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Rainfall Interception in a *Pinus eldarica* Plantation in a Semi-arid Climate Zone: An Application of the Gash Model

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ABSTRACT

Forest canopy rainfall interception loss (*I*), canopy water storage (*S*), and the ratio of mean evaporation to mean rainfall intensity ($\overline{E}/\overline{R}$) are important components of the water balance in arid and semi-arid climate zones. The goal of this project was to quantify *I* and *S* and to evaluate the Gash interception model for rainfall interception in a mature semi-arid *Pinus eldarica* Medw afforestation planted in the Chitgar Forest Park near Tehran city, Iran. Measurements of gross precipitation (P_G) and throughfall (*TF*) were recorded on an event basis from September 2009 to April 2010. For the measurement period, P_G totaled 164.8 mm and *I* totaled 61.2 mm. *I* was calculated as the difference between P_G and *TF*. On the event scale, the ratio of I:P_G ranged between 0.195 and 1, and averaged 0.614. There was a strong logarithmic correlation between *I*: P_G and P_G (R^2= 0.861; P value≤ 0.01). As the size of rainfall events increased, I:P_G decreased. The mean method estimated *S* to be 1.8 mm. The Gash model accurately estimated *I* to be within 1.1 mm of the total measured value. The results demonstrate that intercepted rainfall represents a considerable portion of P_G in *P.eldarica* afforested regions of the semi-arid climate zone of Iran where soil moisture is a limiting factor for plant growth and productivity.

Keywords: Afforestation, Canopy water storage, Iran, Mean method, Throughfall.

INTRODUCTION

Afforestation is proposed for arid and semi-arid regions because it is assumed to reduce soil erosion (Zhou *et al*., 2002), combat desertification (Grünzweig *et al*., 2003), increase CO_2 fixation (De Los Rios-Carrasco *et al*., 2009), and provide recreational opportunities (Hüttl *et al*., 2000). However, afforestation may have undesirable hydrological implications. For example, converting grassland to a forest may reduce groundwater recharge and local water availability because trees extract water from deep layers in the soil profile during drier periods and intercept precipitation during rainfall events (Iroumé and Huber, 2002).

Rainfall interception loss (*I*) is the proportion of gross rainfall (P_G) that is intercepted, stored and subsequently evaporated from leaves, branches and stems of vegetation during or following rainfall. In forests, *I* can be substantial, representing between 10 and 40% of annual P_G (Scatena, 1990; Asdak *et al*., 1998, Levia and Frost, 2003). Therefore, quantifying the magnitude of *I* is vital in semi-arid and arid regions where soil moisture is a limiting factor affecting plant growth and productivity (Návar *et al*., 1999a; 1999b, Carlyle-Moses, 2004).

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Throughfall (*TF*) is the portion of P_G that directly reaches the forest floor through gaps in the canopy [free throughfall coefficient (*p*)] (Gash, 1979; Herbst *et al*., 2008) or water dripping from leaves and branches (canopy drip). Stemflow (*SF*) is rainfall that reaches the ground by flowing down stems or trunks (e.g. Návar and Bryan, 1990; Návar, 2011). *I* is estimated using the difference between P_G measured above the canopy and the sum of throughfall (*TF*) and stemflow (*SF*) (Hutchinson and Roberts, 1981; Mahendrappa, 1990; Tobón Marin *et al*., 2000; Xiao *et al*., 2000; Herbst *et al*., 2008).

Canopy (water) storage capacity (*S*) is one of the important variables influencing *I* (e.g. Rutter *et al*., 1971; Jackson, 1975; Liu, 1997; Pypker *et al*., 2005; Crockford and Richardson, 2000). The water stored in the canopy can either evaporate directly to the atmosphere, be absorbed by the canopy, or drop to the ground as throughfall or stemflow. *S* depends on the characteristics of the intercepting surface. These characteristics include leaf area index (*LAI*) (Liu, 1998; Llorens and Gallart, 2000; Fleischbein *et al*., 2005) and leaf shape, bark morphology (e.g. Pypker *et al*., 2011), dimension and orientation of the branches (Jackson, 1975; Návar and Bryan, 1990), rainfall intensity (Calder *et al*., 1996; Jackson, 1975) as well as climatic factors such as wind speed (Hörmann *et al*., 1996; Jackson, 1975).

Various types of regression equations have been proposed to calculate *I* (Zinke, 1967; Jackson, 1975). However, even for the same vegetation type, the equations frequently differed because of the unique characteristics of each forest stand (van Dijk and Bruijnzeel, 2001). Gash (1979) introduced a simpler storm-based model that has been used with considerable success to estimate *I* in a wide range of coniferous and broadleaf forests (e.g. Gash *et al*., 1980; Pearce *et al*., 1980) as well as tropical rainforests (e.g. Lloyd *et al*., 1988; Hutjes *et al*., 1990). However, attempts to use the analytical model in more open forests tended to overestimate *I* (Teklehaimanot *et al*., 1991; Gash *et al*., 1995; Návar, 2012). This led to the development of a 'sparse canopy' version of the Gash model in which evaporation from the wet canopy was considered linearly dependent on canopy cover fraction (*c*) (Gash *et al*., 1995).

Land managers in Iran are faced with year round water shortages because the country has vast expanses of arid and semi-arid regions. During the dry period (May to October), the water shortages become particularly severe. Knowledge about the amount of rainfall intercepted by different tree species will help managers choose suitable species. Furthermore, evidence demonstrating the applicability of the Gash model in this region will provide a tool for land managers to estimate *I* for different forest types. Currently, *Pinus eldarica* is a widely accepted species for afforestation in Iran, as well as other countries with similar climates (De Los Ríos-Carrasco *et al*., 2009), because *P. eldarica* tolerates drought (Sardabi, 1998). To our knowledge, a comprehensive investigation on the impact of *P. eldarica* on *I* has not been reported for forests in Iran, nor in other countries in the region, despite the widespread use of this species in afforestation efforts. Therefore, the objectives of this paper are to (i) quantify how *TF* and *I* are partitioned in a planted *P. eldarica* forest located in a semi-arid climate zone of Iran and (ii) determine *S* using the mean method and (iii) assess the applicability of the Gash model (Gash *et al*., 1995) for *P. eldarica* forests.

MATERIALS AND METHODS

Site Description

The study occurred in a nearly closed canopied, forty-year-old pure and even-aged *Pinus eldarica* Medw. afforestation located in the Chitgar Forest Park of Tehran, Iran (Figure 1). The pine forest covers 366.5 ha of the Park and represents 45% of the total area. *TF* measurements were made in a 270 m^2 plot (35˚10´ N, 51˚10´ E, and 1269 m asl).Tree density was 1185 trees ha^{-1} and the total basal area was 64.5 m^2 ha^{-1}. Mean tree height and diameter at breast height (*DBH*) were 11 m and 23.5 cm, respectively. Measurements were performed from September 2009 to April 2010.

From 1996-2010, mean annual precipitation was 267.6 mm (SE: ±20.4 mm) (Chitgar Meteorological Station (35° 44´ N, 51° 10´ E, and

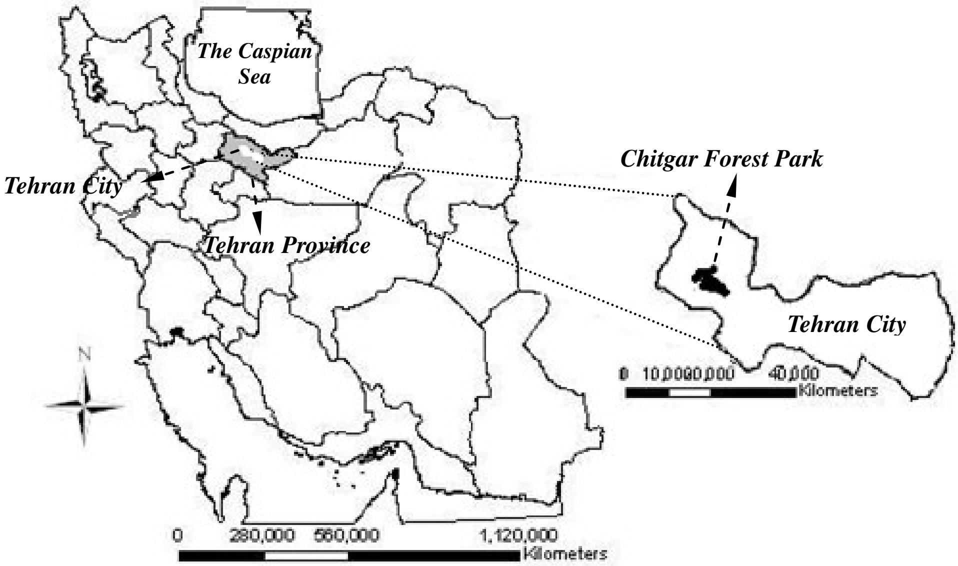

Figure 1. Location of the Chitgar Forest Park near Tehran city, Iran (the sample plot inside the Park not shown).

1305 m asl). For this region, the wettest and driest months are March (45.4 mm; SE: ±10.7 mm) and August (0.9 mm; SE: ±0.4 mm), respectively. In this region, the dry period begins in May and ends in October. The wet period extends from November to April, and historically accounts for 88% of the total annual precipitation. The mean annual temperature is 17.2°C (SE: ±0.1°C); August is the warmest month with average temperature of 29.4°C (SE: ±0.3°C) and January is the coldest month (3.8°C; SE: ±0.8°C).

Field Measurements

Gross Rainfall (P_G)

P_G was measured by 6 cylindrical plastic collectors that were 9 cm in diameter and 20 cm in height. The 6 collectors were placed in a neighboring open area that was 15 m from the *P. eldarica* forest. The quantity of water in the collectors was measured manually using a graduated cylinder with an accuracy of 1 ml. After a rain event, rainwater was measured from each of the rainfall collectors 2 hours following an event if the event occurred during daylight hours or at sunrise if the event occurred at night (Carlyle-Moses *et al*., 2004). The average from the 6 rainfall collectors was used to estimate P_G. Rainfall events were defined as separate rain events as long as there was at least 2 hours without rain. In this dry climate, 2 hours was assumed to be sufficient for the canopy to completely dry (Carlyle-Moses *et al*., 2004).

Throughfall (*TF*), Stemflow (*SF*) and Rainfall Interception Loss (*I*)

TF was measured using 45 rain collectors of the same design as the collectors used to quantify P_G. *TF* collectors were randomly placed beneath the forest canopy within the study plot (Figure 2). *TF* volume was measured at the same time P_G was measured. In the present study, *SF* was not directly measured because *P. eldarica* has rough bark and a canopy structure that is similar to other species with low stemflow (Helvey and Patric, 1965; Geiger, 1965; Llorens *et al*., 1997, 2000; Lankreijer *et al*., 1993; Návar, 2012). While *Pinus* trees can have stemflow above 5% of gross precipitation, the vast majority of studies have found *Pinus* species to have stemflow values well below 5% of gross precipitation (Zink, 1967; Steinbuck, 2002). For example, Návar (2011) reported less than 0.20% for

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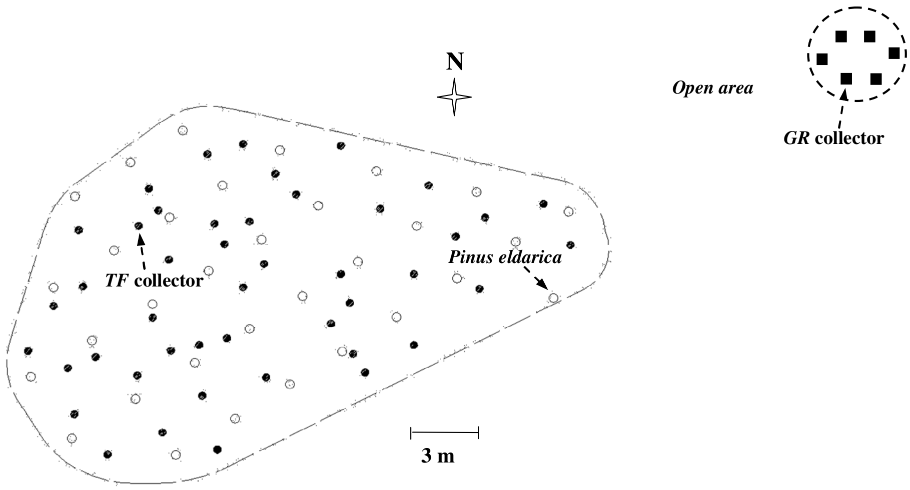

Figure 2. Positions of *Pinus eldarica* trees (open circles) and throughfall (*TF*) collectors (filled circles) in the study plot. Gross rainfall (P_G) collectors are shown in an open adjacent area. The actual positions of trees and collectors in the study plot were surveyed using a compass and a tape measure.

semi-arid pines of northern Mexico. Furthermore, *P. eldarica* has plagiophile branch structuring. Past research has demonstrated that trees with plagiophile branching have reduced stemflow relative to forests with more erectile branch structure and smooth bark (Pypker *et al*., 2011, Levia and Frost, 2003, André *et al*., 2008). Hence, we calculated *I* as the difference between P_G and *TF*.

Canopy Storage Capacity (*S*) and Free Throughfall Coefficient (*p*)

For the purposes of this paper, we define *S* as an estimate of the water remaining in the canopy after rainfall ceases and evaporation is negligible (Gash *et al*., 1995). To estimate *S*, we applied the commonly used mean method (Jackson, 1975; Pypker *et al*., 2005; Link *et al*., 2004; Návar, 2012). The mean method estimates *S*, *p* and the ratio of the mean evaporation rate to the mean rainfall intensity ($\overline{E}/\overline{R}$) by creating two linear regressions (A and B) that relate *TF* to P_G (Jackson, 1975; Pypker *et al*., 2005; Link *et al*. 2004). The first regression line (A) is fit to all the rainfall events where P_G was sufficient to saturate the canopy and the second regression (B) is fit to all the rainfall events where P_G was insufficient to saturate the canopy. When using the mean method, the difference between P_G and *TF* at the intersection point provides an estimate of *S*, the slope of the second regression line provides the estimate of *p* and one minus the slope of the first regression line represents $\overline{E}/\overline{R}$ (Leyton *et al*., 1967; Jackson., 1975; Klaassen *et al*., 1998; Llorens and Gallart, 2000; Pypker *et al*., 2005). The amount of rainfall sufficient to saturate the canopy (P_s) was estimated subjectively by locating the inflection point on the graph relating *TF* to P_G.

Gash Model (*I*)

In this study, a comparison was made between *I* estimated by the field measurements and by the revised Gash model (Gash *et al*., 1995). The revised Gash model is a powerful tool for estimating *I* because of its simple requirements of *S*, *p*, and $\overline{E}/\overline{R}$ (Gash *et al*., 1995). The Gash model is the most common rainfall interception model used in interception studies (Muzylo *et al*., 2009) although it has been reported by some to incorrectly predict *I* in sparse forests (Návar, 2012). This model might be a valuable tool for studying rainfall interception loss in forests in Iran. The Gash model is, however, limited by the following assumptions outlined in Gash (1979): (1) rainfall is represented by a series of discrete storms separated by periods long enough to allow the canopy to completely dry up; (2) the

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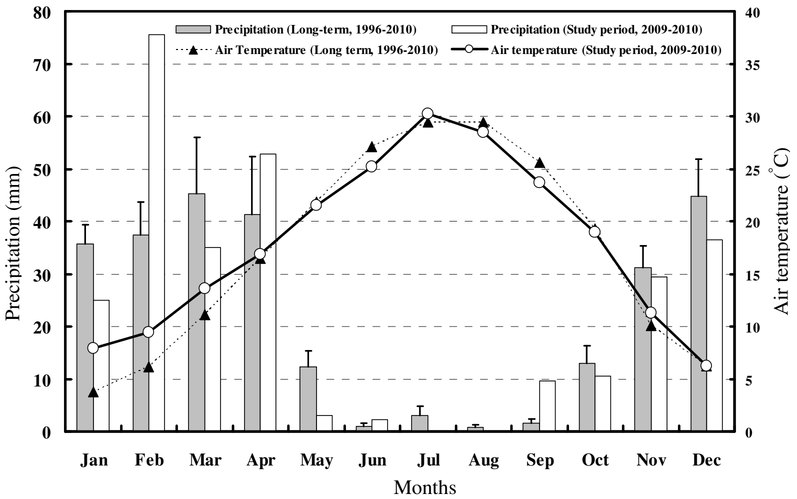

Figure 3. Long-term and study period mean monthly precipitation (mm) and air temperature (°C) at the Chitgar Forest Park Meteorological station. The darker bars and dashed line indicate the long-term (1996-2010) monthly means of the precipitation and air temperature, respectively. The light bars and open circles represent the precipitation and air temperature during the study period, respectively. Error bars show the standard error (SE) of monthly precipitation for the long-term record.

meteorological conditions are constant throughout the storm; and (3) there is no drip from the canopy during wet-up. Clearly, assumptions 2 and 3 are frequently violated during a storm as meteorological conditions such as wind speed, rainfall intensity and vapor pressure deficit can change throughout the storm and wind speeds may vary and shake the canopy causing drip during wet-up. Yet, the Gash model has proven be very robust in predicting annual *I* (Gash *et al*., 1995). The following is the Gash model for sparse canopies (Gash *et al*., 1995). The interception (I_c) during m small storms that were insufficient to saturate the canopy is described by:

$$I_c = c\sum_{j=1}^{m} P_{G,j} \quad (1)$$

Where, *c* represents the canopy cover. The canopy cover was assumed to equal 1-p (Gash *et al*., 1995; Herbst *et al*., 2008). The amount of interception for *n* storms sufficient to saturate the canopy (I_n) (i.e. ≥ the amount of rainfall to saturate the canopy–P_s) is calculated as sum of the amount of water lost during wet-up (I_w), the evaporation after canopy saturation, but prior to rainfall ceasing (I_s) and the evaporation after the storm ceases (I_a). These interception variables are calculated as:

$$I_w = ncP_s - ncS_c \quad (2)$$

$$I_a = ncS_c \quad (3)$$

$$I_S = (\overline{E}/\overline{R})\sum_{j=1}^{n}(P_G - P_s) \quad (4)$$

$$I_n = I_W + I_a + I_S \quad (5)$$

Where, S_c= *S*/c and (Gash *et al*., 1995). We parameterized the Gash model using estimates of *p*, *S*, P_s, and $\overline{E}/\overline{R}$ by applying the mean method to half of the rainfall data. This resulted in estimates of *p, S,* P_s, and $\overline{E}/\overline{R}$ equal to 0.16, 2.09 mm, 2.68 mm, and 0.11, respectively. These results were then applied to the other half of the data set to determine if the Gash model can accurately estimate *I*.

RESULTS

Long-term Average and Observed Meteorology

From September 2009 to April 2010, the cumulative gross precipitation was 279.6 mm, slightly more than the long-term average of 267.6 mm. The annual distribution of precipitation during the study period was similar to that of the long-term average because most of the precipitation recorded

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during the study period (91%) occurred during the wet period (from November to May; Figure 3). Historically, the wet period accounts for 88% of the total annual precipitation. The wettest and driest months in the long-term records were March (45.4 mm) and August (0.9 mm), respectively. However, during the study period, the wettest month was February (75.5 mm) and the driest months were July and August (0 mm) (Figure 3). Average air temperature was 17.8°C during the study period, similar to the long-term average temperature of 17.2°C. Historically, August was the warmest month (average temperature of 29.4°C), but, during the study period, July was the warmest (30.3°C). Like the long-term average, January was the coldest month during the study period (7.9°C) (Figure 3).

Gross Rainfall (P_G) and Throughfall (*TF*)

From September 2009 to April 2010, 164.8 mm of rain fell in thirty rainfall events. Cumulative P_G for an individual rainfall event ranged from 0.2 mm to 27.5 mm, with a mean P_G depth per event of 5.5 mm. The rainfall events were grouped into three classes (Table 1) to allow for a better understanding of the relationship between P_G and *I*. The three classes are: $P_G \leq 1.5$ mm, 1.5 mm$<P_G \leq 5.5$ mm, and $P_G>5.5$ mm. This resulted in 10 rainfall events being allocated to each of the three classes.

Of the 30 rainfall events recorded during the measurement period, 103.6 mm, or 62.8% of the cumulative P_G reached the forest floor as *TF*. Mean *TF* was 3.5 mm (CV: 72.9%) or 38.6% of P_G and ranged from 0.0 to 80.5% for P_G events of 0.2 to 27.5 mm, respectively. For the $P_G \leq 1.5$ mm, 1.5 mm$\leq P_G \leq 5.5$ mm, and $P_G \geq 5.5$ mm rainfall event classes, the mean TF:P_G values were 8.9, 40, and 67%, respectively (Table 1).

Rainfall Interception Loss (*I*)

Rainfall interception loss totaled 61.2 mm, or 37.2% of the total P_G for the study period. The percentage lost to *I* depended on storm size, with the percentage varying from 19.5% of P_G for larger rainfall events (27.5 mm) to 100.0% of P_G (0.2 mm) for smaller rainfall events.

The ratio of *I* to P_G (relative *I* or I:P_G) was correlated with P_G (Figure 4). The mean values of I:P_G showed a decreasing trend, with a decreasing ratio as P_G increased. A negative logarithmic significant relationship (r^2= 0.861; P value$\leq$ 0.01) was fitted between I:P_G and P_G.

Canopy (Water) Storage Capacity (*S*)

S was determined using a method that related P_G to *TF* (Figure 5). The mean method (Klaassen *et al*., 1998; Jackson, 1975) estimated *S* to be 1.8 mm (Figure 5).

Lastly, the mean method estimated *p* and $\overline{E}/\overline{R}$ to be 0.1 and 0.16, respectively.

Gash Model

The Gash Model accurately estimated *I* (Figure 6). On a per-storm basis, the difference between modeled and measured values ranged from 0.03 to 1.6 mm, with the greatest differences occurring for the largest storms. The Gash model predicted *I* to be 26.7 mm, and this only differed from the measured *I* (25.6 mm) by 1.1 mm. The slope of the line relating the measured and modeled estimates of *I* was 0.86 (95% CI = 0.17). The measured and modeled estimates of *I* were not statistically different because the slope was not significantly different from 1 (P-value>0.1).

Table 1. Mean cumulative gross rainfall (P_G), mean throughfall as a percentage of P_G (TF:P_G), and mean rainfall interception as a percentage of P_G (I:P_G) for rainfall events from September 2009 to April 2010. The relationships are provided for three P_G classes.

P_G class (mm)	Frequency	P_G (mm)	TF:P_G (%)	I:P_G (%)
< 1.5	10	7.8	8.9	91.1
1.5-5.5	10	34.7	40.0	60.0
> 5.5	10	122.3	67.0	33.0

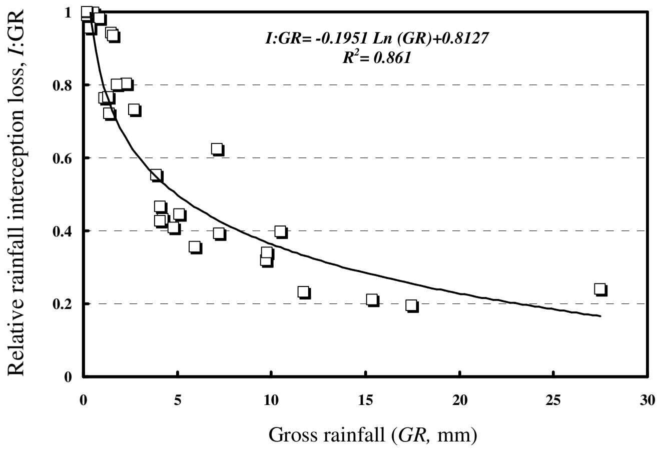

Figure 4. The relationship between relative rainfall interception loss (I:P_G) and P_G in *Pinus eldarica* afforestation.

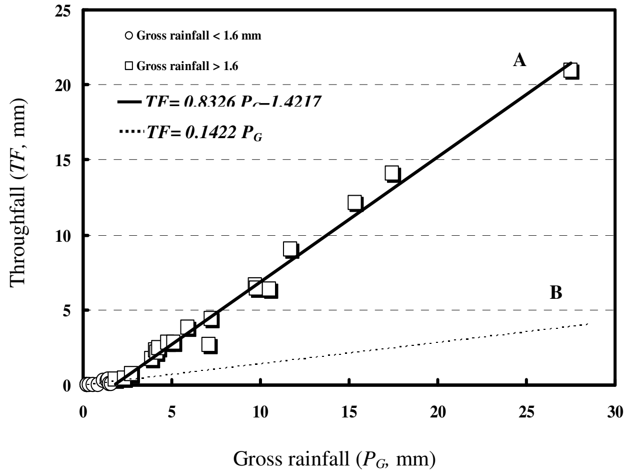

Figure 5. Estimation of canopy storage capacity (S) and free throughfall coefficient (p) using the relationship between gross rainfall (P_G) and throughfall (TF) during the study period (Mean method). The difference between P_G and TF at the inflection point estimates the canopy storage capacity (S). The slope of regression B represents p and 1 minus the slope of the A regression line represents the ratio of mean evaporation to mean rainfall intensity ($\overline{E}/\overline{R}$).

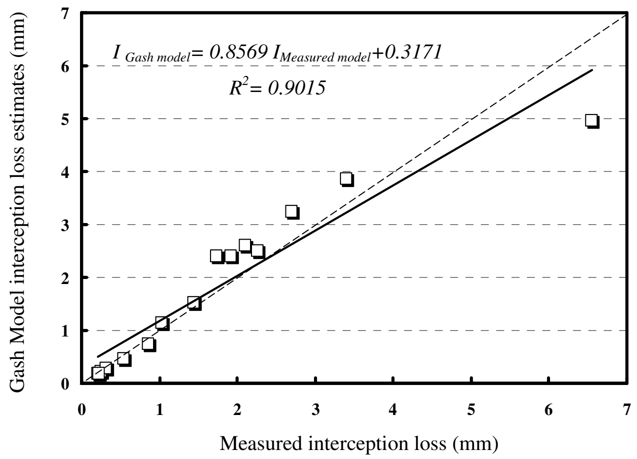

Figure 6. A comparison between Gash model estimates of I to measured I for half of the data. The 1:1 line is the dashed line. The solid line represents a linear regression between the x-axis and y-axis.

DISCUSSION

Partitioning of Gross Precipitation between Throughfall and Interception Loss

A review of the literature on rainfall partitioning in various pine stands (Table 2) indicates that the values for TF:P_G and I:P_G obtained in the present study differed slightly with those measured in other pine forests (Table 3). Llorens *et al*. (1997) reported that the average values of TF:P_G and I:P_G in a *Pinus sylvestris* forest in Eastern Pyrenees, Spain, were 0.747 and 0.24, respectively. Mahendrappa (1990) reported *TF* and *I* for a *Pinus strobus* plantation in Canada to be 65 and 30.7% of annual P_G, respectively. In Portugal, the measured value of *TF* in a *Pinus pinaster* forest was 82.6% of P_G during the two years of measurement (Valente *et al*., 1997). It is noteworthy that value of I:P_G obtained in our study (0.37) was on the high end of the 0.12 to 0.42 measured by others in needle-leaved evergreen forests (Hibbert, 1967; Zinke, 1967) (Table 2). The partitioning of rainfall into *TF* and *I* in forest ecosystems has been demonstrated to be a function of incident rainfall characteristics (amount, intensity, duration, and temporal distribution of rainfall events) (Jackson, 1975; Crockford and Richardson, 2000; Xiao *et al*., 2000; Marin *et al*., 2000; Huber and Iroumé, 2001; Iroumé and Huber, 2002; Link *et al*., 2004; Návar, 2012), meteorological conditions (air temperature, relative humidity, wind speed, and wind direction) (Crockford and Richardson, 2000), and forest structure (species composition, stand age, basal area, stand density and canopy morphology and architecture) (Forgeard *et al*., 1980; Xiao *et al*., 2000; Iroumé and Huber, 2002; Carlyle-Moses, 2004; Fleischbein *et al*., 2005; Deguchi *et al*., 2006; Staelens *et al*., 2008; Muzylo *et al*., 2009). Given the dry nature of this region, it is likely that the differences in rainfall partitioning reported by other researchers were due, in part, to differences in the above mentioned factors.

The size of P_G had a major impact on the partitioning of rainfall into *TF* and *I* for the *P. eldarica* afforestation in this study. As the size of P_G increased, the ratio of *I* to P_G (I:P_G) decreased. For example, as P_G increased from < 1.5 mm to > 5.5 mm, I:P_G decreased from 0.91 to 0.33, respectively (Table 1). In this study, 67% of the rainfall events were less than 5.5 mm, therefore, the large proportion of incident P_G wetted the crown surface and subsequently contributed to interception loss. Therefore, part of the difference in interception loss between this study and others in the literature may have resulted from different storm sizes. However, while *TF* and P_G were well correlated, the lowest *TF* values were not synchronized with the lowest values of P_G (0.22), thereby suggesting that the climatic factors also played a very important role in the rainfall partitioning.

Estimate of Canopy (Water) Storage Capacity

In the present study, *S* was estimated to be 1.8 mm (Table 3). The estimates of *S* in the present study fall within the range reported for other pine forests. For example, using artificial wetting, Llorens and Gallart (2000) determined *S* in a *Pinus sylvestris* forest (1,400 trees ha^{-1}) in Eastern Pyrenees, Spain, to be 2 mm. Liu (1998) determined *S* to be 0.7 mm for a *Pinus elliottii* afforestation (1,190 trees ha^{-1} similar to this study). Llorens (1997) also reports an *S* of 1.3 mm by an indirect method for a *Pinus sylvestris* afforestation (2,400 trees ha^{-1}). Lastly, Návar (2012) reported a mean value of 1.03 mm for temperate, dry *P. pseudostrobus* forests in northern Mexico.

Changes in rainfall intensity (Calder *et al*., 1996; Jackson, 1975) and wind speed (Jackson, 1975; Hörmann *et al*., 1996) are correlated with changes in *S*. The nature of the intercepting surface also controls the size of *S* (type of species, leaf shape, dimension and orientation) (Jackson, 1975; Liu, 1998; Llorens and Gallart, 2000; Fleischbein *et al*., 2005). Wind movement of the canopy may greatly reduce the amount of water which can be held before drainage occurs (Jackson, 1975; Hörmann *et al*., 1996). Therefore, the amount of *S* may vary from event to event even if canopy characteristics remain constant.

Table 2. A review of measured values of relative throughfall ($TF:P_G$), relative rainfall interception ($I:P_G$) as well as relative stemflow ($SF:P_G$) obtained from various research carried out on different species of pine (stand). *TF*, *SF*, *I*, and P_G are referred to throughfall, stemflow, rainfall interception, and gross rainfall, respectively.

Tree Species	$I:P_G$ (%)	$TF:P_G$ (%)	$SF:P_G$ (%)	Tree density (Stem ha^{-1})	Location	References
Pinus pinaster	17.1	82.6	0.3	312	Portugal	Valente *et al*. (1997)
Pinus radiata	18.3	72.8	8.9	1708	South-Eastern Australia	Crockford and Richardson (1990)
Pinus wallichiana	21	76.3	2.7	1200	India	Singh (1987)
Pinus densiflora	14	83	3	1575	Etajima Island (West Japan)	Mitsudera *et al*. (1984)
Pinus radiata	30	----	----	450	New Zealand	Kelliher *et al*. (1992)
Pinus sylvestris	32	38-53	15-30	4600	Crowthorne, Berks	Rutter (1963)
Pinus massoniana	27.2	70.4	2.4	2628	China	Cao *et al*. (2008)
Pinus sylvestris	24	74.7	1.3	2400	Eastern Pyrenees, Spain	Llorens *et al*. (1997)
Pinus radiata	26.5	----	----	1493	Shoalhaven-Australia	Pook *et al*. (1991)
Pinus nigra	35	65	----	600	Southeast England	Rutter *et al*. (1971)
Pinus sylvestris	42.4	57.6	----	1870	Northeast Scotland	Gash *et al*. (1980)
Pinus strobus	30.7	65	5.3	----	Canada	Mahendrappa (1990)
Pinus resinosa	28.3	69	0.7	----	Canada	Mahendrappa (1990)
Pinus pinaster	12.6 - 21	76-83	1-6	800	Southwest Europe	Loustau *et al*. (1992)
Pinus pinaster	12.5	87.5	----	430	France	Lankreijer *et al*. (1993)
Pinus pseudostrobus	17.8	82.0	0.20	125	Northern Mexico	Návar (2011; 2012)

Table 3. A review of measured values of canopy storage capacity (*S*), free throughfall coefficient (*p*) and the measurement methods used to estimate *S* and *p* in coniferous forests.

Species	Density (trees ha^{-1})	*S* (mm)	*p*	Method	References
Pinus sylvestris	509	2.3	0.2	Direct	Llorens and Gallart (2000)
Pinus sylvestris	764	1.2	0.4	Direct	Llorens and Gallart (2000)
Pinus sylvestris	800	0.8	0.3	Regression line	Gash and Morton (1978)
Pinus sylvestris	1400	2	0.2	Direct	Llorens and Gallart (2000)
Pinus sylvestris	1782	1.5	0.3	Direct	Llorens and Gallart (2000)
Pinus sylvestris	1870	1	0.1	Regression line	Gash *et al*. (1980)
Pinus sylvestris	2400	1.3	0.1	Regression line	Llorens (1997)
Pinus sylvestris	2674	2.7	0.1	Direct	Llorens and Gallart (2000)
Pinus sylvestris	2900	0.3	----	----	Perttu *et al*. (1980)
Pinus sylvestris	4600	1.6	----	Regression line	Rutter (1963)
Pinus eldarica	1185	1.77	0.1	Regression line (Mean method)	This study
Pinus pinaster	312	0.4	0.4	Regression line	Valente *et al*. (1997)
Pinus pinaster	430	0.3	0.4	Regression line	Lankreijer *et al*. (1993)
Pinus pinaster	800	0.5	0.6	Regression line	Loustau *et al*. (1992)
Pinus elliottii	464	0.4	---	Direct	Liu (1998)
Pinus elliottii	496	0.5	---	Direct	Liu (1998)
Pinus elliottii	672	0.4	---	Direct	Liu (1998)
Pinus elliottii	1190	0.7	---	Direct	Liu (1998)
Pinus nigra	600	1.1	0.3	Regression line	Rutter *et al*. (1971)
Pinus nigra	600	1	----	----	Robins (1974)
Pinus radiata	450	0.4	----	Regression line	Kelliher *et al*. (1992)
Pinus pseudostrobus	125	1.03	0.26	Regression line and optical densitometers	Návar (2012)

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Several studies have investigated the effects of changes in forest cover on the water recharge (Bosch and Hewlett, 1982; Blackie, 1993; Sahin and Hall, 1996). The reduction in water recharge upon afforestation is mainly due to an increase in interception, evaporation, and transpiration (Van der Salm *et al*., 2007). The rainfall interception from afforestations with *P. eldarica* in Iran is considerable, averaging 37% of P_G. Therefore, rainfall interception loss needs to be considered in future water balance studies and in the selection of tree species for afforestation practices. Furthermore, future research is needed to quantify the full hydrological (transpiration and rainfall interception loss) effect of these afforestation practices.

Gash Model

The Gash model proved to accurately estimate *I* for storms up to 30 mm in size. Past research on *I* in other coniferous forests have also successfully applied the Gash model (Gash *et al*., 1980; Gash *et al*., 1999; Valente *et al*., 1997; Návar *et al*., 1999a and b; Návar, 2013). As with past research, there were some inaccuracies on an individual storm basis (e.g. Llorens, 1997). However, the model often accurately predicts total *I* (e.g. Llorens, 1997). Hence, his model could be a valuable tool for estimating *TF* in watersheds dominated by *P. eldarica* for years with varying annual precipitation. Ultimately, the estimates of *TF* could be used to better understand annual changes in streamflow.

CONCLUSIONS

This study was carried out in a forty-year-old *Pinus eldarica* afforestation during a 9-month period in a semi-arid climate zone of Iran. *I* and *TF* represented 37.2 and 62.8% of annual P_G, respectively. It was observed that rainfall partitioning into *TF* and *I* was strongly affected by the size of P_G; with the ratio of I:P_G declining as P_G increased. *S* in the *P. eldarica* stand was 1.8 mm.

This research is the first to document rainfall partitioning and *S* in a *P. eldarica* afforestation. In the semi-arid climate zone of Iran, plant growth and productivity is strongly affected by water availability. Therefore, *I* should be considered when selecting species for afforestation projects in the semi-arid climate regions as it can be significant.

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اندازه گیری باران ربایی کاج تهران(*Pinus eldarica*) در اقلیم نیمه خشک: کاربرد مدل Gash

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چکیده

باران‌ربایی (I)، ظرفیت نگهداری آب روی تاج‌پوشش (S) و نسبت میانگین تبخیر به میانگین شدت بارندگی ($\overline{E}/\overline{R}$) از اجزای مهم تعادل آب در مناطق خشک و نیمه‌خشک می‌باشند. هدف از این تحقیق تعیین مقدار باران‌ربایی و ظرفیت نگهداری آب روی تاج‌پوشش و همچنین ارزیابی مدل Gash

برای بر آورد باران‌ربایی در یک توده خالص جنگلکاری شده کاج تهران (*Pinus eldarica* Medw) واقع در پارک جنگلی چیتگر تهران می‌باشد. اندازه‌گیری بارندگی در هر بارش (P_G) و تاج‌بارش (TF) از مهر ۱۳۸۸ تا اردیبهشت ۱۳۸۹ صورت گرفت. در این دوره در مجموع ۱۶۴/۸ میلی‌متر بارندگی جمع‌آوری شد که ۶۱/۲ میلی‌متر آن به باران‌ربایی اختصاص پیدا کرد. باران‌ربایی از تفاوت بین بارندگی در هر بارش و تاج‌بارش محاسبه گردید. نسبت باران‌ربایی به بارندگی در هر بارش ($I:P_G$) بین ۰/۱۹۵ و ۱ و به طور میانگین ۰/۶۱۴ بدست آمد. نتایج نشان داد رابطه لگاریتمی قوی بین نسبت باران‌ربایی به بارندگی و بارندگی در هر بارش ($r^2= 0.861$; p value ≤ 0.01) وجود دارد به طوری که با افزایش مقدار بارندگی در هر بارش، نسبت باران‌ربایی به بارندگی در هر بارش کاهش نشان میدهد. ظرفیت نگهداری تاج‌پوشش با استفاده از روش میانگین ۱/۸ میلی متر اندازه‌گیری گردید. مدل Gash، باران‌ربایی را با ۱/۱ میلی‌متر اختلاف نسبت به مقدار باران‌ربایی اندازه‌گیری شده در توده برآورد کرد. باران‌ربایی سهم قابل توجهی از بارندگی در هر بارش را در توده جنگلکاری *P.eldarica* در منطقه نیمه خشک ایران که رطوبت خاک عامل محدود کننده رشد و تولید گیاهان به حساب می‌آید، به خود اختصاص می‌دهد.

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