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# The dynamics of rainfall interception by a seasonal temperate rainforest

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**Abstract**

Net canopy interception ($I_{net}$) during rainfall in an old-growth Douglas-fir–western hemlock ecosystem was 22.8 and 25.0% of the gross rainfall ($P_G$) for 1999 and 2000, respectively. The average direct throughfall proportion ($p$) and canopy storage capacity ($S$) derived from high-temporal resolution throughfall measurements were 0.36 and 3.3 mm, respectively. Derived values of $S$ were very sensitive to the estimated evaporation during canopy wetting ($I_w$). Evaporation during wetting was typically small due to low vapor pressure deficits that usually occur at the start of an event, therefore $I_w$ is best estimated using the Penman method during canopy wetting, rather than assuming a constant evaporation rate over an entire event. $S$ varied seasonally, from an average of 3.0 mm in the spring and fall, to 4.1 mm in the summer, coincident with canopy phenology changes. Interception losses during large storms that saturated the canopy accounted for 81% of $I_{net}$. Canopy drying after events comprised 47% of $I_{net}$, evaporation during rainfall comprised 33%, and evaporation during wetting accounted for 1%. Interception associated with small storms insufficient to saturate the canopy accounted for 19% of $I_{net}$. The Gash analytical model accurately estimated both $I_{net}$ and the individual components of $I_{net}$ in this system when applied on an event basis, and when the Penman method was used to compute evaporation during rainfall. The Gash model performed poorly when applied on a daily basis, due to a rainfall regime characterized by long-duration events, which violated the assumption of one rain event per day.


*Keywords:* Douglas-fir–western hemlock ecosystem; Penman method; Gash model

## 1. Introduction

The interception of precipitation (rain and snow) by vegetation canopies is a major component of the surface water balance. Annual net interception losses ($I_{net}$) in temperate forests were observed to range from 11 to 36% of gross precipitation ($P_G$) in deciduous canopies, and from 9 to 48% of $P_G$ in coniferous canopies (Hörmann et al., 1996). The evaporation of intercepted water from forest canopies reduces the amount of water entering the soil profile, relative to other vegetation canopies (Calder, 1998). Land surface changes that alter interception are hypothesized to contribute to increased peak flows following forest harvest (Jones, 2000), and decreased streamflows during afforestation (Calder, 1998). The reduction in infiltration due to interception losses may reduce the risk

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**Nomenclature**

| | |
|---|---|
| $\delta e$ | vapor pressure deficit (Pa) |
| $\bar{E}/\bar{R}$ | ratio of evaporation rate to rainfall rate during saturated canopy conditions (dimensionless) |
| $I_a$ | interception loss during canopy drying (mm) |
| $I_c$ | interception loss during canopy wetting for $P_G < P_s$ (mm) |
| $I_{net}$ | net interception loss (mm) |
| $I_s$ | interception loss during saturated canopy conditions (mm) |
| $I_w$ | interception loss during canopy wetting for events $P_G \geq P_s$ (mm) |
| $p$ | direct throughfall proportion (dimensionless) |
| $P_G$ | gross rainfall (mm) |
| $P'_G$ | gross rainfall required to saturate the canopy (mm) |
| $P_n$ | net throughfall (mm) |
| $R_n$ | net radiation (W m$^{-2}$) |
| $S$ | saturation storage of the canopy (mm) |
| $T_a$ | air temperature (°C) |
| $u$ | wind velocity (m s$^{-1}$) |
| $z_{0,M}$ | roughness length for momentum (m) |
| $z_{0,H}$ | roughness length for heat (m) |

of landslides (Keim et al., in press; Miller and Sias, 1998). Interception also affects biological processes including the spread of plant pathogens (Huber and Gillespie, 1992), and the carbon cycle by reducing soil water content and increasing the risk of drought stress.

Throughfall, or net rainfall ($P_n$) below a vegetation canopy consists of the fraction of $P_G$ that falls directly through the canopy ($p$), the fraction that drains from the canopy before and after the storage capacity of the canopy ($S$) is saturated, and the fraction of $P_G$ diverted to stemflow. Interception losses in closed canopies are largely controlled by $S$, $p$, the ratio of the evaporation rate to rainfall rate during saturated conditions ($\bar{E}/\bar{R}$), and the temporal distribution of $P_G$ that affects the number of canopy wetting and drying cycles. The derivation of these canopy interception and climate parameters is therefore necessary to predict interception losses under variable climate conditions, and to parameterize interception models.

A number of interception studies have been completed in tropical (Asdak et al., 1998; Hutjes et al., 1990; Jetten, 1996; Lloyd et al., 1988), temperate broadleaf (Hörmann et al., 1996; Neal et al., 1993) and temperate conifer forests (Klaassen et al., 1998; Rutter et al., 1971; Valente et al., 1997). The majority of interception studies in temperate conifer canopies have been completed in relatively young plantation forests in Europe (Ford and Deans, 1978; Gash and Stewart, 1977; Gash et al., 1980; Johnson, 1990; Kelliher et al., 1992; Loustau et al., 1992b; Rutter et al., 1971; Viville et al., 1993). Table 1 shows literature values of $S$ for a variety of conifer canopies to illustrate the range of variation between different forests. Most of the canopies listed in Table 1 are relatively young, uniform plantations, whereas the focus of this investigation is on an old, unmanaged, structurally and biologically diverse canopy. More comprehensive summaries of interception losses and canopy parameters can be found in Zinke (1967); Hörmann et al. (1996); Llorens and Gallart (2000). The determination of canopy parameters (e.g. $S$) at temporal resolutions associated with seasonal canopy structure variations is needed to improve our understanding of interception (Loustau et al., 1992a). Most investigations lack sufficiently high-resolution throughfall and detailed within-canopy weather data to assess the influence of temporal changes in canopy structure and within-event weather variations on the evaporation of intercepted water.

Old-growth forests in the Pacific Northwest (PNW) region of the US are characterized by tall canopies, often exceeding 60 m in height, high leaf area indices (LAI), large spatial variation in species diversity and canopy closure, abundant lichen and bryophyte communities, and a large quantity of coarse woody debris (Franklin and Waring, 1980). Annual climate is highly variable in this region, characterized by extended periods of frequent precipitation (mixed rain and snow) in the winter, shorter periods of rain in the spring and autumn months, and isolated, brief rain showers during the summer. Although the effect of a vegetation canopy on snowfall is significant (Pomeroy et al., 1998; Storck et al., 2002) the measurement of snow interception at a remote site is difficult and labor intensive, therefore only rainfall interception is addressed in this paper. Because only rainfall interception is considered in this paper, precipitation

Table 1
Literature values of conifer canopy storage capacities ($S$)

| Canopy type | $S$ (mm) | Height (m) | LAI | Stem density (trees $ha^{-1}$) | Reference |
|---|---|---|---|---|---|
| *Pseudotsuga menziesii* | 2.7–4.3 | 60 | 8.6 | 560 | This study |
| *P. menziesii* | 1.2 | 24 | 12 | na[a] | Rutter et al. (1975) |
| *P. menziesii* | 2.4 | 18 | 9–13 | 800 | Klaassen et al. (1998) |
| *Pinus nigra* | 1.0 | 20 | 5.1 | 600 | Rutter et al. (1975) |
| *Pinus sylvestris* | 1.02 (est.) | 15 | na | 1870 | Gash et al. (1980) |
| *P. sylvestris* | 0.8 | 18 | na | 800 | Gash and Morton (1978) |
| *Pinus* sp. | 0.50–0.55 | 12.6 | 3 | 800 | Loustau et al. (1992a) |
| *Picea stichensis* | ∼2 | 12 | na | 3800 | Hutchings et al. (1988) |
| *P. stichensis* | 0.75 | 12.9 | na | 3600 | Gash et al. (1980) |
| *P. stichensis* | 1.2 | 8.9 | na | 4250 | Gash et al. (1980) |

[a] Not available.

falling during the snowfall-dominated winter months of December, January, February, and March is not evaluated. Canopy parameters derived for younger, predominantly plantation forests are unlikely to be applicable to the complex, highly heterogeneous forests of this region. Consequently, canopy interception models developed and tested in other climates should be validated for the variable PNW climate prior to widespread application in this region.

Previous studies in old-growth Douglas-fir ecosystems in Oregon found $I_{net}$ to be 14% of gross precipitation for the months of October–April, and 24% of $P_G$ for the period from May to September (Rothacher, 1963). Studies of similar canopies on Vancouver Island, BC found annual $I_{net}$ to range from 20 to 40% of $P_G$ over a 5.5-year period (McMinn, 1960). $I_{net}$ from the same stands during the summer ranged from 30 to 57% of $P_G$. Similarly, interception losses in second growth coast redwood and Douglas-fir forests in northern California are approximately 20% of winter $P_G$ (Lewis et al., 2000). Previous old-growth interception studies did not attempt to determine $S$, $p$, or $\bar{E}/\bar{R}$ for these systems. Detailed canopy interception characteristics are needed to improve our understanding of the interception process in these systems, to test generalized models, and ultimately lead to improved hydrologic models.

A variety of empirical, physically-based, and analytical models have been developed to estimate interception losses from climate data. Rutter developed a simple physically-based model of a canopy water balance that allowed estimates of $I_{net}$ to be made from derived or estimated canopy parameters ($p$ and $S$), and wet-canopy evaporation computed using the Penman method (Rutter et al., 1971, 1975; Rutter and Morton, 1977). The Rutter and similar models have been widely applied and tested in a range of environments and conditions (Gash and Morton, 1978; Jetten, 1996; Lankreijer et al., 1993; Schellekens et al., 1999), and have been modified for sparse canopies (Valente et al., 1997). Analytical models that combine the simplicity of the empirical models with a physical representation of the interception process have been developed to estimate $P_n$ from $P_G$ records and estimates of $\bar{E}/\bar{R}$ (Gash, 1979; Gash et al., 1980, 1995). The Gash analytical model was demonstrated to be effective in a wide range of canopies, but requires the determination of canopy cover, $S$, and an estimate of wet-canopy evaporation.

## 2. Objectives

The objective of this investigation was to evaluate the dynamics of rainfall interception processes in an old-growth Douglas-fir–western hemlock seasonal temperate rainforest. This study builds on previous investigations of throughfall in similar canopies (McMinn, 1960; Rothacher, 1963) to determine the key canopy parameters for interception modeling and to evaluate how these parameters change seasonally. Specific goals were to: (1) test the sensitivity of different techniques used to derive $S$ from measured throughfall; (2) determine $p$ and $S$ for individual rain events and explore the effects of event characteristics on interception losses; (3) compare the interception characteristics of this old-growth forest with other forest canopies; (4) quantify the interception components in a PNW old-growth forest; (5) test the validity of the Gash analytical model on a daily and event basis, using several methods to estimate $\bar{E}/\bar{R}$.

## 3. Methods and materials

### 3.1. Site description

This study was conducted at the Wind River Canopy Crane Research Facility (WRCCRF), located within the T.T. Munger Research Natural Area of the Gifford Pinchot National Forest, in southwestern Washington, USA. The site is located on a gently sloping alluvial fan in the Wind River Valley in the Cascade Mountains at 45°49′N latitude, 121°57′W longitude, at an elevation of 367.5 m a.m.s.l. Located within the research area is an 85 m tower crane that is used as a sensor platform for micrometeorological measurements. Rotation of the 87 m crane jib defines a 2.3 ha circular plot where throughfall measurements were conducted. The physical setting, ecological characteristics, and infrastructure of the WRCCRF are described in detail by Shaw et al. (in press).

The site is composed of a 500-year-old forest canopy, dominated by Douglas-fir (*Pseudotsuga menzesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). Understory tree species include Pacific yew (*Taxus brevifolia*), Pacific silver fir (*Abies amabilis*), and vine maple (*Acer circinatum*). The canopy height is approximately 60 m, with the tallest trees reaching 65 m (Ishii et al., 2000). A high diversity of non-vascular plants exist in the canopy, dominated by lichens (∼1.3 t ha$^{-1}$) in the mid and upper canopy and a similar amount of bryophytes in the lower canopy (McCune et al., 1997). Over 3 years, the average leaf area index (LAI) of all species at the site was 8.6 ± 1.1, ranging from 9.3 ± 2.1 to 8.2 ± 1.8 determined using the vertical line intercept method (Thomas and Winner, 2000).

Climate at the site is characterized by cool, wet winters and warm, dry summers, with an average annual precipitation of 2467 mm. Less than 10% of the precipitation occurs between June and September (Shaw et al., in press). Fog is rarely observed at the site, so input of occult precipitation (intercepted wind-driven fog) is assumed to be negligible. Mean annual air temperature is 8.7 °C, with the mean monthly maximum of 17.3 °C occurring in August, and the mean monthly minimum of −0.1 °C in January. The snow-free period below the forest canopy in 1999 and 2000 ranged from 5 April 1999 to 10 January 2000, and from 4 April to 21 December 2000 (Link, 2001). Precipitation during the 1999 and 2000 sampling periods was 62 and 65% of the long-term average, due primarily to a later than normal seasonal shift from dry summer to wet winter conditions.

### 3.2. Throughfall measurements

Throughfall was measured using large roving arrays of automated and manual rain gauges. Using a large number of gauges samples across the range of variability (Kimmins, 1973; Kostelnik et al., 1989; Puckett, 1991), and periodically moving gauges further increases the effective number of sampling points within the plot to reduce errors in throughfall sampling by increasing the number of sampling points within the plot (Lloyd and Marques Filhode, 1988; Wilm, 1943). The array of automated gauges was used to measure interception losses and to derive canopy interception parameters for individual events, and the manual gauge array was used to measure the interception losses over extended periods for model validation. The automated array contained 24 tipping-bucket rain gauges (TE-525I, Texas Electronics Inc., Dallas, TX) equipped with individual data loggers (HOBO Event, Onset Computer Corp., Bourne, MA). Gauges had a 325 cm$^2$ collection area, and were calibrated to record 0.254 mm per tip. The manual array was composed of 44 throughfall collectors, each with a 94 cm$^2$ collection area, and total storage capacity of 400 mm. Studies of throughfall variability in coniferous canopies indicated that approximately 30 gauges are required to sample throughfall to within 5% of the spatial mean (Kimmins, 1973); the number of gauges in this study exceeded this target. The manual array was operated from 8 April to 8 November 1999 and from 30 March to 16 June 2000. The tipping-bucket array was operated from 30 March to 4 December 2000. The total throughfall volumes measured by the automatic and manual arrays differed by 2.1% during the period when both arrays were run concurrently, confirming that the two arrays measured comparable throughfall volumes. Stemflow in old-growth ecosystems was found to be roughly 0.3% of $P_G$ (Rothacher, 1963), therefore we assumed stemflow to be negligible in this ecosystem.

Gauges were located throughout the 2.3 ha circular plot according to a stratified random sampling design to provide even coverage of the entire plot while capturing the full range of variation. Gauges were randomly relocated within the plot every 4–8 weeks depending on the number of rainfall events occurring in the preceding sampling period. The gauges were mounted approximately 1 m above the ground to minimize collection of splashed water and debris, and funnels and tipping buckets were cleaned and leveled after each relocation.

### 3.3. Meteorological data collection

Gross rainfall was measured with a tipping-bucket gauge at a meteorological station located in an open area approximately 500 m to the south of the study site. Additional precipitation instrumentation at the open site included a shielded weighing precipitation gauge (Model 5–780, Belfort Instrument Co., Baltimore, MD) to measure total precipitation (rain + snow), and sonic snow depth sensor (Judd Communications Inc., Logan, UT), recorded at half-hour intervals. The supplemental records were used to validate the tipping-bucket record, and to identify snowfall events, respectively.

Net radiation was measured with a four-component net radiometer mounted at the highest point on the crane, 85 m above the ground (Model CNR-1, Kipp and Zonen Inc., Bohemia, NY). Meteorological stations were installed on the crane tower at 73, 57, 40, 23, and 12 m above the ground. Air temperature ($T_a$) and relative humidity sensors (Model HMP35C, Vaisala Inc., Sunnyvale, CA) were installed in mechanically aspirated Gill multi-plate radiation shields. Wind velocities ($u$) were measured at each station with sonic anemometers (Gill Solent HS and R2, Lymington, UK). The sonic anemometers operated acceptably during low rainfall rates, but data quality was observed to degrade at higher rainfall rates (Paw U et al., in press).

### 3.4. Methods for calculation of interception parameters

#### 3.4.1. Theory

*3.4.1.1. Within-event analysis.* When a rainfall event begins, throughfall is composed entirely of the direct component (i.e. rainfall that has not contacted the foliage), and $P_n$ will increase approximately linearly with $P_G$ at a constant rate <1, until the canopy becomes saturated (Fig. 1). Once the accumulated precipitation required to saturate the canopy ($P'_G$) is reached, an inflection point in the $P_G$ versus $P_n$ plot occurs, and $P_n$ increases as water drips from foliage. After the canopy is saturated, the slope of the $P_n$–$P_G$ curve will be unity if there is no evaporation, will be <1 if evaporation during rainfall is occurring, or may be greater than 1 if occult precipitation interception exceeds evaporative losses.

Throughfall components are described based on the analytical model developed by Gash (1979), where the throughfall during canopy wetting is given by:

$$P_n = pP_G, \quad P_G < P'_G \tag{1}$$

The throughfall after saturation is reached is given by:

$$P_n = pP'_G + \left(1 - \frac{\bar{E}}{\bar{R}}\right)(P_G - P'_G), \quad P_G \geq P'_G \tag{2}$$

$S$ is computed as:

$$S = (1 - p)P'_G - I_w \tag{3}$$

where $I_w$ is the intercepted rainfall that is evaporated during canopy wetting. $I_w$ can either be assumed negligible, estimated using a method such as the Penman formula, or estimated as $(\bar{E}/\bar{R})\ P'_G$ assuming that $\bar{E}/\bar{R}$ is constant throughout the entire event. Constant $\bar{E}/\bar{R}$ during precipitation was typically assumed in many previous interception studies.

*3.4.1.2. Multiple-event analysis.* Canopy interception parameters are commonly derived from the relationship between cumulative $P_G$ and $P_n$ volumes collected on a weekly or event basis (Gash and Morton, 1978; Klaassen et al., 1998; Leyton et al., 1967; Rowe, 1983). Using the simplest method (minimum, or Leyton method), the canopy saturation point is estimated by identifying the inflection point in the

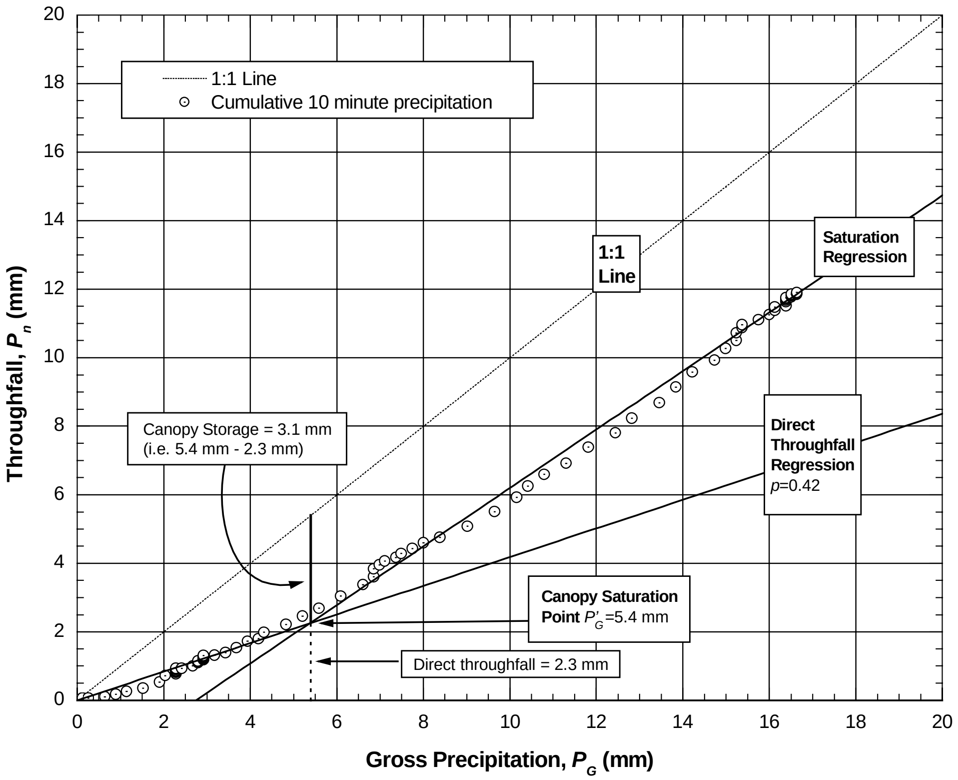


Fig. 1. Example (event 11) plot of data used to determine canopy direct throughfall proportion and saturation storage capacity, assuming no evaporation during canopy wetting. Linear regressions are fit to a scatterplot of throughfall vs. gross precipitation, by optimizing the fit of Eq. (1) and (2).

$P_n$–$P_G$ relation subjectively, and a line of unit slope is fitted to events with minimal evaporation (Fig. 2). $S$ is determined from the intercept on the $x$-axis, and $p$ is the slope of the regression line for all points less than $P'_G$. $S$ can also be computed using an iterative least squares fitting procedure, using Eq. (1) and (2) to optimize the values for $p$, $P'_G$, and $\bar{E}/\bar{R}$ (mean method). Modifications to this method have been made to account for lower evaporation during partial canopy saturation (Gash et al., 1995), however it was shown that this refinement has minimal impact on the derived value of $S$ (Klaassen et al., 1998).

### 3.4.2. Derivation of canopy parameters

For this analysis, rainfall events were defined as occasions when cumulative $P_G$ exceeded 0.5 mm, provided that there was a minimum of 6 h without rainfall between events. Cumulative rainfall records for each gauge and event were evaluated manually to identify gauges that had clogged or failed during an individual event, and the average $P_n$ was computed from all functioning gauges.

Canopy interception parameters were derived using the minimum (Leyton) method relating $P_G$ to $P_n$ for all events measured with the tipping-bucket array in 2000. Interception parameters were also derived from 10 min resolution $P_G$ and $P_n$ records for each event, using the iterative least squares method described above. Canopy storage capacity was determined for each event exceeding 10 mm $P_G$, and preceded by a minimum dry period of 24 h to increase the likelihood that the canopy was dry prior to the event. The 10 mm threshold assured a distinct inflection point for the determination of $P'_G$. To test the sensitivity of $S$ to estimated $I_w$, $S$ was computed from Eqs. (1)–(3) by three methods: (1) $I_w$ assumed negligible; (2)

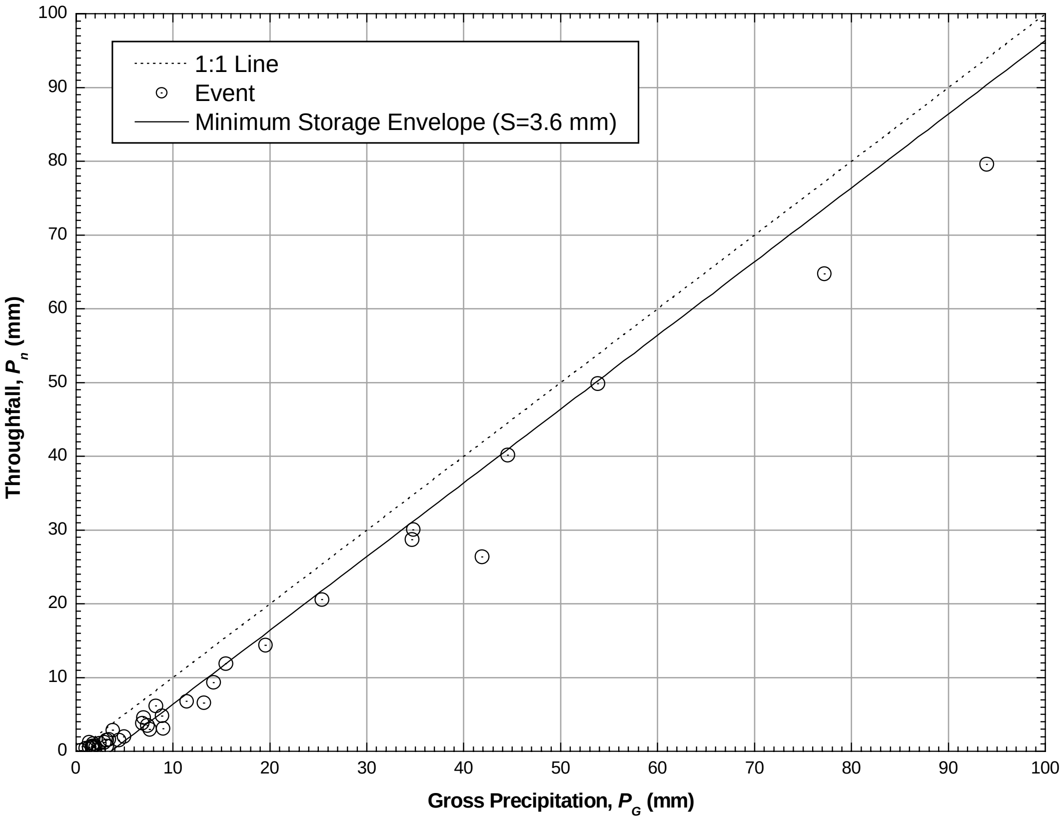


Fig. 2. Canopy saturation storage capacity ($S$) estimated using the minimum, or Leyton method on all rainfall events.

$I_w$ estimated from $\bar{E}/\bar{R}$; (3) $I_w$ computed using the Penman method. The parameters $p$ and $\bar{E}/\bar{R}$ were determined from the regression fits to Eqs. (1) and (2), respectively.

### 3.5. The Gash analytical model

The Gash analytical model of interception can be applied to given estimates of $S$, $p$ (or fraction of canopy cover) and $\bar{E}/\bar{R}$, and measured event or daily rainfall data (Gash, 1979; Gash et al., 1980, 1995). The model typically assumes that: (1) only one event occurs per day; (2) rainfall may be represented by a succession of discrete storms, separated by periods to allow the canopy to completely dry; (3) rainfall and evaporation rates are constant for all periods of rainfall. The model also includes a formulation for stemflow and evaporation of water stored on wetted trunks. In this evaluation, we make the assumption that stemflow is negligible (Rothacher, 1963), and implicitly include the storage associated with branches and trunks into the derivation of $S$.

#### 3.5.1. Interception components

For this investigation, we computed the interception components by applying a simplified version of the Gash analytical model (Gash, 1979), with the assumptions noted above. We used the original formulation of the Gash model rather than the sparse canopy version (Gash et al., 1995) because the values for $p$ and $S$ were derived per unit of ground area. Evaporation during rainfall was computed using the sparse canopy modification discussed by Gash et al. (1999). The amount of interception for $m$ small storms insufficient to saturate the canopy ($I_c$) is computed as:

$$I_c = (1 - p)\sum_{j=1}^{m} P_{G,j} \tag{4}$$

The amount of interception for $n$ large storms with rainfall $\geq P'_G$ is estimated by computing the interception occurring during wetting up of the canopy ($I_w$), the evaporation during canopy saturation ($I_s$), and the evaporation after rainfall ceases ($I_a$), given by:

$$I_w = n(1-p)P'_G - nS \quad (5)$$

$$I_s = (\bar{E}/\bar{R})\sum_{j=1}^{n} P_{G,j} - P'_G \quad (6)$$

$$I_a = nS \quad (7)$$

The net interception loss ($I_{net}$) is computed as:

$$I_{net} = I_c + I_w + I_s + I_a \quad (8)$$

The mean amount of rainfall necessary to saturate the canopy ($P'_G$) is derived from interception theory presented by Gash (1979), and is computed as:

$$P'_G = -\frac{\bar{R}S}{\bar{E}} \ln\left[1 - \frac{\bar{E}}{\bar{R}(1-p)}\right] \quad (9)$$

### 3.5.2. Evaporation

$\bar{E}/\bar{R}$ can be estimated either using the slope of the linear regression relating $P_G$ to $P_n$ when the canopy is saturated, or using the Penman equation (Loustau et al., 1992a; Pearce and Rowe, 1981). For this investigation, we estimated $\bar{E}/\bar{R}$ using both the regression and Penman techniques, and assume $\bar{E}/\bar{R}$ is constant for the entire study period to evaluate the sensitivity of the model to this parameter.

When applying the Penman equation under saturated canopy conditions, roughness lengths for heat and momentum can be assumed to be equal (i.e. $\ln(z_{0,M}/z_{0,H}) = 0$), but then computed evaporation should be scaled by the fraction of canopy cover to prevent overestimation of evaporation (Gash et al., 1999). It has also been suggested that overestimation of wet-canopy evaporation can be avoided by increasing $\ln(z_{0,M}/z_{0,H})$ to a value of 2.0 (Garratt and Francey, 1978; Lankreijer et al., 1993), however the validity of this approach has been questioned (Gash et al., 1999). In this investigation, we computed wet-canopy evaporation using the Gash et al. (1999) approach, and tested the impact of using the latter approach (which assumes a closed canopy). Wet-canopy evaporation using both methods was computed assuming that the zero-plane displacement and roughness lengths for momentum are $0.75h$ and $0.1h$, respectively, where $h$ is the canopy height, and canopy cover is 0.70 (Song, 1998).

## 4. Results and discussion

The results obtained in this study include high spatial and temporal resolution throughfall data and a detailed vertical profile of the meteorological variables that control interception and evaporation during rainfall. The high temporal resolution throughfall data enable the investigation of how saturation storage ($S$) changes over the course of a season in a conifer canopy. $S$ is normally considered to be a constant term in evergreen canopies (Gash et al., 1980; Rutter et al., 1975), but in reality $S$ may vary because LAI varies seasonally with phenological development, and may change as a result of storm damage (Thomas and Winner, 2000).

### 4.1. Within-event weather and rainfall variability

Figs. 3 and 4 show detailed rainfall and within-canopy weather data for events with low evaporation (event 30, Table 3) and with relatively high evaporation (event 15, Table 3), respectively. These figures show the effect of the forest canopy on throughfall intensity, and illustrate conditions that control evaporation during rainfall.

Event 30 (Fig. 3), began at 2100 h on 30 September and lasted 31 h. During this period, over 53 mm of rain fell. The event was characterized by relatively low rainfall intensity, low net radiation ($R_n$) and wind speeds, and very low vapor pressure deficit ($\delta e$). Total interception loss was 4.0 mm, principally from canopy drying following the event. Event 15, shown in Fig. 4, began at 0310 h on 10 May, and lasted 70 h. During this period, over 77 mm of rain fell. This event was characterized by high winds with several brief pulses of intense rainfall, relatively high $R_n$, and a consistent and fairly large $\delta e$.

Both events illustrate the typical time lag of 1–2 h between significant cumulative $P_G$ and $P_n$, associated with wetting up of the canopy (Figs. 3a and 4a). Figs. 3b and 4b show the mean $P_G$ and $P_n$ and the interception storage rate, computed as the difference between $P_G$ and $P_n$. Positive values indicate that the

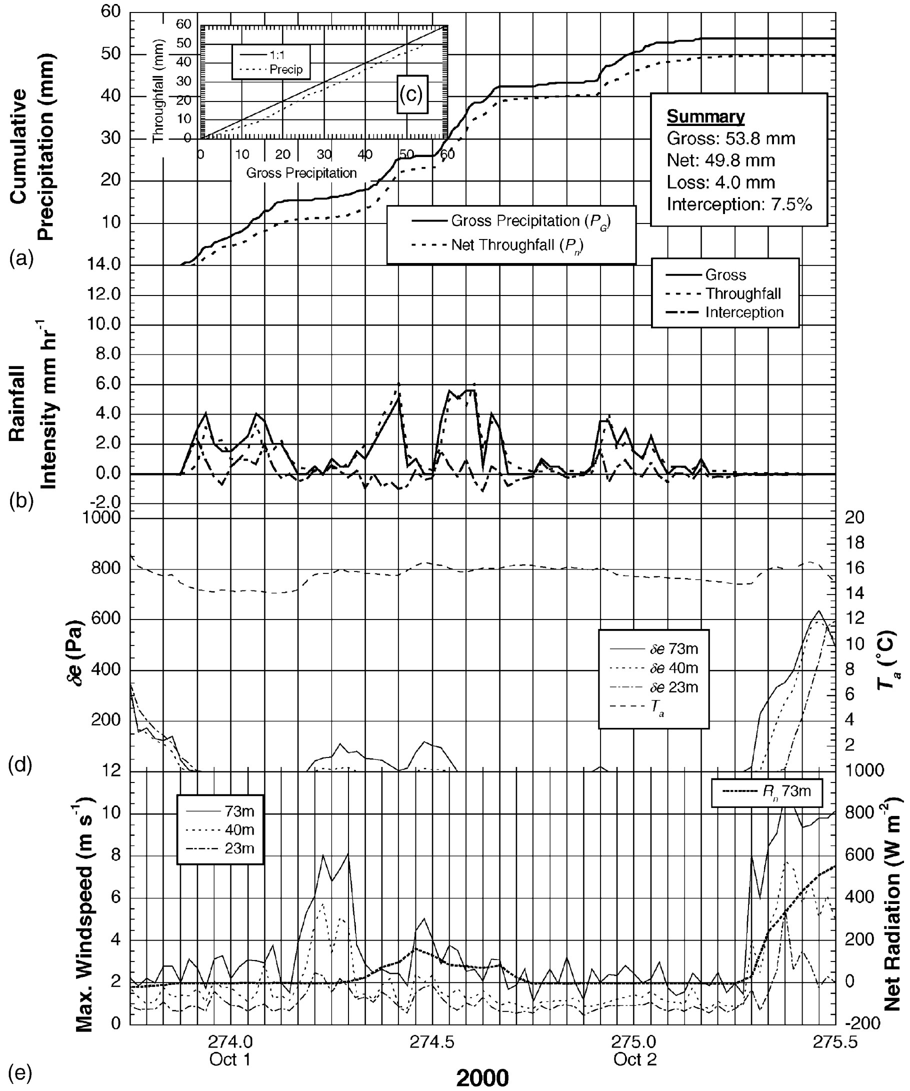


Fig. 3. Detailed meteorological data for a precipitation event with low evaporation (event 30).

canopy was gaining water; negative values indicate that the canopy was losing water. Canopy wetting at the beginning of each event is indicated by a period where the interception rate was positive. Once the canopy was saturated, the interception rate oscillated around zero, probably as a result of a combination of *S* briefly decreasing during high winds and the temporal lag between periods of canopy supersaturation and drainage under varying rainfall intensity. This oscillation was more intense for event 15 which had very high wind speeds and large short-term variation in rainfall intensity, while event 30 showed a more damped oscillation. The dynamic relationship between wind speed and canopy storage has been observed in other detailed studies (Hörmann et al., 1996). While a dynamic relationship between *S* and precipitation intensity has been hypothesized and is included in physically-based interception models (Rutter et al., 1971, 1975), these data are some of the few actual observations of this relationship that we are aware of.

Figs. 3c and 4c show cumulative $P_n$ versus $P_G$ to illustrate the effect of the forest canopy on the vol-

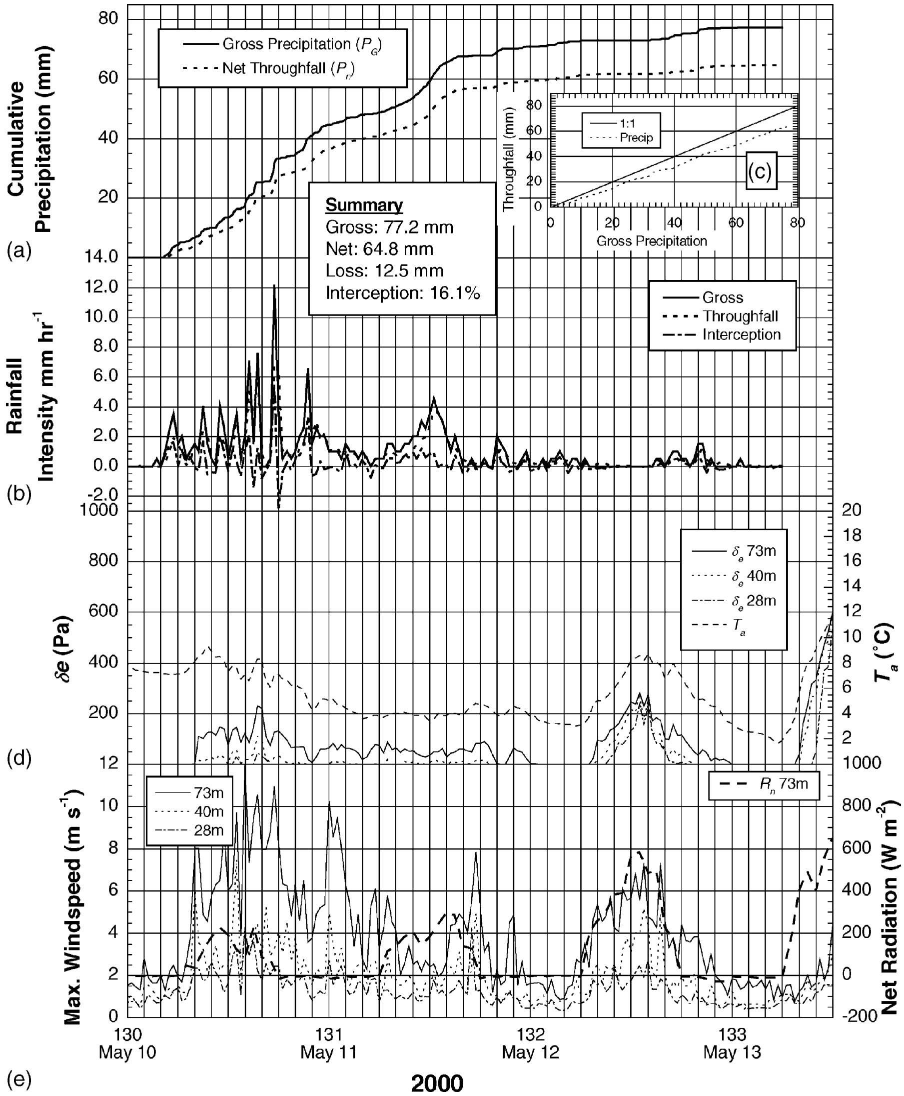


Fig. 4. Detailed meteorological data for a precipitation event with relatively high evaporation (event 15).

ume of throughfall received at the forest floor. The inflection point where direct throughfall shifts to saturated canopy throughfall is evident on both insets. The saturated throughfall line in Fig. 3c has a slope of 1.00, indicating that insignificant evaporation occurred during this event. The significant evaporation that occurred during event 15 is indicated by the slope of 0.86 (Fig. 4c).

Meteorological conditions above and within the forest are shown in Figs. 3 and 4d and e. Figs. 3d and 4d show the air temperature ($T_a$) measured at 73 m, and $\delta e$ at 73, 40 and 23 m. Figs. 3e and 4e show the net radiation measured at 85 m and the maximum half-hourly wind speeds at 73 m, 40 m, and 23 m. Maximum wind speeds are presented because mechanical dislodging of intercepted water is likely to be a function of the maximum, rather than the mean wind speed.

The microclimatic differences that account for there being virtually no evaporation during event 30, and relatively large evaporation during event 15 can be observed by comparing Figs. 3 and 4. During event 30, the saturation deficit ($\delta e$) at 73 m decreased prior to the event, and remained close to zero for the duration of the event. Very small $\delta e$ values at the beginning of events are typical, and are hypothesized to result from evaporating raindrops (Klaassen et al., 1996). Wind speeds are low and the vapor pressure deficit within the canopy was also very small throughout the entire event, indicating that negligible evaporation could occur, as observed in the throughfall record. During event 15, $\delta e$ above 40 m was positive during most of the event, wind speeds were relatively high, and $R_n$ was positive during the day, indicating potential for evaporation. Brief increases in $T_a$ also produced $\delta e$ values that extended through the entire canopy, as occurred during day 132 of event 15. The increases in $\delta e$, coupled with the associated $R_n$ and $u$ increases, caused the canopy to partially dry and rewet during the event, contributing to the interception losses observed in the $P_n$ record.

### 4.2. Throughfall and interception loss

Table 2 summarizes the gross rainfall, throughfall and hence by difference, interception loss for the entire 1999 and 2000 measurement periods. The confidence levels for the mean of the total throughfall percentages for both the 1999 and 2000 measurement periods were within 4% at the 95% confidence level, despite the differences in the sensor arrays. $P_G$, $P_n$, $I_{net}$, and percent losses for the 43 events that occurred in 2000 are presented in Table 3, to show the variability in event characteristics. The confidence level for the mean of the total throughfall percentages for the storms exceeding 10 mm was 10% at the 95% confidence level, due to the smaller number of gauges in the automated array and greater variability over shorter time periods. Spatial variation in throughfall was observed to increase steeply for small events (<10 mm), as was noted in other canopies (Kimmins, 1973), therefore results for the smallest events should be viewed with caution. Estimated $\bar{E}/\bar{R}$ for events exceeding 10 mm are also shown in Table 3. $I_n$ was 22.8 and 25.0% of $P_G$ for the measurement periods in 1999 and 2000, respectively. In 2000, $I_{net}$ was 28.0, 69.4, and 18.0% of $P_G$ for the spring, summer, and autumn periods respectively; these are similar to values obtained in previous studies (McMinn, 1960; Rothacher, 1963). Table 3 shows that interception losses are highly temporally variable, and are correlated with event size, decreasing as event magnitude increases.

The observed average evaporation rate during saturated canopy conditions was 0.14 mm h$^{-1}$, but during events rates were highly variable, ranging from 0.01 to 0.26 mm h$^{-1}$ (not shown). Evaporation rates are similar to those observed in plantation forests, which ranged from 0.03 to 0.24 mm h$^{-1}$ (Rutter et al., 1971). There did not appear to be a relationship between estimated evaporation rate and time of year. Evaporation was closely related to both meteorological conditions and rainfall regime (i.e. continuity and intensity), particularly where the canopy partially dries and rewets during an event, as shown in Fig. 4.

The frequency distribution of individual gauge catch volumes for all events >10 mm is presented in Fig. 5. Of the 237 sampling points, 23% of the gauges recorded throughfall equaling or exceeding $P_G$, due to gaps and drip points in the canopy. This compares with a 3% $P_G$ exceedance found in a young plantation forest (Gash and Stewart, 1977). The difference is probably due to greater heterogeneity and structural complexity of the old-growth canopy.

### 4.3. Canopy interception parameters

#### 4.3.1. Direct throughfall

The advantage of using an array of tipping-bucket gauges to measure the time variation of throughfall is that $p$ and $S$ can be determined for each event to investigate the change in canopy interception parameters

Table 2
Precipitation and interception summary

| Measurement period | $P_G$ (mm) | $P_n$ (mm) | $I_{net}$ (mm) | $P_G$ (%) |
|---|---|---|---|---|
| 8 April to 8 November 1999 | 450.9 | 348.2 | 102.7 | 22.8 |
| 30 March to 3 December 2000 | 618.7 | 398.0 | 155.0 | 25.0 |

Table 3
Detailed interception summary, 2000

| Event | Start (Julian Day) | Duration (h) | $P_G$ (mm) | $P_n$ (mm) | $I_{net}$ (mm) | Loss (%) | $\bar{E}/\bar{R}$ | $S$ (mm) | $p$ (dimensionless) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 95.51 | 2.67 | 0.51 | 0.09 | 0.42 | 82.6 | | | 0.17 |
| 2 | 97.17 | 14.16 | 6.86 | 3.80 | 3.06 | 44.6 | | | 0.17 |
| 3 | 104.48 | 50.16 | 41.91 | 26.38 | 15.53 | 37.0 | 0.34 | 2.7 | 0.38 |
| 4 | 107.14 | 3.83 | 1.02 | 0.40 | 0.62 | 60.9 | | | 0.35 |
| 5 | 112.94 | 6.33 | 4.95 | 2.00 | 2.95 | 59.6 | | | 0.25 |
| 6 | 113.67 | 16.17 | 3.81 | 2.85 | 0.96 | 25.2 | | | 0.19 |
| 7 | 114.51 | 6.50 | 6.99 | 4.58 | 2.40 | 34.4 | | | 0.30 |
| 8 | 116.15 | 15.33 | 19.56 | 14.39 | 5.17 | 26.4 | 0.18 | 2.9 | 0.33 |
| 9 | 118.65 | 30.67 | 13.21 | 6.57 | 6.64 | 50.3 | 0.38 | 2.9 | 0.23 |
| 10 | 122.93 | 7.00 | 1.78 | 0.63 | 1.15 | 64.6 | | | 0.37 |
| 11 | 123.99 | 12.67 | 15.49 | 11.90 | 3.59 | 23.2 | 0.14 | 2.8 | 0.42 |
| 12 | 125.11 | 20.83 | 1.65 | 0.57 | 1.09 | 65.7 | | | 0.34 |
| 13 | 126.06 | 21.17 | 8.89 | 4.77 | 4.12 | 46.4 | | | 0.39 |
| 14 | 129.42 | 12.83 | 4.45 | 1.52 | 2.92 | 65.7 | | | 0.32 |
| 15 | 130.13 | 69.50 | 77.22 | 64.76 | 12.46 | 16.1 | 0.14 | 3.4 | 0.41 |
| 16 | 136.29 | 0.66 | 1.40 | 0.52 | 0.88 | 62.7 | | | 0.35 |
| 17 | 139.85 | 7.83 | 2.41 | 1.08 | 1.33 | 55.1 | | | 0.29 |
| 18 | 147.06 | 9.33 | 7.37 | 3.48 | 3.89 | 52.8 | | | 0.32 |
| 19 | 148.22 | 6.00 | 8.26 | 6.16 | 2.09 | 25.3 | | | 0.36 |
| 20 | 149.19 | 13.67 | 9.02 | 3.09 | 5.93 | 65.8 | | | 0.28 |
| 21 | 158.97 | 15.33 | 3.18 | 1.50 | 1.67 | 52.6 | | | 0.26 |
| 22 | 160.00 | 4.33 | 1.78 | 1.04 | 0.74 | 41.8 | | | 0.55 |
| 23 | 161.57 | 91.67 | 93.98 | 79.56 | 14.42 | 15.3 | 0.12 | 4.3 | 0.58 |
| 24 | 231.61 | 14.00 | 2.29 | 0.07 | 2.22 | 97.1 | | | 0.03 |
| 25 | 246.31 | 7.50 | 3.18 | 0.68 | 2.49 | 78.4 | | | 0.18 |
| 26 | 246.94 | 12.17 | 1.40 | 0.46 | 0.93 | 66.8 | | | 0.32 |
| 27 | 248.62 | 9.00 | 2.03 | 0.53 | 1.50 | 73.9 | | | 0.26 |
| 28 | 252.08 | 31.33 | 7.62 | 2.98 | 4.64 | 60.9 | | | 0.16 |
| 29 | 254.10 | 19.00 | 2.92 | 1.21 | 1.71 | 58.4 | | | 0.30 |
| 30 | 273.88 | 31.00 | 53.85 | 49.82 | 4.03 | 7.5 | 0.02 | 4.1 | 0.64 |
| 31 | 283.41 | 15.33 | 3.43 | 1.63 | 1.79 | 52.3 | | | 0.29 |
| 32 | 287.78 | 8.17 | 1.65 | 0.67 | 0.98 | 59.2 | | | 0.40 |
| 33 | 290.15 | 4.17 | 1.65 | 0.53 | 1.12 | 67.9 | | | 0.29 |
| 34 | 291.90 | 8.67 | 14.22 | 9.30 | 4.93 | 34.6 | 0.16 | 4.0 | 0.32 |
| 35 | 293.87 | 35.83 | 44.58 | 40.14 | 4.43 | 9.9 | 0.04 | 4.1 | 0.48 |
| 36 | 300.26 | 3.67 | 1.91 | 0.73 | 1.18 | 61.9 | | | 0.35 |
| 37 | 301.86 | 36.83 | 25.40 | 20.55 | 4.85 | 19.1 | 0.16 | 2.7 | 0.55 |
| 38 | 309.10 | 20.00 | 11.43 | 6.75 | 4.68 | 41.0 | 0.31 | 2.8 | 0.33 |
| 39 | 310.72 | 9.83 | 1.40 | 1.20 | 0.20 | 14.3 | | | 0.85 |
| 40 | 312.92 | 43.83 | 26.80 | 19.07 | 7.73 | 28.8 | | na[a] | na |
| 41 | 331.68 | 16.17 | 34.67 | 28.70 | 5.97 | 17.2 | 0.13 | 3.2 | 0.50 |
| 42 | 334.94 | 19.33 | 34.80 | 30.04 | 4.76 | 13.7 | 0.13 | 3.6 | 0.37 |
| 43 | 337.13 | 6.00 | 7.87 | 7.08 | 0.79 | 10.0 | | | 0.73 |
| Total | | | 618.74 | 463.79 | 154.95 | 25.0 | | | |
| Mean | | 18.38 | 14.39 | 10.79 | | 45.28 | 0.17 | 3.3 | 0.36 |
| Min | | 0.66 | 0.51 | 0.07 | | 7.49 | 0.02 | 2.7 | 0.03 |
| Max | | 91.67 | 93.98 | 79.56 | | 97.10 | 0.38 | 4.3 | 0.85 |

Approximately 25% of the throughfall array gauges clogged due to heavy litterfall prior to event 40 and were excluded from the analysis, therefore $S$ and $p$ were not computed for this event.

[a] Not available.

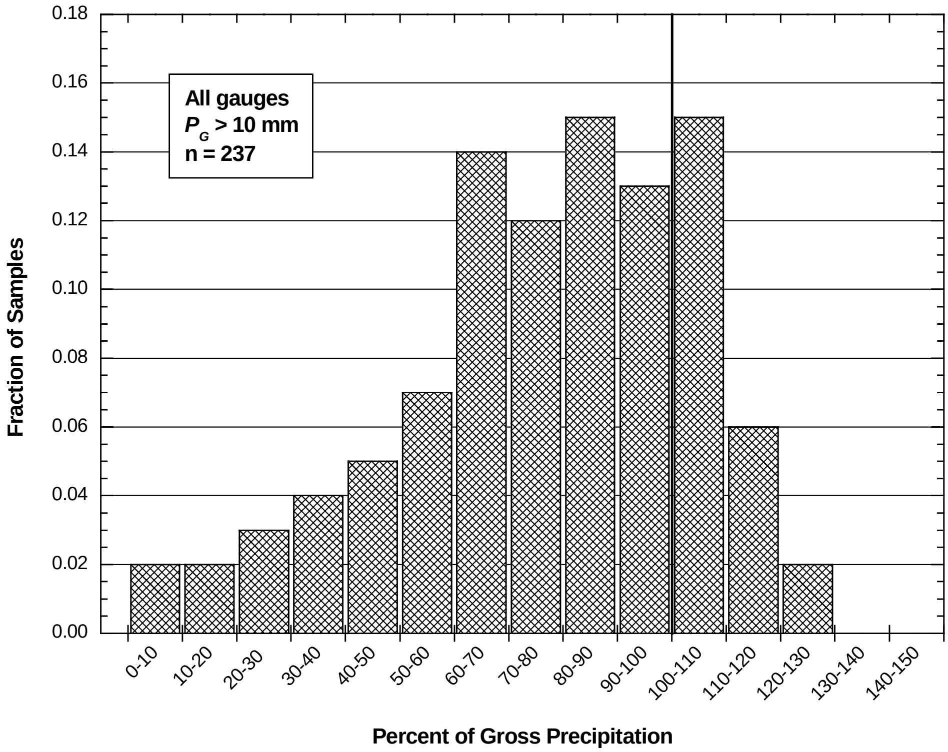


Fig. 5. Frequency distribution of the gauge catch expressed as a percentage of the gross rainfall, for all events exceeding 10 mm. Mean gauge catch for these events is 76.3% of $P_G$.

over time. The mean value for $p$ was 0.36, but $p$ ranged from 0.03 to 0.85 between events (Table 3). The mean value for $p$ was slightly higher than values for plantation forests probably owing to the presence of large gaps and greater structural complexity of the old-growth canopy relative to the more uniform canopy structure of younger plantations.

The frequency distribution for $p$ is shown in Fig. 6. Almost 70% of the values range between 0.20 and 0.50. The canopy gap fraction is frequently used as a proxy for $p$ (e.g. Flerchinger and Saxton, 1989; Jetten, 1996), and is usually assumed to be a static quantity. The canopy gap fraction derived from spatially distributed radiation measurements (Parker et al., in press; Song, 1998) was 0.30, similar to the value estimated from the $P_n$ record. The range of variation in $p$ probably results from variations in raindrop sizes (Calder, 1996) and dislodging of intercepted drops by wind gusts (Hörmann et al., 1996) during periods of partial canopy saturation. No relationship was found between $p$ and time since last rainfall, maximum wind speed, rainfall intensity during wetting, or season. This variability indicates that the assumption of a constant $p$ is frequently incorrect, as rainfall may contact the canopy and be released prior to canopy saturation.

#### 4.3.2. Saturation storage

Canopy saturation ($S$) values computed from (Eq. (3)) when $I_w$ was assumed negligible, estimated from $\bar{E}/\bar{R}$, and estimated using the Penman equation are shown in Table 4. Comparison between the $S$ values computed for $I_w = 0$, and $I_w$ using the Penman method indicate that the assumption of negligible $I_w$ is valid for most events due to very small $\delta e$ during canopy wetting. Several events with sporadic rainfall and high evaporative demand during wetting (e.g. 9 and 23) exhibited larger differences between $S$ computed using the different methods. The assumption of constant $\bar{E}/\bar{R}$ during events is not appropriate during the wetting phase, and may contribute to the observed

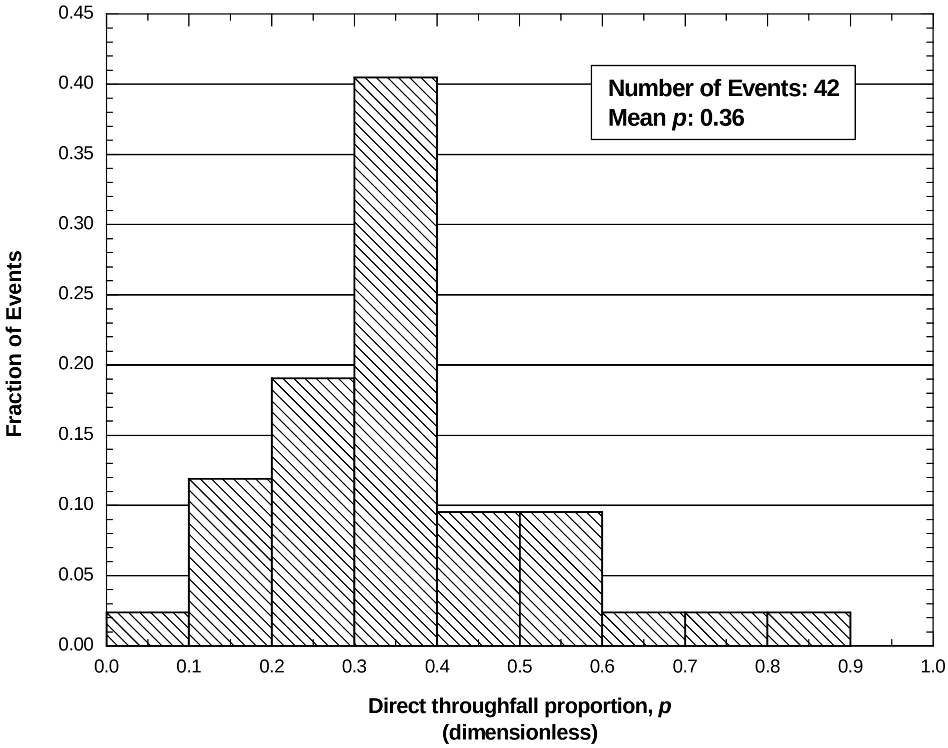


Fig. 6. Frequency distribution of the direct throughfall proportion computed for all events.

Table 4
Saturation storage derivation on 2000 data

| Individual events | $I_w$ assumed negligible $S$ (mm) | $I_w$ estimated as $\bar{E}/\bar{R}$ for $P_G > P'_G$ $S$ (mm) | $I_w$ estimated using the Penman equation $S$ (mm) |
|---|---|---|---|
| 3 | 3.3 | 1.7 | 2.7 |
| 8 | 2.9 | 2.7 | 2.9 |
| 9 | 3.7 | 1.4 | 2.9 |
| 11 | 3.1 | 2.3 | 2.8 |
| 15 | 3.4 | 2.7 | 3.4 |
| 23 | 5.7 | 4.2 | 4.3 |
| 30 | 4.1 | 4.1 | 4.1 |
| 34 | 4.2 | 3.6 | 4.0 |
| 35 | 4.1 | 4.2 | 4.1 |
| 37 | 2.7 | 1.9 | 2.7 |
| 38 | 2.7 | 2.1 | 2.8 |
| 41 | 3.2 | 2.3 | 3.2 |
| 42 | 3.5 | 3.5 | 3.6 |
| Mean | 3.6 | 2.8 | 3.3 |
| All events (technique) | Saturation storage (mm) | | |
| Minimum (Leyton) | 3.6 | | |
| Mean (NLSF on all points) | 3.5 | | |

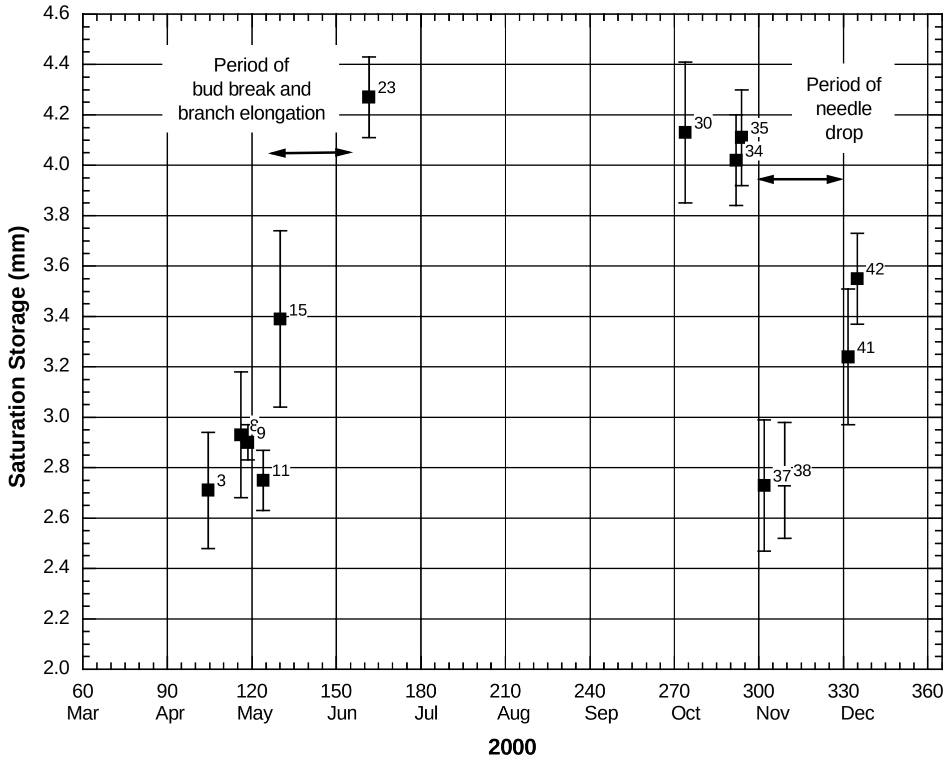


Fig. 7. Temporal variation in the canopy saturation storage capacity ($S$), determined using the regression method shown in Fig. 1. Error bars are determined by propagation errors associated with the parameters $p$, $P'_G$, and $\bar{E}/\bar{R}$, determined by the optimization technique.

underestimation of $S$ when fitting Eqs. (1) and (2) to the full dataset (i.e. applying the mean method described by Klaassen et al. (1998)).

The mean $S$ for the 13 storms large enough to completely saturate the canopy was 3.3 mm, and ranged from 2.7 to 4.3 mm (Table 4). The values for $S$ appeared to be related to season, increasing from an average of 3.0 mm in the spring and autumn to a maximum of 4.1 mm (a 37% increase) in the summer (Fig. 7). Phenological measurements (Shaw, unpublished data) indicate that the rise in $S$ was coincident with the timing of bud break and branch elongation. The timing of the $S$ decrease in autumn was consistent with the timing of seasonal needle drop (Klopatek, pers. commun.). $S$ variations at WRCCRF were also affected by the presence of deciduous understory species (mainly vine maple) that undergo a seasonal change in leaf area of roughly 1.0 $m^2\,m^{-2}$. $S$ may also be affected by the moisture status of other canopy elements such as bark and canopy epiphytes, which may dry at a slower rate than the foliage and therefore absorb less water in the spring and autumn periods which were characterized by low $\delta e$ and shorter intervals between events.

The values for $S$ relative to LAI are particularly large compared to values determined for other conifer canopies (Table 1). The large $S$ probably results from the unique characteristics of PNW old-growth forests. In particular, $S$ is expected to be strongly affected by the abundant bryophyte and epiphyte communities and high storage capacity of the deep, rough bark characteristic of old trees. These results indicate that LAI is a poor proxy for canopy storage capacity in biologically and structurally diverse canopies.

Estimates of $S$ at 65 unique random sample locations were computed to assess the within-canopy spatial variation of canopy storage (Fig. 8). The relationship between the fraction of mean canopy storage and fraction of locations appears approximately exponential, with values much less than $S$ corresponding to canopy gaps, and values much greater than $S$

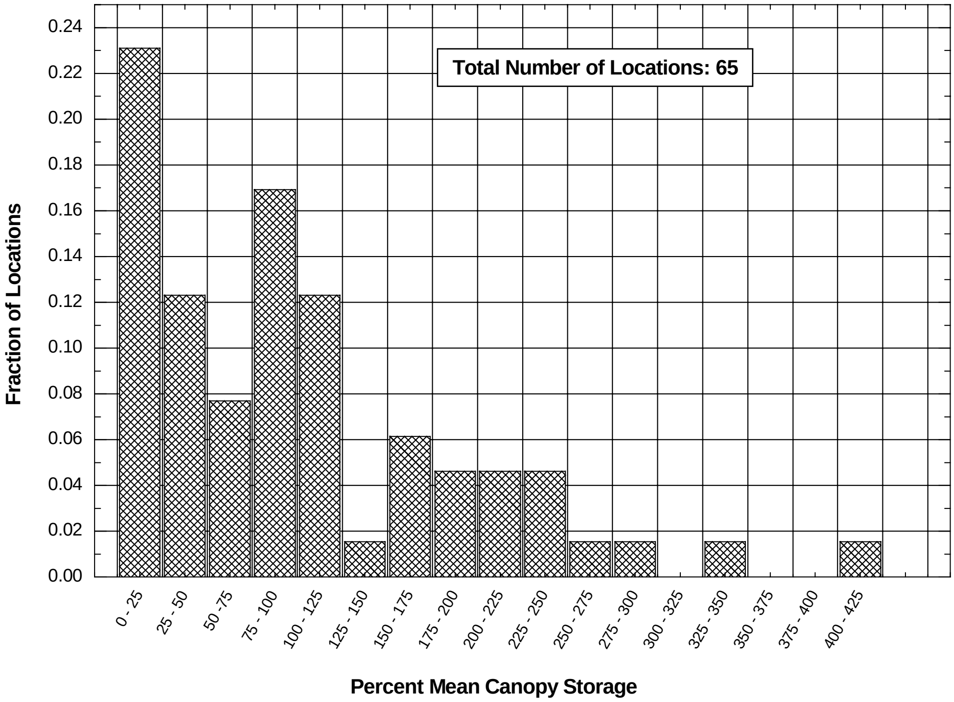


Fig. 8. Variability of canopy saturation storage capacity within the WRCCRF crane circle.

corresponding to dense areas of branch overlap. Assuming $S = 3.3$ mm, the range of variability suggests that over 13 mm of rainfall is necessary to completely saturate all portions of the canopy. The observed curvature at the inflection point in the $P_G$ versus $P_n$ plots probably results from sequential saturation of different portions of the canopy during the wetting phase.

In deciduous forests, wind speed was demonstrated to reduce $S$ by the mechanical shaking of the canopy elements (Hörmann et al., 1996). When computed on an event basis, no relationship was found between $S$ and either the mean or maximum wind speeds during an event in this study. Wind does not appear to be a major factor controlling the interception capacity of the WRCCRF canopy, perhaps because of: (i) lower $u$ relative to more exposed sites; (ii) stronger retention of water by conifer foliage, bark and epiphytes relative to deciduous canopies; (iii) attenuation of wind in the upper portion of the canopy which has a relatively low LAI and correspondingly low storage capacity.

In some conifer forests, $S$ has also been observed to vary dynamically with rainfall intensity, which acts as a proxy for raindrop size/kinetic energy (Calder, 1996). However $S$ at the WRCCRF exhibited no relationship to rainfall intensity during the wetting phase (defined as $P_G < 10$ mm), so we conclude that $S$ was not strongly related to rainfall intensity in this canopy. Raindrop sizes are modified by contact with foliage, so the particularly deep canopy at this site may reduce the dependence of $S$ on intensity by homogenizing the size distribution of raindrops in the upper layers of the canopy prior to contact with the lower layers.

The storage volume per unit leaf area of this canopy was estimated to be $0.4\,\mathrm{mm\,m^{-2}}$. Although we do not explicitly consider the volume of water stored on branch and stem elements, these volumes were implicitly accounted for in the derivation of $S$. Storage per LAI is a common parameter in many hydrological models but varies greatly between models (e.g. $0.1\,\mathrm{mm\,m^{-2}}$ (Wigmosta et al., 1994), $0.2\,\mathrm{mm\,m^{-2}}$ (Dickinson, 1984), $1.0\,\mathrm{mm\,m^{-2}}$ (Flerchinger et al., 1996)). These results will therefore improve the simulation of interception processes in hydrologic models of old, temperate rainforest canopies.

## 5. Testing a simple analytical model

The Gash analytical model of canopy interception can be an effective tool to estimate interception loss provided that it is validated for the environment in which it is applied. Here we test several versions of the model to assess the estimates of the interception components and to identify the most appropriate version for PNW canopies.

### 5.1. Model application

The simplified Gash analytical model neglecting stemflow was applied for the 1999 and 2000 measurement periods to capture all events unaffected by snowfall. The model was applied on an event basis using both the throughfall-estimated $\bar{E}/\bar{R}$ from 2000, and the $\bar{E}/\bar{R}$ estimated using the Penman equation. For the Penman computations we used two assumptions that Gash et al. (1999) found gave reasonable results: (1) that $\ln(z_{0,M}/z_{0,H}) = 0$ (as used for closed forest canopies by e.g. Gash et al. (1999)), and that evaporation was reduced in proportion to canopy cover; (2) that $\ln(z_{0,M}/z_{0,H}) = 2$ (an approximation appropriate for a more permeable canopy (e.g. Lankreijer et al., 1993)), and that there was complete canopy cover. The model was also applied on a daily basis, to assess the errors associated with using this approach. Strong seasonal variation in both rainfall and evaporation rates were not evident, therefore mean $\bar{E}/\bar{R}$ rates, of 0.122 and 0.102, estimated using the throughfall record and Penman equation (sparse canopy assumption), respectively, were assumed for the entire 2000 period. In 1999, the mean $\bar{E}/\bar{R}$ of 0.122 from the 2000 regressions, and $\bar{E}/\bar{R}$ of 0.058 estimated using the Penman method were used. Mean canopy parameters $S = 3.3$ mm and $p = 0.36$ were used for the entire time period. The components of interception loss associated with events $<P_G$ ($I_c$), and with the canopy wetting ($I_w$), saturated canopy ($I_s$) and drying phases ($I_a$) of events $\geq P'_G$ are compared to evaluate the importance of each component of the canopy water balance.

In 2000, interception components were quantified for each event from the high-resolution throughfall records, and summed to determine the seasonal totals. $I_c$ was determined by computing the difference between $P_G$ and $P_n$ for all events $<P'_G$. $I_s$ was determined by computing the difference between $P_G$ and $P_n$ for the time period between $P_G = P'_G$ and the cessation of $P_G$ for all events $>P'_G$. The optimized $P'_G$ and $S$ values computed from Eqs. (1)–(3) were used for events >10 mm, and estimated from the mean $P'_G$ and $S$ values for all events $>P'_G$ and <10 mm (i.e. events for which the inflection point on the $P_G$ versus $P_n$ plot is poorly defined). $I_a$ was computed from the $S$ values either derived for each event, or estimated as discussed above. $I_w$ was computed from the difference between $I_{net}$ and $I_a + I_s$.

### 5.2. Model results and discussion

Results of the Gash analytical model for 1999 and 2000 are presented in Table 5. Interception components $I_c$, $I_w$, $I_s$, and $I_a$ could be measured only in 2000 when the tipping-bucket array was operational. $I_a$ was the largest component of $I_{net}$, comprising approximately half of the total volume, followed by $I_s$ and $I_c$. Evaporation from small storms comprised a larger proportion of interception loss than for sparse canopies (e.g. Loustau et al., 1992a), due to the high $S$ associated with this stand. $I_s$ was relatively large (33%), due to the interaction of relatively high $\bar{E}/\bar{R}$, in a rainfall regime characterized by long-duration storms (Table 3). The relative contributions of the four interception components were very close to the values of 19, 5, 34, and 42%, for $I_c$, $I_w$, $I_s$, and $I_a$, respectively, observed by Gash (1979) in a temperate conifer forest.

The $I_{net}$ estimated with the event-based Gash analytical model, using the Penman-estimated $\bar{E}/\bar{R}$ with both roughness length-canopy closure assumptions closely matched the measured $I_{net}$ values for both years. The sparse canopy approach produced a slightly better estimate of wet-canopy interception loss than the closed canopy approach, although both approaches gave similar results as was noted for denser canopies (Gash et al., 1999). Between storms, the individual components of the interception loss varied from the actual components of interception loss, due to errors introduced by assuming static values for $p$, $S$, and $\bar{E}/\bar{R}$. Relatively good agreement also occurred when using the $\bar{E}/\bar{R}$ estimated from the throughfall record for 2000, however the errors are much greater when applying the 2000-derived $\bar{E}/\bar{R}$ to 1999 (0.122), due to a lower $\bar{E}/\bar{R}$ value for this period (0.058 estimated using the Penman equation). These results also show that mean $\bar{E}/\bar{R}$ values can vary greatly between years,

Table 5
Gash analytical model performance

| Interception component | Measured | | Event, $P_n$ estimated $\bar{E}/\bar{R}$ | | | Event, Penman estimated $\bar{E}/\bar{R}$ | | | | | | Daily, Penman estimated $\bar{E}/\bar{R}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I$ (mm) | Total (%) | $I$ (mm) | Total (%) | Error (%) | $I$ (mm) | | Total (%) | | Error (%) | | $I$ (mm) | Total (%) | Error (%) |
| 1999 | | | | | | | | | | | | | | |
| $I_c$ | | | 37.0 | 29 | | 36.9 | | 35 | | | | 54.7 | 40 | |
| $I_w$ | | | 5.1 | 4 | | 5.1 | | 5 | | | | 6.6 | 5 | |
| $I_s$ | | | 38.1 | 30 | | 18.2 | | 17 | | | | 15.5 | 11 | |
| $I_a$ | | | 46.5 | 37 | | 46.8 | | 44 | | | | 60.2 | 44 | |
| Total, $I_{net}$ | 102.7 | | 126.7 | 100 | 23 | 106.9 | | 100 | | 4 | | 136.9 | 100 | 33 |
| Loss (%) | 22.8 | | 28.1 | | | 23.8 | | | | | | 30.4 | | |
| | | | | | | Option 1 | Option 2 | Option 1 | Option 2 | Option 1 | Option 2 | | | |
| 2000 | | | | | | | | | | | | | | |
| $I_c$ | 28.8 | 19 | 31.2 | 19 | 8 | 31.2 | 31.3 | 20 | 20 | 8 | 9 | 48.2 | 24 | 67 |
| $I_w$ | 1.2 | 1 | 8.0 | 5 | 548 | 8.0 | 8.0 | 5 | 5 | 548 | 649 | 11.7 | 6 | 843 |
| $I_s$ | 51.3 | 33 | 53.9 | 32 | 5 | 45.2 | 39.7 | 29 | 26 | −12 | −22 | 36.5 | 18 | −29 |
| $I_a$ | 73.6 | 47 | 73.6 | 44 | 0 | 73.6 | 73.8 | 47 | 48 | 0 | 0 | 107.0 | 53 | 45 |
| Total, $I_{net}$ | 155.0 | 100% | 166.4 | 100 | 8 | 158.0 | 152.9 | 100 | 100 | 2 | −1 | 203.4 | 100 | 31 |
| Loss (%) | 25 | | 27 | | | 26 | 25 | | | 33 | | | | |

Option 1: assumes $\ln(z_{0,M}/z_{0,H}) = 0$, and Penman ET scaled by canopy cover (0.70). Option 2: assumes $\ln(z_{0,M}/z_{0,H}) = 2$, and complete canopy cover. Only the manual throughfall array was operational in 1999, therefore interception components could not be computed for this period. Fifty nine events, and 65 days with rainfall occurred during the 1999 period (8 April–8 November). Forty three events, and 73 days with rainfall occurred during the 2000 period (30 March–3 December).

and may introduce error when using the Gash model to compute interception loss. These results indicate that the Penman method should be used to estimate evaporation during rainfall if sufficient data exist, due to the between-year variability of $\bar{E}/\bar{R}$.

The daily application of the Gash analytical model overestimated $I_{\text{net}}$ by an average of 32% for the 2 years. The inherent assumptions of the daily application, that only one event occurs per rain day, and that the canopy dries completely between events caused multi-day continuous storms to be parsed into a series of smaller events. As a result, $I_c$ was overestimated due to a greater estimated number of small storms. Estimated $I_a$ also increased due to a larger number of canopy wetting and drying cycles. $I_s$ was underestimated due to a smaller amount of precipitation that was assumed to occur under saturated canopy conditions. Similar errors of 34.6% in $I_{\text{net}}$ were observed for daily application of the model (Hutjes et al., 1990).

The results of the modeling investigation indicate the importance of the precipitation regime in controlling $I_{\text{net}}$ and influencing model performance. If a precipitation season is characterized by a large number of events that are close to $P'_G$, $I_{\text{net}}$ will be relatively large, as suggested by the daily application of the model. Events characterized by intermittent precipitation where the canopy partially dries during an event, will result in larger $\bar{E}/\bar{R}$ relative to continuous events, greater $I_s$ and larger $I_{\text{net}}$. However, if the precipitation regime is characterized by large long-duration events, the fractional loss will be smaller due to a reduced number of canopy wetting cycles. In addition, conditions of prolonged precipitation with shorter dry intervals, may result in lower $I_{\text{net}}$ relative to Gash estimates in cases where the assumption of complete canopy drying between events is violated, and water is retained on canopy elements between events. Although the performance of the analytical model was very good for both 1999 and 2000, the assumption of complete canopy drying between events is likely to be violated during periods with more frequent precipitation and low evaporative demand. The application of physically-based models (e.g. Valente et al., 1997), or an analytical model that explicitly accounts for the temporal variability in rainfall (e.g. Zeng et al., 2000) is likely to be more appropriate during these periods.

## 6. Conclusions

This study indicated that several common methods to derive $S$ from long-term rainfall and throughfall data yield approximately similar results. The storage capacity value for the WRCCRF old-growth canopy was much higher than for plantations of similar species, despite higher plantation LAI values in some instances. This difference may be attributed primarily to the presence of abundant lichen and bryophyte communities in the forest canopy. The high-resolution rainfall and throughfall data indicate that $p$ and $S$, which are frequently considered to be constant terms vary both between events and seasonally. The seasonal change in $S$ appears to result primarily from seasonal LAI changes, but may also be affected by antecedent conditions that affect the moisture status of the canopy elements (i.e. leaves, bark, branches, and epiphytes). Despite these variations, The Gash analytical model was effective in estimating both the magnitude and relative proportions of the interception components when applied on an event basis, and when using the Penman method to estimate $I_s$. Application of the Gash model assuming a constant $\bar{E}/\bar{R}$ or one rainfall event per day, is not appropriate in the PNW climate regime characterized by extended periods of continuous rainfall and variable evaporation during rainfall.

Additional study of interception dynamics of individual canopy elements and layers is needed to further improve our understanding of interception processes in old-growth forests. Lichens and mosses can absorb roughly 6–10 times their dry weight of water (McCune, pers. commun.), and probably play a very important role in rainfall interception, however the interception dynamics of these species are poorly understood. Micrometeorological analyses suggest that evaporation from deep canopy layers should be limited by low $T_a$, $\delta e$ and $u$, whereas upper layers of the canopy may partially dry during events. The assumption that $\ln(z_{0,\text{M}}/z_{0,\text{H}}) = 0$ may be invalid for cases where there is a vertical gradient of canopy wetness, leading to an overestimation of wet-canopy evaporation during these conditions. Measurements of the moisture dynamics of canopy elements, detailed canopy microclimate, and evaporation during rainfall using eddy-covariance techniques, will improve models of how specific canopy elements, intercept, retain, and release water.

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