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Efficiency of the reformulated Gash's interception model in semiarid afforestations

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ABSTRACT

Interception loss (*I*) can remove substantial portions of water from forested watersheds. Thus, *I* prediction models are crucial if we are to balance human and ecosystem water needs under a shifting climate. This is particularly true for arid/semiarid regions that rely on afforestation efforts for economic or agricultural needs, yet very few of these regions have selected, applied and validated an *I* prediction model. This study applied/evaluated the reformulated Gash *I* model to a data set of 54 storms using 50 manual throughfall (*TF*) observations per site, for two stands of common afforestation tree species in semiarid Northern Iran: *Pinus eldarica* (Eldar pine) and *Cupressus arizonica* (Arizona cypress). The reformulated Gash model has rarely been evaluated in semiarid forest stands of these common species. Each species intercepted substantial rainfall during commonly experienced storm conditions—up to 56% (*C. arizonica*) and 65% (*P. eldarica*). Mean *TF* was modestly higher under *C. arizonica* (76%) than *P. eldarica* (73%). However, water storage (*S*) was nearly double for *P. eldarica* compared to *C. arizonica* (1.2–0.7 mm, respectively). Canopy structural differences also altered the gap fraction (*p*) for *P. eldarica* (0.38) in relation to *C. arizonica* (0.49). Modeling error was low (−1.3% *vs.* −2.6% for *P. eldarica* and *C. arizonica*, respectively), generally underestimating *I*. On the whole, the validated model performed better for *C. arizonica* than *P. eldarica* stands, likely as a result of influence from canopy structural functions not parameterized by the model (*e.g.*, *P. eldarica*'s higher *LAI*, horizontal leaves/branches, high crown length, and rougher bark) which directly alter *S*, *p*, and *TF* parameters, or indirectly influence the ratio of mean evaporation rate from the wet canopy (mm h^{-1}) to the mean rainfall intensity (mm h^{-1}) ($\bar{E}/\bar{R}$) by sheltering intercepted rain water from boundary layer meteorological conditions. It is, therefore, suggested that future work seek to parameterize these canopy parameters. Since *I* reduces the quantity of water for infiltration and recharge, *I* estimates and prediction tools are of great value to semiarid and arid regions undergoing afforestation because the model allows land managers to predict impacts of afforestation on water inputs for current and future rainfall scenarios.

1. Introduction

Arid and semiarid ecosystems cover one-third of total Earth's land (Reynolds, 2001), and are among the world's most fragile ecosystems due to periodic droughts and increasing overexploitation of meager water resources (Malagnoux et al., 2007). Moreover, a large proportion of arid and semiarid ecosystems are situated among the poorest countries in the world. Water availability has been reported to alter regeneration survival, biomass production, soil properties, carbon sequestration, vegetation composition, irrigation planning, and selection of the tree species for afforestation goals (*e.g.*, Eamus, 2003; Jenerette and Lal, 2005; Jazirei, 2009). These important ecohydrological connections are even more fragile in the water-scarce arid and semiarid ecosystems. In these areas water resource managers must deal with limited precipitation (*GR*) and increased desertification risks. Hence, it is important to understand the amount of rainfall reaching the ground (*NR*) in order to develop effective water plan strategies.

When rain falls onto canopy cover (gross rainfall, *GR*), a sizable portion is intercepted by the canopy and evaporated back

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to the atmosphere; this process is termed rainfall interception (*I*). Some *GR* reaches the forest floor directly through canopy gaps (free throughfall), or by dripping from the canopy layer (canopy drip). The sum of free throughfall and canopy drip is throughfall (*TF*). Moreover, stemflow (*SF*) is defined as the amount of *GR* reaching the forest floor by running down the stem/trunk. Therefore, the actual amount of water that reaches the forest floor (*TF* + *SF*) is net rainfall (*NR*).

Vegetation affects the amount of evaporation from a catchment through transpiration and *I*, thereby altering the timing and quantity of available water for storage and runoff. Studies have shown that reduced runoff in conjunction with root-enhanced slope stability from afforestation is effective in controlling soil erosion (Feng et al., 2010). However, some concerns have been raised regarding the impact large-scale afforestation in arid and semiarid regions will have on aquifer recharge because evapotranspiration from forests is greater than from grasslands, shrublands, or degraded lands (*e.g.*, Eastham et al., 1988; Sun et al., 2006; Zhang et al., 2008; Wang et al., 2011). The greater evapotranspiration from forests occurs because transpiration, *I*, and evaporation tend to increase when grasslands, shrublands, or degraded lands are replaced with trees in afforestation plots (Farley et al., 2005).

Within forests, *I* tends to be higher in conifers than in broadleaves (Carlyle-Moses and Gash, 2011). A significant percentage of *GR* is lost to *I*. For example, *I* varies from nine percent in Amazonia forests (Lloyd et al., 1988) to values as high as 60% in coniferous stands (Forgeard et al., 1980). Large variability in *I* is strongly tied to forest structure (*e.g.*, density, seasonal change, vegetation area index, gap fraction, and canopy storage capacity), and climate condition (rainfall, evaporation, and wind characteristics) (Crockford and Richardson, 2000; Pypker et al., 2005, 2011; Staelens et al., 2008; Muzylo et al., 2012; Motahari et al., 2013; Van Stan et al., 2013). The proportion of *GR* lost to *I* changes with storm size (Sadeghi and Attarod, 2014). As *GR* increases, the ratio of *I* to *GR* (*I*:*GR*) decreases; hence frequent small storms typically result in the greatest proportion of *GR* that is lost to *I*. Past meteorological data in the semiarid zone of Iran demonstrates average annual rainfall is constant, but the number of small storms (*i.e.*, 0.1–5.0 mm) have increased (Sadeghi and Attarod, 2014). Similar results have been reported by Lauenroth and Bradford (2009) in arid and semiarid regions of USA. This indicates a notable effect on the future water availability of forest ecosystems, hence knowledge of *I* and its components will help forest managerial decisions regarding afforestation, thinning treatments, irrigation, and survival regeneration under future climate change.

I models allow experimental results to be extrapolated both in time and space, and they are needed as a component of hydrological and meteorological prediction tools for forest managers. Gash (1979) proposed a simple storm-based model known as the Gash analytical model. This model incorporates simple features of linear regression models and has been applied with considerable success in a wide range of conditions, from temperate forests (Gash et al., 1980; Wang et al., 2013) to tropical rainforests (Lloyd et al., 1988; Hutjes et al., 1990; Muzylo et al., 2009). However, researchers have found that the Gash analytical model overestimates when applied to sparse forests (*e.g.*, Lankreijer et al., 1993). This led to reformulations of the Gash model (Gash et al., 1995; Valente et al., 1997) to take into account forest sparseness and improve forest boundary conditions. In the reformulated version of the Gash model, wet canopy evaporation is considered linearly dependent to the canopy cover fraction (*c*) (Valente et al., 1997). Recent applications of the reformulated Gash model indicate the model predictions are improved for a wide range of conditions of canopy cover, from closed to very sparse canopy (*e.g.*, Gash et al., 1995; Valente et al., 1997; Dykes, 1997; Carlyle-Moses and Price, 1999; Muzylo et al., 2009; Motahari et al., 2013).

The reformulated Gash model has rarely been validated in semiarid afforestations (*e.g.*, Motahari et al., 2013). Therefore, this research addresses the following questions: (i) Do *TF* and *I* differ between afforested stands of *Pinus eldarica* (Eldar pine), and *Cupressus arizonica* (Arizona cypress) in a semiarid zone of Iran? (ii) Are canopy storage capacities different in *P. eldarica* compared with *C. arizonica* as calculated by three common regression methods? (iii) Can the reformulated Gash analytical model accurately predict interception loss for *P. eldarica* and *C. arizonica*?

2. Materials and methods

2.1. Study plot

The experimental plots are located in the Chitgar Forest Park in the Northern Iran (near the city of Tehran) at an altitude of 1225–1313 m above sea level (35°42′ N and 51°08′ E). Separate, 0.3 ha pure stands of *P. eldarica* and *C. arizonica* (44-years-old at the time of the study) were selected. The species selection was strongly motivated by the existence of substantial *P. eldarica* and *C. arizonica* plantations in semiarid and arid zones of Iran and other countries. These species are, therefore, a dominant species across semiarid-arid landscapes, accounting for about 48% of the total trees in the Chitgar Forest Park. At the *P. eldarica* plot, mean tree height (±SE) was 9.1 (±0.6) m, mean diameter at breast height (DBH) was 22 (±3) cm, mean height of crown length was 2.9 (±0.3) m, and tree density was 1020 stems ha^{-1}. For *C. arizonica*, these values were 8.0 (±0.5) m, 20 (±3) cm, 3.1 (±0.2) m, and 960 stems ha^{-1}, respectively. The plots were on a relatively flat area (average slope of approximately two percent) (Fig. 1).

Average annual rainfall at a meteorological station located within four km of the plots, Chitgar Meteorological Station (1997–2013, 35° 44′ N, 51° 10′ E, and 1215 m a.s.l), is about 272 mm, with 12% falling during the dry period (May–October). Snow rarely occurs in this region and input of occult precipitation is assumed to be negligible. Mean annual air temperature is around 17 °C and mean monthly temperature ranges from 3.8 °C in January to 30.2 °C in August, with strong seasonality. The climate is semiarid, with warm summers. The prevailing wind direction is from the west-north-west with wind speed averaging 3.1 m s^{-1}.

2.2. Measurement of gross rainfall (GR) and throughfall (TF)

Measurements were conducted from 23 August 2012 to 23 August 2013. The rainfall and air temperature in study period were 44 mm and 0.6 °C above the average amount of 1996–2012, respectively. *GR* was measured using ten manual rain-gauges (280 mm diameter) located in a nearby clearing (<30 m away). *GR* and *TF* were measured immediately after storm. A rain event was defined as a period with more than 0.4 mm of total *GR*. In this climate, the drying time for canopy wetting was assumed to be shorter than other climates (excluding arid); hence 4 h (in dry periods) to 10 h (in wet period) where no rain fell were applied to separate rain storms.

Based on past rainfall measurements at Chitgar Meteorological station, *GR* was separated into five storm classes (Fig. 2). The five storm classes were very small (0.1–2.5 mm), small (2.6–5.0 mm), middle (5.1–7.5 mm), large (7.6–10.0 mm), and very large (>10 mm). Relative frequency and relative amount for each class are given in Fig. 2.

Fifty manual rain-gauges (similar to the *GR* rain-gauges) were located in each stand. To overcome the great spatial variability of *TF*, rain-gauges are placed randomly underneath the forest canopy. To improve the long-term sampling, half the rain-gauges were relocated to new random position after five storms.