SPATIOTEMPORAL THROUGHFALL CHARACTERIZATION OF HETEROGENEOUS FOREST COMMUNITIES IN THE SOUTHEASTERN U.S.

By

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Abstract of Thesis Presented to the Graduate School
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The spatial and temporal influence of heterogeneous forest communities on interception loss was characterized for the southeastern United States. Throughfall was measured simultaneously in five forest types, i.e., mature pine, 13 year-old pine plantation, wetland, hardwood, and mixed hardwood/pine, that comprise the landscape in Fort Benning, Columbus, GA. The 1995 Gash interception model was determined to be valid for use in all forest types using seasonal canopy cover values and annual average canopy cover values. The model predicted interception loss with an agreement of -8.1 to 10.5% using annual average canopy cover values. Application of seasonal canopy cover values in lieu of annual averages improved accuracy in all cases with an overall range from -7.3 to 4.5%. An investigation of the model's performance within forests of varying canopy cover showed that the model predicts interception with an agreement of -5.7 to 8.2% using seasonal canopy cover values. A watershed scale intercomparison of the influence of forest community and seasonal variation on interception showed that appropriate characterization of forests is necessary when applying the 1995 Gash model over seasonal or shorter duration time periods. Additionally, application of the model at sub-watershed spatial scales showed that significant variation among results can be expected as the extent of the spatial scale is reduced. The field experimentation and water-budget analysis in this study provide insight into the relative net water input into the heterogeneous forest communities that are typical of the southeastern United States.

CHAPTER 1
INTRODUCTION

Interception losses modify the dynamics of the watershed hydrological and geochemical cycles. They lower the intensity of precipitation and wash solid particles and dissolved carbon from leaves affecting soil-water chemistry and weathering processes. Nutrient loading is impacted by interception losses because microbial activity is affected by soil moisture. Interception losses also affect rainfall-runoff by reducing the water input available for runoff. Depending on the vegetation type, interception losses can account for 10 to 40% of the total incident precipitation (Dingman, 1994). Furthermore, the distribution of vegetation types among heterogeneous landscapes can influence the spatial variability of interception losses (Crockford and Richardson, 2000).

Most methods for calculating interception use a running water balance approach. In this type of approach, the total incident precipitation equals the sum of the throughfall, stemflow, evaporation from the trunk, and evaporation from the canopy. Models that use a water balance approach are affected by the spatiotemporal accuracy of the interception loss calculation. The first physically based model for calculating rainfall interception was the Rutter model (cited in Rutter et al., 1971). The Rutter model is a running water balance model in which total evaporation from a wet canopy is calculated on a per storm basis. Rutter et al. (1975) were able to predict throughfall within 10% of the measured values in a pine stand. Gash and Morton (1978) used the Rutter model to predict interception loss from a Scots pine forest within 7% of the measured values (Gash and Morton, 1978). However, the Rutter model underestimated interception by 20% to 32%

in an artificially defoliated hardwood stand (Rutter et al., 1975). Gash (1979) introduced a variation of the Rutter model. The 1979 Gash model differs from the Rutter model in that it considers the arithmetic average instead of the actual rainfall and evaporation rates for individual storm events, thus simplifying the model and minimizing the data requirements.

In both the Rutter and Gash models, evaporation is calculated per unit area of ground. This formulation is problematic for sparsely vegetated forests. The 1979 Gash model overestimated interception losses by as much as 29 to 44% in a sparse pine forest in Portugal (Valente et al., 1997). The Gash model was revised (Gash et al., 1995) to calculate evaporation per unit area of canopy rather than per unit area of ground. The revised 1979 Gash model, the 1995 Gash model, greatly improves the accuracy of the interception loss predictions in sparse forests. The 1995 Gash model was used by Valente et al. (1997) to predict interception losses for the same pine forest in Portugal to within 3% of the measured values. Using the 1995 Gash model, Dykes (1997) estimated interception losses for a tropical rain forest in Borneo within 5% of measured values. Carlyle-Moses and Price (1999) estimated interception losses on a hardwood stand in Ontario, Canada, to less than 1% of measured values using the 1995 Gash model.

Many studies have validated the 1995 Gash interception model for use in homogeneous landscapes (van Dijk and Bruinjnzeel, 2001; Jackson, 2000; Carlyle-Moses and Price, 1999; Návar et al., 1999; Dykes, 1997; Valente et al., 1997; Dolman, 1987); few studies have incorporated interception models over large heterogeneous landscapes.

The goal of this research was to characterize the net water input into the heterogeneous forest communities that are distinctive of the southeast United States. The

1995 Gash interception model was chosen for this study since it has been validated in many different landscapes and it accounts for canopy cover variations. The objectives of this study were to 1) simultaneously calibrate the 1995 Gash interception model for use in the five forest types considered in this study, 2) use the model to predict rainfall interception and intercompare the results across forest types and canopy densities, 3) explore the influence of seasonal canopy characteristics on the model's performance, and 4) apply the model at the watershed scale to identify critical differences among available approaches to modeling interception in a heterogeneous landscape.

CHAPTER 2
STUDY AREA

The study was conducted at the Fort Benning military reservation, located in southwest Georgia. Long, hot summers and mild winters characterize the region's climate. Average annual precipitation is about 830 mm with a monthly average of 69 mm. Most of the precipitation occurs in the spring and summer as a result of thunderstorms. Heavy rains are typical during the summer but can occur in any month. Snow accounts for less than 1% of the annual precipitation. The soils in the area are dominated by loamy sand with some sandy loam.

Two second-order watersheds, Bonham-1 and Bonham-2, were selected for this study. These watersheds were selected because they contain most of the region's predominant forest types. The Bonham-1 watershed has an area of 762 ha, a minimum elevation of 87.8 m and maximum elevation of 144.2 m, and an average slope of 9.6%. The Bonham-2 watershed has an area of 2,211 ha, a minimum elevation of 90.5 m, a maximum elevation of 159.1 m, and an average slope of 8.6%.

The two watersheds have a heterogeneous land cover consisting of either open or forested areas (Figure 1). The open areas are either military, brush, or wildlife openings. The military openings are clear-cut parcels of land dominated by grass and bare soil that are used as military training grounds. The brush openings consist of tall grass and immature crateagus. The wildlife openings are natural openings in the forests that are vegetated primarily by grass. The forested areas include five forest types–mature pine, pine plantation, riparian wetland, hardwood, and mixed hardwood/pine. The mature pine, which consists of loblolly (*Pinus taeda*) and short leaf pine (*Pinus echinata*), is the dominant forest type of each watershed. The pine plantation is a 13 year-old long leaf pine (*Pinus palustris*) stand planted in rows. The wetland vegetation consists mostly of various hardwood trees along with a range of wetland understory vegetation. The hardwood stands are generally mature scrub oak (*Quercus berberidifolia*). White oak (*Quercus alba*), short leaf pine, and loblolly pine are the dominant species in the mixed pine/hardwood stands. Table 1 describes the total area and relative contribution of each forest type. The forests are managed using prescribed burning on a three-year cycle. A majority of the land area included in this study was burned within one year of the study period.

Table 1. Land use distribution in the Bonham-1 and Bonham-2 watersheds.

Land Cover	Watershed Area (m^2)	Watershed Area (%)
Mature Pine	1,293,800	43.7
Pine Plantation	118,700	4.0
Wetland	299,000	10.1
Hardwood	542,600	18.3
Mixed	506,700	17.1
Openings (military, wildlife and brush)	202,900	6.8

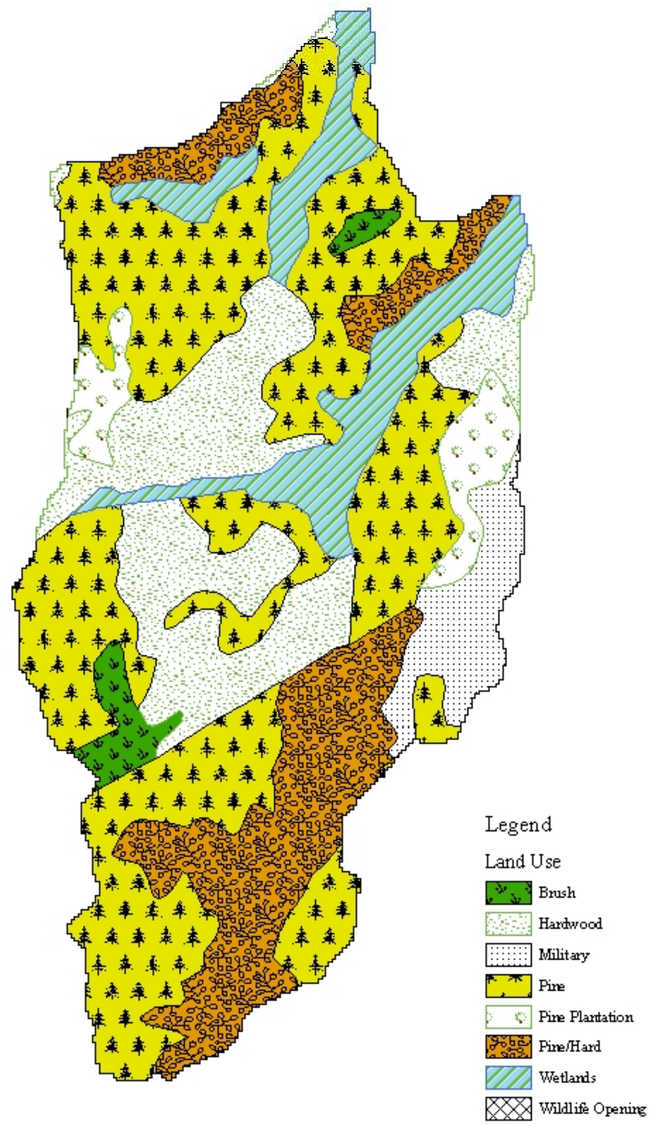

Figure 1. Land use for the Bonham-1 and Bonham-2 study watersheds.

CHAPTER 3
INSTRUMENTATION/EXPERIMENT DESIGN

The experiment was conducted from April 4, 2001 through June 11, 2002. Canopy parameters, climatic variables, and interception components were measured throughout this period. The measured data include precipitation, throughfall, stemflow, atmospheric conditions, and canopy cover. The following sections describe the experimental equipment and methods applied to this study.

Study Plots

A rectangular plot was established in each forest community. Table 2 lists the vegetation distribution and statistics for the all plots. The plots were randomly selected within areas having vegetation that is consistent with the average vegetation density and distribution for the respective forest community (Figure 2). The dimensions of each plot were determined by the size and geometry of each land-use type and ranged from 10 x 40 meters to 30 x 30 meters. Each plot was subdivided into four sampling grids of equal size. Each grid was outfitted with four throughfall collectors and one tipping bucket rain gauge. The throughfall collectors and tipping buckets were randomly placed on the ground within the confines of the grid. To ensure randomness, each instrument was relocated within the grid after data were collected.

The throughfall data were collected using eight-inch diameter tipping bucket rain gauges (model RG-100a, RainWise®) and throughfall collectors. The tipping buckets were calibrated to 0.01 inches per tip. Each tipping bucket was equipped with a data logger (HOBO-8000, Onset Inc.) that recorded the number of tips and the date and time of each tip. Clogging of the tipping buckets resulted in the omission of data for brief time periods. To reduce clogging, the installed plastic screen and cotter pin at the throat of the tipping bucket collector was removed and a plastic mesh was placed over the mouth of the collector. The mesh was pushed down into the collector to create a sock-filter arrangement so that the effective collection area of the gauge was not reduced.

The throughfall collectors consisted of two-liter plastic bottles with six-inch diameter funnels. The plastic bottles and funnels were supported by stands made of 3/8-inch plywood and six-inch PVC pipe. The PVC pipe was secured to the plywood base using silicon adhesive. Data were collected from the instruments on a bi-weekly basis.

A parallel experiment with a shorter duration was conducted to study the effect of varying canopy cover on interception modeling. Two additional plots for both the wetland and mature pine communities were monitored from February 1 through April 29, 2002. Each additional plot had a significantly different canopy cover than the other plots in the respective forest community. The additional plots, referred to as wetland B, wetland C, mature pine B, and mature pine C, were selected based on a visual inspection and a spherical densiometer survey. The instrumentation and methods used for these plots were identical to those described above.

Stemflow was measured in the wetland, mature pine, pine plantation, and hardwood plots. For these plots, the dominant tree species were further sub-divided into three classes of diameter at breast height (DBH) and projected crown radius. Stemflow gauges were installed in each plot such that the dominant tree species were sampled and that a representative tree from each DBH and projected crown radius category was included.

The mixed plot stemflow was determined by averaging the pine and hardwood measurements.

Stemflow was measured by attaching split plastic tubing to the representative trees in each plot. Nails or staples and silicon sealant were used as the method of attachment. The tubing was wound around each tree in a 360-degree spiral and routed to a tipping bucket (model RG-100a, RainWise®) equipped with a data logger (HOBO-8000, Onset Inc.).

Canopy Cover Data

Canopy cover was determined by direct measurement with a Model-A spherical densiometer using the method outlined by Lemmon (1956). This method provides a simple and reliable measure of canopy cover (Bunell and Vales, 1990). Readings were taken in the center of each study plot on a bi-weekly basis throughout the study period.

Climate Data

Precipitation data were measured at a height of 15 centimeters by two tipping bucket rain gauges (model RG-100a, RainWise®). Each tipping bucket gauge was equipped with an 8-inch diameter collector and calibrated to 0.01 inches per tip. Data loggers (HOBO-8000, Onset Inc.) were used to store the date and time of each tip. The tipping buckets were located in a 50 x 150 meter clearing on the boundary between the Bonham-1 and Bonham-2 watersheds. The distance from the precipitation gauges to the throughfall plots ranged from 315 to 900 meters. The clearing is centrally located and is within 900 meters of each land-use plot. Storm totals were calculated as the average recording of the two rain gauges. Data were collected from the instruments on a bi-weekly basis.

Atmospheric measurements were continuously recorded by the Ecosystem Characterization and Monitoring Initiative (ECMI) meteorological monitoring station ME-04 “McKenna Mount.” The atmospheric data includes air temperature, barometric pressure, relative humidity, solar radiation, wind speed, and precipitation. The station is located at UTM coordinates 706387 Easting and 3583703 Northing. The station is approximately 7 kilometers south of the Bonham-2 watershed. Data were collected in 1-minute intervals and averaged over 30-minute periods. The air temperature and relative humidity data were collected with a temperature and relative humidity probe (model HMP45C, Vaisala) at an installation height of 2 meters. Barometric pressure data were collected with a pressure transmitter (model PT101B, Vaisala) at an installation height of 1.75 meters. Solar radiation data were collected with a pyranometer with a silicon photovoltaic detector (model LI200X, Li-Cor) at an installation height of 2.5 meters. Wind speed data were collected using a four-blade heilcoid propeller sensor (model 05103-5, R. M. Young) at 3 meters. Finally, precipitation data were collected with a tipping bucket rain gauge (model TE525MM, Texas Electronics) mounted at 3 meters.

Table 2. Plot vegetation and distribution statistics.

Plot	Tree Type	Number of Trees	Percent of Total	Minimum Height (meters)	Maximum Height (meters)	Average Height (meters)	Average Projected Canopy Radius (meters)	Average Diameter (meters)	Trees per Hectare	Distance From B2 Precipitation Gauge (meters)
Wet	**Sweet Gum**	29	60	5.0	31.0	12.88	1.62	0.14	1200	325
	Bay	8	17	5.0	16.0	9.75	1.31	0.07		
	Long L. Pine	4	8	4.0	8.0	6.00	0.90	0.05		
	Water Oak	4	8	4.0	28.0	11.13	1.23	0.12		
	Dog Wood	3	6	6.0	14.5	10.50	2.33	0.11		
Wet B	**Sweet Gum**	21	46	6.0	28.0	17.60	1.70	0.23	1150	343
	Long L. Pine	9	20	14.0	21.0	18.89	1.80	0.23		
	Dog Wood	6	13	4.0	14.0	7.83	1.82	0.08		
	Water Oak	6	13	9.0	28.0	16.58	2.33	0.19		
	Bay	4	9	5.0	13.0	9.13	1.60	0.07		
Wet C	**Sweet Gum**	21	54	3.0	25.0	14.98	2.18	0.20	975	395
	Long L. Pine	8	21	3.8	5.0	4.25	0.78	0.05		
	Dog Wood	8	21	3.0	6.5	4.44	1.19	0.06		
	Water Oak	2	5	9.5	23.0	16.25	1.80	0.18		
Pine	**Loblolly Pine**	41	82	4.0	22.0	13.76	2.08	0.21	556	573
	Oak	5	10	6.0	15.0	9.80	2.34	0.14		
	Crateagus	4	8	5.0	9.0	6.50	2.38	0.11		
Pine B	**Loblolly Pine**	33	100	4.0	25.5	12.86	2.14	0.20	367	675

Plot	Tree Type	Number of Trees	Percent of Total	Minimum Height (meters)	Maximum Height (meters)	Average Height (meters)	Average Projected Canopy Radius (meters)	Average Diameter (meters)	Trees per Hectare	Distance From B2 Precipitation Gauge (meters)
Pine C	**Long Leaf Pine**	13	76	2.5	19.0	11.31	1.21	0.14	189	529
	Loblolly Pine	3	18	16.0	22.0	19.33	3.30	0.33		
	Dogwood	1	6	7.0	7.0	7.00	1.30	0.20		
Plantation	**Long Leaf Pine**	80	98	5.0	9.0	8.00	1.00	0.10	2050	900
	Oak	2	2	8.0	8.0	8.00	0.50	0.07		
Mixed	**Oak**	30	47	3.0	17.0	11.77	2.30	0.16	711	480
	Loblolly Pine	23	36	5.0	18.0	13.17	1.47	0.18		
	Cherry	3	5	3.0	8.0	5.67	1.50	0.07		
	Plum	3	5	3.0	4.0	3.50	1.00	0.08		
	Dogwood	3	5	6.0	7.0	6.33	2.17	0.07		
	Crateagus	1	2	5.0	5.0	5.00	1.50	0.07		
	Sassafras	1	2	15.0	15.0	15.00	1.00	0.13		
Hardwood	**Oak**	125	98	5.0	10.0	9.00	1.20	0.14	1411	523
	Long Leaf Pine	2	2	8.0	8.0	8.00	0.70	0.60		

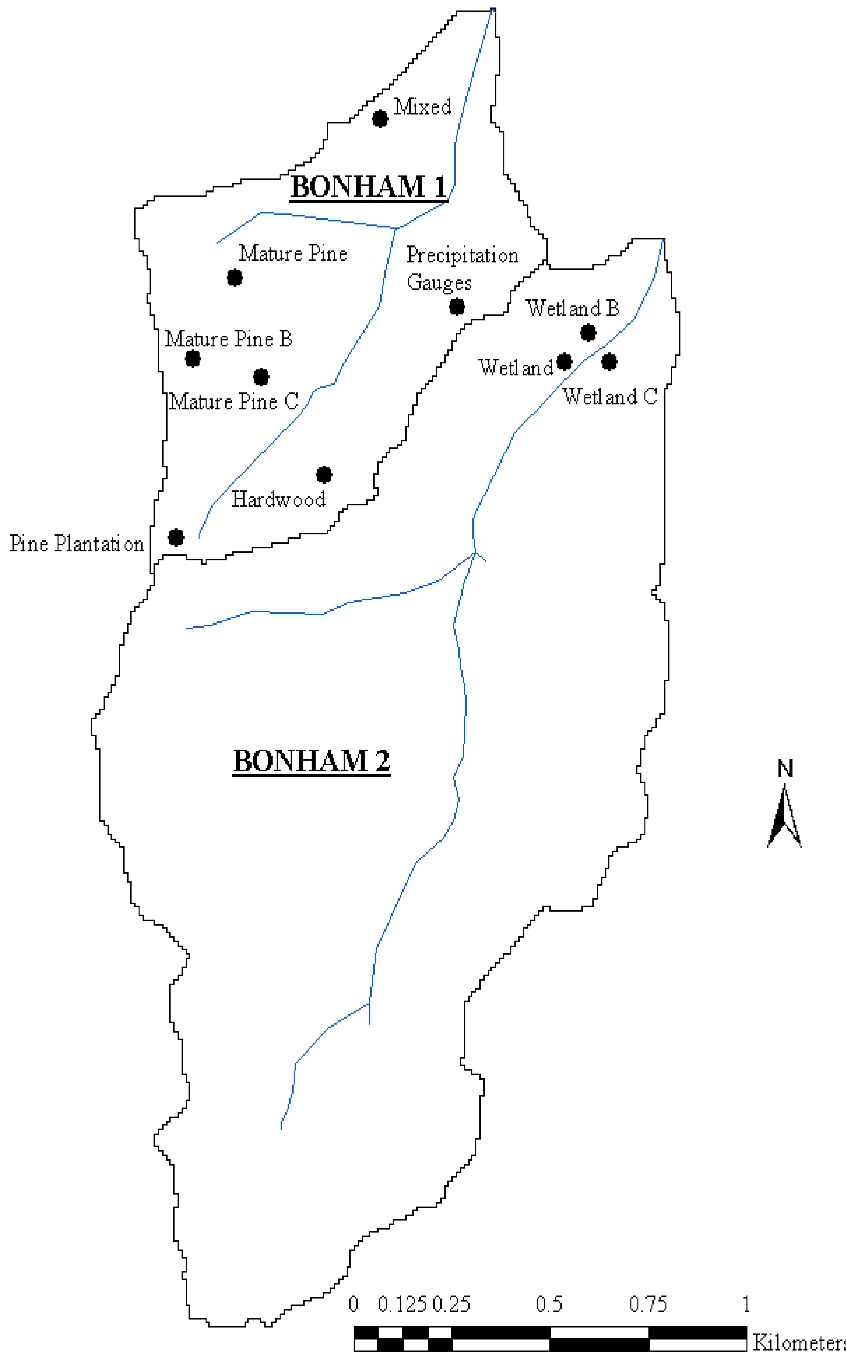

Figure 2. Plot locations in the Bonham-1 and Bonham-2 study watersheds.

CHAPTER 4
METHODOLOGY

The 1995 Gash model uses a canopy water balance approach. The precipitation reaching the canopy either evaporates, runs down the trunk, or falls to the ground as canopy drip. The model considers each precipitation event as an individual event with enough time between events to allow the trunk and canopy to completely dry. The total interception loss is the summation of the interception losses from a series of individual events over a period of time.

Each precipitation event consists of a wetting up period, a saturation period, and a drying out period. During each event, intercepted precipitation is lost through evaporation. The 1995 Gash model assumes the amount of precipitation lost due to evaporation is a function of the unit area of canopy. This approach requires the determination of specific canopy and trunk parameters and the measurement of several atmospheric parameters. The necessary canopy parameters include the canopy cover expressed as a percent of canopy per unit area, the canopy storage capacity, and the trunk storage capacity. The required atmospheric parameters are the gross precipitation per storm event, the average evaporation rate from a saturated canopy, and the mean rainfall rate per storm event.

Interception losses using the 1995 Gash model are calculated using the following equation:

$$\sum_{j=1}^{n+m} I_j = c\sum_{j=1}^{m} PG_j + (cE_c / R)\sum_{j=1}^{n}(PG_j - P'G) + c\sum_{j=1}^{n} P'G_j + q \times st + pt\sum_{j=1}^{n-q} PG_j \qquad (1)$$

where I is the interception loss, n is the number of saturation events, m is the number of non-saturation events, c is the mean canopy cover, PG is the total rainfall during the event, E_c is the mean evaporation rate from a saturated canopy scaled in proportion to canopy cover, R is the mean rainfall rate, $P'G$ is the amount of rainfall necessary to fill the canopy storage capacity, q is the number of events that saturate the trunk storage capacity, st is the trunk storage capacity, and pt is the incident precipitation reaching the trunks.

The experimental data were used to determine the canopy specific parameters, climatic variables, and interception components. The total rainfall during the event is the average of the two tipping bucket rain gauges. The mean rainfall rate is the total rainfall during the event divided by the storm duration. Average annual canopy cover is calculated by averaging all measured values during the experiment. An event is any period where precipitation was recorded without a break of more than three hours between successive recordings. The mean evaporation rate from a saturated canopy scaled in proportion to canopy cover is equal to the mean evaporation rate multiplied by the canopy cover. The mean evaporation rate E was determined using the REF-ET Reference Evapotranspiration program (Allen, 2000) with the Penman equation (Penman, 1948; 1963). The hourly average atmospheric measurements taken from the meteorological monitoring station were used to calculate evaporation.

The amount of rainfall necessary to fill the canopy storage capacity $P'G$ is given by the following equation (Carlyle-Moses and Price, 1999):

$$P'G = -(R / E_c) S_c * \ln[1 - (E_c / R)] \qquad (2)$$

where R is the mean precipitation rate falling on a saturated canopy, E_c is the mean evaporation rate scaled in proportion to canopy cover where $E_c = E * c$, and S_c is the canopy storage capacity per unit area of cover where $S_c = S / c$. The canopy storage capacity S was determined by plotting precipitation versus throughfall for saturation events and drawing a regression line. The negative regression line intercept divided by the canopy cover is the canopy storage capacity. Only storm events of 2.8 mm or more were used to determine the canopy storage capacity. The trunk storage capacity and the incident precipitation reaching the trunks were determined by the method used by Gash and Morton (1978) and Carlyle-Moses and Price (1999) where st is the slope and pt is the negative regression line intercept of the stemflow versus incident precipitation graph.

CHAPTER 5
RESULTS / DISCUSSION

Precipitation and Evapotranspiration

During the study period, 140 discrete storm events generated 752.8 mm of precipitation. The events ranged in intensity from 0.3 to 14.4 mm/hr with an average intensity of 1.8 mm/hr. Total rainfall accumulation for each event ranged from 0.3 to 73.2 mm with an average of 5.4 mm (Figure 3). Approximately 46% of all storms deposited less than 1 mm. During this period, 45% of all precipitation fell between 1900 and 0700. The duration of each event ranged from 0.5 to 34 hours with 50% of all events being one hour or less (Figure 4). The regional precipitation network showed no systematic spatial trend. Although some spatial variation of individual events is indicated, no bias is expected over the study period.

The average evaporation rate during precipitation events is 0.1 mm hr^{-1}. This value is somewhat lower than the 0.18 – 0.45 mm hr^{-1} range cited by Carlyle-Moses and Price (1999) for Ontario, Canada. However, as 45% of the events recorded in this study occurred at night, this rate is reasonable.

Measured Throughfall

The five forest types exhibited a range of measured throughfall. Observed throughfall and derived interception values are summarized in Table 3. The total throughfall measurements ranged from 553.8 mm in the mixed plot to 614.6 mm in the wetland plot. Throughfall plus stemflow accounted for 77.7 to 82.5% of incident precipitation for mature pine and hardwood forests, respectively. Interception losses were largest in the mature pine forest (22.3%) and smallest in the hardwood forest (17.4%). Annual interception losses were very consistent, within 2%, for all forest communities except pine. Overall, these values compare well with published results. Dolman (1987) found interception to be 18% of incident precipitation in an oak hardwood forest. Klaassen et al. (1998) found interception to be approximately 22.3% of incident precipitation for a mixed forest comprised of mostly Douglas fir, Scotch pine, and oak. Huber and Iroume (2001) report interception losses between 11 and 39% of incident precipitation for Monterey pine forests while Lankreijer et al. (1993) and Liu (2001) found interception to account for 13% and 12%, respectively, in a maritime pine forest.

Gash Model Parameters

The 1995 Gash model parameters were derived from the experimental measurements. The canopy specific parameters, climatic variables, and interception components are summarized in Table 4 by forest type. Despite the similarity in interception percentage, the canopy parameters exhibit a significant range of variability. The precipitation required to saturate the canopy was determined using equation 2. The *P'G* values ranged from 1.14 mm for the wetland plot to 4.00 mm for the pine plantation plot.

The measured canopy cover values are shown in Figure 5. Annual average canopy cover ranges from 43% in the pine plantation to 88% in the wetland forest. However, the wetland, hardwood, and, to some extent, the mixed plots exhibit a strong seasonal variability. These deciduous canopies drop most of their leaves at the end of the year resulting in a significantly lower canopy cover in January, February, and March. New leaf growth during April and May gradually increases the canopy cover.

The canopy storage capacity was determined for each plot by scaling the precipitation versus throughfall regression line intercept by the annual average canopy cover. The canopy storage capacity values ranged from 0.98 mm for the wetland plot to 1.97 mm for the mature pine plot. The mature pine and pine plantation values fall within the range of 0.4 to 3 mm reported by Liu (1998) and Llorens (2000), respectively. Little experimental data exist for wetland forests. However, Liu's (1998) 0.94 mm canopy storage capacity for a cypress wetland in Florida compares favorably with this study's 0.98 mm. This study's hardwood and mixed species canopy storage capacities are 1.40 and 1.58 mm, respectively. These values are slightly higher than the 1.0 mm for an oak and maple hardwood forest reported by Carlyle-Moses and Price (1999) and 1.2 mm for a Douglas fir, Scotch pine, and oak mixed forest reported by Klaassen et al. (1998).

Stemflow

Stemflow was measured on an individual event basis and problems with the instrumentation preclude the use of this data to quantify the total amount of stemflow over the study period. However, the collected data were sufficient to develop a linear regression model to predict stemflow on an event basis. The cumulative calculated stemflow during the study period ranged from 3.68 mm for the mixed plot to 14.23 mm for the pine plantation plot. The percent of incident precipitation for calculated stemflow ranged from 0.5% for the pine, hardwood, and mixed plots to 2.0% for the pine plantation plots. Published stemflow values for various pine species range from 0.3% (Valente et al., 1995) to 2.4% (Hanchi and Rapp, 1997). Stemflow values published for hardwood forests range from negligible amounts (Liu, 1998; Lankreijer et al., 1993) to 4.3% (Carlyle-Moses and Price, 1999) of incident precipitation. Klaassen et al. (1996) reports that stemflow accounted for 2% of gross precipitation in a mixed hardwood forest.

Additionally, Liu (1998) states that stemflow in a cypress wetland accounts for less that 3% of total precipitation. The agreement of the stemflow values with published values also provides validation for the parameter values determined from the regression line, i.e. trunk storage capacity and incident precipitation reaching the trunks.

Model Results using Annual Average Canopy Cover

Interception was modeled using equation 1 and the measured canopy parameters. Table 5 summarizes the results using the average annual canopy cover values. The model performed well with little error for the mature pine, wetland, and mixed plots. The model overestimated interception by 8.1% in the pine plantation plot. This is reasonable considering the dynamic growth of the pine plantation. However, the model under-estimated interception by 10.5% in the hardwood plot. Overall, these results demonstrate that the model predicts interception with reasonable accuracy across a range of forest communities when annual average canopy cover values are used (Figure 6).

Model Results using Seasonal Canopy Cover

As previously noted, the wetland, mixed, and hardwood plots exhibit a distinct seasonal variation in canopy cover. The wetland canopy cover drops from an average of 93% during the spring and summer (typically mid April to late November) to 75% during the winter (typically late November to mid April). The mixed plot experiences a smaller decrease, from 77% to 70%, during the same time period. The hardwood plot experiences the most pronounced seasonal variation. Its canopy cover decreases from an average of 60% during the spring and summer to 37% during the winter. The pine and pine plantation plots do not show a distinct seasonal variation in canopy cover. The canopy cover in the pine plot is 64% throughout the year. The pine plantation canopy cover increases from 40% in the spring and summer to 50% in the winter. Tree growth is the most likely cause of this change.

The 1995 Gash model (equation 1) was reapplied using seasonal canopy cover values. Table 6 summarizes the results using the seasonal canopy cover values. In all cases, the application of seasonal canopy cover values improved the results (Figure 7). This is most evident with the hardwood forest where predicted interception error decreases from 10.5 to 2.4%. This result strongly suggests that forests having a significant seasonal canopy cover variation will benefit from the inclusion of routine vegetation cover information. Overall, the 1995 Gash model results show that excellent interception predictions are possible using measured canopy parameters.

Canopy Density Comparison

Teklehaimanot and Jarvis (1991) examined the effect of tree density on canopy storage capacity for a Sitka spruce plantation. They concluded that canopy storage capacity is a property of individual trees and is unaffected by tree density. This suggests that canopy storage capacity is consistent among tree species and spatial variations of interception losses are a function of canopy cover only. To test this assumption, our study established additional wetland and mature pine plots with varying canopy density. Data for the canopy density comparison were collected from February 1, 2002 to April 29, 2002.

During this period, 24 individual storm events generated 243.0 mm of precipitation. The event intensities were comparable to the yearlong study while the total rainfall accumulation for each event covered the entire range observed during the year. The net values of throughfall, stemflow, and interception loss are summarized in Table 7. The canopy cover averaged 64, 46, and 29% for the mature pine (MP), mature pine B (MP_B), and mature pine C (MP_C) plots, respectively.

The calibrated Gash model was applied to the additional mature pine plots. The agreement between predicted and measured interception using a seasonal canopy cover value was -0.5 (MP), -4.5 (MP_B), and 1.8% (MP_C). The 1995 Gash model predicts interception with excellent agreement for the wide range of mature pine forest canopy covers, 29 to 64%, included in this study.

The canopy cover averaged 80, 78, and 66% for the wetland (W), wetland B (W_B), and wetland C (W_C) plots, respectively. A seasonal variation in canopy density was noticed in all plots, the most significant being a 33% change in the W_C plot. Interception in the three plots was modeled using equation 1, the plot canopy cover, and the wetland parameters. The agreement between predicted and measured interception using seasonal canopy cover values was -5.7 (W), 25.2 (W_B), and 28.5% (W_C). The agreement for W, the wetland calibration plot, is reasonable, however, plots W_B and W_C are in poor agreement.

One possible explanation for the poor agreement is the physical difference between plot W and plots W_B and W_C. While the mature pine plots had similar understories, plot W had dense understory vegetation and plots W_B and W_C had sparse understories. The plot W understory vegetation consisted mostly of immature sweet gum, water oak, and dogwood up to 4 meters tall. Additionally, plot W contains a different tree species distribution plots W_B and W_C (Table 2). Plot W is composed of only 5% pine while plots W_B and W_C are 20% pine. As pine has a high canopy storage capacity, a higher pine percentage will effectively increase the plot's overall canopy storage capacity.

Physically based corrections were used to adjust the canopy cover and canopy storage capacity to account for the variation in wetland composition. Plot statistics were used to determine the percentage of total canopy area contributed by the overstory for plot W. The canopy cover contributed by the overstory vegetation may be described as

$$C_{Wadj} = A_O / A_T \tag{3}$$

where C_{Wadj} is the adjusted canopy cover for the W plot, A_o represents the sum of the projected canopy area for all trees greater than 12 meters tall, and A_T represents the sum of the projected canopy area for all trees in the plot scaled by the measured canopy cover. Using equation 3, C_{Wadj} is 66%.

The canopy storage capacity for plot W was adjusted to account for the difference in species composition. Weighted averaging was used to account for the difference in pine contribution. The adjusted canopy storage capacity S_{adj} is described by the following equations:

$$S_{adj} = (S_W * R_B + S_P * R_P) / C_{Wadj} \tag{4}$$

$$R_P = (\text{\% pine in the } W_B \text{ and } W_C \text{ plots - \% pine in W plot}) \tag{5}$$

$$R_B = (1 - R_P) \tag{6}$$

where S_W and S_P are the precipitation versus throughfall graph linear regression intercept for plot W and plot MP, respectively. The above algorithm results in an adjusted wetland canopy storage capacity of 1.50 mm. This canopy storage capacity is applicable for the wetland communities with sparse understories.

Using the adjusted canopy storage capacity and the seasonal canopy cover in equation 1, the difference between the measured and predicted interception loss improves to 6.3 and 8.2% for plots W_B and W_C, respectively. The 1995 Gash model predicts interception within reasonable agreement for the wetland forest included in this study once adjustments are made to compensate for the physical differences among plots.

Variations in tree species and understory composition among heterogeneous forests have a significant impact on model parameters and subsequent interception prediction. The present results suggest that forests that are comprised of multiple species may require species-specific corrections to model parameters. In addition, the relative composition of overstory and understory should be considered prior to applying experimentally determined parameters to other sites. The methods introduced here to correct canopy cover measurements and canopy storage capacity provide a preliminary approach to characterize canopy specific parameters on the basis of site characteristics. While the applied methods draw from a physically based approach, the corrections were based on a limited dataset and require additional study.

Table 3. Measured precipitation, throughfall, and derived stemflow for 4/04/01 through 6/11/02.

	Wetland	Pine	Pine Plantation	Hardwood	Mixed
Gross Measured Precipitation (mm)	752.8	752.8	724.8	724.8	684.9
Measured Throughfall (mm)	614.5	580.8	583.3	594.5	553.8
Stemflow (mm)	4.9	4.1	14.2	3.9	3.7
Actual Interception (mm)	133.4	167.9	127.3	126.4	127.4
Throughfall Percent of Total Precipitation	81.6	77.2	80.5	82.0	80.9
Stemflow Percent of Total Precipitation	0.65	0.54	1.96	0.54	0.54
Interception Percent of Total Precipitation	17.7	22.3	17.6	17.4	18.6

Table 4. Derived canopy specific parameters, climatic variables, and interception components.

	Wetland	**Pine**	**Pine Plantation**	**Hardwood**	**Mixed**
PG (mm)	752.8	752.8	724.8	724.8	684.9
n	71	53	45	52	51
m	69	87	90	83	76
R (mm hr^{-1})	2.03	2.03	2.02	2.02	1.95
S (mm)	0.98	1.97	1.70	1.40	1.58
E (mm hr^{-1})	0.10	0.10	0.10	0.10	0.10
c	0.88	0.64	0.43	0.52	0.74
pt (mm)	0.02	0.01	0.05	0.01	0.01
st (mm)	0.16	0.13	0.46	0.08	0.10
P't (mm)	9.41	9.29	9.20	6.82	8.20
Ec (mm hr^{-1})	0.09	0.06	0.04	0.05	0.07
P'G (mm)	1.14	3.13	4.00	2.73	2.18

Table 5. Model results using average annual canopy cover values.

	Wetland	Pine	Pine Plantation	Hardwood	Mixed
Gross Measured Precipitation (mm)	752.8	752.8	724.8	724.8	684.9
Measured Throughfall (mm)	614.5	580.8	583.3	594.5	553.8
Stemflow (mm)	4.9	4.1	14.2	3.9	3.7
Actual Interception (mm)	133.4	167.9	127.3	126.4	127.4
Predicted Interception Using Average Canopy Cover (mm)	126.7	161.7	137.6	113.1	135.2
Percent Difference (Actual and Predicted Interception)	5.0	3.7	-8.1	10.5	-6.1
Throughfall Percent of Total Precipitation	81.6	77.2	80.5	82.0	80.9
Stemflow Percent of Total Precipitation	0.65	0.54	1.96	0.54	0.54
Interception Percent of Total Precipitation	17.7	22.3	17.6	17.4	18.6

Table 6. Model results using seasonal canopy cover values.

	Wetland	Pine	Pine Plantation	Hardwood	Mixed
Gross Measured Precipitation (mm)	752.8	752.8	724.8	724.8	684.9
Measured Throughfall (mm)	614.5	580.8	583.3	594.5	553.8
Stemflow (mm)	4.9	4.1	14.2	3.9	3.7
Actual Interception (mm)	133.4	167.9	127.3	126.4	127.4
Predicted Interception Using Seasonal Canopy Cover (mm)	127.4	166.7	136.6	123.4	134.1
Percent Difference (Actual and Predicted Interception)	4.5	0.7	-7.3	2.4	-5.3
Throughfall Percent of Total Precipitation	81.6	77.2	80.5	82.0	80.9
Stemflow Percent of Total Precipitation	0.65	0.54	1.96	0.54	0.54
Interception Percent of Total Precipitation	17.7	22.3	17.6	17.4	18.6

Table 7. Density comparison results for 2/01/02 to 4/29/02 using seasonal canopy cover.

	Wetland	Wetland B	Wetland C	Pine	Pine B	Pine C
Canopy Cover Range (%)	67 - 87	69 - 85	49 - 82	48 - 80	41 - 55	17 - 34
Average Canopy Cover (%)	88	78	66	64	44	29
Gross Measured Precipitation (mm)	243.0	243.0	243.0	243.0	243.0	243.0
Measured Throughfall (mm)	215.3	205.8	208.1	204.0	211.9	211.9
Stemflow (mm)	2.3	2.3	2.3	1.9	1.9	1.9
Actual Interception (mm)	25.4	34.9	32.6	37.1	29.2	29.2
Predicted Interception (mm)	26.8	26.1[1] 32.8[2]	23.3[1] 30.0[2]	37.3	32.2	28.7
Percent Difference (Actual and Predicted Interception)	-5.7	25.2[1] 6.3[2]	28.5[1] 8.2[2]	-0.5	-10.2	1.7
Throughfall Percent of Total Precipitation	88.6	84.7	85.6	83.9	87.2	87.2
Stemflow Percent of Total Precipitation	0.96	0.96	0.96	0.80	0.80	0.80
Interception Percent of Total Precipitation	10.4	14.4	13.4	15.3	12.0	12.0

1 – Calculated using unadjusted canopy cover and canopy storage capacity.
2 – Calculated using adjusted canopy cover and canopy storage capacity.

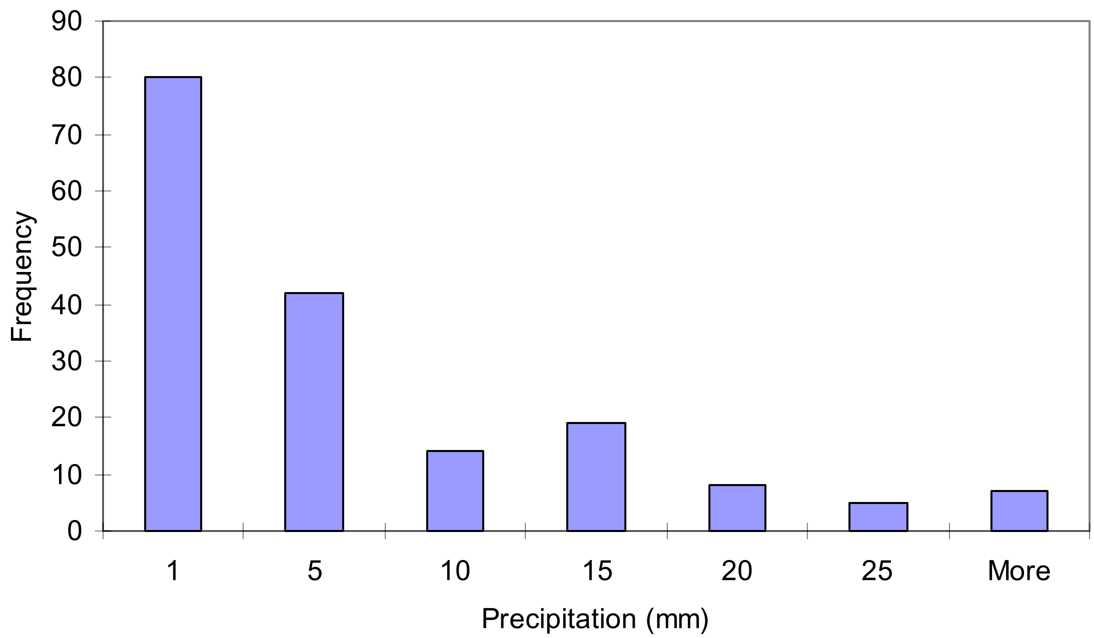

Figure 3. Cumulative precipitation event totals for 4/04/01 through 6/11/02.

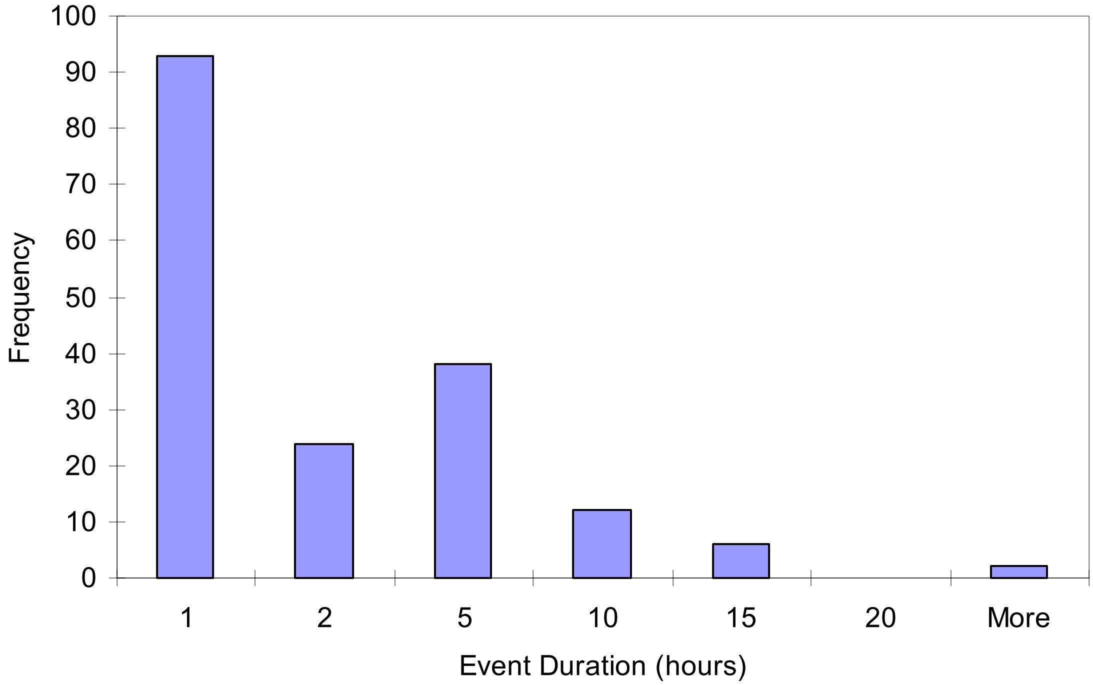

Figure 4. Precipitation event durations for 4/04/01 through 6/11/02.

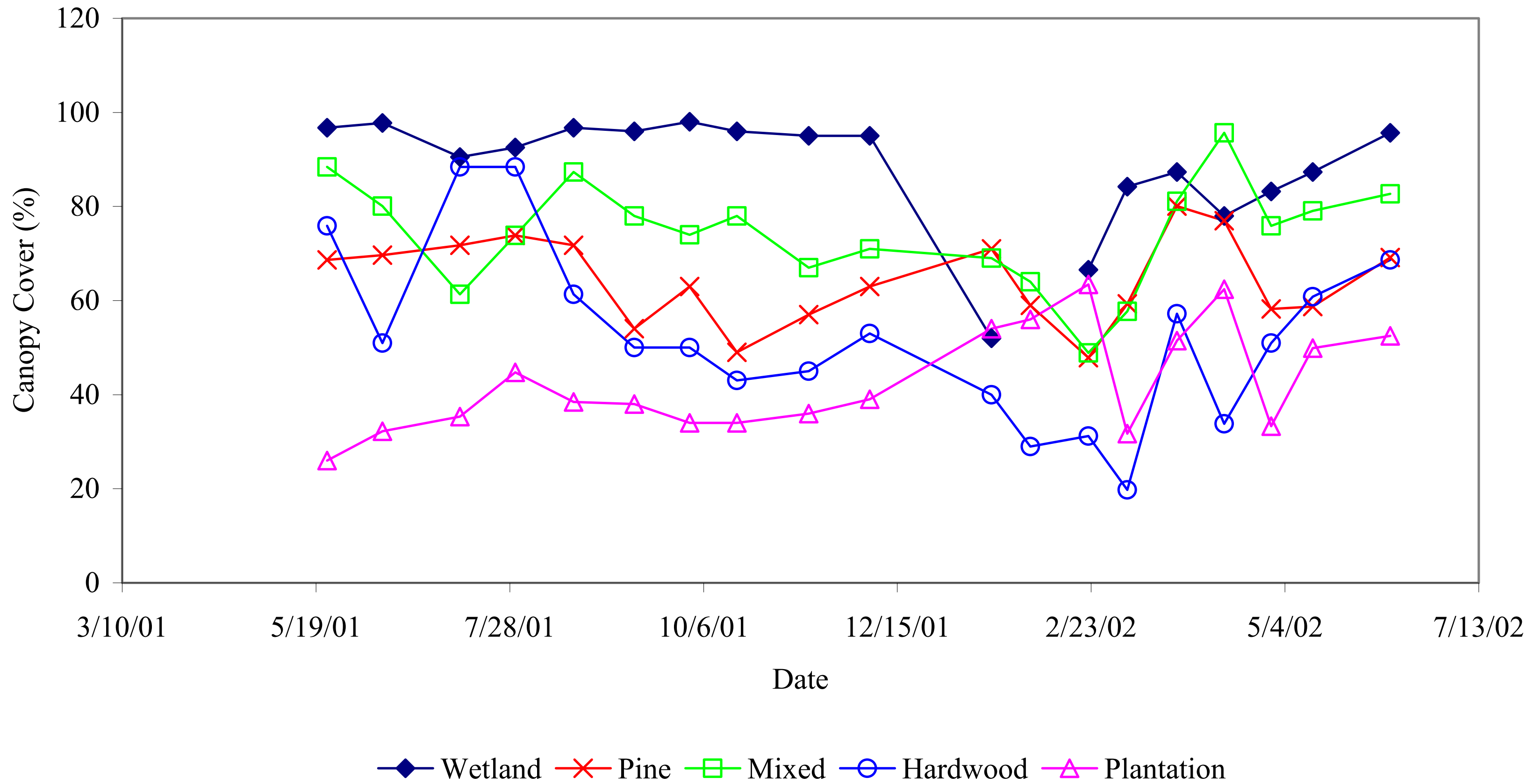

Figure 5. Canopy cover measurements for the five forest types.

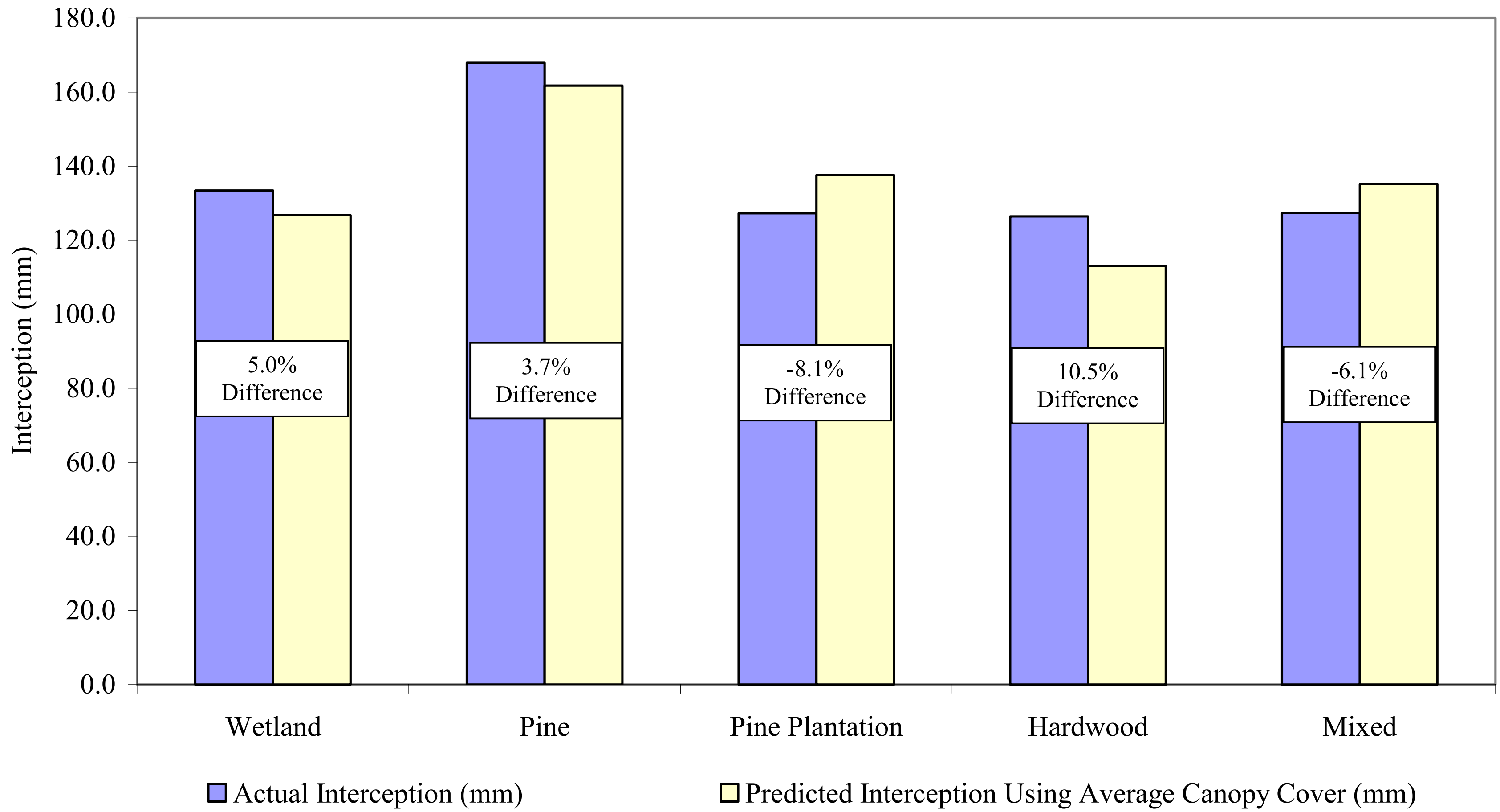

Figure 6. Measured and modeled interception results using average canopy cover.

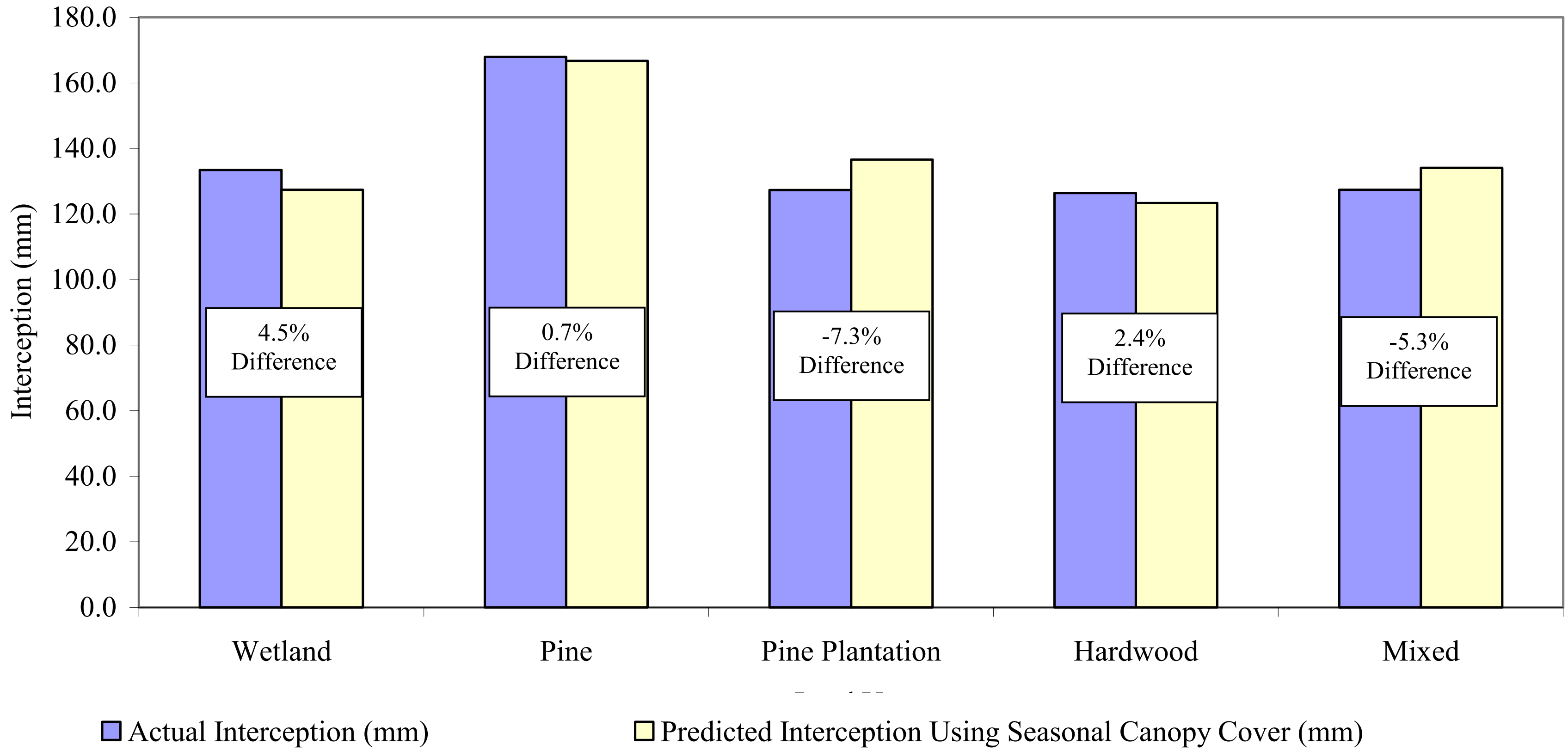

Figure 7. Measured and modeled interception results using seasonal canopy cover.

CHAPTER 6
WATERSHED SCALE APPLICATION

Watershed hydrology has transitioned from the prediction of rainfall-runoff and land surface-atmospheric interactions using lumped approaches (Liou et al., 1999) to the more advanced application of distributed land-use, soils, and topographic data (Bonan et al., 2002). The current study's results were used to consider the relative importance of capturing the spatiotemporal variability of the water input resulting from distributed throughfall. Three approaches to predict throughfall using the 1995 Gash interception model were compared at a watershed scale. The first approach is a lumped approach wherein the predominant vegetation type is used to predict the magnitude of water input on a seasonal basis. The second and third approaches use land use maps to distribute throughfall in the watershed spatially and temporally. The second approach assumes a constant canopy cover value while the third captures the seasonal dynamics of leaf fall and growth.

The interception for the period from April 29, 2001 to April 29, 2002 was modeled using all three approaches. During this period, 836 mm of precipitation fell on the study watershed. The lumped approach was applied with the mature pine forest type that covers 47% of the watershed. Table 8 summarizes the total throughfall by forest type and aggregate watershed on a seasonal basis. The 1995 Gash model predicts 659 mm of throughfall and 79% of total gross precipitation, using the lumped approach. By taking into account the spatial variation in forest type and applying the annual average canopy cover, the model predicts 687 mm of throughfall or

82% of gross precipitation. When the model is further refined to include seasonal canopy cover as well as spatially distributed forest types, the predicted throughfall is 680 mm or 81% of gross precipitation. The predicted annual throughfall varies by 4% between the lumped approach and the spatially and seasonally distributed forests. The choice of approach does not appear to be significant when the 1995 Gash model is applied over long temporal periods and when the interception by the dominant species is similar to that of the other species.

Larger differences among the watershed responses are observed for smaller spatial scales and shorter temporal periods (Figures 8 through 11). An examination of the watershed results by individual forest type shows that the lumped approach under-predicts annual throughfall for all forest types. Most significantly, it under-predicts throughfall by 7% for hardwood forests and 6% for wetland forests when an annual average canopy cover is used or by 6% for hardwood and wetland forests using seasonal canopy cover. This error is of particular concern for the riparian wetland forest as the watershed storm response is most critical for areas closest to the stream in watersheds dominated by the saturation excess mechanisms of runoff generation.

When shorter temporal periods are examined, i.e. seasonal instead of annual, the associated errors with the lumped approach are more pronounced. For example, the lumped approach predicts wetland throughfall within 1% of the spatially distributed approach using seasonal canopy cover during the winter. However, the difference between the approaches is 10% during the summer. A large seasonal variation is also seen in the pine plantation communities where the error ranges from a 1% over-prediction to an 11% under-prediction in throughfall.

Clearly, throughfall is controlled by the plant architecture, plant physiology, and rainfall input and timing. The "best" model would ideally include all details. However, often the details are not available. These results demonstrate that there is not a significant variation among approaches when applying models over aggregated spatial scales and long temporal periods. However, when smaller scales or shorter temporal periods are of interest, an appropriate landscape characterization is necessary to capture the variability of water input.

Table 8. Throughfall results using the distributed approach.

		Precipitation (mm)	Mature Pine (mm)	Wetland (mm)	Pine Plantation (mm)	Mixed (mm)	Hardwood (mm)	Watershed Total (mm)
Annual Average Canopy Cover	**Spring**	250.5	201.8 (0%)	212.6 (5%)	207.6 (3%)	206.0 (2%)	215.2 (6%)	209.6 (4%)
	Summer	231.3	173.6 (0%)	188.3 (8%)	180.0 (4%)	178.6 (3%)	189.1 (8%)	183.0 (5%)
	Fall	138.2	110.3 (0%)	115.8 (5%)	112.8 (2%)	112.3 (2%)	117.9 (7%)	114.6 (4%)
	Winter	215.7	173.4 (0%)	182.2 (5%)	178.5 (3%)	176.6 (2%)	184.9 (6%)	180.0 (4%)
	Total	**835.6**	**659.1 (0%)**	**699.0 (6%)**	**679.0 (3%)**	**673.4 (2%)**	**707.2 (7%)**	**687.2 (4%)**
Seasonal Canopy Cover	**Spring**	250.5	196.5 (0%)	211.3 (7%)	204.4 (4%)	203.6 (4%)	210.3 (7%)	205.7 (4%)
	Summer	231.3	166.7 (0%)	184.2 (10%)	188.1 (11%)	173.4 (4%)	174.8 (5%)	176.3 (5%)
	Fall	138.2	113.0 (0%)	113.6 (1%)	115.1 (2%)	110.4 (-2%)	119.2 (5%)	115.5 (2%)
	Winter	215.7	174.5 (0%)	185.1 (6%)	173.2 (-1%)	181.1 (4%)	189.9 (8%)	182.3 (4%)
	Total	**835.6**	**650.6 (0%)**	**694.3 (6%)**	**680.7 (4%)**	**668.5 (3%)**	**694.1 (6%)**	**679.9 (4%)**

Numbers in parenthesis represent the percent difference from the lumped prediction using mature pine.

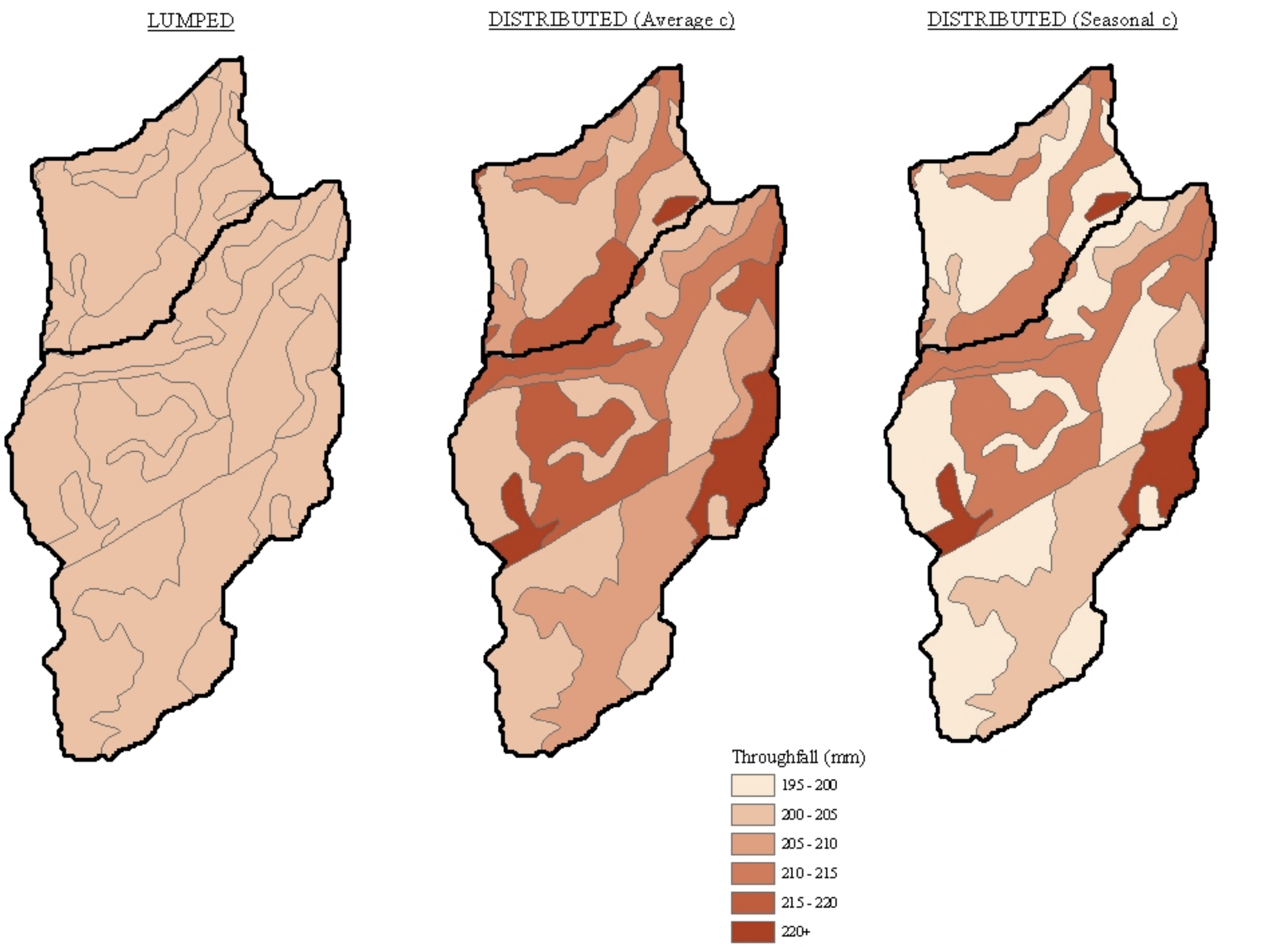

Figure 8. Watershed scale results for the Spring season (April 2001 through June 2001).

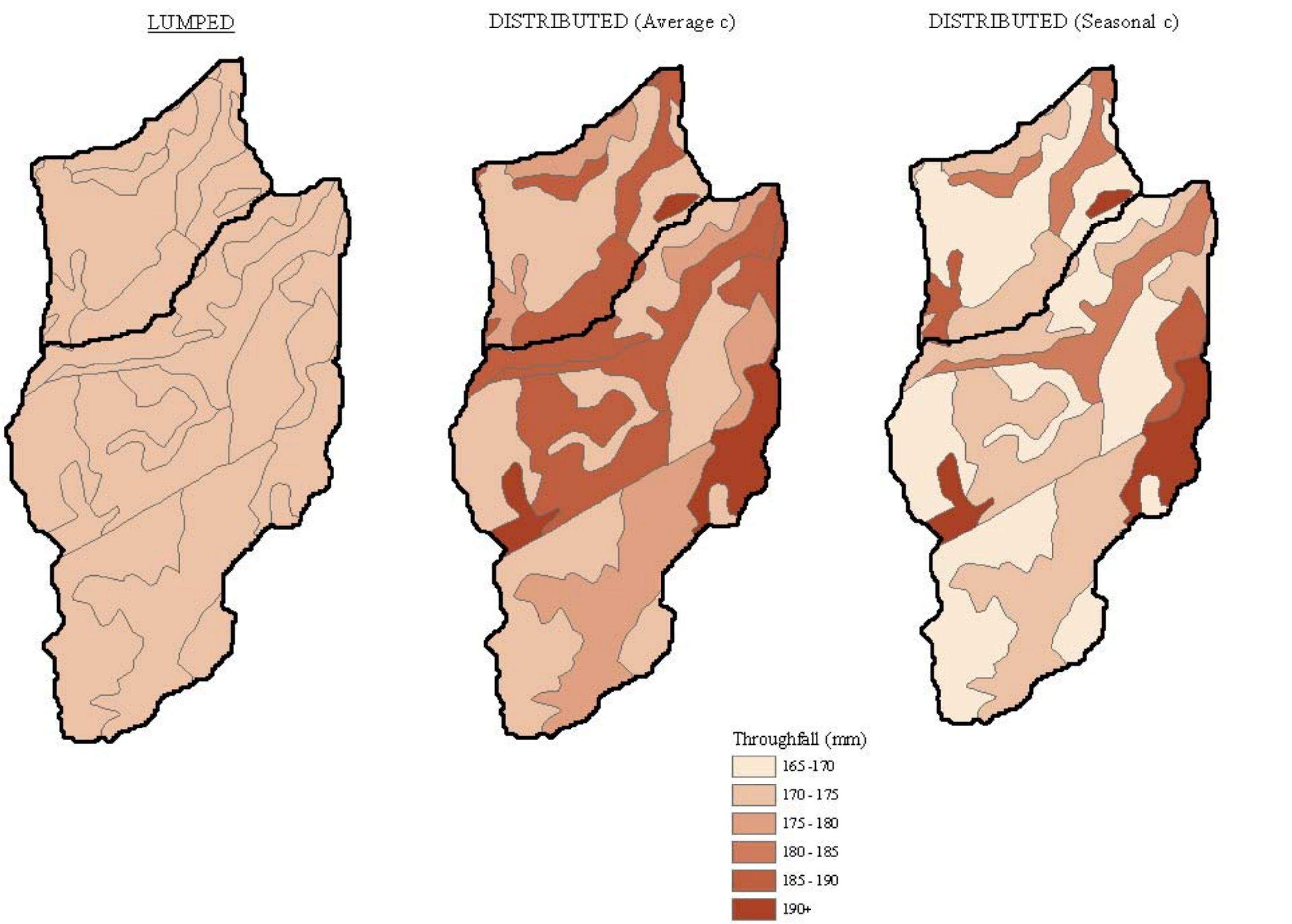

Figure 9. Watershed scale results for the Summer season (July 2001 through September 2001).

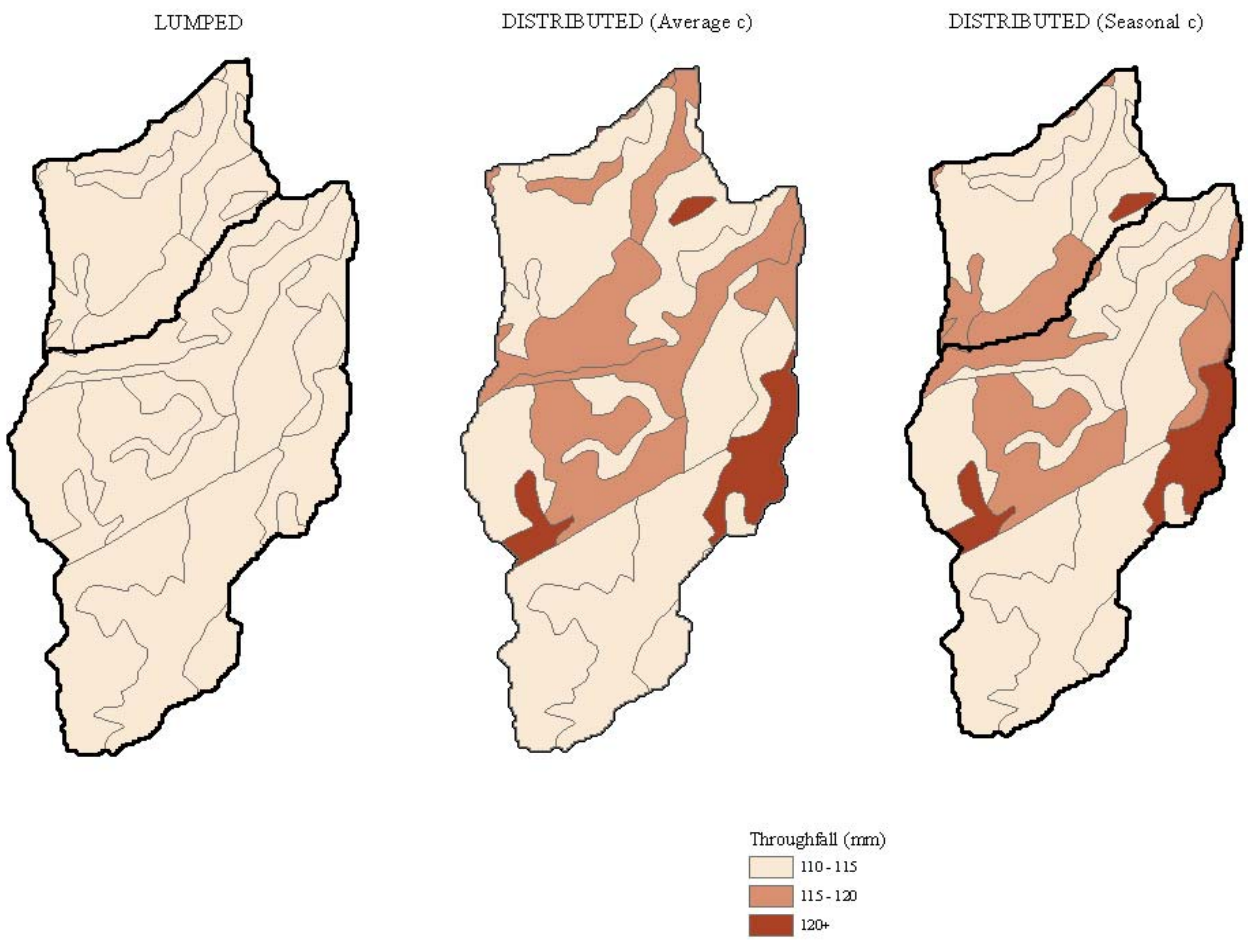

Figure 10. Watershed scale results for the Fall season (October 2001 through December 2001).

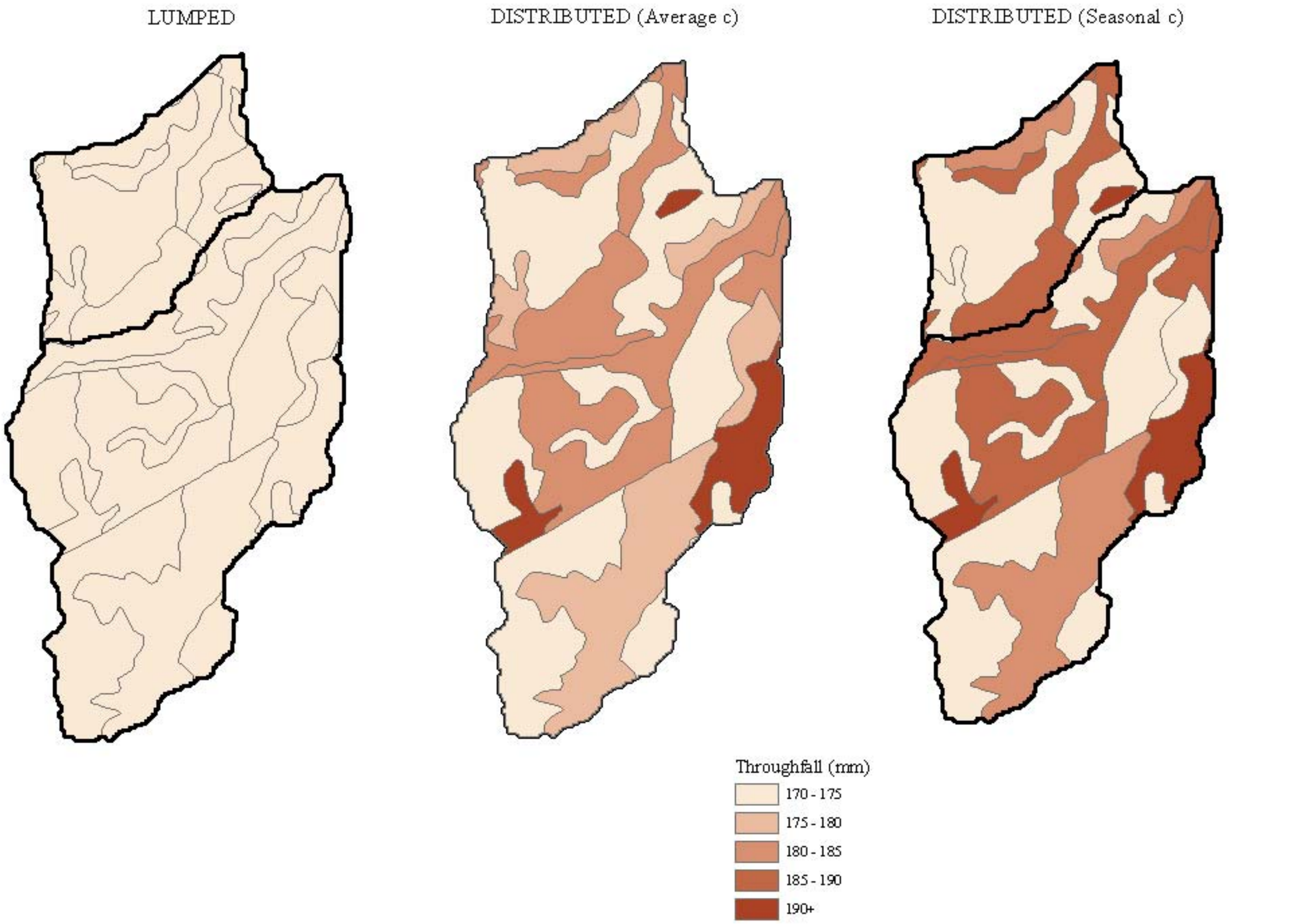

Figure 11. Watershed scale results for the Winter season (January 2002 through March 2002).

CHAPTER 7
CONCLUSION

This study derived a set of parameters, coefficients, and physical properties for wetland, mature pine, pine plantation, mixed, and hardwood land uses that are appropriate for studying diverse forested communities. Application of the parameters in the 1995 Gash interception model demonstrates its ability to predict interception losses accurately provided that the model parameters are representative of the modeled region. Application of seasonal canopy cover values in lieu of annual average values improved the agreement of the modeled and the actual interception loss for all five land uses included in this study. Furthermore, the model predicts interception accurately when applied over land uses of varying canopy cover as long as the canopy cover is adjusted for the area of interest. A new approach is proposed to correct derived parameters for site-specific vegetation in riparian wetlands. A watershed scale intercomparison of the influence of forest community and seasonal variation on interception demonstrated that appropriate characterization of forests is necessary when applying the 1995 Gash model over seasonal or shorter duration time periods. Additionally, application of the model at sub-watershed spatial scales demonstrated that significant variation between results can be expected as the extent of the spatial scale is reduced. The field experimentation and water budget analysis in this study provide insight into the characterization of the net water input into the heterogeneous forest communities distinctive to the southeast United States.

APPENDIX A
PRECIPITATION VERSUS THROUGHFALL GRAPHS

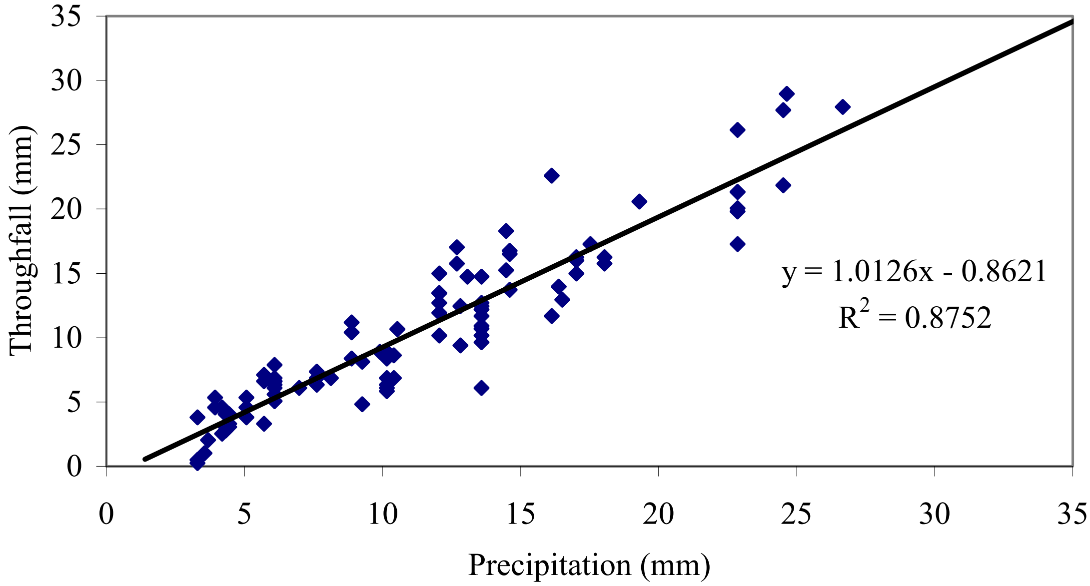

Figure A-1. Precipitation versus throughfall graph used to determine canopy storage capacity for the wetland plot.

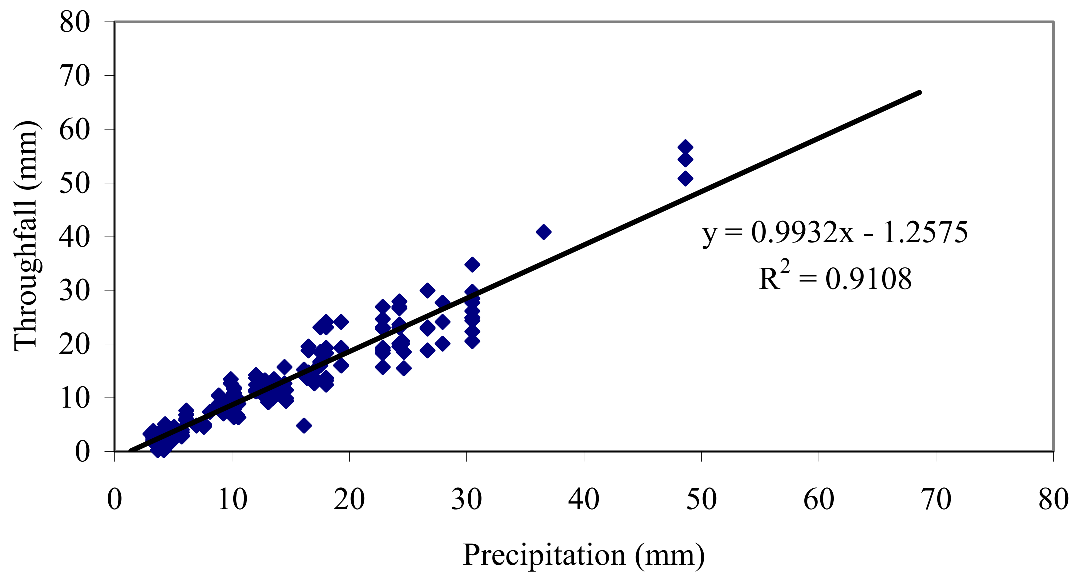

Figure A-2. Precipitation versus throughfall graph used to determine canopy storage capacity for the pine plot.

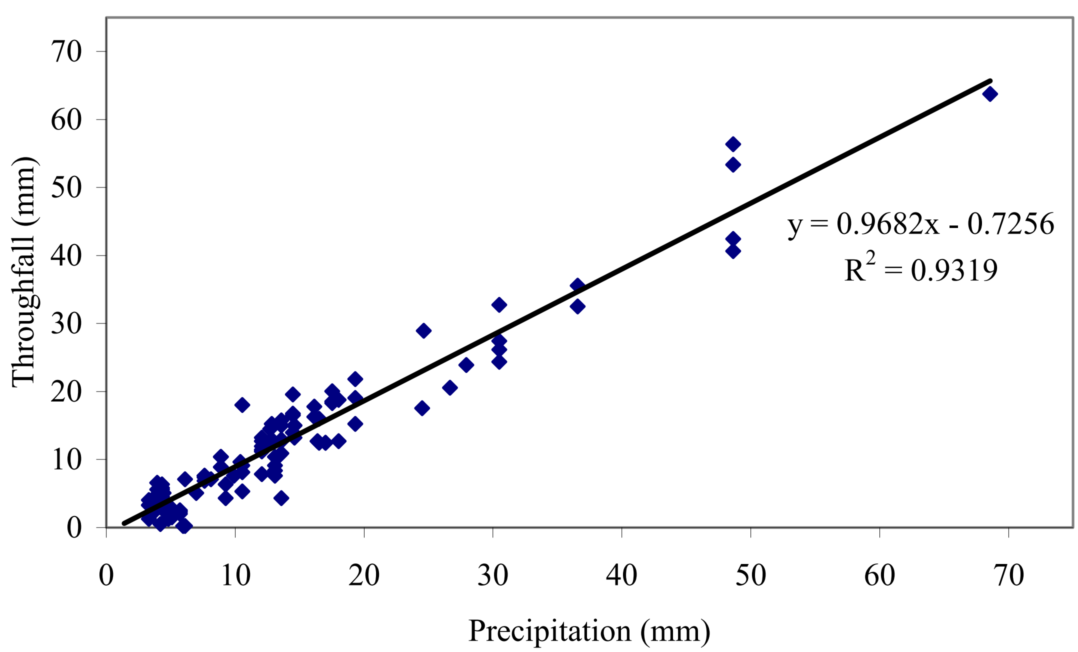

Figure A-3. Precipitation versus throughfall graph used to determine canopy storage capacity for the pine plantation plot.

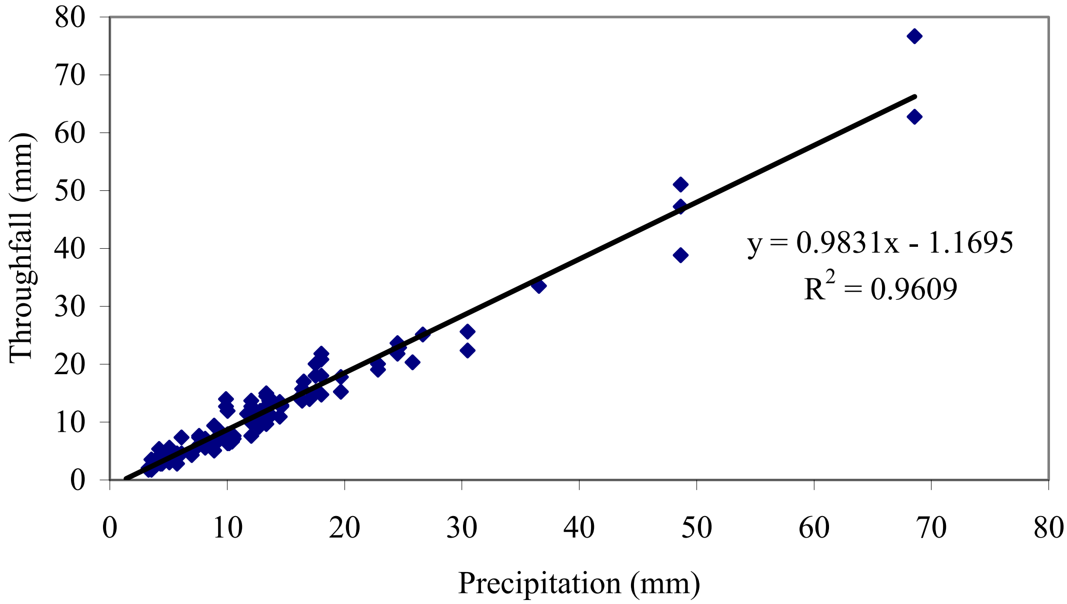

Figure A-4. Precipitation versus throughfall graph used to determine canopy storage capacity for the mixed plot.

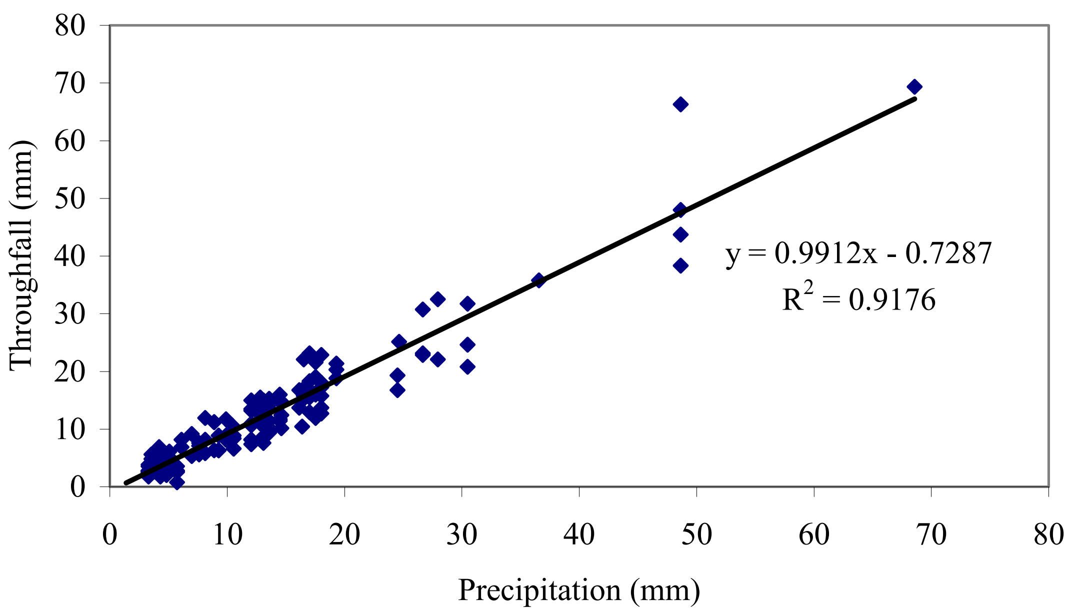

Figure A-5. Precipitation versus throughfall graph used to determine canopy storage capacity for the hardwood plot.

APPENDIX B
PRECIPITATION VERSUS STEMFLOW GRAPHS

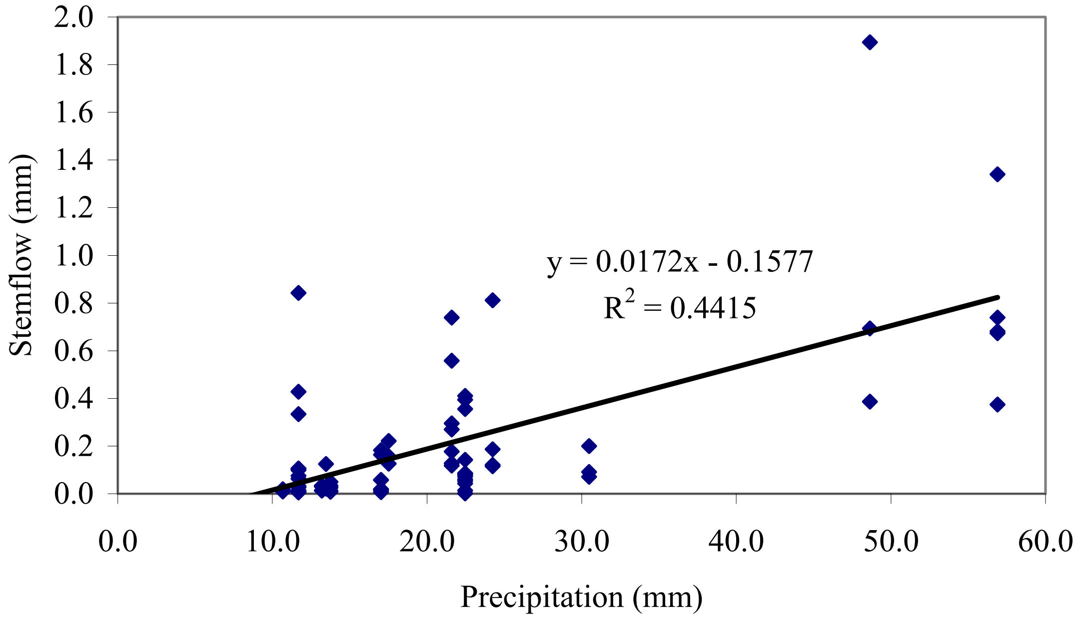

Figure B-1. Precipitation versus stemflow graph used to determine trunk storage capacity and precipitation reaching the trunks for the wetland plot.

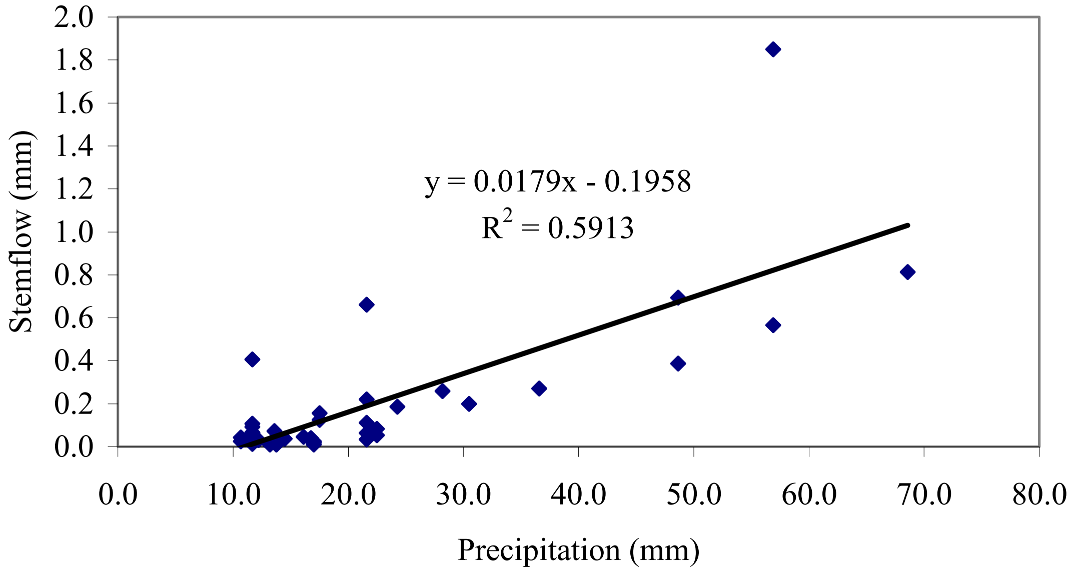

Figure B-2. Precipitation versus stemflow graph used to determine trunk storage capacity and precipitation reaching the trunks for the pine plot.

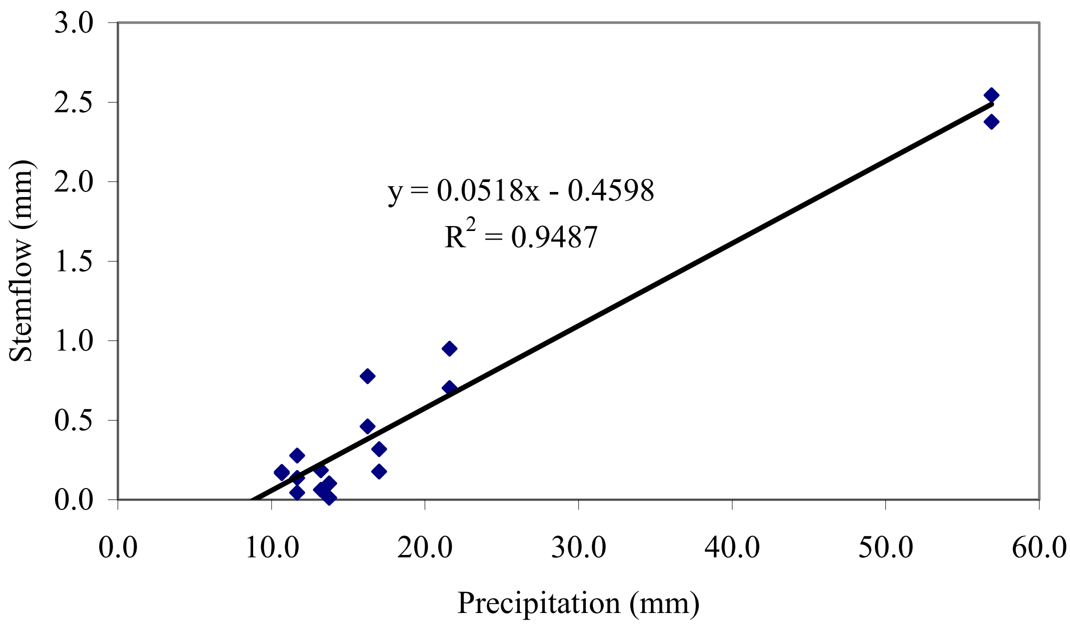

Figure B-3. Precipitation versus stemflow graph used to determine trunk storage capacity and precipitation reaching the trunks for the pine plantation plot.

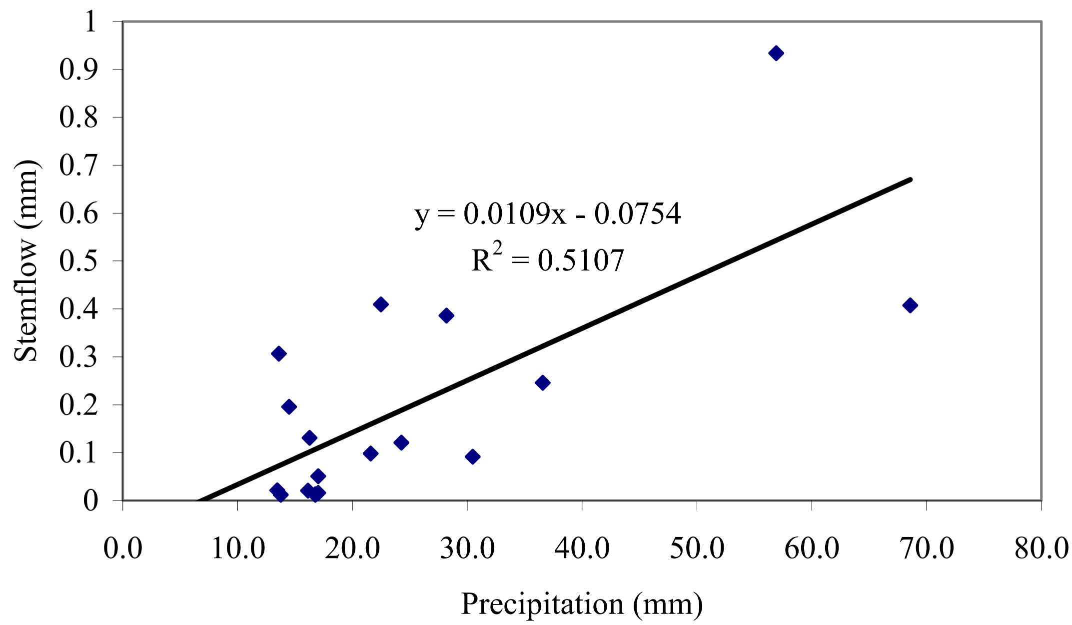

Figure B-4. Precipitation versus stemflow graph used to determine trunk storage capacity and precipitation reaching the trunks for the hardwood plot.

LIST OF REFERENCES

Allen, R. G. 2000. "REF-ET, Reference Evapotranspiration Calculator Version Windows 2.0". Univ. of Idaho Res. and Ext. Center, Kimberly, ID, 82 p.

Bonan, G.B., K.W. Oleson, M. Vertenstein, S. Levis, X. Zeng, Y. Dai, R.E. Dickinson, and Z.-L.Yang, 2002: The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model. Journal of Climate, submitted.

Bunnell, F. L., Vales, D. J., 1990. Comparison of methods for estimating forest overstory cover: differences among techniques. Canadian Journal of Forest Research 20: 101-107.

Carlyle-Moses, D. E., Price, A. G., 1999. An evaluation of the Gash interception model in a northern hardwood stand. Journal of Hydrology 214: 103–110.

Crockford, R. H., Richardson, D. P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrological Processes 14: 2903–2920.

Dingman, S. L., 1994. Physical Hydrology. Upper Saddle River, New Jersey: Prentice-Hall, Inc.

Dolman, A. J., 1987. Summer and winter rainfall interception in an oak forest. Predictions with an analytical and a numerical simulation model. Journal of Hydrology 90: 1–9.

Dykes, A. P., 1997. Rainfall interception from a lowland tropical rainforest in Brunei. Journal of Hydrology 200: 260–279.

Gash, J. H. C., 1979. An analytical model of rainfall interception by forests. Quarterly Journal of the Royal Meteorological Society 105: 43–55.

Gash, J. H. C., Lloyd, C. R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology 170: 79–86.

Gash, J. H. C., Morton, A. J., 1978. An application of the Rutter model to the estimation of the interception loss from Thetford forest. Journal of Hydrology 38: 49–58.

Hanchi, A., Rapp, M., 1997. Stemflow determination in forest stands. Forest Ecology and Management 97: 231–235.

Huber, A., Iroume, A., 2001. Variability of annual rainfall partitioning for different sites and forest covers in Chile. Journal of Hydrology 248: 78–92.

Jackson, N. A., 2000. Measured and modeled rainfall interception loss from an agroforestry system in Kenya. Agricultural and Forest Meteorology 100: 323–336.

Klaassen, W., Bosveld, F., de Water, E., 1998. Water storage and evaporation as constituents of rainfall interception. Journal of Hydrology 212–213: 36–50.

Klaassen, W., Lankreijer, H. J. M., Veen, A. W. L., 1996. Rainfall interception near a forest edge. Journal of Hydrology 185: 349–361.

Lankreijer, H., Lundberg, A., Grelle, A., Lindroth, A., Seibert, J., 1993. Evaporation and storage of intercepted rain analyzed by comparing two models applied to a boreal forest. Agricultural and Forest Meteorology 98–99: 595–604.

Lemmon, P. E., 1956. A spherical densiometer for estimating forest overstory density. Forest Science 2: 314 – 320.

Liou, Y., Galantowicz, J. F., England, A. W., 1999. A Land Surface Process/Radiobrightness Model with Coupled Heat and Moisture Transport for Prairie Grassland. IEEE Transactions on Geoscience and Remote Sensing, Volume 37, No. 4: 1848–1859.

Liu, S., 1998. Estimation of rainfall storage capacity in the canopies of cypress wetlands and slash pine uplands in North-Central Florida. Journal of Hydrology 207: 32–41.

Liu, S., 2001. Evaluation of the Liu model for prediction rainfall interception in forests world-wide. Hydrological Processes 15: 2341–2360.

Llorens, P., Gallart, F., 2000. A simplified method for forest water storage capacity measurement. Journal of Hydrology 240: 131–144.

Návar, J., Charles, F., Jurando, E., 1999. Spatial variations of interception loss components by Tamaulipan thornscrub in northeastern Mexico. Forest Ecology and Management 124: 231–239.

Penman, H.L., 1948. Natural Evaporation from open water, bare soil and grass. Proceedings of the Royal Society, Series A. 193: 120-145.

Penman, H.L., 1963. Vegetation and Hydrology. Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England. 125 pp.

Rutter, A. J., 1963. Studies in the water relations of pinus sylvestris in plantation conditions I. Measurements of rainfall and interception. Journal of Ecology 51: 191–203.

Rutter, A. J., Dershaw, K. A., Robins, P. C., Morton, A. J., 1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9: 367–384.

Rutter, A. J., Morton, A. J., 1977. A predictive model of rainfall interception in forests. III. Sensitivity of the model to stand parameters and meteorological variables. Journal of Applied Ecology, Volume 14, Issue 2: 567–588.

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. Journal of Applied Ecology 12: 367–380.

Teklehaimanot, Z., Jarvis, P. G., 1991. Direct Measurement of Evaporation of Intercepted Water from Forest Canopies. Journal of Applied Ecology. Volume 28, Issue 2: 603–618.

Valente, F., David, J. S., Gash, J. H. C., 1997. Modeling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. Journal of Hydrology 190: 141–162.

van Dijk, A. I. J. M., Bruijnzeel, L. A., 2001. Modeling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1. Model description. Journal of Hydrology 247: 230–238.

van Dijk, A. I. J. M., Bruijnzeel, L. A., 2001. Modeling rainfall interception by vegetation of variable density using an adapted analytical model. Part 2. Model validation for a tropical upland mixed cropping system. Journal of Hydrology 247: 239–262.

BIOGRAPHICAL SKETCH

Malcolm Lewis Bryant was born in Morgantown, West Virginia, on September 15, 1965. He is a graduate of Vanguard High School in Ocala, Florida. He attended Georgia Southern University from 1983 to 1984 and Central Florida Community College from 1985 to 1987 where he earned an Associate of Science degree in radiation protection. From 1987 to 1998 he worked in the commercial nuclear power industry as a health physics technician and radiological engineer. In 1993 he married his wife, Kim. He earned a Bachelor of Science degree in technology (nuclear) in 1997 from Regent's College in Albany, New York. In 2000 his son, Trevor, was born. He received a second Bachelor of Science degree in civil engineering from the University of Florida in 2001. He enrolled in the Master of Science in water resources engineering in the summer of 2001.