast, the differences between measured and estimated values of stemflow in absolute percentages in these rain events range from 10.8 to 24.1, obviously due to relatively smaller quantities of stemflow in relation to the total amount of rainfall.

From the comparison of the previous measured and estimated values it can be argued that the developed models can give satisfactory estimates of throughfall, stemflow and interception losses on a single rain event time scale.

4 Conclusion

The mean monthly percentages of throughfall, stemflow and interception losses in relation to the mean monthly values of the corresponding gross rainfall, varied through the year and ranged from 55.8% to 65.4%, 3.9% to 8.3% and 26.3% to 40.0%, respectively. These fluctuations can be the result of the spring growth of vegetation, of the second year leaf fall during May - June and of the precipitation characteristics in summer and winter.

The three hydrological components on a single rain event time scale were correlated significantly to the parameters of magnitude of gross rainfall GR, to duration of gross rainfall D and to weighted arithmetic mean of the wind speed WS. Additionally, throughfall and stemflow were also correlated significantly to the maximum intensity of rainfall MI. The negative correlation of stemflow to wind speed is against the findings of previous investigators worked with other tree species. This may be the result of the dense foliage of maquis covering the branches and most of the tree’s trunk and “protecting” the bark from rainfall when it co – occurs with wind. The developed models for throughfall, stemflow and interception losses yield satisfactory estimates mainly from rainfall events greater than 10.0 mm.

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References:

[1] Bultot, F., Dupriez, G.L. & Bodeux, A. 1972. Interception de la pluie par la végétation forestière estimation de l'interception journalière à l'aide d'un modèle mathématique. Journal of Hydrology, 17, 193-223.

[2] Crockford, R.H., Richardson, D.P. & Sageman, R. 1996. Chemistry of rainfall, throughfall and stemflow in a eucalypt forest and a pine plantation in south-eastern Australia: 2.

Throughfall. Hydrological Processes, 10, 13-24.

[3] Crockford, R.H., Topaldis, S. & Richardson, D.P. 1991. Water repellency in a dry sclerophyll eucalypt forest – measurements and processes. Hydrological Processes, 5, 405-420.

[4] Crockford, R.H. & Richardson, D.P. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrological Processes, 14, 2903-2920.

[5] FAO – Unesco 1988. Soil map of the World. FAO – Unesco, Rome, Italy.

[6] Herwitz, S.R. 1987. Raindrop impact and water flow on the vegetative surfaces of trees and the effects on stemflow and throughfall generation. Earth Surf. Proc. Land. 12, 425-432.

[7] Herwitz, S.R. 1991. Aboveground adventitious roots and stemflow chemistry of Ceratopetalum virchowii in an Australian montane tropical rain forest. Biotropica 23(3), 210-218.

[8] Jackson, I.J. 1971. Problems of throughfall and interception assessment under tropical forest. Journal of Hydrology, 12, 234-254.

[9] Jackson, I.J. 1975. Relationships between rainfall parameters and interception by tropical forest. Journal of Hydrology, 24, 215-238.

[10] Kuraji, K., Yuri, T., Nobuaki, T. & Isamu, K. 2001. Generation of stemflow volume and chemistry in a mature Japanese cypress forest. Hydrological Processes, 15, 1967-1978.

[11] Lee, R. 1980. Forest Hydrology. Columbia University Press, New York; 349.

[12] Levia, D.F. 2004. Differential winter generation under contrasting storm conditions in a southern New England broad-leaved decidious forest. Hydrological Processes, 18, 1105-1112.

[13] Levia, D.F.Jr. & Herwitz, S.R. 2002. Winter chemical leaching from deciduous tree branches as a function of branch inclination angle in central Massachusetts. Hydrological Processes, 16, 2867-2879.

[14] Llorens, P., Poch, R., Latron, J. & Gallrt, F. 1997. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. Journal of Hydrology, 199, 331-345.

[15] Quezel, P. 1981. Floristic composition and phytosociological structure of sclerophyllous matorral around the mediterranean. In: Di Castri F., Goodall D.W. and Specht R.L. (eds), Mediterranean-type Shrublands. Elsevier, Amsterdam, pp. 107–121.

[16] Rogerson, T.L. 1967. Throughfall in pole-sized Loblolly Pine as affected by stand density. In: W.E. Sopper and H.W. Lull (eds), International Symposium on Forest Hydrology. Pergamon, Oxford, 187-190.

[17] Vouzaras, A. 1981. Rain characteristics in the Varetada region. Forest Res. (in Greek) II(4), 443-468.

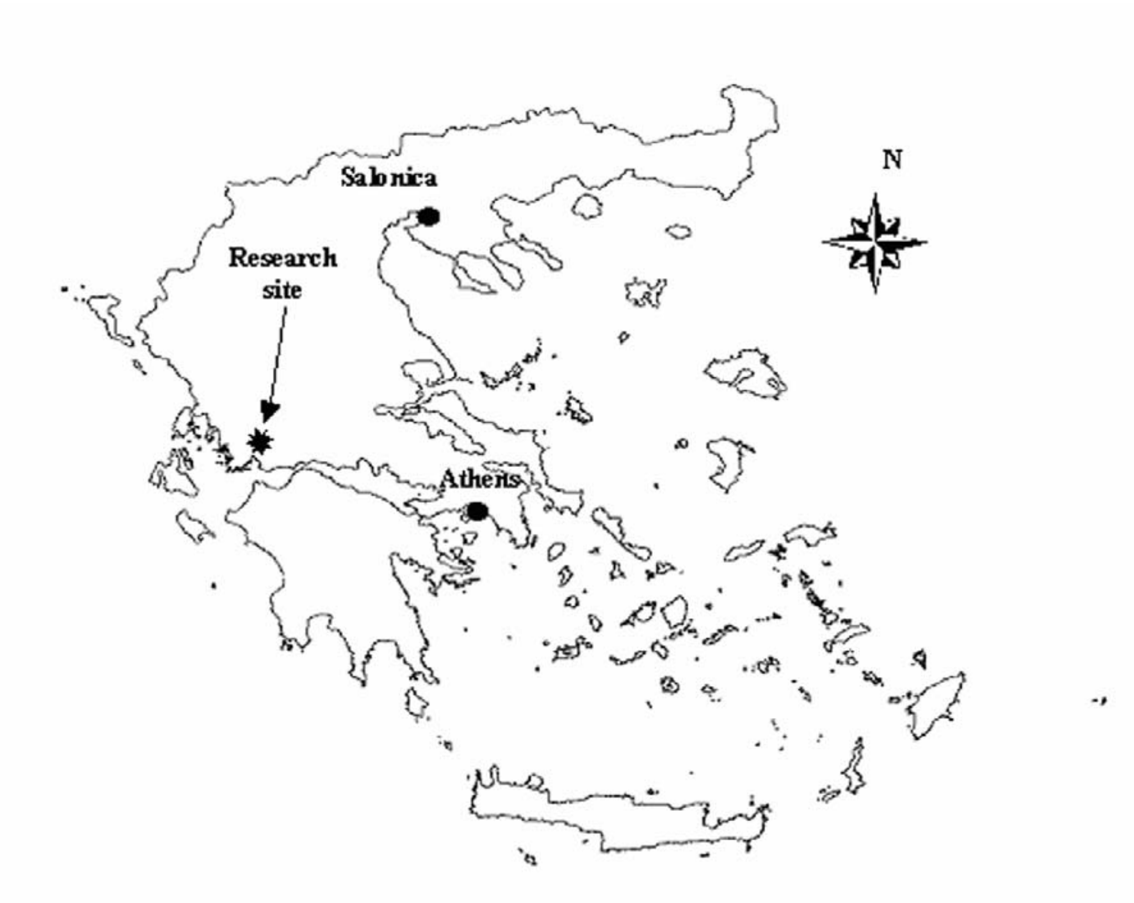
[18] Xiao, Q., McPherson, E.G., Ustin, S.L., Grismer, M.E. & Simpson, J.R. 2000. Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrological Processes,14,763-784.

Figure Captions

Figure 1. Location of the research site in Greece.

Figure 2. Mean monthly percentage of throughfall/gross rainfall (+), stemflow/gross rainfall (o) and interception losses/gross rainfall (x)

Figure 3. Measured (1m) and estimated (1e) values of throughfall, stemflow and interception losses



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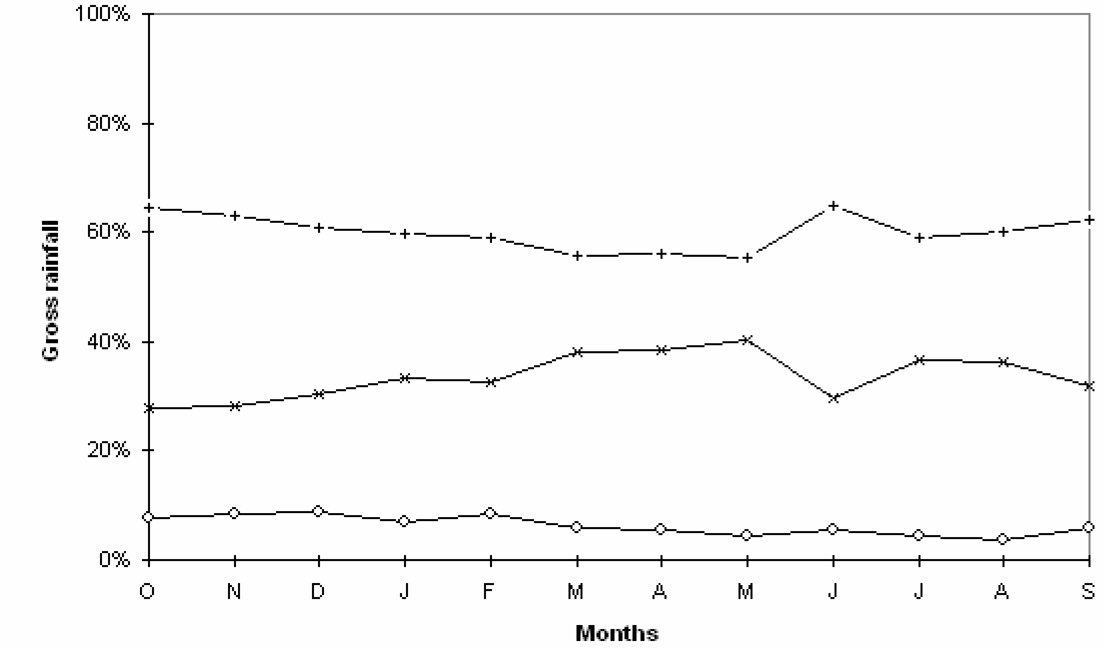

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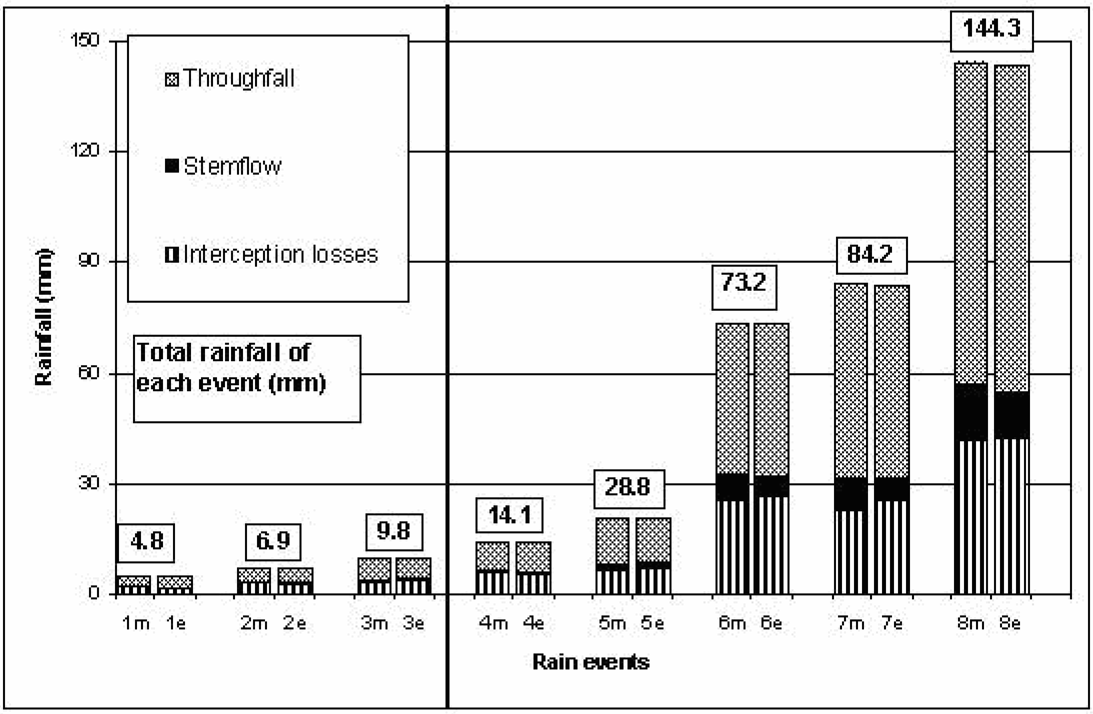

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