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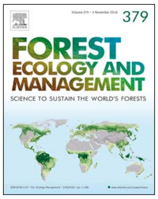

A seasonal evaluation of the reformulated Gash interception model for semi-arid deciduous oak forest stands

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ABSTRACT

Interception represents a significant component of the water budget of forests, diverting significant quantities of precipitation away from soil moisture, transpiration, and surface and groundwater recharge. There are several physically-based models of forest interception but their utility across seasonal variability is limited because few studies have collected field data of both the growing (leaf on) and dormant (leaf off) seasons and explored how seasonality affects parameters of simulations. Rainfall partitioning modelling using the Reformulated Gash Analytical Model (RGAM) for Brant's oak (*Quercus brantii*) forest plots in the Zagros forest, Iran, simulated interception values close to the observed, with an underestimation of 4.0% and 7.5% for the leafed and leafless periods, respectively. Model parameters varied seasonally: free throughfall coefficient, canopy storage capacity, canopy saturation point, and ratio of mean wet evaporation rate to mean rainfall intensity were ~0.60, 1.0 mm, 2.6 mm, and 0.15 in the leafed period and ~0.80, 0.1 mm, 0.5 mm, and 0.04 in the leafless period, respectively. In this application, the RGAM was highly sensitive to change in the ratio of mean wet evaporation rate to mean rainfall intensity, and less sensitive to canopy cover and canopy storage capacity, especially in the leafless period. Therefore, canopy structure is less important for rainfall interception predictions by RGAM.

1. Introduction

Drylands, ranging from hyper-arid to dry subhumid areas, cover about 41% of earth's land surface and are limited by soil moisture, the result of low rainfall and high evaporation (Kharazipour, 2009). In these areas with scarce water resources, a good understanding of eco-hydrological processes is clearly essential for effective water resources management and land use planning. One such process is evaporative loss from dryland forests during rainfall.

The canopy affects hydrological and biogeochemical fluxes because, prior to reaching the forest floor, the water must first pass through the forest canopy (Levia et al., 2011). Interception loss, the evaporation which results from rainfall intercepted by forest canopy that evaporates before reaching the ground, is a loss or sink term in the water balance of a catchment and an important component of the total forest evaporation (Gash and Morton, 1978). Models of interception loss have been developed to make predictions based on rainfall and canopy characteristics (Valente et al., 1997; Van Dijk and Bruijnzeel, 2001). These models have been based largely on either the Rutter (Rutter et al., 1975, 1971) or Gash (Gash, 1979; Gash et al., 1995) models. The original Gash (1979) model requires less data and features an empirical approach, while preserving much of the fundamental physical reasoning explicit in the Rutter model. However, it overestimates interception for sparse forest (Gash et al., 1995; Valente et al., 1997) because it assumes that the evaporation area extends to the whole plot area, whereas the actual evaporating area is greatly reduced in these types of forests (Teklehaimanot and Jarvis, 1991). The so-called RGAM (Gash et al., 1995) is a more robust and accurate reformulation of the original Gash model for sparse forests (Carlyle-Moses and Price, 1999; Deguchi et al., 2006; Valente et al., 1997; Zhang et al., 2006) that treats the open and the covered areas separately.

Models to predict interception loss have been applied less frequently in deciduous forests than evergreen forests. Furthermore, most studies of deciduous forests have only included measurements from the leafed period (De Miranda and Butler, 1986; Cantú Silva and Okumura, 1996; Price and Carlyle-Moses, 2003) and few studies have included both the leafed and leafless periods (Dolman, 1987; Park, 2000; Herbst et al., 2008; Mużyło et al., 2012). The small number of rainfall interception modelling studies in deciduous forests is probably the consequence of difficulties in model application in this kind of forest. For example,

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rainfall partitioning measurements in leafed and leafless periods requires the observation period to be longer than in other types of cover. In addition, since such forests must be parameterized for both seasons because of significant seasonal changes in the canopy structure (Deguchi et al., 2006; Carlyle-Moses and Price, 2007; Herbst et al., 2008; Šraj et al., 2008, Mużyło et al., 2012), the required parameters are greater (see reviews by Liu, 2001; Llorens and Gallart, 2000).

Sensitivity analysis is a useful tool because it clarifies model inputs are most and least important to predictions. Generally, interception is determined by vegetation characteristics, rainfall characteristics, and the evaporative demand (Gerrits and Savenije, 2011). In deciduous forests with canopy structure that varies throughout the year, interception models may be sensitive to different parameters depending on season. For example, in a review study by Linhoss and Siegert (2016) it was found that canopy storage capacity is among the most influential parameters on modelled interception loss. We expect an opposite finding when using the Gash model since it does not account for intermittency because of considering rainfall as one storm event per day, and thus reduces canopy storage capacity potential error.

Mediterranean areas are frequently covered by open woodlands, savannah-type ecosystems, isolated trees, or shrub formations, and there is less knowledge on the rainfall partitioning process in these ecosystems compared to closed forests (Llorens and Domingo, 2007). This is true for the semiarid mountainous zone of western Iran (the Zagros), where deciduous oak woodlands cover about six million ha (Talebi et al., 2014), occupying critical areas in terms of soil and water resources. In Zagros, forest ecosystems are mostly characterized by widely separated trees (mostly Brant's oak (*Quercus brantii* var. *persica*)) and an understory of herbs and shrubs that is frequently exploited for agroforestry. In these areas with scarce water resources, a good understanding of ecohydrological processes is essential for effective water resources management and land use planning. In a previous interception study of individual Brant's oak (or Persian oak) trees, Fathizadeh et al. (2013) reported an annual interception loss of 20%, but neither the original Gash (1979) model nor the reformulated, sparse versions (Gash et al., 1995; Valente et al., 1997) have been applied to the deciduous forests of Zagros in Iran. The objectives of this research are to: (1) explore the influence of seasonal changes in canopy characteristics on predicted and measured interception losses across forest canopy densities (2) evaluate how seasonal changes affect the model influential parameters.

2. Materials and methods

2.1. Site description

The experimental work took place in the Southern Zagros forests of the western Iranian state of Ilam, protected forests of Dalab region (46°22′E, 33°42′N) (Fig. 1).

Dalab is a hilly and undulating region with an elevation ranging from 1050 to 2250 m above sea level and an area of about 4000 ha. Forests of Brant's oak, or Persian oak, the main woody species in this region, is usually found in pure stands and covers about 3.5 million hectares in Zagros. The other important tree and shrub species of *Pistacia atlantica*, *Acer cinerascens*, *Crataegus azarolus, Cerasus microcarpa, Daphne mucronata, Amygdalus orientalis,* and *Lonicera nummularifolia* are found only as individual trees or in groups of small to medium size. Density of stands varies across the study area from 30 to 100 trees per hectare.

Based on long-term climatic data (1999–2015) from the Eyvan synoptic station (46°21′, 33°45′, and 1320 m a.s.l), the nearest meteorological station to the Dalab woodlands (≤4 km), the average annual precipitation is 652.6 mm (SD = 130.2 mm) and the mean annual air temperature is 17 °C (SD = 0.5 °C) with an absolute maximum of 42.8 °C in August and an absolute minimum of −14.0 °C in January. The meteorological records also indicate annual open water evaporation to be 2126.8 mm (SD = ± 273.6 mm), the average annual relative humidity of 38% and the maximum annual wind speed of 35 m/s. The monthly precipitation distribution is sub-Mediterranean with strong seasonality in rainfall distribution. The dry period begins in May and ends in October, and the wet period extends from November to April and historically accounts for 91.5% of the total annual precipitation.

Twelve 60 m × 60 m plots of pure Brant's oak but various canopy structure were established at least 60 m apart from each other (Table 1).

The plots were on a relatively flat area (average slope of approximately five percent). The understory was either bare soil or grass. Rainfall events were sampled during two canopy development stages: leafed (including leaf burst and senescence) and leafless. In previous work at this site, Fathizadeh et al. (2017) quantified the relationship between canopy structure and canopy storage capacity.

2.2. Measurements and methods of analysis

2.2.1. Gross precipitation (GP) and throughfall (TF)

GP was measured with 3 cylindrical plastic rain gauges, 9 cm in diameter, placed in a neighboring open area (< 30 m away) near each plot. GP was measured immediately after each storm. A rain event was defined as a period with more than 0.4 mm of total GP in the leafed period and more than 0.2 mm of total GP in the leafless period, separated by a period of at least 6 h (in dry periods) to 10 h (in wet period) of no rainfall (Sadeghi et al., 2015).

In each plot, 30 canopy TF collectors (identical to the GP rain gauges) were placed under the canopy. To overcome the great spatial variability of TF, rain-gauges were placed randomly underneath the forest canopy. TF at each gauge was measured after every rainfall event, or after several individual events when independent collection was not possible. Average, long-term TF is best measured using a combination of fixed and manual roving gauges to provide representative samples (Bruijnzeel, 2000; Waterloo et al., 1999). Therefore, half of the rain-gauges were relocated to new random positions after every five storms.

Stemflow (Sf) is often neglected in studies (e.g. Pereira et al., 2009; Pypker et al., 2005; Sadeghi et al., 2015) because it is small in volume and expensive to measure. Moreover, rough-barked species like *Q. brantii* typically have low Sf (e.g., Bahmani et al., 2012; Carlyle-Moses et al., 2004; Helvey and Patric, 1965; Toba and Ohta, 2005). Therefore, Sf was assumed to be negligible and *I* was calculated as the difference between GP and TF.

2.2.2. Analytical model of interception loss

The original Gash (1979) model is a storm-based simplification of the Rutter model that considers rainfall to occur in a series of discrete storms, each of which comprises a period of wetting-up, a period of saturation, and a period of drying-out to empty the canopy storage. Although this model was designed to run on an event basis, it is usually applied on a daily basis, assuming one rainfall event per rainy day. The original model was reformulated by Gash et al. (1995) to encompass the specific case of sparse forests, resulting in the "Reformulated Gash Analytical Model (RGAM)" that is based on evaporation per unit area of canopy rather than per unit ground area.

Canopy structure parameters, climatic parameters and interception components of the sparse model were estimated using field data.

Canopy storage capacity (S) is defined as the minimum amount of rainfall the canopy can hold while saturated. We used the mean method (Klaassen et al., 1998) to estimate S of the leafed and leafless periods. The mean method requires two regression lines relating GP to TF for storms that are either insufficient (R_1) or sufficient (R_2) to saturate the canopy. The first linear regression (R_1) corresponds to the pre-saturation period, where GP is lower than the precipitation necessary to saturate the canopy (P'_G):

$$R_1 = TF = a_1 \times GP, GP < P'_G (mm) \quad (1)$$