Using Sensitivity Analysis and Fine-Scale Field Measurements to Understand How Canopy Interception Models Function

MISSISSIPPI STATE UNIVERSITY

AGU FALL MEETING

USDA NIFA — United States Department of Agriculture, National Institute of Food and Agriculture

National Science Foundation — WHERE DISCOVERIES BEGIN

Courtney M. Siegert[1*], Delphis F. Levia[2], Asia S. Dowtin[2], Sean A. Hudson[2], Anna C. Linhoss[1]

[1]Mississippi State University, [2]University of Delaware, [*]Courtney.Siegert@msstate.edu

Abstract H11G-1432 The capacity of the forest canopy to intercept precipitation and partition the remaining water into throughfall and stemflow largely influences the surface water budget in forested ecosystems. These processes are controlled by species-specific traits, canopy seasonality, and meteorological conditions. The complexity of these interacting factors at varying temporal and spatial scales can lead to errors in estimating canopy interception and reduce accuracy of derivative watershed hydrologic modeling efforts. To improve interception estimates, model calibration and validation must be assessed using long-term, fine-scale field measurements that capture the variability of all interacting factors. As such, field measurements of subcanopy hydrologic fluxes and meteorological conditions during discrete storm events were taken from 2007 to 2012 in a deciduous forest dominated by *Fagus grandifolia* and *Liriodendron tulipifera* in Fair Hill, Maryland, USA.

Preliminary results suggest that many of the current interception models (*e.g.*, Gash and Rutter-types) are driven primarily by evaporation terms. However, field measurements indicate that a large degree of variability in both throughfall and stemflow partitioning is derived from biophysical characteristics. For example, even within the small 12-hectare research catchment, differences in species composition induced by slight changes in elevation, coupled with slope orientation, resulted in sufficient canopy variability whereby throughfall fluxes were definitively different across small distances. Additionally, smaller trees were more efficient in generating stemflow, while species with smoother bark generated large quantities of stemflow under a variety of storm conditions—a mechanism that may further confound modeling efforts. To improve canopy interception estimates, model sensitivity analysis was used to determine the influence of current model parameters and how biophysical canopy characteristics may be further integrated into such models.

Introduction

Interception (I) by the forest canopy plays a critical role in determining net hydrologic inputs by diverting significant quantities of precipitation that would otherwise be directed to soil moisture, transpiration, and surface and groundwater recharge. Direct measurements of precipitation (P_C), throughfall (TF), and stemflow (SF) provide reasonable estimates of I, but do not account for the variability introduced through the diversity of canopy characteristics, seasonality, or storm and meteorological conditions, nor do they provide a means to incorporate these effects into dynamic or scenario-based models. In contrast, interception models often rely on indirect estimates of canopy partitioning that are derived from canopy storage capacity, rainfall characteristics, canopy drainage, and evaporation (*e.g.*, Deguchi et al., 2006; Gash, 1979; Rutter et al., 1972; Zeng et al., 2000). Because of the significance of interception in the water budget, it is important to determine the most suitable models for use in any particular circumstance. There are a variety of existing forest interception models including simple empirical, probabilistic models, and physical or mechanistic models, which are particularly useful because they allow investigation into the system's processes and inner workings.

Field Study: Site Description

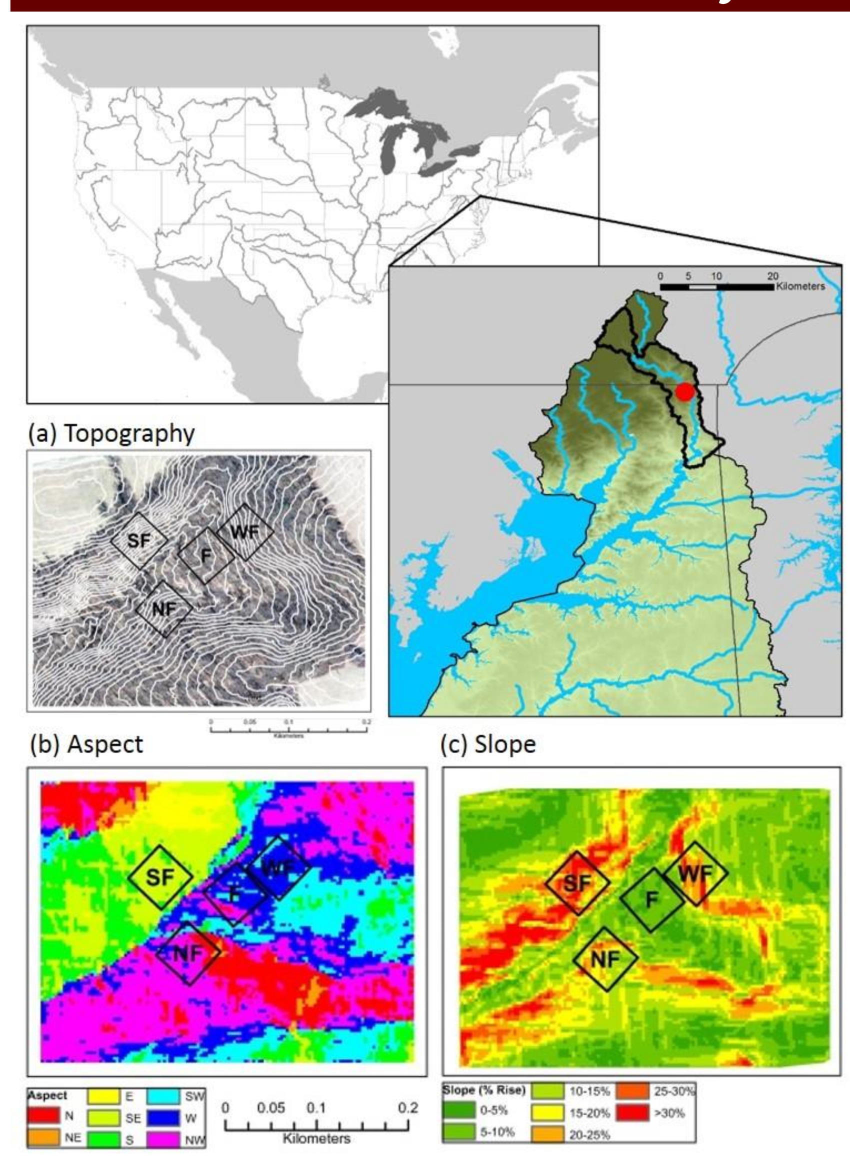

Figure 1. Location of experimental forest in northeastern Maryland and 4 subplots across the landscape including north-facing (NF), west-facing (WF), south-facing (SF), and a flat central plot (F). Adapted from Siegert et al. (2016).

An experimental research site was located at Fair Hill Natural Resources Management Area (FH-NRMA) in northeastern Maryland (39°42'N, 75°50'W) within a 12 hectare forested catchment with a stand density of 225 trees ha^{-1}, stand basal area of 36.8 m^2 ha^{-1}, mean diameter at breast height (DBH) of 40.8 cm, and mean tree height of 27.8 m. The forest canopy was comprised of *Liriodendron tulipifera* L. (yellow poplar), *Fagus grandifolia* Ehrh. (American Beech), *Acer rubrum* L. (red maple), *Quercus alba* L. (white oak) and *Betula lenta* L. (sweet birch).

- At the primary site, throughfall (TF) was measured using 10 tipping buckets (TE525MM, Dallas, TX) located underneath canopies of *F. grandifolia* and *L. tulipifera*. An additional four subplots (2500m^2) were established across different landscape positions (Fig. 1a-c) and species compositions (Table 1). Subplot TF was measured using 1L HDPE collectors fitted with 20.3cm funnels.
- At the primary site, stemflow (SF) was measured using collars draining into 50L collectors on two *F. grandifolia* and two *L. tulipifera* trees.
- Bulk precipitation was measured using a TE525MM tipping bucket in an open clearing ~0.5km south of the site. Temperature, radiation, wind speed and direction, humidity, and soil moisture were also monitored here (Delaware Environmental Observing System).
- All data were collected during discrete rainfall events.

Table 1. Subplot site descriptions. Species composition was measured as a percentage of the number of stems (>10 cm DBH) of an individual species relative to the total number of stems per subplot. Plant area index (PAI) was measured seasonally with an LAI-2000 (Li-Cor, Lincoln, NE) and accounts for both woody and foliar tree components. (Siegert et al. 2016)

	North-Facing	Flat	West-Facing	South-Facing
Species Composition (%)				
A. rubrum	4.8	14.0	9.7	8.8
B. lenta	9.7	21.1	31.9	20.6
F. grandifolia	38.7	28.1	20.8	22.5
L. tulipifera	11.3	14.0	6.9	8.8
Quercus spp.	30.6	19.3	22.2	29.4
Misc. spp.	4.8	3.5	8.3	9.8
Stems (ha^{-1})	248	228	288	408
Basal Area (m^2 ha^{-1})	32.8	26.4	42.0	51.6
PAI (m^2 m^{-2}, Leafless)	1.09	1.76	0.99	1.21
PAI (m^2 m^{-2}, Leafed)	5.58	5.51	5.37	5.14
ΔPAI	4.49	3.75	4.41	3.93
Slope (°)	7.6	3.9	9.0	15.0
Aspect (°)	312.1	NA	257.9	141.1

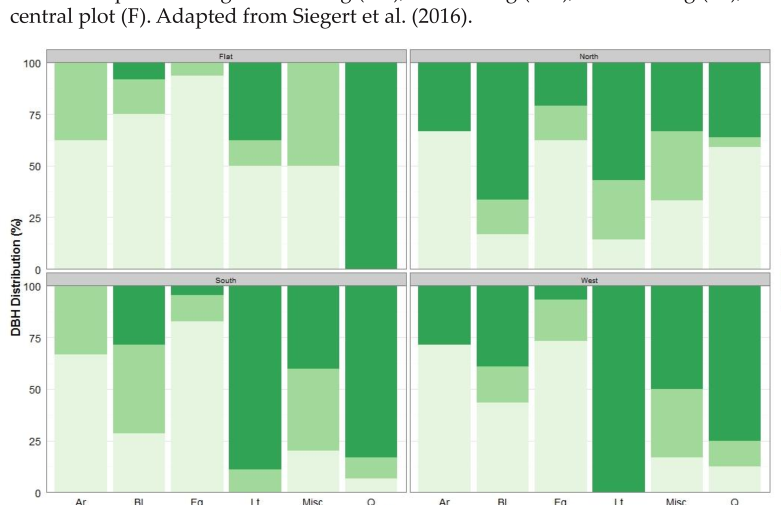

Figure 2. Distribution of species by DBH class as a function of percent of stems relative to the total number of stems for each species across each of the four subplots. Species abbreviations are *A. rubrum* (Ar), *B. lenta* (Bl), *F. grandifolia* (Fg), *L. tulipifera* (Lt), Miscellaneous species (Misc.), and *Quercus* spp. (Q). (Siegert et al. 2016)

Field Study Results & Analysis

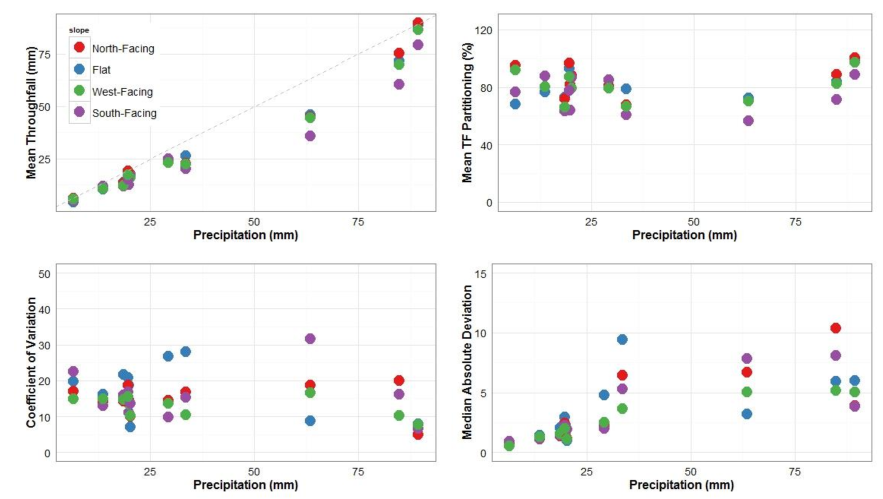

Figure 3. Location of experimental forest in northeastern Maryland and 4 subplots across the landscape including north-facing (NF), west-facing (WF), south-facing (SF), and a flat central plot (F). Adapted from Siegert et al. (2016)

Throughfall

Table 2. Pairwise comparison of throughfall volumetric flux across four landscape positions using Wilcoxon rank sum test. September 2011-September 2012. (Siegert et al. 2016)

	North-Facing	Flat	West-Facing
Flat	0.575	-	-
West-Facing	0.190	0.575	-
South-Facing	0.001**	0.037*	0.190

*** p < 0.001; ** p < 0.010; * p < 0.050

- Small-scale topographic variability affects TF via species composition.
- Steeper slopes with overlapping canopies intercept the most rainfall.
- Steeper slopes also result in greater spatial variability in TF flux.
- Local features as determinants of water fluxes are important at longer time scales.

Stemflow

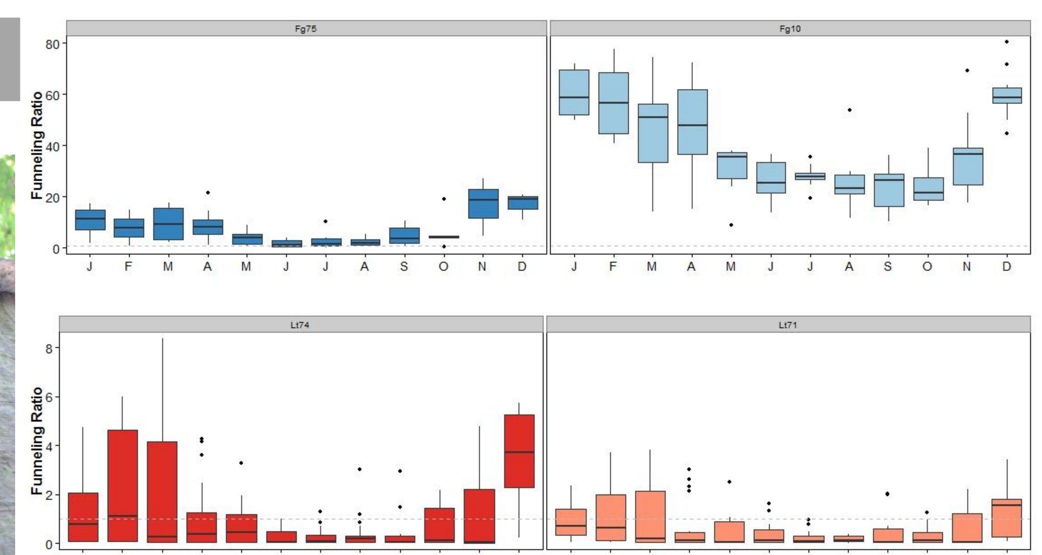

Figure 4. Relationship between rainfall magnitude and funneling ratio (FR) by individual trees (see Table 4). The horizontal dashed gray line indicates FR=1, where stemflow volume is the same as rainfall over a given tree basal area. Data collected during 158 rainfall events from 2007-2010. (Siegert and Levia 2014)

Table 3. Physical characteristics of trees selected for stemflow hydrologic monitoring. Adapted from Siegert and Levia (2014).

Tree Code	Species	DBH (cm)	Basal Area (cm^2)	Canopy Area (m^2)	Bark Thickness (mm)	FR (Leafed)	FR (Leafless)
Fg75	*F. grandifolia*	74.9	4406.1	125.6	2.0	3.7	11.1
Fg10	*F. grandifolia*	10.3	83.3	15.0	0.5	27.5	50.6
Lt73	*L. tulipifera*	73.1	4196.8	97.6	27.0	0.5	1.9
Lt71	*L. tulipifera*	71.1	3970.3	95.5	22.0	0.4	1.0

- Interspecific stemflow response varies with canopy leaf phase and seasonality.
- Funneling ratios in subcanopy trees exhibit higher rainfall scavenging efficiency.
- Additional variability induced by storm characteristics.

Canopy Interception

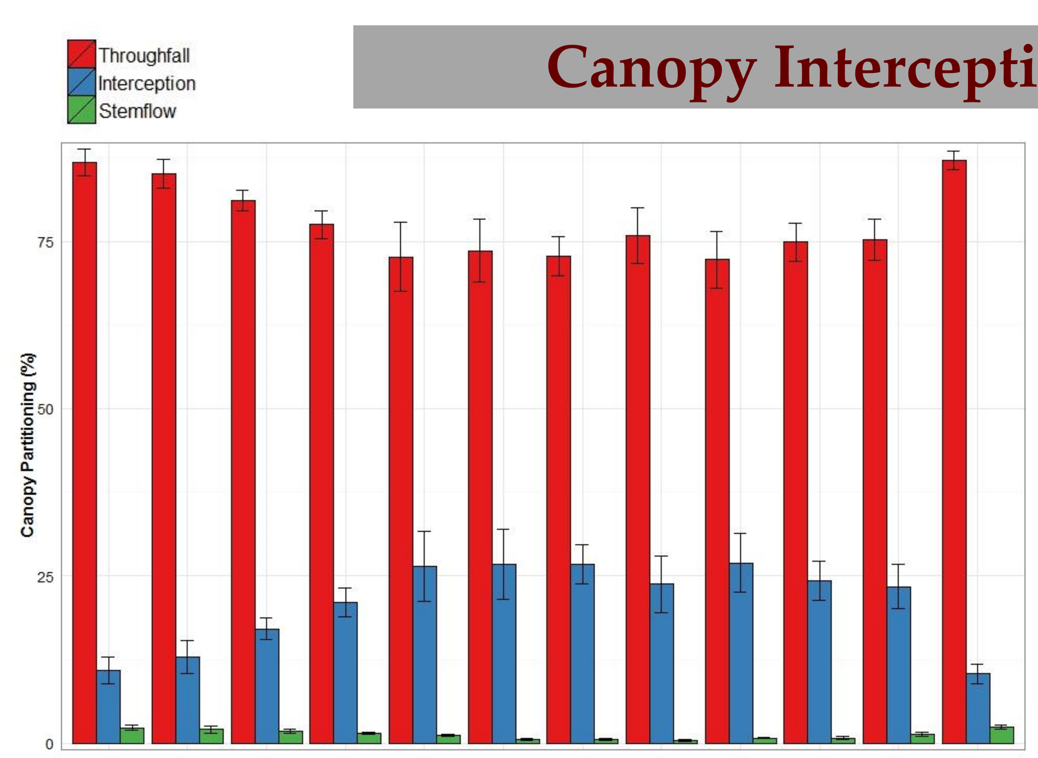

Figure 5. Average monthly canopy partitioning into throughfall, stemflow, and interception. Data collected during 154 events from 2007-2011. Standard errors plotted as whiskers calculated from 6 to 19 events per month.

Model Results & Analysis

Global uncertainty and sensitivity analysis techniques were used to compare five mechanistic interception models using 1-hour rainfall scenarios at low, medium, and high rainfall intensities:

- Rutter (Rutter et al. 1972)
- Gash (Gash 1979)
- Liu (Liu 1997)
- Rutter Sparse (Valente et al. 1997)
- Gash Sparse (Gash et al. 1995)

Probability Distribution Functions (PDFs) for each of the 14 model inputs (Table 5) were set according to measured data and literature values. PDFs for climatic variables were determined based on hourly measurements made in Perthshire, MS (33.97°, -90.90° NRCS SCAN Site #2046) in 2014 and are representative of rainfall conditions across diurnal and seasonal timescales.

Table 4. Model input descriptions, abbreviations, and probability distribution functions (PDFs). R=Rutter, RS=Rutter Sparse, G=Gash, GS=Gash Sparse, and L=Liu. An "X" indicates that the input is used in the corresponding model.

Parameter Description	Abbreviation	Units	R	RS	G	GS	L	Input PDF
Cumulative Gross Precipitation*	Pg	mm	X	X	X	X	X	Low - *U*(0.290, 1.265) Med - *U*(1.265, 2.240) High - *U*(2.240, 3.215)
Canopy Storage Capacity	S	mm	X	X	X	X	X	*U*(0.29, 2.24)
Trunk Storage Capacity	S_t	mm		X	X	X	X	*U*(0.0037, 0.9800)
Free Throughfall Coefficient	p	%	X		X		X	*U*(0.06, 0.55)
Stemflow Coefficient	p_t	%	X		X	X		*U*(0.0031, 0.0600)
Drainage Partitioning Coefficient	p_d	%		X				*U*(0.0076, 0.0324)
Canopy Cover	C_c	%		X		X		*U*(0.43, 0.95)
Empirical Drainage Input	b	mm	X					*U*(3.0, 4.6)
Canopy Drip	D_S	mm hr^{-1}	X					*U*(0.024, 0.740)
Trunk / Canopy Evaporation	ϵ	%	X	X				*U*(0.022, 0.024)
Net Radiation	R_n	MJ m^{-2} hr^{-1}	X	X	X	X	X	*U*(0.00, 0.56)
Maximum Temperature	T_{cmax}	° C	X	X	X	X	X	*U*(0.8, 22.5)
Maximum Humidity	H_{max}	%	X	X	X	X	X	*U*(73, 99)
Wind Speed	u_2	m s^{-1}	X	X	X	X	X	*U*(1.0, 7.1)

*The Rutter and Rutter Sparse models use R (mean rainfall rate) rather than P_g. However, we calculate R directly from P_g in our 1-hour rainfall simulations.

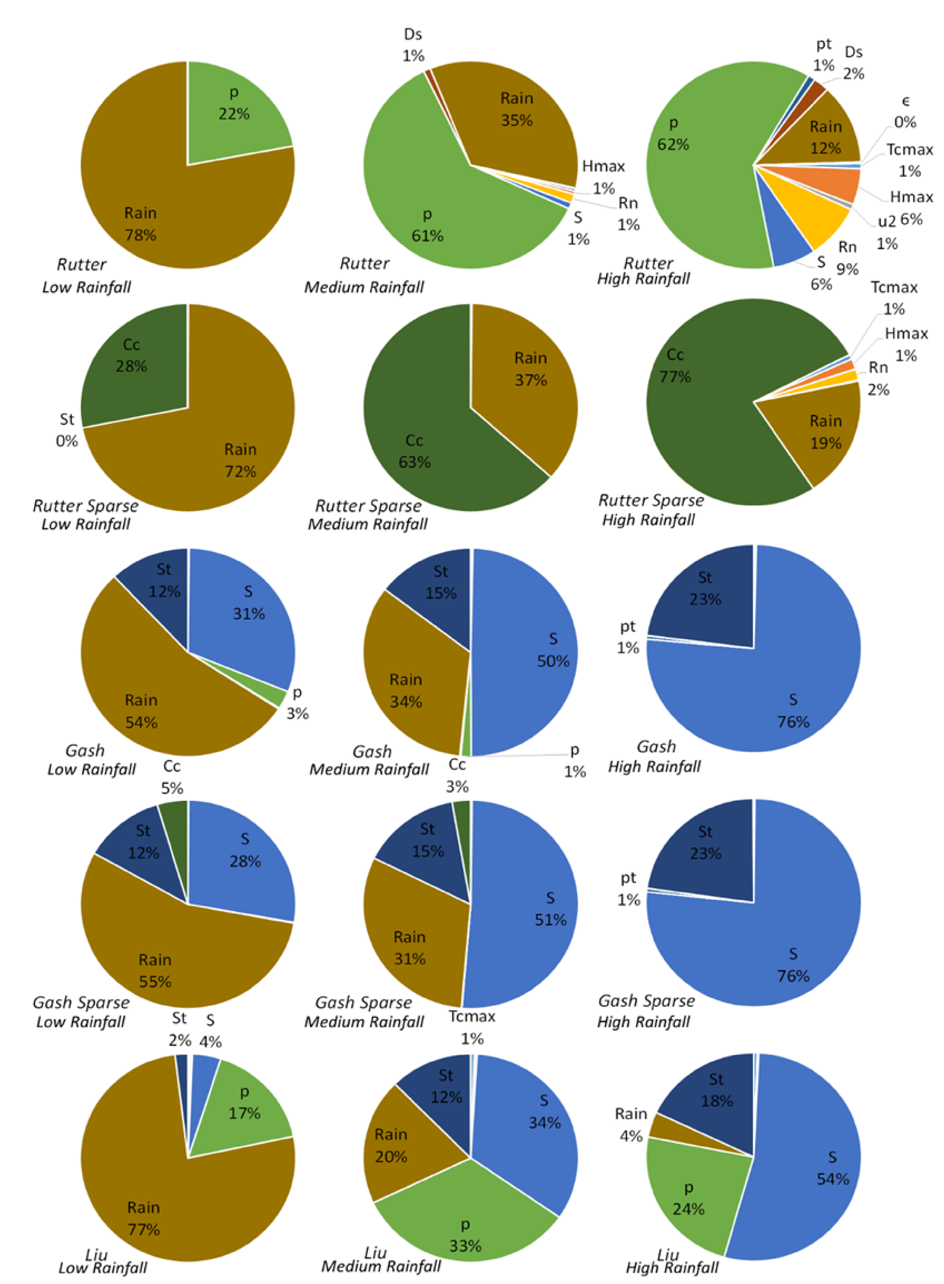

Figure 7. Global sensitivity analysis of the five interception models under low (0.290mm to 1.265mm), medium (1.265mm to 2.240mm), and high (2.240mm to 3.215mm) 1-hour rainfall scenarios. The figure shows the total sensitivity index for each of the inputs. Inputs that have less than 1% importance are not shown or labeled for clarity.

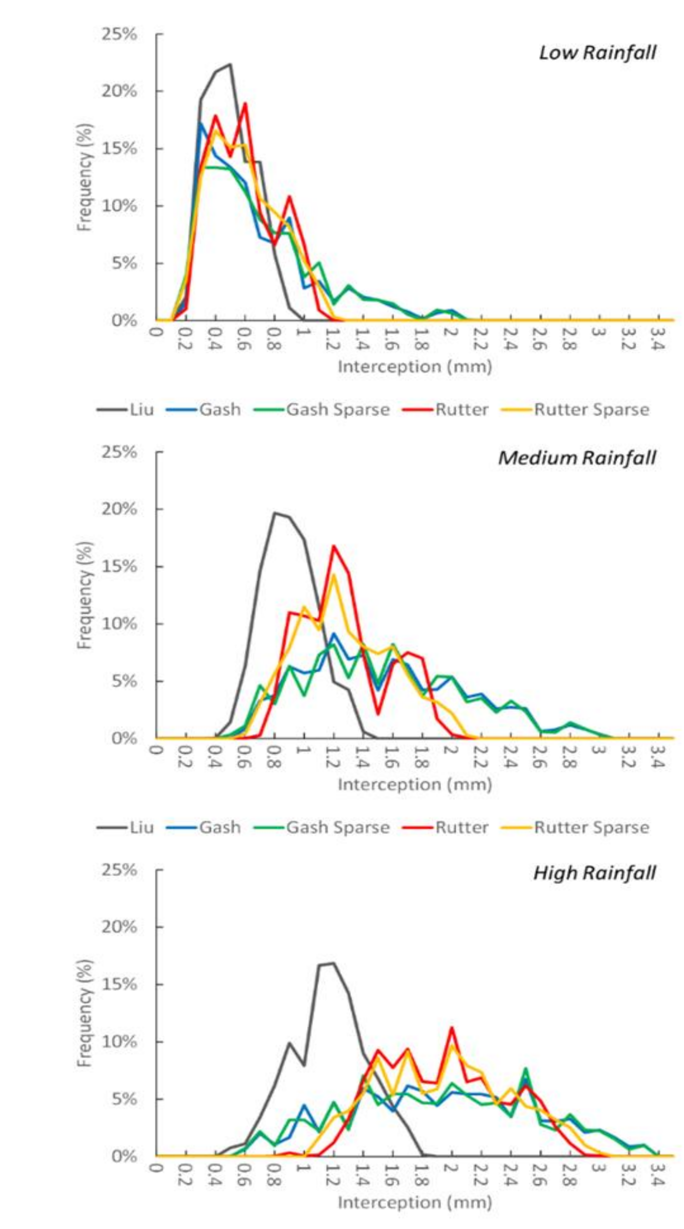

Figure 6. Sobol global uncertainty analysis histograms for the low (0.290mm to 1.265mm), medium (1.265mm to 2.240mm), and high (2.240mm to 3.215mm) 1-hour rainfall scenarios.

Conclusions

- Under small rainfall conditions, gross precipitation [P_G] is the most important parameter.
- Under larger rainfall scenarios, canopy characteristics such as canopy storage capacity [S], canopy cover [C_c], free throughfall coefficient [p], and trunk storage capacity [S_t] are increasingly important.
- As such, future modeling efforts, should aim to:
  1. Obtain reliable measurements of canopy spatial characteristics,
  2. Breakdown canopy and trunk storage capacity variables into easily measureable physical components, and
  3. Explicitly simulate rainfall characteristics such as duration and intensity, the individual influence of which may be masked in the larger [P_G].

References

Deguchi, A., Hattori, S., Park, H.T., 2006. The influence of seasonal changes in canopy structure on interception loss: Application of the revised Gash model. J. Hydrol. 318, 80–102.
Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Q. J. R. Meteorol. Soc. 105, 43–55.
Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. J. Hydrol. 170, 79–86.
Liu, S., 1997. A new model for the prediction of rainfall interception in forest canopies. Ecol. Modell. 99, 151–159.
Ponce, V.M., Hawkins, R.H., 1996. Runoff curve number: has it reached maturity? J. Hydrol. Eng. 1, 11–19.
Rutter, A.J., Kershaw, K.A., Robins, P.C., Morton, A.J., 1972. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. Agric. Meteorol. 9, 367–384.
Rutter, A.J., Morton, A.J., Robins, P.C., 1975. A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. J. Appl. Ecol. 12, 367–387.
Siegert, C.M., Levia, D.F., 2014. Seasonal and meteorological effects on differential stemflow funneling ratios for two deciduous tree species. J. Hydrol. 519, 446–454.
Siegert, C.M., Levia, D.F., Hudson, S.A., Dowtin, A.L., Zhang, F., Mitchell, M.J., 2016. Small-scale topographic variability influences tree species distribution and canopy throughfall partitioning in a temperate deciduous forest. For. Ecol. Manage. 359, 109–117.
Valente, F., David, J.S., Gash, J.H.C., 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. J. Hydrol. 190, 141–162.
Zeng, N., Shuttleworth, J.W., Gash, J.H.C., 2000. Influence of temporal variability of rainfall on interception loss. Part I. Point analysis. J. Hydrol. 228, 228–241.

Acknowledgements

The authors would like to acknowledge the financial support received from the US National Science Foundation (Ref. Nos. EAR-0724971, BCS-1233592) and the University of Delaware Mather Research Award (2012). This material is also based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, McIntire Stennis project #1002493. Many thanks are given to the Delaware Environmental Observing System (DEOS) for meteorological data; to Ranger Rachel Temby and the Maryland Department of Natural Resources for access to the research site at Fair Hill Natural Resource Management Area.