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Throughfall, stemflow, and rainfall interception in a natural pure forest of chestnut-leaved oak (*Quercus castaneifolia* C.A. Mey.) in the Caspian Forest of Iran

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Abstract. In forest ecosystems, rainfall is partitioned by forest canopies into throughfall (TF), stemflow (SF), and interception loss (I). In the present study the partitioning of rainfall was studied in a natural chestnut-leaved oak (*Quercus castaneifolia* C.A.Mey) forest situated in the Caspian Forest, north of Iran. Measurements were carried out on a rainfall event basis in a 0.12 ha sample plot of an oak forest, during 2009 and 2010, from July to October. Gross rainfall (GR) was measured in an open area close to the study plot. Thirty five throughfall collectors were randomly placed beneath the oak forest canopies and SF was collected from nine selected oak trees using the spiral type SF collection collars. The cumulative GR amount of 28 events was 651.5 mm. The amount of cumulative GR transformed into TF, SF and I were 489 mm, 2.6 mm, and 159.9 mm, respectively. On the event scale average ratios of TF:GR, SF:GR, and I:GR were 75%, 0.4%, and 24.6%, respectively. A fairly strong negative correlation was observed between I:GR and GR. As the intensity of the rainfall events increased, the interception loss in the oak forest canopies decreased. We concluded that interception in the oak forest represents a remarkable percentage of GR and it was strongly affected by the amount of GR.
Keywords interception loss, oak, stemflow, throughfall, the Caspian Forest.

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Introduction

The interaction between vegetation and rainfall is of considerable significance from physiological, ecological, and hydrological points of view (Marin et al. 2000, Iida et al. 2005). When rain falls on forest canopies, a proportion reaches the forest floor as throughfall (TF) and stemflow (SF), and the remainder is retained in the canopy and subsequently evaporated. TF, which is the part of the gross rainfall (GR), drips from foliage or branches of canopy or reaches the forest floor by passing directly through tree canopies (Hanchi & Rapp 1997, Ahmadi et al. 2009) and has a notable contribution to the hydrologic budgets of forest areas. SF is another part of GR, flowing down along the stems and tree trunks and reaching the forest floor. SF is usually a minor component of the water balance of forest ecosystems while stem density and crown structure are important factors for SF generation. SF volume is a function of tree species, crown size, leaf shape and orientation, branch angle, and bark roughness (Levia et al. 2010).

Canopy interception loss (I) is the proportion of rainfall intercepted by trees canopies and evaporated (Price & Carlyle-Moses 2003), thus not reaching the forest floor. Interception (I) is generally calculated indirectly, as difference between GR and net rainfall (NR), i.e., sum of TF and SF (Staelens et al. 2008, Herbst et al. 2006). Thus, NR reaches the forest floor through the canopy via two main pathways, SF and TF (Manfroi et al. 2004, Levia & Herwitz 2005, André et al. 2008).

Partitioning of rainfall in forests is affected by the amount, intensity and duration of rainfall and the temporal distribution of rain events. TF and SF amounts are often strongly correlated with the amount of rainfall (Marin et al. 2000, Xiao et al. 2000). Literature reviews shows that rainfall partitioning depends on climate factors and vegetation structure (Crockford & Richardson 2000), and is a function of rainfall characteristics, meteorological conditions, vegetation structure, and the interactions between these factors (Hall 2003, Toba & Ohta 2005, Deguchi et al. 2006, Staelens et al. 2008).

The temperate deciduous forests of northern Iran, known as the Caspian forests, cover about 2 million hectares of a narrow strip over 800 km long and 20-70 km wide, ranging from the level of the Caspian Sea up to 2200 m. Oak *(Quercus castaneifolia* C.A. Mey.), one of the most important broadleaf species in the Caspian forests, occupies approximately 6.6% of the total forest area in the region.

The objective of this study was to quantify the partitioning of GR into TF, SF, and I in a natural pure oak forest within the growing season, from July to October. No comprehensive and integrated research has been performed in the Caspian forests concerning the partitioning of rainfall in natural oak forests and the present study is, therefore, the first which consider rainfall partitioning within the canopy of an oak forest.

Materials and methods

Site description

The study was performed in the Kheyrud Forest Research Station of Tehran University, located approximately 7 km east of Nowshahr, Mazandaran province, northern Iran (Figure 1).

Data were measured during the 2009 and 2010 growing seasons, inside a 0.12 ha plot (36°35′N, 51°37′E, and 1550 m above the level of the Caspian Sea) of a pure and natural oak forest.

Tree density of the study plot was 175 tree. ha^{-1}. Mean tree height (h) and diameter at breast height (DBH) were 28 m and 36 cm, respectively. Trees diameters ranged from 18 to 52.5 cm. Mean angle of the south facing slope of the site is 18°.

A 23-years record of the meteorological parameters (1985-2008) recorded at Nowshahr Meteorological Station (36°39′N, 51°30′E, and 7.5 m above the level of the Caspian Sea), indicated that the mean annual rainfall and air temperature are 1303 mm and 16.2°C, respectively. October and August are the wettest (average 235 mm) and driest (average 42 mm) months, respectively. An average of 38% of the total annual rain falls between July and October (Figure 2). The data also show that February and August are the coldest (7.1° C) and the warmest (25.1° C) months, respectively.

According to Nowshahr Meteorological Station, mean annual pan evaporation (E) reached 1031.2 mm (CV%: 5.9); the highest average monthly E value was 155.4 mm which occurred in August while the lowest was 26.2 mm corresponding to January.

No documented report is available concerning the rainfall gradient across the range of altitude in the Caspian forests and in the Kheyrud forest research station. A documented study, however, showed an air temperature gradient of 0.42° C per 100 m elevation difference in the forest research station (Javanshir et al. 1997).

Field measurements

Gross rainfall (GR) measurement. Gross

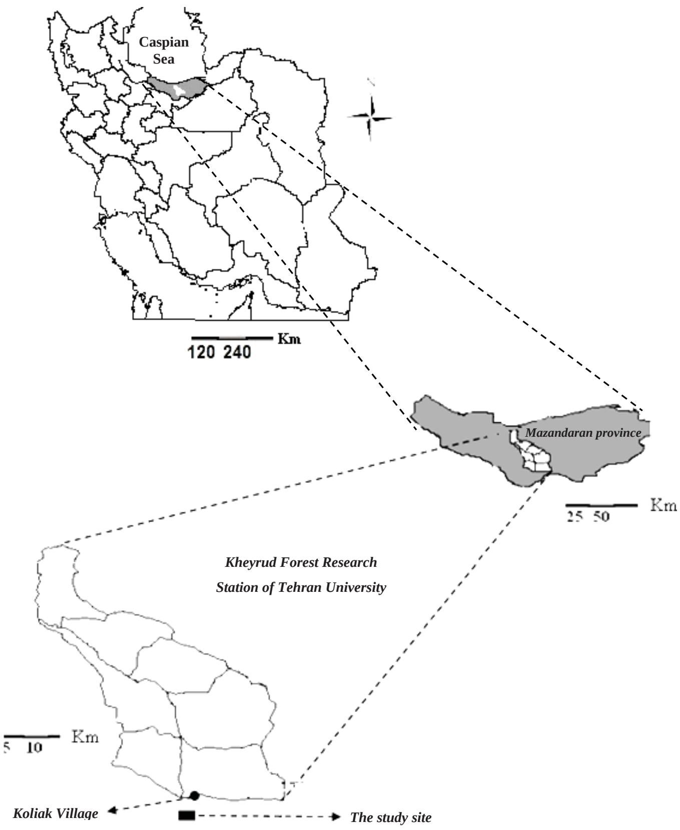

Figure 1 Study site location near the upper border of the Forest Research Station of Tehran University, in the Caspian forests, North of Iran

rainfall (GR) amounts were measured in the neighboring open area (150 m away from the study plot), outside the forest, 2009 and 2010, both from July to October, using three self-produced cylindrical collectors with 9 cm diameter. Mean rainfall event was determined based on an average of the three collectors. GR was measured after an event or at sunrise if the rainfall occurred during the night (Carlyle-Moses et al. 2004).

TF was measured using the same kind of manual rainfall collectors used for measuring rainfall. Thirty five collectors were distributed randomly (Carlyle-Moses et al. 2004) underneath the oak tree canopies (Figure 3). TF value was measured at the same method of GR. Mean TF amount for each event was calculated via the collected TF from all the 35 manual collectors.

SF was collected from 9 selected oak trees using spiral-type SF collection collars installed at the level of the breast height during the measurement period (Toba & Ohta 2005, Ahmadi et al. 2009). The collectors encircled the trunk at least 1.5 times with an inclined position. SF was diverted from the spiral-type collars to a 20-L collection bin via plastic tubing (Figure 4).

For selection of sampling trees for SF measurement, all trees inside the study plot with DBH > 7.5 cm were divided into three groups (Ahmadi et al. 2009): DBH < 25 cm, DBH = 25-50 cm, and DBH > 50 cm (Figure 5).

For each of the above-mentioned DBH group, three individual trees were chosen randomly. SF volume was measured on a rainfall event basis with the same method used for GR measurement. SF collected by nine selected oak trees with different diameters was then averaged to obtain SF per event.

Crown projection area (CPA)

Crown projection area (CPA) is required for calculation of the SF equivalent depth. The standard method of measuring the CPA is to

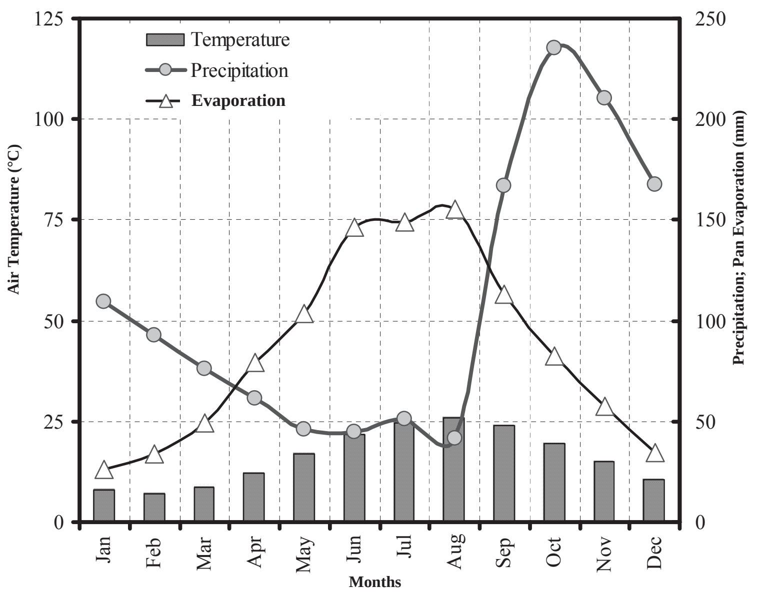

Figure 2 Monthly mean air temperature, precipitation, and pan evaporation recorded at the Nowshahr Meteorological Station, the nearest synoptic weather station to the study site, (mean 1985-2008). Dry spells occur during the growing season, from May to November, when $P \leq 2T$

project the edges of the crown to a horizontal surface (Delphis & Levia 2004). To calculate SF depth, the CPA was measured with a clinometer and a tape measure only for the 9 SF sampling trees. The crown radius was measured as the distance from the center of the tree bole to the edge of the crown. To attain the best estimate of mean crown diameter, the average of 4 main directional crown radii was used.

The corresponding SF depth of each selected tree was measured by dividing the collected SF volume by the CPA (Shachnovich et al. 2008). Finally, the SF depths of the 9 selected trees were averaged to determine the mean SF depth for each event.

Results

Gross rainfall (GR)

During the study period, 28 rainfall events were recorded. The cumulative GR amount was 651.5 mm; mean GR was 23.2 mm. GR ranged from 3.6 to 50.1 mm (Table 1). In order to better understand the relationships among GR, TF, SF and I, and also taking into account the frequency and extremes of rainfall, GR events were grouped into 5 classes of 7.5 mm interval: GR $\leq$ 7.5 mm, 7.5 mm $\leq$ GR $\leq$ 15 mm, 15 mm $\leq$ GR $\leq$ 22.5 mm, 22.5 mm $\leq$ GR $\leq$ 30 mm, and GR $\geq$ 30 mm (Figure 6).

Out of the 28 total number of rains, 3, 7, 7, 1, and 10 events were respectively assigned to the previously mentioned classes. Cumulative depths of the GR classes were 15.9 mm, 63.7 mm, 139.7 mm, 29.9 mm, and 402.3 mm, respectively.

Rainfall partitioning

Throughfall (TF). Cumulative TF depth was 489 mm (75%) of the cumulative GR during the measurement period. Mean TF depth, as a proportion of GR, was 17.4 mm, and ranged from 2.1 mm (60% of the corresponding GR) to 40.2 mm (89% of the corresponding GR) (Table 1).

TF was found to be closely related to GR amount. A very strong positive linear relationship was observed between TF and GR depths, at the event scale, in other words, TF increased with higher GR (r^2 = 0.98; $p \leq 0.01$).

Figure 7 shows the relative importance of

Figure 3 Distribution of throughfall (TF) and stemflow (SF) collectors inside the oak (*Quercus castaneifolia*) forest

Figure 4 A stemflow (SF) collector

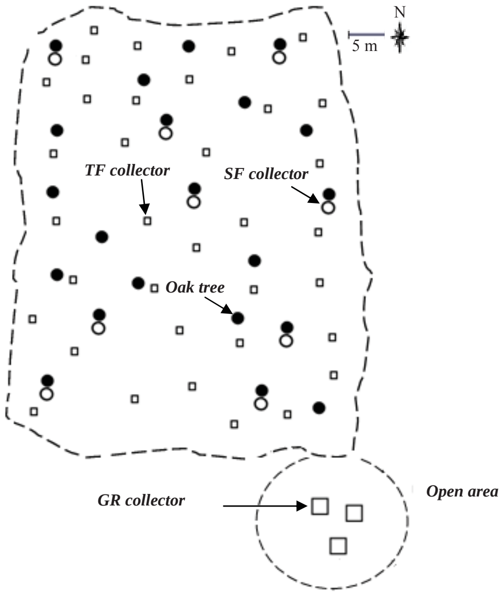

Figure 5 Disposition of the oak trees (filled circles), throughfall (TF) gauges (open squares) and stemflow (SF) collectors (open circles) in the study plot of Kheyrud Forest Research Station of Tehran University. Gross rainfall (GR) gauges (larger open squares) are shown in an open adjacent area

TF (the ratio TF:GR) in relation to GR. TF:GR was correlated with the GR amount and a fairly strong positive power relationship ($r^2 = 0.67$; $p \leq 0.01$) can explain the relation between these two parameters.

For rainfall event classes of GR ≤ 7.5, 7.5 ≤ GR ≤ 15, 15 ≤ GR ≤ 22.5, 22.5 ≤ GR ≤ 30, and GR ≥ 30 mm, the TF:GR ratios were 63.3 %, 70% , 74.1 %, 75.2%, and 79.3 %, respectively (Figure 6).

Stemflow (SF). Cumulative SF depth of 28 rainfall events was 2.6 mm or 0.4% of the cumulative GR (Table 1). Average SF amount was 0.03 mm. A strong positive relationship ($r^2 = 0.74$; $p \leq 0.01$) was observed between mean SF and GR depths at the event scale.

A weak exponential relationship ($r^2 = 0.37$; $p \leq 0.01$) was observed between SF:GR and GR (Figure 8). For the rainfall event classes of GR, the average SF:GR values between classes were not significantly different.

Interception loss (I). The results showed that the cumulative interception loss was 159.9 mm, corresponding to 24.6% of GR. I ranged widely from 13% to 40.1% of GR during the study period (Table 1).

A positive power correlation ($r^2 = 0.90$; $p \leq 0.01$) was observed between I and GR amount. Interception increases with an increasing amount of GR, while I:GR decreases with increasing rainfall heights as shown by the power regression ($r^2 = 0.61$; $p \leq 0.01$)(Figure 9).

For the rainfall event classes of GR ≤ 7.5, 7.5 ≤ GR ≤ 15, 15 ≤ GR ≤ 22.5, 22.5 ≤ GR ≤ 30, and GR ≥ 30 mm, the average I:GR values were 34.5% , 28.1% , 24.4% , 24.3%, and 19.2%, respectively.

Net rainfall (NR). NR amount was 491.6 mm or 75.4% of the cumulative GR (651.5 mm) which means that this amount of water reached the forest floor partly as TF (489 mm) and the rest as SF (2.6 mm)(Table 1). The remaining 159.9 mm or 24.6% of total GR was intercepted by the oak tree canopies and subsequently lost through evaporation. The average amount of NR was 17.5 mm.

Table 1 Cumulative, maximum, and minimum of gross rainfall (GR) depths and the partitioning into throughfall (TF), stemflow (SF), interception loss (I), and also net rainfall (NR) during the study period, (2009 and 2010, July to October)

	GR		TF		SF		I		NR	
	mm	%	mm	%	mm	%	mm	%	mm	%
Cumulative	651.5	100	489.0	75	2.600	0.40	159.9	24.6	491.6	75.4
Minimum	3.6	100	2.1	60	0.001	0.02	1.3	13.0	2.2	60.5
Maximum	50.1	100	40.2	89	0.130	1.00	10.4	40.1	40.3	90.0

A very strong positive linear relationship ($r^2 = 0.98$; $p \leq 0.01$) was observed between the NR and GR values and also a power regression ($r^2 = 0.67$; $p \leq 0.01$) was observed between NR: GR and GR (Figure 10).

Discussion

To evaluate the effect of oak forest canopy on gross rainfall (GR) redistribution, TF, SF, and I in a natural oak forest situated at the Caspian forests of Iran, were measured over the growing seasons 2009 and 2010.

For 28 rainfall events cumulative GR depth (651.5 mm) was attributed to TF, SF, and I as follows: 489 mm, 2.6 mm, and 159.9 mm, respectively. The percentage of GR partitioning into TF:GR, SF:GR and I:GR were 75%, 0.4% and 24.6%, respectively.

A literature review on rainfall redistributions measured in a variety of oak forests in terms of age, structure, and genus (Table 2) indicates that the values of TF:GR, SF:GR and I:GR ob-

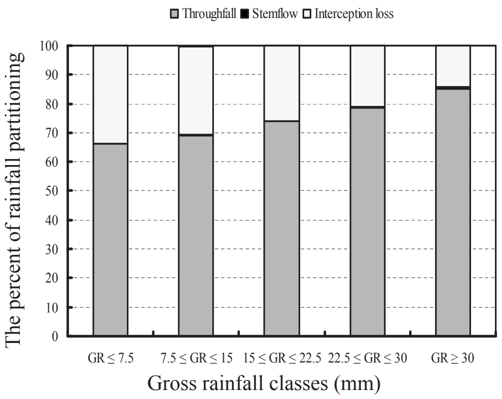

Figure 6 Percentes of gross rainfall (GR) events and cumulative gross rainfall depth for different GR classes during the measurement periods (2009 and 2010, July to October)

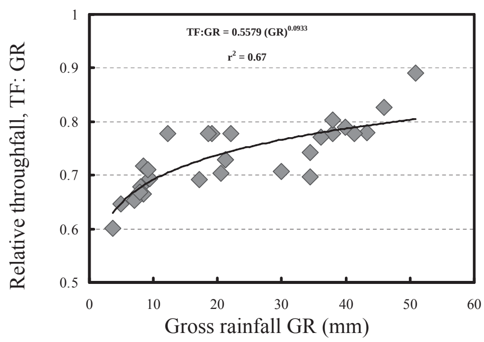

Figure 7 Relationship between the relative throughfall (TF:GR) vs. gross rainfall (GR). Each symbol refers to a rainfall event (true for the next figures)

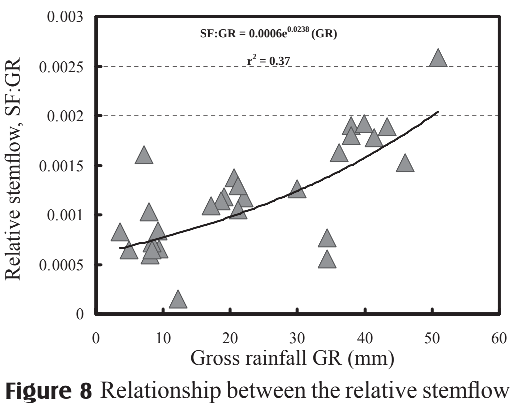

Figure 8 Relationship between the relative stemflow (SF:GR) vs. gross rainfall (GR)

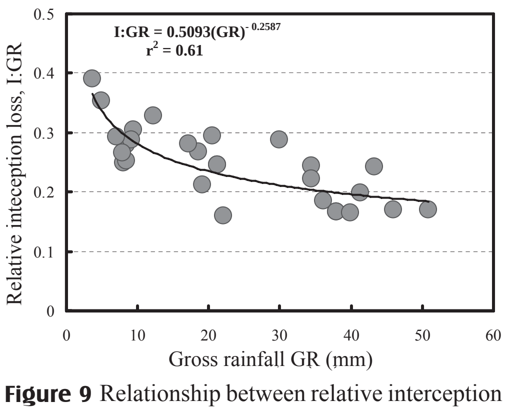

Figure 9 Relationship between relative interception loss (I:GR) and gross rainfall (GR)

tained in our study are comparable with those measured in other environments.

Toba & Ohta (2005) reported that the portions of TF, SF, and I were 72.4%, 2.5%, 24% of GR, respectively, during the growing season in an oak forest (*Quercus acutissima*) located in Japan. Carlyle-Moses et al. (2004) reported that the average values of TF:GR, SF:GR and I:GR in oak (*Quercus cupreata* and *Quercus canbyi*) forest were 84.2%, 0.8%, and 15%, respectively. For an oak forest in Japan Silva & Okumura (1996) stated the values 72%, 10%, and 18% for the parameter ratios mentioned above. The values of TF: GR obtained in the present study are similar to the values mentioned by other researchers, although higher values of TF were reported. Our results showed that SF constituted a small percentage of GR in the oak forest and was strongly correlated with GR size, as reported by other studies (Deguchi et al. 2006, Keith Owens et al. 2006, Ahmadi et al. 2009).

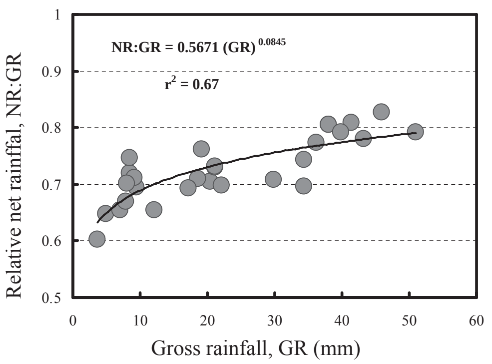

Figure 10 Relationship between relative net rainfall (NR:GR) and gross rainfall (GR) in the natural oak forest

The differences in rainfall characteristics and meteorological conditions and especially in forest structure, in particular, are probably responsible for the dissimilarity in quantity of rainfall redistribution for different forest stands (Marin et al. 2000, Xiao et al. 2000, Hall 2003, Fleischbein et al. 2005, Toba & Ohta 2005, Deguchi et al. 2006, Staelens et al. 2008). In this study, at the event scale the average value of I:GR accounted for 24.6%. A comprehensive and integrated review on rainfall partitioning studies in various oak forests (Silva & Okumura 1996, Carlyle-Moses et al. 2004, Toba & Ohta 2005) indicates that the value of I:GR obtained in the present study is nearly equal to those measured in other forests during the leafed period. The value of I:GR for broad leaved deciduous forests was reported typically between 15% and 25% (Dolman 1987).

Redistribution of rainfall into TF, SF, and I in forest ecosystems depends on incident rainfall characteristics (amount, mean intensity, duration, and structure), meteorological conditions (air temperature, relative humidity, wind speed and direction) and forest structure (species composition, stand age and density, as well as canopy morphology and architecture) as declared by many authors (Marin et al. 2000, Xiao et al. 2000, Hall 2003, Fleischbein et al. 2005, Toba & Ohta 2005, Deguchi et al. 2006,

Table 2 A review of measured values of relative throughfall (TF:GR), relative stem flow (SF: GR), as well as relative interception loss (I:GR) obtained from a variety of research on oak forests

Location	Tree species	Study period	TF:GR (%)	SF:GR (%)	I:GR (%)	References
Japan	*Quercus.serrata*	Growing season	72.0	10.0	18	Silva & Okumura 1996
Mexico	*Quercus canbyi* *Quercus cupreata*	Annual	84.2	0.8	15	Carlyle-Moses et al. 2004
Japan	*Quercus serrata*	Growing season	78.7	2.0	18	Toba & Ohta 2005
Japan	*Quercus. acutissima*	Growing season	72.4	2.5	24	Toba & Ohta 2005

Staelens et al. 2008). Our results confirmed that the GR amount has a major effect on rainfall redistribution into TF, SF, and I in the oak forest as shown in previous research (Deguchi et al. 2006, Ahmadi et al. 2009). The higher the GR, the greater the TF and SF amounts, as well as the TF: GR and SF:GR ratios as reported (Marin et al. 2000, Staenles et al. 2008). The study indicated that GR allocated to SF was not important in the oak forest. Low stemflow generation in the oak forest is related to high bark roughness, and bark water storage capacity of oak trees (Levia & Herwitz 2005).

During the study period interception losses increased with the size of GR events; however, as expected, higher I:GR values were observed for the smaller GR events as shown by many authors (Rowe 1983, Xiao et al. 2000, Marin et al. 2000, Fleischbein et al. 2005). The magnitude of I:GR for small events is a result of a large portion of incident rainfall retained on the canopy which evaporates during and after the rainfall.

The present study shows that interception loss takes out a notable amount of incident rainfall and its measurement, therefore, is a significant element in the assessment of water balance in the oak natural forests of Iran.

Conclusions

This research was performed in the Caspian forests for quantifying the amount of gross rainfall allocated to throughfall, stemflow and interception loss in the oak forest, during 2009 and 2010 growing seasons. On the event scale the mean value of net rainfall was 75.4% of the gross rainfall and the remaining 24.6% was intercepted by the trees canopies. This study emphasized that the fraction of interception loss has a large effect on the water balance and hydrological studies of oak natural forest ecosystems. Our results showed that rainfall partitioning into net rainfall and interception loss was strongly affected by the amount of gross rainfall. Although the data collected in this 2-year study demonstrate that throughfall and interception are the main components of gross rainfall partitioning, other characteristics of forest structure such as percentage of canopy cover, leaf area index, tree density as well as climatic factors (i.e., rainfall duration, intensity and distribution; relative humidity, wind speed) should be monitored to better describe the role of a forest cover on the water balance at the catchment scale.

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