THE SIGNIFICANCE OF FOREST COVER, TOPOGRAPHIC POSITION AND SOME METEOROLOGICAL VARIABLES FOR THROUGHFALL OF RAIN UNDER A BALSAM FIR FOREST IN WESTERN NEWFOUNDLAND

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by

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Abstract

Throughfall, the process of rainfall passage through a tree canopy to the forest floor, is a major water flux in the forest hydrological cycle. Balsam fir has not been studied for this flux in western Newfoundland where it is the predominant tree species.

Data were collected from June 7 to October 7 1998 to describe throughfall magnitudes and variability. An analysis of variance model was applied to investigate balsam fir forest cover, topographic position and interaction of these factors on throughfall receipt. A sample size of 36 plots for incident rainfall and 36 for throughfall was monitored during the study. Correlative relationships with meteorological variables recorded by a on-site data logger system were also investigated.

Balsam fir forest cover was found to be the predominant variable influencing throughfall flux on a seasonal basis, with the throughfall percentage averaging 85% of incident rainfall over 28 discrete rainfall events. High inter-event variability in throughfall flux was found and is attributed to differences in the character of the rainfall events over the study duration. Topographic position was not significant on a seasonal basis. Significant meteorological influence amongst collections was detected. Air temperature, relative humidity and wind speed were not correlated with the throughfall magnitudes. Weighting of rainfall amounts and intensities did exhibit significant correlation. Analyses of wind direction at the plot level demonstrated significant windward and leeward effects on throughfall magnitudes. The throughfall process was dominated by canopy saturation and

a steady state drip, although minor occult precipitation influences were observed. An exceedance of throughfall over incident rainfall was also observed, indicating the presence of non steady state throughfall regimes for balsam fir forest cover.

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List of Variables and Scientific Units

Variables

C Maximum storage capicity: the upper limit of water that can be held on the forest canopy before shedding or drainage of intercepted rainfall via throughfall or stemflow fluxes occur.

Ic Crown interecption loss: incident rainfall that is intercepted and evaporated from the canopy during a rainfall event and after the cessation of the event.

P_g Incident rainfall: the rainfall quantity measured in a clear unobstructed site at ground level or more rarely above the forest canopy.

P_n Net precipitation: the sum of throughfall and stemflow fluxes.

P_t Throughfall: the intercepted rainfall that reaches the forest floor from direct passage or drip through the forest canopy.

P_s Stemflow: the intercepted rainfall that reaches the forest floor by running down tree trunks

$P_{t(\%)}$ Throughfall percentage: the measured throughfall flux computed as a percentage of measured incident rainfall.

$SP_{t(\%)}$ Standardized throughfall percentage: the recalculation of individual $P_{t(\%)}$ values as a percentage of the maximum $P_{t(\%)}$ value which is reassigned as the 100% value.

Scientific Units

^{o}C Degrees Celsius, used with reference to air temperatures

cm Centimetres, used as a length measure

ha Hectares, used as an area meausre

km Kilometres, used as a distance meaure

km hr^{-1} Kilometres per hour, used for wind speeds

m Metres, used a distance measure

mm Millimetres, used as a depth measure for incident rainfall and throughfall

m s^{-1} Metres per second, used for wind speeds

mm hr^{-1} Millmetres per hour, used as a meaure for incident rainfall intensity.

1.0 Introduction

This thesis examines the throughfall component of the forest hydrological cycle for a representative balsam fir forest in western Newfoundland. Throughfall is the process of rainfall passage through a tree canopy to the forest floor. It may be influenced by (i) the structure of a forest canopy, (ii) ambient rainfall and meteorological conditions, and (iii) topographic conditions. These factors may also interact to influence the throughfall process.

Strategic forest research directions in Canada require study of issues which can contribute to the achievement of sustainable forest management (Natural Resources Canada 1998). The Canadian Council of Forest Ministers (CCFM 1997) indicated that a greater understanding of the forest hydrological cycle is required in support of forest ecosystem management. Studies of rainfall and its process interactions with forested environments are therefore not solely of academic interest. Some key broad-knowledge components related to rainfall and forest interactions that are required for enhancing sound forest management include an understanding of (i) soil formation processes, (ii) soil nutrient cycling, (iii) water supply and quality, (iv) air pollution monitoring of forests, (v) forest growth and timber supplies, (vi) watershed and habitat protection for fisheries and wildlife, and (vii) forest soil conservation. Additionally, these knowledge components require various levels of data resolution at a range of spatial scales to aid development of practical forest management methods, models and policies.

Forest stands of insular Newfoundland are known to have moderate to severe limitations for growth due to inherent soil moisture and fertility properties (Titus *et al.* 1997). Some knowledge of forest soil erodibility conditions in Newfoundland and Labrador is available (van Kesteren 1994, 2000). However, there is no information on forest cover modifications of rainfall receipt for Newfoundland conditions and potential interactions with forest soil resources. Balsam fir is the predominant tree species in western Newfoundland and has not been studied for throughfall water flux. Considering the high level of utilization of the forest landbase in western Newfoundland by the forest industry, significant impacts could result from interactions between rainfall processes and forests. The present work has been undertaken to broaden the knowledge of the throughfall process, to promote a better understanding of the forest hydrologic cycle and to aid development of sustainable management practices for Newfoundland's balsam fir ecosystems. Field data were collected from June 7 to October 7 in 1998 at a study site near Deer Lake in western Newfoundland (Fig. 1.1). These data were used to investigate throughfall variability for two experimental factors (i) forest cover and (ii) topographic position utilizing an analysis of variance model. Inferential hypotheses of no significant throughfall differences for these experimental factors were tested. Additionally, exploratory analyses of throughfall data for potential correlative relationships with selected meteorological variables was completed.

Following this introductory chapter, a review of relevent literature (Chapter. 2) is presented, after which the study area (Chapter. 3) is described and illustrated. Methodological procedures (Chapter. 4) are followed by presentation of all results (Chapter.

5). Results are discussed and analyzed in chapter 6, concluding with an overall summary of findings (Chapter. 7).

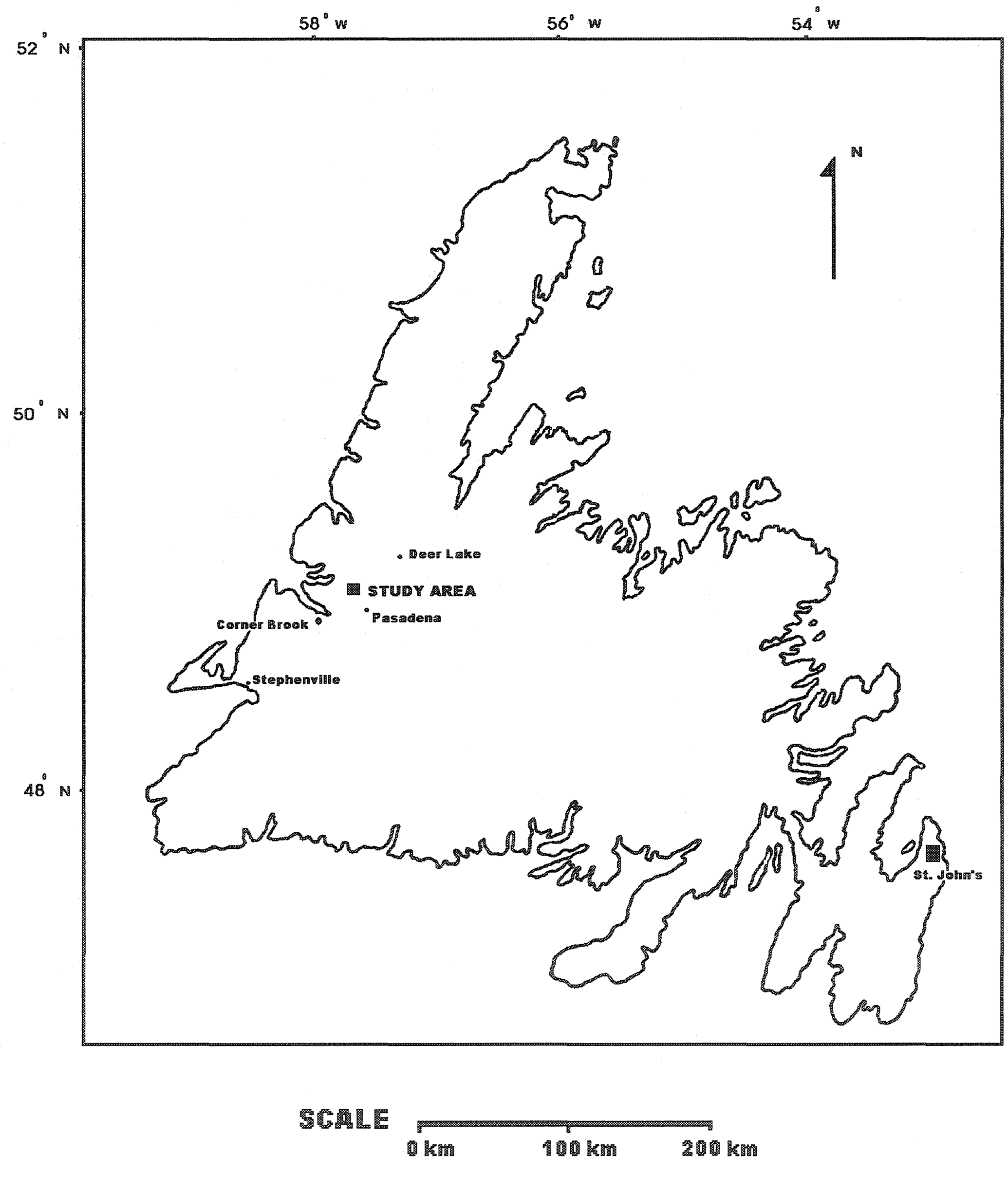

Figure 1.1. The island of Newfoundland showing the general location of the study area.

2.0 Literature Review

This chapter presents an overview of the empirical context of the throughfall process and considerations for field sampling. This is followed by a statement of the study objectives. Relevant literature in relation to the study objectives is then reviewed and followed by a concluding synopsis.

2.1 Empirical Context of the Throughfall Process

A study of rainfall interactions with forested environments, of which throughfall is a key flux, requires application of a robust conceptual framework for investigation and advancement of knowledge of these processes. A brief description and discussion of the processes of rainfall interaction with forests, together with empirical formulation, follows. The primary components of rainfall in a forested environment can be stated in the form of a simple balance equation **[1]**. This balance can be computed for individual rainfall events or for a summation of rainfall events on seasonal, annual or other specified discrete time intervals.

[1] $\mathbf{P_g - P_n - I_c = 0}$ (after Hewlett and Nutter 1969), where $\mathbf{P_g}$ is incident rainfall, $\mathbf{P_n}$ is net rainfall, and $\mathbf{I_c}$ is crown interception loss.

Incident rainfall, $\mathbf{P_g}$, also known as gross, direct or bulk rainfall, is the total quantity of rainfall measured during a specified time interval. Thus, different levels of data resolution, such as hourly, daily or weekly totals can be recorded depending upon instrumentation and scheduling of sample collection. $\mathbf{P_g}$ is usually measured at an open, unobstructed site or, less commonly, above the forest canopy. Measurement sites should be large enough such that the adjacent trees will not unduly influence the gross rainfall catch. The general guideline for open-site rain gauge placement is that the orifice should be at a minimum horizontal distance from the stand edge given by a 45° subtended angle from the dominant canopy height (Hewlett and Nutter 1969). In forested areas such open sites may be difficult to locate and therefore rain gauges should be located at the nearest forest opening; distances exceeding 1 or 2 km, however, would not be suitable.

Crown interception loss, $\mathbf{I_c}$ includes incident rainfall that is intercepted and evaporated during the rainfall event, together with evaporation of crown-retained rainfall after the event. Direct absorption of rainwater into the tree components (eg. absorption by bark) is usually considered to be a negligible component of $\mathbf{I_c}$ (Rutter 1975). Crown interception loss is computed by rearranging equation [1] as follows:

[2] $\mathbf{I_c = P_g - P_n}$

Net rainfall, $\mathbf{P_n}$, is the sum of throughfall and stemflow, where:

[3] $\mathbf{P_n = P_t + P_s}$

Stemflow, $\mathbf{P_s}$, is intercepted rainfall that reaches the ground surface by running down tree trunks. Stemflow includes direct interception of incident precipitation by tree trunks, as well as indirect sources, some of which may reach the trunk due to redirection by suitable branch and crown morphologies. Stemflow is thus computed from rearranging equations **[2]** and **[3]** to give equation **[4]**.

[4] $\mathbf{P_s = P_g - (I_c + P_t)}$

Throughfall, $\mathbf{P_t}$, is the sum of (i) intercepted water that drips through the canopy, eventually reaching the forest floor and (ii) bulk rainfall that reaches the forest floor directly (without interception) through the forest canopy. Throughfall is computed from the rearrangement of equations **[2]** and **[3]** to give equation **[5]**. Throughfall is often expressed as a percentage of incident rainfall (equation **[6]**) to allow for comparison across different tree species or studies of the same species. Incident rainfall, stemflow and throughfall are most commonly measured directly to compute the crown interception magnitude.

[5] $\mathbf{P_t = P_g - (I_c + P_s)}$

[6] $\mathbf{P_t / P_g \times 100\%}$

A related variable upon which crown interception, throughfall and stemflow are dependent is the canopy storage capacity. Maximum canopy storage, represented by $\mathbf{C}$, is the upper limit of water that a tree or tree species canopy can hold without shedding or draining of intercepted rainfall via throughfall or stemflow fluxes. $\mathbf{C}$, when cited for a given tree species, is an estimated magnitude for a forest stand canopy specifically related to its age or other stand conditions. Under conditions of: (i) continuous rainfall from storms large enough to wet the canopy completely, (ii) limited evaporation, or (iii) rainfall events separated by time periods long enough to allow for complete drying of the canopy, $\mathbf{C}$ may be calculated from equation **[7]**, where b is a fitted regression coefficient:

[7] $\mathbf{C} = \mathbf{bP_g} - \mathbf{P_n}$ (Rutter 1975).

As such, $\mathbf{C}$ becomes independent of storm magnitude once the maximum value has been reached and theoretically a steady state will be achieved between $\mathbf{C}$ and $\mathbf{I_c}$ (Leonard 1967). By extension, the throughfall ($\mathbf{P_t}$) and stemflow ($\mathbf{P_s}$) components of net rainfall ($\mathbf{P_n}$) will reach a constant proportion in relation to $\mathbf{P_g}$ as regulated by the maximum canopy storage. This can be illustrated through rearrangement of equations **[3]** and **[7]** to give equation **[8]**, in which $\mathbf{C}$ is assumed to have reached its maximum constant value.

[8] $\mathbf{C} = \mathbf{bP_g} - (\mathbf{P_t} + \mathbf{P_s})$

Under a theoretical condition of no evaporation, the coefficient **b** in equation **[8]** becomes unity and maximum storage capacity and crown interception would achieve equality as expressed in equation [9].

$$[9]\ (\mathbf{C} = \mathbf{P_g} - \mathbf{P_n}) = (\mathbf{I_c} = \mathbf{P_g} - \mathbf{P_n})$$

Evaporative loss is usually not considered to be negligible (Leonard 1967) and interception and maximum crown storage do not achieve equality of magnitudes.

Leonard (1967) presented a theoretical treatment of the interrelationships of crown interception, canopy storage and evaporation (Fig. 2.1). The x-axis on Figure 2.1 represents increasing magnitude of incident rainfall, whereas increasing interception (which is controlled by the evaporation magnitude) appears on the y-axis. The intersection of $\mathbf{I_c}$ and **C** by vertical line ab in Figure 2.1 represents the transition to a steady-state draining of the canopy. This state is also referred to as the waterbox concept, in which canopy wetting must reach saturation before drainage will occur Klassen *et al.* (1998).

During continuous rain, evaporation from dense coniferous (Lankreijer *et al.* 1999) and boreal (Klassen *et al.* 1998) forests is reported as having low magnitude or minor importance in the interception process. Evaporation is considered to reach earlier equilibrium than canopy saturation due to a reduction of vapour pressure deficits and air temperature gradients between the ambient air and foliage surfaces as the canopy becomes wetted during rainfall (Horton 1919; Lenoard 1967). Windy conditions may complicate the steady state condition through an increase of $\mathbf{P_n}$ from canopy movements, enhancing drip and an equal but opposite increase in the evaporative potential (Horton 1919). However, Klassen *et al.* (1996) found that interception was independent of wind velocity, although evaporative potential should be expected to increase, thus suggesting that storage capacities could be wind dependent. Pearce *et al.* (1980) indicated that daytime and nighttime evaporation interception losses during rainfall on a mixed evergreen forest were similar and dominantly controlled by advected energy, not by the radiation balance.

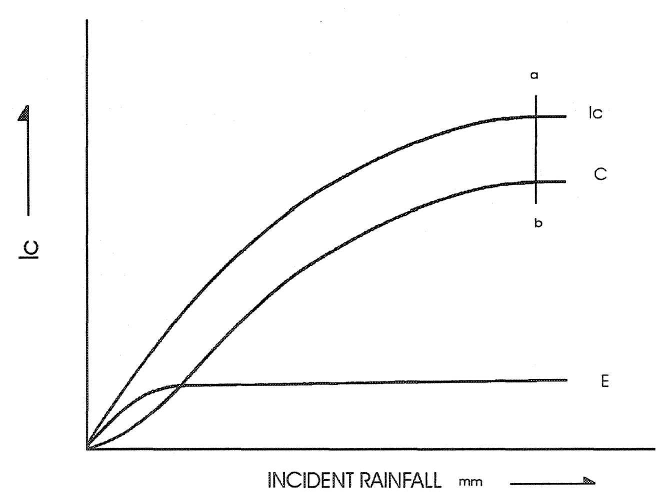

Figure 2.1. Theoretical relationships between incident rainfall, crown interception (**Ic**), maximum crown storage (**C**) and evaporation (**E**) [after Leonard 1967].

Figure 2.1 is also instructive in potentially dealing with the complexity of incident rainfall and its partitioning into the different hydrological fluxes. In this figure, the zone to the left of the ab intersection line hypothetically represents a non-steady state in which there is more inherent variability of the incident rainfall partitioning. Consequently, since maximum storage capacity has not been attained, $\mathbf{P_t}$ and $\mathbf{P_s}$ fluxes will not be a constant proportion of $\mathbf{P_g}$ since the ratio of $\mathbf{I_c}$ to $\mathbf{C}$ is also changing as the incident rainfall increases. However, to the right of intersection line ab, a steady-state relationship of $\mathbf{P_t}$ and $\mathbf{P_s}$ fluxes exists, as regulated through the attainment of maximum storage capacity. Intuitively then, the detection of empirical relationships may be less difficult for steady-state, compared to non-steady state throughfall regimes.

A common approach for modelling throughfall quantity has been through simple linear regression of the form Y = a + bX (Rothacher 1963; Rogerson 1967; Patric 1966; Lawson 1967; Mahendrappa and Kingston 1982; Mathers and Taylor 1983; Viville *et al.* 1992; Spittlehouse 1997). In this approach incident rainfall amount is modelled as the independent (X) variable with the predicted dependent (Y) variable being throughfall quantity. Table 2.1 presents a simple simulated data set to illustrate throughfall modeling.

Table 2.1. Simulated data for throughfall modelling.

$\mathbf{P}_{g(mm)}$	$\mathbf{P}_{t(mm)}$	$\mathbf{P}_{t(\%)}$
0	0	0
10	5	50
20	10	50
30	15	50
40	20	50
50	25	50
60	30	50

Figures 2.2 and 2.3 are derived from plotting of these simulated data.

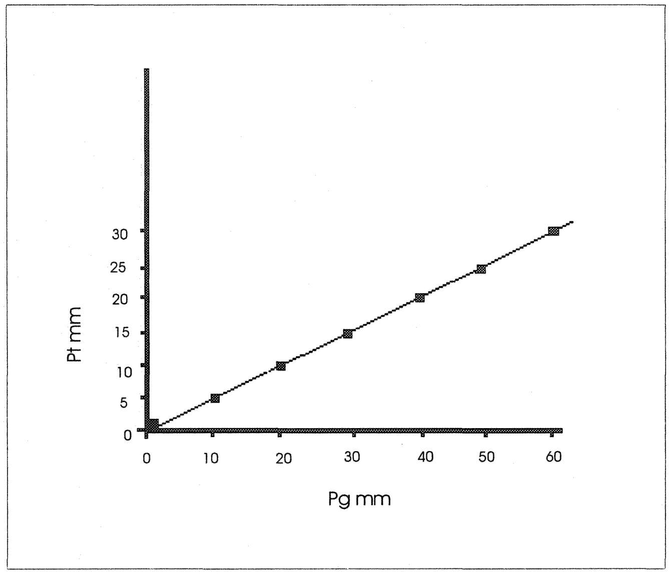

Figure 2.2. Regression of a steady state throughfall process

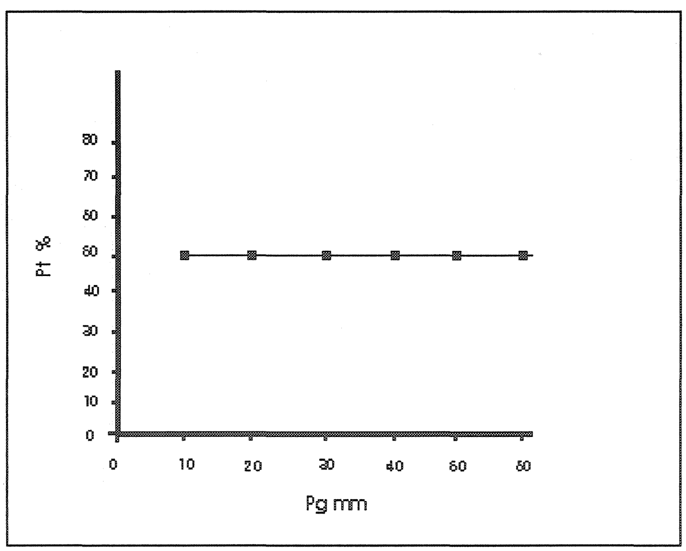

Figure 2.3. Steady state throughfall expressed as a percentage

Figure 2.2 illustrates a theoretical steady state in which there is a continuous throughfall flux responding proportionately to incident rainfall increases. Theoretically, a statistical relationship of Y = 0.0 + 0.5X with an $r^2 = 1.0$ would be achieved between $\mathbf{P_g}$ and $\mathbf{P_t}$ during this process due to canopy storage being maximized. Figure 2.3 illustrates the steady state condition where throughfall is expressed on a percentage basis which remains constant in the simulated data range similar to the right of intersection ab on figure 2.1. However, Mahendrappa and Kingston (1982) indicated scatter and departure from linearity, in a natural balsam fir forest, particularly in the lower end of their regression plots, providing evidence that steady state dynamics may not be the dominant process in all ranges of throughfall data.

The formulation of and derivations for rainfall partitioning do not suggest process and variable complexity. Rutter (1975) noted, however, the complexity of interrelationships between variable rainfall conditions (such as duration, intensity, continuity or intermittency) and interception and storage capacity. Maximum storage capacity in reality represents a complex integration of vertical storage capacities that are dependent on corresponding biomass component distributions within individual trees and aggregations of trees forming a canopy (Hutchings *et al.* 1988). Since evaporation is spatially and temporally variable, wetting and drying cycles can result in varying depths and magnitudes of rainfall penetration into a canopy (Leyton *et al.* 1967). Variations in vertical degrees of wetness can therefore be out of phase with the attainment of maximum storage capacity for full individual trees or a full integrated canopy. This could be of particular importance under conditions of intermittent and/or low intensity rainfall. Canopy storage may be sub-maximal while producing throughfall and stemflow fluxes. This may occur due to high intensity rainfalls enabling passage of primary drops or secondary coalesced drops through a canopy and thus reduction in interception (Calder 1995). In this manner, a pre-saturation canopy drip component of throughfall may restrict the attainment of maximum storage capacity and consequent steady-state drainage of the canopy under differing rainfall conditions. Klassen *et al*. (1998) also indicated that, in dense coniferous forests, storage may be underestimated and evaporation overestimated and that these systematic errors are likely explained by a lack of accounting for canopy drainage before saturation.

Measured point throughfall exceedance of incident rainfall offers an apparent challenge to the balance approach of equation **[1].** Throughfall exceedance was reported by Mahendrappa and Kingston (1982) for a small number of their monitoring gauges and Herwitz (1987) noted the same condition on some measurements. Additionally, Kingston and Harrison (1998) note that throughfall exceedance was common for an isolated oak tree, although caution must be noted for isolated trees versus forested conditions (Hevely and Patric 1965; Horton 1919). However, exceedances can be physically explained by throughfall concentration zones that can develop in canopies under different rainfall conditions (Puckett 1991; Patric 1967). Additionally, Olson *et al.* (1981) reported canopy interception of occult precipitation as a cause of exceedances at a small high elevation study site in New Hampshire.

The balance equation [1] for rainfall in a forested environment can consequently be considered a complex spatio-temporal integration of both incident rainfall and canopy variables regulated through canopy storage capacity, interception, stemflow and throughfall fluxes. The complexity of this integration may arise from relationships that are not necessarily additive functions of individual variables. Given the complexities of inter and intra level feedbacks in the rainfall - forest environment flux partitioning problem, empirical studies generally measure and report estimates of integrated values of many sub-processes.

2.2 Sampling for Throughfall Flux

Sampling methods for throughfall flux estimation are important since they can directly affect data quality and quantity. By extension, throughfall process investigations could be hampered by systematic data errors related to methodological issues. Two primary considerations relating to throughfall sampling can be identified, these being sampling apparatus and sampling design.

Data quality is dependent on the collection apparatus utilized in throughfall studies. Throughfall studies have commonly used two types of collection apparatus. These are funnel type gauges and trough type gauges (Thimonier 1998). The use of standard meteorological rain gauges would be ideal but costs can restrict usage for studies with large sample numbers (Mahendrappa and Kingston 1982). Funnel gauges of an improvised construction are thus more often utilized than standard gauges. Kimmins (1973) notes that a widely varying number of sizes of collector gauges have been used in throughfall studies. This is evident in some literature previously cited with respective funnel orifice sizes reported as 15 cm, 15.2 cm, 29 cm, 11 cm, 7.6 cm, 12.4 cm and 9.9 cm diameters. Small diameter improvised funnel gauges of 6.1 cm and 7.6 cm performed well when tested against standard gauges in open rainfall conditions (Huff 1955; Buchanan *et al.* 1978). Additionally, in throughfall studies for balsam fir in New Brunswick, a small improvised funnel gauge of diameter 6.1 cm was found to perform with no significant difference from standardized meteorological gauges of 9 cm and 10 cm diameters (Mahendrappa and Kingston 1982). Two other studies that addressed throughfall for balsam fir had differing funnel sizes of 19.5 cm and 16.2 cm (Olson *et al.* 1981; Freedman and Prager 1986) but no information regarding comparative performance to standard gauging is reported. A prerequisite before accepting any improvised funnel gauge for throughfall study is that it is of sufficient accuracy. Thus, it would be important to test and calibrate any improvised gauge to assess comparative performance to standard gauges.

Trough gauges have been employed in throughfall studies in an effort to more robustly sample with respect to canopy variations (Thimonier 1998) and to reduce the potential sampling bias associated with concentrated drip points (Kostelik *et al* 1989). However, trough gauges may be subjected to greater evaporative losses due to larger surface area exposure than funnel gauges (Thimonier 1998). Splash errors arising from sloping of the troughs to allow adequate drainage to collection bottles may occur. Trough gauges are also characterized by variable size and are larger than funnel type gauges. Trough gauge sizes cited in the literature for length, width and depth dimensions were 120 cm x 12.7 cm x 15.2 cm (Kostelik *et al.* 1989) and 400 cm x 10 cm x 30 cm (Reynolds and Neal 1991). Clements (1971) reports using trough gauges with an surface area of 645 cm^2, though other dimensions are not given.

Kostelik *et al.* (1989) suggest that funnel gauges could underestimate throughfall flux compared to trough type gauges. Reynolds and Neal (1991) however, concluded from a comparative study that there was no statistically significant difference between the funnel and trough types of gauges and thus little to choose between the types. However, improvised funnel type gauges could offer advantages of simplicity and reduced costs. It appears from the literature that funnel type gauges are in more common usage, which is likely related to such advantages. Leyton *et al.* (1965) report that no general formula was possible for deriving the number and types of gauges for their throughfall studies but measures of statistical reliability of data were essential. It is also noteworthy that the number (Heavly and Patric 1965) and location (Thmonier 1998) of gauges in a study is stated as being more important than the type of gauge for reliable estimation of throughfall flux. Gauge location has been undertaken by three basic approaches, namely

(i) systematic fixed (ii) random fixed and (iii) random roving. In a systematic fixed approach gauges are non randomly assigned to specified locations. This approach can been used to investigate throughfall processes with respect to distances from trees, variation in crown width or other tree scale variables. Useful insights into throughfall variability may be acquired from this system. However, the derivation of probability based relationships from systematic approaches could be limited due the non random locations of the sampling. In a random fixed approach gauges are randomly located and are fixed during the study time frame. The fixed random system approach is suited to the study of individual storms or shorter term variation in throughfall flux (Kimmins 1973; Thimonier 1998) at the stand scale. This approach is generally simple with respect to logistics and is also potentially useful for investigating throughfall process within an inferential and probabilistic framework. The third approach, random roving, has been used to randomly relocate gauge positions after each individual collection. This system can be used with a covariance adjustment procedure to enable data grouping and mean throughfall estimation over a longer term synthesis of collections. Fewer gauges may be required with this procedure but field logistics are more complex due to relocations. Additionally, reduced standard errors around means have been achieved but the mean throughfall estimates themselves may be less accurate than those derived from fixed random approaches (Kimmins 1973).

Case studies investigating issues of sample size estimation for the number of gauges are few

(Thimonier 1998) and rarely has sampling effort for studies been predetermined with respect to actual throughfall variability (Lawerence and Fernandez 1993). Czarnowski and Olszewski (1970) undertook a study investigating the number and spacing or rain gauges under an old growth oak forest. A systematic placement of one hundred gauges was established at 1 meter intervals and individual gauge mean throughfall was computed over twenty six rainfall events. Mean throughfalls were then recomputed from an iterative resampling selection of one to one hundred gauges. A minimal improvement of mean estimation for the full sample of one hundred gauges was achieved for sampling iterations greater than thirty gauges. The authors concluded that a minimum number of thirty gauges could be used in this forested environment to produce mean throughfall estimates with an accuracy of ±3.5% of the one hundred gauge sample. Later, Kimmins (1973) undertook a study in which ninety four gauges were located randomly in a 40 m x 20 m plot. Initially the sample size estimation formulation, $N = t^2 \times cv^2/c^2$ was applied, where N, t, cv and c are, respectively, the estimated number of collectors, students t value for the desired confidence interval, coefficient of variation, and desired confidence interval expressed as a percentage of the mean. This method enabled the maintenance of a constant percentage error while estimated sample numbers changed in response to changes in the coefficient of variation. Large estimated sample sizes resulted when a confidence interval of ninety five percent with an error of five percent of the mean was required. To further investigate the variability of mean throughfall estimation one hundred random iterations of two to ninety four gauge combinations were resampled for means, standard deviations and coefficients of variation.

It was noted that the rate of improvement of mean throughfall estimation within 5%, 10%, and 20% of the true mean value of the ninety four gauges, at a 95% confidence interval, decreased markedly for numbers greater than thirty collectors. This confirmed the earlier findings of Czarnowski and Olszewski (1970) and it was concluded that a sample size of thirty collectors was reasonable, although the standard deviations around the mean could be rather wide.

Kostelik *et al.* (1989) applied the sample size estimation formulation, $n = t^2 (\alpha, n-1) x\ s^2/d^2$, where n, t, s and d are estimated number of collectors, students t value for the desired confidence interval with tail area α and n-1 degrees of freedom, estimated population standard deviation, and acceptable standard error of the mean, respectively. Since n has a mathematical presence on both sides of the equation, these authors proposed that an iterative solution yielding a converging sample size estimate could be undertaken. A sample size of fourteen gauges from six rainfall events was required to give a mean throughfall estimate within ten percent of the true mean with a ninety five percent confidence interval. More recently, Puckett (1991) applied the formulation $N = t^2 \times cv^2/c^2$, initially reported by Kimmins (1973). A method of convergence criteria for successive sample size estimates was also used by Puckett (1991) for five different rainfall events. Sample sizes were estimated at eleven and thirty seven gauges for a mean throughfall estimate within ten and five percent of the true mean respectively, with ninety five percent confidence. Lawrence and Fernandez (1993) also applied the sample size estimation formulation of Kimmins (1973) and reported a sample size estimate of twenty four gauges being required to achieve a mean throughfall estimate within ten percent of the true mean with ninety five percent confidence.

Sample size estimation is in reality not independent of rainfall and canopy structure, since variability of mean throughfall estimates is intrinsically related to the interaction of these factors (Hevely and Patric 1965). Thus, sample size determination could vary by individual collection in comparison to a number of grouped collections. It has also been noted that increasing sample sizes must be considered in terms of improved accuracy versus effort and costs (Thimonier 1998; Mahendrappa and Kingston 1982). Lawrence and Fernandez (1993) indicate that the optimum sample sizes for specified levels of statistical confidence are likely to be site specific due to differences in stand composition, topography and rainfall climate. In that regard, Thimonier (1998) and Kimmins (1973) state the need to undertake pilot studies in order to establish a reasonable sample size estimate specific to given study site and objectives.

2.3 Study Objectives

Four specific study objectives will be addressed by this thesis.

1. To provide knowledge of local throughfall flux magnitude and variability for balsam fir, *Abies balsamea*, the predominant conifer species of western Newfoundland.

2. To utilize an explicit experimental design and inferential hypothesis testing to investigate potential dependence of throughfall flux upon balsam fir forest cover at the stand scale in western Newfoundland.

3. To utilize an explicit experimental design and inferential hypothesis testing to investigate potential dependence of throughfall flux upon microscale topographic conditions in western Newfoundland.

4. To analyze the influence of selected meteorological variables on throughfall receipt for balsam fir and provide progress towards an analysis framework for these relationships.

2.3.1 Objective 1 - Throughfall flux for balsam fir

The literature review did not reveal any case studies that reported throughfall conditions for balsam fir, *Abies balsamea*, for Newfoundland, which is the predominant conifer species of the insular portion of the province. Consultation with a knowledgeable researcher confirmed the lack of such data regarding this species for Newfoundland (Roberts, B.A. pers. comm. 1997). Three case studies reported throughfall data for balsam fir in naturally developed stand conditions. Mahendrappa and Kingston (1982) and Freedman and Prager (1986) conducted work in the Maritime provinces of Canada while Olson *et al.* (1981) reported work in the eastern United States. Other throughfall studies concentrated predominantly on coniferous plantation and thinned stand conditions in North American and European locations.

2.3.2 Objective 2 - Forest cover

Forest cover can be broadly defined as an extensive continuous area of land dominated by trees of a given lifeform such as coniferous or deciduous species. There is general consensus that forest cover is a major factor contributing to differences in bulk rainfall partitioning (Parker 1983). Thimonier (1998) indicated that variability of throughfall measurements possesses a spatial component with two levels of resolution: (i) the tree scale and (ii) the stand scale. In reality these two scales can form a continuum, with throughfall estimation and modelling for stand scales often being empirically derived from plot measurements at the tree scale. A distinction for the tree scale should be noted if throughfall study is made on individual or isolated trees. In such cases, with more exposed trees, results of rainfall partitioning studies may differ markedly from those results from denser forests (Horton 1919, Zinke 1967).

The tree scale provides a useful level of integration since it is discrete and can be used at a lifeform level of coniferous or deciduous tree cover as well as utilizing genera and species classification. At the tree scale a consideration of differing biomass components can help in the understanding of differences in throughfall magnitudes. Horton (1919) and Leonard (1967) recognized that differing species exhibited distinct water retention and flow patterns related to foliage characteristics such as venation patterns, shape and size, surface roughness, orientation within canopy and phenological development. The way that foliage interacts with ambient micro-meteorological conditions thus becomes an important factor influencing incident rainfall partitioning. Leonard (1967) for example, indicated that a large heavily veined leaf in cool still air will have maximum storage capacity. Twig and branch morphology and their structural arrangements are no less important and salient differences are present with respect to lifeform, genera and species of trees (Puckett 1991). Herwitz (1987), for example, has shown that branch inclination angles of tropical trees are of primary importance for stemflow and throughfall generation. Individual biomass components will also summate to the tree scale and these components can be expected to have quantifiable relationships with the individual tree sizes. For example, Lavigne (1982) derived prediction equations for biomass components of major Newfoundland tree species using tree height and diameter breast height as independent variables.

Individual trees can be aggregated to form forest stands which are homogeneous and distinguishable units with respect to some given classification criteria (Smith 1962). Forest stands can be defined on the basis of species composition and mensurational characteristics which are related to autecological and synecological requirements. Thus, for example, stands of the same tree age could be characterized by differing species mixes, densities, diameter and height distributions. Forest stands can be expected to be characterized by some point to point internal variations at the tree scale. However, such variations should not exceed the limits of the stand classification criteria. Additionally, forest stands can be silviculturally originated through reforested and afforested plantations or through manipulation of natural stands. An example of a natural stand manipulation would be a stand thinning to a consistent tree spacing and stem density which significantly alters its natural tree scale physiognomic variability. Differing natural or silviculturally manipulated stand characteristics could be expected to result in significant differences in rainfall partitioning. Considering the inherent difficulties of field isolation of individual biomass components and development of appropriate measurement methods, it is not surprising that studies have predominantly concentrated on incident rainfall partitioning with respect to lifeform, genera and species differences at the tree and stand scales.

The most common forest cover relationship investigated at the tree scale was that of distance from tree stems and measured quantity of throughfall. Clements (1971) stated that the quantity of throughfall can be expected to increase with increasing distance from a tree stem and is also potentially influenced by crown density (Puckett 1991). Most tree scale studies have been undertaken in plantation and thinned stand conditions. Higher throughfalls with increasing distance from individual trees have been reported by Beier *et al.* (1993), Pederson (1992), Bouten *et al.* (1992), Johnson (1990), and Reynolds and Henderson (1967), for Norway spruce, Skita spruce, Douglas fir, larch and beech, respectively. Conversely, for Norway and Sitka spruce, Seiler and Matzner (1995) and Ford and Deans (1978) found relationships of decreasing throughfall with increasing distance from trees. Loustau *et al.* (1992) found no significant throughfall relationship to stem distance for thinned maritime pine. In naturally developed black spruce in Ontario, Carelton and Kavanagh (1990) reported consistently lower throughfall close to tree trunks and the highest below mid crown position. Herwitz (1987) found higher throughfall magnitudes occurred closer to the stems of three tropical rainforest species, attributed to insloping branch patterns. Studying an isolated oak tree King and Harrison (1998), observed a general increase in throughfall with distance from the stem. Johnson (1990) reported mean throughfall significantly decreased for canopy densities of greater than seventy percent in a Sitka spruce plantation. Rogerson (1967) demonstrated that tree density, expressed as basal area, in a loblolly pine plantation was a significant predictor variable for throughfall magnitudes. Significant positive correlations were reported between crown densities and throughfall in dense old growth Douglas fir stands (Rothacher 1963). Differences in species, stand conditions, experimental designs and rainfall climates have likely contributed to the variability exemplified by these studies at the tree scale.

Only two studies investigating throughfall variability at the stand scale were encountered. Loustau *et al.* (1992) found a negligible effect on mean throughfall from the spatial distribution of stems in a maritime pine plantation. Similarly, Neal *et al.* (1991) working in a beech plantation found that throughfall differences were related to plot to plot differences and not spatial effects.

2.3.3 Objective 3 - Topography

Linacre (1992) and Hutchinson (1970) noted the influence of terrain variables, in particular elevation and landform, on incident rainfall receipt at varying scales. The spatial domain of rainfall amounts and intensities at smaller resolution scales over a wide range of climates and physiographic conditions has emerged as an important research topic (Berndtsson and Niemczynowicz 1988). Sharon and Arazi (1997) noted that small scale local topographic influences have received much less attention than rainfall dynamics related to larger – scale orographic affects. Corbett (1965) recommended the use of topographic facets defined on the basis of uniform slope and aspect criteria relative to specified scales of delineation for rainfall monitoring in forested watersheds. In watersheds with large elevational differences facets should also be differentiated considering elevational zonation. Similarly, De Laine

(1969) recommended monitoring with random rain gauge placements within distinct topographically stratified subcatchments to account for rainfall variability.

A limited number of case studies investigating the effect of microscale topographic features on incident rainfall was found during the review. In an earlier study in the San Gabriel Mountains of California, Burns (1953) reported that elevation, aspect and slope were correlated with annual precipitation amount over an elevation range of 485 to 1636 m. James (1964) reported a windward reduction and a leeward increase in rainfall receipt for a small hill rising from 121 m at the base to 182 m in western Oregon. No rainfall variability was reported for a ridge and valley with relief of 106 m oriented perpendicular to the prevailing wind flow in the interior of New Brunswick, Canada (Dickison 1968). Jackson (1969) concluded that in a 500 ha coastal catchment in Tanzania with elevations ranging from of 53 m to 114 m, storm track passage was the primary control over rainfall variability, with no relationship to local relief differences. In a rugged forested catchment of 90 hectares, Jackson and Aldridge (1972) reported patterns of rain gauge catch for some individual storms associated with wind direction and elevation in a small catchment near Wellington, New Zealand. A study by Sharon and Arazi (1997) reported detection of fine scale rainfall distributions in relation to local wind fields in an eight hectare valley with hilly topography and an available relief of one hundred meters in the interior of Israel. Bradley *et al.* (1998) reported windward decrease and leeward increase in rainfall receipt attributed to changes in wind speed distribution in the presence of an isolated hill feature of 300 m in relief on a small isolated South Pacific island. Thus, variable findings on interactions between microscale topography and wind, as influencing incident rainfall receipt, have been noted (Poreh and Mechrez 1984). Resolution of instrumentation, monitoring and data treatment, as well as differing local topography of study sites, could account for such variability. Recent studies have had success in detecting and modelling wind-topographic interaction effects on incident rainfall. For example, Stow and Dirks (1998) utilized specialized high resolution electronic gauging. In contrast, studies which utilize low resolution and manual rain gauges may not always detect variability of incident rainfall related to terrain and wind interactions.

2.3.4 Objective 4 - Meteorological conditions

The potential dependence of throughfall on meteorological conditions has been noted, but a consistent and robust treatment was not evident in the scientific literature. Inter and intra storm wetting and drying of canopies and precipitation parameters of individual storms or rainy days, for example, may influence throughfall flux (Schulze 1978 *et al.*; Leyton *et al.* 1967). Studies often report coarse resolution, lumped P_t values of weekly or longer duration samplings. King and Harrison (1998) noted however, that data measured and averaged at coarse resolutions can restrict detailed analysis of throughfall variability in response to meteorological conditions during individual storms.

A commonly reported meteorological relationship was the linear increase of absolute throughfall magnitudes with increasing quantity of incident rainfall, modelled through regression equations. Coefficients of determination of 0.96, 0.93 and 0.87 have been reported for old growth Douglas fir, balsam fir and mixed hardwood, respectively (Rothacher 1963; Mahendrappa and Kingston 1982; Mathers and Taylor 1983). Regression equations have also been reported for western hemlock and Sitka spruce, white pine and tropical rainforest species but coefficients were not given (Patric 1966; Hevely 1967; Herwitz 1987).

Rainfall intensity has also been indicated as a potential variable that can influence throughfall magnitudes (Kostelik *et al.* 1989). Mathers and Taylor (1983) reported that mean rainfall intensity was not a significant correlate or predictor of throughfall magnitude in a multiple correlation and regression approach. Mean rainfall intensity or maximum rainfall intensity in combination with incident rainfall, did not result in a significant improvement of throughfall prediction (Lawson 1967). However, Rogerson (1965) reported a small increase in throughfall predictability by including the rainfall intensity as a prediction variable. In British Columbia, short duration high intensity storms were reported to have less interception loss, and thus greater throughfall magnitudes than longer duration low intensity storms for the same incident rainfall (Spittlehouse 1997).

Canopy drying and resulting throughfall magnitudes may be influenced by air temperature.

Mean air temperature during rain events was not correlated with the magnitude of throughfall (Mathers and Taylor 1983). Lawson (1967) reported that inclusion of the long term mean air temperature for the day on which a storm occurred increased the significance of throughfall prediction when used in combination with incident rainfall of the storm.

Mathers and Taylor (1983) reported that mean wind speed and direction were not correlated with the magnitude of throughfall. Klasen *et al.* (1996) reported that wind velocity during rain had no statistically significant effect on throughfall magnitude measured at a forest stand edge in the Netherlands. King and Harrison (1998) reported a general trend of outward radial increases of throughfall under an isolated oak tree in England with patterns related to upwind and leeward effects of differing wind directions.

2.4 Synopsis

A substantial body of literature has investigated throughfall from the disciplinary context of forest ecology and forest soil nutrition. However, studies examining physical and geographic influences on throughfall flux are rare. Sampling apparatus and methods for throughfall measurement are generally well developed. Leyton *et al.* (1967) indicated the apparent ease with which empirical estimation of throughfall fluxes can be achieved through direct measurement. Consequently, a reasonable understanding of the physical process, as described by equation **[5]**, has been achieved. However, Kimmins (1973) and

Rogerson (1967) indicated that studies infrequently report throughfall variability in relation to study area and forest stand characteristics. An *a priori* stance that mean throughfall magnitudes will be significantly different than mean incident rainfall magnitudes is assumed in the studies reviewed. However, under differing stand and rainfall conditions this may not be the case and comparison of throughfall and incident rainfall remains as an important research consideration. Additionally, papers citing throughfall investigation for balsam fir documented few details of throughfall variability (Mahendrappa and Kingston 1982; Olson *et al*. 1981; Freedman and Prager 1986). In the experimental design of throughfall studies, topographic variables were not included and few examined meteorological variables. Consequently, designs that consider forest cover variability in isolation of terrain influences and meteorological conditions have neglected some important potential variable interactions influencing throughfall flux.

3.0 Study Area Location and Description

This chapter describes the salient features of the physical environment, climatic character and forested terrain of the study area. Maps and photographs are included to supplement descriptions and to demonstrate the suitability of the area for addressing the study objectives.

The study was undertaken in western Newfoundland, northeast of the city of Corner Brook (Fig. 1.1). Figure 3.1 portrays the regional setting of the study area on the western margin of the Deer Lake basin. Deer Lake is of geological origin, with alignment accordant with structural grain, and subsequently modified by glacial deepening (Yoxall 1981). The bedrock geology of the study area consists of undivided sedimentary rocks and greenschist emplaced by the Middle Ordovician (Hibbard 1985). Surficial geology has been classified as morainal veneer over hummocky bedrock complex with minor outcrop exposures (Wells *et al.* 1972; Kirby *et al.* 1992). The dominant soils are gleyed humo-ferric and orthic ferro-humic podzols (Kirby *et al.* 1992; Wells *et al.* 1972). The hummocky surface expression is observable from the general contour pattern (Fig. 3.2). Local relief within the immediate study area is of the order of tens of metres with a general southwest to northeast downward summit trend. The study area elevations range from 380 masl to a maximum of 457 masl (Fig. 3.2). Regionally within the western Newfoundland ecoregion, elevations generally reach 750- 800 masl, with summits above treeline throughout (Damman 1983). Only two summits reach elevations above 800 masl.

Figure 3.1. Regional setting of the study area ■ displayed on National Topographic Series Map 12 H – Sandy Lake.

Figure 3.2. Local setting and study site location □ displayed on National Topographic Series Map 12 H/4 – Pasadena.

The study site for this research was selected because the local terrain is characterized by relatively uniform hilly topography with homogenous balsam fir stands, recent clearcuts and a suitable location for placement of a near-surface meteorological tower (Figs. 3.3 and 3.4). Preliminary interpretation of aerial photos was undertaken in March 1997, followed by a reconnaissance investigation of the study area in late May 1997. Two contrasting cover type areas representative of the regional hilly terrain were selected for the full study design. One was a logged clearcut suitable for sampling incident rainfall receipt, the other was a uniform mature balsam fir forest suitable for throughfall determination. These two areas were then stratified on the basis of local topographic conditions (Figs. 3.4 and 3.5). Side slopes and summits were delineated through interpretation of aerial photographs at an original scale of 1:12,500, applying the method demonstrated in van Kesteren (1996). A site was selected for the establishment of a 3-m high meteorological tower supporting selected instrumentation. Clearcut harvest conditions that had occurred in 1990 are evident through comparison of Figs. 3.3 and 3.4.

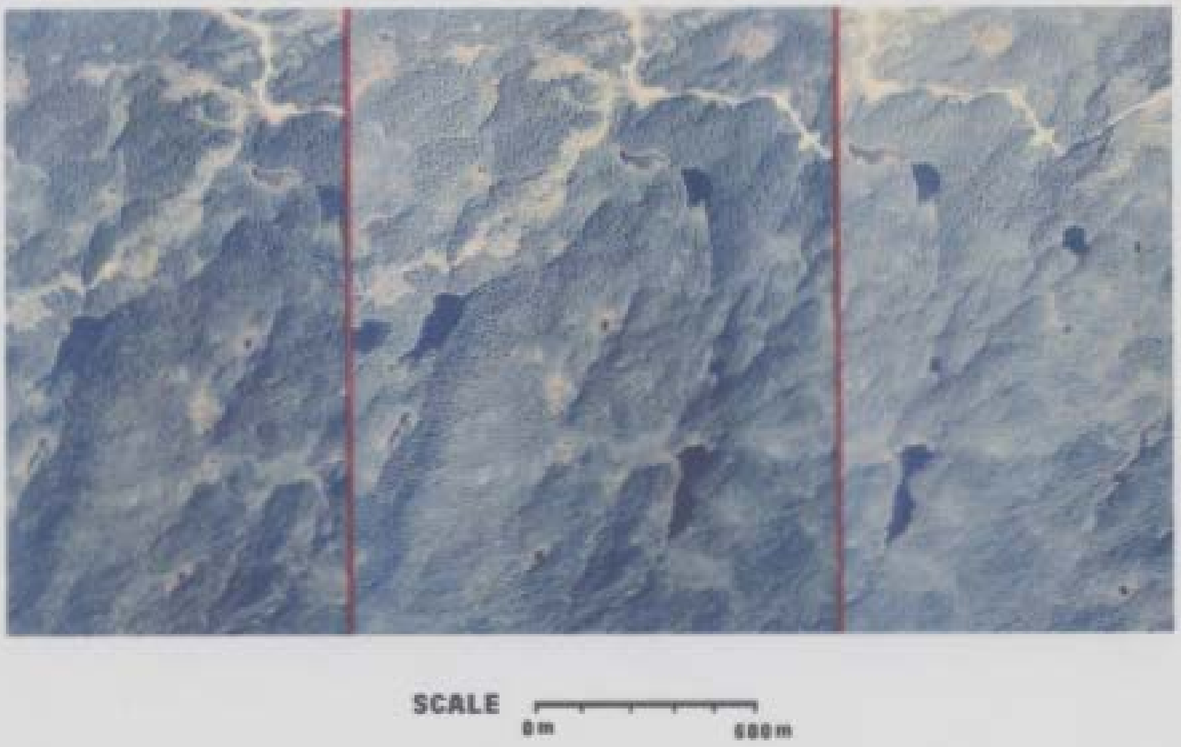

Figure 3.3. Stereogram of the study site before clearcut harvest operations.

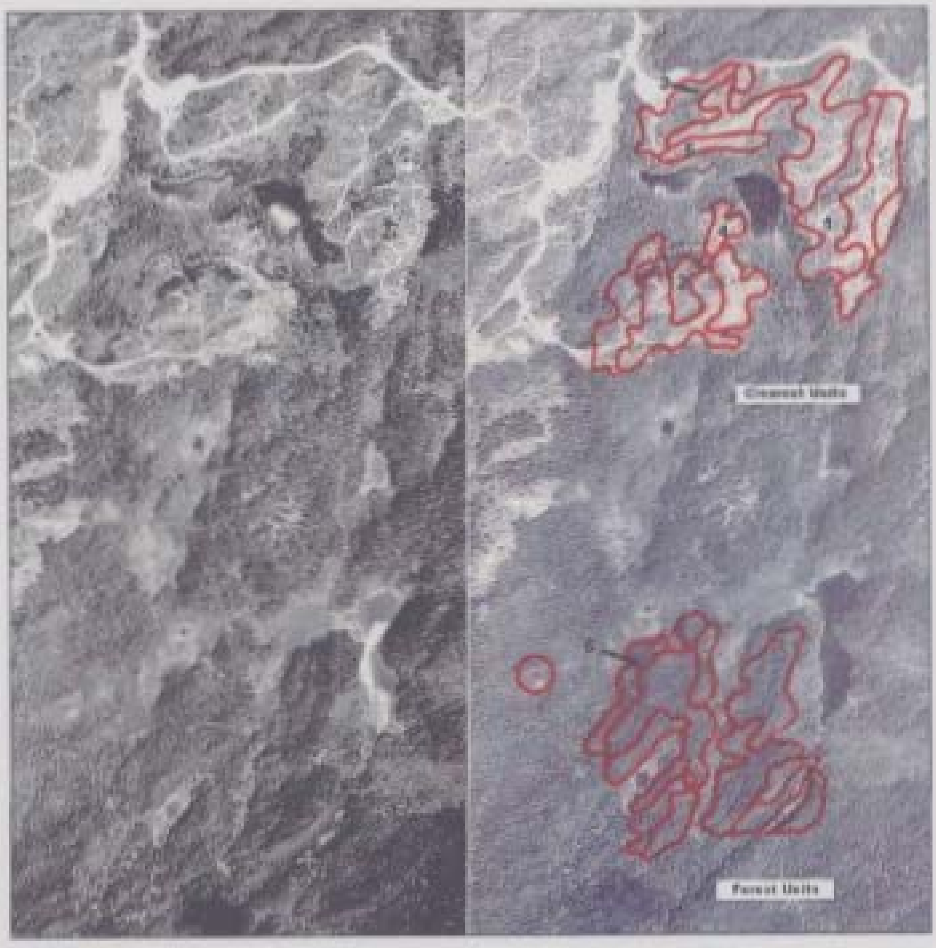

Figure 3.4. Stereogram of topographic units on clearcut (upper) and mature balsam fir forest (lower) areas and meteorological tower location - O. Labelled areas correspond to ground views in Figs. 3.6 to 3.10.

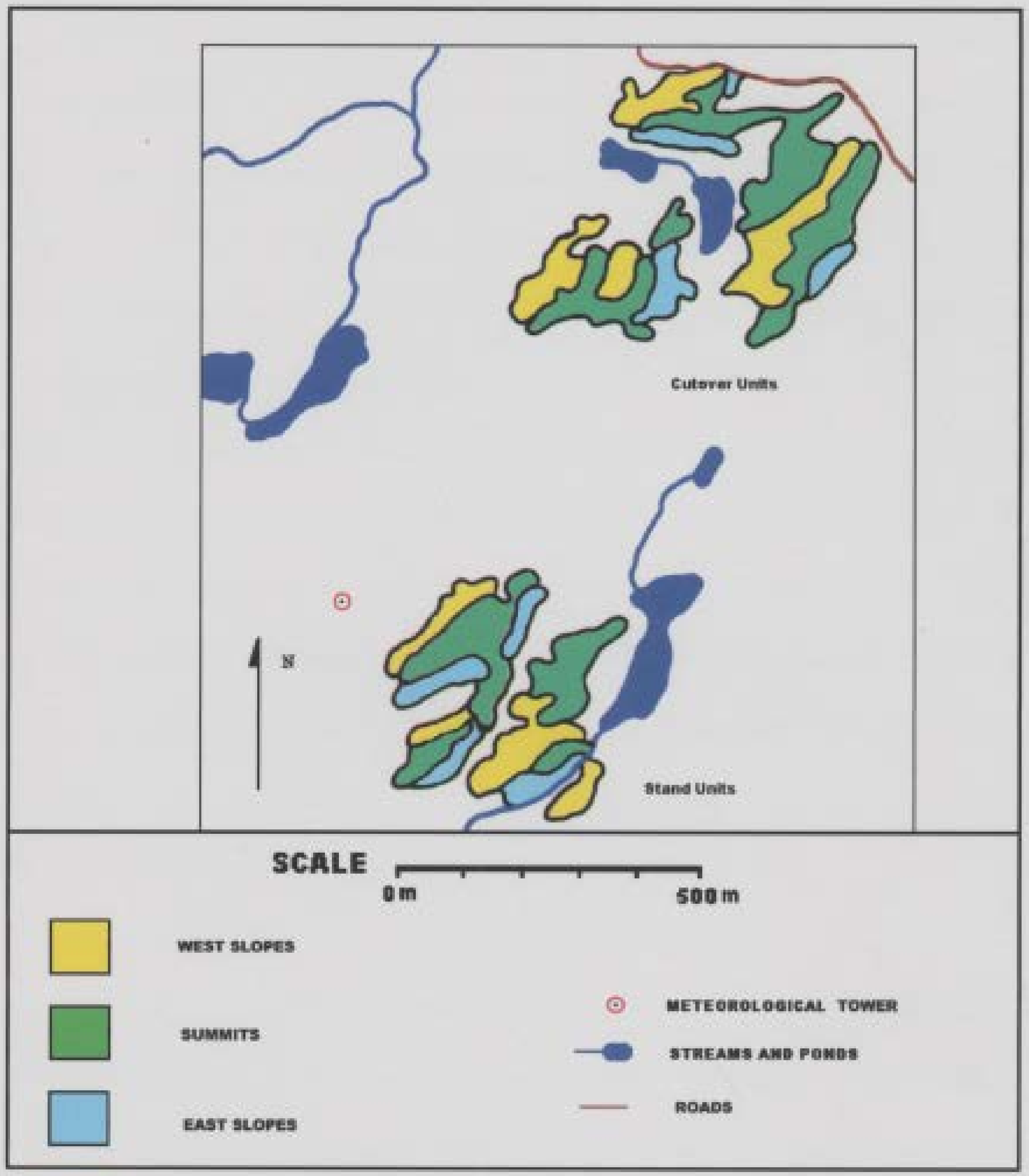

Figure 3.5. Thematic map of classified cutover and forest stand topographic units.

3.1 Climate

The broader climate of insular Newfoundland is predominantly influenced by atmospheric circulation patterns of the northern hemisphere mid-latitudes and its geographic location with respect to the Canadian mainland (Banfield 1983). The presence of the Labrador Current is a further significant influence along with the proximity of a surrounding cold ocean surface. The months of December through March are characterized by mean air temperatures below freezing with cold arctic air outbreaks commonly depressing temperatures into the -15 to -25 ° C range, while in summer, temperatures can reach 25 to 32 ° C in the central lowlands and the west coast Humber River valley (Banfield 1983, 1993). The Canadian climatic scheme of Sanderson (1948) classifies the island as "perhumid", which is characterized by no significant seasonal moisture deficit. Island wide annual potential evaporation has been estimated at between 300 to 400 mm (Agriculture Canada 1976).

The study area falls within the "the western hills and mountains" climate zone (Banfield 1983) and has an annual observed precipitation of between 1250 and 1600 mm, with the larger amounts at higher elevations. Measurable precipitation in this zone can occur on approximately 200 days of the year in coastal areas that are immediately backed by higher ground (Banfield 1983). Mean annual rainfall at Corner Brook is 849 mm and accounts for 66.8% of annual precipitation with snowfall accounting for 33.2% (Environment Canada

2002). Rainfall during the months of December through March had a mean of 38 mm. Mean annual rainfall at Deer Lake Airport is 718 mm and accounts for 62.8% of annual precipitation with snowfall accounting for 37.2% (Environment Canada 2002). Mean winter rainfall during the months of December through March had a mean of 22 mm.

Table 3.1 presents mean rainfall, snowfall and temperature data, from June to October corresponding to the study duration, for the Corner Brook (4.6 masl) and Deer Lake Airport (21.9 masl) weather observation stations (Environment Canada 2002). Corner Brook and Deer Lake stations, which are approximately 20 km southwest and 30 km northeast of the study area, respectively (Fig. 1.1) both provide meaningful summaries of long term climate data. On an annual basis June to October have the greatest mean monthly rainfalls with a total combined rainfall of 58.1% and 64.0% of the annual amounts for Corner Brook and Deer Lake, while snowfall is rare from June through mid – October. Mean annual potential evapotranspiration is estimated to be 573 mm and 544 mm for Corner Brook and Deer Lake, respectively (Phillips 1976). However, in spite of stronger winds, it is likely that evaporation at higher elevations will be reduced due to lower air temperatures and less solar radiation. Autumnal fog may also develop at higher elevations from low cloud layers associated with low pressure warm sector air (Banfield 1981). Moving inland from the coastal Corner Brook location increasing elevations and rugged topography can enhance precipitation receipt, whereas the Deer Lake locale can experience rainshadow effects during westerly air flows (Banfield 1981).

Table 3.1. Mean monthly (1971-2000) rainfall, snowfall and temperature for Corner Brook (4.6 masl) and Deer Lake Airport (21.9 masl) between June and October.

Corner Brook				Deer Lake		
	Rain (mm)	Snow (cm)	Temp (° C)	Rain (mm)	Snow (cm)	Temp (° C)
June	83.9	0.2	13.1	79.9	0.5	12.0
July	91.0	0.0	17.3	91.6	0.0	16.1
August	98.6	0.0	16.9	100.1	0.0	15.4
September	104.2	0.1	12.7	96.1	0.1	10.9
October	115.7	7.9	7.2	92.4	8.1	5.3
Total	493.4	8.2	--	460.1	8.7	--

Table 3.2 presents long-term mean wind and sunshine data for Stephenville Airport. Although located approximately 85 km to the southwest of the study area, it is the nearest station with these data (Fig. 1.1) (Environment Canada 1984). This location would be more exposed to southwest and northwest airflows off the Gulf of St. Lawrence.

Table 3.2. Monthly percentage total (1951-1980) of wind observations by direction (N – North, NE – Northeast, E –East, SE – Southeast, S –South, SW – Southwest, W – West, NW – Northwest), by wind speed > 28 km hr^{-1} and bright sunshine hours (1942-1990) for Stephenville Airport (8.0 masl).

	Calm	N	NE	E	SE	S	SW	W	NW	>28 km hr^{-1}	Sunshine
June	14.6	4.1	17.1	11.3	3.4	6.8	23.6	13.2	5.9	4.8	93.6
uly	16.1	3.3	14.5	9.7	3.9	8.5	26.4	13.6	4.0	4.0	203.1
August	12.8	4.5	14.3	8.6	3.6	8.7	25.0	16.0	6.5	5.5	189.3
September	11.2	6.0	16.4	7.9	3.2	8.8	20.3	18.1	8.1	8.8	134.1
October	10.1	7.9	14.7	8.8	3.7	7.7	15.9	20.4	10.8	10.9	97.6

These data are also broadly reflective of the seasonal passage from summer to autumn. Winds from SW and W averaged over June to October had observed percentage frequencies of 22.2% and 16.3%, respectively. Southwesterly winds from the Gulf of St. Lawrence had the highest occurrence of any wind direction overall. Seasonally, there is a trend of decreased frequency of winds from the SW along with an increase in cooler W winds as summer passes to autumn. Combined wind directions from the NE and E averaged 24.7% over the summer to autumn season, with no apparent seasonal trend. Winds from the S and SE generally remain constant with low average occurrences of 8.1% and 3.6%, respectively. An increase in strength of autumnal winds is demonstrated by the decrease in percentage frequency of calm conditions and an increase in wind speeds exceeding 28 km hr^{-1}. Winds from the N and NW exhibit a seasonal increase in frequency as summer passes into the autumn season and reflect colder air mass influences throughout the region. Bright sunshine hours also demonstrate a mid summer peak followed by an autumnal decrease.

Principal cyclonic storm tracks for the summer months lie across the Gulf of St. Lawrence and through the Strait of Belle Isle, affecting most of western Newfoundland (Banfield 1993). In the autumn season storm tracks migrate southward and cyclones are characterized by increasing intensity and colder air incursions following the cold front. These systems move under the influence of a prevailing upper westerly flow but day-to-day near–surface wind directions vary with the passage of individual pressure systems. Summer low pressure systems, originating in the central United States or south central Canada from the conflict between tropical Gulf and modified Pacific air masses, though less intense than winter frontal cyclones, can produce significant rainfall in the study region. In addition, late summer and autumn low pressure systems that originate as North Atlantic Ocean tropical storms and hurricanes, can bring heavy convective rains. During winter, rainfall occurs largely within warm sector air associated with low pressure systems tracking across the study region. Air flowing across the Gulf of St. Lawrence can be significantly influenced and added heat and moisture can result in cyclonic rejuvenation during winter (Banfield 1993). Moisture laden air can also be uplifted as it reaches the western Newfoundland coastal region resulting in a significant orographic precipitation influence for the western Newfoundland region. Northeasterlies and easterlies and are also noted as significant winds during cyclonic precipitation events within the region (Brookes 1972).

3.2 Forest Vegetation and Terrain

The predominant forest cover in the study area is balsam fir of age 41-60 years, and dominant height of 6.6-9.5 m and crown density of 51- 75% . As determined from throughfall plot survey data recorded in 1998, balsam fir had an average live height of 4.88 m, average dead height of 2.78 m, average live stem density of 9683 stems ha^{-1}, dead stem density of 2030 stems ha^{-1} and mean breast height stand age determined from dominant trees was 47 years. Average relative species density indicates the predominance of balsam fir (Table 3.3).

Table 3.3. Average tree species density (%) of the throughfall plots.

Species	Density(%)
Balsam fir	95.1
Black spruce	3.3
White spruce	0.9
White birch	0.7

White spruce and white birch were infrequently and randomly interspersed throughout the balsam fir cover. Black spruce occurred on lower slope positions associated with poorer site drainage. Clearcut sites in the study area were harvested in 1990 and are characteristically distributed over similar terrain as the predominant balsam fir cover. Figs. 3.6 to 3.10 provide ground views of selected topographic units and forest conditions in the study area. These units are also visible on an air photo stereopair (Fig. 3.4).

Figure 3.6. The northern boundary (in red) of the study area, viewed from approximately 500 metres to the north., portraying the characteristic hilly nature of the terrain. In the centre and left foregrounds are lowland mature mixed black spruce and balsam fir stands bounding two fen wetlands. The boundary is demarcated by a logging access road (Fig. 3.4). Westerly aspect slopes with ridge lines portraying the transition to summits, typical of the clearcut topographic positions in the study area (Fig. 3.4), are portrayed in areas labelled 1, 2 and 3.

Figure 3.7. Characteristic clearcut terrain within the study area. Areas labelled 1 and 2 (viewed from the west at approximate distances of 250 and 150 metres, respectively) are a closer ground view of the same areas shown in Fig. 3.6. In the left foreground there is a small pond with a surrounding marsh and fen complex. Residual mature stands of balsam fir, with some black spruce in lowland positions, are visible in the centre background, left midground and right foreground. Area 1 is west-facing with a slope of approximately 45-50% and a summit height of 25 to 30 metres above the pond level. Area 2 is also west-facing with a slope of 60-70% and a local relief of 20 to 25 metres above area 4. Residual uncut white birch and balsam fir, visible along the ridge line, are 10-12 metres high. Area 4 is a discordant summit rising from the marsh fen complex in the foreground and falling away into a valley opposite (Fig. 3.4).

Figure 3.8. A closeup view of area 3 viewed from approximately 25 metres distance. In the foreground is the logging access road which forms the northern boundary of the study area (see also Fig. 3.4). This site is west-facing with a slope of 45% and a local relief 15 to 20 metres. The upper ridge clearly shows the break of slope associated with the hill summits. An immature balsam fir cover, along with white birch and other hardwood shrubs, is characteristic of regenerating clearcut harvest sites in western Newfoundland. The height of the regenerating vegetation is 1 to 2 metres. Interspersed along the upper slope are residual mature white birch which are not foliated, having subsequently undergone die back.

Figure 3.9. Area 5 portrays a southeast-facing slope, and is the opposing slope to Area 3 (see also Fig. 3.4). Viewing distance is roughly 150 metres. In the centre there is a marsh and fen complex with surrounding mature balsam fir and black spruce in lowland positions. This site has a slope of approximately 45% and a local relief between 15 and 20 metres. On the upper slope is visible a 4 m radius incident rainfall plot cleared of regenerating vegetation.

Figure 3.10. Area 6 is a westerly aspect forest topographic unit with a slope of 30% and local relief of 10 to 15 m. The upper ridge line is the transition to the summit topographic position. A uniform balsam fir forest cover between 6 and 10 m high occupies the site. In the fore and middle ground is a mixed balsam fir and black spruce krummholz, 1 to 3 m high. Area 6 was viewed from the meteorological tower site at a distance 200 metres to the west (see also Fig. 3.4).

4.0 Methods

This chapter documents the experimental design to investigate forest cover and topography as variables in the throughfall process. Diagrammatic and cartographic detail is provided for the statistical and field perspectives of the experimental design along with the hypotheses to be tested. Details are also provided on instrumentation and a pilot study that was undertaken to aid in sample size determination for the primary thesis experiment. Analysis methods for throughfall in relation to meteorological variables are also described.

4.1 Experimental Design – Forest Cover and Topography

For this research the interactions of local topographic conditions and forest cover with incident rainfall and throughfall are analyzed by means of a factorial (two factor), fixed effects, nested analysis of variance model (Zar 1996). Analysis of variance (ANOVA) is a broadly applicable statistical analysis for experiments with subpopulations of $k \geq 3$. Factorial applications enable testing of individual experimental factors and factor interactions. Levels of a classification system, in particular those based on spatial criteria (Dutilleul 1993), can be used to define the experimental factors. Within this context variability amongst the classification levels, as measured by means of a specified dependent variable, can be tested for statistical significance. The ANOVA analysis is performed for incident rainfall and throughfall on an individual collection basis and for all collections grouped, using Systat 7.0 (1997; Table 4.1).

Table 4.1. Parameters of the experimental design. Experimental factors A and B are fixed and fully crossed, whereas Factor C is random and nested within the fully crossed factors. F is the F ratio computed from the mean square (MS) of the experimental factors, v_1 and v_2 are degrees of freedom for the numerator and denominator of the F ratio, and * - MS_e is the error mean square within replicates (Zar 1996).

Source of Variation	F	v_1	v_2
A	MS_A/MS_C	DF_A	DF_C
B	MS_B/MS_C	DF_B	DF_C
AB	MS_{AB}/MS_C	DF_{AB}	DF_C
C	MS_C/MS_e	DF_C	DF_e

Factor A is forest cover; it has two levels: Level 1 is a balsam fir clearcut; Level 2 is a mature balsam fir stand of 41 - 60 years of age. Factor B is topographic position; it has three levels: Level 1 is east-facing slopes; Level 2 is southwest to northeast trending summits; Level 3 is west- facing slopes.

The three topographic levels were replicated four times for each of the two forest cover classes. Since each individual replicate is not present at each combination of the two-crossed factors, they are nested (Factor C) within the two-factor fully crossed design (Fig. 4.1). Each replicate of topographic position was sampled with three randomly located funnel rain gauges (Figs. 4.2 and 4.3; Table 4.2). On a per collection basis each cell has twelve funnel gauge measurements, whereas, for the full season there were 26 collection events during the study period, with each analytical cell providing a total of 312 measurements (26 x 12) per cell.

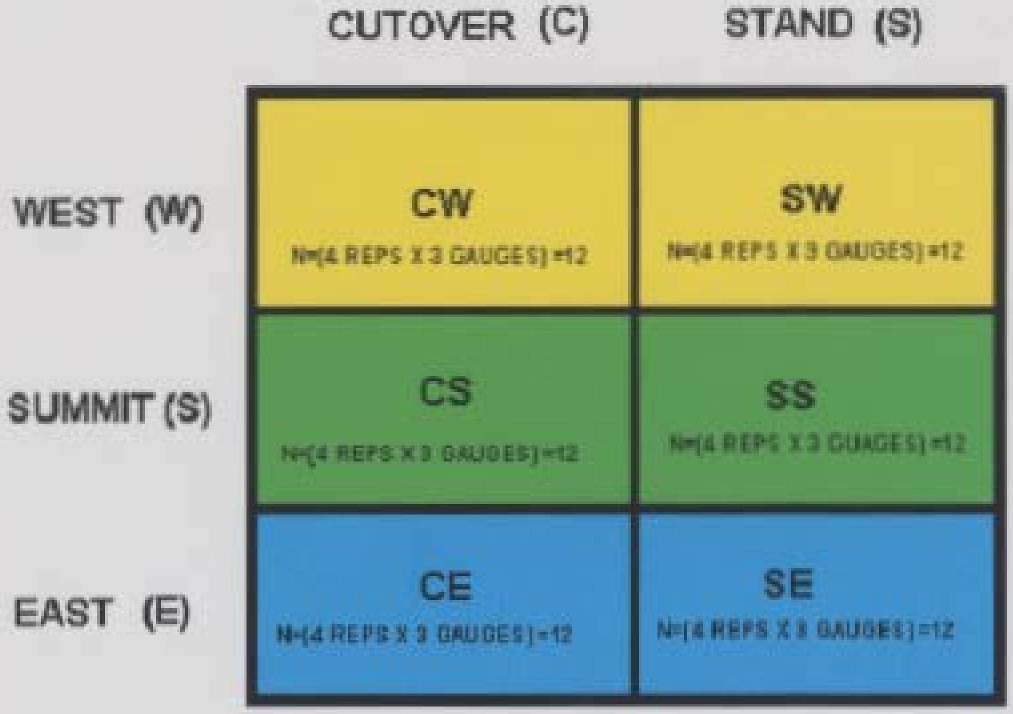

Figure 4.1. Factorial layout of the nested ANOVA design.

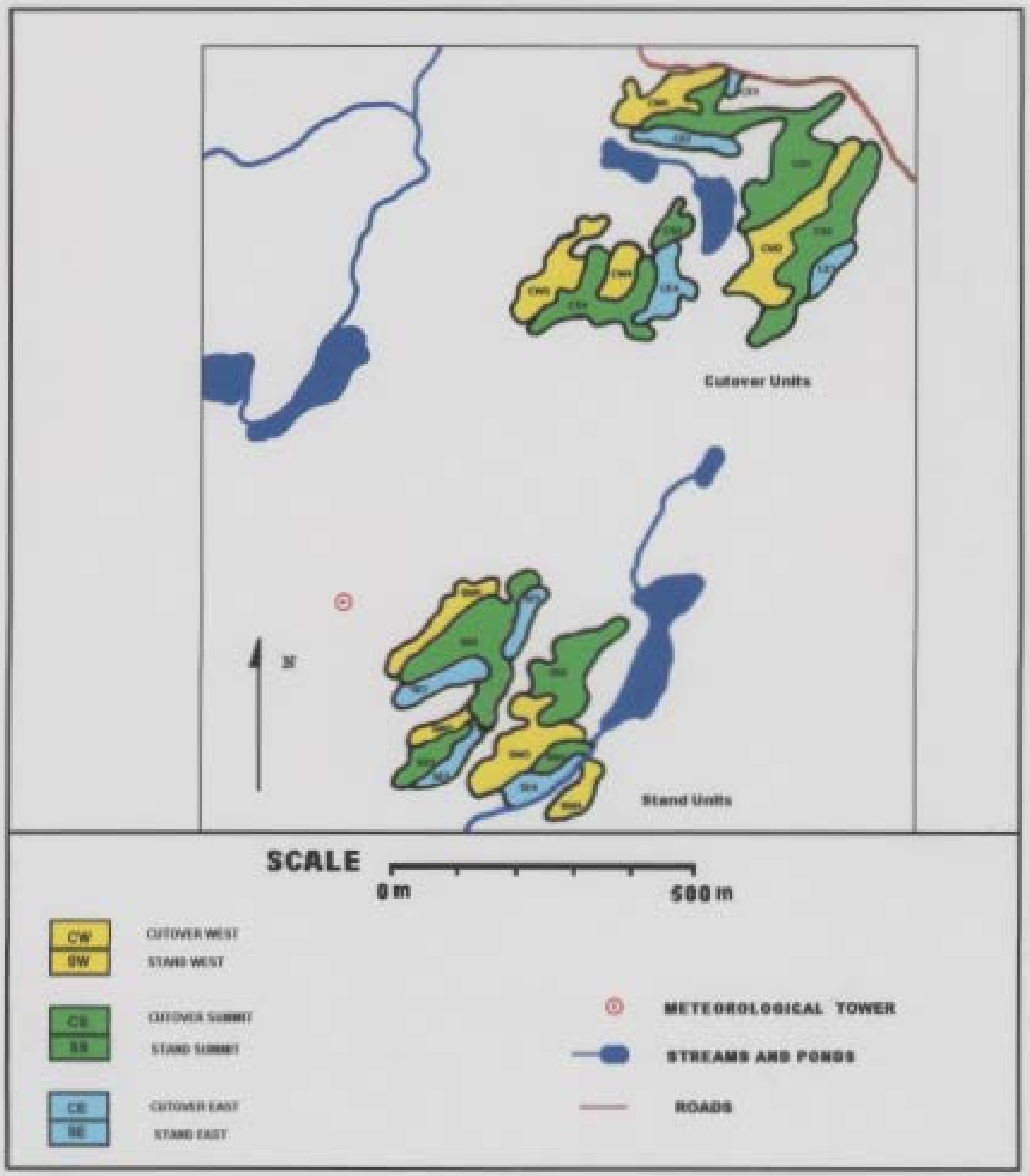

Figure 4.2. Field layout of the experimental design in a thematic map format.

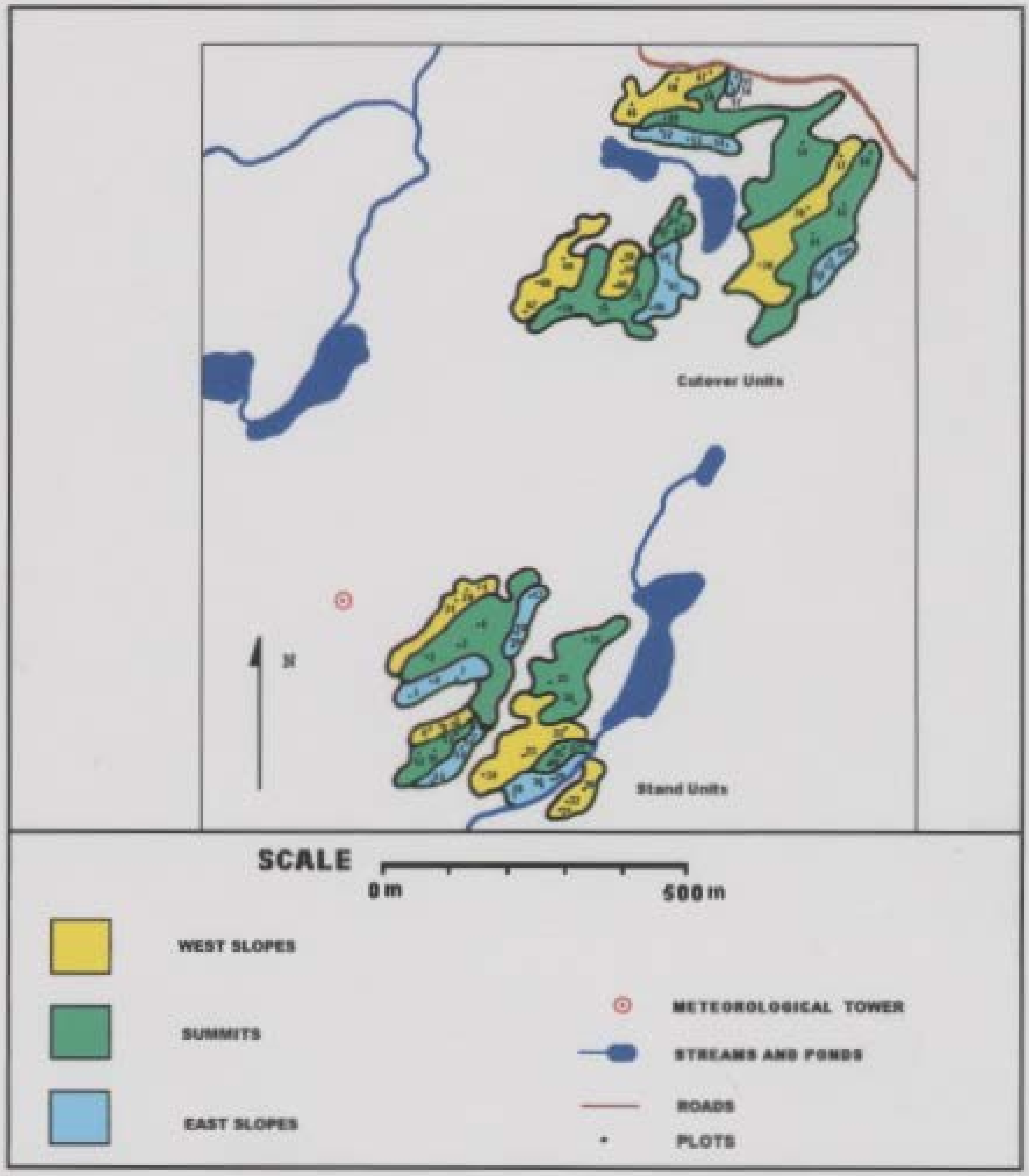

Figure 4.3. Field plot locations.

Table 4.2. Location, elevation (metres above sea level) and slope angle (percent) and aspects in degrees from true north for funnel gauge locations.

Plot	Latitude (N)	Longitude (W)	Elevation	Slope	Aspect	Plot	Latitude (N)	Longitude (W)	Elevation	Slope	Aspect
1	49° 04' 45"	57° 43' 52"	451.2	20	290	37	49° 05' 11"	57° 43' 24"	387.9	38	286
2	49° 04' 40"	57° 43' 58"	438.5	< 5	N/A	38	49° 05' 04"	57° 43' 31"	404.3	45	260
3	49° 04' 41"	57° 43' 55"	441.8	< 5	N/A	39	49° 05' 08"	57° 43' 27"	404.0	45	274
4	49° 04' 43"	57° 43' 53"	448.4	< 5	N/A	40	49° 05' 11"	57° 43' 23"	381.9	< 5	N/A
5	49° 04' 39"	57° 43' 56"	436.6	38	142	41	49° 05' 07"	57° 43' 27"	414.5	< 5	N/A
6	49° 04' 40	57° 43' 55"	428.1	57	150	42	49° 05' 09"	57° 43' 24"	399.1	< 5	N/A
7	49° 04' 40	57° 43' 54"	430.0	38	156	43	49° 05' 06"	57° 43' 25"	414.7	32	96
8	49° 04' 38"	57° 43' 55"	430.6	57	286	44	49° 05' 04"	57° 43' 26"	411.2	57	92
9	49° 04' 38"	57° 43' 56"	427.7	56	282	45	49° 05' 06"	57° 43' 24"	399.3	45	88
10	49° 04' 38"	57° 43' 54"	427.9	53	288	46	49° 05' 13"	57° 43' 39"	394.8	43	284
11	49° 04' 37"	57° 43' 54"	428.7	< 5	N/A	47	49° 05' 15"	57° 43' 34"	386.2	46	298
12	49° 04' 37"	57° 43' 56"	424.6	< 5	N/A	48	49° 05' 15"	57° 43' 37"	379.4	45	292
13	49° 04' 38"	57° 43' 54"	432.7	< 5	N/A	49	49° 05' 12"	57° 43' 39"	393.7	< 5	N/A
14	49° 04' 36"	57° 43' 54"	420.2	54	128	50	49° 05' 14"	57° 43' 35"	395.0	< 5	N/A
15	49° 04' 35"	57° 43' 57"	412.8	36	122	51	49° 05' 13"	57° 43' 27"	393.0	< 5	N/A
16	49° 04' 37"	57° 43' 52"	413.9	66	130	52	49° 05' 12"	57° 43' 38"	399.3	68	164
17	49° 04' 45"	57° 43' 47"	439.0	41	96	53	49° 05' 12"	57° 43' 36"	393.8	28	168
18	49° 04' 43"	57° 43' 48"	436.1	50	108	54	49° 05' 11"	57° 43' 34"	393.4	39	158
19	49° 04' 42"	57° 43' 49"	432.1	59	112	55	49° 05' 15"	57° 43' 33"	381.3	40	84
20	49° 04' 45"	57° 43' 53"	450.5	30	284	56	49° 05' 14"	57° 43' 34"	388.8	47	92
21	49° 04' 45"	57° 43' 52"	453.6	33	278	57	49° 05' 14"	57° 43' 33"	384.8	31	94
22	49° 04' 39"	57° 43' 43"	423.3	54	322	58	49° 05' 05"	57° 43' 42"	423.8	32	280
23	49° 04' 37"	57° 43' 47"	420.0	57	268	59	49° 05' 04"	57° 43' 43"	427.6	16	276
24	49° 04' 37"	57° 43' 49"	411.1	41	246	60	49° 05' 04"	57° 43' 42	426.1	37	268
25	49° 04' 37"	57° 43' 44"	432.5	< 5	N/A	61	49° 05' 06"	57° 43' 38"	394.3	< 5	N/A
26	49° 04' 37"	57° 43' 45"	432.6	< 5	N/A	62	49° 05' 45"	57° 43' 37"	395.5	< 5	N/A
27	49° 04' 37"	57° 43' 43"	430.7	< 5	N/A	63	49° 05' 07"	57° 43' 38"	398.8	< 5	N/A
28	49° 04' 45"	57° 43' 48"	417.0	56	132	64	49° 05' 06"	57° 43' 38"	400.9	45	88
29	49° 04' 36"	57° 43' 44"	420.0	58	146	65	49° 05' 05"	57° 43' 38"	415.1	66	94
30	49° 04' 35"	57° 43' 42"	413.6	54	280	66	49° 05' 02"	57° 43' 40"	435.0	57	136
31	49° 04' 34"	57° 43' 44"	402.7	40	272	67	49° 05' 02"	57° 43' 49"	430.2	34	298
32	49° 04' 35"	57° 43' 43"	416.1	48	276	68	49° 05' 03"	57° 43' 49"	417.4	14	268
33	49° 04' 41"	57° 43' 44"	428.0	< 5	N/A	69	49° 05' 05"	57° 43' 46"	421.9	59	292
34	49° 04' 40"	57° 43' 44"	428.4	< 5	N/A	70	49° 05' 01"	57° 43' 47"	434.8	< 5	N/A
35	49° 04' 43"	57° 43' 43"	436.1	< 5	N/A	71	49° 05' 04"	57° 43' 44"	430.6	< 5	N/A
36	49° 04' 36"	57° 43' 45"	412.4	62	134	72	49° 05' 03"	57° 43' 41"	438.4	< 5	N/A

Nesting in an ANOVA design is most appropriate for the study since the experimental design can be tested for within-cell variability. Thus a more robust testing of the primary hypotheses for the fixed factors A or B and their potential interactions, "AB", can be achieved (Zar 1996). Also, the topographic positions are nominally classified for the ANOVA design, and it is likely that these levels will exhibit some quantitative differences in aspect, slope gradient or other field variables. Therefore, testing for within-cell variability is advisable. An important consideration for the ANOVA model is the assumption of homogeneity of variance and normality of data distribution amongst the cells of a factorial design (Zar 1996). However, the robustness of this statistical model is well accepted in spite of salient departures from normality (Zar 1996), and when largest to smallest cell variance ratios are approximately 10:1 or smaller (Tabachnick and Fidell 1996). The Shaprio-Wilk (1965) test is recommended by Anderson and McLean (1974) for normality testing. Where assumptions of homogeneity of variance and normality for the ANOVA are strongly violated, non parametric Mann Whitney U tests (MW) and Kruskal – Wallis (KW) tests are employed (BMDP 7.0 1992). Tukey tests (Zar 1996) for significant ANOVA tests and pairwise multiple comparison tests (Hollander and Wolfe 1973) for significant KW tests are employed as post hoc analyses. There is nothing sacrosanct about any probability value (Warren 1986) and no strong logical reason for a chosing a 0.05 p value (Cochran 1983). Studies investigating topographic and landscape factors have noted the uncontrolled variability that can be present in field studies and have thus used less rigourous probability values of 0.2 (van Kessel *et al.* 1993; Jowkin and Schoenau 1998) and 0.1 (van Kesteren 1996). For all analyses a probability level of 0.10 was chosen for reporting significance. The corresponding hypotheses, null and alternate, to be tested by this ANOVA model are as follows:

Null and Alternate 1:

H_O: There is no difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions.

H_A: There is a difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions.

<u>**Null and Alternate 2:**</u>

H_O: There is no difference in mean throughfall and mean incident rainfall between topographic positions.

H_A: There is a difference in mean throughfall and mean incident rainfall between topographic positions.

<u>**Null and Alternate 3:**</u>

H_O: There is no interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall.

H_A: There is an interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall.

<u>**Null and Alternate 4:**</u>

H_O: There is no difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover.

H_A: There is a difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover.

4.2 Instrumentation

4.2.1 Rainfall gauges

A simple inexpensive funnel rain gauge construction was improvised for the sampling of incident rainfall and throughfall at the random locations throughout the topographic units. Nalgene laboratory bottles of 500 and 1000 ml capacity were used for throughfall and incident rainfall gauges, respectively. Through a hole in the bottle cap, a 9.2 cm diameter orifice funnel was inserted and sealed with plumber's compound. The rainfall catches from three gauges of each improvised type were compared with three standard rain gauges having a 10.0 cm orifice. All were placed with orifice heights at 30 cm above the ground surface. Appendix 1 presents the comparison data. Incident rainfall data were collected for 22 events over the time period of June 14 1997 to September 1 1997. The sampling was conducted at the Pasadena Canadian Forest Service station on a flat field site with no obstructions. Funnel gauges catches were read for rainfall depth in a graduated cylinder with 0.2 mm divisions calibrated to the 10 cm diameter standard gauage. Catches depths were then corrected by the ratio of orifice areas of the 9.2 cm diameter funnel to the 10 cm standard gauge resulting in a resolution of 0.23 mm for the funnel gauges. A subsequent accuracy of ± 0.2 mm for throughfall and incident rainfall funnel gauge readings could be expected. A correlation coefficient of $r = 0.99$, $p < 0.001$ was calculated for the standard versus 1000 and 500 ml funnel gauges. (Fig. 4.4). The coefficient indicates that there are no significant performance differences between the improvised gauges and a standard rain gauge.

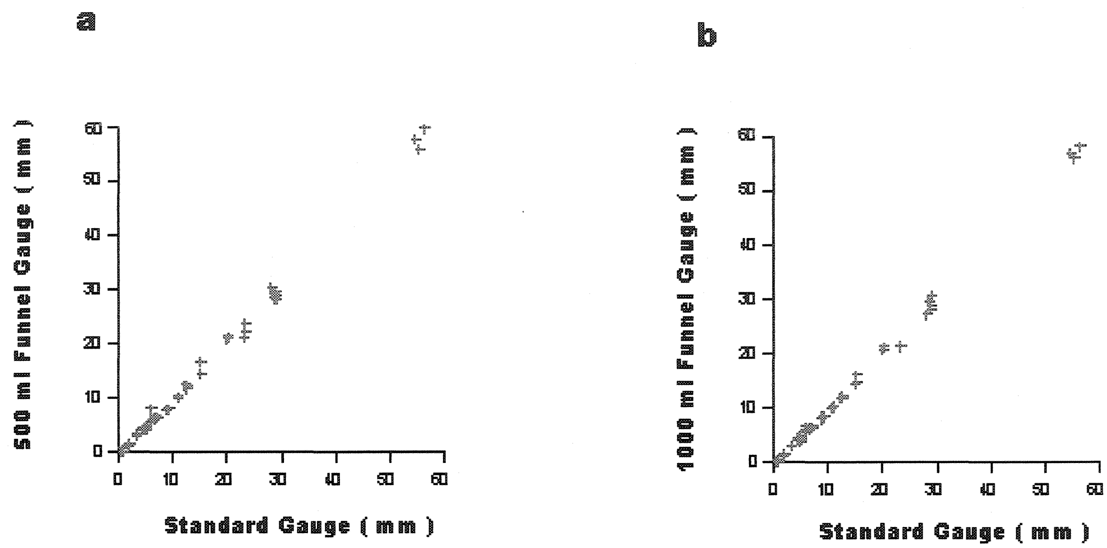

Figure 4.4. Scatterplot of incident rainfall receipt for standard rain gauge versus improvised funnel rain gauges **a**: 500ml and **b**: 1000 ml bottle attachments, $r = 0.99$, $p < 0.001$.

Having concluded that the funnel type raingauges would be of sufficient accuracy and precision, gauge placement at fixed random locations within the classified topographic units were employed to determine incident rainfall and throughfall for the full study area. One season of data was acquired from June 7 to October 7, 1998.

In order to minimize potential rain gauge obstruction tree regeneration and minor vegetation was cleared from the centre of each P_g collector to a radius of four metres to create a 1/200 hectare plot area (Fig. 4.5). All gauges were established horizontally at 30 cm orifice height above the ground surface by attachment to a survey stake firmly driven into the ground.

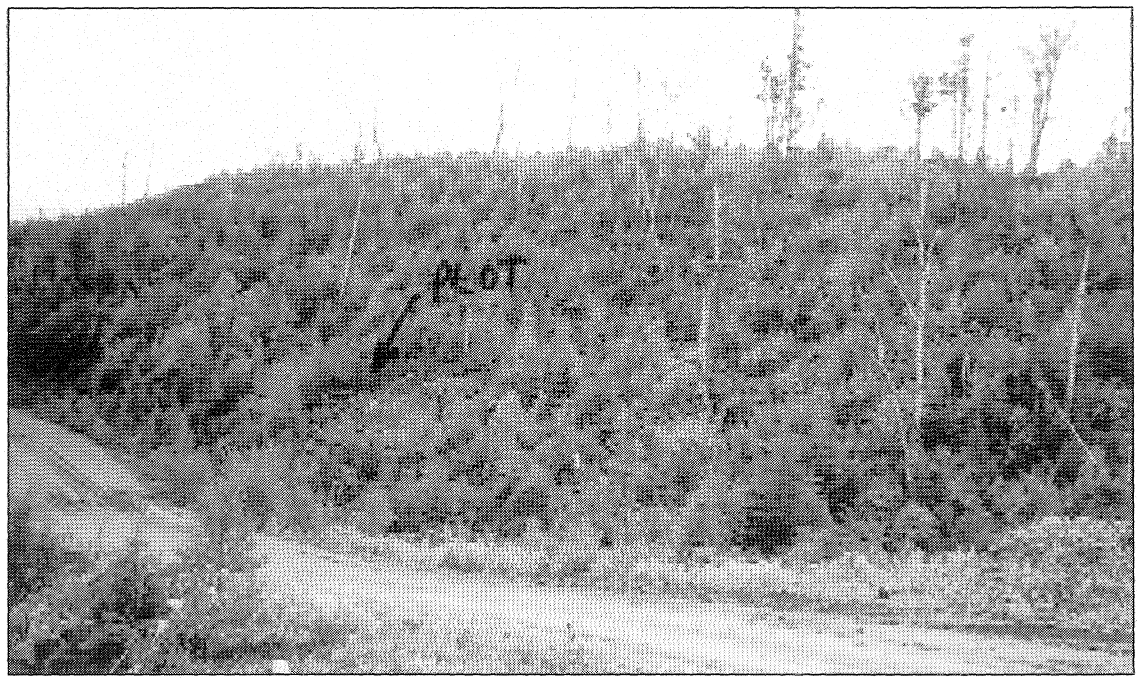

Figure 4.5. A typical cleared plot for incident rainfall measurement on clearcut site.

Figure 4.6. A typical gauged forest stand throughfall plot.

All trees > 1 m high within a four metre radius of the gauge placement on throughfall plots were classified by species and measured for breast height diameter, total height and distance and azimuth from plot centre (Fig. 4.6).

4.2.2 Meteorological tower

Figure 4.7 portrays the meteorological tower location at a GPS determined elevation of 459 masl. This tower was instrumented (with noted accuracies) with a Texas Electronics tipping bucket rain gauge (0.1mm/tip), a Campbell HMP35C relative humidity (± 2%) and air temperature probe (± 0.2° C), a Campbell Met 1 wind speed sensor (0.11 m/s) and a Campbell Met 1 wind direction sensor (± 5°).

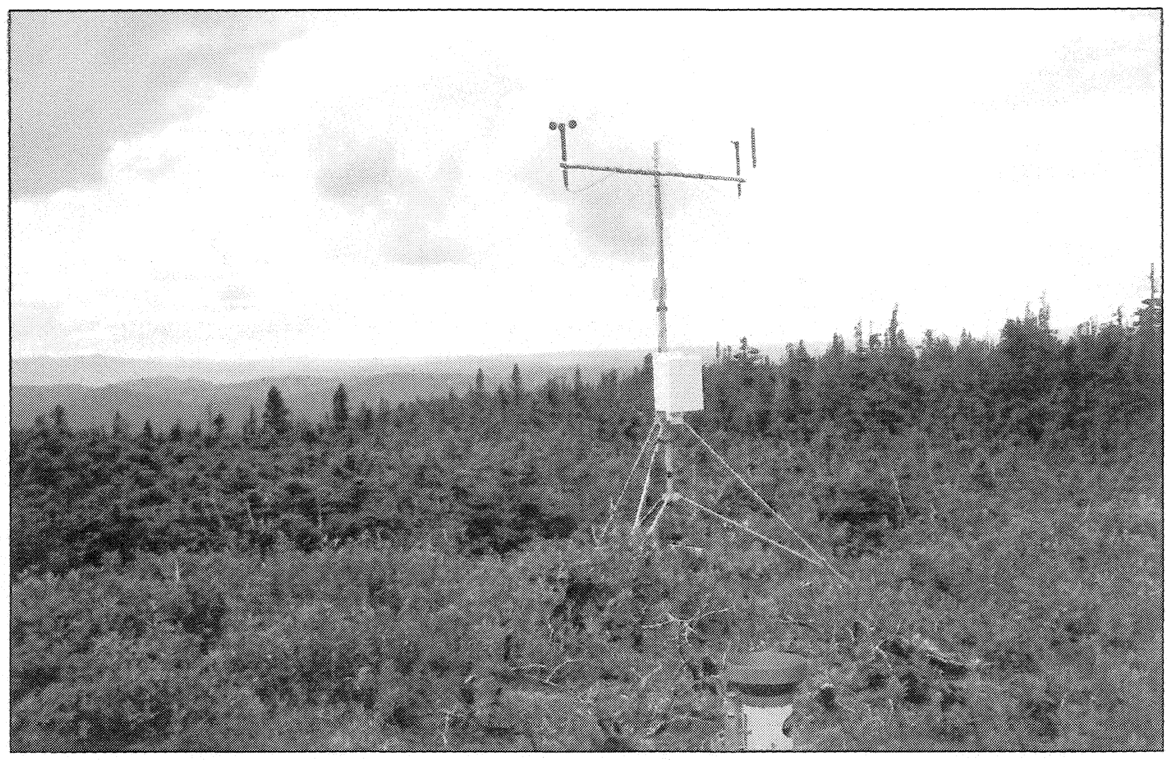

Figure 4.7. Meteorological instrumentation site. Foreground: tipping bucket rain gauge, Tower mid height: relative humidity and air temperature probe. Tower top left and right, respectively: wind speed sensor and wind direction sensor.

Figure 4.8. Downloading of data and monitoring of meteorological instrumentation undertaken approximately every two weeks. Data logger and data storage module are mounted in a weather proof protective case attached to the tower.

A Campbell Scientific CR10X data logger and SM 192 storage module were employed for data recording and storage (Fig. 4.8). This instrumentation was used to acquire hourly average values of meteorological variables relevant to the study. An important component of this research was the measurement of discrete rainfall events, in contrast to previous studies of throughfall that used weekly or larger collection intervals. Discrete events as much as possible corresponded to rainfalls forecast. For example, if showers were forecast for a specific day(s) followed by clearing, the gauges were read on the following clear day. The forecast showers could then be considered a discrete "event" and would not be mixed with the next forecast rainfall. Measurements were taken after each incident rainfall event and cessation of canopy drip requiring from 8 to10 person hours to complete.

4.3 Sample Size Determination

A pilot study was undertaken to determine sample size for the experimental design. Six collections were recorded over the period from June 18, 1997 to July 16, 1997 at the experimental field site. Six funnel gauges each were used to monitor incident rainfall and throughfall (Appendix 2). Sample size determination followed Lawrence and Fernandez (1993), utilizing the estimation formula $n = t^2cv^2/(E\%)^2$, where n is the estimated sample size, t is the student's t value for a desired probability level, cv is the coefficient of variation and E is the chosen allowable standard error as a percentage of the mean. Degrees of freedom for t are n-1, or five, since the number of gauges for $\mathbf{P_g}$ and $\mathbf{P_t}$ are six each. A two-tailed probability value for t was chosen as $p = 0.10$ for the sample size estimation. Tables 4.3 and 4.4 present the range of sample size estimates, rounded to the nearest unit gauge, that would be required to give reliable estimates of $\mathbf{P_g}$ and $\mathbf{P_t}$ for the 90 percent confidence interval, with specified allowable standard errors for the six collection events.

Table 4.3. Sample size estimates for $\mathbf{P_g}$ for six rainfall events monitored in the summer of 1997. Coll# is collection number, SD is the standard deviation and other terms are as stated in the sample estimation formulation.

Coll #	P_g mean (mm)	SD (mm)	CV (%)	n (E=10%)	n (E=12.5%)	n (E=15%)
1	5.8	0.49	8.45	3	1	1
2	21.1	0.76	3.58	1	1	1
3	27.6	0.78	2.83	1	1	1
4	15.8	0.98	6.16	2	1	1
5	3.5	0.16	4.63	1	1	1
6	41.1	1.51	3.67	1	1	1
				mean n=2	mean n=1	mean n=1

Table 4.4. Sample size estimates for $\mathbf{P_t}$ for six rainfall events monitored in the summer of 1997. Coll# is collection number, SD is the standard deviation and other terms are as stated in the sample estimation formulation.

Coll #	**Pt** mean (mm)	SD (mm)	CV (%)	n (E=10%)	n (E=12.5%)	n (E=18%)
1	3.9	1.22	31.28	40	25	12
2	12.5	2.06	16.40	11	7	3
3	27.9	9.05	32.44	43	27	13
4	9.4	4.00	42.40	73	47	23
5	2.0	0.73	37.10	56	36	17
6	19.3	3.95	20.49	17	11	5
				mean n=40	mean n=26	mean n=12

Mean sample sizes for $\mathbf{P_t}$ increased with decrease in allowable error levels. Sample size estimates within the chosen allowable error levels varied. For an allowable error of 10% the largest and smallest sample size estimates were 73 and 17 with a mean of 40. An allowable error of 12.5% resulted in a mean number of gauges of 26 with 5 of 6 sample size estimates of $\leq$ 36 gauges. On average, 12 gauges per topographic position could be expected have an allowable error of 18%. These mean values were similar to those noted in the literature review, which concluded that 30 gauges was a practical sample size for throughfall estimation. For P_g the largest sample size estimate was 3 with a mean of 2. Variability for P_g sample sizes across allowable error levels was markedly less than for P_t. Logistical constraints on field sampling on a per event basis, the need for a balanced sample size for the experiment, and similar estimates from the literature were taken into consideration. A sample size of 36 P_t and 36 P_g funnel gauges could provide reasonable mean estimates within an allowable error range of 10% to 12.5% and was therefore chosen for this study.

4.4 Collection Differences and Meteorological Variables

A simple exploratory analysis investigated potential effects of some meteorological variables on throughfall. Since throughfall measurements across a set of tree-scale plots may be influenced by both meteorological and canopy factors, the throughfall data is standardized to remove potential confounding effects due to canopy variability on a per plot basis. This standardization is achieved by computing the throughfall percentages on a per plot basis for the different collection events (Eq. [6]). Incident rainfall (P_g) data are derived from the meteorological tower rain gauge record. The $P_{t(\%)}$ values are standardized through reassignment of the maximum $P_{t(\%)}$ plot value to 100% and recomputing other plot values as a percentage of the new maximum value. This process generates new throughfall percentage data ($SP_{t(\%)}$) for each plot which are standardized across all twenty-eight collections. A mean collection $SP_{t(\%)}$ value of 100%, although unlikely, would occur if all plots within a given collection achieved their maximum values for that collection. The $\mathbf{SP}_{t(\%)}$ data are then screened for differences amongst collections using the KW test and post hoc multiple comparisons (BMDP 7.0 1992). A significant KW test should indicate that differences exist amongst collections due to prevailing meteorological conditions, irrespective of canopy variability at the level of individual tree-scale plots. The $\mathbf{SP}_{t(\%)}$ data are also compiled by collection event and a ranking from 1 to 28 generated to provide a cross tabulated plot frequency. By definition rank 1 is the maximum $\mathbf{SP}_{t(\%)}$ (100%) value for each plot. Ranks 2 to 28 on a plot by plot basis are therefore characterized by different values expressed as a percentage fraction of the rank 1 values of each plot. The cross tabulated data are then plotted as a histogram of numbers of plots by rankings for each collection, providing a visual analysis of meteorological patterns and influences for the individual collections.

Simple linear correlation is then used to investigate meteorological influences on the throughfall process (Systat 7.0 1997). For each individual collection the $\mathbf{SP}_{t(\%)}$ data are averaged over the 36 throughfall plots and the mean collection values are correlated with the following meteorological variables: (i) mean air temperature for the full time between individual collections, (ii) mean relative humidity for the full time between individual collections, (iii) mean wind speed during rain for individual collections, (iv) mean rainfall intensity for individual collections, and (v) incident rainfall amount (recorded by the tipping bucket rain gauge) for individual collections. For meteorological variables (i) to (iii), the mean value represents the average of all hourly values, which were derived from a sixty second scan rate on the data logger. For incident rainfall intensity (iv), individual rain periods were defined on the basis of minimum one-hour break periods between rain and no rain within the individual collections. The tipping bucket incident rainfall record was used to determine the one-hour intervals between discrete rain periods. Event incident rainfall intensities were then computed by two different methods and expressed as mm hr^{-1}. Intensity factor one (INT1) was computed from the total duration time and total rainfall amount of all individual rain periods within the collection. Intensity factor two (INT2) was computed as an average of individual rain period intensities within the collection. Application of a one hour break period for incident rainfall has no affect on throughfall quantities since no corresponding break period intra-collection throughfall subtotals were measured. The subsequent analysis used the total event throughfall, ($\mathbf{P}_t$), which is comprised of intra collection drip, measured after cessation of all drip at the end of the events. The range of mean wind directions encountered during rain for individual events was partitioned into predominant wind sector categories. A comparison of wind sectors for differences in $\mathbf{SP}_{t(\%)}$ was undertaken utilizing the MW test. Comparisons were investigated for all plots grouped and for individual plots. Mean wind direction was computed by the method of determining mean angle from variables with circular distributions (Zar 1996), also derived from a sixty second scan rate on the data logger. For all correlation and MW analyses a probability level of 0.10 was also chosen for reporting significance.

Mean air temperature and mean relative humidity were selected to examine potential canopy drying effects between collections, which could thus affect canopy storage and throughfall flux. Mean wind speed and direction may potentially affect canopy drying or rainfall penetration into the canopy, as well as topographic aspect interactions, which could in turn influence the throughfall process. Mean rainfall intensity was selected since it may contribute to throughfall flux before canopy saturation has been attained. Incident rainfall amount was selected to explore the steady-state drip throughfall process assumed to occur after canopy saturation. Ensuing discussions of meteorological effects on throughfall reverted to the non standardized values when comparing other case studies.

5.0 Results

This chapter reports the results of the primary thesis experiment investigating forest cover and topographic position as factors in the throughfall process. Results are reported on the basis of the 26 collection events combined and for individual collection events. Also reported are the results of collection difference screening and correlation analyses investigating the potential influence of selected meteorological variables on throughfall. The results are presented in tabular and graphical formats along with descriptions of trends, patterns and anomalies.

5.1 Incident Rainfall and Throughfall

Funnel gauge data for $\mathbf{P_t}$ (mm) and $\mathbf{P_g}$ (mm) were recorded between June 7 and October 7 1998 (Appendix 3 and 4). Means, standard deviations and coefficients of variation (Tables 5.1- 5.3)[1] for $\mathbf{P_g}$, $\mathbf{P_t}$, and $\mathbf{P_{t(\%)}}$ are used to describe variability across the 36 incident rainfall and 36 throughfall funnel gauges within individual collection events. Mean throughfall percentage ($\mathbf{P_{t(\%)}}$) averaged 85% over thirty six gauges for all twenty eight events, with a standard deviation of 41.2% and a coefficient of variation of 48.3%. Total incident rainfall recorded at the meteorological tower site from June 7 to October 7 1998 was 575.2 mm.

[1] The difference in number of collection events for $\mathbf{P_g}$ and $\mathbf{P_t}$ (n = 26) and $\mathbf{P_{t(\%)}}$ (n = 28) (Tables 5.1-5.3) resulted from two shower-free periods that permitted collection of throughfall gauges but due to the subsequent renewed start of showers the corresponding incident rainfall collection on the cutover plots could not be completed on the same day. Thus, throughfall collections 17 and 18, together with 19 and 20 (Table 5.3), are combined in the totals of $\mathbf{P_g}$ and $\mathbf{P_t}$ collection numbers 17 and 18 (Table 5.1 and 5.2) respectively, to create a balanced $\mathbf{P_g}$ and $\mathbf{P_t}$ data set for the nested ANOVA.

Incident rainfall collected by the thirty six open cutover gauges for this study period was of similar magnitude, averaging 596.5 mm. There was a 3.7% difference between the tipping bucket and averaged funnel gauge totals with an average event difference of 0.14% between gauges. Coefficients of variation for throughfall percentages ranged from a high of 67.6% to a low of 24.1% over all twenty eight collections. Throughfall exceeded incident rainfall for collections 7, 23, 20,13 and 15, with ranked values of 143.2%, 116.0%, 112.5% 111.2% and 101.4% of $\mathbf{P_{t(\%)}}$, respectively. The number of individual throughfall measurements that exceeded incident rainfall was 279, out of total of 1003 measurements, representing 27.8% of the full data set. The individual $\mathbf{P_{t(\%)}}$ exceedance measurements from all plots over all collections ranged from 100.1% to 267.1%. Individual throughfall percentages that were below exceedance values ranged from 0% to 99.9%. Occult precipitation in the form of low cloud with visible wind impaction of drizzle on the stand canopy was directly observed in association with one event (collection number 19, Aug. 31 1998). Average wind speed for this event was 13.0 m s^{-1} (Table 5.15) with a low intensity precipitation of 0.6 mm $hour^{-1}$ (Table 5.17).

Table 5.1. Incident rainfall recorded by tipping bucket –Tb(mm), mean P_g (mm), standard deviation (SD) and coefficient of variation (CV) by collection events (C1 - C26), m/d is month and day of collection.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Tb (mm)	3.9	19.6	19.4	12.7	0.3	22.4	25.0	8.3	5.9	5.1	7.2	5.8	5.0
Mean P_g mm	3.9	22.3	21.0	13.7	0.2	23.5	28.2	9.6	6.5	5.0	8.6	6.4	5.6
SD mm	0.44	1.57	1.28	0.76	0.098	2.25	1.46	0.62	0.48	0.27	0.56	0.47	0.47
CV %	1.34	7.05	4.77	5.55	42.61	10.00	5.17	6.49	7.43	5.38	6.49	7.30	8.39
m/d	06/19	06/22	07/02	07/07	07/09	07/13	07/16	07/20	07/23	07/27	08/01	08/04	08/10
	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26
Tb (mm)	66.1	16.3	34.3	59.9	27.8	67.3	32.9	9.5	26.6	9.8	38.0	8.7	37.4
Mean P_g mm	71.1	16.3	34.7	58.2	25.7	69.5	34.5	8.4	26.5	10.7	41.3	8.6	36.6
SD mm	9.02	0.96	1.37	3.82	1.00	5.89	2.44	0.76	1.85	0.75	2.19	0.88	2.81
CV %	12.69	5.88	3.95	6.57	3.89	8.48	7.06	9.05	6.99	6.99	5.30	10.26	7.68
m/d	08/15	08/17	08/20	08/27	09/02	09/08	09/10	09/14	09/18	09/21	09/24	09/29	10/06

Table 5.2. Mean P_t (mm), standard deviation (SD) and coefficient of variation (CV) by collection events (C1 - C26), m/d is month and day of collection.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Mean P_t mm	3.3	16.7	16.3	9.8	0.2	19.1	35.8	6.8	4.0	3.2	5.7	5.2	5.6
SD mm	2.11	6.85	5.35	4.81	0.078	5.17	11.88	3.07	2.67	1.84	3.58	3.11	2.84
CV %	63.94	41.04	32.92	49.28	45.88	27.10	33.18	45.48	67.59	56.79	62.37	59.58	51.17
m/d	06/19	06/22	07/02	07/07	07/09	07/13	07/16	07/20	07/23	07/27	08/01	08/04	08/10
	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26
Mean P_t mm	63.5	16.5	29.5	51.8	24.5	58.6	28.6	11.0	22.7	7.8	35.9	2.9	26.0
SD mm	19.34	7.97	7.90	11.81	6.36	15.83	9.39	3.63	5.57	3.21	11.37	2.02	9.96
CV %	30.47	48.24	26.83	22.78	26.01	27.00	32.89	32.94	24.53	41.37	31.70	70.14	38.37
m/d	08/15	08/17	08/20	08/27	09/02	09/08	09/10	09/14	09/18	09/21	09/24	09/29	10/06

Table 5.3. Mean $P_{t(\%)}$, standard deviation (SD) and coefficient of variation (CV) by collection events (C1 - C28), m/d is month and day of collection.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Mean $P_{t(\%)}$	83.0	85.2	83.7	76.9	65.3	85.2	143.2	81.5	67.0	63.5
SD %	53.43	34.90	27.54	37.82	25.77	23.05	47.56	36.92	45.27	36.09
CV %	63.47	40.96	32.90	49.21	39.46	27.06	33.20	45.31	67.61	56.85
m/d	06/19	06/22	07/02	07/07	07/09	07/13	07/16	07/20	07/23	07/27
	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Mean $P_{t(\%)}$	79.7	90.0	111.2	96.0	101.4	85.6	66.4	88.0	63.7	112.5
SD %	49.74	53.76	56.85	29.95	48.94	23.03	40.78	21.18	25.16	34.72
CV %	62.40	59.71	51.11	30.46	48.27	26.83	61.42	24.07	39.50	30.85
m/d	08/01	08/04	08/10	08/15	08/17	08/20	08/24	08/27	08/31	09/02
	C21	C22	C23	C24	C25	C26	C27	C28		
Mean $P_{t(\%)}$	87.1	86.8	116.0	85.4	79.2	94.4	33.1	69.4		
SD %	23.52	28.54	38.16	20.96	32.71	29.89	23.22	26.66		
CV %	27.00	38.89	32.91	24.55	41.32	30.60	70.24	38.40		
m/d	09/08	09/10	09/14	09/18	09/21	09/24	09/29	10/06		

Figure 5.1 presents a comparison of collection incident rainfall magnitude (Appendix 9) with throughfall magnitude, averaged for the 36 throughfall funnel gauges by collection (Appendix 5).

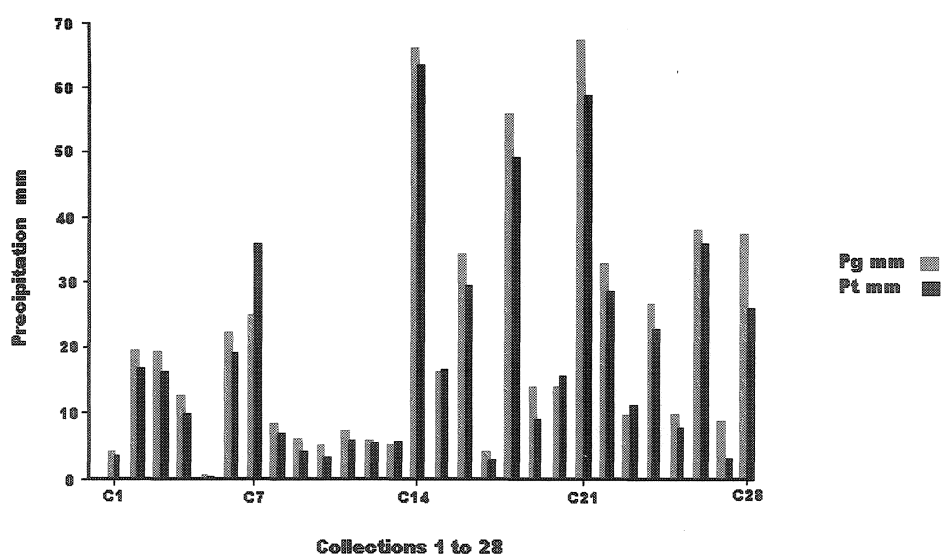

Figure 5.1. Comparison of incident rainfall (P_g) and throughfall (P_t) magnitudes for 28 collections.

5.2 Experimental Design

Cell variance, normality and related probability levels for experimental data for the grouped and individual collections are presented in Table 5.4 and Appendix 6, respectively. For the grouped collection data, the largest computed variance ratio (1:1.10) occurred between cells SE and CW.

Table 5.4. Variance and normality statistics for the grouped data of all collection events. The six cells of the experimental design are: **CW** – cutover west, **CS** – cutover summit, **CE** cutover east, **SW** – stand west, **SS** – stand summit, and **SE** – stand east. VAR is the cell variance, W is the Shapiro-Wilk statistic and P is the probability level of W.

	CW	CS	CE	SW	SS	SE
VAR	390.76	356.82	393.85	369.21	362.18	353.12
W	0.85	0.86	0.84	0.85	0.83	0.84
P	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

Figure 5.2 presents frequency histograms of the number of gauge measurements by 5 mm classes of incident rainfall and throughfall for the twenty six grouped collections. These histograms provide a visual depiction of the variability amongst cells of the experimental design and supplement the cell statistics (Table 5.4). All cells are characterized by a salient positive skew in data distribution and in general the pattern of stand throughfall follows that of the cutover incident rainfall. The forest stand cells exhibit a generally smooth stepped pattern, whereas, the cutover cells have a more jagged stepped pattern. Additionally, the forest stand cells appear progressively smoother from the east to the west. A noticeably reduced frequency in the 0-5 mm class of the cutover cells is not

mirrored in the stand cells which demonstrate higher frequencies. The higher stand cell frequencies in the 0-5 mm class are also characterized by a decreasing trend from the east, through the summit and to the west. An opposing pattern is present for the 5-10 mm, class with a decreased frequency in the stand cells and an increase in the cutover cells, relative to the 0-5 mm class. However, within this pattern the stand cell frequencies demonstrate a very slight increasing trend from the east, through summit to the west in contrast to the decrease in 0-5 mm class of stand cells. There is a gap related to low frequencies in the 45–55 mm classes for the cutover cells which is not repeated in the stand cells. Both cells for the cutover and stand are characterized by a maximum class range of 90-95 mm for both incident rainfall and throughfall. Associated increased frequencies in the stand cells is demonstrative of the occasional phenomenon of throughfall exceedance over incident rainfall.

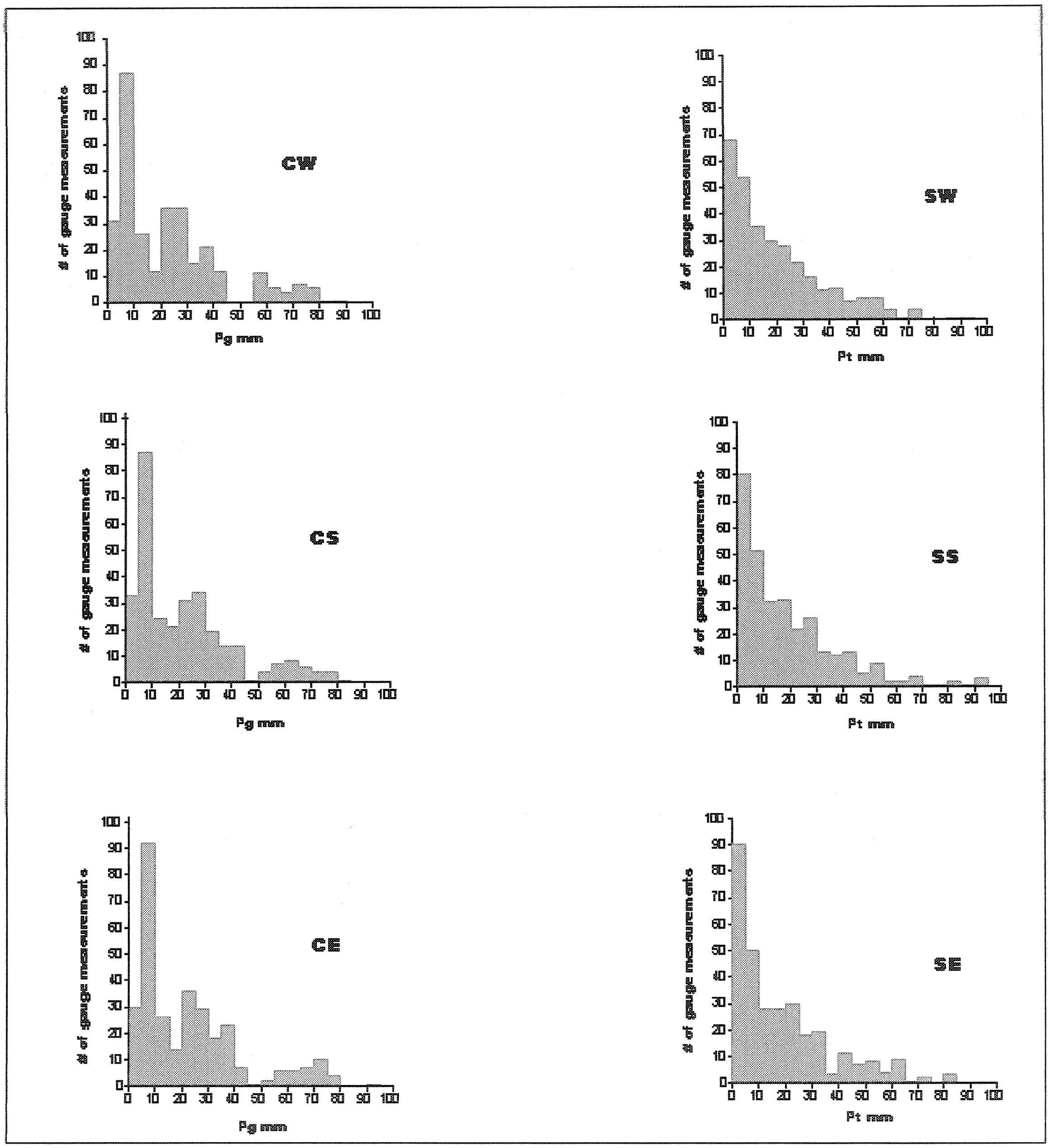

Figure 5.2. Histograms of the number of funnel gauge measurements compiled by 5 mm classes of incident rainfall (P_g) and throughfall (P_t) for the six cells: **CW** – cutover west, **CS** – cutover summit, **CE** cutover east, **SW** – stand west, **SS** – stand summit, and **SE** – stand east.

5.2.1 Forest Cover

The possible role of forest cover (i.e. cutover versus stand sites) for incident rainfall and throughfall receipt is here assessed through statistical analysis of the aforementioned results. The nested ANOVA for forest cover for grouped collections resulted in rejection of the null hypothesis at $p = 0.001$ (Table 5.5). Heteroscedastic variances and non normality at the cell level for individual collections were quite pronounced (Appendix 6).

Table 5.5. Nested ANOVA for all collections grouped. P is probability level, R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions. H_A: There is a difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions.

All Coll.	F ratio	P	Null	Alternate
	14.7	0.001	R	A

The forest cover factor with two levels, cutover and stand, was subsequently tested by the non parametric MW test in addition to the ANOVA for individual collections (Table 5.6). There was significant rejection of the null hypothesis for 22 individual collections with a similar range of probability values of $p = 0.001$ to 0.097 and $p = 0.001$ to 0.079 for the ANOVA and MW tests, respectively. Collections 5, 13,15 and 18 accepted the null hypothesis for the ANOVA testing. The MW tests agreed with the ANOVA results excepting collection 5 which rejected the null hypothesis by the MW test. Acceptance and rejection probabilities for collection 5 were $p = 0.182$ and $p = 0.001$, respectively. Collections 13, 15 and 18 had respective acceptance probabilities for the ANOVA and MW tests of $p = 0.708$, $p = 0.807$, $p = 0.801$, $p = 0.111$, and $p = 0.304$, $p = 0.330$.

Table 5.6. Nested ANOVA for individual collections for the forest cover factor. P are probability levels, U is the MW test statistic. R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions. H_A: There is a difference between mean throughfall and mean incident rainfall for mature balsam fir cover and clearcut cover conditions.

Coll #	F ratio	P	Null	Alternate	U	P	Null	Alternate
1	3.07	0.097	R	A	493.50	0.079	R	A
2	28.66	0.000	R	A	201.50	0.000	R	A
3	22.19	0.000	R	A	212.50	0.000	R	A
4	23.44	0.000	R	A	207.50	0.000	R	A
5	1.92	0.182	A	R	419.00	0.001	R	A
6	24.07	0.000	R	A	266.50	0.000	R	A
7	11.82	0.003	R	A	940.50	0.001	R	A
8	21.76	0.000	R	A	233.50	0.000	R	A
9	16.10	0.001	R	A	216.50	0.000	R	A
10	32.14	0.000	R	A	175.50	0.000	R	A
11	16.15	0.001	R	A	301.00	0.000	R	A
12	4.65	0.040	R	A	315.00	0.000	R	A
13	0.145	0.708	A	R	626.50	0.807	A	R
14	7.30	0.014	R	A	466.00	0.040	R	A
15	0.065	0.801	A	R	506.50	0.111	A	R
16	12.87	0.002	R	A	313.00	0.000	R	A
17	5.52	0.030	R	A	420.00	0.010	R	A
18	1.11	0.304	A	R	561.50	0.33	A	R
19	7.84	0.011	R	A	227.50	0.000	R	A
20	11.53	0.003	R	A	332.50	0.000	R	A
21	15.70	0.001	R	A	959.00	0.001	R	A
22	8.04	0.011	R	A	278.00	0.000	R	A
23	22.95	0.000	R	A	201.50	0.000	R	A
24	6.24	0.022	R	A	309.00	0.000	R	A
25	417.18	0.000	R	A	37.50	0.000	R	A
26	24.94	0.000	R	A	160.00	0.000	R	A

The physical character of these collections was different. Collection 5 was characterized by a very low incident rainfall of 0.3 mm, a rainfall intensity of 2.6 mm hr^{-1} (Table 5.17) and a throughfall percentage of 65.3% (Table 5.3). Collection 13 was characterized by an incident rainfall of 5.0 mm, a rainfall intensity of 1.9 mm hr^{-1} (Table 5.17) and a throughfall percentage of 111.2% (Table 5.3). Collection 15 was characterized by an incident rainfall of 16.3 mm, a rainfall intensity of 5.3 mm hr^{-1} (Table 5.17) and a throughfall percentage of

101.4% (Table 5.3). Collection 18 was characterized by an incident rainfall of 27.8 mm, with a rainfall intensity of 0.9 mm hr^{-1} and a throughfall percentage of 88.1 %.

5.2.2 Topography

The possible role of topographic position (i.e. west-facing, east-facing and summit sites) for incident rainfall and throughfall receipt is here assessed through statistical analysis of the aforementioned results. The nested ANOVA model for the topographic factor for twenty six collections grouped resulted in acceptance of the null hypothesis at p = 0.359 (Table 5.7).

Table 5.7. Nested ANOVA for all collections grouped. P is probability level, R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference in mean throughfall and mean incident rainfall between topographic positions. H_A: There is a difference in mean throughfall and mean incident rainfall between topographic positions.

All	F ratio	P	Null	Alternate
	1.08	0.359	A	R

Heteroscedastic variances and non normality at the cell level for individual collections were quite pronounced (Appendix 6). The topographic factor with three levels, east-facing slopes, summits and west-facing slopes, was subsequently tested by the non parametric KW test in addition to the ANOVA for individual collections. There was acceptance of the null hypothesis for 24 individual collections with a similar range of probability values of p = 0.212 to 0.998 and p = 0.117 to 0.983 for the ANOVA and

KW tests, respectively (Table 5.8). Four collections differed in their respective null hypothesis rejections with the ANOVA and KW tests. Further examination of these collections was undertaken to explore the discrepant acceptances or rejections of the ANOVA and KW testing.

Collection 3 had rejection of the null hypothesis, $p = 0.067$, with the KW test but acceptance with the ANOVA test (Table 5.8). The maximum variance ratio of 1:129.3 between cells CW and SE, is indicative of a lack of homogeneity which can affect ANOVA robustness. The p values obtained for normality for some cells are interpreted as indicating that data distributions for this collection were non-normal. The KW test appears to be the more applicable and statistically inferential for this collection. Pairwise comparison testing corresponding to the significant KW test revealed that west-facing and summit sites were significantly different for the combined receipt of incident rainfall and throughfall (i.e. west = CW + SW and summit = CS + SS, (Fig. 4.3), at at $0.1 < p > 0.05$. Collection 3 had a total combined $\mathbf{P_g}$ and $\mathbf{P_t}$ gauge catch of 475.8 mm for all west aspect slope topographic replicates and 423.3 mm for all summit replicates, resulting in a 12.4% increase for the west aspect versus the summit topographic positions. The mean wind direction for collection 3 was 171 degrees with a mean speed of 14.3 m s^{-1} (Table 5.15) and an incident rainfall of 19.4 mm (Table 5.17) received in 644 minutes (Appendix 9).

Collections 8 had rejection of the null hypothesis, $p = 0.015$, with the KW test but acceptance with the ANOVA test (Table 5.8). The maximum variance ratio of 1:82.5 between cells CW and SE is indicative of a lack of homogeneity which can affect ANOVA robustness. The p values for normality obtained for some cells are interpreted that data distributions for this collection were non-normal. The KW test appears to be the more applicable and statistically inferential for this collection. Pairwise comparisons resulted in significant differences between west aspect and summit topographic positions at $p < 0.05$. Collection 8 had a total combined $\mathbf{P_g}$ and $\mathbf{P_t}$ gauge catch of 212.2 mm for all west-facing slope replicates and 170.7 mm for all summit replicates resulting in a 24.3% increase for the west aspect versus the summit topographic positions. For collection 8, the mean wind direction was 138 degrees with a mean speed of 14.9 m s^{-1} and an incident rainfall of 8.3 mm which was received in 292 minutes.

Collection 24 had rejection of the null hypothesis, $p = 0.058$, with the ANOVA test but acceptance with the KW test (Table 5.8). The maximum variance ratio of 1:258.1 between cells CS and SE is again indicative of a lack of homogeneity affecting ANOVA robustness. However, the W statistics and p values for most cells are interpreted as showing that data distributions for this collection were approximately normal. The ANOVA test appears to be the more applicable and statistically inferential for this collection 24. Tukey multiple comparison testing corresponding to the significant ANOVA test revealed that west-facing and summit sites and west-facing and east-facing sites were significantly different, for receipt of mean incident rainfall and throughfall, at p

= 0.06 and p = 0.09 respectively. Collection 24 had a total combined $\mathbb{P}_g$ and $\mathbb{P}_t$ gauge catch of 984.4 mm for all west-facing slope topographic replicates, 899.1 mm for all summit replicates, and 895.6 mm for all east-facing slope replicates, resulting in respective 9.5% and 9.9% increases for the west aspect versus the summit and east aspect topographic positions. For collection 24 the mean wind direction and speed for the collection was 157 degrees and 15.6 m s^{-1} with an event incident rainfall of 38.0 mm which was received in 1673 minutes.

Collections 25 had rejection of the null hypothesis, p 0.008, with the ANOVA test but acceptance with the KW test (Table 5.8). The maximum variance ratio of 1:29.41 between cells CW and SW demonstrates some lack of homogeneity which can affect ANOVA robustness. The p values for normality obtained for some cells are interpreted that data distributions for this collection approached normality. The ANOVA test appears to have reasonable statistical inferential potential for this collection. Tukey multiple comparison testing corresponding to the significant ANOVA test revealed that west aspect and east aspect topographic positions were significantly different, for receipt of mean incident rainfall and throughfall, at $p < 0.05$. For collection 25 the west and east aspects were significantly different at $p = 0.007$ with a a total combined $\mathbb{P}_g$ and $\mathbb{P}_t$ gauge catch of 157.1 mm for all west-facing topographic replicates and 125.2 mm for all east aspect replicates representing a 25.5% increase for the west aspect. The mean wind direction and speed for the collection was 179 degrees and 17.4 m s^{-1} with an event incident rainfall of 8.7 mm which was received in 491 minutes.

Table 5.8. Nested ANOVA for individual collections for the topographic factor. P are probability levels, H is KW test statistic. R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference in mean throughfall and mean incident rainfall between topographic positions. H_A: There is a difference in mean throughfall and mean incident rainfall between topographic positions.

Coll #	F ratio	P	Null	Alternate	H	P	Null	Alternate
1	0.54	0.593	A	R	0.36	0.835	A	R
2	0.002	0.998	A	R	0.87	0.646	A	R
3	1.65	0.218	A	R	5.45	0.067	R	A
4	0.59	0.567	A	R	0.99	0.608	A	R
5	0.93	0.410	A	R	3.04	0.219	A	R
6	0.96	0.401	A	R	1.63	0.442	A	R
7	0.54	0.594	A	R	0.94	0.624	A	R
8	1.04	0.373	A	R	8.46	0.015	R	A
9	0.54	0.591	A	R	1.39	0.388	A	R
10	0.80	0.464	A	R	1.64	0.440	A	R
11	0.48	0.625	A	R	1.98	0.371	A	R
12	0.77	0.479	A	R	3.88	0.144	A	R
13	1.23	0.313	A	R	1.36	0.508	A	R
14	1.64	0.220	A	R	0.62	0.734	A	R
15	0.64	0.541	A	R	3.70	0.157	A	R
16	1.65	0.219	A	R	2.70	0.260	A	R
17	0.40	0.675	A	R	0.67	0.715	A	R
18	0.36	0.705	A	R	1.48	0.477	A	R
19	0.47	0.634	A	R	0.71	0.700	A	R
20	1.68	0.212	A	R	4.30	0.117	A	R
21	0.48	0.627	A	R	0.03	0.983	A	R
22	0.09	0.915	A	R	2.04	0.360	A	R
23	0.66	0.529	A	R	0.92	0.631	A	R
24	3.31	0.058	R	A	3.19	0.203	A	R
25	6.21	0.008	R	A	3.19	0.203	A	R
26	0.25	0.781	A	R	0.93	0.629	A	R

5.2.3 Forest cover - topographic interaction

The possible role of an interactive effect of forest cover and topographic position for incident rainfall and throughfall receipt is here assessed through statistical analysis of the aforementioned results. The nested ANOVA model for the interaction of forest cover and topographic factors for the twenty six collections grouped resulted in acceptance of the null hypothesis at p = 0.565 (Table 5.9).

Table 5.9. Nested ANOVA for all collections grouped. P is probability level. R is rejection and A is acceptance of stated hypotheses; H_O: There is no interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall. H_A: There is an interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall.

All	F ratio	P	Null	Alternate
	0.59	0.565	A	R

There was acceptance of the null hypothesis for 25 individual collections, with the range of probability values being from p = 0.283 to 0.947, for the ANOVA test (Table 5.10).

Table 5.10. Nested ANOVA for individual collections for the forest cover - topographic interaction. P is probability level. R is rejection and A is acceptance of stated hypotheses; H_O: There is no interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall. H_A: There is an interactive effect of forest cover condition and topographic position upon mean throughfall and mean incident rainfall.

Coll #	F ratio	P	Null	Alternate	Coll #	F ratio	P	Null	Alternate
1	0.99	0.392	A	R	14	0.14	0.869	A	R
2	0.59	0.564	A	R	15	0.15	0.863	A	R
3	0.78	0.473	A	R	16	1.24	0.313	A	R
4	0.65	0.531	A	R	17	0.11	0.897	A	R
5	0.29	0.755	A	R	18	0.06	0.947	A	R
6	0.15	0.858	A	R	19	0.91	0.420	A	R
7	0.48	0.626	A	R	20	0.84	0.447	A	R
8	0.34	0.715	A	R	21	1.12	0.347	A	R
9	0.42	0.664	A	R	22	0.12	0.890	A	R
10	1.22	0.318	A	R	23	0.47	0.634	A	R
11	0.34	0.716	A	R	24	3.31	0.085	R	A
12	0.30	0.746	A	R	25	1.35	0.283	A	R
13	1.31	0.294	A	R	26	0.08	0.921	A	R

Collection 24 was the only individual collection with rejection of the null hypothesis at p = 0.085, indicating a significant forest cover and topographic factor interaction. The mean wind direction for collection 24 was 157 degrees with a mean wind speed of 15.6m s^{-1} (Table 5.15) and an incident rainfall of 38.0mm (Table 5.17).

5.2.4 Nesting of replicates

The possible role of replicate variability within cells for incident rainfall and throughfall reciept is here assessed through statistical analysis of the aforementioned results. The nested ANOVA model for within cell variability of incident rainfall and throughfall for the twenty six collections grouped resulted in acceptance of the null hypothesis at $p = 0.593$ (Table 5.11).

Table 5.11. Nested ANOVA for all collections grouped. P is probability level. R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover. H_A: There is a difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover.

All	F ratio	P	Null	Alternate
	0.892	0.593	A	R

There was acceptance of the null hypothesis for 17 of the 26 individual collections, with probability values ranging from $p = 0.159$ to 0.942 for the ANOVA test (Table 5.12). Conversely, collections 5, 9, 12, 13, 17, and 19 all rejected the null hypothesis at $p \leq 0.05$, whereas collections 22, 24 and 26 had rejections at $0.05 < p < 0.10$. Collection incident rainfall depths ranged from a low of 0.3 mm to a high of 67.3 mm (Table 5.17). Incident rainfalls (P_g) < 10 mm occurred for collections 5, 9, 12 and 13; > 25 < 50 mm for collections 22, 24 and 26; and > 50 mm for collections 17 and 19. Significances at $p \leq 0.05$ were associated with the smaller incident rainfalls of collections 5, 9, 12 and 13 and the greater rainfalls of collections 17 and 19.

Table 5.12. Nested ANOVA for individual collections for nesting of topographic replicates. P is probability level, R is rejection and A is acceptance of stated hypotheses; H_O: There is no difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover. H_A: There is a difference in mean throughfall or mean incident rainfall amongst replicates within the combinations of topography and forest cover.

Coll #	F ratio	P	Null	Alternate	Coll #	F ratio	P	Null	Alternate
1	0.44	0.937	A	R	14	0.69	0.811	A	R
2	0.66	0.841	A	R	15	1.34	0.207	A	R
3	1.23	0.278	A	R	16	1.04	0.438	A	R
4	0.79	0.703	A	R	17	2.59	0.004	R	A
5	3.10	0.001	R	A	18	1.34	0.207	A	R
6	0.98	0.501	A	R	19	2.64	0.004	R	A
7	1.05	0.433	A	R	20	1.21	0.288	A	R
8	1.07	0.410	A	R	21	0.93	0.549	A	R
9	3.10	0.001	R	A	22	1.63	0.088	R	A
10	0.75	0.744	A	R	23	1.30	0.232	A	R
11	1.43	0.159	A	R	24	1.62	0.092	R	A
12	2.07	0.022	R	A	25	0.51	0.942	A	R
13	1.79	0.050	R	A	26	1.66	0.080	R	A

5.3 Throughfall Data Screening for Collection Differences

Testing throughfall magnitudes amongst collections due to prevailing meteorological conditions, irrespective of canopy variability at the level of individual tree scale plots was undertaken. The standardized throughfall percentage (**$SP_{t(\%)}$**) data (Appendix 7) were screened for differences amongst collections using the KW test and post hoc multiple comparisons. The null hypothesis was rejected ($H = 271.6$, $p < 0.001$) indicating a highly significant difference in collections. Appendix 8 presents the z scores of pairwise comparisons of the different collection events. Pairwise collection comparisons indicate that 37 comparisons, from the total of 378, were significant at $p \leq 0.05$; $z \geq 3.82$ and 43 were significant at $0.05 < p \leq 0.10$; $3.82 > z \geq 3.65$. The respective percentages of significant pairwise comparisons were 9.8% and 11.4%. Appendix 7 was rearranged in the form of a cross tabulation of plot frequencies by collection and **$SP_{t(\%)}$** rankings from one to twenty-eight (Table 5.13). The cross tabulated data were then graphed as a histogram of numbers of plots by rankings, for each collection, providing a visual analysis of potential meteorological patterns and influences within and across collections. Figures 5.3 to 5.5 present cross tabulation derived histograms subjectively arranged into groups of collections with varying degrees of salient positive and negative skews and normal distribution patterns, respectively. Examination of the range of z scores (Appendix 8) reveals that collections within the histogram groups are related to the z score range and to the threshold z scores. For example, collection 7 is characterized by maximum positive skew (Fig. 5.3) compared to collection 27 with maximum negative skew (Fig. 5.4). The pairwise statistical comparison between these two collections had the maximum z score of 11.38. This maximum is followed by high but decreasing z score comparisons for collections 7 versus 27, 23 versus 27, 20 versus 27, and 7 versus 9 which demonstrate similarly strong and salient differences in positive and negative skews (Appendix 8, Figs. 5.3 and 5.4). Z scores in the significance level range of $0.5 < p \leq 0.10$ tended to be represented by inter group collection comparisons between positive skew and normal and negative skew and normal patterns. The lower range of z scores tended to be represented by intra group collection comparisons. For example, the lowest z scores, $z = 0.01$, were for a comparisons of collection 17 to 19 and 22 and 24 which can be observed to have similar distribution patterns on Figures 5.4 and 5.5, respectively.

Table 5.13. Cross tabulated plot counts by collection and $SP_{t(\%)}$ rankings.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
C1	5	3	1	3	1	1	0	0	0	3	0	3	1	0
C2	2	1	1	0	2	2	0	2	0	1	4	0	0	2
C3	0	1	0	0	2	3	4	0	0	3	0	2	1	4
C4	1	0	2	2	1	1	1	1	0	0	0	0	2	1
C5	0	0	1	0	0	1	0	0	1	2	2	1	0	2
C6	0	2	0	1	1	1	5	0	3	3	0	1	2	0
C7	14	6	4	3	1	0	1	1	0	0	0	1	1	1
C8	1	0	2	2	1	1	2	0	2	2	1	1	2	0
C9	0	0	0	0	0	1	2	0	1	1	0	2	0	0
C10	0	0	0	1	0	1	0	0	1	0	1	1	2	3
C11	0	0	2	2	2	1	1	2	1	0	2	0	0	0
C12	2	1	2	0	0	1	1	2	4	0	1	1	0	2
C13	4	5	4	4	0	1	1	1	2	0	1	1	2	1
C14	1	3	3	0	2	3	0	3	1	3	0	2	0	1
C15	0	2	4	3	4	1	0	1	0	1	0	2	2	0
C16	0	0	0	1	2	1	0	3	0	5	3	2	4	1
C17	0	1	0	2	2	0	2	0	2	0	0	0	0	2
C18	0	1	1	0	1	3	2	2	0	1	2	2	2	3
C19	0	0	1	0	1	0	0	0	0	0	2	1	1	1
C20	0	1	2	4	4	5	2	6	2	1	1	1	3	0
C21	2	0	2	2	0	1	0	2	5	2	3	0	2	2
C22	1	0	2	2	1	0	2	3	2	2	0	2	2	0
C23	3	9	2	2	3	2	2	1	2	0	3	0	2	1
C24	0	0	0	0	1	1	3	1	2	2	2	4	2	6
C25	0	0	0	0	2	0	1	1	2	1	3	2	0	1
C26	0	0	1	1	1	2	4	4	3	2	1	2	1	2
C27	0	0	1	0	0	1	0	0	0	0	0	0	0	0
C28	0	0	0	0	0	1	0	0	0	1	4	1	1	0

	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28
C1	2	0	0	1	0	2	0	1	1	0	0	2	3	3
C2	1	1	2	2	2	2	1	2	2	3	1	1	0	0
C3	2	3	1	2	1	1	1	1	2	0	2	0	0	0
C4	0	4	2	0	1	3	1	5	0	2	5	0	1	0
C5	0	3	2	1	3	1	1	3	2	4	0	1	1	3
C6	1	2	2	2	2	1	2	0	1	0	1	1	1	1
C7	1	0	1	1	0	0	0	0	0	0	0	0	0	0
C8	1	2	1	3	1	0	1	0	2	1	3	3	0	0
C9	0	1	3	0	1	3	4	0	1	2	1	4	7	2
C10	1	0	3	5	0	0	2	3	1	2	1	3	4	1
C11	1	1	1	2	0	0	3	2	3	3	2	1	2	1
C12	0	0	0	0	0	3	1	2	2	3	3	2	0	0
C13	0	0	2	3	2	0	0	0	1	0	1	0	1	1
C14	2	1	1	1	0	0	3	2	2	0	0	1	1	0
C15	0	2	1	1	4	2	3	0	0	1	1	1	0	0
C16	0	3	1	0	3	1	2	2	2	0	0	0	0	0
C17	0	0	0	0	4	2	2	3	3	2	1	2	4	2
C18	5	1	2	1	1	2	1	1	0	0	0	2	0	0
C19	0	2	3	1	3	3	0	2	2	2	2	5	3	1
C20	1	1	0	1	0	0	0	0	0	0	0	0	1	0
C21	3	0	0	1	2	1	2	1	1	1	1	0	0	2
C22	0	0	3	1	2	2	3	1	2	0	1	0	1	0
C23	0	0	1	1	0	0	0	0	0	0	0	0	0	0
C24	3	4	2	0	0	0	1	0	0	1	0	0	1	0
C25	5	1	0	2	0	3	2	1	2	3	3	1	0	0
C26	7	1	2	0	0	1	0	0	0	1	0	0	0	0
C27	0	0	0	0	1	1	0	0	0	2	2	6	4	19
C28	0	3	0	4	4	2	0	3	4	3	4	0	1	0

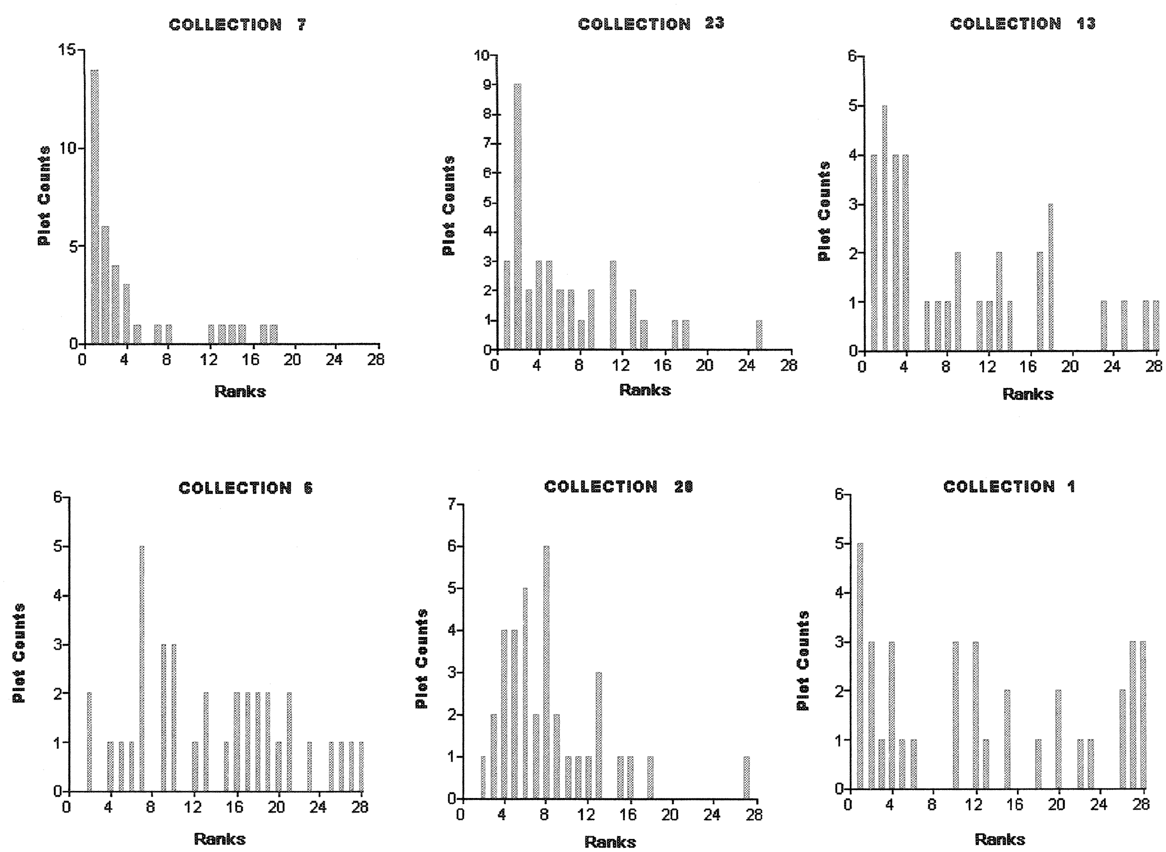

Figure 5.3. Histograms of cross tabulated plot counts and $SP_{t(\%)}$ rankings by collections. This group of collections displays positive skew. Refer also to table 5.13.

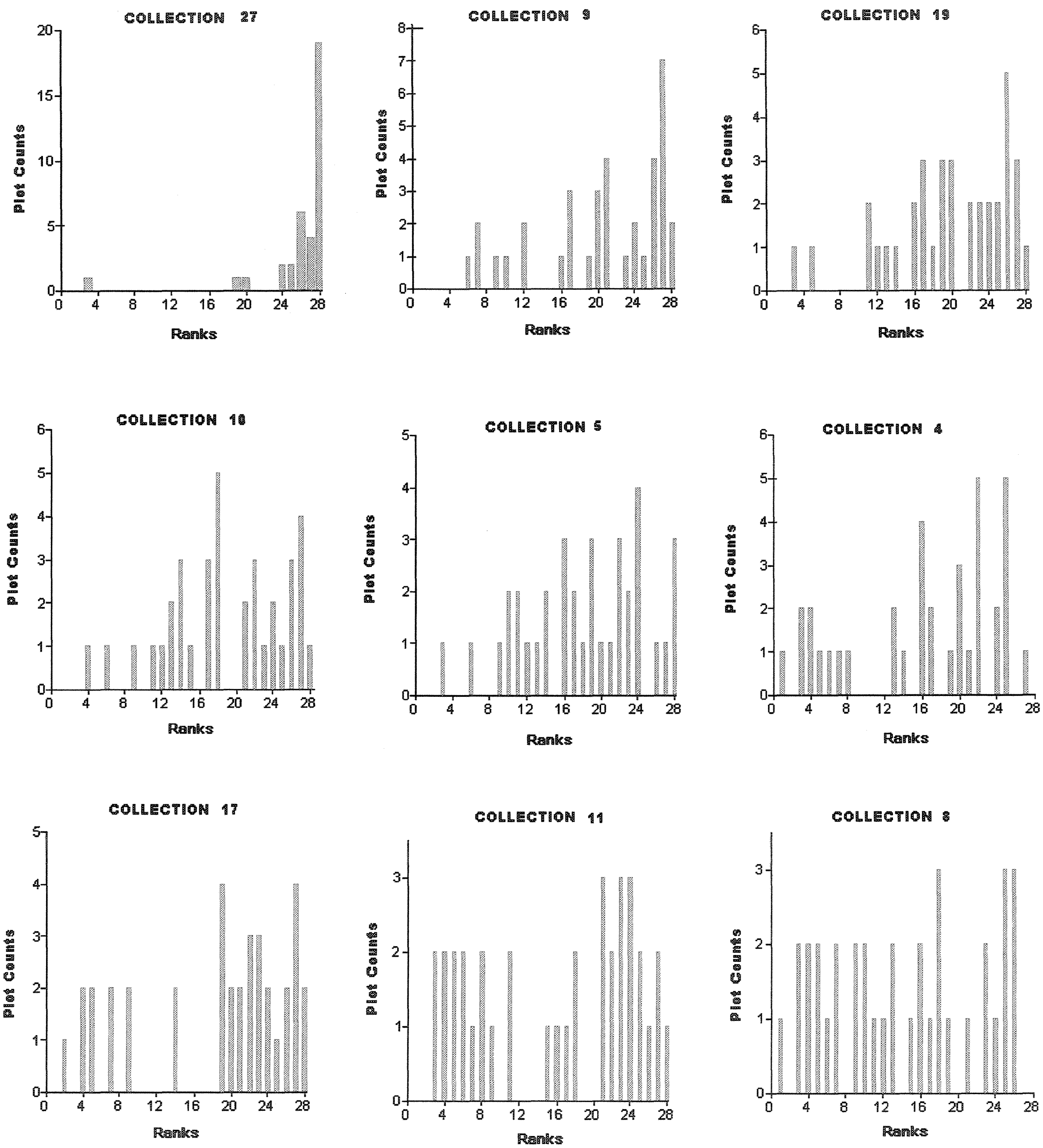

Figure 5.4. Histograms of cross tabulated plot counts and $SP_{t(\%)}$ rankings by collections. This group of collections displays negative skew. Refer also to table 5.13.

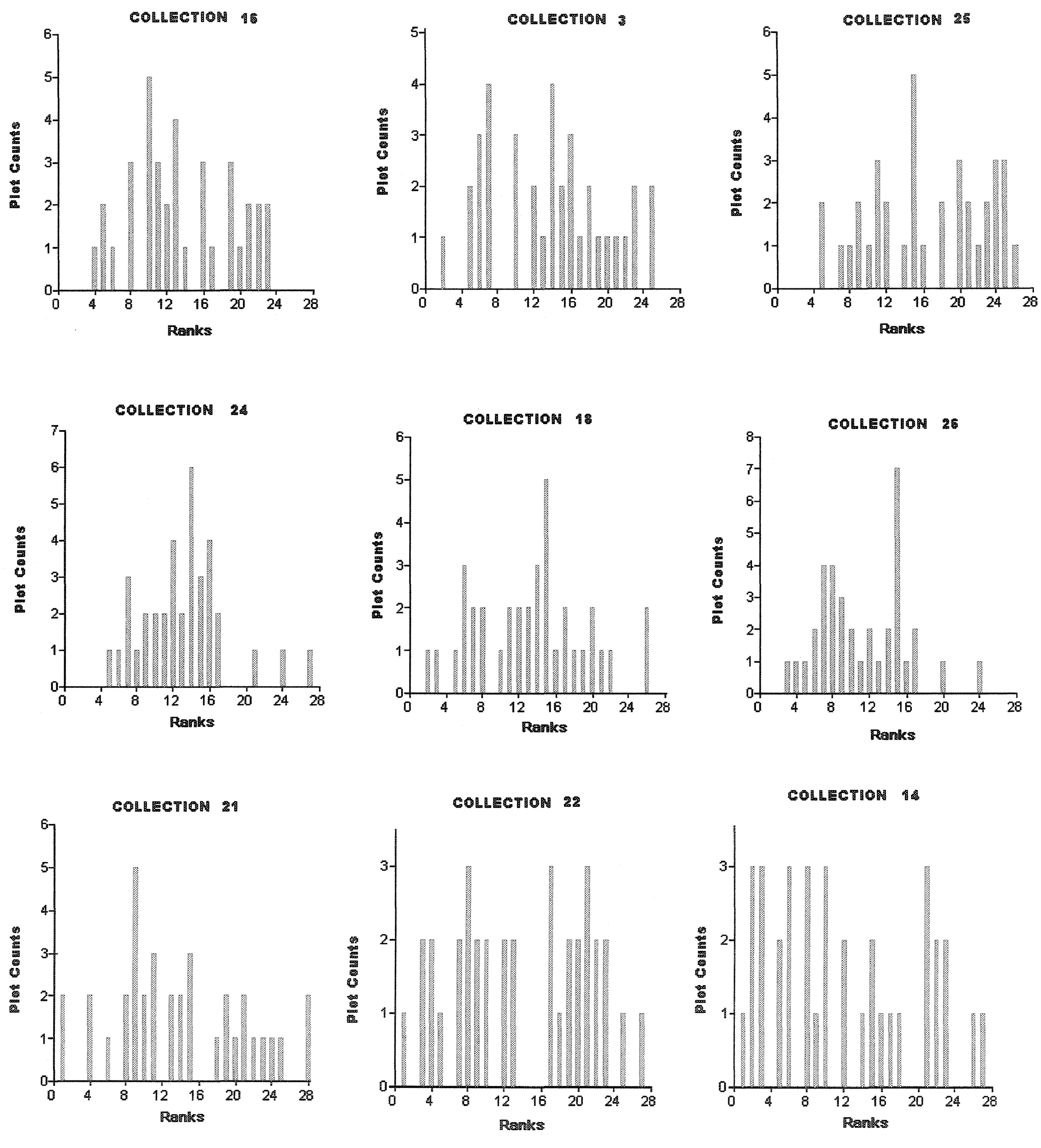

Figure 5.5. Histograms of cross tabulated plot counts and $\mathbf{SP}_{t(\%)}$ rankings by collections. This group of collections appears more as a normal distribution with no predominant skew. Refer also to table 5.13.

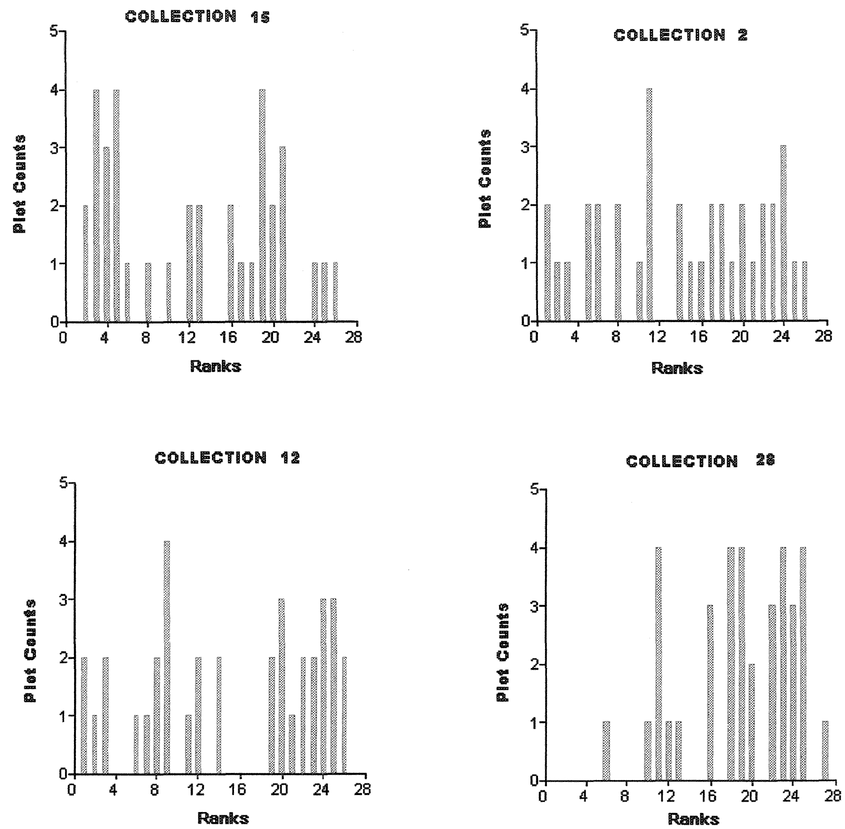

Figure 5.5 (cont'd). Histograms of cross tabulated plot counts and $\mathbf{SP_{t(\%)}}$ rankings by collections. This group of collections appears more as a normal distribution with no predominant skew. Refer also to table 5.13.

5.3.1 Air temperature and relative humidity between collections

Potential relationships of air temperature and relative humidity between collections with collection throughfall magnitudes were investigated through correlation analysis. Table 5.14 presents the collection mean standardized percentage throughfall data ($\mathbf{SP_{t(\%)}}$), air temperatures and relative humidity. Air temperature, as would be expected, has a general trend of summer increase followed by an autumnal decrease. Relative humidity does not appear to have any trend and is characterized by mean collection values that are generally > 70% up to a maximum value of 100%. Additionally, the $\mathbf{SP}_{t(\%)}$ data does not appear to exhibit any temporal trend.

Table 5.14. Correlation data for mean collection air temperature (TEMP), mean collection relative humidity (RH) and standardized percent throughfall $S_{Pt(\%)}$ for 28 throughfall collection events (Coll #).

Coll #	Mean $\mathbf{SP}_{t(\%)}$	TEMP	RH	Coll #	Mean $\mathbf{SP}_{t(\%)}$	TEMP	RH
1	55.2	13.0	63	15	61.2	14.7	85
2	55.6	11.8	97	16	55.0	14.4	86
3	54.0	12.6	78	17	41.3	11.6	91
4	49.9	13.8	78	18	57.2	11.5	80
5	43.1	14.9	78	19	41.7	9.8	97
6	55.0	11.6	83	20	70.2	11.6	99
7	88.4	12.7	88	21	56.6	9.7	95
8	56.0	18.9	87	22	56.1	10.7	100
9	32.2	16.7	74	23	74.0	11.4	98
10	40.5	14.5	82	24	55.6	9.5	89
11	47.8	15.9	77	25	48.5	5.4	92
12	54.0	15.1	72	26	59.6	8.4	89
13	68.2	16.1	79	27	20.6	8.9	88
14	61.7	19.2	91	28	44.1	6.4	93

Figure 5.6 a and b presents scatter plots of mean collection $\mathbf{SP}_{t(\%)}$ versus mean temperature and mean collection $\mathbf{SP}_{t(\%)}$ versus mean relative humidity. Respective correlation coefficients of r = 0.13 and r = 0.19 were not significant. In both plots the spread of $\mathbf{SP}_{t(\%)}$ is small with most data points in the 40% - 60% range. However, the 40% - 60% band of $\mathbf{SP}_{t(\%)}$ of Fig. 5.6a is characterized by a larger x-axis spread associated with the seasonal temperature trends. This pattern contrasts with that of relative humidity (Fig. 5.6b) which demonstrates a relatively narrow x-axis dispersion of the $\mathbf{SP}_{t(\%)}$ data due to a corresponding restricted range in the relative humidity. However, the pattern of both plots demonstrates

that the throughfall magnitude has a relatively stable range.

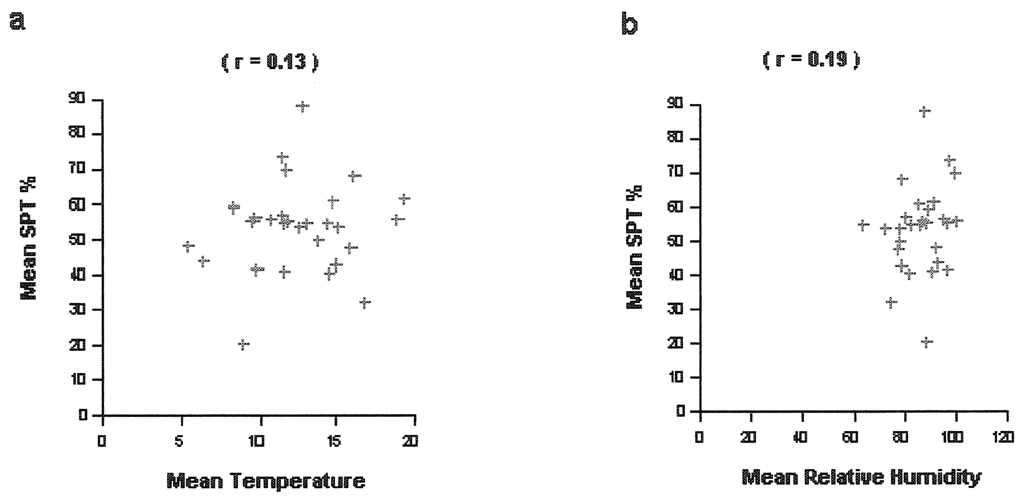

Figure 5.6. Scatter plot (**a**) mean collection air temperature (° C) and mean collection $\mathbf{SP_{t(\%)}}$ for all throughfall plots grouped. Correlation coefficient (**r**) not significant at $p > 0.5$. Scatter plot (**b**) mean collection relative humidity and mean collection $\mathbf{SP_{t(\%)}}$ for all throughfall plots grouped. Correlation coefficient (**r**) not significant at $p > 0.3$

5.3.2 Wind direction and wind speed during collections

Potential relationships of wind direction and wind speed during collections with collection throughfall magnitudes were investigated utilizing MW testing and correlation analysis. Table 5.15 presents the collection mean standardized percentage throughfall data ($\mathbf{SP_{t(\%)}}$) and the associated wind direction and wind speed. Mean wind directions were all from between northeast and south (49 – 179 degrees true azimuth) during rainfall events. The range of wind directions enabled a midpoint value partitioning into two groups, defined as 49 to 114 and >114 degrees, which were nominally referred to as NE and SE wind sectors with 13 and 15 collection events, respectively. However, there does not appear to be major seasonal change in wind direction from summer to autumn. Mean wind speeds, however, do appear to strengthen in the later collections of autumn as the season changes. As noted previously, the $\mathbf{SP}_{t(\%)}$ data do not appear to exhibit any visible trend.

Table 5.15. Data for mean collection mean wind direction in degrees (DIR), mean collection wind speed (SPEED) in m s^{-1} and standardized percent throughfall $S_{Pt(\%)}$ for 28 throughfall collection events (Coll #).

Coll #	Mean $\mathbf{SP}_{t(\%)}$	DIR	SPEED	Coll #	Mean $\mathbf{SP}_{t(\%)}$	DIR	SPEED
1	55.2	143	10.3	15	61.2	138	18.9
2	55.6	74	15.7	16	55.0	133	11.4
3	54.0	171	14.3	17	41.3	80	13.4
4	49.9	80	10.7	18	57.2	89	19.9
5	43.1	130	15.7	19	41.7	96	13.0
6	55.0	55	16.0	20	70.2	141	12.2
7	88.4	162	11.7	21	56.6	49	23.4
8	56.0	139	14.9	22	56.1	93	16.2
9	32.2	119	15.6	23	74.0	105	10.1
10	40.5	171	11.9	24	55.6	57	20.0
11	47.8	150	12.7	25	48.5	136	17.6
12	54.0	135	15.3	26	59.6	157	15.6
13	68.2	102	13.8	27	20.6	179	17.4
14	61.7	83	23.7	28	44.1	111	21.1

Figure 28 (a) presents a scatter plot of mean collection $\mathbf{SP}_{t(\%)}$ versus mean wind speed while (b) presents a histogram of mean collection $\mathbf{SP}_{t(\%)}$ versus mean wind direction. The correlation coefficient of $r = -0.14$ was not significant (Fig. 28 a), while the MW test statistic, $U = 117$, was also not significant (Fig. 28b). In both plots (Fig. 28a and b) the vertical range of $SP_{t(\%)}$ shows most data contained within 40% - 60%. A somewhat larger x-axis dispersion is associated with most wind speeds and directions, ranging predominantly between 10 – 16 m s^{-1} and 55 to 170 degrees, respectively. The pattern of both plots demonstrates that the throughfall magnitude has a relatively stable range.

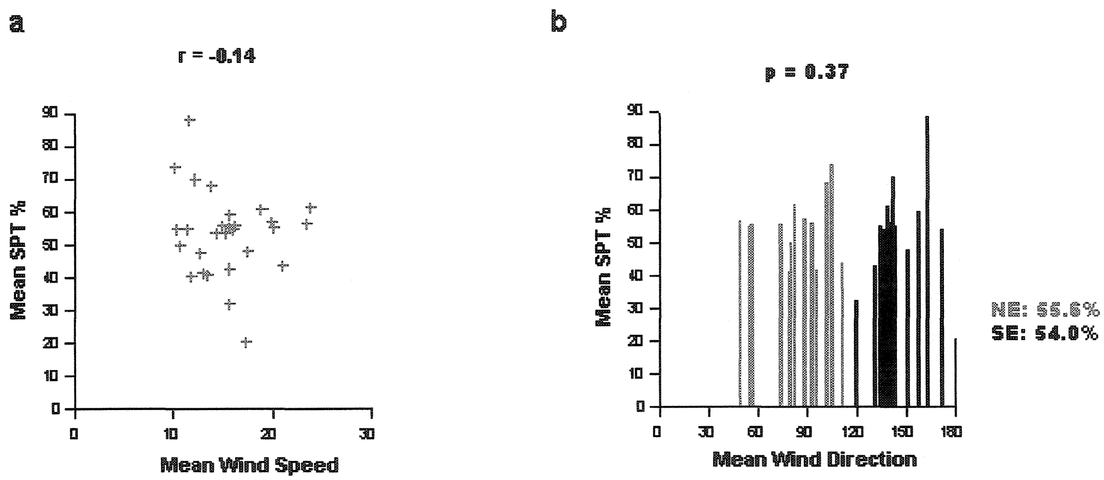

Figure 5.7. Scatter plot (a) mean collection wind speed (metres per second) and mean collection $SP_{t(\%)}$ for all throughfall plots grouped. Correlation coefficient (r) not significant at $p > 0.4$. Histogram (b) of mean collection wind direction (degrees true) and mean collection $SP_{t(\%)}$ for all throughfall plots grouped. Median $SP_{t(\%)}$ values for northeast sector winds (NE) compared to southeast (SE) sector not significant at $p = 0.37$.

MW U tests (Table 5.16) were undertaken for mean collection wind directions (Table 5.15) and individual collection $SP_{t(\%)}$ values for each throughfall plot (Appendix 7). Eleven of the 36 plots demonstrated significant differences ($p \leq 0.10$) in throughfall magnitudes between NE and SE wind sectors. In rank order of strength of probabilities, significantly greater throughfall magnitudes were associated with NE sector winds for plots 18, 16, 22, 29, 36 and 13, with the probability values ranging from p = 0.001 to p = 0.102. Significantly greater throughfall magnitudes were associated with SE sector winds for plots 19, 1, 20, 27, and 24, with the probability values ranging from p = 0.016 to p = 0.093. The eleven plots having statistically significant wind direction effects were comprised of 5 easterly aspect, 3 summit and 3 westerly aspect topographic positions (Fig. 5.8). Specifically, greater throughfall magnitudes associated with NE sector winds occurred for 4 easterly aspect plots, 1 summit plot and 1 westerly aspect plot, whereas greater throughfall magnitudes associated with SE sector winds occurred for 1 easterly aspect plot, 2 summit plots and 2 westerly aspect plots.

Table 5.16. Results of Mann Whitney U tests for northeast sector winds compared with southeast sector winds for individual throughfall plots. Plots with significantly different median $\mathbf{SP}_{t(\%)}$ values at $p \leq 0.10$*.

Plot	U	p	Plot	U	p
1	34	0.030*	19	45	0.016*
2	92	0.800	20	56	0.056*
3	83	0.504	21	102	0.836
4	89	0.695	22	151	0.014*
5	69	0.189	23	131	0.123
6	104	0.765	24	61	0. 093*
7	106	0.695	25	128	0.160
8	77	0.497	26	87	0.629
9	85	0.771	27	56	0.056*
10	90	0.758	28	129	0.147
11	125	0.205	29	140	0.050*
12	100	0.662	30	94	0.872
13	133	0.102*	31	109	0.596
14	106	0.695	32	69	0.123
15	86	0.596	33	88	0.662
16	154	0.009*	34	131	0.123
17	99	0.945	35	125	0.205
18	173	0.001*	36	135	0.085*

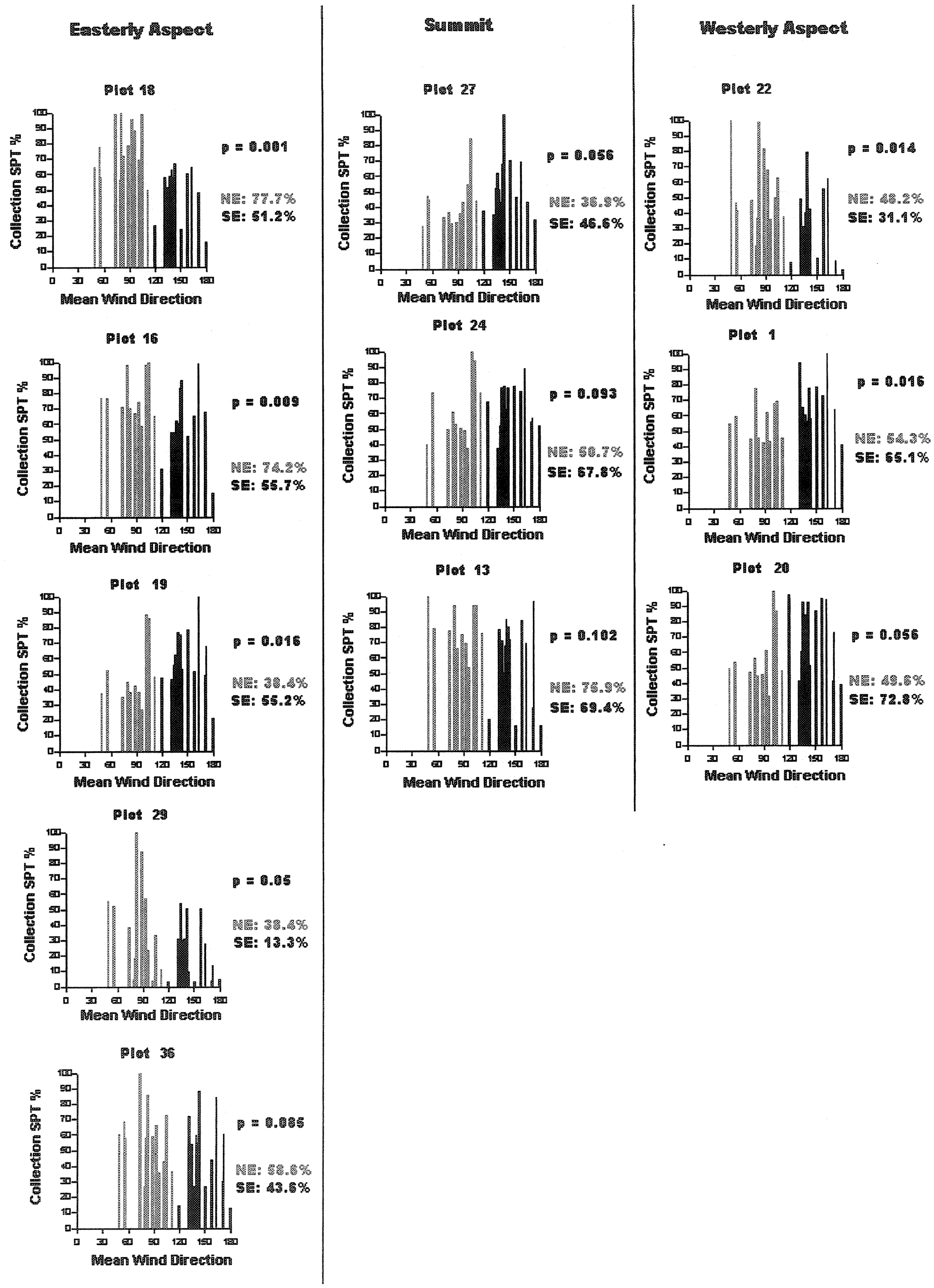

Figure 5.8. Histograms of mean collection wind direction (degrees true) and collection $SP_{t(\%)}$ for plots having significantly different median throughfall, ($p \leq 0.10$), associated northeast sector winds (NE) and southeast (SE) sector winds, grouped according to topographic position.

5.3.3 Incident rainfall depth and intensity

Potential relationships between incident rainfall depth and intensity between collections and collection throughfall magnitudes were investigated through correlation analysis. Table 5.17 presents the collection mean standardized percentage throughfall data (**$SP_{t(\%)}$**), collection incident rainfall, rainfall intensity factors 1 and 2, (as defined in 4.4) and the product of rainfall depth and intensity factor 1. Appendix 9 presents the rain period separation data by collection used to compute the rainfall intensity factors. Incident rainfall depths are characterized by a greater frequency of collections > 30 mm in the latter half of the data record which corresponds to the late summer to autumn time frame. The rainfall intensity factors, rainfall depth and intensity product and **$SP_{t(\%)}$** data do not appear to exhibit any salient trends. Figure 5.9 presents scatter plots of (a) mean collection **$SP_{t(\%)}$** and incident rainfall, (b) mean collection **$SP_{t(\%)}$** and rainfall intensity factor 1, (c) mean collection **$SP_{t(\%)}$** and rainfall intensity factor 2, and (d) mean collection **$SP_{t(\%)}$** and the product of incident rainfall and rainfall intensity factor one. Correlation coefficients of $r = 0.26$, 0.18 and 0.06, corresponding to scatterplots a, b, and c respectively, were not significant. Scatterplot d did demonstrate a significant correlation coefficient of 0.42, providing an evidential result of the potential of rainfall depth and intensity interactions to influence throughfall magnitudes. It is noteworthy that correlation of rainfall intensity factors 1 and 2 (Fig. 5.9 b and c) results in a narrowing of the x-axis dispersion of the **$SP_{t(\%)}$** data set, with more visually apparent positive trend and outlier recognition. Furthermore, scatterplot b, after removal of two apparent outlier collections, attained a highly significant correlation coefficient, ($r = 0.547$, $p = 0.004$) compared to the initial $r = 0.18$, $p > 0.3$. The product weighting of rainfall depth and intensity also noticeably reduced the outlier status of these collections (Fig. 5.9 d).

Table 5.17. Correlation data for rainfall depth (mm), rainfall intensity (mm hr^{-1}) factors 1 and 2 (INT 1, INT 2), rainfall depth and intensity factor 1 product (Depth x Int 1) and standardized percent throughfall $S_{Pt(\%)}$ for 28 throughfall collection events (Coll #).

Coll #	Mean $SP_{t(\%)}$	Depth	Int 1	Depth x Int 1	Int 2	Coll #	Mean $SP_{t(\%)}$	Depth	Int 1	Depth x Int 1	Int 2
1	55.2	3.9	2.0	7.7	3.3	15	61.2	16.3	5.3	86.2	5.3
2	55.6	19.6	2.2	43.7	3.8	16	55.0	34.3	2.3	77.5	3.7
3	54.0	19.4	1.8	35.1	3.9	17	41.3	4.0	0.9	3.6	3.0
4	49.9	12.7	0.9	10.8	4.0	18	57.2	55.9	1.6	89.4	2.0
5	43.1	0.3	2.6	0.8	2.6	19	41.7	14.0	0.6	8.3	1.1
6	55.0	22.4	1.4	31.8	2.6	20	70.2	13.8	1.8	24.8	3.9
7	88.4	25.0	3.3	83.3	4.0	21	56.6	67.3	1.9	124.5	2.9
8	56.0	8.3	1.7	14.2	2.5	22	56.1	32.9	1.7	55.9	2.9
9	32.2	5.9	5.1	29.9	6.8	23	74.0	9.5	1.9	18.4	5.4
10	40.5	5.1	1.5	7.4	2.2	24	55.6	26.6	1.1	29.8	2.9
11	47.8	7.2	1.3	9.5	3.7	25	48.5	9.8	1.1	10.9	3.4
12	54.0	5.8	3.2	18.7	3.2	26	59.6	38.0	1.4	51.7	2.2
13	68.2	5.0	1.9	9.5	1.8	27	20.6	8.7	1.1	9.2	3.6
14	61.7	66.1	1.4	93.2	3.6	28	44.1	37.4	1.0	37.8	2.3

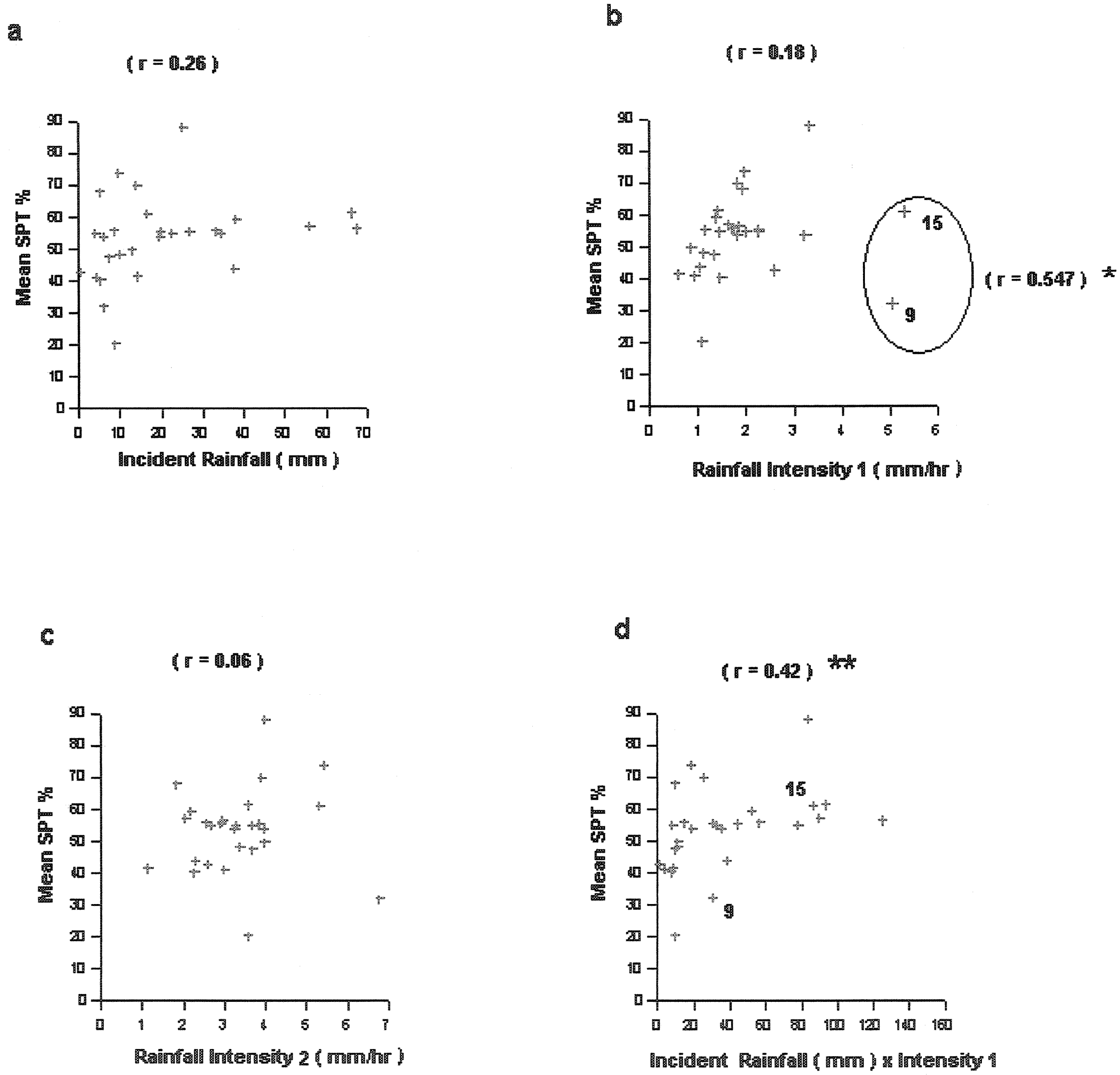

Figure 5.9. (**a**) Scatter plot of collection incident rainfall and mean collection **SP$_{t(\%)}$** for all throughfall plots grouped. Correlation coefficient (**r**) not significant at $p > 0.1$. (**b**) Scatter plot of collection rainfall intensity factor 1 and mean collection **SP$_{t(\%)}$** for all throughfall plots grouped. Correlation coefficient (r) not significant ($p > 0.3$). Removal of apparent outlier collections 9 and 15 results in significance at $p = 0.004$, (**r = 0. 547 ***). (**c**) Scatter plot of rainfall intensity factor 2 and mean collection **SP$_{t(\%)}$** for all throughfall plots grouped. Correlation coefficient (**r**) not significant ($p > 0.7$). (**d**) Scatter plot of the product of incident rainfall and intensity factor 1 and mean collection **SP$_{t(\%)}$** for all throughfall plots grouped. Correlation coefficient (**r = 0. 42**) ** significant at $p = 0.03$. Note reduction in scatter with reference to collections 9 and 15.

6.0 Discussion and Interpretation

This chapter initially presents a summary of major study findings and interpretations which are grouped in connection with the four major thesis objectives. Following the summary, the remaining bulk of the chapter provides detailed discussion of these findings.

Objective 1. To provide knowledge of local throughfall flux magnitude and variability for balsam fir.

- For the summer-autumn study duration, throughfall averaged 85%, ensuring a high proportion of incident rainfall typically reaches the forest floor.
- Inter event throughfall variability with a standard deviation of 41% and intra event plot to plot variability with standard deviations ranging from 24.5% to 68% were noticeably high.
- Measured throughfall exceedance of incident rainfall ($P_{t(\%)}$ > 100%) was common, occurring for slightly over one quarter of all measurements and contributes significantly to the variability around mean throughfall percentage estimates.
- Exceedance values arise from stand structural characteristics of second growth balsam fir interacting with specific incident rainfall characteristics, which can lead to the development of concentrated canopy drainage.
- Occult interception was directly observed during one event but was concluded to be a minor contribution to throughfall flux. Occult contributions to throughfall flux will increase at higher elevation sites during rain events characterized by low cloud impaction on forest stand covers.

Objective 2. To investigate potential dependence of throughfall flux upon balsam fir forest cover at the stand scale.

- Second growth balsam fir is predominantly a reducer of incident rainfall receipt on a seasonal basis and for most individual events.

- For most incident rainfall conditions, point to point throughfall measurements in second growth balsam fir forest integrated to a stable, steady state, stand based throughfall percentage estimate.

- A small number of individual events characterized by throughfall exceedance values result in the reductive influence of the forest cover being statistically non significant.

- The occurrence of exceedance events suggests that an atypical non steady state throughfall process driven by concentrated point to point canopy drainage can predominate under certain incident rainfall conditions, with resultant measured estimates of throughfall and incident rainfall approaching equivalency.

- Forest cover was an independent factor influencing throughfall and had no interactive co-dependency on topographic position on a seasonal basis and for individual events, excepting one instance.

Objective 3. To investigate potential dependence of throughfall flux upon microscale topographic conditions.

- Topographic position was not a significant determinant of throughfall and incident rainfall on a seasonal basis as well as for most individual events.

- A small number of individual events had statistically significant windward reductions and leeward enhancements of incident rainfall and throughfall.

- The detected topographic-wind relationships are considered to be robust, reflecting microscale terrain effects on incident rainfall and throughfall with no significant interacting synoptic scale impact.

- Topographic position was an independent factor influencing throughfall and had no interactive co-dependency on forest cover on a seasonal basis and for individual collections, excepting one instance.

- As far as can be determined, this study is the first to examine microscale topographic effects in the throughfall process and as such provides progress towards an integrating framework for understanding the throughfall process in a landscape and geographic context.

Objective 4. To analyse the influence of selected meteorological variables on throughfall receipt for balsam fir.

- Statistically significant throughfall magnitude differences amongst events were detectable and can be attributed to ambient meteorological conditions during the events.

- Three distinct throughfall process regimes can be identified: (i) typical steady state, (ii) terminated steady state and (iii) exceedance non steady state. These regimes are related to the event incident rainfall differences and are characterized by distinct throughfall percentage estimates.

- Correlation analysis reveals that a typical steady state throughfall process regime was predominant during the study, but terminated steady state and exceedance non steady state throughfall regimes also occurred.

- Improved predictive modeling and understanding of throughfall process regimes could be achieved by considering event rainfall intensity and weightings of rainfall amount and intensity as independent variables.

- Significant wind directional effects for individual plots were detected and demonstrate the process of windward reduction and leeward enhancement of throughfall magnitudes at the forest stand and landscape level.

The summary of findings provides a focus for the detailed discussion of thesis results which follows. These discussions incorporate both descriptive statistics, inferential significance testing arising from the experimental design, exploratory correlation analyses and reference to relevant literature. Discussion and interpretation of the statistical results are undertaken to enhance the understanding of the throughfall process with respect to its magnitude and variability and potential physical controls. The discussion sections generally follow the format of the results chapter and are additionally structurally linked to the thesis objectives.

6.1 Incident Rainfall and Throughfall

6.1.1 Magnitude of incident rainfall

Differences in incident rainfall amongst case studies will be important for partitioning or predicting the absolute (mm) throughfall fluxes (Fig. 2.2) for respective study locations. However, these differences will be less critical for comparisons of mean throughfall percentage magnitudes if canopy regulated steady state is achieved between incident rainfall and throughfall (Fig. 2.1 and 2.3). In their aforementioned studies of throughfall for balsam fir, Olson *et al.* (1981), Mahendrappa and Kingston (1982) and Freedman and Prager (1986) report respective total incident rainfalls ($\mathbf{P_g}$) of (i) 389 mm, (ii) 371 mm and 268 mm and (iii) 458.4 mm. The present study reports a $\mathbf{P_g}$ total of 575 mm, which is a substantially higher magnitude than these case studies of the 1980's. Regional climate differences have likely contributed to this contrast as well as differences in study period duration. The normal total rainfall for the Corner Brook climate station is 493 mm for the June through October period, compared with 575 mm recorded at the study site for the 1998 field data collection season. However, any one or more of three large rainfall events (Table 5.17, Collections 14, 18, 21) that occurred in the summer-fall could account for much of the difference from the long-term normal rainfall. Additionally, the Corner Brook station is at 4 masl., in contrast with the meteorological tower site of the present study located at an elevation of 459 masl. This elevational difference could also have contributed to the larger recorded 1998 rainfall at the study site.

6.1.2 Throughfall magnitude and variability for balsam fir

Throughfall measurements in the present study were recorded to correspond with discrete rainfall events. The seasonal mean throughfall percentage ($P_{t(\%)}$) value derived in the present study was 85.0%. Olson *et al.* (1981) and Mahendrappa and Kingston (1982) also sampled throughfall by discrete rainfall events. However, Freedman and Prager (1986) conducted sample measurements on a systematic weekly basis. Olson *et al.* (1981) reported throughfall percentages of 118%, 110%, and 126% for three distinct balsam fir stands. Mahendrappa and Kingston (1982) report two mean throughfall percentages of 76.0% and 79.9% for balsam fir derived in separate sampling seasons. Freedman and Prager (1986) report mean throughfall percentages of 67.1% and 66.7% for two mixed stands of red spruce and balsam fir. The balsam fir component of these stands, however, was only 8.2% and 6.7% of the stand basal areas, respectively. Considering the mixed stand condition of red spruce and balsam fir, low percentage of balsam fir and the greater wettability of young red spruce foliage contrasted to young balsam fir foliage (Boyce *et al.* 1991), comparability of values derived by Freedman and Prager (1986) is questionable. In the present study, the seasonal mean throughfall percentage value was closest to those of Mahendrappa and Kingston (1982).

These authors also reported a coefficient of variation < 15% amongst all throughfall measurements, whereas the present work had no discrete event with as low a variability expressed either as a coefficient of variation or standard deviation. The seasonal mean throughfall percentage had a high standard deviation (41%) which was probably inflated by infrequent outlier events having high and low mean values (Table 5.3, eg. C7, C13, C23, and C27). Measures of variability were not provided by Freedman and Prager (1986) or Olson *et al.* (1981). In case studies that do not describe variability of event throughfall percentage magnitudes, it remains difficult to judge the utility of an overall seasonal throughfall percentage and whether it represents a relatively stable steady state mean value. Additionally, biological and sampling differences (Freedman and Prager 1986) and a different throughfall generating mechanism than classic canopy interception of incident rainfall (Olson *et al.* 1981) hinders throughfall comparisons for these studies.

6.1.3 Throughfall exceedance of incident rainfall

Throughfall percentages exceeding 100% (Olson *et al.* 1981) for the White Mountains of New Hampshire were attributed to clouds covering this subalpine balsam fir forest for 30-50% of the time, along with droplet impaction from increasing wind speeds at these elevations (Lovett 1984, Reiners and Lang 1979). However, it was not reported whether exceedances occurred on all plots over all rainfall events or over just a portion of plots and events. This contrasts with the findings of Mahendrappa and Kingston (1982) which state that only a few exceedance cases were present in their data. In the present study exceedance values were relatively common with 28% of individual plot values and 5 of

28 events (Fig. 5.1) having average plot values ≥ 100% throughfall. Individual plot exceedance values were most frequent within the events that had mean throughfall percentages ≥ 100%. Since these events are also outliers, they will likely contribute to a reduced stability for a steady state seasonal mean throughfall percentage value. Potential processes leading to throughfall exceedance of incident rainfall have been described but not well researched. A primary mechanism is the potential influence of overlapping foliage and branching patterns that could contribute to high intensity concentrated drip points for throughfall (Pucket 1991). Herwitz (1987) provides some confirmation from both experimental and field studies that concentrated exceedance throughfall drip points could develop on the underside of insloping branches during conditions of high rainfall intensities above certain thresholds. The cloud impaction mechanism described by Olson *et al.* (1981) is also noted as leading to throughfall in exceedance of incident rainfall. During one event (Table 5.17, coll. 19) there was frequent direct on-site observation of impaction of wind driven low stratus cloud and scud on the forest canopy, with associated fine drizzly rainfall which was characterized by the low intensity rainfall rate or 0.6 mm hr^{-1}. However, it is noteworthy that this event did not result in an exceedance value for the event throughfall percentage although the contribution from the occult precipitation plausibly was a significant proportion of the total throughfall flux. Throughfall flux due to occult precipitation influences could also have contributed to a portion of the throughfall flux during other similar conditions during other events. However, whilst the data and measurement techniques of the present study were not capable of separating and

estimating this proportion, the process of low cloud impaction (Olson *et al.* 1981) can be confirmed by direct observation. Banfield (1983) notes that the precipitation climatology of western Newfoundland, particularly the amounts, frequency and spatial distribution, is strongly influenced by the presence of insular Newfoundland's highest uplands, The Long Range Mountains. Additionally, Robertson and Roberts (1982) have described a typical forest zonation from coastal balsam fir forest to upland tuckamore (krummholz) formations for the Western Brook Pond area located in Gros Morne National Park, approximately 75 km north of the present study. Thus, potential throughfall fluxes from cloud impaction could occur for other western Newfoundland forest ecosystems, including balsam fir, due to orographic uplifting effects during synoptically determined moist air flows crossing the study region.

6.1.4 Balsam fir stand structure and throughfall processes

Throughfall processes are also highly dependent on stand structure. Intra species throughfall percentage values will have increased utility when presented in conjunction with information on relevant stand characteristics. Mahendrappa and Kingston (1982) and Mahendrappa (1974) report low variability (< 15%) in throughfall measurements for uniform balsam fir stands of average age of 49 years, 12.9 m mean height, densities of 2959 stems ha^{-1} with crown closure of 90%. Olson *et al.* (1981) report respective throughfall percentages of 118%, 110%, and 126% associated with average stand characteristics of ages 22, 31, and 79 years, heights of 4.9m, 5.3m, and 6.4m, densities of

10,625 (8825 live + 1800 dead), 17,900 (15,050 live + 2850 dead), and 7175 (3825 live + 3350 dead) stems ha^{-1}. These stand conditions most closely resemble the stand structure of the present study which is a naturally developed second growth stand originating from understory advance regeneration following clear cut harvesting in the early 1950 s. In such a stand structure, there is a dominant canopy height class but there can be variability in average tree height due to the presence of high densities of suppressed live and dead subdominant trees in the canopy. These balsam fir stand conditions have commonly developed from release of advanced understory regeneration following pre-1970 clearcut forest harvests, which have not been subjected to precommercial thinning silivicultural practices. The higher throughfall variability reported in the present study, in comparison to Mahendrappa and Kingston (1982), may relate to less uniform stand structures.

The increased frequency of individual plot exceedances within outlier exceedance collections suggests that concentrated, but spatially heterogeneous, drainage points may become commonly established in second growth balsam fir forest canopies and be potentially related to rainfall characteristics such as “intensity thresholds”, as shown by Herwitz (1987). Conversely, throughfall percentages that are representative of a stable seasonal mean may result from a more spatially homogeneous and uniform drip drainage from a saturated canopy. This is suggestive of the establishment of a steady state throughfall production as theoretically implied by Leonard (1967, Fig. 2.1) and referred to as the “waterbox” concept (Klasen *et al.*. 1998). Within the study area of the present work, the throughfall process appears to be predominantly steady state drip and less frequently high intensity drainage and impaction interception. It may also be further surmised that these processes may have singular predominance or state transitions associated with certain incident rainfall, meteorological conditions and stand structural differences.

6.2 The Role of Forest Cover

6.2.1 All collections grouped

There is a strong consensus from theory and empirical study that throughfall flux derived from incident rainfalls is of reduced magnitude (Leonard 1967, Parker 1983). Empirically, this consensus has been supported from studies that have observed throughfall at the tree scale of individual plots and at the stand scale, with grouped plot data that have developed predictive regression equations. However, notwithstanding the consensus, these studies have proceeded from an implicit *a priori* position without explicit experimental verification. The experimental design and hypothesis statement of the present work has explicitly tested the consensus through a balanced comparative spatial and temporal sampling of uniform forest stand and forest clearcut harvest conditions. The strong rejection of the null hypothesis for all collections combined over the full study period supports second growth balsam fir cover in western Newfoundland as a dominant reducer of incident surface rainfall receipt under a variety of incident rainfall meteorological conditions. The result is stand based and demonstrates that averaged tree scale differences measured at a plot level translate into a statistically significant stand difference. This also supports the argument that the throughfall process, although spatially heterogeneous on a point to point basis, does tend towards a stability on a seasonal basis for uniform stand conditions. Cell variance homogeneity for the grouped seasonal data was good, although normality was somewhat violated due to positive skew in the data. However, the strong rejection ($p \leq 0.001$) and noted robustness of ANOVA models for moderate departures from normality supports the utility of the experimental approach (Table 5.5).

6.2.2 Individual collections

For the ANOVA experiment, most individual collections rejected the null hypothesis. The rejections support second growth balsam fir cover in western Newfoundland as a dominant and reductive factor for incident rainfall receipt for individual events. The acceptances support an inference that incident rainfall and throughfall fluxes were not significantly different and the forest cover does not act as a reductive factor. It would be expected that most individual collections would reject the null hypothesis since the seasonal rejection is based on compilation of the grouped individual collection data. The similar rejection and acceptances for individual collections by both the ANOVA and MW tests demonstrates that the ANOVA model may still have good inferential utility in spite of cell variance heterogeneity and strong departures from normality (Appendix 6).

Acceptances of the null hypothesis for collections 5, 13, 15 and 18 could be related to the statistical properties of the cell data, the degree of agreement of the ANOVA analysis compared to the MW test and a reasoned interpretation of causal physical characteristics during these events.

Collection 5 was in disagreement for the non parametric versus the parametric testing. The MW test resulted in a highly significant rejection of the null hypothesis ($p = 0.001$), whereas the ANOVA produced acceptance at $p = 0.182$. An examination of the cell variances indicated a variance ratio at the maximum limit of 1:10 between cells CE and SW. However, the W statistics ranging from 0.76 to 0.23 indicate that the cell data are strongly removed from a normal distribution. this collection was also characterized by a very small incident rainfall of 0.3 mm, with a rainfall intensity 2.6 mm hr^{-1} and a throughfall percentage ($P_{t(\%)}$) of 65.3%. If this rainfall amount was capable of resulting in a non significant difference between cutover incident rainfall depth and stand throughfall depth, intuitively the mean $P_{t(\%)}$ would be closer to 100%. It is noteworthy that two individual plots, numbers 1 and 9, were outliers having $\mathbf{P_t}$ values of 0.5 mm and 0.0 mm, respectively (Appendix 5). These could be a contributory cause of the lack of cell normality for this collection and for the better performance of the MW test. It seems reasonable to assume that the resulting rejection by the non parametric MW test may have more inferential validity than the acceptance by the ANOVA and that for collection 5 there was indeed a significant forest cover effect.

While small event collections demand caution in the confidence attached to statistical findings and presentation of average quantities, due to measurement error, meaningful interpretation of the spatial and quantitative limits of the throughfall process can be still derived.

King and Harrison (1998), for example, concluded that useful information on the pattern and process of throughfall was derived from a small event of 1.0 mm in spite of proportionately large measurement error. The rainfall amount and intensity characteristics of collection 5 were characteristic of a very brief and localised shower that may have had a spatially uneven rainout. Notwithstanding that the study area was small at 0.95 km^2, a throughfall occurrence frequency of 35 of 36 topographically dispersed plots provides useful information on the spatial character of throughfall response for very small rainfall events.

Mahendrappa and Kingston (1982) indicate a fitted incident rainfall data value of < 1.0 mm in their regression equation for balsam fir, with a predicted a threshold value of 0.77 mm of incident rainfall necessary for the start of throughfall. The incident rainfall magnitude of 0.3 mm for collection 5 is in the order of magnitude of the predicted value while also providing a meaningful empirical threshold value for throughfall production in second growth balsam fir stands.

Significance levels for the ANOVA and MW tests values for collection 13 were both > 0.7, hence strong acceptance of the null hypothesis. The maximum variance ratio of 1:125.9 between cells CE and SS indicates a violation of the assumption of variance homogeneity, but the W statistics and p values could be interpreted as indicating that the data for this collection were not highly removed from normality. A mean collection $P_{t(\%)}$ value (Table 5.3) of 111.2% potentially indicates that there was an approximate equivalency of incident rainfall and throughfall fluxes during this event. This would be expected if there was an acceptance of no significant difference between cutover incident rainfall and stand throughfall. A number of plot outliers (Appendix 5; plots 3, 4, 20, 21, 24, 33 and 35) having exceedance values ranging from 263.6% to 161.9% have likely contributed to cell heteroscedacity, but there were also certain plot $P_{t(\%)}$ values considerably under 100% (exceedance values), such as plot 29, which had a $P_{t(\%)}$ value of 4.6%. The MW test would, however, be expected to perform robustly with respect to these outliers since it is a rank test. Additionally, the ANOVA test appears to have performed robustly considering the cell data normality and similarity of acceptance p values for both tests. Collection 13 was also characterised by a fairly small incident rainfall of 5.0 mm, of which 4.8 mm fell in one rain period of 151 minutes duration. This intensity characteristic may indicate a convective rainfall resulting in exceedances on some throughfall plots with a numerical convergence of mean incident rainfall and throughfall for the collection. The statistical inference of acceptance of the null hypothesis for both tests thus appears to be supported by the physical rainfall characteristics of this collection.

Collection 15 accepted the null hypothesis for both the ANOVA and MW tests but with a considerable difference in p values of 0.801 and 0.111, respectively. The p value of the MW test is very close to 0.10 which was set as the study rejection threshold probability. The maximum variance ratio of 1:201.3 between cells CS and SS indicates a violation of the assumption of variance homogeneity. The W statistics and p values could be interpreted as indicating that there was variability and departure from normality within cells. A mean collection $\mathbf{P}_{t(\%)}$ value (Table 5.3) of 101.4% indicates that there was an approximate equivalency of incident rainfall and throughfall fluxes during this event. This would be expected if there was an acceptance of no significant difference between cutover incident rainfall and stand throughfall. A number of plot outliers (Appendix 5; plots 3, 4, 12, 15, 20, 21 24, 33 and 35) having exceedance values ranging from 215.6% to 114.0% have likely contributed to greater stand cell heteroscedacity compared with cutover cell variances for this collection. It is notable that a number of these plots are common to both collections 13 and 15 in producing exceedance values of $\mathbf{P}_{t(\%)}$ and may therefore reflect unique canopy structures that interact with specific rainfall conditions to produce throughfall exceedance. The near equivalence of mean incident rainfall and mean throughfall for collection 15 is characterized by high variability in throughfall data as demonstrated by high stand cell variances. The apparent convergence may therefore only reflect a numerical averaging and not a physically uniform and spatially convergent process during the event. Collection 15 involved one continuous period of rainfall of 16.3 mm and a rainfall intensity of 5.3 mm hr^{-1}. Similarly collection 13 had two delineated rain periods but with the lager proportion of rainfall in one period. It could thus be argued, for both collections 13 and 15, that throughfall fluxes for individual collections may not be significantly different than incident rainfall magnitudes averaged over a number of representative stand plots. However, this argument is more strongly supported for collection 13 than for collection 15. The acceptance of the null hypothesis for collection 15 based on the MW test probably requires caution, considering the close to threshold p value and stand cell variance attributes.

Collection 18 was characterized by acceptance of the null hypothesis for the ANOVA and MW tests with respective p values of 0.304 and 0.330. The maximum variance ratio of 1:86.0 was between cells CW and SS. The W statistics and p values indicate that the cell data distributions were removed from normality. As noted in Chapter 5, the throughfall data for collection 18 (Table 5.2) consisted of the summed gauge totals for collections 19 and 20 (Table 5.3 and Appendix 5). The mean $\mathbf{P}_{t(\%)}$ value of 88.1%, as computed from the means of collections 19 and 20 (Table 5.3), indicates that on average there is a potential tendency for equivalence of incident rainfall and throughfall fluxes. When the $\mathbf{P}_{t(\%)}$ value is recomputed from the mean of the $\mathbf{P}_g$ mm and $\mathbf{P}_t$ mm (Table 5.1 and 5.2) the value is closer to equivalence at 95.3%. It is possible that the tipping bucket rain gauge, at a higher elevation, was influenced by observed passage of low stratus cloud and scud during event 19 (Table 5.3) and had an increased catch as a result. This increased catch would be reflected in the combined tipping bucket total of 27.8 mm for collections 19 and 20 (Table 5.3 and Appendix 9) compared with the mean cutover $\mathbf{P_g}$ mm catch of 25.7 mm (Table 5.1). This is noteworthy since the ANOVA and MW tests are computed on the basis of the balanced cutover and stand plot data, which results in the 95.3% computation for $\mathbf{P_{t(\%)}}$.

Although the summation of collections 19 and 20 was unplanned in the study, it offers an opportunity to examine how the $\mathbf{P_{t(\%)}}$ data variability may respond to a combination of different events. The standard deviation of the throughfall gauge totals for collection 18 was 6.46 mm (Table 5.2). This represents 22.8% of the tipping bucket catch, which is less than the respective $\mathbf{P_{t(\%)}}$ standard deviations of 25.2% and 34.7% for collections 19 and 20 (Table 5.3). It is evident that combination of collections 19 and 20 has reduced the overall throughfall variability for collection 18 (Table 5.2) although the finer temporal resolution of collections 19 and 20 is associated with large differences in their respective mean $\mathbf{P_{t(\%)}}$ values of 63.7% and 112.5% (Table 5.3). This finding supports that of King and Harrison (1998) who note that detailed analysis of throughfall variability in response to meteorological conditions could be restricted by coarse data resolutions.

The $\mathbf{P_{t(\%)}}$ differences between collections 19 and 20 could be related to their rain period structures and intensities (Appendix 9). Collection 19 had a relatively low rainfall intensity of 0.6 mm hr^{-1} and was directly observed on-site to include occult interception and throughfall drip. Collection 20 had a maximum individual rain period total of 10.7 mm with an intensity of 2.7 mm hr^{-1}, resulting in 77.5% of the incident rainfall for this event. Clearly these two events had quite different characteristics, with collection 19 having a primarily throughfall drip response, whereas collection 20 plausibly responded more via concentrated canopy drainage, with exceedances due to a threshold incident rainfall intensity.

In summary, for collection 5 the null hypothesis is most strongly rejected on the basis of the MW test. Generally, collections 13, 15 and 18 appear to have a statistical equivalency or tendency towards equivalency between incident rainfall and throughfall depths. The statistical inferences for these collections appear to be reasonably in concert with process mechanisms which support the statistical findings.

6.3 The Role of Topography

6.3.1 All collections grouped

The literature review of case studies of throughfall conditions found no examples that explicitly examined topography, in spite of its known influence on rainfall receipt at varying scales. Forest covers are widely distributed over varying terrain types, with potential interacting effects amongst rainfall, topographic features and wind. Consequently, examination of topography at different scales may contribute useful integrating frameworks for understanding forested landscape system influences on incident rainfall partitioning and throughfall fluxes. The consideration of size, distance and raincell relationships, as discussed (Section 6.6.3) is relevant with respect to the topographic replication of the present study. Synoptic scale orographic rainfall gradients occur from coastal to adjacent upland locations of western Newfoundland (Banfield 1983). However, the experimental area of this study is very small relative to the synoptic scale, and systematic orographic influence during this microscale topographic investigation is considered to be minimal. The reported acceptance of the null hypothesis ($p = 0.359$) for all collections combined indicates that the replicated east-facing, summit and west-facing topographic positions had no significant effect during the study duration upon differential incident rainfall or throughfall receipt (Table 5.7). Proceeding from this statistical inference some useful interpretations regarding landscape may be drawn. The present study could provide a threshold estimate of area size for the separation of local topographic from regional synoptic gradient effects. Sampling at distances greater than encompassed by the study size area could lead to differences influenced by meso-scale or synoptic rainfall gradient effects as well as the micro scale. However, this would likely apply only for the range of hill sizes and relief structures characteristic of the present study area. Since the east-facing, summit and west-facing topographic positions did not show a significant effect, simple random sampling irrespective of topographic position could suffice for summer through autumn season estimation of throughfall or incident rainfall for this type of terrain.

Notwithstanding the robustness of the hypothesis acceptance with regard to data statistical properties (Sections 5.2, 6.6.1), it is useful to note the salient east to west pattern in stand cell data distribution (Fig. 5.2). There is recognizable increasing smoothness of the frequency distribution from the east-facing topographic positions to the west aspects. Since the cutover cells do not exhibit the east to west smoothing pattern it is a reasonable inference that the smoothing probably reflects an interactive influence of canopy and meteorological conditions. That is to say, during rainfalls accompanied by winds from between northeast to southeast, there was a probability of enhanced canopy frictional drag on east-facing topographic positions. On west-facing leeward topographic positions during these same events, divergence and reduced down wind turbulence may have become more prevalent. The east to west smoothing apparent in the stand cell data distribution may thus indicate a topographic, wind and canopy interaction in throughfall receipt pattern. This pattern still remains indicative of topographic differentiation that may have biological and forest ecosystem significance, although the difference magnitudes were not detectable by the ANOVA analysis.

6.3.2 Individual collections

Most individual collections tested by ANOVA and KW tests supported the inference of no significant topographic effect on incident rainfall and throughfall fluxes (Table 5.8). Although individual collections had high cell variability and departures from normality (Appendix 6), the ANOVA and KW tests appear to have both performed reliably with a similar range of acceptance p values.

Lee (1978) notes a “blowover” effect of decreasing rainfall receipt on (windier) upwind slopes, with compensating leeward side increases for hills, in forest environments. Oke (1978) attributes this process to changes in wind speed as it interacts with obstacles, with a resultant inverse relationship between horizontal wind speed and magnitude of precipitation deposition. Case studies (James 1964; Stow and Dirks 1998) detected similar windward decrease and leeward increase effects in rainfall receipt totals. In the present study, during easterly wind directions a small number of collections with statistically significant west-facing topographic precipitation enhancements are supportive of the processes noted by Lee (1978) and Oke (1978) and demonstrated in case studies.

The wind and incident rainfall data accompanying these collections may provide some indications of what the broader physical controls on these enhancements may have been. It is noteworthy that the largest percentage enhancements for leeward slopes, for collections 8 and 25, were associated with the smaller incident rainfall magnitudes, whilst collections 3 and 24 with the smallest leeward percentage enhancements had the greater incident rainfall. Mean wind directions for these collections were from the southeast. Such wind direction and speed differences may be related to contrasting synoptic meteorological differences. For example, collection 24 had the larger incident rainfall and a mean wind speed of almost 16 m s^{-1}, potentially indicating the increased intensity of an autumunal low pressure system passage. During this event the total rain duration was slightly under 28 hours, compared with 8.9 hours and 4.9 hours for collections 25 and 8 respectively. It is thus surmised that the enhancement effect could be amplified from reduced variability around mean wind directions during shorter, less intense rainfall events and *vice versa.*

At the cell level therefore, the data distributions of the factorial design, although variable, support the topographic enhancement of $\mathbf{P_g}$ and $\mathbf{P_t}$ for specific events. However, the aggregated effect of the majority of collections, being statistically non significant, is leading to a non significant relationship overall for the topographic effect. Conversely, the easterly to westerly aspect stand cell pattern frequency contrast, discussed earlier (Section 6.2, Fig. 5.2), could be related to the effects of the individual collections within the seasonal data distributions. It is noteworthy that the strength of main and post hoc test hypotheses rejections is observed to have a strong association with the percentage increases for the westerly aspect topographic position. For example collection 25, which had the most significant main and post hoc p values of 0.008 and 0.007, was characterized by the largest percentage increase (25.5%) in incident rainfall and throughfall receipt on the west-facing topographic position compared with the easterly aspect. Collections 3, 8 and 24 have a similar association, demonstrating the utility of the statistical tests and inferences for detecting these processes. However, smaller percentage differences between east and west aspect topographic positions that derive from larger incident rainfall events can result in larger absolute differences. Consequently, interpretation based solely on statistical findings may not completely highlight absolute differences between collections which may have ecological or biological significance over and above purely statistical significances.

6.4 Forest cover - topographic interactions

6.4.1 All collections grouped

Significant interactive effects do not negate the findings of independent significance for main experimental factors. Since experimental factor interactions do not have any predefined levels, significant effects are usually interpreted as the differences amongst levels of one factor not being constant at all levels of another factor in the experimental design (Zar 1996). Detailed investigation, through multiple comparison techniques (Zar 1996), are required to elucidate significant interaction relationships.

It is reiterated that the examination of topography as an experimental factor and consequent interactions of forest cover and topography was not addressed in earlier throughfall case studies. In this study, the acceptance of the null hypothesis of no interactive effect of forest cover and topographic position on incident rainfall or throughfall flux for all the collections combined supports the independence of these experimental factors. Previously discussed data homogeneity of variances and normality of the ANOVA factorial cells reasonably support this statistical inference.

6.4.2 Individual collections

Collection 24 was the only individual collection that had a rejection of the null hypothesis indicating a dependent forest cover and topographic factor interaction (Table 5.8). Cell variances were, as noted previously, indicative of a lack of homogeneity although there was some evidence of data normality. Since only this one collection proved to have significant main factor interaction, this effect was considered to be an infrequent occurrence for the prevailing conditions of the experimental design. Detailed multiple comparisons were not undertaken and were considered to be beyond the scope of the present work. However, for collection 24, it is noteworthy that both forest cover and topographic position were also independently significant with ANOVA p values of 0.022 and 0.058 respectively, compared with $p = 0.085$ for the interaction effect. Therefore, within small areas of hilly terrain not subjected to overriding synoptic gradients, interaction of forest cover and topographic position will probably not influence throughfall processes and their estimation from combined (summer through autumn) or most individual collections.

6.5 Nesting of Topographic Replicates

6.5.1 All collections grouped

The acceptance of the null hypothesis for all collections combined over the full study period indicates that topographic replicate variability did not significantly influence seasonal incident rainfall or throughfall receipt. The natural degree of spatial heterogeneity of topographic positions was incorporated and reasonably controlled in the experimental design through an air photo mapping approach (van Kesteren 1996). Strength of the main factor full study duration inferences has been enhanced by the finding of non significance for within cell variability.

6.5.2 Individual collections

Approximately two thirds of individual collections were characterized by no significant relationship for nesting of topographic replicates within the factorial cells of the experimental design. The exceptions were collections 5, 9, 12, 13, 17, 19, 22, 24 and 26 (Table 5.12). For these collections, one or more cells (Fig. 4.1) of the factorial design had one or more replicates contributing to significant variability. However, significant within cell variability does not negate experimental main factor and interaction significances (for these collections) which can be confidently be interpreted as being above the nesting effects (Sokal and Rohlf 1995). Identification of specific cell(s) and replicate(s) responsible for significant nesting was considered beyond the scope of the present work but can be undertaken by applying multiple comparison methods within factorial cells (Zar 1996).

The rejections of the null hypotheses for the nesting factor for collections 5, 9, 12, 13, 17, 19, 22, 24 and 26 had p values ranging from 0.001 to 0.092 (Table 5.12). These rejections likely indicate some similarities and differences in event characteristics which could aid in an explanation of the nesting effect. Collection 5 was significant at $p = 0.001$ for nesting of replicates. This collection is of interest because of the small incident rainfall of 0.3 mm for the event. As previously discussed, notwithstanding that the study area was small at 0.95 km^2, it is highly likely that this event was of small areal extent, with rain falling over a particular replicate(s) leading to the highly significant nesting effect. Collections 9,12 and 13 (Table 5.1), having respective p values of 0.001, 0.022 and 0.05, were also relatively low rainfall episodes ranging from 5.0 to 5.9 mm, providing a further indication that smaller rainfall events had significant nesting effects potentially due to uneven spatial rain receipt. Collections 17 and 19 (Table 5.1) however, with respective rainfalls of 59.9 mm and 67.3 mm, were large events with significant nesting effects (both $p = 0.004$). It is surmised that these two events may have been characterized by systematic increased or decreased rain gauge catches on specific replicates arising from particular spatial variability at the replicate level or directly at the gauging site.

Collections 22, 24 and 26 (Table 5.1) were moderate sized events of 26.6, 38.0 and 37.4 mm respectively, with corresponding p values of 0.088, 0.092 and 0.08. It is noteworthy that these events had the least strong rejection probabilities. Smaller and larger rainfall magnitudes thus appear to have been most conducive to strong nesting effects and are likely due to particular meteorological features associated with these events.

6.6 Considerations for the Experimental Design Approach

Experimental design utilizing ANOVA models has two important facets: (i) the requirements for valid inferential testing deriving from statistical properties of the experimental data of the factorial design (Fig. 4.1) and (ii) the field layout of the factorial design (Fig. 4.2) and its relationship to physical processes that generate the experimental data.

Assumptions of the ANOVA model require homogeneity of variance and normality of data distribution amongst the cells of a factorial design, although homogeneity is considered more critical than normality. Robustness of the model is well accepted in spite of salient departures from normality (Zar 1996) and when largest to smallest cell variance ratio is approximately 10:1 or smaller (Tabachnick and Fidell 1996). Box (1954), cited in Anderson and Mclean (1974), notes that departures from homogeneity of variances of up to nine times in an ANOVA model only resulted in a change of probability (alpha) level from 0.05 to 0.06. The degree of field heterogeneity accepted in an experiment is a matter of subjective judgment and does not invalidate the robustness of the experiment design (Hurlbert 1984). Heterogeneity of experimental factors should, however, be considered with regard to the sensitivity of the analysis and the interpretation of the statistical results. Additionally, experiments which incorporate spatial heterogeneity could help reduce systematic data errors and bias, thus strengthening the statistical inferences that can be derived from an experimental design (Dutilleul 1993). Levels of a classification system, in particular those based on spatial criteria (Dutilleul 1993), can be used to define the experimental factors. Within this context, variability amongst the classification levels as measured by a specified dependent variable can be tested for statistical significance. In the present work the topographic positions which are nominally classified possess some uncontrolled quantitative differences in aspect, slope gradient or other field heterogeneities. Therefore, addressing uncontrolled heterogeneity by a nested design that examines within-cell variability can result in more robust testing of the primary experimental factors and interactions (Zar 1996).

6.6.1 Properties of the experimental data and interpretations

The frequency histograms (Fig. 5.2) for incident rainfall and throughfall over the full study period are characterized by a salient positive skew in data distribution. This pattern is to be expected for short precipitation records with lesser frequency of larger event size classes (Barry and Chorley 1982). In general, since incident rainfall is the primary driver for the throughfall process, the pattern of stand throughfall follows the skewed pattern of cutover incident rainfall, but with reduced magnitudes. Normality of distributional patterns for rainfall–throughfall records may therefore have implications for the application of parametric statistical methods. The level of skew was not considered to have had an undue negative effect on the seasonal ANOVA analysis due to the cell variance homogeneity, although the W statistics, which were uniformly in $> 0.8 \ < 0.9$ range for all experimental cells, indicate some removal from normality.

The noticeably more uniform stepped pattern of throughfall within stand cells in contrast to incident rainfall within cutover cells indicates that forest cover acts to smooth spatial distribution of incident rainfall to the forest floor. A surmised inference from this pattern is that a uniform forest cover acts as a coarse filter and, in spite of plot to plot variations, tends to result in throughfall processes that are characteristically steady state.

On a more detailed level, a notable pattern difference is observable in the 0-5 mm and 5-10 mm classes between cells of the cutover and stand condition. In the cutover cells the 0-5 mm class is of distinctly lesser frequency than in the stand cells, whereas the 5-10 mm class frequency is greater in the cutover cells and less for the stand condition. It is likely that this pattern substantially results from throughfall magnitudes in the 0-5 mm class being generated by incident rainfalls in both the 0–5mm and 5-10 mm classes. A low frequency of incident rainfall events in the 45-55 mm range results in the visible gaps in the histograms for cutover cells. Throughfall is characterized by a trend of lessening frequencies in the 0-5 mm class and increasing frequencies in the 5–10 mm and 10–15 mm classes, from the east to west-facing stand cells. This frequency pattern is surmised to represent a process of throughfall magnitude enhancement on the westerly aspect topographic position. For the maximum class of 90–95 mm, the stand and cutover cells are both characterized by low frequencies of throughfall and incident rainfall, respectively. Although the frequency in the stand cells is greater and can be attributed in throughfall exceedance of incident rainfall, the numbers are quite low and make it difficult to ascertain any trend. There is a noticeable increased throughfall frequency in the stand summit cell for the 90–95 mm class which could be due to some distinct plot variability rather than broader stand - meteorological interactions.

6.6.2 Field layout of the experimental design

Physical controls on spatial and temporal distributions of incident rainfall can act through a hierarchical process–response system that links synoptic, mesoscale and local meteorological scales. Measurements of incident rainfall and resultant throughfall flux magnitudes are likely to be scale dependent, which could subsequently affect interpretation of inferential results and conclusions from an investigation. Investigations of local and micro effects should be at scales small enough to be contained within the spatio-temporal boundaries of individual synoptic systems, whilst at the same time possessing representative physical characteristics of a meso-scale region to enhance extrapolation of findings. Application of an ANOVA experimental design therefore requires consideration of morphological, size and distance relationships at plot, stand and landscape levels that characterize a study area. Interpretation of differing spatial and temporal resolutions of rainfall will depend upon the ratio of characteristic synoptic scales to the scale of a study area. For example, to study synoptic rainfall gradients a suitably large study area which enables observations of storm passage and interactions with the broader landscape would be required. However, utilization of a large area to study potential local and micro influences on rainfall variability would be difficult, since the study scale would not be unambiguously resolvable at the coarser scale of experimental observation. A small study area is thus an important requirement for robust data acquisition which is suitable for investigating potential influences of local effects on incident rainfall and throughfall variability.

The current study area size, measured as a rectangular form with contiguous enclosure of the weather tower site and the farthest east-west and north-south incident rainfall and throughfall replicates is approximately 0.95 km^{2}. This area is small enough to be predominantly influenced by individual raincells resolvable at diameters of 1 km to 10 km (Sumner 1988). A larger study area could have resulted in a data set containing a mixing of local and systematic variations associated with storm passage and synoptic rainfall gradient effects.

Additionally, in application of the ANOVA design, if plots are separated by distances greater than the 1–10 km range, data set error and erroneous inferential interpretations of the experimental results could ensue. The majority of cutover incident rainfall and stand throughfall plots are within a 1.0 km distance of each other. The farthest approximate distance between plots (plots 15 and 40) was 1.2 km. Where incident rainfall has been measured at greater distances than one kilometre from throughfall monitoring gauges, there can be errors in the derivation of throughfall percentage magnitudes for differing events and throughfall averages amongst events. Mahendrappa and Kingston (1982) recommend incident rainfall monitoring sites at no more than 1.0 km from any throughfall sites to reduce error generation. In the present work, the horizontal distance from the meteorological tower site (Fig. 4.7) to the farthest throughfall plot (plot 30) was approximately 0.5 km, enabling robust throughfall percentage computations. Scale dependent errors due to mixed processes is thus considered to be minimal, since the study area size and the plot to plot distances are as fine as the resolvable scale for rain cells (Sumner 1988).

6.7 Collection Differences and Meteorological Influence

Few studies have analyzed throughfall magnitudes with respect to meteorological variables, and for these it is not explicitly clear whether throughfall magnitudes were expressed on an absolute or percentage basis. The use of a $\mathbf{P_t}$ mm or $\mathbf{P_{t(\%)}}$ expressions for investigating throughfall magnitude relationships with meteorological variables can be problematic. On a comparative plot to plot basis, these measurement expressions will be confounded by canopy differences which interact with ambient meteorological conditions during throughfall processes. Examination of potential relationships between meteorological variables and throughfall magnitudes in a robust investigative framework is thus apparently lacking in the scientific literature.

The present study has used a simple approach to standardize all plot $\mathbf{P}_{t(\%)}$ values, thus removing the confounding influence of plot canopy variability, followed by a screening of collection grouped standardized plot values using the KW test. This method is proposed and presented as a useful approach for addressing the need for an investigative framework for throughfall and meteorological interactions. A highly significant KW test, with $p < 0.001$, indicates that meteorological conditions independent of canopy variability were highly likely to have influenced throughfall magnitudes in the present study. Subsequent post hoc pairwise comparisons supplemented the initial screening to provide increased focus on the individual collections that were characterized by significant differences. In conjunction with the pairwise comparisons a histogram plotting approach was employed to aid in visual comparison and interpretation of individual collections (Figs. 5.3 to 5.5).

In general, three patterns in these histograms can be distinguished, namely those that have (i) positive skews (Fig. 5.3), (ii) negative skews (Fig. 5.4) and (iii) approximately normal distributions (Fig. 5.5). Qualitatively, these figures provide useful information on the throughfall response of the full plot record during individual events. The positive skews demonstrate that a high proportion of plots produced large throughfall magnitudes, whereas negative skews demonstrate that a high proportion of plots produced small throughfall magnitudes. It may thus be inferred that during some events canopy variability of individual plots did not contribute to a broad spectrum of differentiated throughfall magnitudes. In contrast, collections which had histograms that appeared as approximately normal frequency distributions did have a broader spectrum.

Conceptually, it is surmised that the three distinctive histogram configurations are related to two different throughfall process regimes; namely (i) a non steady state dynamic and (ii) a steady state dynamic. These regimes can be theoretically related to the rising limb and horizontal "ab" inflexion point, respectively, of Figure 2.1. Collections characterized by positive skews in plot frequency distribution may be associated with non steady states, whereas negative skews and normal distribution patterns are associated with steady states. The collections' statistical descriptions provide support for this interpretive schema.

For example, collections 7, 23 and 13 (Fig. 5.3), having salient positive skews, possess mean $\mathbf{P}_{t(\%)}$ values of 143.2% , 116.0% and 111.2%, respectively. Incident rainfall amounts for collections with positive skew were small to moderate ranging from 3.9 to 25.0 mm with an average of 13.3 mm. The exceedance values for these three collections may have occurred from concentrated branch drainage and spouting processes (Herwitz

1978) in which a spatially homogenous steady state canopy drip is disrupted by increased rainfall intensities. Conceptually, events with exceedance values representing a non steady state throughfall would lie in the horizontal range of the rising limb but vertically above it (Fig. 2.1).

Collections 27, 9 and 19 (Fig. 5.4), with salient negative skews, have mean $\mathbf{P}_{t(\%)}$ values of 33.1%, 67.0% and 63.7%, respectively. The values are substantially below the noted exceedance values above, as well as the overall collection mean $\mathbf{P}_{t(\%)}$ value of 85.0%. Incident rainfall amounts for such collections with negative skew were very small to moderate, ranging from 0.3 to 14.0 mm with an average of 7.4 mm. It is surmised that these events may have achieved steady state drip regimes, but because the rainfalls were smaller, the process terminated early with the resultant $\mathbf{P}_{t(\%)}$ values falling noticeably below the mean collection value. Conceptually, events with low $\mathbf{P}_{t(\%)}$ values may represent a terminated steady state throughfall regime and would lie in the horizontal range to the right of the “ab” inflexion (Fig. 2.1). It is noteworthy that Mahendrappa and Kingston (1982) found increased scatter in the lower end of fitted regressions of $\mathbf{P}_t$ and $\mathbf{P}_g$, providing support for a terminated throughfall regime for smaller events.

In contrast, collections 16, 3 and 25 (Fig. 5.5), having near normal distribution patterns, yielded mean $\mathbf{P}_{t(\%)}$ values of 85.6%, 83.7% and 79.2%, respectively. These values are close to the overall seasonal mean $\mathbf{P}_{t(\%)}$ value of 85.0%. The incident rainfall amounts for these collections were generally larger, ranging from 9.8 to 34.3 mm and averaging 21.2 mm. It is concluded that these events have steady state drip regimes and would lie in the horizontal range to the right of the "ab" inflexion point (Fig. 2.1). However, since their rainfall amounts are larger, an atypical termination of throughfall yield would not be prevalent.

Inter skew pattern comparisons (Fig. 5.3 and 5.4) of collections 7 and 27 and intra skew pattern comparisons of collections 17 and 19 (Fig. 5.4) and 22 and 24 (Fig. 5.5) provide examples of the dissimilarities and similarities of event characteristics. For example, collection 7 had an incident rainfall depth of 25.0 mm with an intensity of 3.3 mm hr^{-1}, producing a mean throughfall of 143.2%, whereas collection 27 had values 8.7 mm, 1.1 mm hr^{-1} and 33.1%. Secondly, collection 17 had an incident rainfall depth of 4.0 mm, an intensity of 0.9 mm hr^{-1} and a mean throughfall of 63.4%, compared with values of 14.0 mm, 0.6 mm hr^{-1} and 63.7% for collection 19 (Appendix 9). Finally, collection 24 featured an incident rainfall depth of 26.6 mm, an intensity of 1.1 mm hr^{-1} and a mean throughfall of 85.4%, which contrasts with values of 32.9 mm, 1.7 mm hr^{-1} and 86.8% for collection 22. Additionally, these differences are statistically supported by the pairwise collection comparison z scores (Appendix 8).

Rutter (1975) observed that variable rainfall characteristics, particularly relationships amongst depth, intensity and rain period structures will influence the throughfall process.

It is noteworthy that across the three primary skew patterns, there are large differences in the collection mean $P_{t(\%)}$ values, whereas within skew patterns there is a tendency towards reduced collection mean variability. In the present study therefore, inter skew pattern differences in the histogram frequency regimes are considered to represent distinct throughfall process regimes arising from incident rainfall variability.

6.8 Selected Meteorological Variables

6.8.1 Air temperature and relative humidity

Intuitively, air temperature and relative humidity could influence throughfall magnitudes by affecting canopy drying rates between collections. There could also potentially be a relationship with seasonally decreasing temperatures. In previous work, mean air temperature during rain events was not correlated with the magnitude of throughfall (Mathers and Taylor 1983), although Lawson (1967) reported that the overall mean air temperature for the entire day on which a storm occurred increased the significance of throughfall prediction when used in combination with incident rainfall of the storm. This latter result presumably reflects a seasonal effect of temperature on throughfall, but it is noteworthy that the temperature was not field measured for the actual storm day. The present study found no significant relationship between field measured air temperatures and throughfall magnitudes (Fig. 5.6a). However, the air temperatures were averaged for the time between events, which contrasts with Mathers and Taylors's procedure.

Additionally mean relative humidity had no significant correlation with the standardized throughfall magnitudes for the collections (Fig. 5.6b). None of the previous studies reviewed reported on relative humidity effects, and this study may be the first investigation of the role of this variable.

Notwithstanding the non significant correlations, it is possible that testing using a different resolution than the mean of the hourly values for these variables could result in improved significance. Additionally, since the time between collections was not constant, a further possibility would be the examination of air temperature and relative humidity data for shorter preset constant time periods before the start of rain for each collection. Application of this approach could more reliably represent canopy drying processes between collections, with a potential for detecting correlative relationships.

6.8.2 Wind speed and wind direction

Mathers and Taylor (1983) reported that mean wind speed and direction were not correlated with the magnitude of throughfall during rain in the Kawartha Lakes region of Ontario. Additionally, Klasen et al. (1996) reported that wind velocity during rain had no statistically significant effect on throughfall magnitude measured on a forest stand edge in the Netherlands. In the present work, there was no significant relationship of wind speed or direction with mean collection standardized throughfall percentages over the full combined plot record (Fig. 5.7 a and b). This finding is therefore in broad agreement with earlier case studies and is perhaps not surprising since the plot record was distributed over the three topographic positions, which could have caused averaging effects.

6.8.2.1 Wind direction effects for individual plots

Further investigation of wind effects for individual plots revealed eleven of thirty six plots with significant differences in throughfall magnitude for NE sector compared to SE sector winds (Fig. 5.8, Table 5.16). Individual plots, which are at tree scale, reflect potential interactive influences of local canopy, incident rainfall, wind and topographic variables in which causation is likely embedded as a multifactored relationship. Excepting for infrequent minor twig breakage and needle drops, no catastrophic canopy change (such as windthrow) was observed on any plots, assuring stable canopy architecture for the study duration. Thus, comparison of individual plots, to search for stand scale patterns, has validity since the dependent variable, which is a standardized throughfall measure, provides experimental control for plot to plot canopy variation. Six proximity clusters of plots can be differentiated: (i) plots 18 and 19, (ii) plots 22 and 27, (iii) plots 1 and 20, (iv) plots 13 and 16 (v) plots 29 and 36 and (vi) plot 24 (Fig. 4.3). It is noteworthy that, with the exception of plots 1, 20 and 24 the remainder are on east-facing replicates or on summits close to the break of slopes of easterly aspect replicates. Stereoscopic observations (Fig. 3.3 and 3.4) also support that these plot groupings could have had significant wind influence due to longer fetches from the east arising from no close intervening hills and the prevalence of open organic terrain and water bodies. Within the clustering pattern, easterly aspect and summit plots predominantly demonstrate a decreased throughfall magnitude during mean wind directions from the southeast throughout the study duration. A contrasting opposite relationship is demonstrated by predominantly west-facing and some summit plots, with an increase in throughfall magnitudes for mean wind directions from the southeast. The physical clustering of field plots and related statistical probabilities is supportive of the leeward enhancement of throughfall magnitude on west-facing slopes, discussed previously. It is reiterated, however, that the enhancements indicated by these associations are on a percentage basis and may not reflect the same trend in absolute amounts. However, it is nevertheless true that plots 19 and 22, associated with east and west aspects, have significant throughfall increases and decreases for SE winds respectively, which is the reverse of the predominant statistically significant plot and physical pattern. It is therefore physically plausible that unique on site plot location and or canopy factors could have resulted in complex scaling interactions with effects that do not reflect the broader stand and landscape pattern.

6.8.3 Incident rainfall amount and intensity

6.8.3.1 Incident rainfall amount

Event incident rainfall amounts ($\mathbf{P_g}$) were characterized by no significant correlation with the mean collection standardized throughfall percentage values ($\mathbf{Sp}_{t(\%)}$) (Fig. 5.9 a). A large proportion of plotted values is contained within the 50% to 60% range of throughfall magnitudes. This pattern resembles a theoretical steady state with throughfall approaching a constant percentage value, regulated through maximum canopy saturation (Figs. 2.1 and 2.3). Balsam fir has been reported as having good predictability (r^2 = 0.93) for $\mathbf{P}_t$ mm dependent upon $\mathbf{P}_g$ mm (Mahedrappa and Kingston 1982). Related regression (Fig. 2.2) for the data range approaching throughfall percentage constancy should also demonstrate reasonable predictability. In addition to the 50% to 60% throughfall range concentration, there is salient variability in throughfall magnitudes, with occurrences of upper and lower values associated with smaller incident rainfall depths. The three data ranges of Figure 5.9 a, namely (i) the 50% to 60% band, (ii) a concentration of upper outlier values and (iii) a concentration of lower outlier values, relate well to the positive and negative skews and normal distribution histogram configurations of plot counts, respectively. It is surmised that this data range pattern represents steady state, terminated steady state and exceedance throughfall regimes, respectively. Plausibly, data set partitions reflecting differing throughfall regimes may result in improved predictive relationships compared with all data grouped.

6.8.3.2 Rainfall intensity

Previous case studies report rainfall intensity as a non significant correlate or predictor of throughfall magnitude (Mathers and Taylor 1983, Lawson 1967). However, Rogerson (1967) reported a small prediction improvement by including rainfall intensity in prediction equations for loblolly pine plantations, while Spittlehouse (1997) noted that short duration intense storms produced greater throughfall than storms with equivalent rainfall depth but lesser intensity, in coniferous coastal forests in British Columbia. In the present study, incident rainfall intensity factors 1 and 2 were characterized by no significant correlation with the mean collection standardized throughfall values (Fig. 5.9 b and c). However, with the removal of two outlier events, collections 9 and 15 (Fig. 5.9 b), a highly significant correlation was achieved for intensity factor 1. Intensity factor 2 also appears to have a number of outliers which may have affected the sensitivity of the correlation analysis (Fig. 5.9 c). It is noteworthy that both intensity factors are computational parameters derived from tipping bucket raw data based on subjective one hour break points for rain periods within events. Generally, intensity computation using no break points between the start and finish of discrete rainfall events would cause a reduction in rainfall intensity, whereas computation using shorter break points would exclude more non rain time within an event, resulting in a higher intensity. Detection of significant correlations could therefore vary and be dependent upon intensity factors derived with differing break points. However, the previous case studies reporting non existent or small rainfall intensity effects did not detail the intensity computational methods or considerations.

6.8.3.3 Weighting of incident rainfall amount and intensity

The product of incident rainfall depth and rainfall intensity factor 1 was computed and tested as a simple weighting for these variables. A significant correlation with throughfall magnitude resulted (Fig. 5.9 d). The outlier status for collections 9 and 15 is reduced by the product weighting. Collection 9, which was a smaller rainfall event but with higher intensity, had the most noticeable positional change in the overall scatter, contrasted to collection 15 which was a moderate sized rain event with high intensity, and which had lesser change. It is concluded that there are threshold levels of rainfall amount and intensity combinations for which different weightings could be developed. Use of weighted measures, particularly in data subsets which appear to be non steady state or atypical throughfall regimes, could improve predictive regression equations.

7.0 Summary and Conclusions

This work is the first to report on throughfall flux magnitudes, variability and process regimes for Newfoundland balsam fir forest conditions. The mean seasonal throughfall percentage reported is very close to the magnitude reported for work completed in New Brunswick, although the balsam fir stand conditions were dissimilar. However, throughfall percentage ($\mathbf{P}_{t(\%)}$) variability for each individual collection event, as well as for all events combined, was greater than reported in other studies for balsam fir. Since the throughfall variability was present across the same set of plots it was likely due to differences in the incident rainfall amounts and other meteorological conditions present during the discretely measured events. Other second growth balsam fir conditions similar to those of the present work may also have potential for high variability of throughfall percentage values. The use of seasonal throughfall averages in hydrological applications, without knowledge of meteorological event variability, may therefore result in inherent errors for specific applications. Throughfall exceedance values ($\mathbf{P}_{t(\%)} > 100\%$) occurred for a little over one quarter of all individual measurements in this study, reflecting interactions of the specific architecture of second growth balsam fir forests and high intensity rainfall conditions, potentially resulting in concentrated canopy drainage. Throughfall drip, due to low stratus canopy impaction, was directly observed and is likely to gain more importance with increasing elevation in western Newfoundland balsam fir forest ecosystems. This confirms findings for high elevation subalpine balsam fir sites in New Hampshire.

On a forest stand and landscape basis over the June through October study period, forest cover type was the predominant determinant of variability in throughfall flux magnitudes. Topographic position alone, as well as the interaction between it and forest cover were found to be statistically non significant for throughfall and incident rainfall receipt over the full study duration. However, although statistical significance for topographic position was not detected for the full study duration, visual pattern analyses of cell experimental data suggest windward slope reduction and leeward slope enhancement of throughfall. Additionally for most individual events, forest stand cover was a statistically significant factor for throughfall differences compared to incident rainfall receipts on forest cutover covers. Topographic position and the interaction of forest cover and topographic position were predominantly non significant for individual collection analyses. However, one quarter of the individual collections, for which the rainfall was accompained by southeast winds, had statistical signifance for the topographic factor. It was useful to analyze individual collections by non parametric statistical tests since non normality and heteroscedacity of data could affect the robustness of ANOVA models. However, both parametric and corresponding non parametric tests resulted in similar acceptances and rejections of hypotheses. Confirmation or refutation of the experimental design probabilistic inferences was enhanced by reasoned physical explanations which were also supported by the experimental data.

A simple standardization approach enabling removal of confounding canopy variability amongst throughfall plots was followed by non parametric testing to screen discrete events for meteorological influence in the throughfall process. The standardization and screening analyses indicated that significant meteorological control over throughfall fluxes was present, independent of plot to plot canopy variability. A histogram plotting approach combined with the screening has identified three distinct throughfall process regimes: (i) a typical steady state, (ii) a terminated steady state and (iii) an exceedance non steady state. Improved understanding of throughfall magnitudes, variability, and processes could be achieved by considering the ambient meteorological conditions that accompany discrete events. Results of preliminary exploratory investigation of candidate meteorological variables have advanced this understanding. Air temperature, relative humidity and wind speed were not significantly correlated with mean collection throughfall magnitudes. However, for individual plots, significant differences were detected between throughfall magnitudes for NE and SE sector wind directions supporting the topographic windward and leeward effects found by the experimental design testing. This appears to be the first research result demonstrating wind and topographic influence in the throughfall process at both the tree and stand scale. Incident rainfall quantity had no significant correlation with collection standardized throughfall percentage. This supports steady state throughfall following canopy saturation as being the primary throughfall process for the second growth balsam fir stand conditions of the study area. Outliers in the correlation, however, demonstrate non steady state exceedance and terminated steady state regimes. In addition, the product of incident rainfall depth and intensity was found to be significantly correlated with throughfall magnitude. Therefore, the development of weightings of rainfall intensity and rainfall depth may have potential to improve throughfall prediction.

An understanding of watershed hydrological responses to forestry operations is an important national water conservation criterion (CCFM 1997). For example, the Main River watershed, in northwestern Newfoundland, is one such locale where planned forestry practices could influence the hydrology of a sensitive original boreal forest cover. Whilst the advancement of knowledge of throughfall for specific forest cover type(s) presented in this work represents a contribution to understanding forestry - watershed interactions at this catchment scale, there remains a need for further throughfall research incorporating other forest covers and the range of precipitation types encountered during the entire annual precipitation regime. Rainfall inputs into forested environments are also a primary environmental driver of chemical depositions. Past and current concerns for forest health due to acid rain deposition in the New England states and Atlantic Provinces regions is a high priority research topic requiring site and region specific data to enhance modelling efforts and calibrations (Arp *et al.* 2001). Forest managers and environmental scientists therefore require a better understanding of how forest harvesting and stand regeneration will affect the amount and chemical nature of rainfall receipt and hydrological partitioning. This investigation of throughfall will therefore contribute to an increased understanding of the forest hydrologic cycle for western Newfoundland and should assist the further development of practical forest management methods for Newfoundland's balsam fir forest ecosystems.

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Appendix 1. Test data for improvised funnel gauges versus standard rain gauge.

Coll. #	Gauge	Rep 1	Rep 2	Rep 3	Coll. #	Gauge	Rep 1	Rep 2	Rep 3
1	Stan.	10.8	10.6	10.8	13	Stan.	5.0	4.8	5.0
1	500	10.2	10.4	10.2	13	500	4.2	4.2	4.2
1	1000	10.5	10.2	10.4	13	1000	4.2	3.9	4.2
2	Stan.	4.2	4.2	4.2	14	Stan.	23.2	23.2	23.0
2	500	4.2	4.4	4.4	14	500	22.4	23.8	21.3
2	1000	4.2	4.4	4.6	14	1000	21.7	21.5	21.5
3	Stan.	3.2	3.2	3.2	15	Stan.	12.6	12.6	12.2
3	500	3.5	3.2	3.2	15	500	12.3	11.8	12.5
3	1000	3.2	3.2	3.2	15	1000	12.0	12.3	12.0
4	Stan.	1.8	1.8	1.6	16	Stan.	20.2	20.0	20.2
4	500	1.4	1.4	1.2	16	500	21.5	21.0	21.5
4	1000	1.4	1.4	1.2	16	1000	21.5	20.8	21.5
5	Stan.	4.6	4.6	4.6	17	Stan.	4.8	5.0	4.8
5	500	4.6	4.6	4.4	17	500	4.4	4.9	4.6
5	1000	4.6	4.4	4.4	17	1000	4.6	4.4	5.1
6	Stan.	54.6	55.4	56.4	18	Stan.	1.6	1.6	1.6
6	500	57.8	56.0	59.9	18	500	1.4	1.6	1.6
6	1000	57.1	56.2	58.3	18	1000	1.4	1.6	1.6
7	Stan.	6.4	6.4	6.4	19	Stan.	8.6	9.2	8.8
7	500	6.2	6.5	6.2	19	500	7.9	8.1	8.1
7	1000	6.2	6.5	6.2	19	1000	8.1	8.6	8.6
8	Stan.	6.0	5.8	6.0	20	Stan.	15.2	15.2	15.0
8	500	5.8	5.8	6.2	20	500	14.6	16.9	16.9
8	1000	6.0	5.5	6.0	20	1000	16.2	14.8	14.6
9	Stan.	0.6	0.8	0.4	21	Stan.	7.0	6.8	6.4
9	500	0.2	0.7	0.2	21	500	6.5	6.7	6.2
9	1000	0.5	0.5	0.2	21	1000	6.5	6.7	6.7
10	Stan.	5.8	5.8	5.8	22	Stan.	1.8	1.6	1.6
10	500	5.5	5.8	5.8	22	500	1.6	1.4	1.6
10	1000	5.5	6.0	5.8	22	1000	1.4	1.4	1.6
11	Stan.	7.0	5.8	6.8	23	Stan.	28.8	29.0	28.0
11	500	6.5	8.1	6.7	23	500	29.6	28.2	30.5
11	1000	6.7	6.7	6.5	23	1000	28.9	30.8	27.3
12	Stan.	28.4	28.6	28.8					
12	500	29.4	28.4	28.9					
12	1000	29.8	29.6	28.2					

Appendix 2. Pilot study data for sample size estimation for the experimental design.

Coll #	Pg mm	Pt mm	Coll #	Pg mm	Pt mm
1	2.2	5.2	4	7.8	16.0
1	4.6	6.0	4	17.4	16.8
1	4.0	6.6	4	8.0	16.2
1	3.4	5.4	4	6.2	16.6
1	5.8	5.8	4	8.6	15.2
1	3.4	5.8	4	8.6	14.2
2	11.4	20.8	5	1.2	3.6
2	16.6	21.8	5	3.0	3.4
2	11.4	21.8	5	1.4	3.8
2	12.2	21.4	5	2.4	3.6
2	12.0	21.0	5	1.4	3.4
2	11.2	19.8	5	2.4	3.4
3	38.8	28.0	6	41.2	21.4
3	17.2	28.4	6	43.4	20.6
3	17.2	26.8	6	42.0	11.8
3	35.2	26.4	6	39.0	22.8
3	30.8	27.8	6	41.0	20.8
3	28.2	28.0	6	40.2	18.2

Appendix 3. Throughfall data tabulated by collection number and plot number. All data are in mm. Missing data : *.

Plot #	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
1	3.7	14.3	20.3	11.6	0.5	15.5	41.2	11.6	6.7	4.9	9.2	5.8	5.5
2	0.9	14.3	14.6	10.6	0.2	20.3	44.2	4.6	3.5	3.2	5.8	4.6	3.7
3	1.4	8.3	15.3	6.5	0.2	17.6	30.5	3.2	7.4	3.5	8.6	9.2	8.1
4	6.2	31.2	16.9	22.2	0.2	22.7	54.3	6.9	11.1	6.9	15.7	15.5	13.2
5	0.7	9.2	18.7	3.2	0.1	14.8	46.2	5.8	6	2.5	7.9	6.2	6.9
6	3	17.3	16.2	9.5	0.2	16.4	34.7	4.6	3.9	3.7	5.8	4.6	5.1
7	1.4	11.6	18.7	5.5	0.2	12.7	35.6	6	3.5	3.7	4.9	4.4	6
8	1.5	10.2	19.7	4.4	0.1	27.3	54.1	5.3	3.5	1.8	4.2	4.9	6.7
9	7.5	19.7	20.3	18	0	19.2	40.7	11.1	4.6	8.1	9.9	4.9	5.8
10	*	9.9	14.6	7.9	0.1	16.2	29.1	7.2	4.2	3	6	4.2	3.7
11	*	38.4	11.8	19.7	0.2	27.3	40.7	6	3.7	4.4	3.2	2.3	2.8
12	*	6.9	8.3	7.4	0.1	30.1	49	1.8	4.6	0.5	3.7	5.8	5.1
13	2.8	15	18.5	9.2	0.2	14.8	17.1	6.9	1.2	1.4	1.2	2.5	4.6
14	*	16.4	18.3	10.2	0.2	16.2	26.6	9.9	2.5	5.3	4.6	3.7	4.4
15	0.5	14.6	22.7	4.9	0.2	18.5	62.4	6.9	4.6	1.4	7.2	6.9	5.8
16	4.9	19.7	15.3	13.9	0.2	20.3	34.9	5.8	2.5	4.9	5.3	4.2	6.9
17	4.9	32.4	27.1	19.7	0.2	30.8	30.1	15.7	5.8	4.6	5.1	4.6	1.8
18	3.5	25.7	8.8	16.9	0.2	23.1	21.3	6.9	2.1	3.2	2.3	3.7	4.6
19	3.5	11.6	22	4.9	0.2	10.6	41.8	8.1	4.6	4.2	9.5	6	7.4
20	3.7	17.1	26.1	11.8	0.2	15	43.5	11.1	10.6	3.9	11.6	9.9	9.2
21	0.5	15.5	17.6	8.3	0.2	28.4	47.6	3.5	7.4	1.8	6.9	10.4	9
22	0	15	2.8	7.4	0.2	16.4	24.5	0.5	0.7	0	1.2	2.8	3.9
23	5.1	24.5	17.6	9.7	0.2	23.4	31.9	10.4	2.1	4.4	3	2.8	6
24	6.2	20.3	23.1	12.7	0.2	16.4	46.2	9.7	8.3	5.8	11.6	9.2	10.4
25	1.2	16	16.2	4.6	0.1	18.3	32.8	7.2	1.2	1.6	2.5	2.1	1.8
26	2.3	9.7	11.1	5.8	0.1	12.9	24.3	4.4	2.1	0.9	4.3	5.8	3.7
27	8.6	14.3	18.3	9	0.2	23.1	37.9	7.9	4.9	4.9	11.1	7.9	6
28	4.2	17.1	10.4	11.8	0.1	20.6	28.4	5.8	1.6	3.5	3.5	2.5	2.8
29	0.5	9.5	3.2	3	0.1	10.9	8.8	0.9	0.2	0.2	0.2	0.5	0.2
30	3.2	14.1	16.9	9.2	0.2	18.7	29.1	8.6	2.3	3.5	4.9	4.2	4.9
31	3.7	15.3	16.9	8.8	0.2	16	26.8	7.6	1.6	2.8	3	3	4.6
32	4.9	15	19	9.7	0.2	14.3	35.6	6.7	2.1	4.2	5.3	4.6	6.9
33	3	17.1	16.9	9.2	0.1	19.7	46.2	5.8	5.8	2.5	10.6	10.4	9.5
34	4.4	19.2	13.4	12.5	0.1	23.6	17.6	8.1	1.2	2.8	2.1	1.2	0.7
35	0.7	13.6	15	3.9	0.1	18.5	50.6	5.5	3.2	0.9	2.8	5.3	9.9
36	3.7	21	12.5	7.9	0.2	16.4	22.7	5.3	0.9	1.6	2.1	1.4	2.3

Plot #	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26
1	49.9	15	36.8	44.2	27.5	60.1	33.5	10.9	26.1	9.7	45.5	5.8	28

2	54.8	12.9	29.1	36.5	17.8	40.2	15.5	8.3	18.5	6.7	25.2	2.1	21.3
3	29.8	23.1	17.1	35.1	26.4	53.4	10.6	11.8	18.7	10.4	32.1	2.5	37.9
4	84.9	35.1	29.1	69.4	41.2	56.4	46.7	9.5	16.4	9.7	31.7	3.5	29.6
5	61.3	19.7	30.3	41.6	23.4	57.1	18.3	14.6	22.9	9.2	41.4	1.6	25.7
6	52.7	12.7	23.1	47.9	24.3	48.6	23.4	12.3	18.5	6	28.7	2.1	22.4
7	70.3	13.4	21	42.3	17.6	53.2	22.2	9.5	19	7.9	32.1	2.1	21
8	90.4	18	25.9	43.2	21.5	54.6	18.7	7.2	19	7.9	37	1.8	20.3
9	47.6	12.5	40.2	50.2	34	56	44.4	17.6	29.6	7.9	43.5	7.4	23.1
10	59.4	10.9	33.5	53.8	23.8	52	32.6	7.6	22.2	5.5	34	4.2	20.1
11	90.6	11.6	30.5	79.8	28.7	53.9	41.8	7.9	20.1	6	29.6	1.6	17.6
12	89.9	29.1	36.3	67.3	25.2	90.9	25.2	9.9	23.6	10.2	52.3	0.7	26.1
13	43.2	10.9	24	45.1	18.3	66.4	22.4	8.8	20.8	4.9	31.4	1.4	28
14	43	9.5	33.1	53.9	27.7	52.9	27.7	11.8	25.7	6.2	31.7	3.7	28.4
15	81.6	33.5	50.2	64.7	25.4	103.8	31.2	13.9	32.6	14.8	63.6	3	45.3
16	65.4	13.9	26.4	58.5	27.7	72.6	34.5	13.4	28.9	8.6	34.9	1.8	34.2
17	84.6	17.3	46.5	63.6	35.4	59.7	51.1	6.5	34	7.9	52.9	3.7	27.5
18	63.1	11.1	23.4	61	27.1	57.3	41.8	12.5	20.6	7.6	30.5	1.8	24.5
19	42.5	21	31.7	42.3	23.6	41.8	21	13.6	23.4	9	32.6	3	29.8
20	54.8	25.4	38.4	51.6	31.7	61.7	37	15.3	26.6	12.3	66.4	6.2	33.3
21	89.2	25.4	31.4	58.5	25.2	70.3	34.5	10.4	13.2	10.2	38.2	2.1	29.4
22	103.6	20.6	16.6	73.8	17.1	107.1	35.4	9.5	17.6	6.2	33.5	0.5	22.2
23	57.1	10.9	34.7	64.5	26.4	72.1	38.2	13.4	27.7	6	34.5	1.8	23.4
24	73.3	26.4	37.5	64	28.9	56.2	33.5	18.5	40.7	15.3	58.7	9.5	57.1
25	83.5	8.8	27.3	43.7	24.7	51.3	26.6	9	21	2.1	24.5	1.4	10.6
26	37.2	14.6	19	35.8	17.3	44.6	15.5	7.6	20.8	5.5	31	1.4	20.6
27	42.1	13.9	39.3	40.5	33.8	41.2	25.7	17.6	25.9	11.1	38.8	6	35.8
28	50.9	9.2	23.6	48.8	22.4	44.6	26.6	7.9	16.4	3.7	18.7	1.4	14.6
29	83.2	6.2	23.4	62	12.9	46.9	23.6	3.9	17.6	3.7	24.3	0.5	5.1
30	50.4	12.7	26.4	41.6	17.3	57.1	22.7	10.9	23.6	6.7	33.5	3.9	23.1
31	45.5	9.9	24.3	37.9	15.3	46.5	20.6	9.2	22	5.3	25	2.5	23.6
32	40.9	12.7	27.1	40.7	22.1	39.8	21	13.4	22.4	6.5	31.7	3.7	25
33	49.7	27.3	33.3	53.4	28.7	71.9	23.1	16.6	24.3	14.3	43.5	4.4	41.6
34	65.7	6	29.8	54.8	19.2	60.6	29.8	4.6	19.2	3.7	26.1	1.8	11.1
35	92	28.9	20.1	58	27.3	64.5	28	13.9	21.7	7.9	34.5	1.4	32.8
36	60.8	4.6	19.9	36.3	13.4	43.5	23.4	7.4	16.4	2.8	17.8	1.2	14.6

Appendix 4. Incident rainfall data tabulated by collection number and plot number. All data are in mm.

Plot	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
37	4.6	24	21.5	13.9	0.2	23.8	28.9	10.4	6.7	5.1	8.6	6.5	5.8
38	4.6	22.7	22.4	13.9	0.2	25.4	29.4	9.5	7.2	5.3	8.8	6.9	5.8
39	4.6	22.7	21.5	13.4	0.2	24	27.3	9.2	6.2	5.1	8.6	6.5	5.3
40	4.6	19.7	21.7	12.9	0.2	16.4	28.9	9.5	6.7	5.3	9	6.9	6.5
41	3.9	22.4	21.5	12.9	0.2	22	29.6	9.5	6.9	5.1	8.8	6.9	6
42	4.4	19.7	20.3	13.2	0.2	18.7	28.4	9.2	6.9	5.1	9.2	6.9	6.5
43	4.6	21	20.1	13.4	0.2	25	28.2	9	6.9	5.1	8.6	6.7	5.8
44	4.6	19	18.3	12.7	0.2	21.5	27.7	8.1	6.9	4.6	8.3	6.7	5.8
45	4.9	20.6	22	13.2	0.2	21	29.8	9.9	7.2	5.3	8.8	6.5	6.2
46	3.7	23.4	21	14.1	0.5	22.7	29.6	9.7	6.9	4.9	8.8	6.7	5.8
47	3.9	23.6	21.7	13.9	0.2	24.3	29.6	9.5	7.2	4.9	9	6.9	5.8
48	3.5	24	21.3	13.6	0.5	23.1	29.6	9.9	7.2	5.1	9	6.7	5.8
49	3.2	24.7	18.7	14.1	0.2	25.7	25.4	9.7	6.2	4.9	7.6	7.2	5.3
50	3.7	22.2	21.7	13.6	0.5	23.4	28.9	9.7	6.7	4.9	8.6	6	5.5
51	3.9	23.1	20.3	14.8	0.2	25	28.4	9.5	6.2	4.4	9	6	5.8
52	3	22	18	13.9	0.2	23.1	24	8.6	5.8	4.4	6.9	5.8	5.3
53	3.7	23.4	19.9	14.6	0.2	23.8	27.3	9.7	6	4.9	8.1	5.8	5.8
54	3.7	22.4	20.6	13.6	0.2	23.6	27.3	9.5	6	4.9	8.8	6	5.5
55	3.9	24	22.2	13.2	0.2	24.5	30.1	9.7	6.7	5.1	9	6.5	5.5
56	3.9	23.4	22.2	13.4	0.2	23.4	30.1	9.9	6.7	5.5	9	6.2	5.5
56	3.7	22.4	21.5	12.5	0.2	22.7	31	9.5	7.2	5.3	9.7	6.5	5.3
58	3.7	23.1	22.4	15	0.2	22.4	28.4	10.4	6.2	5.5	9.2	6.7	5.8
59	3.7	22.9	20.8	14.6	0.2	25.4	26.1	10.2	5.5	4.9	7.4	5.8	4.9
60	3.9	22.2	22.7	14.3	0.5	21	29.4	10.4	6.7	5.3	9.5	6.9	5.8
61	3.5	22.4	18.7	13.2	0.2	25	27.1	7.4	6.2	4.6	8.1	6.7	6.5
62	3.5	20.8	19.7	13.2	0.2	25.9	25.9	9.2	6	4.6	8.1	6	5.8
63	3.7	22.4	20.8	13.2	0.2	25.7	28.4	9.5	6.5	4.9	8.6	6.9	5.8
64	3.9	22.4	21.3	13.6	0.1	24.7	27.3	9.2	6	5.1	8.3	6	5.8
65	3.7	21.5	21.5	13.9	0.2	22.4	27.7	10.2	6	5.3	8.8	6.7	5.8
66	3.7	19	19.7	12	0.2	21.3	27.7	9.7	5.8	4.9	8.1	5.3	4.9
67	3.5	22.9	21.5	14.3	0.2	27.1	27.1	9.9	6.5	5.1	8.8	6.7	4.9
68	3.7	24.7	21.5	14.6	0.2	28.9	27.5	9.9	5.8	5.1	8.3	5.8	4.9
69	3.5	23.1	22	14.8	0.2	23.4	28.2	9.9	6.5	4.9	8.8	6.7	5.3
70	3.5	18.7	19	12.3	0.2	22.2	28.4	8.8	6.5	4.9	8.8	7.2	5.3
71	3.7	23.4	21.5	15	0.2	23.6	27.7	9.7	5.8	5.1	8.3	6	4.9
72	3.9	21.7	23.1	14.3	0.2	23.4	29.6	10.2	6.2	5.3	9.2	5.8	4.6

Plot	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26
37	74.2	16.2	34.9	58.7	26.8	75.4	35.8	9.5	28.7	11.8	43.2	9.2	40.7
38	80	17.1	36.1	58	26.8	72.8	36.1	9	27.3	11.3	43.5	9.5	38.8
39	73.8	16.2	34.2	57.8	25.7	66.1	33.1	8.8	22.2	10.2	39.3	8.6	34

40	53.9	17.8	34.9	56	25.2	63.1	31.2	9.5	28.2	11.1	42.3	9	40.2
41	70.8	17.6	35.4	58.7	26.6	63.6	33.1	9.5	25.4	11.1	41.8	8.8	38.8
42	53.4	17.8	34.5	55	25.2	57.3	33.3	9.2	23.4	11.6	42.1	8.6	37.7
43	72.1	16	33.8	59.2	25.4	73.8	32.6	9	25.2	10.6	40.2	7.9	36.1
44	62.2	16.9	31.7	53.6	24.3	69.8	28.9	9	24.3	9.9	37.7	6.9	36.8
45	69.6	16.9	36.8	60.3	27.3	71.9	35.8	9.7	28.4	12	45.5	9.7	41.2
46	69.6	15.3	34	57.6	24.7	59	34.9	7.4	24.3	9.7	38.8	8.1	31.7
47	59.2	16.6	35.1	57.8	26.6	67.5	35.4	8.8	28.9	11.6	42.1	9.7	39.8
48	79.5	16.9	35.4	58.3	25.2	73.5	34.5	7.9	27.5	11.3	41.2	8.8	37.9
49	63.8	17.3	34.9	59.7	25.2	70.1	33.1	7.6	26.4	10.9	42.3	7.4	36.1
50	70.3	16	34.9	56.4	25	67.7	34	8.8	24.3	9.7	39.8	8.8	34
51	80.2	16.6	36.5	62.9	26.4	76.8	37.9	9	27.1	10.9	41.8	9.5	36.1
52	70.1	14.3	32.4	56.2	23.1	71.2	33.1	7.6	25.9	8.3	32.6	6	30.3
53	74.7	14.6	35.1	62	25.2	77.9	37.2	7.4	27.5	9.9	39.8	7.9	34.2
54	69.4	15	34.9	58.3	24.7	77.9	35.8	7.5	27.3	10.6	40	8.1	33.8
55	76.1	16.2	36.5	59.9	26.1	73.3	36.3	8.3	27.7	11.3	42.8	9	36.3
56	76.5	13.9	35.6	61.3	26.8	74	37.2	8.3	28	10.4	41.4	9.2	36.1
56	68.4	16.9	35.6	61.7	25.9	68	34.5	8.6	26.1	11.3	43	9.5	38.2
58	72.6	16.6	35.6	59	27.3	71.2	34.9	8.1	28	11.1	44.4	9.5	37.5
59	77.9	15.5	35.6	60.6	25.9	70.8	35.8	7.6	26.8	10.4	42.1	9.2	33.1
60	67.1	17.8	35.6	58.5	26.8	62	34.5	8.6	28.2	11.1	43	9	40.5
61	64.3	17.1	33.3	57.1	25	79.5	31.9	9	29.1	11.1	40.7	7.4	40.2
62	66.8	16.6	33.8	44.9	25.3	77.9	32.6	8.6	29.1	11.1	41.2	7.9	40
63	72.8	17.1	34	58.3	25.4	66.6	33.8	8.1	25	10.9	40.5	8.8	38.2
64	71	15.5	34.2	61.3	25.4	73.1	37.2	8.8	27.5	10.6	42.5	9.2	34.7
65	94.3	15.5	35.4	58	25.2	68.9	35.1	8.8	27.1	10.6	41.6	9	37.9
66	57.1	15.7	33.8	51.8	24	68.7	29.1	8.8	25.7	10.6	39.3	6.9	34.5
67	75.6	16	35.6	60.1	26.8	60.3	37.5	6.9	22.4	10.2	43.2	9	34
68	89	17.1	34.9	62.9	26.4	75.4	37.2	6.9	25.2	9.5	40.5	8.8	32.4
69	80.7	17.1	33.8	60.3	25.9	58.5	37.5	7.2	26.1	11.3	41.6	8.3	35.8
70	54.3	16.2	29.8	47.9	24.5	65	29.1	8.1	28	11.6	42.5	7.6	39.8
71	77.9	16	34.9	62.2	26.8	65.7	37	8.3	25.2	10.2	41.8	9	34.9
72	69.6	16.2	35.6	61.3	27.1	66.4	36.5	8.3	24.7	10.4	41.6	9	34.5

Appendix 5. Throughfall % data ($P_{t(\%)}$) tabulated by collection number and plot number. Missing data - *

Coll.	Plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	Pg mm	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
1	Pt mm	3.7	0.9	1.4	6.2	0.7	3	1.4	3	1.4	*	*	*	2.8	*	0.5	4.9	4.9	3.5
	Pt %	94.9	23.7	35.6	160	17.8	77.1	35.6	77.1	35.6	*	*	*	71.1	*	11.9	125	125	88.9
	Pg mm	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6
2	Pt mm	14.3	14.3	8.3	31.2	9.2	17.3	11.6	10.2	19.7	9.9	38.4	6.9	15	16.4	14.6	19.7	32.4	25.7
	Pt %	73.1	73.1	42.5	159	47.2	88.5	59	51.9	100	50.7	196	35.4	76.7	83.8	74.3	100	165	131
	Pg mm	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
3	Pt mm	20.3	14.6	15.3	16.9	18.7	16.2	18.7	19.7	20.3	14.6	11.8	8.3	18.5	18.3	22.7	15.3	27.1	8.8
	Pt %	105	75.1	78.7	87	96.5	83.4	96.5	101	105	75.1	60.8	42.9	95.3	94.2	117	78.7	139	45.3
	Pg mm	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
4	Pt mm	11.6	10.6	6.5	22.2	3.2	9.5	5.5	4.4	18	7.9	19.7	7.4	9.2	10.2	4.9	13.9	19.7	16.9
	Pt %	91.0	83.7	51	175	25.5	74.6	43.7	34.6	142	61.9	155	58.3	72.8	80.1	38.2	109	155	133
	Pg mm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5	Pt mm	0.5	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2
	Pt %	154	77.1	77.1	77.1	38.5	77.1	77.1	38.5	0	38.5	77.1	38.5	77.1	77.1	77.1	77.1	77.1	77.1
	Pg mm	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4
6	Pt mm	15.5	20.3	17.6	22.7	14.8	16.4	12.7	27.3	19.2	16.2	27.3	30.1	14.8	16.2	18.5	20.3	30.8	23.1
	Pt %	69.2	90.8	78.4	101	66.1	73.3	56.8	122	85.7	72.3	122	134	66.1	72.3	82.6	90.8	137	103
	Pg mm	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
7	Pt mm	41.2	44.2	30.5	54.3	46.2	34.7	35.6	54.1	40.7	29.1	40.7	49	17.1	26.6	62.4	34.9	30.1	21.3
	Pt %	165	177	122	217	185	139	142	216	163	117	163	196	68.4	106	250	140	120	85.1
	Pg mm	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
8	Pt mm	11.6	4.6	3.2	6.9	5.8	4.6	6	5.3	11.1	7.2	6	1.8	6.9	9.9	6.9	5.8	15.7	6.9
	Pt %	139	55.7	39	83.6	69.6	55.7	72.4	64.1	134	86.4	72.4	22.3	83.6	120	83.6	69.6	189	83.6
	Pg mm	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
9	Pt mm	6.7	3.5	7.4	11.1	6	3.9	3.5	3.5	4.6	4.2	3.7	4.6	1.2	2.5	4.6	2.5	5.8	2.1
	Pt %	114	58.8	125	188	102	66.6	58.8	58.8	78.4	70.5	62.7	78.4	19.6	43.1	78.4	43.1	98	35.3
	Pg mm	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
10	Pt mm	4.9	3.2	3.5	6.9	2.5	3.7	3.7	1.8	8.1	3	4.4	0.5	1.4	5.3	1.4	4.9	4.6	3.2
	Pt %	95.2	63.5	68	136	49.9	72.5	72.5	36.3	159	58.9	86.1	9.1	27.2	104	27.2	95.2	90.7	63.5
	Pg mm	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
11	Pt mm	9.2	5.8	8.6	15.7	7.9	5.8	4.9	4.2	9.9	6	3.2	3.7	1.2	4.6	7.2	5.3	5.1	2.3
	Pt %	129	80.3	119	218	109	80.3	67.4	57.8	138	83.5	45	51.4	16.1	64.2	99.6	73.9	70.6	32.1

	Pg mm	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
12	Pt mm	5.8	4.6	9.2	15.5	6.2	4.6	4.4	4.9	4.9	4.2	2.3	5.8	2.5	3.7	6.9	4.2	4.6	3.7
	Pt %	99.7	79.7	160	267	108	79.7	75.7	83.7	83.7	71.8	39.9	99.7	43.9	63.8	120	71.8	79.7	63.8
	Pg mm	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
13	Pt mm	5.5	3.7	8.1	13.2	6.9	5.1	6	6.7	5.8	3.7	2.8	5.1	4.6	4.4	5.8	6.9	1.8	4.6
	Pt %	111	74	162	264	139	102	120	134	116	74	55.5	102	92.5	87.9	116	139	37	92.5
	Pg mm	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1
14	Pt mm	49.9	54.8	29.8	84.9	61.3	52.7	70.3	90.4	47.6	59.4	90.6	89.9	43.2	43	81.6	65.4	84.6	63.1
	Pt %	75.6	82.9	45.1	128	92.7	79.8	106	137	72.1	89.9	137	136	65.4	65.1	124	99	128	95.5
	Pg mm	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
15	Pt mm	15	12.9	23.1	35.1	19.7	12.7	13.4	18	12.5	10.9	11.6	29.1	10.9	9.5	33.5	13.9	17.3	11.1
	Pt %	92.2	79.4	142	216	121	78	82.3	111	76.6	66.7	70.9	179	66.7	58.2	206	85.1	106	68.1
	Pg mm	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3
16	Pt mm	36.8	29.1	17.1	29.1	30.3	23.1	21	25.9	40.2	33.5	30.5	36.3	24	33.1	50.2	26.4	46.5	23.4
	Pt %	107	84.9	49.9	84.9	88.3	67.4	61.3	75.5	117	97.7	89	106	70.1	96.4	146	76.8	136	68.1
	Pg mm	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
17	Pt mm	5.1	1.6	5.3	6.7	2.3	3.7	2.3	0.9	4.4	*	0.9	1.8	3.7	3.9	2.1	5.5	1.6	3
	Pt %	127	40.5	133	168	57.8	92.5	57.8	23.1	110	*	23.1	46.2	92.5	98.3	52	139	40.5	75.1
	Pg mm	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9
18	Pt mm	39.1	34.9	29.8	62.7	39.3	44.2	40	42.3	45.8	51.6	78.8	65.4	41.4	49.9	62.7	52.9	62	58
	Pt %	69.9	62.5	53.4	112	70.3	79	71.6	75.7	81.9	92.2	141	117	74	89.3	112	94.7	111	104
	Pg mm	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
19	Pt mm	9.9	6.7	7.9	12.7	2.3	7.6	4.4	4.6	12.9	11.1	11.8	9.5	7.4	11.1	6.5	11.6	16.9	16.4
	Pt %	71	47.9	56.2	90.8	16.5	54.5	31.4	33	92.5	79.3	84.2	67.7	52.8	79.3	46.2	82.6	121	117
	Pg mm	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
20	Pt mm	17.6	11.1	18.5	28.4	21	16.6	13.2	16.9	21	12.7	16.9	15.7	10.9	16.6	19	16.2	18.5	10.6
	Pt %	127	80.4	134	206	153	121	95.5	122	153	92.2	122	114	78.7	121	137	117	134	77.1
	Pg mm	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3
21	Pt mm	60.1	40.2	53.4	56.4	57.1	48.6	53.2	54.6	56	52	53.9	90.9	66.4	52.9	104	72.6	59.7	57.3
	Pt %	89.3	59.8	79.4	83.8	84.9	72.1	79	81.1	83.1	77.3	80	135	98.6	78.7	154	108	88.6	85.2
	Pg mm	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9
22	Pt mm	33.5	15.5	10.6	46.7	18.3	23.4	22.2	18.7	44.4	32.6	41.8	25.2	22.4	27.7	31.2	34.5	51.1	41.8
	Pt %	102	47.1	32.3	142	55.5	71	67.5	56.9	135	99.1	127	76.6	68.2	84.3	94.9	105	155	127
	Pg mm	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
23	Pt mm	10.9	8.3	11.8	9.5	14.6	12.3	9.5	7.2	17.6	7.6	7.9	9.9	8.8	11.8	13.9	13.4	6.5	12.5
	Pt %	114	87.6	124	99.8	153	129	99.8	75.4	185	80.3	82.8	105	92.5	124	146	141	68.1	131

	Pg mm	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
24	Pt mm	26.1	18.5	18.7	16.4	22.9	18.5	19	19	29.6	22.2	20.1	23.6	20.8	25.7	32.6	28.9	34	20.6
	Pt %	98.2	69.5	70.4	61.7	86.1	69.5	71.3	71.3	111	83.4	75.6	88.7	78.2	96.5	123	109	128	77.4
	Pg mm	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
25	Pt mm	9.7	6.7	10.4	9.7	9.2	6	7.9	7.9	7.9	5.5	6	10.2	4.9	6.2	14.8	8.6	7.9	7.6
	Pt %	99.1	68.4	106	99.1	94.4	61.3	80.2	80.2	80.2	56.6	61.3	104	49.5	63.7	151	87.3	80.2	77.9
	Pg mm	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
26	Pt mm	45.5	25.2	32.1	31.7	41.4	28.7	32.1	37	43.5	34	29.6	52.3	31.4	31.7	63.6	34.9	52.9	30.5
	Pt %	120	66.3	84.6	83.4	109	75.4	84.6	97.4	114	89.4	77.9	138	82.8	83.4	167	91.9	139	80.3
	Pg mm	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
27	Pt mm	5.8	2.1	2.5	3.5	1.6	2.1	2.1	1.8	7.4	4.2	1.6	0.7	1.4	3.7	3	1.8	3.7	1.8
	Pt %	66.4	23.9	29.2	39.9	18.6	23.9	23.9	21.3	85	47.8	18.6	8	15.9	42.5	34.5	21.3	42.5	21.3
	Pg mm	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4
28	Pt mm	28	21.3	37.9	29.6	25.7	22.4	21	20.3	23.1	20.1	17.6	26.1	28	28.4	45.3	34.2	27.5	24.5
	Pt %	74.8	56.9	101	79.1	68.6	60	56.3	54.4	61.8	53.8	47	69.9	74.8	76	121	91.5	73.6	65.5

Coll.	Plot	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	Pg mm	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
1	Pt mm	3.5	3.7	0.5	0	5.1	6.2	1.2	2.3	8.6	4.2	0.5	3.2	3.7	4.9	3	4.4	0.7	3.7
	Pt %	88.9	94.9	11.9	0	130	160	29.6	59.3	219	107	11.9	83	94.9	125	77.1	113	17.8	94.9
	Pg mm	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6
2	Pt mm	11.6	17.1	15.5	15	24.5	20.3	16	9.7	14.3	17.1	9.5	14.1	15.3	15	17.1	19.2	13.6	21.0
	Pt %	59	87.3	79	76.7	125	104	81.4	49.5	73.1	87.3	48.4	72	77.9	76.7	87.3	97.9	69.6	107
	Pg mm	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
3	Pt mm	22	26.1	17.6	2.8	17.6	23.1	16.2	11.1	18.3	10.4	3.2	16.9	16.9	19	16.9	13.4	15	12.5
	Pt %	113	135	90.6	14.3	90.6	119	83.4	57.2	94.2	53.6	16.7	87	87	97.7	87	69.1	77.5	64.4
	Pg mm	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
4	Pt mm	4.9	11.8	8.3	7.4	9.7	12.7	4.6	5.8	9	11.8	3	9.2	8.8	9.7	9.2	12.5	3.9	7.9
	Pt %	38.2	92.8	65.5	58.3	76.5	100	36.4	45.5	71	92.8	23.7	72.8	69.2	76.5	72.8	98.3	30.9	61.9
	Pg mm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5	Pt mm	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2
	Pt %	77.1	77.1	77.1	77.1	77.1	77.1	38.5	38.5	77.1	38.5	38.5	77.1	77.1	77.1	38.5	38.5	38.5	77.1

	Pg mm	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4
6	Pt mm	10.6	15	28.4	16.4	23.4	16.4	18.3	12.9	23.1	20.6	10.9	18.7	16	14.3	19.7	23.6	18.5	16.4
	Pt %	47.5	67.1	127	73.3	104	73.3	81.5	57.8	103	91.9	48.5	83.6	71.2	64	87.7	105	82.6	73.3
	Pg mm	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
7	Pt mm	41.8	43.5	47.6	24.5	31.9	46.2	32.8	24.3	37.9	28.4	8.8	29.1	26.8	35.6	46.2	17.6	50.6	22.7
	Pt %	167	174	191	98	128	185	131	97.1	152	114	35.1	117	107	142	185	70.3	203	90.6
	Pg mm	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
8	Pt mm	8.1	11.1	3.5	0.5	10.4	9.7	7.2	4.4	7.9	5.8	0.9	8.6	7.6	6.7	5.8	8.1	5.5	5.3
	Pt %	97.5	134	41.8	5.6	125	117	86.4	52.9	94.7	69.6	11.1	103	91.9	80.8	69.6	97.5	66.9	64.1
	Pg mm	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
9	Pt mm	4.6	10.6	7.4	0.7	2.1	8.3	1.2	2.1	4.9	1.6	0.2	2.3	1.6	2.1	5.8	1.2	3.2	0.9
	Pt %	78.4	180	125	11.8	35.3	141	19.6	35.3	82.3	27.4	3.9	39.2	27.4	35.3	98	19.6	54.9	15.7
	Pg mm	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
10	Pt mm	4.2	3.9	1.8	0	4.4	5.8	1.6	0.9	4.9	3.5	0.2	3.5	2.8	4.2	2.5	2.8	0.9	1.6
	Pt %	81.6	77.1	36.3	0	86.1	113	31.7	18.1	95.2	68	4.5	68	54.4	81.6	49.9	54.4	18.1	31.7
	Pg mm	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
11	Pt mm	9.5	11.6	6.9	1.2	3	11.6	2.5	4.3	11.1	3.5	0.2	4.9	3	5.3	10.6	2.1	2.8	2.1
	Pt %	132	161	96.3	16.1	41.7	161	35.3	59.4	154	48.2	3.2	67.4	41.7	73.9	148	28.9	38.5	28.9
	Pg mm	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
12	Pt mm	6	9.9	10.4	2.8	2.8	9.2	2.1	5.8	7.9	2.5	0.5	4.2	3	4.6	10.4	1.2	5.3	1.4
	Pt %	104	171	179	47.8	47.8	160	35.9	99.7	136	43.9	8	71.8	51.8	79.7	179	19.9	91.7	23.9
	Pg mm	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
13	Pt mm	7.4	9.2	9	3.9	6	10.4	1.8	3.7	6	2.8	0.2	4.9	4.6	6.9	9.5	0.7	9.9	2.3
	Pt %	148	185	180	78.6	120	208	37	74	120	55.5	4.6	97.1	92.5	139	190	13.9	199	46.2
	Pg mm	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1
14	Pt mm	42.5	54.8	89.2	104	57.1	73.3	83.5	37.2	42.1	50.9	83.2	50.4	45.5	40.9	49.7	65.7	92	60.8
	Pt %	64.4	82.9	135	157	86.4	111	126	56.3	63.7	77	126	76.3	68.9	61.9	75.2	99.3	139	92
	Pg mm	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
15	Pt mm	21	25.4	25.4	20.6	10.9	26.4	8.8	14.6	13.9	9.2	6.2	12.7	9.9	12.7	27.3	6	28.9	4.6
	Pt %	129	156	156	126	66.7	162	53.9	89.4	85.1	56.7	38.3	78	61	78	167	36.9	177	28.4
	Pg mm	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3
16	Pt mm	31.7	38.4	31.4	16.6	34.7	37.5	27.3	19	39.3	23.6	23.4	26.4	24.3	27.1	33.3	29.8	20.1	19.9
	Pt %	92.4	112	91.7	48.5	101	109	79.5	55.3	115	68.8	68.1	76.8	70.8	78.9	97.1	87	58.6	58
	Pg mm	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
17	Pt mm	3	4.2	2.8	1.2	2.5	5.1	1.2	0.9	3.2	0.9	0.2	1.4	1.8	2.1	3.5	0.2	2.5	1.2
	Pt %	75.1	104	69.4	28.9	63.6	127	28.9	23.1	80.9	23.1	5.8	34.7	46.2	52	86.7	5.8	63.6	28.9

	Pg mm	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9	55.9
18	Pt mm	39.3	47.4	55.7	72.6	62	59	42.5	34.9	37.2	47.9	61.7	40.2	36.1	38.6	49.9	54.6	55.5	35.1
	Pt %	70.3	84.8	99.7	130	111	106	76.1	62.5	66.6	85.6	110	72	64.5	69.1	89.3	97.6	99.3	62.9
	Pg mm	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
19	Pt mm	6.2	8.1	9	7.9	12.5	10.9	13.6	5.8	13.2	10.2	4.2	6	5.5	5.7	8.6	11.3	5.8	5.3
	Pt %	44.6	57.8	64.4	56.2	89.2	77.6	97.4	41.3	94.1	72.7	29.7	42.9	39.6	40.5	61.1	80.9	41.3	38
	Pg mm	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8
20	Pt mm	17.3	23.6	16.2	9.2	13.9	18	11.1	11.6	20.6	12.3	8.8	11.3	9.7	16.4	20.1	7.9	21.5	8.1
	Pt %	126	171	117	67	101	131	80.4	83.8	149	88.8	63.7	82.1	70.4	119	146	57	156	58.6
	Pg mm	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3
21	Pt mm	41.8	61.7	70.3	107	72.1	56.2	51.3	44.6	41.2	44.6	46.9	57.1	46.5	39.8	71.9	60.6	64.5	43.5
	Pt %	62.2	91.7	104	159	107	83.5	76.3	66.3	61.2	66.3	69.7	84.9	69.1	59.1	107	90	95.9	64.6
	Pg mm	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9	32.9
22	Pt mm	21	37	34.5	35.4	38.2	33.5	26.6	15.5	25.7	26.6	23.6	22.7	20.6	21	23.1	29.8	28	23.4
	Pt %	64	112	105	108	116	102	80.8	47.1	78	80.8	71.7	68.9	62.5	64	70.3	90.7	85	71
	Pg mm	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
23	Pt mm	13.6	15.3	10.4	9.5	13.4	18.5	9	7.6	17.6	7.9	3.9	10.9	9.2	13.4	16.6	4.6	13.9	7.4
	Pt %	144	161	110	99.8	141	195	94.9	80.3	185	82.8	41.4	114	97.4	141	175	48.7	146	77.9
	Pg mm	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
24	Pt mm	23.4	26.6	13.2	17.6	27.7	40.7	21	20.8	25.9	16.4	17.6	23.6	22	22.4	24.3	19.2	21.7	16.4
	Pt %	87.8	100	49.5	66.1	104	153	79.1	78.2	97.4	61.7	66.1	88.7	82.6	84.3	91.3	72.1	81.7	61.7
	Pg mm	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
25	Pt mm	9	12.3	10.2	6.2	6	15.3	2.1	5.5	11.1	3.7	3.7	6.7	5.3	6.5	14.3	3.7	7.9	2.8
	Pt %	92	125	104	63.7	61.3	156	21.2	56.6	113	37.7	37.7	68.4	54.3	66.1	146	37.7	80.2	28.3
	Pg mm	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
26	Pt mm	32.6	66.4	38.2	33.5	34.5	58.7	24.5	31	38.8	18.7	24.3	33.5	25	31.7	43.5	26.1	34.5	17.8
	Pt %	85.8	175	100	88.2	90.7	155	64.5	81.5	102	49.3	63.9	88.2	65.7	83.4	114	68.8	90.7	46.9
	Pg mm	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
27	Pt mm	3	6.2	2.1	0.5	1.8	9.5	1.4	1.4	6	1.4	0.5	3.9	2.5	3.7	4.4	1.8	1.4	1.2
	Pt %	34.5	71.8	23.9	5.3	21.3	109	15.9	15.9	69.1	15.9	5.3	45.2	29.2	42.5	50.5	21.3	15.9	13.3
	Pg mm	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4	37.4
28	Pt mm	29.8	33.3	29.4	22.2	23.4	57.1	10.6	20.6	35.8	14.6	5.1	23.1	23.6	25	41.6	11.1	32.8	14.6
	Pt %	79.8	89	78.5	59.3	62.4	153	28.4	55	95.8	38.9	13.6	61.8	63.1	66.8	111	29.7	87.8	38.9

Appendix 6. Cell variances (VAR) and probability levels of W by individual collections

		CW	CS	CE	SW	SS	SE			CW	CS	CE	SW	SS	SE
	VAR	0.19	0.15	0.27	5	6.06	2.96		VAR	57.41	81.03	80.84	424.16	551.8	214.17
Coll 1	W	0.78	0.91	0.87	0.97	0.92	0.87	Coll 14	W	0.97	0.93	0.88	0.87	0.89	0.94
	P	< 0.00	0.21	0.06	0.93	0.26	0.06		P	0.87	0.36	0.08	0.06	0.1	0.42
	VAR	0.49	3.03	1.62	4.11	84.23	47.04		VAR	0.53	0.46	1.05	38.95	92.56	61.29
Coll 2	W	0.96	0.95	0.93	0.93	0.83	0.92	Coll 15	W	0.97	0.91	0.94	0.86	0.91	0.91
	P	0.66	0.65	0.34	0.38	0.02	0.3		P	0.8	0.4	0.47	0.04	0.2	0.18
	VAR	0.34	1.92	2.071	31.94	9.44	43.95		VAR	0.53	2.79	2.37	50	46.84	96.36
Coll 3	W	0.94	0.94	0.91	0.83	0.94	0.98	Coll 16	W	0.91	0.8	0.95	0.94	0.96	0.82
	P	0.47	0.49	0.19	0.02	0.5	0.97		P	0.19	< 0.00	0.61	0.49	0.79	0.01
	VAR	0.24	0.66	0.48	29.65	32.26	11.34		VAR	2.47	29.61	10.74	127.03	217.34	99.32
Coll 4	W	0.97	0.92	0.97	0.93	0.86	0.92	Coll 17	W	0.86	0.88	0.88	0.94	0.92	0.92
	P	0.87	0.3	0.87	0.35	0.04	0.29		P	0.04	0.08	0.09	0.46	0.31	0.26
	VAR	0.02	0.008	0.001	0.01	0.003	0.002		VAR	0.59	0.71	1.38	34.56	50.74	40.4
Coll 5	W	0.55	0.32	0.23	0.73	0.66	0.55	Coll 18	W	0.92	0.87	0.99	0.97	0.92	0.94
	P	<0.00	<0.00	<0.00	< 0.00	< 0.00	< 0.00		P	0.27	0.06	0.99	0.89	0.26	0.41
	VAR	4.64	8.66	1.8	23.39	24.28	32.02		VAR	36.34	43.75	11.78	289.17	205.38	299.42
Coll 6	W	0.95	0.85	0.95	0.81	0.97	0.92	Coll 19	W	0.93	0.95	0.92	0.82	0.93	0.84
	P	0.61	0.04	0.64	< 0.00	0.93	0.31		P	0.35	0.56	0.28	0.01	0.39	0.02
	VAR	1.42	1.76	3.49	184.36	161.15	88.43		VAR	1.8	6.29	8.6	67.49	106.96	91.87
Coll 7	W	0.89	0.87	0.89	0.96	0.94	0.96	Coll 20	W	0.95	0.95	0.85	0.9	0.93	0.86
	P	0.11	0.1	0.12	0.78	0.48	0.66		P	0.55	0.63	0.03	0.17	0.36	0.05
	VAR	0.15	0.48	0.36	11.53	3.66	12.37		VAR	0.77	0.36	0.48	13.63	14.74	12
Coll 8	W	0.92	0.77	0.91	0.93	0.95	0.85	Coll 21	W	0.94	0.96	0.93	0.94	0.92	0.91
	P	0.3	< 0.00	0.2	0.3	0.56	0.04		P	0.5	0.69	0.33	0.44	0.25	0.19
	VAR	0.3	0.13	0.3	9.56	8.56	3.47		VAR	5.36	3.77	1.58	47.91	7.17	37.61
Coll 9	W	0.93	0.94	0.85	0.93	0.89	0.97	Coll 22	W	0.9	0.94	0.94	0.93	0.97	0.9
	P	0.4	0.42	0.03	0.31	0.1	0.83		P	0.15	0.42	0.44	0.39	0.89	0.17
	VAR	0.04	0.08	0.1	4.39	3.66	2.38		VAR	0.58	0.55	0.91	9.38	12.42	10.39
Coll 10	W	0.86	0.93	0.94	0.98	0.94	0.95	Coll 23	W	0.92	0.9	0.88	0.86	0.98	0.91
	P	0.05	0.32	0.47	0.93	0.41	0.61		P	0.24	0.14	0.1	0.05	0.94	0.22
										CW	CS	CE	SW	SS	SE
	VAR	0.27	0.25	0.47	12.09	20.43	6.84		VAR	2.94	0.68	10.46	140.53	65.28	175.51
Coll 11	W	0.87	0.93	0.91	0.94	0.87	0.99	Coll 24	W	0.95	0.91	0.91	0.86	0.88	0.9
	P	0.05	0.39	0.21	0.49	0.07	0.98		P	0.59	0.2	0.21	0.05	0.09	0.14
	VAR	0.15	0.28	0.2	7.53	17.29	3.6		VAR	0.24	0.51	1.41	7.06	2.38	1
Coll 12	W	0.74	0.83	0.9	0.84	0.92	0.96	Coll 25	W	0.97	0.87	0.92	0.95	0.82	0.94
	P	< 0.00	0.02	0.15	0.02	0.24	0.7		P	0.85	0.06	0.22	0.56	0.01	0.51

	VAR	0.16	0.39	0.11	6.54	13.85	5.25		VAR	10.63	5.48	7.31	102.29	102.28	106.31
Coll 13	W	0.71	0.94	0.92	0.93	0.95	0.94	Coll 26	W	0.92	0.9	0.96	0.65	0.97	0.97
	P	< 0.00	0.43	0.3	0.39	0.62	0.5		P	0.3	0.15	0.76	< 0.00	0.81	0.9

Appendix 7. Standardized percentage throughfall data ($\mathbf{SP}_{(t\%)}$)by plot and collection.

Plots	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
C1	57.6	13.4	22.0	59.9	9.6	55.6	25.0	*	*	*	78.7	*	72.2	95.5	4.8	88.2	65.7	66.9
C2	44.4	41.4	26.2	59.6	25.5	63.8	41.4	24.0	54.2	43.5	100.0	18.1	77.8	67.5	29.8	71.0	87.2	98.5
C3	63.7	42.5	48.6	32.6	52.2	60.1	67.8	46.8	56.7	64.4	31.0	21.9	96.7	75.9	46.8	55.7	73.6	34.1
C4	55.3	47.4	31.5	65.4	13.8	53.8	30.7	16.0	76.8	53.1	79.0	29.7	73.9	64.5	15.3	77.4	81.7	100.0
C5	93.6	43.6	47.6	28.9	20.8	55.6	54.1	17.8	0.0	33.1	39.4	19.7	78.2	62.1	30.9	54.6	40.7	58.0
C6	42.0	51.4	48.5	37.9	35.7	52.8	39.9	56.3	46.3	62.0	62.2	68.4	67.0	58.2	33.1	64.4	72.5	77.7
C7	100.0	100.0	75.4	81.4	100.0	100.0	100.0	100.0	88.0	100.0	83.1	100.0	69.4	85.7	100.0	98.9	63.5	64.0
C8	84.6	31.5	24.1	31.3	37.7	40.2	50.9	29.6	72.3	74.1	37.0	11.4	84.8	96.5	33.5	49.3	100.0	62.9
C9	69.0	33.3	77.5	70.4	55.1	48.0	41.3	27.2	42.4	60.5	32.0	40.0	19.9	34.7	31.4	30.5	51.7	26.5
C10	57.8	35.9	42.0	50.9	27.0	52.3	50.9	16.8	85.8	50.6	44.0	4.6	27.6	84.0	10.9	67.4	47.9	47.8
C11	78.0	45.5	73.4	81.8	59.0	57.9	47.4	26.7	74.7	71.7	23.0	26.2	16.3	51.7	39.9	52.3	37.3	24.2
C12	60.5	45.1	98.5	100.0	58.2	57.5	53.2	38.7	45.3	61.6	20.4	50.8	44.5	51.4	47.9	50.8	42.1	48.0
C13	67.4	41.9	100.0	98.7	75.0	73.3	84.4	62.0	62.5	63.5	28.3	51.9	93.8	70.8	46.3	98.3	19.5	69.6
C14	45.9	46.9	27.9	48.1	50.1	57.5	74.7	63.2	39.0	77.1	70.0	69.4	66.3	52.4	49.5	70.1	67.6	71.9
C15	56.0	45.0	87.6	80.7	65.2	56.2	57.8	51.1	41.4	57.2	36.2	91.2	67.6	46.9	82.4	60.3	56.2	51.2
C16	65.1	48.1	30.8	31.8	47.7	48.6	43.1	34.9	63.4	83.9	45.4	54.0	71.1	77.7	58.6	54.4	71.5	51.2
C17	77.3	22.9	82.1	62.8	31.3	66.7	40.6	10.7	59.4	*	11.8	23.6	93.8	79.2	20.8	98.3	21.4	56.5
C18	42.5	35.4	33.0	42.0	38.0	57.0	50.2	35.0	44.3	79.2	72.0	59.7	75.1	72.0	44.9	67.1	58.5	78.1
C19	43.1	27.1	34.7	34.0	8.9	39.3	22.0	15.3	50.0	68.0	43.0	34.5	53.6	63.9	18.5	58.5	63.7	88.2
C20	77.4	45.5	82.8	77.2	82.4	87.0	67.1	56.5	82.4	79.1	62.5	58.1	79.9	97.2	55.0	83.1	70.8	58.0
C21	54.3	33.8	49.0	31.4	45.9	52.0	55.5	37.5	45.0	66.3	40.9	68.9	100.0	63.4	61.8	76.4	46.8	64.1
C20	61.9	26.7	20.0	53.2	30.0	51.2	47.4	26.3	73.0	85.0	65.0	39.1	69.1	67.9	38.0	74.2	82.0	95.7
C23	69.5	49.6	76.7	37.4	82.9	93.0	70.1	34.9	100.0	68.9	42.3	53.4	93.8	100.0	58.5	100.0	36.0	98.9
C24	59.7	39.4	43.5	23.1	46.5	50.1	50.0	32.9	60.2	71.6	38.6	45.2	79.3	77.7	49.1	77.0	67.5	58.2
C25	60.2	38.7	65.6	37.1	51.0	44.2	56.3	37.1	43.4	48.6	31.3	53.0	50.3	51.3	60.5	61.8	42.4	58.6
C26	72.8	37.5	52.3	31.2	58.9	54.4	59.4	45.0	61.8	76.8	39.8	70.1	83.9	67.2	67.0	65.1	73.6	60.4
C27	40.4	13.5	18.1	14.9	10.1	17.2	16.8	9.8	46.0	41.1	9.5	4.1	16.2	34.3	13.8	15.1	22.5	16.0
C28	45.4	32.2	62.6	29.6	37.1	43.2	39.5	25.1	33.4	46.2	24.0	35.6	75.9	61.3	48.5	64.8	38.8	49.3

Plots	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
C1	53.1	51.3	6.2	0.0	92.4	76.9	22.6	59.5	100.0	93.8	9.4	71.2	88.4	87.4	40.7	100.0	8.8	88.4
C2	35.2	47.2	41.5	48.2	88.6	49.9	62.0	49.7	33.3	76.7	38.4	61.8	72.6	53.8	46.0	86.9	34.4	100.0
C3	67.6	72.8	47.5	9.0	64.2	57.3	63.5	57.4	42.9	47.2	13.3	74.7	81.1	68.6	45.9	61.4	38.3	60.0
C4	22.8	50.2	34.4	36.6	54.2	48.1	27.7	45.7	32.4	81.6	18.8	62.5	64.5	53.7	38.4	87.3	15.3	57.7
C5	46.0	41.7	40.5	48.5	54.6	37.0	29.3	38.7	35.1	33.9	30.6	66.1	71.8	54.1	20.3	34.2	19.0	71.8
C6	28.4	36.3	66.6	46.1	73.9	35.2	62.1	58.0	47.1	80.8	38.5	71.8	66.4	44.9	46.3	93.5	40.8	68.3
C7	100.0	94.0	100.0	61.6	90.4	88.9	100.0	97.4	69.2	100.0	27.9	100.0	100.0	100.0	97.6	62.4	100.0	84.4
C8	58.2	72.3	21.9	3.5	88.8	56.2	65.8	53.1	43.2	61.2	8.9	88.5	85.7	56.7	36.7	86.6	33.0	59.7
C9	46.8	97.5	65.8	7.4	25.0	67.8	14.9	35.4	37.5	24.1	3.1	33.6	25.6	24.8	51.7	17.4	27.1	14.6
C10	48.8	41.7	19.0	0.0	61.0	54.5	24.2	18.2	43.4	59.8	3.6	58.4	50.7	57.3	26.3	48.3	9.0	29.6
C11	78.7	86.8	50.6	10.1	29.6	77.2	26.9	59.6	70.3	42.3	2.6	57.9	38.9	51.9	77.9	25.7	19.0	26.9
C12	61.9	92.7	94.2	30.1	33.9	76.6	27.3	100.0	61.8	38.6	6.3	61.6	48.3	56.0	94.6	17.7	45.3	22.3
C13	88.4	100.0	94.7	49.4	85.2	100.0	28.2	74.2	54.8	48.8	3.7	83.3	86.2	97.4	100.0	12.3	98.2	43.1
C14	38.5	44.8	70.9	98.5	61.2	53.3	96.2	56.5	29.0	67.7	100.0	65.4	64.2	43.5	39.7	88.2	68.7	85.7
C15	77.1	84.4	81.9	79.4	47.2	77.7	41.0	89.7	38.8	49.9	30.4	67.0	56.9	54.8	88.3	32.7	87.5	26.4
C16	55.2	60.5	48.1	30.5	71.6	52.5	60.6	55.5	52.2	60.4	54.1	65.9	66.0	55.4	51.2	77.2	29.0	54.0
C17	44.9	56.3	36.4	18.2	45.0	61.1	22.0	23.2	36.9	20.3	4.6	29.8	43.1	36.5	45.7	5.1	31.4	26.9
C18	42.0	45.8	52.3	81.7	78.5	50.7	58.0	62.7	30.4	75.3	87.7	61.8	60.1	48.5	47.1	86.7	49.0	58.6
C19	26.6	31.3	33.8	35.3	63.2	37.3	74.2	41.4	42.9	63.9	23.6	36.9	37.0	28.4	32.2	71.8	20.4	35.4
C20	75.1	92.4	61.6	42.1	71.2	62.8	61.2	84.1	68.0	78.1	50.6	70.5	65.6	83.5	76.9	50.6	76.9	54.6
C21	37.2	49.6	54.8	100.0	75.9	40.1	58.1	66.5	27.9	58.3	55.4	72.8	64.4	41.5	56.4	79.9	47.3	60.2

C2	38.2	60.8	55.0	67.6	82.2	49.0	61.5	47.3	35.6	71.1	56.9	59.1	58.3	44.9	37.1	80.5	42.0	66.1
C23	85.8	86.8	57.5	62.7	100.0	93.6	72.3	80.6	84.3	72.7	32.9	98.2	90.7	99.1	92.4	43.2	72.1	72.6
C24	52.4	54.0	26.0	41.5	73.9	73.5	60.2	78.5	44.4	54.3	52.5	76.1	77.0	59.2	48.1	64.1	40.3	57.5
C25	55.0	67.6	54.5	40.1	43.5	74.8	16.2	56.8	51.6	33.2	30.0	58.7	50.6	46.4	77.2	33.5	39.6	26.4
C26	51.3	94.4	52.7	55.5	64.2	74.3	49.1	81.8	46.6	43.3	50.7	75.7	61.3	58.5	60.3	61.0	44.8	43.6
C27	20.6	38.8	12.6	3.3	15.1	52.4	12.1	16.0	31.5	14.0	4.2	38.8	27.3	29.9	26.6	18.9	7.9	12.4
C28	47.6	48.1	41.2	37.3	44.2	73.4	21.7	55.2	43.7	34.2	10.8	53.1	58.8	46.9	58.7	26.3	43.3	36.3

Appendix 8. Pairwise collection comparisons ranked by z scores.

Coll	Coll	Z	Coll	Coll	Z	Coll	Coll	Z	Coll	Coll	Z	Coll	Coll	Z	Coll	Coll	Z
7	27	11.38	11	20	4.32	20	24	2.82	2	5	2.20	10	11	1.23	8	24	0.52
23	27	9.13	20	25	4.27	19	22	2.81	3	28	2.19	2	15	1.20	1	8	0.48
20	27	9.05	7	15	4.26	20	22	2.81	12	19	2.19	6	14	1.20	6	12	0.47
7	9	8.41	9	15	4.15	17	22	2.80	12	17	2.18	2	11	1.19	9	19	0.46
13	27	8.39	7	14	4.09	19	24	2.80	13	24	2.16	3	25	1.19	9	17	0.45
7	19	7.95	9	26	4.08	5	18	2.79	2	28	2.15	4	22	1.17	8	16	0.44
7	17	7.90	4	23	4.05	17	24	2.79	13	22	2.15	3	15	1.15	2	21	0.41
7	10	7.88	4	20	3.97	21	23	2.79	1	13	2.12	4	24	1.15	6	18	0.41
5	7	7.66	14	19	3.86	12	13	2.77	10	12	2.12	2	25	1.14	6	8	0.38
7	28	7.61	14	17	3.84	1	20	2.76	4	9	2.11	14	16	1.14	3	21	0.37
14	27	7.29	10	14	3.79	8	9	2.74	23	26	2.08	2	26	1.13	16	18	0.36
15	27	7.12	27	28	3.78	10	22	2.74	4	15	2.05	1	4	1.10	3	12	0.35
26	27	7.05	5	27	3.72	10	24	2.73	13	21	2.05	13	14	1.10	17	28	0.35
7	11	6.65	15	19	3.69	18	28	2.73	15	23	2.01	3	26	1.08	19	28	0.35
7	25	6.60	15	17	3.67	16	19	2.72	20	26	2.00	4	16	1.07	4	11	0.34
18	27	6.51	11	13	3.66	20	21	2.72	5	8	1.99	1	14	1.06	2	22	0.32
21	27	6.34	10	15	3.62	16	17	2.71	4	26	1.97	5	25	1.06	2	24	0.31
4	7	6.31	19	26	3.62	1	19	2.69	8	28	1.94	14	24	1.06	2	12	0.30
22	27	6.24	13	25	3.61	1	17	2.68	15	20	1.93	14	22	1.05	4	25	0.30
24	27	6.23	17	26	3.60	8	13	2.68	5	12	1.90	6	15	1.03	5	17	0.30
9	23	6.16	5	14	3.57	6	19	2.66	13	18	1.88	4	6	1.02	1	18	0.29
16	27	6.15	10	26	3.55	6	17	2.65	12	28	1.84	5	11	1.01	5	19	0.29
6	27	6.10	9	18	3.54	9	12	2.65	14	23	1.83	25	28	1.00	1	2	0.28
9	20	6.08	14	28	3.52	10	16	2.65	9	25	1.81	8	11	0.98	18	24	0.28
1	27	6.02	12	23	3.51	1	10	2.62	11	18	1.78	15	16	0.97	3	22	0.27
3	27	5.97	10	27	3.50	18	23	2.62	9	11	1.76	11	28	0.96	10	28	0.27
2	27	5.92	12	20	3.43	5	21	2.61	14	20	1.76	14	21	0.96	18	22	0.27
7	12	5.76	19	27	3.43	6	10	2.59	18	25	1.73	6	26	0.95	3	8	0.26
8	27	5.71	8	23	3.42	11	14	2.56	12	14	1.67	8	25	0.93	3	24	0.26
19	23	5.70	5	15	3.40	21	28	2.56	4	19	1.65	16	26	0.90	14	26	0.25
7	8	5.67	17	27	3.40	3	19	2.54	4	17	1.64	1	15	0.89	6	21	0.24
17	23	5.67	9	21	3.37	18	20	2.54	11	21	1.60	3	4	0.89	1	3	0.23
10	23	5.63	15	28	3.35	3	17	2.53	8	14	1.58	11	12	0.89	2	16	0.23
12	27	5.62	8	20	3.34	5	22	2.52	4	10	1.57	12	18	0.89	5	10	0.22
19	20	5.62	5	26	3.33	14	25	2.52	21	25	1.56	15	24	0.89	2	8	0.21
17	20	5.59	4	13	3.31	5	24	2.51	11	22	1.51	15	22	0.88	16	21	0.19
10	20	5.55	9	22	3.27	2	19	2.49	11	24	1.50	2	4	0.85	3	16	0.18
2	7	5.46	26	28	3.27	2	17	2.48	12	15	1.50	12	25	0.84	2	6	0.17
9	13	5.42	9	24	3.26	2	13	2.47	22	25	1.46	1	26	0.82	14	15	0.17
3	7	5.41	2	23	3.21	3	10	2.47	24	25	1.45	24	26	0.82	18	21	0.17
5	23	5.41	9	16	3.18	22	28	2.47	1	11	1.43	9	28	0.81	6	22	0.15
23	28	5.35	3	23	3.16	24	28	2.45	4	18	1.43	22	26	0.81	6	24	0.14
5	20	5.33	1	9	3.14	5	16	2.43	12	26	1.43	8	18	0.79	1	21	0.13
6	7	5.29	2	20	3.13	2	10	2.42	11	16	1.42	14	18	0.79	3	6	0.13
20	28	5.27	6	9	3.12	3	13	2.42	8	15	1.41	15	21	0.79	1	6	0.11
7	16	5.23	3	20	3.08	1	5	2.41	1	25	1.39	5	9	0.75	21	24	0.10
7	24	5.15	18	19	3.08	11	15	2.39	2	14	1.37	13	23	0.74	8	12	0.09
7	22	5.14	17	18	3.06	5	6	2.37	16	25	1.37	12	21	0.72	16	22	0.09
4	27	5.08	6	23	3.03	16	28	2.37	6	11	1.36	21	26	0.71	21	22	0.09
7	21	5.05	10	18	3.01	1	28	2.36	4	5	1.35	13	20	0.66	10	17	0.08
1	7	5.02	3	9	3.00	15	25	2.34	17	25	1.35	4	8	0.64	15	26	0.08
13	19	4.96	7	13	2.99	7	20	2.33	19	25	1.35	8	21	0.62	16	24	0.08
13	17	4.93	16	23	2.98	6	28	2.32	13	26	1.34	12	22	0.62	20	23	0.08

10	13	4.89	9	27	2.97	11	26	2.32	8	26	1.33	15	18	0.62	10	19	0.07
7	18	4.88	6	20	2.96	6	13	2.30	3	14	1.32	12	24	0.61	1	16	0.05
25	27	4.78	2	9	2.95	8	19	2.28	6	25	1.32	2	18	0.59	2	3	0.05
11	27	4.73	16	20	2.90	8	17	2.27	4	28	1.30	1	12	0.57	5	28	0.05
5	13	4.67	19	21	2.90	25	26	2.27	11	19	1.30	3	18	0.54	6	16	0.05
13	28	4.61	23	24	2.90	3	5	2.25	11	17	1.30	4	12	0.54	11	25	0.05
11	23	4.40	17	21	2.89	7	23	2.25	10	25	1.28	18	26	0.54	1	22	0.03
23	25	4.35	22	23	2.89	13	16	2.24	13	15	1.27	8	22	0.53	1	24	0.02
7	26	4.34	1	23	2.84	4	14	2.22	4	21	1.26	9	10	0.53	17	19	0.01
9	14	4.32	10	21	2.83	8	10	2.21	3	11	1.24	12	16	0.53	22	24	0.01

Appendix 9. Rain period separations within collections. Min is minutes, T is total and mm is millimetres.

Coll 1

Period	1	2	3	T
Min	27	1	91	119
mm	0.8	0.1	3.0	3.9

Coll 2

Period	1	2	3	4	5	6	7	8	9	T
Min	75	6	330	55	1	57	1	1	1	527
mm	2.3	0.5	15.7	0.5	0.1	0.2	0.1	0.1	0.1	19.6

Coll 3

Period	1	2	3	4	5	6	T
Min	92	1	458	91	1	1	644
mm	2.6	0.1	13.2	3.3	0.1	0.1	19.4

Coll 4

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Min	1	48	1	1	26	515	1	1	1	144	65	1	1	1	1	1	12	1	46	1
mm	0.1	0.3	0.1	0.1	0.2	9	0.1	0.1	0.1	0.7	0.5	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.2	0.1

Period	21	T
Min	26	895
mm	0.2	12.7

Coll 5

Period	1	T
Min	7	7
mm	0.3	0.3

Coll 6

Period	1	2	3	4	5	6	7	T
Min	574	1	113	84	19	154	1	946
mm	14.8	0.1	3	3.3	0.2	0.9	0.1	22.4

Coll 7

Period	1	2	3	4	T
Min	1	134	119	196	450
mm	0.1	1.1	10.5	13.3	25.0

Coll 8

Period	1	2	3	4	T
Min	226	50	15	1	292
mm	7.4	0.4	0.4	0.1	8.3

Coll 9

Period	1	2	3	4	T
Min	17	11	41	1	70
mm	0.5	2.9	2.4	0.1	5.9

Coll 10

Period	1	2	3	4	5	T
Min	9	165	15	1	21	211
mm	0.2	4.1	0.3	0.1	0.4	5.1

Coll 11

Period	1	2	3	4	T
Min	97	1	238	1	327
mm	2.4	0.1	4.6	0.1	7.2

Coll 12

Period	1	T
Min	108	108
mm	5.8	5.8

Coll 13

Period	1	2	T
Min	7	151	158
mm	0.2	4.8	5.0

Coll 14

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	T
Min	1	1	1	222	1618	147	1	1	1	286	124	1	1	122	266	1	15	2809
mm	0.1	0.1	0.1	5.2	53.3	1	0.1	0.1	0.1	1.1	0.5	0.1	0.1	2.4	1.5	0.1	0.2	66.1

Coll 15

Period	1	T
Min	185	185
mm	16.6	16.3

Coll 16

Period	1	2	3	4	T
Min	37	448	1	425	911
mm	2.7	30.2	0.1	1.3	34.3

Coll 17

Period	1	2	3	4	5	T
Min	66	70	1	129	1	267
mm	1.5	1.1	0.1	1.2	0.1	4.0

Coll 18

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	T
Min	104	216	118	49	9	11	616	167	32	43	215	516	1	1	1	2099
mm	1.0	3.5	0.7	0.2	0.4	0.2	34	0.5	0.3	0.2	3.2	11.7	0.1	0.1	0.1	55.9

Coll 19

Period	1	2	3	4	5	6	7	8	9	10	T
Min	51	365	61	59	79	389	25	92	303	1	1425
mm	0.2	2	0.4	0.2	0.4	5.5	0.2	2.9	2.1	0.1	14.0

Coll 20

Period	1	2	3	4	T
Min	241	1	216	1	459
mm	10.7	0.1	2.9	0.1	13.8

Coll 21

Period	1	2	3	4	5	6	7	8	9	10	11	T
Min	1	25	22	1	1	9	132	144	1183	1658	1	2177
mm	0.1	0.2	0.2	0.1	0.1	0.3	1.9	0.8	5.3	58.2	0.1	67.3

Coll 22

Period	1	2	3	4	5	6	7	T
Min	517	1	67	67	397	111	1	1161
mm	14.2	0.1	2.3	2.3	12.9	1	0.1	32.9

Coll 23

Period	1	2	3	4	5	6	7	8	9	10	T
Min	1	1	1	1	1	37	1	12	238	1	294
mm	0.1	0.1	0.1	0.1	0.1	6.2	0.1	0.2	2.4	0.1	9.5

Coll 24

Period	1	2	3	4	5	6	7	8	T
Min	381	48	1	1	371	59	561	1	1423
mm	11.5	0.3	0.1	0.1	10.4	0.8	3.3	0.1	26.6

Coll 25

Period	1	2	3	4	5	T
Min	1	1	282	233	14	531
mm	0.1	0.1	2.5	6.5	0.6	9.8

Coll 26

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	T
Min	26	419	182	49	45	42	1	177	1	14	33	58	1	275	11	339	1673
mm	0.3	15.5	4.7	0.5	0.2	0.6	0.1	3.7	0.1	1.8	0.3	0.3	0.1	6.8	0.5	2.6	38.0

Coll 27

Period	1	2	3	4	5	6	7	8	9	10	11	T
Min	1	1	1	7	141	104	35	129	70	1	1	491
mm	0.1	0.1	0.1	0.4	2.4	1.2	1	1.1	2.1	0.1	0.1	8.7

Coll 28

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Min	1	11	1	207	134	347	7	271	200	98	101	94	37	137	6	73	228	1	264	1
mm	0.1	0.2	0.1	3.8	4.7	5.2	0.2	7.7	1.2	0.9	1.7	1.1	0.9	1.3	0.2	0.6	4.5	0.1	2.7	0.1

Period	21	T
Min	1	2220
mm	0.1	37.4