Final Technical Report

Forest Science Program Project # Y102045

Measurement and Modelling of Disturbance Impacts on Site Hydrology and Productivity in British Columbia's Southern Interior

D.E. Carlyle-Moses

Abstract

The impact that MPB, wildfire and harvesting disturbances have on water and energy balances from the canopy to the rooting zone were determined using the results of an intensive field measurement campaign coupled with the use of simulation models. Research focused on i) determining what factors influence soil moisture and temperature, and thus productivity, and how these factors change under different disturbance and stand regeneration scenarios, and ii) evaluating pertinent hydrologic models and deriving methods of extrapolating model parameters values in time and space.

Introduction

As of 2006, Provincial Aerial Overview of Forest Health surveys indicated that approximately 42 % of all merchantable pine in British Columbia had been killed as a consequence of the current mountain pine beetle (MPB) epidemic (Walton et al., 2007). Large-scale stand mortality is expected to continue due not only to the MPB infestation, with 77 % of all merchantable pine projected to be lost to this infestation by 2014 (Walton et al., 2007), but also commercial harvesting activities, and wildfires - which are predicted to increase in frequency in the region as a result of global climatic change (BC Ministry of Water, Land and Air Protection, 2004). The magnitude and geographic extent of forest disturbance in the province has raised important socio-economic and natural resources management concerns, including the impact of disturbance regimes will have on site hydrology and productivity.

Water and energy partitioning by forested landscapes is influenced in no small part by the biophysical characteristics exhibited by that cover, including, for example, canopy cover fraction, canopy volume and stand height (Oke, 1987). Removal of forest canopy generally leads to increased soil moisture and soil temperatures and extends growing season lengths (Bhatti et al., 2000). However, the magnitude and duration of impacts on soil moisture and temperature are dependent on the type and degree of soil disturbance, residual ground cover, and the time required for vegetation to become established and the characteristics of that re-growth (Mahendrappa and Kingston, 1994; Spittlehouse, 2007). Intuitively, these post-disturbance site characteristics are, in large part, not only a function of the magnitude of disturbance, but also on the type of disturbance itself. For example, although the casual observer may view stands affected by wildfire and by MPB similarly, in that both disturbances kill trees that comprise the overstorey, the post-disturbance understorey plant composition and the biophysical character of the forest floor and soil matrix will differ appreciably between the two stands.

The dissimilarities in site characteristics under different disturbance scenarios may result in important contrasts in the manner water and energy are partitioned and thus on the productivity and future growing conditions of tree species. Currently, any predictions about how hydrologic and ecosystem processes will differ under different disturbance regimes is largely speculative. The ability to predict such impacts is, however, not only of academic interest. Research is needed to provide forest and watershed managers, policy makers, First Nations groups and research scientists with the quantitative information necessary to evaluate the impact different disturbance regimes have on site water availability and temperature regimes and thus the establishment, growth and health of regenerating stands. In addition, little is known about the hydrological effects of partial versus complete stand mortality or of the time to reach hydrologic recovery in these areas once regeneration begins.

Throughfall is an incredibly important part of the hydrologic cycle. It has a great effect on soil processes, groundwater resources, biogeochemical cycles, and the growth of vegetation (Keim, Skaugset, & Weiler, 2005). Previous studies of throughfall variability have indicated that it remains quasi-constant during larger rainfall events where the canopy becomes saturated. However, with smaller events, the variability becomes more dependent on tree characteristics (Carlyle-Moses, Laureano, & Price, 2004). Given the Mountain Pine Beetle's influence on tree characteristics, its impact on throughfall variability could be quite dramatic. Both branch cover, and branch and leaf cover can be important factors in determining the spatial patterns of throughfall variability in forest stands (Staelens, Schrijver, Verheyen, & Verhoest 2006). It can however be difficult to determine the effect of canopy cover on relative throughfall, as many characteristics are difficult to parameterize (Shachnovich, Berliner, & Bar 2008**).** Studies have also indicated that the temporal stability of throughfall patterns in forest stands can be assessed using geostatistical models and methods (Staelens, et al., 2006) (Keim, et al., 2005). Despite the widespread use of these methods and numerous studies on throughfall variability, the Mayson Lake research site should be able to provide key insights that will contribute to knowledge of throughfall in conifer forests. There is, at this time, no published data and analysis on the impact of the Mountain Pine Beetle on throughfall in forest stands. As British Columbian forests have been devastated by the proliferation of the beetle, analysis of the throughfall in these plots could yield to a broader understanding of the beetle's impact on the water cycle in the area. It may also be helpful in attempting to predict the beetle's potential effects on the water balance and hydrologic cycle as it spreads further east across the continent.

One aspect of site hydrology that will likely be modified is stemflow production, which is defined as precipitation that is intercepted by vegetation cover and diverted down the stem or trunk of the vegetation. Studies conducted in mature coniferous forests, including lodgepole pine (*Pinus contorta* var. *latifolia*) stands, suggest that stemflow is a minor component of the water balance of these stands. However, our research conducted at Mayson Lake in 2008, along with the few other studies conducted in juvenile coniferous forests, suggests that stemflow in these environments may be a more important water balance component.The ability of a tree to produce stemflow can be described using the stemflow-funnelling ratio. This is the ratio between stemflow volume collected at the base of the tree's trunk to the volume that would have been collected by a rain gauge having a diameter equal to that of the tree's trunk in the absence of vegetation cover. It is calculated as: F = Stemflow Volume / (Rainfall depth [mm] x Tree Basal Area [m^2]) where F is the funnelling ration (dimensionless),

The stemflow-funnelling ratio is an effective tool to assess how efficient a tree is at funnelling water to its base. Because certain trees have the ability to concentrate large volumes of water at their bases, stemflow in certain forested landscapes is helpful because it: is an important groundwater recharge mechanism; can contribute to the quick response of storm hydrographs; and can be a source of nutrients that create so-called "fertile islands" in the soil that surrounds trees. Funnelling-ratio research has been conducted in temperate deciduous and tropical rainforests, as well as on certain shrub species, but not in coniferous forests. We believed that if we could show that the magnitude of F values in coniferous forests, such as juvenile lodgepole pine stands, is appreciable then further research into the importance of stemflow as a hydrologic process and as an important point source of water for regulating tree growth could be warranted.

Small-scale spatial variability of precipitation input may have important implications for hydrologic simulation exercises and field-based studies (e.g., Shah, 1996; Koren et al., 1999). Many canopy interception loss studies, for example, assume that the rainfall depth caught by a gauge located in a clearing in close proximity to the forest stand of interest is that which falls on the forest canopy (e.g., Carlyle-Moses and Price, 2007; Shachnovich et al., 2008). However, depending on the spatial nature of the rainfall input, the assumption of alike rainfall inputs to the area in which the gauge is situated and the forested area may not be valid. Small-scale spatial variability of rainfall may be a consequence of the spatial extent of the rain producing cloud, especially for convective storms (see Goodrich et al., 1995; Stevens et al., 2008) and or characteristics of the landscape such as topographic relief (e.g., Buytaert et al., 2006) and proximity to moisture sources such as oceans and lakes (e.g., Ellouze et al., 2009).

Since 1995 stand-scale hydrologic process research has been carried out at Mayson Lake on the Thompson-Bonaparte Plateau in South-Central British Columbia (Redding et al., 2007). The principal objective of the research program at this site is to determine the impact of forest disturbance and subsequent re-growth on hydrologic processes such as snow accumulation and melt (see Winkler et al., 2005), as well as rainfall interception loss (see Moore et al., 2008). Over the course of various projects observations made by researchers at the site suggested that the variability of precipitation over small spatial scales may not be inconsequential and that this spatial variability may be temporally persistent (i.e., that certain areas in the study area consistently received more or less precipitation than the average input over the area). Thus, as part of the research project the spatio-temporal variability of growing-season rainfall will be assessed.

Methods

Rainfall was measured during the growing-season of 2009 from June 1st – September 30th within a 20 km^2 area of the Thompson-Bonaparte Plateau. The selected area is located ~ 60 km NNW of Kamloops at 51^o 13’ N, 120^o 24’ W (Figure 1). The site, which varies in elevation from 1254 to 1460 m above mean sea level, is classified as being in the dry Montane Spruce biogeoclimatic zone of the British Columbia Biogeoclimatic Ecosystem Classification (BEC) system (Lloyd et al. 1990). The nearest long-term meteorological station with a comparable elevation to the study site, 1155 m above mean sea level, is Bridge Lake 2 (Meteorological Service of Canada Climate Station ID = 1160986). This station, located ~ 41 km NNW of the study area, has a mean annual precipitation of ~ 600 mm (1980 – 2000) with approximately half of this depth falling during the growing-season (mid-May to September, inclusive) in the form of rain. Snow dominates the form of precipitation that falls during the dormant season. Mean annual temperature at the Bridge Lake 2 station is 3.7 ^{o}C with mean monthly temperatures ranging from -7.8 ^{o}C in December to 14.2 ^{o}C in July and August. Land cover in the study area is a mosaic of clear-cuts and juvenile stands dominated by planted lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex

Loud.) as well as mature stands of lodgepole pine and those comprised of hybrid spruce (*Picea glauca* (Moench) Voss × *P. engelmannii* Parry ex Engelm.) - subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and pine.

Rainfall was measured using HOBO S-RGB-M002 tipping bucket rain gauges (Onset Computer Corporation, Pocasset, MA, USA) with orifice diameters of 15.4 cm and manufacture's stated resolutions of 0.2 mm per tip and accuracies of ± 1 % up to intensities of 20 mm h^{-1}. Gauges were calibrated in the lab using the methods outlined in the product's manual, and were found to have resolutions ranging from 0.18 to 0.22 mm per tip with an average of 0.20 mm per tip. Gauges were situated in 15 sites throughout the study area. Although gauges needed to be located in clearings, free from obstructions, and be easily accessible for frequent monitoring, every attempt was made to distribute the gauges evenly throughout the study area. At each location, the tipping bucket rain gauge was mounted onto a 3.2 cm diameter steel bar that was secured into the ground. The gauge was positioned on the bar so that the gauge orifice was ~ 1 m above the ground surface. Gauges were situated so that no obstructions, such as trees, entered a conical space defined by a 45^{o} angle centered on the gauge (Brakensiek et al. 1979). Data from each of the gauges were downloaded once every 2 to 3 weeks throughout the study period, and more frequently during periods of rainy weather. During data downloads, the gauges were examined for signs of disturbance from wildlife such as bears or grazing cattle. Data associated with gauges that had been disturbed since the last site visit were discarded. For the purposes of this study a rainfall event was defined as any gauge receiving rainfall ≥ 0.2 mm bounded by 8 hours in which no measurable rain fell.

Downloaded data were entered into an Microsoft Excel® Spreadsheet and then into a GIS program (SAGA – System for Automated Geoscientific Analysis - http://www.saga-gis.org) for analysis. The point rainfall depth data for each rainfall event was analyzed using inverse distance weighting interpolation (Dingman, 2002):

$$p_o = \frac{1}{D}\sum_{n=1}^{N} d_n^{-b} \cdot p_n \qquad (1)$$

where p_o is the interpolated rainfall depth (mm) for a raster cell within the GIS coverage area, D is the weighted sum of the individual weights of each of n gauges used for the interpolation, p_n is the depth of rainfall (mm) recorded by the n^{th} gauge, and d_n^{-b} is the weight assigned to that n^{th} gauge with d equal to the distance from the gauge (m) and the exponent b, which describes the exponential rate of decay of influence of a gauge depth on an interpolated depth, assigned a value of 2 (see Daly et al., 2002).

Interpolation was completed using a neighborhood size large enough to include all gauges (6000 m), while the raster cell size chosen for this analysis was 10 m^2 for a total of 2 x 10^5 cells. Raster maps were produced for each event as well as for cumulative rainfall throughout the season. Based on the interpolated rainfall data the mean, standard deviation and range of event, accumulative and study-period cumulative rainfall depths were calculated by the SAGA GIS system. Coefficient of variation (CV) data for event, accumulative, and cumulative rainfall were calculated using the mean and standard deviation values.

The number of gauges required to obtain an estimate of mean areal rainfall to within a desired confidence interval (e.g., ± 5 %) at the event, accumulative, and study-period time-scales was found using (Kimmins, 1973):

$$n' = \frac{t^2 \cdot CV^2}{CI^2} \tag{2}$$

where n' is the estimated number of gauges required, t is the Student t-value (assumed to be 2.0 for α values of 0.05, see Kimmins (1973)), CV is the coefficient of variation (%) and CI is the confidence interval (%).

To determine if high or low rainfall areas persist among events temporal stability analysis was conducted using a method similar to that used to investigate temporal stability of throughfall spatial variability (see Keim et al., 2005). Rainfall is standardized to zero mean and unit variance as:

$$\hat{p}_i = \frac{(p_i - \bar{p})}{SD_p} \tag{3}$$

where $\hat{p}_i$ is the standardized rainfall at sample point i, p_i is the actual rainfall depth at gauge i, and $\bar{p}$ and SD_p represent the mean and standard deviation of rainfall depth measured at all gauges.

A temporal stability of standardized rainfall plot is constructed by plotting $\hat{p}$ for each gauge during each event, with gauges sorted from 1 to n by the mean $\hat{p}$ for all events.

Throughfall

Throughfall was measured over the 2009 growing-season using manually-read cylindrical polyethylene throughfall gauges having a diameter of 0.29 m. A total of 64 gauges were used in each of 3 study plots for a total of 192 gauges. In each plot, 32 gauges were kept in fixed locations over the course of the study (stationary gauges), while the remaining 32 gauges were relocated to a new position within the plot approximately every 4 weeks over the 20 week study period (roving gauges). The position of the gauges within the plot was determined as follows: Within each plot 8 markers were placed at a spacing of 8 m along each of four 64 m long transects. Each of the stationary and roving gauges used in the study were assigned to a randomly selected marker. Around each marker, the position of a stationary gauge was found by taking a random azimuth and a random distance from the marker (from 0 – 4.0 m). Roving buckets were then reassigned, using the same method, on a monthly basis. Throughfall was measured on a rainfall event basis, where a rainfall is defined as an event with at least 0.4 mm of rain falling within a time span bounded by 8 hours of dry conditions. This is in order to ensure that the forest canopy has time to dry between events, so events can be considered independent of one another. Rainfall was measured via a combination of tipping bucket rain gauge, and two types of cylindrical rain gauge. The effects of other meteorological factors and tree characteristics were also measured. The tipping bucket rain gauges recorded rainfall intensity, while wind speed was measured via anemometer at each stand's automated meteorological station. Tree characteristics such as the species of the nearest tree, the distance to that tree, and its diameter at breast height (DBH) were recorded and measured using a measuring tape and a caliper. The tree density for each stand has also been determined around each of the, 8m spaced, markers. Finally, the canopy cover fraction above each throughfall gauge has been was measured using an instrument referred to as a moosehorn, which is similar in design and function to densitometers that have been used in other studies.

In analyzing this large quantity of data, a number of different statistical techniques were employed. Due to missing data as a result of animal activity, a few uncommon techniques were required in order to provide an in depth and statistically meaningful analysis. While having an additional year's data could have allowed for a thorough analysis using standard techniques, in the case of the Mayson Lake site, this would be more difficult. Due to the impact of the mountain pine beetle, forest stand and individual tree characteristics are changing from year to year, making it very difficult to study the factors influencing throughfall variation over multiple years. This does not, however, hamper analysis of the beetle's influence, as all three stands have been damaged to a different extent by. Using throughfall and rainfall data, simple linear regression equations were found for each of the 32 stationary gauges in each of the 3 plots. Because the largest recorded storm event was significantly larger than any other in the dataset, a separate set of equations was derived excluding the event. Using these equations, in addition to tree characteristic data, multiple regression equations were created using Minitab 14 statistical software. A linear transformation was required in order to include canopy cover in the analysis. Using the slopes and intercepts of the simple linear regression equations as response variables and the canopy cover cubed (as a ratio i.e., 40% canopy cover = $.40^3$ in our model), the distance to the nearest tree in cm and basal area of the nearest tree in cm^2 as predictor variables in a multiple regression. Basal area at breast height was chosen over diameter at breast height in order to include trees that had forked trunks at or before breast height. These were derived using simple geometry. Stepwise backward linear regressions were performed to determine the important tree characteristics influencing throughfall, and the extent of their influence, at the 95% confidence level. Thus the backward elimination regressions were run with an alpha of .05 to eliminate. The statistically significant predictor variables for slope and y-intercept were discovered, and two equations were created to model both the slopes of the throughfall vs rainfall plot and the y-intercepts of the same regression line, in each stand. This gave a total of six slope predicting equations and six intercept predicting equations. One in each plot that included analysis of the 40+ mm event and one that did not for both slope and intercept.

With the ultimate goal of analyzing how well the models derived from our stationary buckets would predict throughfall in random gauges for each storm event, these equations were used to model the relationship between throughfall and rainfall of all random gauges for all periods in all plots. This led to equations for each random gauge that could, with some accuracy, predict the amount of throughfall that would make it to the ground for a given canopy cover, distance to nearest tree, and basal area of that nearest tree at breast height. Next, the rainfall data for each event was entered into each gauge's equation to get the predicted throughfall values for that gauge for each event. Finally, these predicted values were compared against the actual measured values of throughfall in the random gauges. The correlation coefficient and coefficient of determination were found in order to determine the strength of the predictions. Where equations predicted throughfall to be negative it was assumed to be the equivalent of predicting a zero millimeter measurement.

Plots A, B, and C contained seven, seven, and five stemflow collars, respectively. Stemflow in these three plots was collected using stemflow collars constructed from 2.5 cm corrugated flexible tube that is cut in half lengthwise, then wrapped 360^{o} around the tree on a downward angle and secured with nails and silicone sealant (Levia, 2004). A pipe running from the stemflow collar diverts the intercepted stemflow to a collection container at the base of the tree. Stemflow collection containers in these three plots ranged in size from 4 L milk jugs to 20 L plastic drums depending on the expected stemflow production of each tree.

Plots D and E were sampled more heavily for stemflow than plots A, B, and C because research during the summer of 2008 showed that juvenile lodgepole pines are more efficient stemflow producers when compared to mature trees (McKee & Carlyle-Moses, 2010). Thirty-six and thirty-seven trees were sampled for stemflow in plots D and E respectively. Twelve small trees, 12 medium trees, and 12 large trees were sampled in Plot D in order to achieve a representative sample. The same sampling method was used in Plot E with the addition of one extra medium tree. Each Stemflow collar was made from the top of a two litre pop bottle to collect and divert stemflow to a collection container. The top of the pop bottle was inverted and cut vertically. This cone could then be adjusted to fit a variety of juvenile pine diameters. The cone was secured where it overlaps itself using a staple; a tube was then inserted at the base of the cone. Silicone was used to fill in the gaps between the tree, the cone, and the tube. Three of the trees being sampled for stemflow in Plot E, one small, one medium, and one large, emptied into a tipping bucket rain gauge rather than a standard collection container. The use of tipping bucket rain gauges allowed for stemflow start and stop timings to be monitored along with providing a general idea of production rate. It is important to note that accurate stemflow production rates cannot be determine with the type of gauge used due to the large volume of stemflow produced by the majority of rainfall events. Plot E also contained one small, one medium, and one large tree that had their branches removed and stemflow collars attached. This was to determine the influence that wind speed and wind direction had on stemflow production. These trees were located just outside the plot on the northeast edge so that experiments inside the plot were not influenced by human damage to these trees.

All stemflow collars in the five plots were tested weekly to determine if any leakage was occurring due to tree growth and animal disturbance. If a collar had a leak it was noted and promptly repaired. Collected stemflow was measured after each event using a measuring cylinder.

Stand level characteristics were recorded along with individual tree characteristics for trees associated with throughfall and stemflow collection. The point-quarter method was used to determine tree density and species dominance for each plot (Mueller Dombois & Ellenberg, 1974). Distance to the nearest tree, diameter of nearest tree, gauge position relative to tree canopies, and canopy cover above the gauge were recorded for each throughfall gauge. Distance was determined using a measuring tape and diameter was recorded using measuring callipers. Canopy cover was calculated using a moosehorn with four readings taken directly over the collection container standing on the north, south, east, and west sides of the container. Type of canopy cover for each gauge was one of: open, covered (including number of canopies), and drip (including number of canopies).

In order to relate stemflow production to tree architecture, tree characteristics were recorded for each plot. In plots A, B, and C, tree diameter and height were recorded for all trees being sampled for stemflow. Due to the focus of this research on juvenile trees, more detailed tree characteristics were recorded in plots D and E. In these two plots, tree height, number of branches, canopy width, and tree diameter were recorded for each tree being sampled for stemflow. North, south, east, and west facing branches were selected at the base of the tree, one third of the way up, two thirds of the way up, and at the top of the tree. Branching angle was recorded for each of these branches. The distance from the tip of the north branch to the tip of the south branch was also recorded using a measuring tape for each level, along with the distance from the tip of the west branch to the tip of the east branch. If a north, south, east, or west branch did not exist at a certain level, the distance measurement was taken from the tip of an existing branch to the trunk of the tree. A measuring stick was used to measure tree heights and tree diameter was measured using callipers.

A proximity matrix was developed for plots D and E to determine if sheltering by neighbouring trees influenced stemflow production. All tree canopies within 45^{o} of the base of a stemflow tree were recorded. Distance from the stemflow tree, diameter, and height were all recorded. A proximity statistic was calculated for each stemflow tree by dividing average height of surrounding trees by the average distance to surrounding trees, which was then multiplied by the number of surround trees.

Results

Rainfall and Rainfall Variability

Data from 3 of the gauges were discarded due to instrument error and thus the analysis was completed using the remaining 12 gauges. The geographic position of each of the 12 gauges is shown in Figure 2. A total of 29 rainfall events were measured during the study period and included in the analysis. All tipping buckets were deemed operational for 25 of the 29 events. For three events 11 gauges were functioning properly, while for one event data from 9 gauges was available. Average study-period rainfall depth measured by the gauges was 129.4 mm with event rainfalls ranging from 0.1 to 46.7 mm, while the average area-weighted areal rainfall depth for the period was 125.5 mm with an associated standard deviation of ±10.2 mm, a coefficient of variation of 8 % and a range of 91.0 to 151.4 mm (Figure 3). Using 12 gauges during this study resulted in an estimate of areal cumulative rainfall over the entire study period to within ± 5 % at the 95 % confidence level. Areal event rainfall depths ranged from an average of 0.1 mm to 46.0 mm. Table 1 lists the date of rainfall event occurrence, the mean depth recorded by the gauges, as well as the mean, range, standard deviation and coefficient of variation of the area-weighted rainfall inputs.

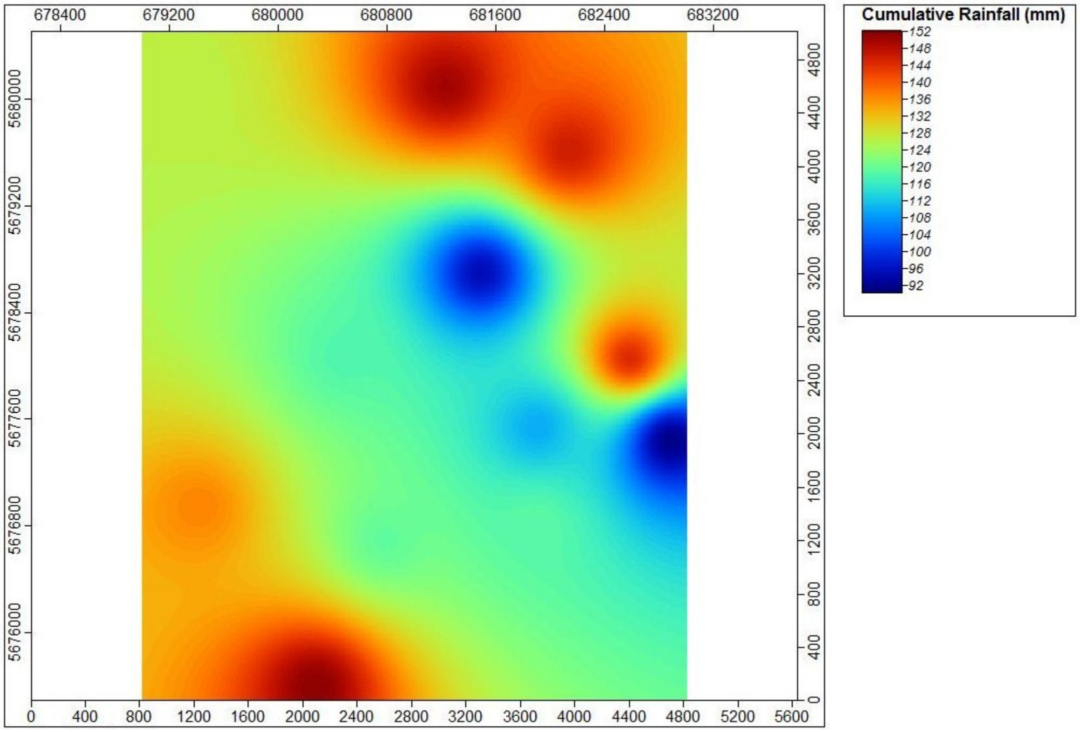

Figure 3: Spatial distribution of cumulative study period rainfall over a 20 km2 area of the Thompson-Bonaparte Plateau.

In addition to range, standard deviation and coefficient of variation statistics as indictors of rainfall spatial variability, it is of interest to note that at least one of the rain gauges recorded no measurable precipitation for 18 of the 29 events (62 % of events), including events with rainfall depths as great as 16.1 mm falling on portions of the study area. Of the 6 gauges with a complete study-period rainfall record, 4 recorded no measureable rainfall for four events and 2 gauges recorded no rainfall for 3 events. The spatial variability of rainfall, expressed as a coefficient of variability, typically decreased with increasing rainfall depth (Figure 4) ranging from a high of 125 % for an area-weighted rainfall depth of 0.8 mm to 8 % for an area-weighted average rainfall of 9.8 mm. However, some relatively large events exhibited large spatial variability over the study area. For example, the range of rainfall input for an event with an area-weighted average of 13.5 mm was 0.2 to 26.4 mm with an associated coefficient of variation of 39 % and although the largest event of the period (46.0 mm) had a coefficient of variation of only 9 %, the area-weighted range of rainfall during this event was 37.5 to 57.2 mm. The coefficient of variation of accumulative rainfall decreased asymptotically with increasing rainfall

Table 1: Characteristics of event rainfalls over the study period of June 1st – September 30th 2009.

Rainfall Date	*n* Gauges	Average Depth (mm)	Area-Weighted Average Depth (mm)	Range (mm)	Standard Deviation (mm)	Coefficient of Variation
12/06/09	12	0.6	0.6	0.0 – 3.6	0.6	1.07
14-15/06/09	12	4.5	4.4	2.6 – 11.0	1.5	0.34
16/06/09	12	0.8	0.8	0.0 – 5.2	1.0	1.25
17/06/09	12	3.3	3.3	2.0 – 5.8	0.9	0.27
18-20/06/09	12	8.2	8.1	6.2 – 10.9	0.7	0.09
21/06/09	12	1.7	1.7	1.0 – 2.4	0.3	0.16
24/06/09	12	2.1	2.1	1.6 – 2.7	0.2	0.09
25-26/06/09	12	9.7	9.8	7.1 – 12.2	0.8	0.08
06-07/07/09	12	46.7	46.0	37.5 – 57.2	4.3	0.09
08-09/07/09	12	1.0	0.9	0.0 – 5.1	0.9	0.95
09/07/09	12	1.5	1.5	0.0 – 3.1	0.6	0.41
15/07/09	12	0.4	0.4	0.0 – 1.1	0.2	0.43
25/07/09	12	2.0	1.8	0.0 – 5.5	1.0	0.58
26/07/09	12	2.2	1.7	0.0 – 5.1	1.1	0.66
04/08/09	12	0.1	0.1	0.0 – 0.4	0.1	1.07
06/08/09	12	0.1	0.1	0.0 – 0.2	0.1	0.55
08/08/09	12	0.2	0.2	0.0 – 1.1	0.2	1.09
10/08/09	12	1.6	1.6	0.0 – 2.4	0.3	0.17
12-13/08/09	12	0.4	0.4	0.0 – 1.5	0.2	0.56
13/08/09	12	1.7	1.8	0.0 – 6.9	1.2	0.69
15/08/09	12	0.2	0.2	0.0 – 1.1	0.2	0.97
31/08-02/09/09	9	7.9	6.3	0.0 – 16.1	3.3	0.53
03/09/09	12	13.7	13.5	0.2 – 26.4	5.3	0.39
05/09/09	12	1.2	1.3	0.4 – 2.1	0.4	0.32
06-07/09/09	12	4.3	4.3	2.9 – 7.2	0.8	0.19
09/09/09	12	2.4	2.4	1.9 – 3.3	0.3	0.11
16-17/09/09	11	3.6	3.9	0.0 – 6.0	0.9	0.26
17-18/09/09	11	0.8	0.7	0.0 – 1.1	0.1	0.20
19/09/09	11	6.6	6.1	0.0 – 8.8	1.1	0.18
Season		129.4	125.5	91.0 – 151.4	10.2	0.08

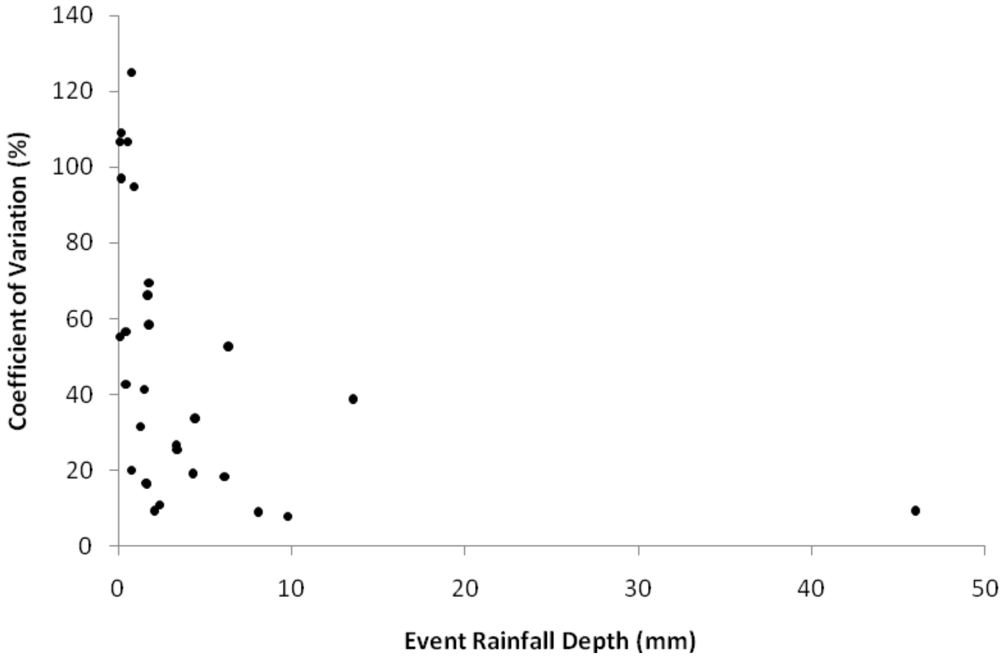

Figure 4: Relationship between coefficient of variation (%) and mean areal rainfall depth (mm) during the study period.

depth until reaching a quasi-constant value of 7 to 10 % once a total of ~20 mm of rain had fallen (Figure 5).

Temporal stability analysis (Figure 6) suggested that 2 of the 12 gauges (gauges 11 and 12) received standardized rainfall inputs that were statistically ($p \leq 0.05$) higher than the all-gauge average over the course of the study period, while 3 of the gauges (gauges 1, 2, and 3) received statistically lower standardized rainfall depths ($p \leq 0.05$) than the average for the period. Seven of the 12 gauges showed no statistically significant ($p \leq 0.05$) temporal trend in relative gauge catch. Average standardized rainfall for each gauge over the study period was plotted against the elevation at which the gauge was located to determine if temporal patterns in rainfall delivery were related to elevation. A best-fit linear regression through the data found that the slope was statistically different from zero (0.0035 ± 0.0023, $p \leq 0.05$) with a r^2 value of +0.18:

$$\delta_i = 0.0035E - 4.57 \qquad (4)$$

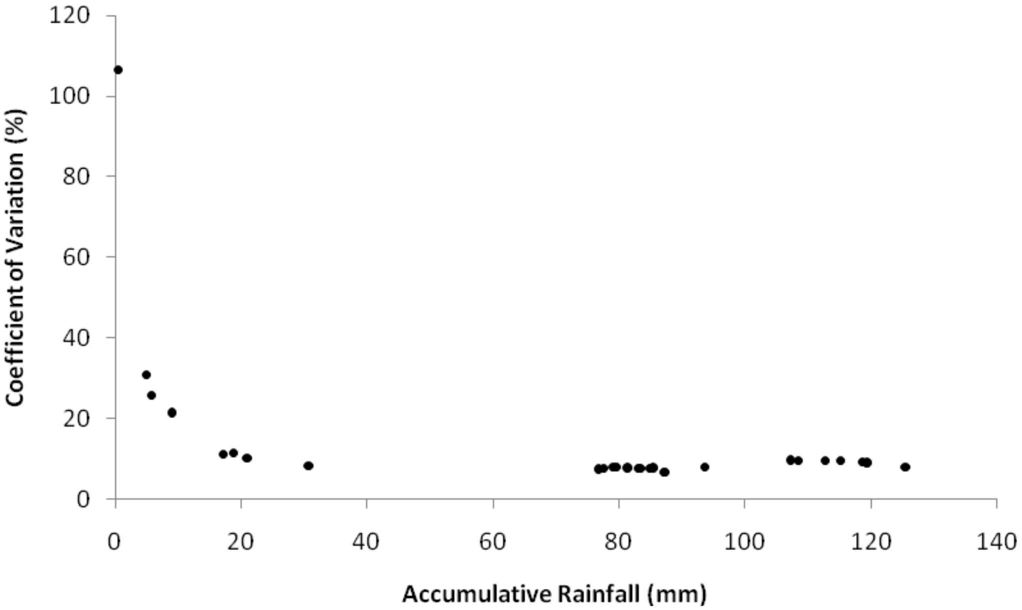

Figure 5: Coefficient of variation (%) with accumulative mean areal rainfall depth (mm) during the study period.

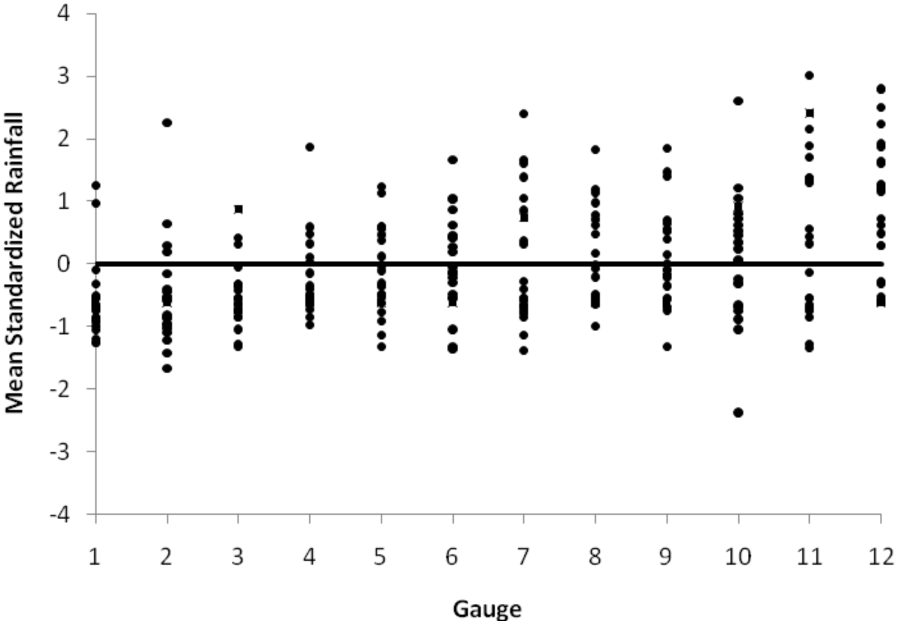

Figure 6: Temporal stability plot of standardized rainfall for the 12 rainfall gauges used during the study.

where E is elevation in meters above mean sea level.

Using Eq. 2, the number of gauges required to estimate mean accumulative areal rainfall once rainfall depth exceeded ~20 mm to within ± 5 and ± 10 % at the 95 % confidence level were 17 and 5, respectively. This suggests that gauge densities of 1 gauge per 1.2 km^2 and 1 gauge per 4.7 km^2 are required for estimates of mean accumulative rainfall at the levels of accuracy. At the rainfall event scale 11 of 17 events that were < 2 mm required >100 gauges to estimate the mean areal rainfall to within ± 10 % at the 95 % confidence level. Twenty-seven gauges were required, on average, to sample rainfalls > 2 mm with same degree of accuracy. These gauge densities are however, based on the assumption that rainfall delivery over the study area is not systematically related to factors such as elevation. Although only 18 % of the variation in mean standardized rainfall was explained by elevation, it is important to note that this analysis was only conducted for the 12 gauges and not the interpolated rainfall field over the entire study-area.

Throughfall

In the creation of models for each stationary throughfall bucket, a very strong relationship was noted between rainfall and throughfall. While this is to be expected, it should be noted that the relationship was slightly stronger when the largest (approximately 40mm) event was included. Before carrying out the multiple regression analysis to determine the significance of each of our predictor variables, and by extension the most accurate predictive models, some of the data had to be transformed. A non-linear relationship could be easily identified between the canopy cover and the slope of the throughfall vs rainfall regression line. Because canopy cover included open space with a value of 0.0 a more standard logarithmic transformation was not possible. Therefore it was transformed by taking it to the power of three which yielded a linear relationship. The relationship with the other variables was either obviously linear or showed no other type of relationship. The inclusion of the 40 mm event in the derivation of the regression equations for the stationary buckets had a noticeable effect. Although in most cases the removal of the large event resulted in a regression line with a similar slope, it was important to continue with both datasets in order to ensure the maximum possible strength of the analysis.

Significant predictors of the slope and intercepts of the throughfall vs rainfall regression line yielded differences between the influences of tree characteristics in the three different stands (Table 2). This also gives hints as to the extent of influence of other variables that cannot be measured on a per gauge basis. Additionally the predictors and equations were dependent on whether or not the 40mm event was included in the analysis. As expected, the canopy cover fraction proved to be the best predictor of throughfall depth, and was included in the majority of models created. However, under some circumstances basal area and distance proved useful in improving the models. In two cases distance from the nearest tree was the only significant predictor of throughfall. It should be noted that these cases were ones in which the 40mm event was not included in the analysis. Although the models varied in their ability to predict the throughfall of our random gauges, for the most part a moderate to strong relationship could be found between our predicted values and the actual values (Figure 7). In certain situations, such as when the tree and gauge characteristics were especially different from the "normal" conditions the model could not accurately predict those gauges. Additionally, the models were somewhat prone to predicting slightly negative values of throughfall depth during small rainfall events. This can in almost all cases be attributed to the error associated with the models. Despite these issues, on a per event basis, the residual values associated with the predictions were not alarmingly high.

Plot-Scale Throughfall

Throughfall was measured for 25 events throughout the study period, but due to isolated rainfall patterns and complications in collection of data 4 events had to be left out of the analyses, leaving the total number of events at 21. The rainfall and throughfall amounts for each plot and each event are shown in Table 3, as well as the total gross rainfall and total gross throughfall for each plot.

Table 2: Significant predictors and regression equations for deriving random gauge prediction models

		Significant Predictors Slope	**Regression Equation Slope**
Stand A	**Full Data Set**	Canopy Cover, Basal Area	Y= 1.0611 – 0.431CC3 – 0.00027BA
	Without Largest Event	Canopy Cover	Y = 0.9972 – 0.54CC3
Stand B	**Full Data Set**	Canopy Cover	Y = 0.9972 – 0.54CC3
	Without Largest Event	Distance	Y= 0.6221 + 0.00276D
Stand C	**Full Data Set**	Canopy Cover	Y= 1.054 - 0.125CC3
	Without Largest Event	None	Y= 1.193
		Significant Predictors Intercept	**Regression Equation Intercept**
Stand A	**Full Data Set**	Canopy Cover	Y= -0.6178 -0.81CC3
	Without Largest Event	Distance	Y= -0.8847 + 0.0025D
Stand B	**Full Data Set**	Canopy Cover, Basal Area, Distance	Y= -0.5634 -0.77CC3 + 0.0072D - 0.00283BA
	Without Largest Event	Canopy Cover, Basal Area	Y= 0.07372 -1.30CC3 -0.00180BA
Stand C	**Full Data Set**	Canopy Cover	Y=-0.1062 -1.52CC3
	Without Largest Event	Canopy Cover	Y=-0.7354 -1.45CC3

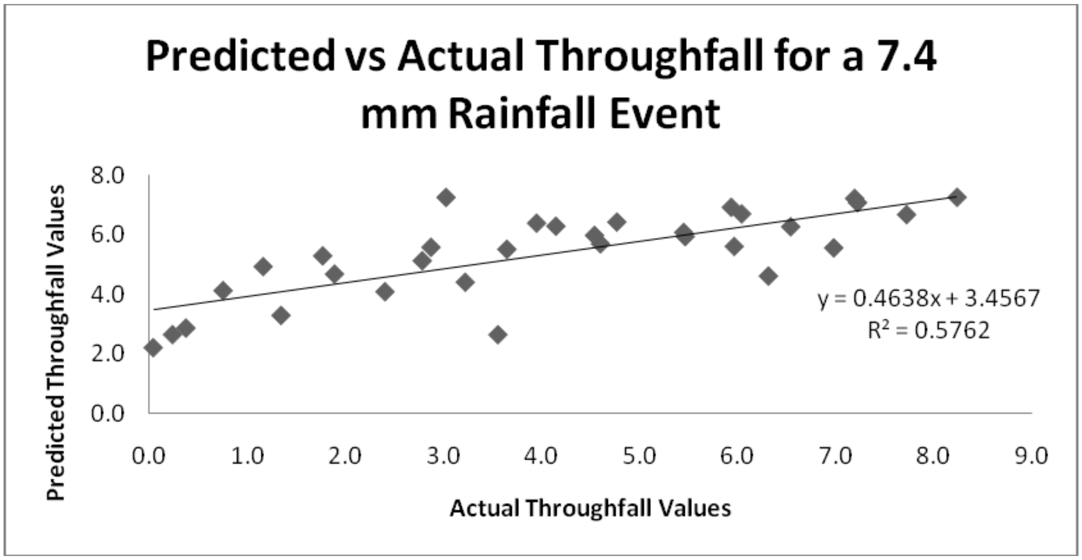

Figure 7: Example of Predicted vs Actual Throughfall values.

Event #	Date of Event	Rainfall A	Throughfall A	Rainfall B	Throughfall B	Rainfall C	Throughfall C
		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	15-Jun	5.5	4.2	5.5	5.5	5.5	3.5
2	18-Jun	2.9	1.6	2.8	1.6	2.5	1.7
3	20-Jun	7.4	4.4	7.5	4.6	7.3	5.0
4	22-Jun	1.4	0.6	1.4	0.6	1.3	0.7
5	25-Jun	1.8	0.87	1.8	1.1	1.8	1.2
6	26-Jun	9.1	6.33	9.0	7	8.4	6.8
7	7-Jul	41.5	35	40.7	34.5	39.3	37.2
8	9-Jul	1.0	0.5	0.9	0.5	1.0	0.5
9	10-Jul	1.3	0.6	1.2	0.7	1.0	0.3
10	16-Jul	0.5	0	0.5	0.2	0.5	0.1
11	26-Jul	1.3	0.6	1.1	0.5	0.9	0.4
12	27-Jul	1.4	0.5	1.4	0.6	1.5	0.7
13	11-Aug	1.5	0.6	1.5	0.7	1.4	0.7
14	13-Aug	0.3	0	0.3	0	0.2	0.0
15	4-Sep	15.4	13.4	16.3	14.6	16.6	15.5
16	6-Sep	1.0	0.4	0.9	0.5	0.8	0.4
17	8-Sep	3.5	2.1	3.4	2.2	3.2	2.7
18	10-Sep	2.2	0.8	2.1	0.9	2.1	1.1
19	17-Sep	3.2	1.6	3.1	1.8	2.9	2.2
20	20-Sep	7.0	3.4	6.8	4.3	6.8	4.8
21	19-Oct	9.8	6.8	9.7	7.7	9.6	9.0
	Totals:	119.0	84.3	118.0	90.1	114.6	94.5

Table 3: Rainfall and throughfall measurements in mm for each plot and each event

A paired, two-tailed t-test showed no significant difference between the throughfall means of the roving and the stationary gauges in all events and all plots, except for three. Table 4 shows a summary of the calculated p-values from the t-test that was operated on the two means. For the three events that did not pass the test we were unable to pool the means, so we only used the throughfall means from the 32 roving gauges and left out the throughfall means from the 32 stationary gauges.

Table 4: P-values of t-test conducted on throughfall means. **Bold** values are statistically different and therefore were not pooled.

Event #	Date of Event	Plot A	Plot B	Plot C
		t-test p-value	t-test p-value	t-test p-value
1	15-Jun	0.905	0.099	0.597
2	18-Jun	0.762	0.245	0.433
3	20-Jun	0.247	0.103	0.314
4	22-Jun	0.555	0.148	0.505
5	25-Jun	0.257	0.541	0.510
6	26-Jun	0.515	**0.036**	0.492
7	7-Jul	0.387	0.556	0.859
8	9-Jul	0.561	0.893	**0.042**
9	10-Jul	0.305	0.866	0.062
10	16-Jul	0.143	0.810	0.068
11	26-Jul	0.437	0.767	0.610
12	27-Jul	0.664	0.981	0.067
13	11-Aug	0.425	0.697	0.162
14	13-Aug	0.321	0.102	0.386
15	4-Sep	0.432	0.543	**0.000**
16	6-Sep	0.888	0.703	0.134
17	8-Sep	0.655	0.731	0.184
18	10-Sep	0.547	0.809	0.217
19	17-Sep	0.567	0.340	0.114
20	20-Sep	0.140	0.668	0.209
21	19-Oct	0.568	0.252	0.561

The mean throughfall depth variation was found to be very well explained the rainfall depth variation in all three plots, as $r^2 = 0.99$ for all three plots. The relationship between throughfall and rainfall for each plot is shown in Fig. 8. The equations of the regression analyses for the three lines that best fit that scatter of Fig. 1 are:

Plot A:

TF = $0.854\ R_g - 0.826$; $n = 21$

Plot B:

TF = $0.864\ R_g - 0.566$; $n = 21$

Plot C:

TF = $0.965\ R_g - 0.719$; $n = 21$

where TF is the throughfall depth (mm), R_g is the gross rainfall depth (mm), and n is the number of rainfall events.

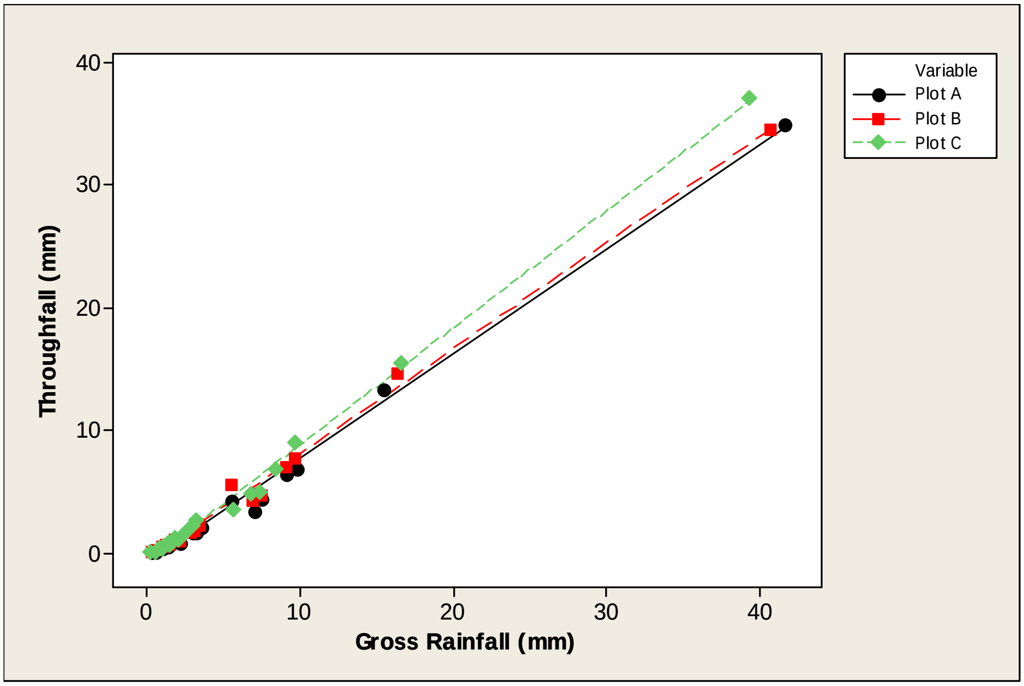

Fig 8. Scatterplot with best fit line of throughfall depth (mm) as a function of gross rainfall (mm) for 21 events in 3 different forest plots.

Stemflow

The influence of a number of variables on stemflow production was accessed using multiple regression. Tree characteristics versus stemflow volume and meteorological conditions versus stemflow volume were run as two separate multiple regressions. Tree characteristics were analysed on the event basis and meteorological characteristics were analysed on a per tree basis.

Twelve different tree characteristics and seven meteorological conditions were used as independent variables. The goal of this stage of the data analysis was to identify which variables should be included in the final multiple regression analysis employing both tree characteristics and meteorological conditions. The analysis was conducted in this manner because a multiple regression could not be conducted with all independent variables versus stemflow volume due to some only changing from tree to tree while others only changed from event to event.

The first stage analysis revealed that many different tree characteristics had some influence on stemflow production for different rainfall events. However, canopy width at various levels, branching angle at various levels, and diameter at the base were the most prominent variables. Due to the variety of variables it was decided that all would be used in the multiple regression when producing the final model. When examining meteorological conditions it was found that only one variable was consistently prominent throughout. Gross precipitation explained over 80% of the variation in stemflow production for 31 of the 34 trees tested. Storm duration was significant for nine trees and maximum gust during the storm was significant for two trees, however, these variables had very low r-squared values. Only three variables explained between 4% and 10% of the variation in stemflow with the remainder of the variables explaining less than 3.3% of the variation. Due to these findings gross precipitation was the only meteorological variable that was included in the final model.

A modified version of the stemflow model used by Park & Hattori (2002) was used to model stemflow in plot E. Park & Hattori (2002) provide the following model for determining stemflow for an individual tree or entire stand:

$SF = aPg - b$

$a = A(\mathrm{DBH})^{\beta 1}$

$b = B(\mathrm{DBH})^{\beta 3}$

Where:

SF = stemflow

Pg = gross precipitation

DBH = diameter at breast height

Stemflow was graphed against gross precipitation for each individual tree. All slope (a) and intercept (b) values are then graphed against the diameter of the individual trees. According to Park and Hattori (2002) a versus DBH and b versus DBH should produce power relationships.

However, stemflow production was not accurately modelled using only diameter and b versus diameter did not produce a power relationship (Figure 9.X, Figure 9.Y).

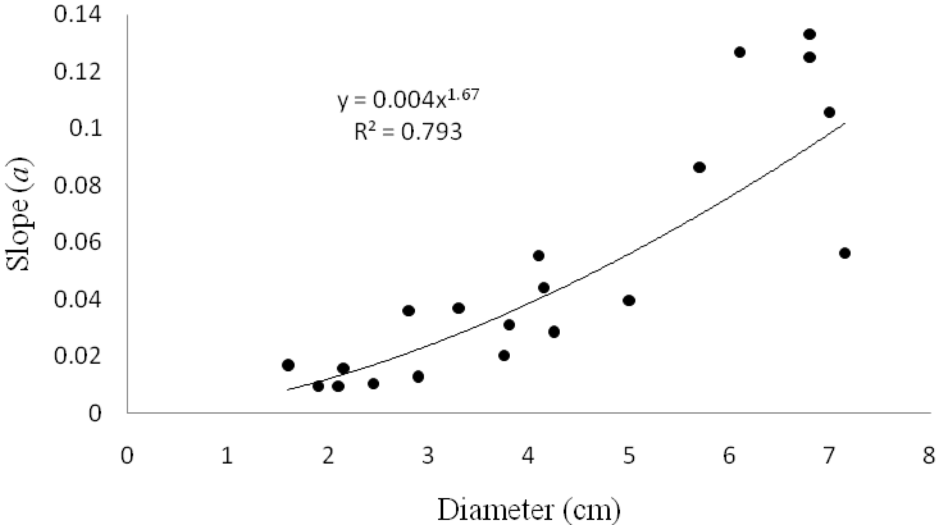

Figure 9.X Slope values versus diameter highlighting the power relationship shown by Park and Hattori (2002).

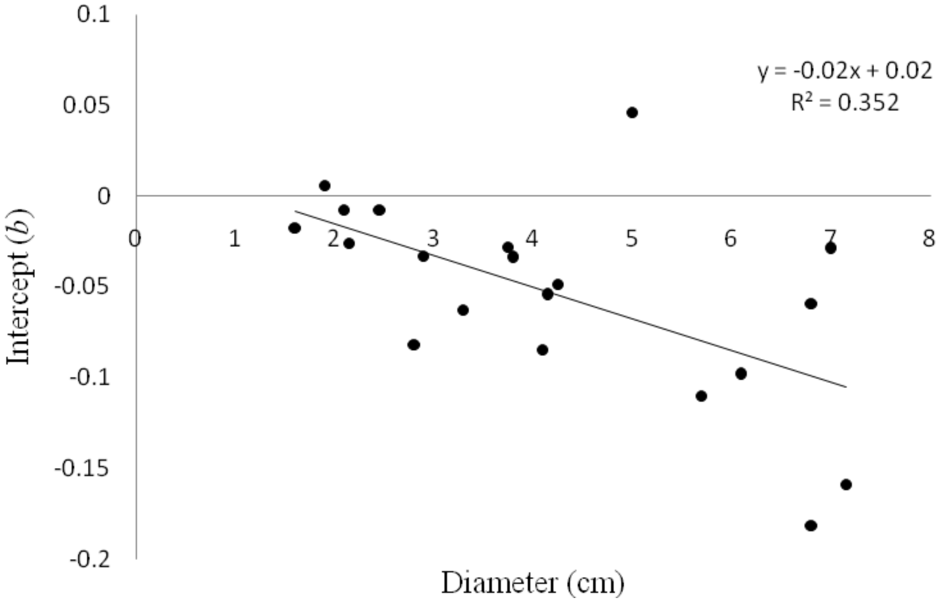

Figure 9.Y Intercept values versus diameter showing a fairly weak linear relationship

Therefore, stepwise multiple regression using *a* and *b* values as dependent variables was conducted to determine which tree characteristics best explained these slope and intercept values.

Tree height, diameter at the base, number of branches, proximity to other tress, canopy width and branching angle were used as independent variables in the stepwise regression analysis. Four canopy width and four branching angles measurements were used for the analysis with measurements taken at the base of the tree, one-third up, two-thirds up, and at the top of the tree. Upon performing regression analysis multicollinearity was found to be a problem. Tree diameter at the base, height, number of branches, and canopy width at differing levels were highly correlated resulting in the removal of diameter when performing analysis on the slope, and the removal of diameter and number of branches when performing analysis on the intercept. The result passed the multicollinearity test, however correlation between independent variables remained fairly high. This was resolved by replacing the four separate canopy width measurements with one variable, crown projected area (CPA). Crown projected area is the area of the tree looking down at the widest part of the tree. CPA solved all multicollinearity problems and also increased the accuracy of the model. Crown projected area and branching angle two-thirds of the way up the tree explained 76.8% of the variation in a. Branching angle at the bottom of the tree and crown projected area explained 55.2% of the variation in b. Following are the two equations:

$a = 0.04085\ CPA + 0.001237\ Angle_{2/3} - 0.008308$

$b = 0.002768\ Angle_{bottom} - 0.05970\ CPA - 0.0007261$

$\mathrm{SF} = (0.04085\ CPA + 0.001237\ Angle_{2/3} - 0.008308) \cdot Pg - (0.002768\ Angle_{bottom} - 0.05970\ CPA - 0.0007261)$

Slope (a) represents stemflow production, therefore stemflow production increases as crown projected area and as branching angle two-thirds of the way up the tree increases. A tree with a wider canopy will produce more stemflow as it is able to capture more precipitation and the more inclined the branches intercepting the precipitation the greater the flow along branches. Intercept (b) represents the storage capacity of the tree, the amount of precipitation required before stemflow production begins. A tree with a wider canopy will have a larger storage capacity and as the angle of the lower branches of the tree become more negative more water will become throughfall, specifically canopy drip. The model incorrectly assumes this water is becoming storage; however this does not affect the performance of the model because this water is simply taking away from stemflow which is correct whether it be in the form of storage or canopy drip.

Next predicted stemflow values were produced using the derived equation. Observed values were then graphed against predicted values in order to access the accuracy of the model (Pineiro *et al.* 2008). The model was successful in predicting 82.8% of the variation in stemflow production. Total predicted stemflow volume was 147.3 L and observed stemflow volume totalled 144.0 L. Figure 10 shows observed stemflow values versus predicted stemflow values along with a 1:1 line for accessing accuracy. Analysis of the slope found that it did not differ significantly from one.

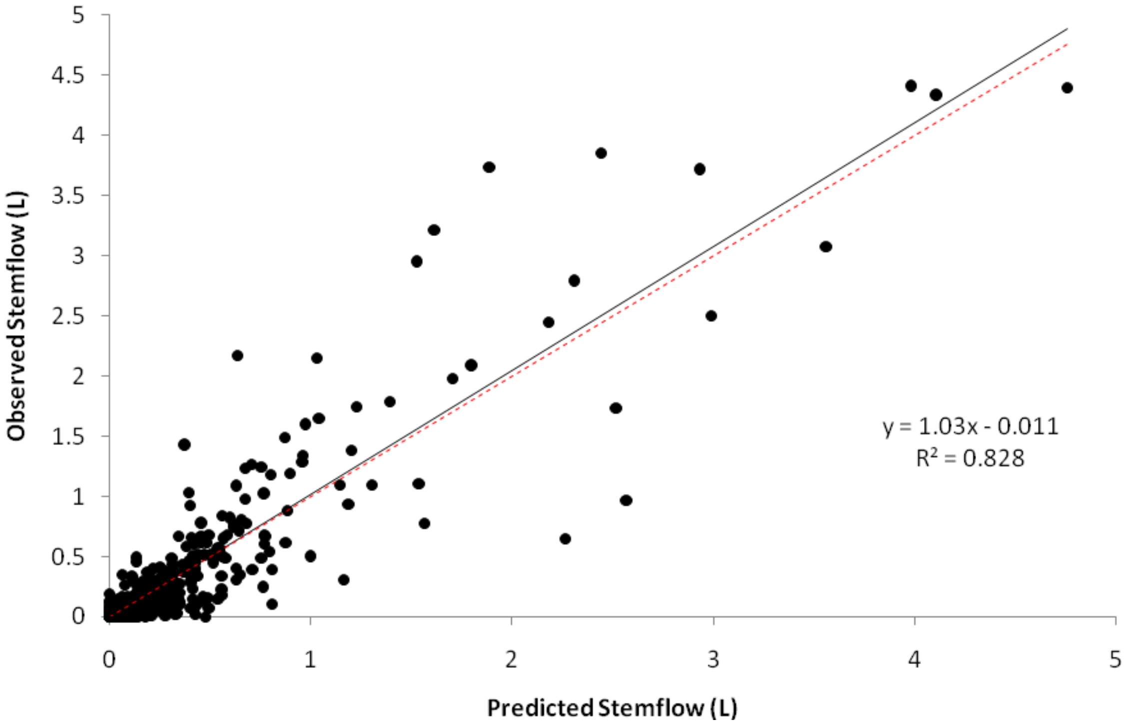

Figure 10: Observed stemflow versus predicted stemflow derived from Eq. ___ for plot E ( ) and the 1:1 line (------). The solid line shows the linear relationship between observed and predicted and the broken line is a 1:1 line for accessing accuracy.

The model developed using Plot E data was then applied to Plot D data. The above procedure was repeated to determine the accuracy of the model when applied to a different plot. Predicted stemflow values were found to explain 72.1% of the variations in observed data; however for large events the model greatly over predicted the amount of stemflow produced. The over prediction in large events can be seen in Figure 11. As expected, the slope was found to differ significantly from one.

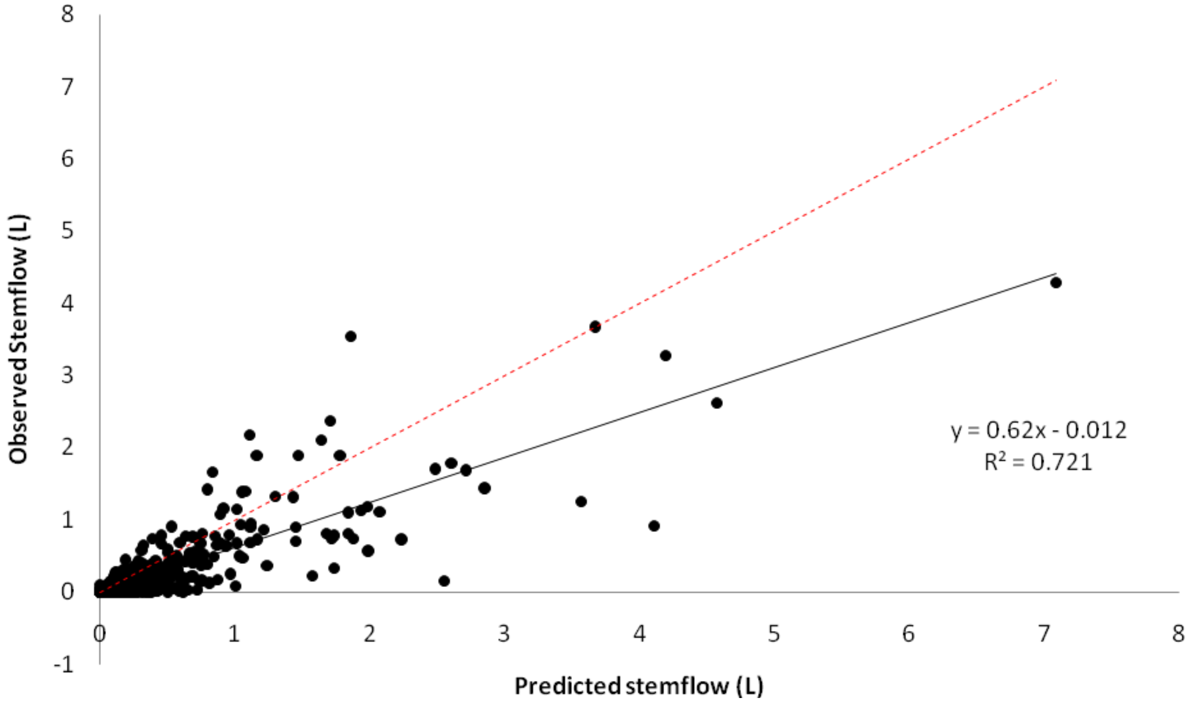

Figure 11: Observed stemflow versus predicted stemflow for plot D. Relationship between observed and predicted values is should by the solid black line. The broken line represents a 1:1 line for accessing accuracy.

Discussion, Conclusions and Management Implications

The results of this study indicate that the spatial variability of rainfall over a small geographic area of the Thompson-Bonaparte Plateau was relatively high, especially at the event-scale. If, for example, only one gauge was used to estimate rainfall depth over the study area, our results suggest that 3 to 4 of the 29 events (10 – 14 % of events) would not have been recorded. Over the study-period cumulative rainfall depths ranged from 91.0 to 151.4 mm, suggesting that some areas received 166 % more rainfall than other areas. Future studies requiring accurate estimates of rainfall delivery over an area of interest on the Thompson-Bonaparte Plateau should take this hypsometric relationship into consideration. Assuming that the rainfall and landscape conditions for this study are typical for this region, which we suspect they are, gauge densities 1 gauge per 1.2 km^2 and 1 gauge per 4.7 km^2 would be required to estimate mean accumulative rainfalls > 20 mm to within ± 5 and 10 % at the 95 % confidence level, respectively. Obtaining the same degree of accuracy at the individual rainfall event scale would require an unmanageable number of gauges for almost all small rainfalls and for many larger rainfall inputs as well. Future studies should also take into account the amount of animal activity in the area. Fencing around the gauges would have likely prevented the loss of data that we experienced.

Throughfall

The more “round-a-bout” method of using the slopes and intercepts of the stationary regression lines to was necessary. It allowed for a more detailed analysis and the inclusion of rainfall events where data collection was somewhat limited by animal activity. It must be recognized that there is the potential for greater error in the models derived in this way than by those that could be found by a more straightforward method of simply including rainfall in the multiple regression analysis. However, given that the predictive power of our models is higher than was expected, it is likely that these errors are minimal or negligible. It is also difficult to assess the strengths or weaknesses in including the 40mm event in the modeling process. Overall both models showed similar predictive strengths in both Stands A and B. Stand A shows the most dramatic differences between predictive strength of the models during the September period. It should be noted that the locations of the random throughfall gauges were at locations of fairly high canopy cover fractions. In stand B the only major difference between the predictive powers of the two model types was when the model lacking the large rainfall attempted to predict that same event. This, intuitively, should be expected. In stand C, where a statistically significant equation could not be derived for the data when the 40mm event was included, it should be noted that the strength of our models in predicting throughfall in random gauges was more variable. Because Stand C is more open and in an overall healthier condition than the other tree stands it is likely that other variables that could not be measured on a per gauge basis had a greater influence on the distribution of rainfall throughout the stand. Wind speed, direction, and overall stand density are examples of such variables.

As previously stated the models derived from analysis of the stationary gauges yielded more accurate than expected predictions. In most cases, aside from a few cases noted above, both models showed a similar accuracy. The negative values predicted for throughfall in random gauges can, for the most part, are slight and can be taken as part of the errors associated with our modeling process and the models themselves. Additionally, as a negative reading is an impossibility, were one to use these models to predict throughfall and throughfall variation within forest stands, any negative values could be assumed as a predicted zero value. This could further improve the accuracy of the models. Given that the significant predictors for throughfall rarely include distance to the nearest tree, when the more important canopy cover fraction is included in the model, it seems that a stratified sampling method, or one using gauges at varying distances to trees is unlikely to be necessary. This study does not suggest that there are major problems with using a random sampling method in future throughfall studies. The use of the modeling methods derived here may be useful and applicable to other conifer forest stands. In combination with other studies, this one can provide insight into the influence of canopy characteristics on throughfall variability and throughfall variability in general in conifer stands. It will also help predict the hydrological impact caused by forest parasites and add to our understanding of forest pathology.

The coefficient of determination values, $r^2 = 0.99$ for all three plots, are abnormally high for studies in the field of hydrology, although in this situation it is completely reasonable to have these high values. The values attained in this paper are very similar to values in other throughfall papers; Carlyle-Moses et al. (2004) found $r^2 = 0.998$.

The three linear regression relationships (plot A, $TF = 0.854\ R_g - 0.826$, plot B, $TF = 0.864\ R_g – 0.566$, and plot C, $TF = 0.965\ R_g – 0.719$) where all somewhat similar in both slope values and intercept values. The y-intercepts of these equations are a first approximation of the storage capacity. The storage capacity represents the amount of water intercepted and stored within the tree canopy in mm.

Analysis of the regression equations suggests that plot A had the highest storage capacity, 0.826, and plot b has the lowest storage capacity, 0.566. With a given amount of rain input, plot B will end up with more throughfall based on its storage capacity compared to the other two plots. Plot A and C will have more water held up within its canopy, thus less available for throughfall. Specific reasons for the difference in storage capacities are beyond the scope of this paper, but one possible reason could be the health of the canopy; plot B is significantly more affected by the mountain pine beetle infestation than the other plots, which could have affected the amount of water that the needles and the tree in general are able to store.

Examining the equations produced, greater slopes will produce greater amounts of throughfall, with increasing rainfall. The results provided very similar slopes between all three plots (A=0.854, B=0.864, C=0.965). Figure 1 displays the three different lines with the difference in slopes clearly illustrating that plot C has the highest slope and plot A has the lowest. These results suggest that with more rainfall, a greater proportion of throughfall will be produced in plot C while in plot A, a smaller proportion of throughfall will be measured. Detailed explanations for these results are again beyond the scope of this paper, but an explanation could be the distance between tree boles within the plots. During data collection it was evident in plot C that there seemed to be greater distance between the tree boles and more open spaces within the plot compared to both plot A and B.

The slopes of the regression analysis can also be said to be equal to the evaporation rate of the forest plot, where the evaporation rate is equal to the slope multiplied by the rainfall intensity ($E = aR$, where a is the slope and R is the rainfall intensity) (Carlyle-Moses, 2009).

Regression analysis has allowed us to assume that although the relationships between plots A, B, and C are very similar, there are some slight differences that we can attribute to different forest characteristics such as age, pine beetle attack stage, and distribution. We were able to visualize these differences as well as observe them numerically through the scatterplot and equations of the line.

References

Aboal, J.R., Jimenez, M.S., Morales, P., Gil, P. (2000). Effects of thinning on throughfall in Canary Islands pine forest the - role of fog. Journal of Hydrology 238, 218-230.

Brakensiek, D.L., H.B. Osborn and W.J. Rawls (Eds.). (1979). Field Manual for Research in Agricultural Hydrology Science and Education Administration, US Department of Agriculture, Washington DC.

Bryant, M.L., Bhat, S., Jacobs, J.M. (2005). Measurements and modeling of throughfall variability for five forest communities in the southeastern US. Journal of Hydrology 312, 95-108.

Buytaert, W., R. Celleri, P. Willems, B. De Bièvre, and G. Wyseure. 2006. Spatial and temporal rainfall variability in mountainous areas: A case study from the south Ecuadorian Andes. Journal of Hydrology 329: 413-421.

Carlyle-Moses D.E. and A.G. Price. (2007) Modelling canopy interception loss from a Madrean pine-oak stand, northeastern Mexico. Hydrological Processes 21: 2572-2580

Carlyle-Moses, D.E., Flores Laureano, J.S., Price, A.G. (2004) Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. Journal of Hydrology 297, 124-135.

Daly, C. W.P. Gibson, G.H. Taylor, G.L. Johnson and P. Pasteris. (2002). A knowledge-based approach to the statistical mapping of climate. Climate Research 22: 99-113.

Dingman SL (2002) Physical Hydrology, 2nd edn. Prentice-Hall, Upper Saddle River, New Jersey

Ellouze, M., C. Azri and H. Abida. (2009). Spatial variability of monthly and annual rainfall data over southern Tunisia. Atmospheric Research 9: 832-839.

Goodrich, D.C., J.M. Faures, D.A. Woolhiser, L.J. Lane and S. Sorooshian. 1995. Measurement and analysis of small-scale convective storm rainfall variability. Journal of Hydrology 173: 283-308.

Keim R.F., A.E. Skaugset and M. Weiler. (2005). Temporal persistence of spatial patterns in throughfall. Journal of Hydrology 314: 263-274

Kimmins, J.P. (1973). Some statistical aspects of sampling throughfall precipitation in nutrient cycling studies in British Columbia coastal forest. Ecology 54: 1008–1019

Koren, V.I., B.D. Finnerty, J.C. Schaake, M.B. Smith, D.-J. Seo and Q.-Y Duan. (1999). Scale dependencies of hydrologic models to spatial variability of precipitation. Journal of Hydrology 217: 285-302.

Levia Jr, D.F., Frost, E.E. (2006). Variability of throughfall volume and solute inputs in wooded ecosystems. Progress in Physical Geography 30 (5), 605-632.

Lloyd, D., K. Angove, G. Hope and C. Thompson. (1990). A guide to site identification and interpretation for the Kamloops Forest Region. B.C. Min. For., Res. Br., Victoria, B.C., Land Management. Handbook. No. 23.

Loescher, H.W., Powers, J.S., Oberbaur, S.F. (2002). Spatial variation of throughfall volume in an old-growth tropical wet forest, Costa Rica. Journal of Tropical Ecology 18 (3), 397-407.

Moore R.D., R.D. Winkler, D.E. Carlyle-Moses, D.L. Spittlehouse, T. Giles, J. Phillips, J. Leach B. Eaton, P. Owens, E. Petticrew, W. Blake, B. Heise and T.E. Redding. (2008) Watershed response to the McLure forest fire: Presentation summaries from the Fishtrap Creek workshop, March 2008. Streamline: Watershed Management Bulletin 12: 1-11.

Oke, T.R. (1978). Boundary Layer Climates. London: Methuen & Co. Ltd.

Redding T.E., R.D. Winkler, D.E. Carlyle-Moses and D. L Spittlehouse. (2007). Mayson Lake study examines hydrological processes. LINK 9(2), 10-11.

Robinson, M. and Ward, R.C (2000). Principles of Hydrology. London: McGraw-Hill Publishing Company

Shachnovich, Y., P.R. Berliner and P. Bar. 2008. Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid zone. Journal of Hydrology 349: 168-177.

Shah, S.M.S., P.E. O'Connell and J.R.M. Hosking. (1996). Modelling the effects of spatial variability in rainfall on catchment response. 1. Formulation and calibration of a stochastic rainfall field model. Journal of Hydrology 175: 67-88.

Staelens, J., De Schrijver, A., Verheyen, K., Verhoest, N.E.C. (2006). Spatial variability and temporal stability of throughfall water under a dominant beech (Fagus sylvatica L.) tree in relationship to canopy cover. *Journal of Hydrology 330*, 651-662.

Stevens, M.R., J.A. Dupree, and J.M. Kuzmiak. (2008). Temporal and spatial variations in precipitation, streamflow, suspended-sediment loads and yields, and land-condition trend analysis at the U.S. Army Piñon Canyon maneuver site, Las Animas County, Colorado, 1983 Through 2007. Scientific Investigations Report 2008-5111, U.S. Geological Survey, Reston, Virginia.

Winkler, R.D., D.L. Spittlehouse, and D.L. Golding. (2005). Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. Hydrological Processes 19: 51-62.