Rainfall Interception in a *Robinia pseudoacacia* Forest Stand: Estimates Using Gash's Analytical Model

Li Wang[1]; Qingfeng Zhang[2]; Ming'an Shao[3]; and Quanjiu Wang[4]

Abstract: The authors have studied the principal components of rainfall interception loss in a planted forest stand of *Robinia pseudoacacia* on the Loess Plateau. The purpose was to provide new information about the applicability of the original Gash analytical model to a new geographic location and to one of the primary species being used in the region's reforestation program. The authors estimated forest structure parameters, including the mean evaporation rate, canopy storage capacity at saturation, free throughfall coefficient, rainfall fraction diverted to the trunks, and trunk storage capacity by using the intercepts and slopes obtained from regression analyses of the measured interception loss, throughfall, and stemflow versus gross rainfall. The interception and components of interception loss for trees in a *Robinia pseudoacacia* forest located on a south-facing slope were calculated using Gash's analytical model. The total estimated interception loss during the period of observation was 10.8% greater than that calculated on the basis of measurements of the gross rainfall, throughfall, and stemflow. The good agreement between the estimated and measured values indicates that Gash's analytical model is suitable for estimating interception loss in forests on the Loess Plateau of China. **DOI: 10.1061/(ASCE)HE.1943-5584.0000640.**

CE Database subject headings: Rainfall; Forests; China; Hydrologic models.

Author keywords: Interception loss; Gross rainfall; Throughfall; *Robinia pseudoacacia* forest; Mean evaporation rate; Canopy storage capacity.

Introduction

Studies on the interception and evaporation of rainfall have contributed significantly to the scientific understanding of the effects of afforestation on water balance in catchment areas (Zeng et al. 2000; Orlandini and Lamberti 2000; Herbst et al. 2006). On the Loess Plateau, the conversion of cropland to forest resulted in a decrease in the water yield, in part because of an increase in losses through rainfall interception (Huang et al. 2003; Li et al. 2007; Wang et al. 2008). Interception loss in planted forests accounted for 8.5–18.7% of the gross rainfall in the Loess Plateau (Zhang et al. 1995; Yu and Chen 1996; Wei et al. 1998; Wei et al. 2008); this suggests that rainfall interception is of critical importance in the water budgets of forests. Interception by forests can be predicted using the analytical model developed by Gash (Gash 1979; Návar and Bryan 1994; Carlyle-Moses et al. 1999; Wang et al. 2006; Wallace and McJannet 2006; Herbst et al. 2008). A number of parameters must be considered when modeling rainfall interception, including hydrologic factors such as the canopy storage capacity at saturation, free throughfall coefficient, proportion of rainfall intercepted by branches and stems, and evaporation rate during storms. These parameters have been estimated in many other ecosystems (Gash et al. 1980; Sambasiva 1987; Návar and Bryan 1994; Wang et al. 2006), but no estimates are available for planted forests such as those which cover a large area of the Loess Plateau.

The purposes of this study were to (1) estimate the parameters associated with rainfall interception in a semiarid area of planted forest on the Loess Plateau, and (2) use the data to estimate the interception loss using Gash's analytical model of rainfall interception (Gash 1979). This study will contribute new information about the applicability of the original Gash analytical model to a new geographic location and to one of the primary species being used in the region's reforestation program; namely, *Robinia pseudoacacia*.

[1]Associate Professor, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F Univ., Yangling, Shaanxi 712100, People's Republic of China; Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China (corresponding author). E-mail: wangli5208@nwsuaf.edu.cn

[2]Associate Professor, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F Univ., Yangling, Shaanxi 712100, People's Republic of China. E-mail: zhqf@nwsuaf.edu.cn

[3]Professor, Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China. E-mail: mashao@ms.iswc.ac.cn

[4]Professor, Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China. E-mail: wquanjiu@163.com

Note. This manuscript was submitted on March 21, 2011; approved on April 25, 2012; published online on April 28, 2012. Discussion period open until September 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 18, No. 4, April 1, 2013. © ASCE, ISSN 1084-0699/2013/4-474-479/$25.00.

Materials and Methods

Study Site

This study was performed in the Yan'gou watershed, which covers an area of 46.9 km^2, near the city of Yan'an in the north of Shaanxi province, China (36°28′–36°32′ N; 109°20′–109°35′ E). The area consists primarily of loess gullies, at a density of approximately 4.8 $km\,km^{-2}$, and hills reaching altitudes of 986–1,425 m (relative to sea level). The climate is inland semiarid temperate, with warm summers. The mean annual precipitation is approximately 537 mm (1961–2001), 80% of which falls between June and September; the potential annual evapotranspiration is approximately 1,570 mm (Xu and Sidle 2001; Liu et al. 2005).

The area's natural biome consists of temperate deciduous broadleaf forest; the zonal climax vegetation is oak forest dominated by

Quercus liaotungensis. However, oak forests now account for less than 10% of the vegetation-covered area in the catchment because of denudation and estrepement during the last 100 years. The planted forests (which include economically valuable trees such as apple and pear) are dominated by *Robinia pseudoacacia* planted in the late 1970s, and cover 40.7% of the total catchment area (Xu and Liu 2004).

Experimental Design

The authors focused on a *R. pseudoacacia* monoculture forest stand situated on a south-facing slope. *R. pseudoacacia* are the primary afforestation species in both the catchment and the Loess Plateau as a whole. The *R. pseudoacacia* stand was planted in 1979, and the forest age was 27 years old at the time of the study, which was conducted from May–September, 2006. Thinning was carried out by local foresters once every 4 years (the last such thinning being in 2003), but no thinning or clearcutting occurred during the study period. The leaf area index (LAI), which was measured with a portable LI-COR device (LAI-2000, Lincoln, Nebraska), increased from 1.2 to 4.1 during the study period. The canopy was not completely closed until the LAI reached the highest value (4.1). The mean height of the trees in the stand was 6.9 m; their mean stem diameter at breast height was 10.2 cm. There were estimated to be approximately 9 million *R. pseudoacacia* trees m^2 (900 per ha^{-1}). Three sampling plots measuring 20×20 m were established. In each plot, all of the individual *R. pseudoacacia* trees were monitored to assess their capacity for interception and the patterns of rainwater delivery to the soil. Throughfall was collected in 10 iron buckets, each of which was 20 cm in diameter and 30 cm deep, in each plot. The buckets were placed randomly in pits under the vegetation. Filters were placed over the buckets to prevent accumulation of leaves and other debris. The stemflow was collected through 1-m long plastic tubes wrapped $1.5 \times$ around the trunks of all selected trees in each plot and sealed with silicone along the trunk to prevent water from running beneath the tube (Christiansen et al. 2006). Holes measuring 5 mm in diameter were drilled at 8-cm intervals along each tube to allow the water to flow into the tube. The tubes (2 cm in diameter) were connected to a closed bucket on the ground. This system is effective for retaining collected stemflow (Chen et al. 1994; Wei et al. 2008).

Meteorological Data

Meteorological data were collected from instruments mounted on a portable scaffolding tower at a height of 10.5 m above the ground. The net radiation (R_n) 1 m above the canopy was measured at 30-s intervals using three net radiometers, each one installed above a row of plants in each of the sampling plots. Subsequent calculations were based on the mean values of readings from these three net radiometers. Two of the radiometers malfunctioned over the course of the study, resulting in the loss of two weeks' data. For this 2-week period, only the R_n data collected from the stand in which the one remaining net radiometer was working were used. Every 2 months, the net radiometers were calibrated against a factory-calibrated instrument that had not previously been used in the field.

The wind speed was measured with anemometers (R.M., Young Wind Sentry, 03101, Michigan) mounted at two levels (1.0 and 2.0 m) above the canopy on the portable tower. The air temperature and relative humidity were measured with a probe obtained from Vaisala (model HMP 35A, Helsinki, Finland) installed alongside the net radiometers at a distance of 1 m from the leaves. The instruments were connected to data loggers (CR10, Campbell Scientific, Logan, Utah); means or totals of their readings were recorded hourly. For practical reasons, two standard rain gauges with automatic tipping systems (the top rim of the collection container is 70 cm above the ground in accordance with the China Meteorological Administration standard) were installed outside the forest to measure the gross rainfall and the duration of every rainfall event. The rainfall measurements obtained with the gauge were used to calculate the interception. The rainfall duration was assumed to be the same as that recorded at the microclimate station from May–October 2006, during which 42 individual storms were monitored.

With these meteorological data, the mean hourly evaporation rate from the wet canopy, $\bar{E}$, was calculated using the Monteith-Penman equation to verify the estimated mean evaporation rate during storms, with the assumption that the surface resistance was zero

$$\lambda E = \frac{\Delta R_n + \rho C_p D / r_a}{\Delta + \gamma} \tag{1}$$

in which R_n = net radiation ($\mathrm{W\,m^{-2}}$); ρ = air density at 25°C (1.184×10^3 $\mathrm{g\,m^{-3}}$); C_p = specific heat capacity of air ($1.010\ \mathrm{J\,g^{-1}\,°C^{-1}}$); e = actual vapor pressure (kPa); D = vapor pressure deficit (kPa); r_a aerodynamic resistance ($\mathrm{s\,m^{-1}}$); λ = latent heat of vaporization at 25°C ($2.435 \times 10^3\ \mathrm{J\,g^{-1}}$); Δ = rate of increase in saturated vapor pressure with temperature ($\mathrm{kPa\,°C^{-1}}$); and γ = Psychrometer constant at 25°C ($0.0664\ \mathrm{kPa\,°C^{-1}}$). r_a is defined by the following equation:

$$r_a = \frac{\{\ln[(z-d)/z_0]\}^2}{k^2 U} \tag{2}$$

in which k is the Von Karman constant (0.41); z = height of the meteorological instruments above the ground (m); z_0 = roughness length (m) and is a function of the canopy height ($z_0 = 0.1h$); u = wind speed ($\mathrm{m\,s^{-1}}$); and d = zero plane displacement (m), which was assumed to be equal to $0.75h$.

Rainfall intensity $>0.5\ \mathrm{mm\,h^{-1}}$ was considered to be indicative of wet canopy conditions (Gash 1979).

Derivation of Forest Structure Parameters

Gash (1979) proposed the following analytical model for rainfall interception loss:

$$\sum_{j=1}^{n+m} I_j = n(1-p-p_t)P'_G + \left(\frac{\bar{E}}{\bar{R}}\right)\sum_{j=1}^{n}(P_{Gj} - P'_G) + (1-p-p_t)\sum_{j=1}^{m} P_{Gj} + qS_t + p_t \sum_{j=1}^{m+n-q} P_{Gj} \tag{3}$$

in which $\sum_{j=1}^{n+m} I_j$ = rainfall interception (mm); n = number of storms sufficiently large to saturate the canopy; m = number of storms that would not saturate the canopy; q = number of storms that would saturate the trunks; S_t = trunk water store (mm); $\bar{E}$ = mean rate of evaporation from a saturated canopy ($\mathrm{mm\,h^{-1}}$); $\bar{R}$ = mean rainfall rate onto a saturated canopy ($\mathrm{mm\,h^{-1}}$); p = free through coefficient; p_t = proportion of rainfall diverted to the trunk; P'_G = rainfall necessary to just saturate the canopy (mm); and P_{Gj} = gross rainfall on the canopy (mm).

The mean evaporation rate during storms was estimated from a regression of gross rainfall and interception loss. Gash (1979) showed that the slope of a plot of storm interception loss (I) against gross storm rainfall (P_G) is $\bar{E}/\bar{R}$. The regression model assumes that $\bar{E}/\bar{R}$ is constant during storms; $\bar{R}$ can be calculated from the observed rainfall intensities. Therefore, $\bar{E}$ can be calculated by multiplying $\bar{R}$ by the slope.

J. Hydrol. Eng., 2013, 18(4): 474-479

Net rainfall was plotted against gross rainfall, and the relationship between the two variables was subjected to linear regression analysis. The canopy storage at saturation (S) was estimated as the intercept of the regression line with the gross rainfall axis, as described by Leyton et al. (1967). This method gives better estimates than the traditional method, which includes evaporation during storms by regressing the same relationship through all points and may thus overestimate the canopy storage capacity at saturation (Zinke 1967).

The free throughfall coefficient, p, is usually estimated from the slope of the regression between rainfall and gross rainfall for storms smaller than 1 mm (Rutter et al. 1975; Gash and Morton 1978; Návar and Bryan 1994). However, because this method relies exclusively on data from small storms, the error in the estimate can be large.

The fraction of the rainfall diverted to the trunks (p_t) and the trunk storage capacity (S_t) were estimated as the negative intercept and the slope, respectively, from a linear regression of stemflow versus gross rainfall. Each of the rainfall events matching the previous criteria that produced any stemflow was included in this regression.

The minimum rainfall necessary to saturate the canopy (mm), P'_G, was calculated using the following equation:

$$P'_G = \left(\frac{-\bar{R}S}{\bar{E}}\right) \ln\left[1 - \left(\frac{\bar{E}}{\bar{R}}\right)(1 - p - p_t)^{-1}\right] \quad (4)$$

Results and Discussion

The quantity of gross rainfall received at the study site from May–October 2006 was 352.87 mm, and 42 individual storms were recorded. The mean precipitation per event was 8.40 mm. The precipitation from July–September was 293.95 mm, accounting for 83.3% of the gross rainfall, which was a reflection of the nonuniform rainfall distribution across the year, in which more than 70% of the rain typically falls between July and September on the Loess Plateau. The smallest and largest rainfall intensities from May–October 2006 were 0.13 and 8.02 mm h^{-1}, and the mean intensity was 2.82 mm h^{-1}. The total interception loss calculated from measurements of gross rainfall, throughfall (314.52 mm), and stemflow (8.14 mm) for the *R. pseudoacacia* forest stand was 30.21 mm, corresponding with 8.6% of total gross rainfall.

Evaporation Rates during the Storm

The mean rainfall duration for the 42 storms was 3.1 h. Taking into account the slope (0.039) of the interception model in Fig. 1, a mean rainfall rate of $\bar{R} = 2.82$ mm h^{-1} is indicative of an mean evaporation rate of $\bar{E} = 0.11$ mm h^{-1}. The value of $\bar{E}$ predicted by the Monteith-Penman equation is 0.08 mm h^{-1}. Independent predictions of $\bar{E}$ using regression analysis as shown in Fig. 1 are typically overestimates (Návar and Bryan 1994). The measured mean available energy during the periods of rainfall is approximately 75.2 W m^{-2}, corresponding with an evaporation rate of 0.10–0.11 mm h^{-1}. The similarity between the estimated (by Fig. 1) and the measured $\bar{E}$ reported in this paper (by mean available energy during the periods of rainfall) suggests that there was little error associated with the method for determining $\bar{E}$ (Fig. 1). One factor that could cause the evaporation rate to be overestimated is the loss of intercepted rainfall by processes such as absorption by leaves. Wang (1986) found that *R. pseudoacacia* leaves absorb a large quantity of intercepted rainwater, possibly as a method to

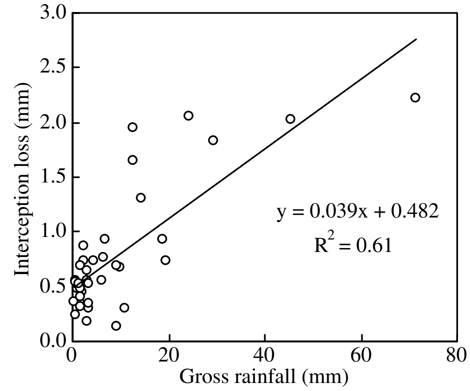

Fig. 1. Relationship between measured interception loss and gross rainfall; in total 42 storms were observed

remediate internal water deficits, especially in the dry season. Loss of rainfall by splashing off leaves could also result in the overestimation of evaporation rates during storms. Fan et al. (2000) reported significant splash on the forest canopy.

Canopy Storage Capacity at Saturation

Fig. 2 shows a plot and regression analysis of net rainfall versus gross rainfall; these data indicate that the canopy storage capacity at saturation was 0.36 mm. This value is similar to the estimate reported by Wang et al. (2006), 0.35 mm, for a subtropical forest in China, but significantly smaller than the values of (1) 0.64 mm (winter) and 1.02 mm (summer) reported by Leyton et al. (1967) for the canopy storage capacity at saturation of a hornbeam plantation in England, (2) those of 0.75 and 1.2 mm observed by Gash et al. (1980) in two pine stands of different density, (3) that of 0.80 mm reported by Sambasiva (1987) for cashew trees in India, and (4) that of 0.80 mm reported by Návar and Bryan (1994) for a semiarid plant community in Mexico.

The accuracy of this value (0.36 mm) was checked by using field measurements to estimate the canopy storage capacity at saturation for each of the months from June–October (Wang et al. 2006). The monthly values for this period ranged from 0.32–0.47 mm, with a mean value of 0.37 (± 0.073) mm. This is very similar to the value of 0.36 mm obtained through regression analysis. As only one rainfall event occurred in the month of May, data from this month were not examined.

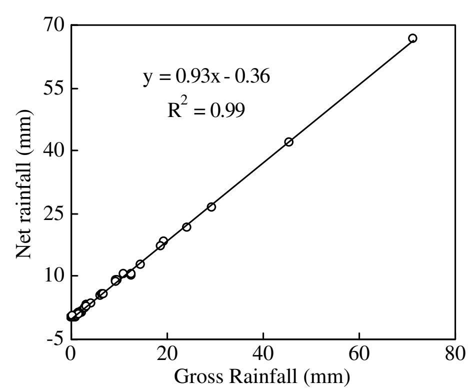

Fig. 2. Linear regression analysis used when estimating canopy saturation (adapted from Leyton et al. 1967)

J. Hydrol. Eng., 2013, 18(4): 474-479

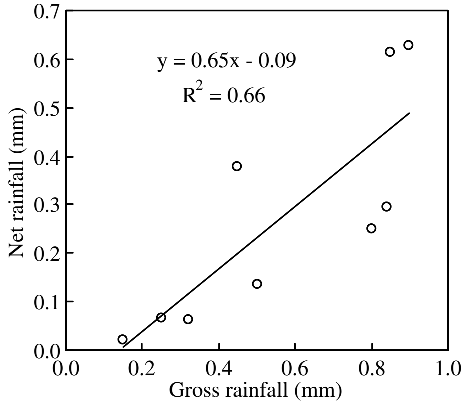

Fig. 3. Relationship between net and gross rainfall for storms smaller than 1 mm; in total, 42 storms were observed, nine of which were less than 1 mm

The Free Throughfall Coefficient

The free throughfall coefficient, p, was estimated on the basis of rainfall data from storms in which less than 1 mm of rain fell. On average, the gross and net rainfall for these storms were 5.06 and 2.45 mm, respectively; the relevant regression analysis is shown in Fig. 3 ($y = 0.65x - 0.09$, $R^2 = 0.66$, $p = 0.65$). For time periods in which no storms smaller than 1 mm occurred, p was calculated as the ratio of net to gross rainfall for the smallest recorded storm (Návar and Bryan 1994). If it is assumed that no storms smaller than 1 mm were recorded in this study, and the free throughfall coefficient is estimated from the smallest storm (for which gross and net rainfall were 1.28 and 0.76 mm, respectively), this produces a value of p equal to 0.59 (0.76/1.28). It is possible that this approach may underestimate the free throughfall coefficient because it was obtained using data from only one storm.

Rainfall on the Stem and Branches

Fig. 4 shows the relationship between stemflow and gross rainfall. The regression line, $y = 0.032x - 0.078$, provides values for two important parameters, the storage capacity of the branches and stems (0.078 mm, S_t) and the proportion of the gross rainfall that ends up as stemflow (0.032, p_t). Rutter et al. (1975) noted that the quantity of rainwater that ends up as stemflow does not significantly affect the overall water balance, and the interception model is not sensitive to this parameter (Gash and Morton 1978). In the authors' study, the observed stemflow (8.14 mm) was a small component of the overall water balance, representing 2.3% of the total gross rainfall.

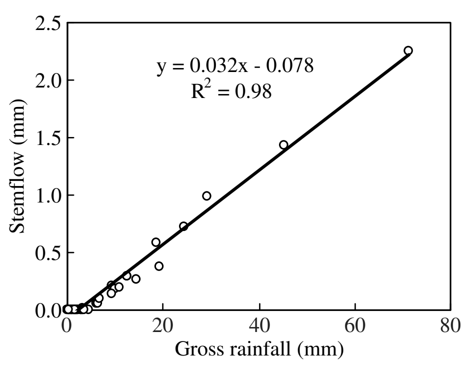

Fig. 4. Relationship between stemflow and gross rainfall

Table 1. Components of the Total Interception Loss Estimated with the Analytical Model of Gash for 42 Storms in 2006

Components of interception loss	Analytical form	Value (mm)
Small storms	$(1-p-p_t)\sum_{j=1}^{m} P_{Gj}$	4.56
Wetting-up the canopy	$n(1-p-p_t)P'_G - nS$	5.56
Evaporation from saturation until rainfall ceases	$(\bar{E}/\bar{R})\sum_{j=1}^{n}(P_{Gj} - P'_G)$	11.33
Evaporation after rainfall ceases	nS	9.72
Evaporation from trunks	$qS_t + p_t\sum_{j=1}^{m+n-q} P_{Gj}$	2.3
Total interception loss		33.47

Analytical Model of Rainfall Interception

Using the previously described set of estimated canopy parameters, (i.e., P'_G, n, m, and $q = 1.78$, 27, 15, and 18 mm, respectively), the total interception loss for the studied period was estimated using the model (3) as shown in Table 1.

The total estimated interception loss calculated using Gash's (1979) analytical model during the period of observation was 10.8% higher than that calculated on the basis of the measured gross rainfall, throughfall, and stemflow. This overestimate is comparable with those obtained with Gash's model in other ecosystems. For example, Gash and Morton (1978) showed that interception was overestimated by 6.9% in a study conducted in England. Wang et al. (2006) found that the estimated interception loss in a tropical rainforest stand was in good agreement with the measured value, being overestimated by only 1%. Pearce et al. (1980) obtained an overestimate of 3.4% when applying Gash's model in a study conducted in New Zealand. Šraj et al. (2008) found that the simulated cumulative interception loss was 15.2% greater than the value measured in Mediterranean forests. Sambasiva (1987) found that the predicted interception loss in a tropical forest in India was within 10% of the measured value.

Error Analysis

The error in the accuracy of the model's predictions that can be attributed to a given variable X is estimated as follows:

$$\frac{\Delta I}{\Delta X} = \frac{\partial I}{\partial X}\Delta X \tag{5}$$

If the variables are independent, the resultant errors can be summed quadratically to give the total error in the estimate. The sensitivity of the model was tested with respect to the variables $\bar{E}$, S, p, and p_t. The error in $\bar{E}$ was evaluated on the basis of calculations that used the Penman-Monteith equation (0.08 $\mathrm{mm\,h^{-1}}$). The error in the canopy storage at saturation (S) was calculated on the basis of the estimated values for each of the months from June–October. The error in the free throughfall coefficient (p) was assigned on the basis of the levels estimated for the storm in which the gross and net rainfall were recorded as 1.28 and 0.76, respectively. The error in the gross rainfall (p_t) was estimated on the basis of its 95% confidence interval.

Total interception loss was highly sensitive to $\bar{E}$, S, and p (Table 2). A change of $\bar{E}$ from 0.11 to 0.08 $\mathrm{mm\,h^{-1}}$ caused a change in the error of 3.09 mm, which corresponds with 9.23% of the total interception loss. The error derived for p (on the basis of a change from 0.36 to 0.47), is 3.75 mm, which represents 11.20% of the total interception loss. Changing the canopy capacity (S) from 0.65 to 0.59 caused a change in the error of 2.97 mm, which corresponds with 8.87% of the total interception loss. The error in the variable p_t had little influence on the accuracy

J. Hydrol. Eng., 2013, 18(4): 474-479

Table 2. Sensitivity of the Analytical Model of Total Rainfall Interception

Interception loss parameters	Mean values	New parameters	Error (mm)
Average evaporation rate ($\bar{E}$)	0.11	0.08	3.09
Free throughfall coefficient (p)	0.65	0.59	3.75
Canopy storage coefficient (S)	0.36	0.47	2.97
Proportion of rainfall that is stemflow (p_t)	0.032	0.050	0.62

of the estimated total interception loss. The error resulting from all of the variables considered is 10.43 mm, which corresponds with 31.15% of the total interception loss.

Conclusions

Error analysis shows that the there is good agreement between the experimental and predicted values for rainfall interception. The canopy storage capacity observed in this research deviated significantly from estimates reported for other plant communities (Gash et al. 1980; Sambasiva 1987; Návar and Bryan 1994), but the authors' measured values were consistent and exhibited little error. Overall, the authors' results indicate that rainfall interception loss in the Loess Plateau of China can be estimated with a reasonable degree of accuracy by using measurements of the gross rainfall, throughfall, and stemflow in conjunction with Gash's analytical model. It is predictable that in the future the area of planted forests will increase rapidly because of the government policy of converting cropland to forest on the Loess Plateau (Wang et al. 2008), and the authors' study provides forest plantation managers with valuable information for estimating the interception loss and assessing the hydrological impacts of land use modification.

Acknowledgments

The field work in this study was supported by grants from the CAS Action-plan for Western Development (the 3rd), the Western Light Project of the Chinese Academy of Sciences (2007YB02), and the CAS/SAFEA International Partnership Program for Creative Research Teams-Process simulation of soil and water of a watershed. The authors are indebted to the farmers in Yan'an City for their active participation in plot sampling and data collection. The authors' appreciation also goes to Dr. David Warrington from the United Kingdom for his help to revise the manuscript, and the editors and three reviewers for their helpful suggestions and comments.

References

Carlyle-Moses, D. E., and Price, A. G. (1999). "An evaluation of the Gash interception model in a northern hardwood stand." *J. Hydrol.*, 214(1), 103–110.

Chen, Y. M., Wu, Q. X., and Liu, X. D. (1994). "A study on redistribution of precipitation by artificial Chinese pine in Loess hilly region." *J. North China Inst. Water Conserv. Hydroelectr. Power*, 1(1), 62–68.

Christiansen, J. R., Elberling, B., and Jansson, P. E. (2006). "Modeling water balance and nitrate leaching in temperate Norway spruce and beech forests located on the same soil type with the CoupModel." *Forest Ecol. Manage.*, 237(1), 545–556.

Fan, S. X., Pei, T. F., Jiang, D. M., Cao, C. Y., and Lamusa, A. (2000). "Rainfall interception capacity of forest canopy between two different stands." *Chinese J. Appl. Ecol.*, 11(5), 671–674 (in Chinese with English abstract).

Gash, J. H. C. (1979). "An analytical model of rainfall interception by forests." *Q. J. Roy. Meteorol. Soc.*, 105(443), 43–53.

Gash, J. H. C., and Morton, A. J. (1978). "An application of the Rutter model to the estimation of the interception loss from Thetford forest." *J. Hydrol.*, 38(1), 49–58.

Gash, J. H. C., Wright, I. R., and Lloyd, C. R. (1980). "Comparative estimates of interception loss from three coniferous forests in Great Britain." *J. Hydrol.*, 48(1), 89–105.

Herbst, M., Roberts, J. M., Rosier, P. T. W., and Gowing, D. J. (2006). "Measuring and modelling the rainfall interception loss by hedgerows in southern England." *Agr. Forest Meteorol.*, 141(2), 244–256.

Herbst, M., Rosier, P. T. W., McNeil, D. D., Harding, R. J., and Growing, D. J. (2008). "Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest." *Agr. Forest Meteorol.*, 148(11), 1655–1667.

Huang, M., Zhang, L., and Gallichand, J. (2003). "Runoff responses to afforestation in a watershed of the Loess Plateau, China." *Hydrol. Process.*, 17(13), 2599–2609.

Leyton, L., Reynolds, E. R. C., and Thompson, F. B. (1967). "Rainfall interception in a forest and moorland." *International symposium on forest hydrology*, W. E. Sopper and H. W. Lull, eds., Pergamon, Toronto, 163–178.

Li, L. J., et al. (2007). "Assessing the impact of climate variability and human activities on streamflow from the Wuding River Basin in China." *Hydrol. Process.*, 21(25), 3485–3491.

Liu, P. L., Zheng, S. Q., Ju, T. J., Wang, S. Q., and Xu, Y. (2005). "Ecological and environmental construction in the Yan'gou watershed of the Loess Plateau: Models and benefits." *Res. Soil Water Conserv.*, 5(1), 88–91 (in Chinese with English abstract).

Návar, J., and Bryan, R. B. (1994). "Fitting the analytical model of rainfall interception of Gash to individual shrubs of semi-arid vegetation in northeastern Mexico." *Agr. Forest Meteorol.*, 68(3), 133–143.

Orlandini, S., and Lamberti, A. (2000). "Effect of wind on precipitation intercepted by steep mountain slopes." *J. Hydrol. Eng.*, 5(4), 346–354.

Pearce, A. J., Rowe, L. K., and Stewart, J. B. (1980). "Nighttime, wet canopy evaporation rates and the water balance of an evergreen mixed forest." *Water Resour. Res.*, 16(5), 955–959.

Rutter, A. J., Morton, A. J., and Robins, P. C. (1975). "A predictive model of rainfall interception by forests, II. Generalization of the model and comparison with observations in some coniferous and hardwood stands." *J. Appl. Ecol.*, 12(1), 367–380.

Sambasiva, R. A. (1987). "Interception losses of rainfall from cashew trees." *J. Hydrol.*, 90(3), 293–301.

Šraj, M., Brilly, M., and Mikoš, M. (2008). "Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia." *Agr. Forest Meteorol.*, 148(1), 121–134.

Wallace, J., and McJannet, D. (2006). "On interception modeling of a lowland coastal rainforest in northern Queensland, Australia." *J. Hydrol.*, 329(3–4), 477–488.

Wang, L., Wei, S. P., and Wu, F. Q. (2008). "Soil water environment and vegetation growth in the hilly and gully region of the Loess Plateau." *Acta Ecol. Sinica*, 29(1), 1543–1553 (in Chinese with English abstract).

Wang, X., Zhang, Y. P., and Liu, W. J. (2006). "Modeling canopy rainfall interception of a tropical seasonal rainforest in Sishuangbana, southwest China." *Acta Ecol. Sinica*, 26(1), 722–729 (in Chinese with English abstract).

Wang, Y. H. (1986). "A quantitative study of the benefits of Black Locust (Robinia pseudoacacia) on water and soil conservation in the eastern loess area of Gansu Province." *J. Beijing Forestry Univ.*, 8(1), 35–52 (in Chinese with English abstract).

Wei, S. P., Wang, L., and Wu, F. Q. (2008). "Hydrological properties of canopy of acacia in Loess hilly and gully region." *J. Nanjing Forest. Univ.*, 32(1), 43–48 (in Chinese with English abstract).

Wei, T. X., Zhu, J. Z., Zhang, X. P., He, K. N., and Gao, Z. J. (1998). "The regularity of water consumption of Black Locust and Chinese pine on the Loess Plateau in southwest of Shanxi Province." *J. Beijing Forest. Univ.*, 20(1), 36–39 (in Chinese with English abstract).

J. Hydrol. Eng., 2013, 18(4): 474-479

Xu, M. X., and Liu, G. B. (2004). "The characteristics and evolution of soil nutrient in artificial Black Locust (Robinia pseudoacacia) forestland in the hilly Loess Plateau." *Plant Nutr. Fert. Sci.*, 10(1), 40–46 (in Chinese with English abstract).

Xu, Y., and Sidle, R. C. (2001). "Land use change and its regulation of Yan'gou Watershed in Loess hilly-gully region." *Acta Geogr. Sinica*, 56(1), 657–666 (in Chinese with English abstract).

Yu, X. X., and Chen, L. H. (1996). "A study on water balance of protective forest ecosystem in the Loess area." *Acta Ecol. Sinica*, 16(1), 238–245 (in Chinese with English abstract).

Zeng, N., Shuttleworth, J. W., and Gash, J. H. C. (2000). "Influence of temporal variability of rainfall on interception loss. Part I. Point analysis." *J. Hydrol.*, 228(3), 228–241.

Zhang, J. J., He, K. N., and Zhu, J. Z. (1995). "The study on the crown interception of soil wand water conservation forests in the Loess Plateau of Shanxi Province." *J. Beijing Forest. Univ.*, 17(1), 27–31 (in Chinese with English abstract).

Zinke, P. J. (1967). "Forest interception studies in the United States." *International symposium on forest hydrology*, W. E. Sopper and H. W. Lull, eds., Pergamon, Toronto, 137–161.

J. Hydrol. Eng., 2013, 18(4): 474-479