Plumas Geo-Hydrology P.O. Box 1922, Portola, CA 96122
LAND AND WATER RESOURCES tel. (530) 836-2208, fax (530) 836-0959

Canopy interception in a coniferous forest in eastern Plumas County, California

Final Technical Summary Report

July 28, 2008

Prepared for

Brian Morris, Plumas County Flood Control and Water Conservation District

By

Burkhard Bohm, Geologist/Hydrologist
water@gotsky.com

Table of Contents

Executive summary

Purpose and scope

The purpose of this study is to assess the impact of tree canopy interception in a pine forest on moisture reaching forest floor. Field experiments were conducted in the winter of 2005/06 on private land near Blairsden, in eastern Plumas County, California. In specific the objectives of this study were:

1. To examine effect of forest canopy on the amount of throughfall.
2. To examine to what extent reduced canopy density can increase the amount of moisture reaching the forest floor.
3. To examine the feasibility of using isotope tracers to assess impact of tree canopy interception on base flow.

Data collection

1. Field data collection was conducted at twenty stations in a partially overstocked forest, with fifteen stations on a north facing slope and five on a south facing slope. A control station was established on an open meadow between the stations. Data were collected from December 2005 to March 2006.
2. Data collection included:
    a. Forest canopy density (closure) measurements with a wide angle lens mounted on a digital camera. For comparison canopy density was also measured with a spherical mirror densiometer.
    b. Throughfall depth.
    c. Throughfall samples for analysis of the stable isotopes deuterium and oxygen-18 in water.

Results:

1. For the purpose of this study the wide angle lens canopy data were used, however, since the current forest management is based on densiometer canopy closure data, a comparison was conducted between the data sets. Despite the data scatter wide angle lens and densiometer canopy densities show some correlation, however densiometer values are on average 20% higher.
2. After 8 storms the average throughfall depth in the forest stations was 57 cm, compared to the 75 cm total storm depth in the meadow. Thereby the amount of precipitin evaporated due to canopy interception was 24%.
3. Canopy interception increased with storm depth.
4. These data suggest that isotope composition in throughfall is affected by canopy interception:
    a. The hypothesized process is partial evaporation of intercepted precipitation, before it is released from the canopy as throughfall.
    b. The correlation of isotope shift on the one side and throughfall depth and canopy density on the other side is not very clear, suggesting that the underlying process is more complex than initially thought.
5. The data were examined to determine by how much throughfall would increase if forest canopy closure was reduced to 40%.
    a. Based on wide angle photo canopy density data throughfall could increase by as much as 9%.
    b. Since canopy closure measured with a spherical densiometer is significantly greater the throughfall increase could exceed 20% in high density forest stands (excluding clearings).
6. Also under a forest canopy reduction to 40% scenario:

a. The isotope signature would be large enough to be detected under current lab analysis resolution.

b. Comparison of throughfall data with simultaneously collected data from a nearby seasonal stream, a spring and a well, suggest that isotope changes under reduced forest canopy density maybe detected in ground water and baseflow.

7. The implications of these results are;

    a. Impacts of forest management practices that result in reduced forest canopy closure have the potential to increase ground water recharge and thereby increase baseflow.

    b. More so these results suggest that overstocked forests may have significant adverse impacts on the water balance.

Recommendations

The most important recommendations made at the end of this report are highlighted:

1. The sheer volume and complexity of the data deserves further analysis, if not further field data collection. Data should be collected in an area of this watershed that has recently been logged for fire safety thinning, including continuous stream and ground water isotope monitoring.
2. Investigate the utility of using isotope signatures from moisture in woody tree tissue to characterize soil moisture.
3. Verify the impact of reduced forest canopy in extensive forest thinning or burn areas by systematic collection of stream and spring isotope data.
4. Conduct a literature search.

Introduction

A number of field measurements were conducted to assess the impact of tree canopy interception on moisture reaching a forest floor in a pine forest. Field experiments were conducted in the winter of 2005/06 at a forested lot near Blairsden, in eastern Plumas County, California at an elevation of about 4640 ft. A wealth of data has been collected from precipitation, stream and ground waters. This report is a summary of observations and conclusions. Being the result of several iterations of data analysis, in the opinion of the author the sheer volume and complexity of the data does deserve further comprehensive analysis, if not further field data collection.

It is common knowledge that when one gets caught in a rainstorm, to avoid getting wet, is to find shelter under a large tree. Also, in the pine forests of the Sierra Nevada it is typical to find less snow on the ground under large trees and in dense forests, when compared to meadows and clearings. This study investigates methods to quantify the effect of forest canopy interception on baseflow. Numerous field studies have provided convincing data that support the notion that vegetation can affect baseflow, which is based in accepted hydrologic concepts.

The objective of this study is twofold:

1. To continue what was initiated in a pilot study conducted in 1996/97 (Bohm, 1997) by collecting new throughfall data, and re-test the hypothesis that reduced canopy density increases the amount of moisture reaching the forest floor, and thereby may increase baseflow.
2. To examine the feasibility of using isotope tracers to assess impact of tree canopy interception on soil infiltration, ground water recharge and stream base flow.

The interest in understanding the connection between forest canopy density and stream flow evolved from an ongoing debate between the author and several other hydrologists involved in stream and watershed restoration projects in the Plumas NF and private land. The key observation is that the geomorphic features of many ephemeral streams and their riparian surroundings seem to hint that at one time these were populated by beavers, implying that these were once perennial streams. Why would the flow regime have changed in these streams? Several factors could contribute to this, including changing climate and land use. While the impact of climate change on small stream flow regime is still being verified, the impact of fire suppression on forest vegetation density is apparently well established. For example increased spring flow after wildfires seem to be a common observation (reference). A connection between stream flow regime and vegetation is founded in commonly accepted hydrologic concepts (e.g. Bosch & Hewlett, 1982).

If the conclusions based on the above mentioned geomorphic observations are realistic, then it is reasonable to ask how forest thinning, if not catastrophic wildfires, will affect a watershed's water balance. Since impact of evapotranspiration and hence vegetation on water balance is a well accepted concept, the logical next step is to ask to what extent does reduction of vegetation density increase baseflow, if not the overall water yield from a watershed. To be clear, this study is not to advocate aggressive vegetation management for the purpose of increasing water yield, but to enhance a balanced discussion about local watershed management concerns.

The focus of this study is on only one aspect of evapotranspiration, i.e. evaporation from the forest canopy.

Background

A preliminary study conducted in 1995/96 indicated that evaporation of rain and snow intercepted in high density forest canopies can be substantial (Bohm, 1997). For the sake of watershed restoration estimating the impact of interception on streamflow is in the opinion of the author an essential component of watershed management. However, there are reasons to believe that the precision of stream flow measurements is insufficient to detect the effect of increasing or decreasing forest canopy density. To help circumvent these difficulties it was proposed to apply naturally occurring oxygen-18 and deuterium isotope tracer techniques. The objective is to develop methods that can help provide a seasonal and aerial averaged measure of canopy interception impact on ground water recharge and stream flow.

In specific this project entails:

a. Examining evaporation loss during forest canopy interception and infiltration through forest litter and soil measuring the naturally occurring environmental isotopes deuterium and oxygen-

18 in throughfall and soil moisture.

b. Comparison of this study with the 1995/96 preliminary throughfall field study results.

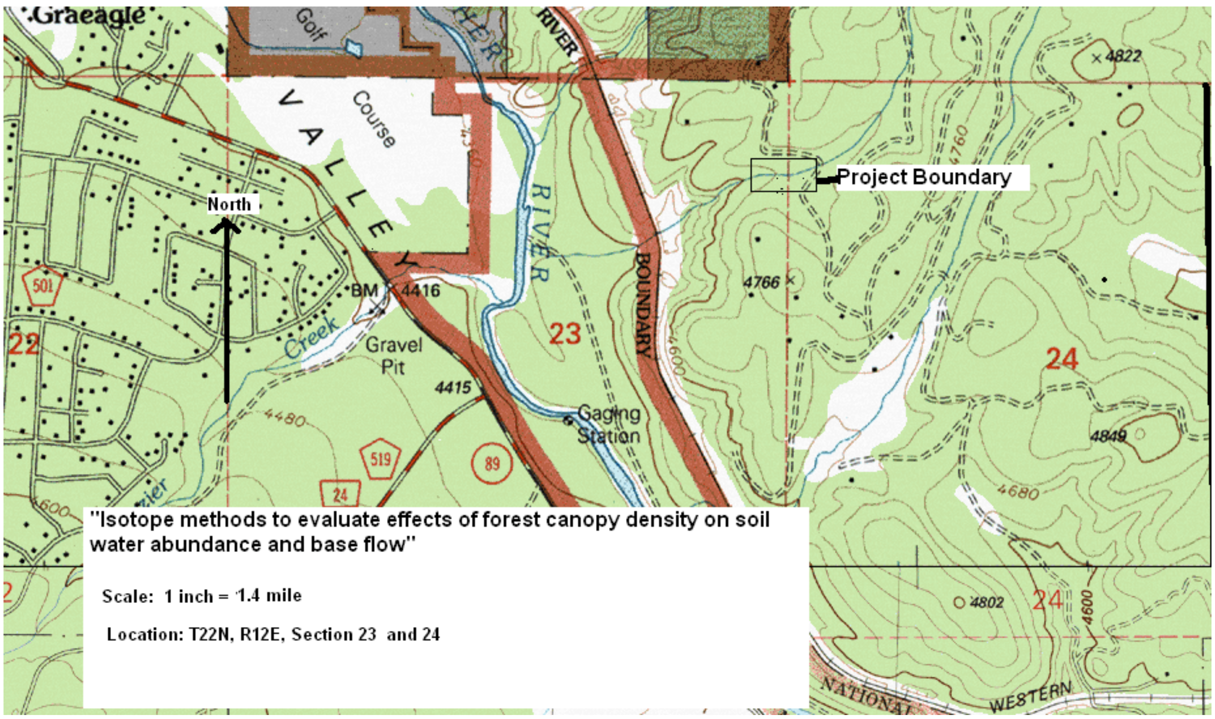
c. Examining to what extent the isotope signatures induced by evaporation in the forest canopy and in soil waters can be recognized in ground water and base flow.

d. Examine if the effect of forest canopy thinning can be noticed in ground water and baseflow.

The intent is to identify means whereby one can estimate the impact of forest canopy interception by comparing pre- and post-project isotope signatures in precipitation, soil moisture, springs and stream water samples.

Project location

This project is located in the Middle Fork Feather River (MFFR) watershed at one specific location, a 13 acre forested parcel about 1 mile north of the town of Clio in eastern Plumas County (see location map), at an elevation of 4600+ ft. Given the intensity of field data collection necessary during the winter the project focused on a limited area, near the author's residence.



Working hypothesis

To start, it is important to establish the working hypothesis.

1. The term "throughfall" implies the amount of precipitation penetrating the canopy and reaching the forest floor.
2. The term interception is the fraction of precipitation which ends up on branches and leaves of tree canopies. Some of this is returned to the atmosphere by evaporation, while some is eventually shaken off by wind, thereby becoming throughfall.
3. The denser the forest canopy, the less throughfall reaches the forest floor.
4. Partial evaporation of temporarily intercepted throughfall results in isotope enrichment. Part of the remaining fraction (partially evaporated) eventually falls to the forest floor, carrying an isotope enrichment signature. In other words the degree of isotope enrichment in throughfall samples is expected to correlate with canopy density and throughfall depth.
5. Isotope enrichment in soil moisture, correspondingly, is expected to correlate with isotope enrichment in throughfall.

6. Correspondingly isotope signatures in base flow and ground water are expected to reflect the integrated effect of average tree canopy density in a forested watershed.

Acknowledgments

A number of individuals have been instrumental in helping to conceptualize the queries leading to this study proposal. First, credit is due to the Plumas Watershed Forum who authorized and funded this study. David Decker and Jim Thomas of the Desert Research Institute gave valuable advice in field data collection methodology. They also provided valuable report review comments. This study ha also benefited from many helpful suggestions from Terry Benoit and Jim Wilcox of the FR-CRM. Credit is also due to John Sheehan of the FR-CRM for his continuing support since inception of the 1997 study.

Experimental Setup

Throughfall stations

A total of 20 stations were randomly established at approximately 25 ft intervals along two east-west transects in a forested parcel, spaced about 150 ft apart. Each station was marked with a wooden stake, with an alphabetic letter assigned to each station.

7. The first transect located on a north facing slope, had ten stations on an east-west line (stations A-G, M-O), and five stations in a north-south line (stations H-L).
8. The second transect with five stations is arranged on an east-west line on a south facing slope (stations P-T).
9. At each station an open 5 quart plastic bucket (top opening diameter 20.3 cm) was placed on the forest floor to capture precipitation under the given local conditions.
10. A control station was established in a meadow about half way between the two transects, with an open 5 gallon plastic bucket (top opening diameter 27.1 cm).

Vegetation

The parcel is covered with a pine dominated conifer forest, including mostly Jeffrey Pines and to lesser extent red cedars. The parcel is visibly overstocked with small diameter trees, scattered among larger trees with DBH's (diameter at breast height) up to 24 inches, or more. The southern transect is mostly in an overstocked forest, and the northern transect forest has been thinned substantially in 1995.

The stations can therefore be categorized into two groups:

11. Stations A through O: dense forest, not thinned, with variable canopy coverage on a 15% north facing slope. Tree stem diameters range from about 2 inches up to 24 inches or more.
12. Stations P through T: mostly trees taller than 30 ft, though usually less than 24 inches in diameter. This area has been thinned and partially logged in 1995, selectively taking out small diameter trees, and a select number of large diameter trees.

Field Data

Forest canopy measured from wide angle lens photos

Forest canopy density was measured in percentages of sky area, using a Canon A70 digital camera with a wide angle lens. This is a very convenient and time saving method. Percentages of blue sky pixels were estimated with the Photoshop Elements software. These measurements were made in the spring of 2006. For the duration of the experiment it is assumed that the canopy density has not changed.

Forest canopy measured with a densiometer

Forest management practices are typically based on forest canopy closure data collected with a densiometer, not with a camera. For that reason it was deemed prudent to also measure canopy density with a spherical densiometer. This is an instrument with a concave mirror, used for measuring forest overstory density. These measurements were made in the spring of 2008. It is deemed safe to assume that since the collection of throughfall data in 2005/2006 the canopy density had not changed significantly. A comparison between wide angle lens and densiometer canopy data is presented in attachment D.

Canopy density distribution

The frequency distribution of canopy density for both types of data is shown in Figure 1, and the canopy densities are summarized as follows. Among the 21 stations:

13. The densiometer data are consistently larger than the wide angle lens data, on average by 20 percent (79% versus 59%).
14. While the wide angle lens data cover the entire range from 10% (meadow station) to 90%, densiometer data range from 30% to more than 90%.
15. Among the densiometer data 62% of the station have closures greater than 70%, while among the wide angle lens data only 29% have densities greater than 70%, clearly the densiometer data are skewed towards the higher densities. In fact 43% have densities greater than 90%.

The canopy data are presented in Attachment D. For the purpose of this study wide angle lens canopy density data were used, though a brief comparison of using densiometer data was included.

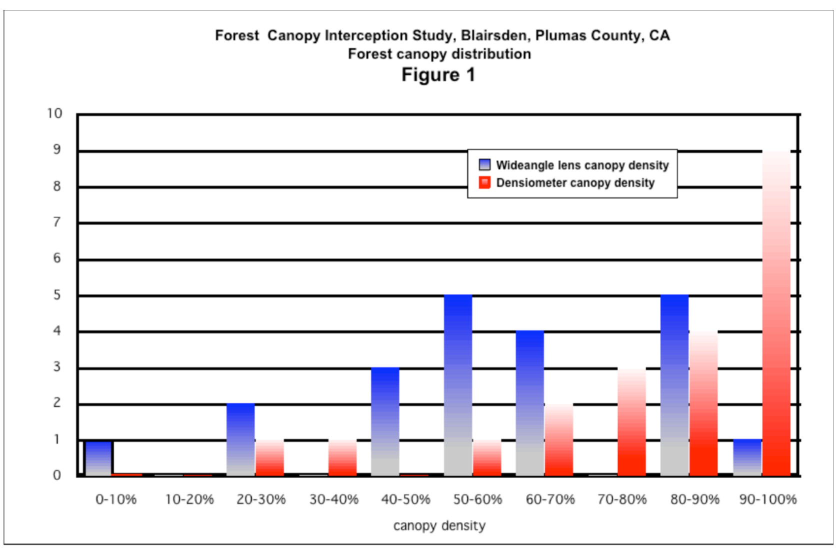
Precipitation measurements

Eight storms were monitored, beginning in the third week of December 2005 and ending in the last week of March 2006. During each storm, at each station depth of throughfall was captured in five-quart plastic buckets with 20 cm diameter top openings, placed on the forest floor.

Precipitation captured in each bucket was measured with a specially designed four inch diameter cylinder, within 24 hours past the end of the storm. Smaller volumes were measured with a glass graduated cylinder.

The depth of throughfall (precipitation) at each station was calculated from the volume of water captured and the top inside diameter of the 1 gallon bucket. Actual storm depth was approximated by measuring precipitation depth in a 5 gallon bucket placed amidst the meadow. However, these storm depth data are most likely too low, since its location violated the minimum distance-to-tree rule for a standard precipitation gage (30 degrees angle of elevation to nearest tree), and the canopy density measured here was 10%. In the absence of a better location the actual storm depths need to be compared with data collected at the nearby Mohawk Ranger Station.

Mohawk Ranger Station is located about five miles to the northwest, west of the town of Blairsden.



Isotope sample collection

More than 240 water samples were collected. Due to budget constraint no more than 170 were analyzed for the stable isotopes O-18 and deuterium. A breakdown by water source type is tabulated below.

Throughfall samples were collected after each storm from each station. Ground water samples were collected from a low discharge spring and a residential well. Stream water samples were collected from a seasonal stream at one location in the meadow. Several samples were also collected at one single location from forest floor runoff.

Water samples were collected in 40 ml glass vials with Teflon lined caps. Samples were shipped to UC Davis Isotope Lab for analysis of the environmental isotopes in water, deuterium and oxygen-18. Due to budget limitations samples from only four storms (out of eight) were submitted to the lab.

Soil core samples were collected from ten selected throughfall data collection stations at the end of the major precipitation season. Five cores are from the north and five from the south facing slope. Cores were collected from depths between 24 and 30 inches below surface in six-inch long, 1 _ inch diameter brass tubes. The tubes were sealed with plastic caps and electric tape and kept frozen until submitted to the lab.

Soil samples were processed at a special lab at Desert Research Institute (DRI) in Reno, NV, to extract soil moisture. Soil moisture extract samples were then sent to University of Nevada Isotope Lab for analysis of deuterium and oxygen-18.

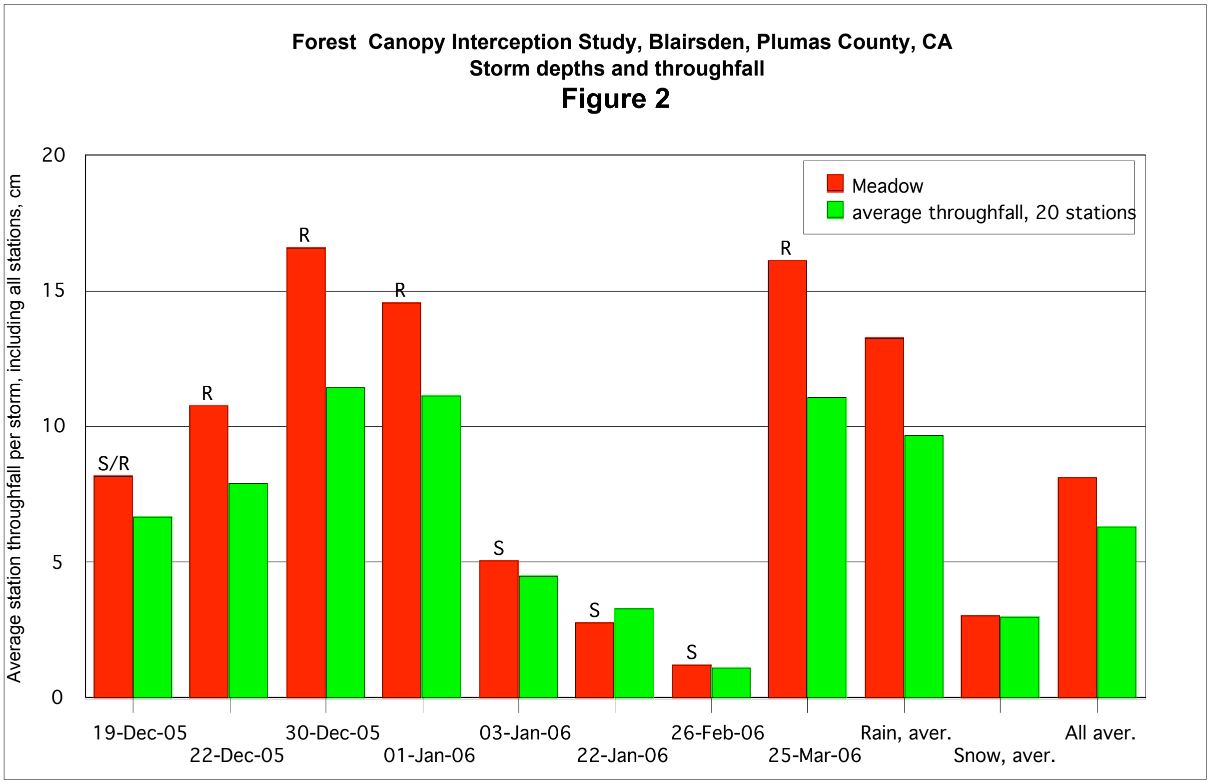
Table 1: Number of samples submitted for isotope lab analysis

throughfall & precipitation	101
ground water	16
stream flow & runoff	35
soil moisture	12
total	164
Total samples collected	244

Throughfall depth observations

Canopy density and depth of throughfall

Figure 2, - Storm depths and throughfall



1. This bar diagram compares each storm depth measured in the meadow (red) with the corresponding 20 station average forest throughfall depth (green).
2. The storms are plotted in the order of date at which they occurred, with the letters 'R' and 'S' denoting rain or snow.
   a. Four of these storms were predominantly rain storms, if not entirely rain. The other four storms are snow storms.
   b. Snow storm depth is significantly less than rain storm depth. Of the total 75.4 cm meadow precipitation, 77% are attributed to rain and 23% to snow. A similar pattern was observed in the 1995/96 study.
   c. Average throughfall depth is typically significantly less than storm depth due to canopy interception.
   d. The difference between meadow precipitation depth and average throughfall is significantly less in the snowstorms. In one storm throughfall depth was even greater than in the meadow. This is due to the nature of throughfall in snow storms (discussion below).

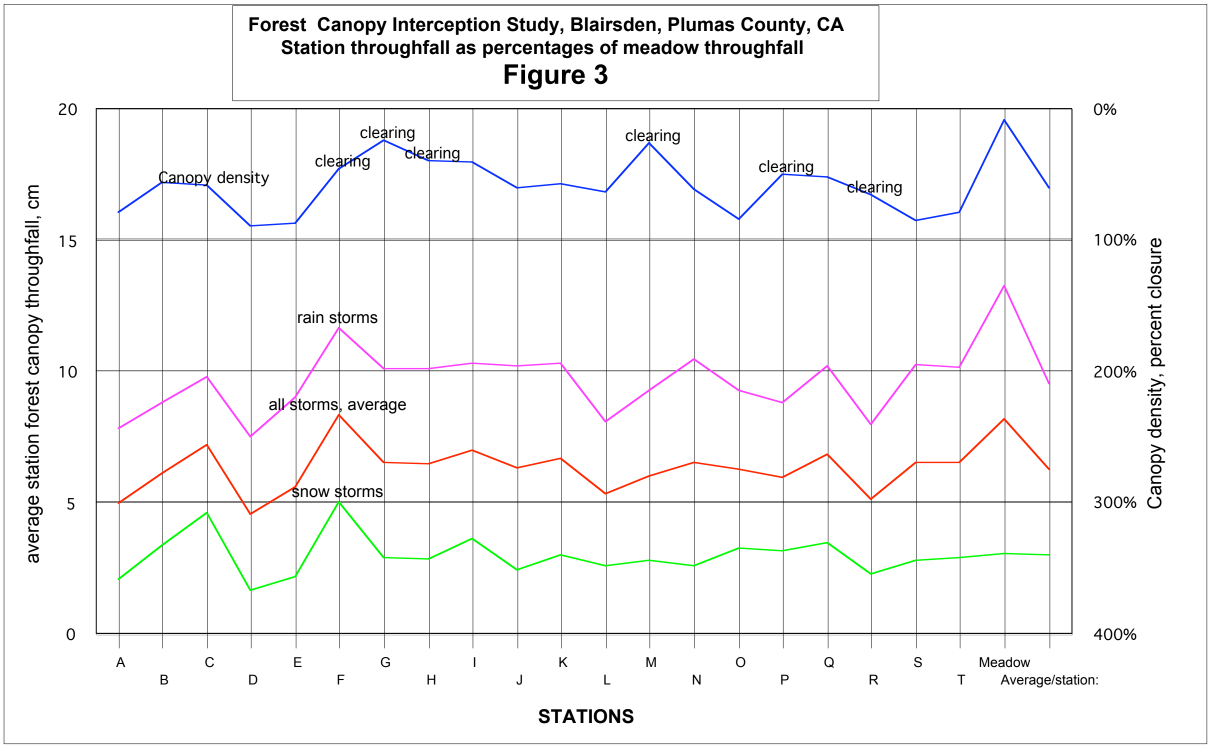
It should be noted that wet tree stems were observed only during very windy storm conditions, when wind was blowing the rain against the trunk for a long period of time. More importantly, when examining a typical pine tree, it can be seen that its branches are not particularly suited for inviting water to run from the branches towards the trunk ("stem"). This is different than in a typical deciduous tree. In pine trees excess water most likely drips off the branches before it can reach the trunk. This maybe one explanation for the observation made by Bosch and Hewlett (1982), stating that the impact of vegetation on the water budget is most significant in watersheds dominated by pine forests.

Evidently the amount of canopy interception is significant. The entire profile's mean station throughfall for

8 storms is 57.2 cm, which is 76% of the 75.4 cm measured in the meadow. In other words 24% of the total precipitation was returned to the atmosphere via evaporation from forest canopy.

Station throughfall compared to meadow throughfall

Figure 3, Station throughfall as percentages of meadow throughfall



1. In this figure average throughfall depth at each station is compared to tree canopy density. To facilitate an easier visual comparison, the canopy density axis is inverted on the right.
    a. The throughfall station averages are shown as percentages of open meadow precipitation.
    b. The stations are arranged roughly as in the order in the forest. Three data sets are compared:
        i. Green - averages of snow storms.
        ii. Purple - averages of rain storms.
        iii. Blue - percent canopy density
2. The throughfall data profiles of both storm types mimic the canopy profile to about more than 75%. However, the rain storm profile mimics the canopy profile far better than the snow storm profile.
    a. The rain storm station averages are greater than the snow storm percentages.
    b. In about 25% of the stations snow storm throughfall depth exceeds open meadow precipitation.
    c. Since the rain storm profile in these data correlates far better with the canopy profile, apparently the effect of canopy interception increases with storm depth.
3. Some stations however, consistently deviate from the patterns;
    a. Stations associated with forest clearings (G, H, M, P, R) received less throughfall than would be expected under given canopy density.
    b. Station F, on the other hand was affected by stem flow, moisture dropping from a branch, as observed in-situ.
    c. Evidently stations associated with forest clearings constitute a sub population of data.

Discussion

Correlation between throughfall depth and percent open sky is convincing for some stations, and less convincing, if not absent in others. It is possible that these correlations will improve when canopy aspect is brought into play, or a wider canopy perimeter is included.

Variation in average throughfall is significant. Compared to meadow precipitation, snow storms range from 65% to 157% and rain storms range from 54% to 84%. Canopy density ranges from 10% to more than 90%. Evidently in the rain storms the correlation between throughfall and canopy density is much better than in snow storms.

When looking at individual storms, the relations are by far not as convincing, although the effect of canopy interception remains evident in each storm. To make things more complicated, the data scatter significantly from storm to storm, although the variance of throughfall does not increase with storm depth. This is to be expected, and the various factors that may give rise to this variance are discussed later in this report.

When looking at all stations correlation between canopy density and throughfall is very poor in both storm types. However the correlation constants (R-square) for the total throughfall values improve significantly when only stations from high density forest stands are included, without clearings. Though still not very good, the correlation is best when comparing throughfall with densiometer canopy densities, instead of wide angle lens densities (Attachment D).

One important further step would be non-parametric testing of correlation (Spearman's rank correlation) to verify increasing canopy interception with storm depth. In other words a good linear relationship can not be established probably due to other confounding factors (aspect, tree sizes, species, storm direction, wind strength, etc.)

General observations about canopy interception

Canopy interception is hypothesized as precipitation retained in the canopy and at least partially evaporated before dripping to the ground. Since the rain storm profile mimics the open sky profile reasonably well this model seems to apply to rainstorms. However, this is far less so in snow storms. Why this is so can only be speculated on at this time.

One likely possibility is that snow is better retained in the tree canopy. When the air temperature remains at or below freezing the only way moisture can return to the atmosphere is by sublimation. This does not result in isotope enrichment. If on the other hand air temperature increases after a snow storm snow struts melting, partially evaporates, and then drips to the ground.

On the other hand when the amount of snow in parts of the canopy is excessive it may slide off in large chunks, depending on tree type and size. It can be envisioned that the amount of throughfall released under such conditions can be much larger than the steady throughfall seen in rain storms.

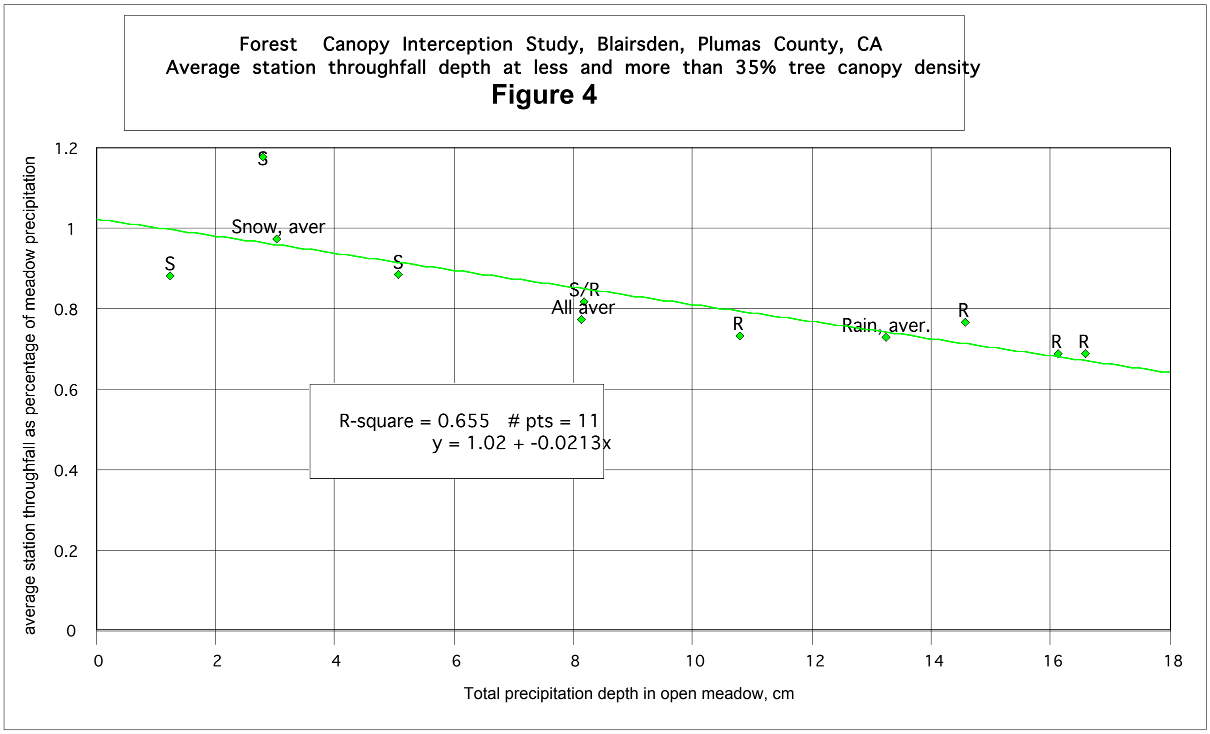
Another possibility is air turbulence affected by localized tree/canopy arrangements (aerodynamic effect). Snow flakes are much more susceptible to turbulence than rain drops. These possibilities can be further examined visually by watching the process in the forest.

These factors can serve as a possible explanation why the effect of canopy interception is minimal during small storms, but it increases during large storms.

The December 22 storm throughfall samples do not display the elongated patterns seen in the other storms. This is probably due to the samples being collected too early, before canopy evaporation and simultaneous drip-through could come into effect.

Evidently, it can be seen that these confounding factors make for poor correlations between canopy density and throughfall depth. On the other hand correlation may improve with larger data populations, if not larger diameter canopy densities.

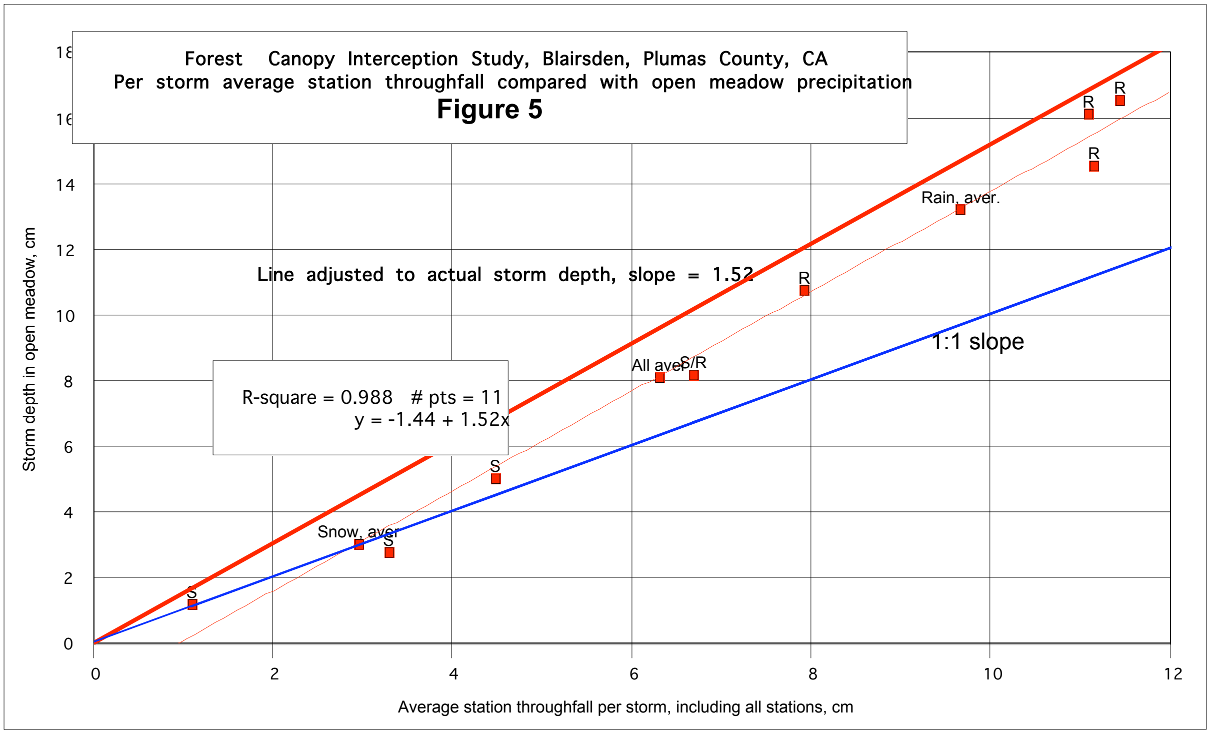
Figure 4, Dependency of average station throughfall percentage on storm depth



1. This diagram compares average station throughfall (percent of open meadow) with meadow storm depth.
   a. Total precipitation measured per storm in the open meadow is plotted on the horizontal axis (x-axis).
   b. Average station throughfall per storm (green) expressed as percentage of open meadow precipitation is plotted on the left vertical axis (y-axis). Rain (R) and snow (S) storm types are indicated next to each plotting position
2. Average station throughfall per storm (green) expressed as percentage of open meadow precipitation is a measure of canopy interception representing an approximate 'areal average':
   a. Average station throughfall is almost 100% below 3 cm total storm depth. On the other hand, it decreases down to about 65% at a storm depth of 17 cm.
   b. In other words, according to these data, the effect of canopy interception is minimal during small storms, but it increases during large storms (which seems counterintuitive).
   c. The degree to which canopy interception becomes effective is specific for this forest section and can be quantified by the slope of the green line. Although the correlation coefficient is only 0.65, looking at this diagram the correlation is convincing.

Average station throughfall dependent on storm depth

Figure 5, Average station throughfall compared with open meadow precipitation



1. Actual storm depth in the meadow is compared to average station throughfall depth, measured in cm. Storm types are indicated together with storm date (end of storm).
   a. The linear correlation is remarkably good as indicated in the correlation coefficient R-square of 0.988. The regression equation is not affected by including snow, rain and all storm averages, as indicated.
   b. The slope of the line is 1.52 (greater than a 1:1 slope). In other words, compared to open meadow precipitation, the forest canopy interception effect diminishes the original storm depth on the average by 34% (1 - 1/1.52 = 34%).
2. The line's y-intercept is negative (-1.44), suggesting that at zero cm storm depth throughfall depth is still about 1 cm. This is of course contradictory, since throughfall should be zero at zero storm depth. The reason is that the meadow precipitation depth data are slightly diminished by canopy interception.
   a. The meadow station canopy density is not zero, but 10% (305 densiometer value).
   b. The meadow station does not qualify as a rain gauging station since obstacles (trees) are reaching above the 30 degree angle of elevation line. .
3. A preliminary comparison of the meadow precipitation data with rain gauge data collected at the Mohawk Ranger Station led to conclude that actual storm depth were higher than actually measured in the meadow. Consequently the line was redrawn by shifting it upwards by the interval 1.44. Thereby the meadow values (vertical axis) increase, reflecting actual storm depth as it would be measured in a precipitation gauge.

Discussion

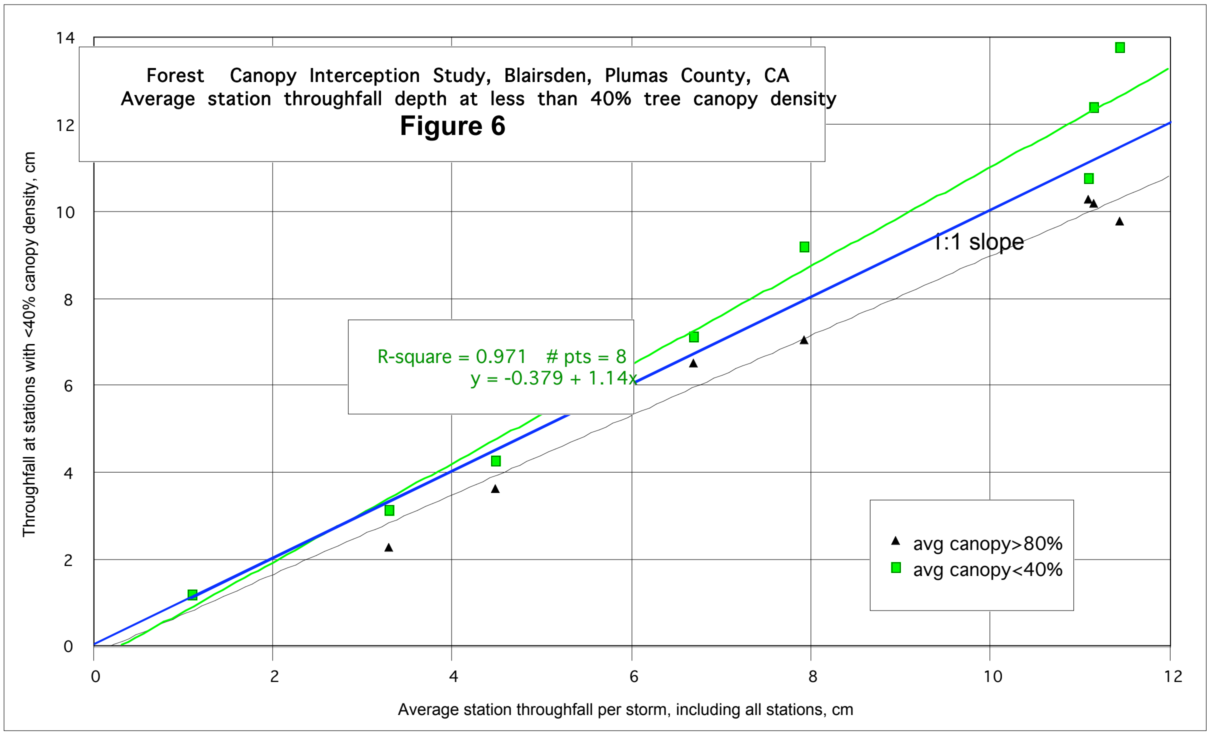
The slope of the line in Figure 5 is expected to increase above 1:1 the greater the average canopy contrast between the two groups. In this case average canopy density of the 20 stations is 62%. It is worth examining the relation between total throughfall depth per season and average station canopy density.

Compared to open meadow precipitation, the forest canopy interception effect is significant, reducing the original storm depth on the average by more than 30%. For example in a 15 cm storm, canopy throughfall is reduced to 10 cm. This is comparable to what is reported in the literature.

To be clear, the purpose of this discussion is not to advocate the utility of complete forest removal for water resources management. The hydrologic benefit of watershed management is best measured in terms of long term self-sustaining ecological health of a watershed. Nevertheless, this explains the observation made by some researchers why spring flow often increases after a major fire (references?). It also suggest the plausibility of forest canopy thinning increasing the water balance.

It should also be kept in mind that during winter when most ground water recharge occurs, water loss from dormant vegetation is probably minimal. Nevertheless it should be clarified to what extent forest vegetation can survive in the uplands where depth to ground water exceeds rooting depth, only on soil moisture left after infiltration.

Figure 6, Average station throughfall at less and more than 35% tree canopy density



1. This diagram examines a hypothetical scenario, assuming a reduction of canopy thickness to less-or-equal-to 40% (forest thinning scenario). Data are plotted for the 8 storms only.
   a. Average station throughfall per storm including all 21 stations is plotted on the x-axis. This represents average throughfall in the forest under current conditions. In this case the average canopy density is 62%, ranging from 10% to 91%.
   b. On the y-axis are plotted station average throughfall per storm (blue) only for those stations with canopy density less than 40%. This includes only four stations with an average canopy thickness of 29%. All four stations are also included in the group plotted on the x-axis.
   c. As expected, under these conditions the linear regression line slope is greater than 1, i.e. 1.14, with a very high correlation coefficient R-square = 0.98.
2. With an R-square value of 0.98 the linear correlation is convincing:
   a. Since the slope is greater than 1.0, again the effect of canopy interception is evident.
   b. The line intercepts the y-axis at -0.38, although it is expected to be zero. Compared to the -1.44 cm value in Figure 5, this discrepancy is negligible, maybe since the lower section of the line is unduly affected by the snow storms, where the effect of canopy interception appears to be less than in rainstorms.
3. With the regression line y-axis intercept at zero, in the stations with canopy density less than 40% canopy density, throughfall is increased by 14%, compared to the totality of stations in this data set. When the regression line is forced through the origin the slope is diminished to 1.11. In other words by thinning a forest canopy interception can be reduced significantly. For example in a 10 cm storm, canopy throughfall can be increased by about 1 to 1.5 cm.
4. For comparison data are also plotted for stations with canopy density greater than 80% (black). Average canopy density for these five stations is 87%.
   a. Average station throughfall for the >80% canopy density group is significantly less compared to the average of all stations. For example for an all inclusive station average of 11 cm, for a greater than 80% canopy density station average is only 10 cm.
   b. Under these conditions the linear correlation line slope is only 0.92 (less than 1.00), with a very high correlation coefficient R-square = 0.99.

Discussion

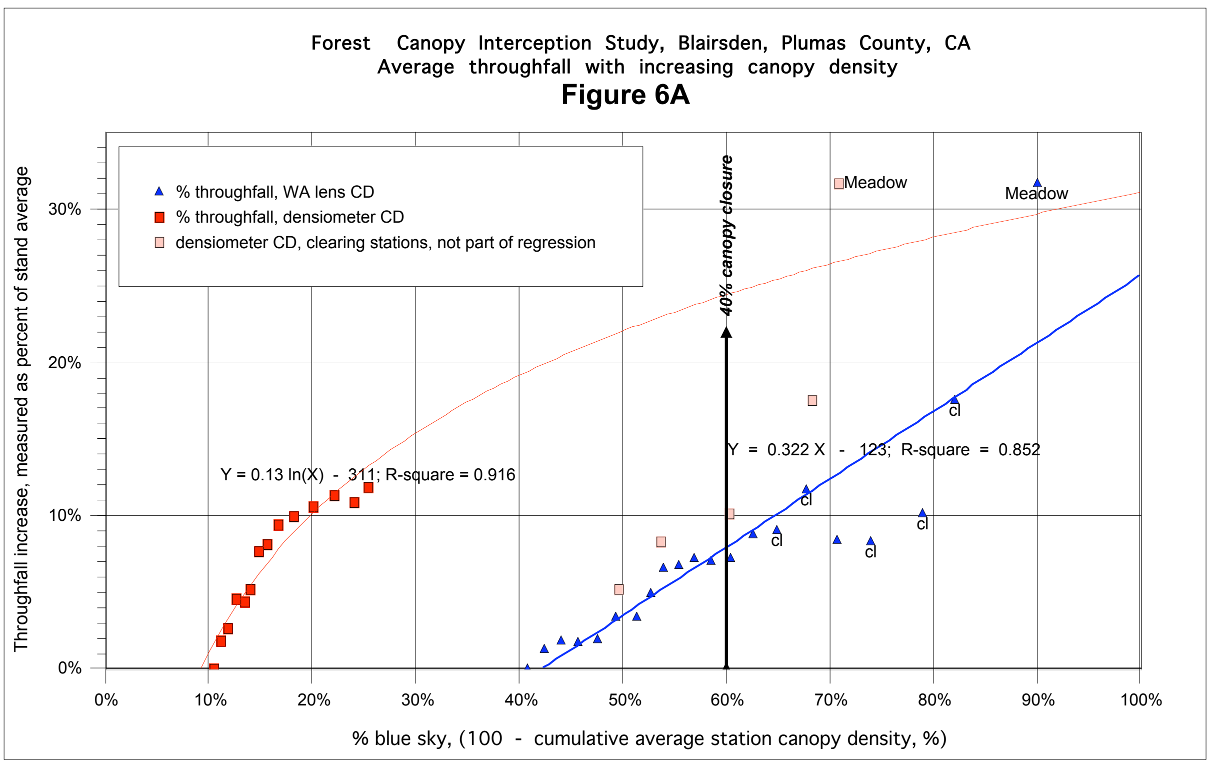
Again, this line is representative for the stations selected herein. Contrasted here are an average canopy density of 29% (thinned) with 62% (not thinned) to explore possible methods to collect and study larger data sets, sets that are statistically more representative.

Cumulative average throughfall estimates

In the preceding section it was demonstrated that reduced canopy closure in a forest stand can significantly increase the amount throughfall reaching the soil. In this case it was assumed all stations' canopy density was reduced to less than one particular threshold, i.e. less-equal than 40%.

The same concept can be expanded by estimating the amount of throughfall increase when the average canopy closure decreases. This will establish a continuous curve that relates closure to throughfall. Nevertheless, it would be interesting to see the impact of an entire range of possible canopy reduction scenarios. For that purpose the stations were rearranged in the order decreasing canopy density. Throughfall and canopy closure was then calculated as an average of stations, including more and more stations while the average canopy density decreases. Correspondingly throughfall is expected to increase.

In Figure 6A the results were plotted in blue for the wide angle lens canopy densities. To ease the regression instead of canopy density the canopy opening percentage was plotted on the x-axis. The blue data suggests a linear trend and the regression equation is given. However a few stations deviate significantly often suggesting they receive less throughfall than expected from the trend of the bulk of the remaining stations. Again, this supports the previously made observation that the stations in forest clearings are a different data population.



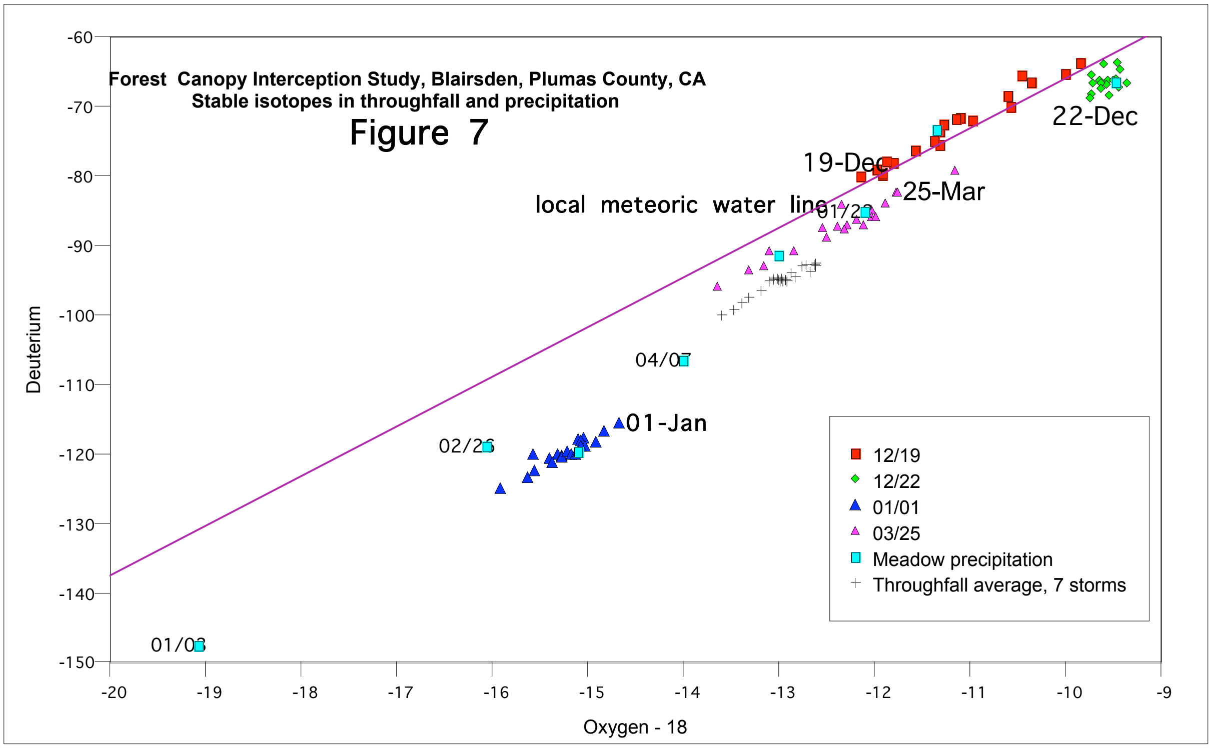
Although the remaining data analysis discussed in this report is based on the wide angle lens canopy closure data, it deemed prudent to conduct a similar comparison based on canopy closure data measured with a densiometer - plotted in red. Different than done previously, the stations located in or adjacent to clearings were not included in the regression analysis. The best fit suggests a logarithmic relation, and the regression coefficient R2 of 0.916 is even better than in the wide angle lens data.

The two curves derived from the regression can be used to estimate the increase if the average canopy closure was decreased to 40% (60% canopy opening, blue sky). Based on the wide angle lens data the increase would be about 8%. Estimating the increase based on the densiometer data may be somewhat tenuous without data that cover that range. Nevertheless, it is encouraging to see that the projection of the regression equation is bracketed by the meadow data. Most likely then under canopy density reduction to 40% the throughfall increase could be more than 20%.

Stable isotopes deuterium and O-18 in throughfall

Storm isotope signatures

Figure 7, stable isotopes in throughfall by storm



1. This is a standard plot depicting the isotopes of oxygen-18 (x-axis) and deuterium (y-axis). The local meteoric water line (LMWL) serves as a reference line. It is a regression of snow isotope data collected in American Valley, Last Chance watershed and elsewhere in the region.
2. The plot includes the major 8 storms for which station data were collected, plus a number of minor storms. Isotope composition varied considerably from storm to storm, probably depending on the storm path preceding arrival at this site.
   a. Station throughfall data were plotted, for the four storms for which samples were submitted for lab analysis. These storms comprise 66% of the total precipitation depth collected for this project.
   b. Meadow precipitation for the remaining storms is plotted in light blue, comprising the remaining 36% of the total precipitation of that season.
   c. Average station throughfall for the measured storms (plotted as black '+') was calculated like a mixture, weighted by each station's throughfall depth:
      Cmix = (C1xT1 + C2xT2 + ... + CixTi)/(T1 + T2 + ... + Ti), were 'C' and 'T' are isotope composition and throughfall depth for each storm, and 'i' is the number of storms.
3. Effect of canopy interception:
   a. With one exception, as expected all storms display elongated patterns, suggesting the effect of canopy evaporation. Evaporation results in the O-18 and deuterium composition shifting to the upper right.
   b. The O-18 and deuterium shifts of up to 2.5 and 16 per mil are parallel to the LMWL s expected for evaporation under cold conditions.
   c. The December 22 storm throughfall samples do not display the elongated patterns seen in the other storms. This is probably due to the samples being collected too early, before

canopy evaporation and simultaneous drip-through could come into effect. This will be further discussed later in this report.

d. Unexpectedly meadow precipitation samples (blue) never plot at the lower left of each respective group. This could be due to several reasons (see further discussion below).

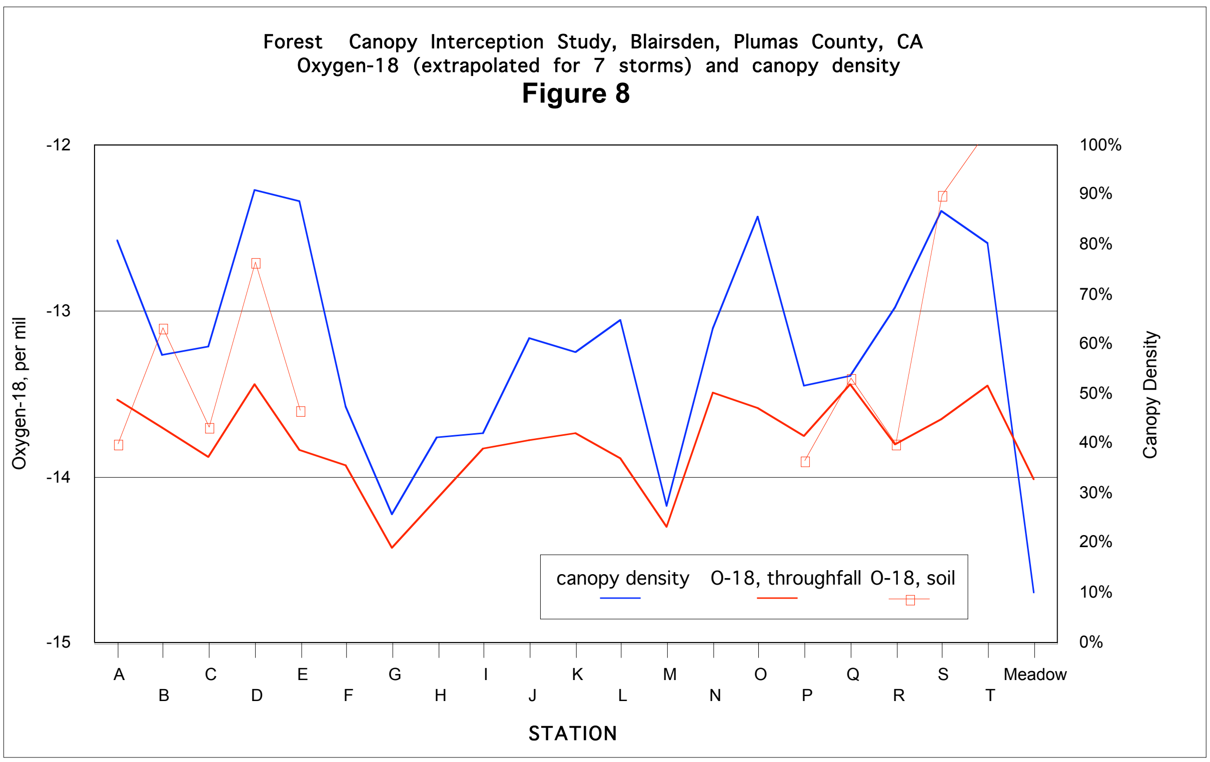
e. Also plotted are the per station mixtures. (Black crosses - '+'). The values were calculated by weighing each isotope value by their respective station throughfall depth for each storm.

Discussion

The meadow samples do not plot in the lower left end of each storm group. Since the meadow has the lowest canopy density one would expect the least amount of evaporation and hence the least enrichment. The reason for this contradiction maybe found in one or several factors, such as aspect, too small canopy perimeter measured aerodynamics in clearings, etc.

Isotopes in throughfall correlating with canopy density

Figure 8, O-18 and canopy density



1. Shown in Figure 8 and Figure 9 are oxygen-18 and deuterium of throughfall and soils, compared with canopy density. The stations are arranged roughly in the order as they are arranged spatially in the forest.
   a. The plotted isotope values are the extrapolated station averages for seven storms (see discussion below).
   b. The storm of 22-Dec was not included since in it no correlation between isotope values and canopy density can be recognized (probably due to sampling too early after storm ended).
2. The throughfall isotope "profiles" closely mimic the canopy density profile, which is a strong indication that throughfall isotope composition is affected by canopy interception. The isotope values increase upwards in response to evaporation (enrichment).
3. Also shown are isotope values measured in soil cores collected at ten selected stations.

a. Soil oxygen-18 profiles mimic the throughfall isotope profiles reasonably well, suggesting that throughfall measured indeed is representative of ground water recharge.

b. On the other hand, significant deviations in the deuterium data maybe due to evaporation of soil moisture, since the cores were taken too late in the season July 2006).

c. Deviations may also be related to problems with sampling technique (stations S and T).

Discussion

The apparent correlation between canopy and isotope enrichment is not always as expected. For example, unexpectedly, the meadow station which has the lowest canopy density does not have the lowest O-18 and deuterium. Correspondingly the highest O-18 and deuterium values do not match up with the largest canopy density value. One reason could be that the effective canopy perimeter determining throughfall characteristics in some stations may be much larger than what was measured.

The soil moisture isotope values are deemed the most dependable indicator of throughfall isotope composition. Soil values mimic the throughfall values consistently, but they are higher in most stations. This is probably not due to sampling error, since great care was exercised while handling the cores in the field. Possible reasons could be:

a. At the time (May 2006) when the cores were taken at some stations soil moisture was at field capacity and affected by evaporation in the unsaturated zone (i.e. Sampled too late in the year).

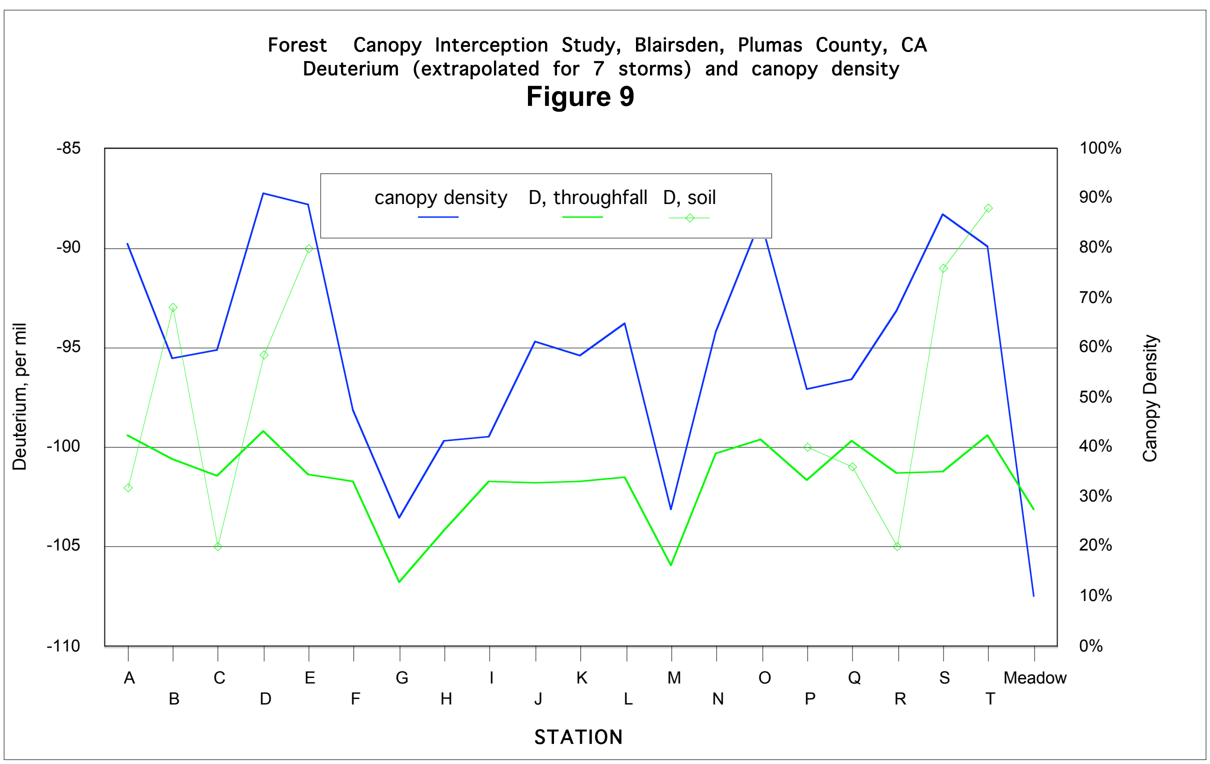
b. Some stations soil moisture was affected by lateral moisture migration, following soil stratification downhill.

c. The estimated throughfall station averages are significantly off since at least the December 22 storm data could not be included.

Since soil moisture is still deemed the most reliable indicator of throughfall isotope composition alternative ways are needed. For that purpose in February 2007 one pint plastic cups filled with clean sand and _ inch PVC access sampling tubes were installed at stations A through D. So far no soil moisture samples have been recovered from these.

Another solution could be sampling woody tissue in nearby trees.

Figure 9, Deuterium and canopy density



Evaluating effects of forest canopy changes on isotope signature

In the following the seasonal average isotope signature is estimated as it is a combination of individual storm depth and individual station isotope signal. Essentially the estimate constitutes a mixing calculation.

Effects on individual storm throughfall depth

The linear relationships identified in Figure 5 and Figure 6 are very useful to test to what extent a reduced canopy density may increase the amount of moisture reaching the forest floor. As noted earlier, canopy interception (reduction of throughfall) increases with storm depth. Hence any such estimates need to take the long term seasonal storm depth distribution into account.

Thereby, knowing storm depth, one can estimate the amount of throughfall, using the linear equation $Y = aX + b$ in Figure 5. The estimated throughfall depth can then be plugged into the linear equation derived from Figure 6, assuming the forest canopy has been thinned to less-than-or-equal-to 40%.

The methodology is demonstrated in Table 2. Using the measured average throughfall values for each storm, the throughfall under reduced canopy density was estimated, using the equation

$$Y = 1.14\,X - 0.38,$$

Where X is the all-station average throughfall depth for a particular storm and Y is the estimated throughfall average for only those stations with less than 40% canopy density (average canopy density for the 4 stations included is 29%). Based on this approach the estimated throughfall would have increased from 57.2 cm to 61.8 cm. This is an increase of 9%.

Probably this estimate is conservatively low, since the line implied in the above equation should pass through the origin (at zero storm depth throughfall depth is nil). Although thereby the slope 'a' may diminish somewhat the constant 'b' should be zero which increases the estimate.

It should be noted that this approach implies two caveats:

1. The constants 'a' and 'b' in the aforementioned linear equations apply to that particular set of stations used in this study, where 'a' is the slope and 'b' is the y-axis intercept. To come up with a data set that is applicable for an entire area proposed for thinning, one may have to apply more sophisticated canopy data collection and analysis (for example geostatistics, Kriging, remote sensing).
2. The estimated increase in throughfall applies to the storm pattern observed in this data set. For a more comprehensive analysis one would have to estimate the same effect for the typical long term storm depth distribution for this location or nearby areas. This can be accomplished by using precipitation data from the nearest precipitation gauging station (in this case Mohawk Ranger Station).

Admittedly this analysis applies to a limited data set, but it characterizes the nature of throughfall data and points to methods that can be applied to more comprehensive and larger data sets.

Average station throughfall isotope composition

The isotope data as measured for throughfall at each station are tabulated in attachment B. A summary of the data is given in Table 3 below. Station average isotope values are given for three storms, i.e. those for which complete suites of station samples were analyzed. Calculation procedures are explained in Attachment C.

As expected, the station averages vary significantly. The data were evaluated in a fashion similar to the throughfall depth data, by comparing the average of all stations with the average of those stations with less than 40% canopy density. The December 22 storm was not included since its samples show virtually no impact from canopy interception due to timing of sampling (see discussion above).

As can be seen in the table, the shift in isotope composition is noticeable (row 7 & 8, Table 3). As expected, the shift is towards less enrichment (less evaporation). However the shift is inconsistent, between storms, though it is tempting to correlate the magnitude of the shifts with storm depth. The inconsistencies probably need to be attributed to the fact that snow and rain storms are put together here.

The average isotope composition for each station was then derived by weighing each station's isotope value by its respective throughfall depth for each storm. Thereby a seasonal average was derived for each station, which is actually a quasi-seasonal mixing value for each station after 3 storms.

Average station throughfall was calculated like a mixture, weighted by each station's throughfall depth:

Cmix = (C1xT1 + C2xT2 + ... + CixTi)/(T1 + T2 + ... + Ti),

Were ‘C’ and ‘T’ are isotope composition and throughfall depth for each storm, and ‘i’ is the number of storms. The signature for the entire season’s storms was then recalculated by adjusting the values with the remaining meadow isotope values (weighted by storm depth).

Table 2. Estimated throughfall depth per storm under reduced canopy density

(canopy densities measured from wide angle lens photos)

	avg canopy density	19-Dec 2005	22-Dec 2005	30-Dec 2005	01-Jan 2006	03-Jan 2006	22-Jan 2006	26-Feb 2006	25-Mar 2006	Rain, aver.	Snow, aver.	All aver.	Total Throughfall
Storm type		S/R	Rain	Rain	Rain	Snow	Snow	Snow	Rain				
All station aver. Throughfall, cm	62%	6.7	7.9	11.4	11.2	4.5	3.3	1.1	11.1	9.7	3.0	6.3	57.2
Estimated throughfall increase under reduced canopy density, cm:													
			Assumed station canopy density is less-or-equal 41%										
	equation y = ax + b, see Figure 6							a = 1.14		b = -0.38			
All station avg., cm		7.26	8.65	12.66	12.34	4.73	3.39	0.87	12.27		Total, cm:		61.8
Increased by:		8%	9%	11%	11%	6%	2%	-21%	11%				40%
		Estimated throughfall increase for the season:											9%

Since the four storms include only 66% of the season's total precipitation depth, the preceding values are not necessarily representative of stream and ground water derived from this section of the forested watershed. For that reason the available additional 4 meadow isotope values and their respective storm depths were used to extrapolate a seasonal station mixture of isotope values. The 8th meadow sample, representing about 22% of the season’s precipitation, was lost when the glass vial broke. Unfortunately this leaves an uncertainty in the extrapolation of the seasonal throughfall isotope signature.

Although these estimates are based on a limited data set they nevertheless suggest that using isotopes to measure the impact of forest canopy changes on baseflow is feasible. If indeed the average isotope shifts are significantly larger than the lab measurement precision (as indicated in the last two rows of Table 3), then a strategic sampling program of springs and baseflow may very well accomplish this.

A station average was also derived for the soil data (only 10 stations). Since each station’s soil moisture composition is already a seasonal integrated signal, the aerial soil water signal is approximated by the soil water average. These values can be compared with local ground and stream waters to arrive at a determination to what extent these are determined by the forest canopy characteristics, and the changes imparted on the same.

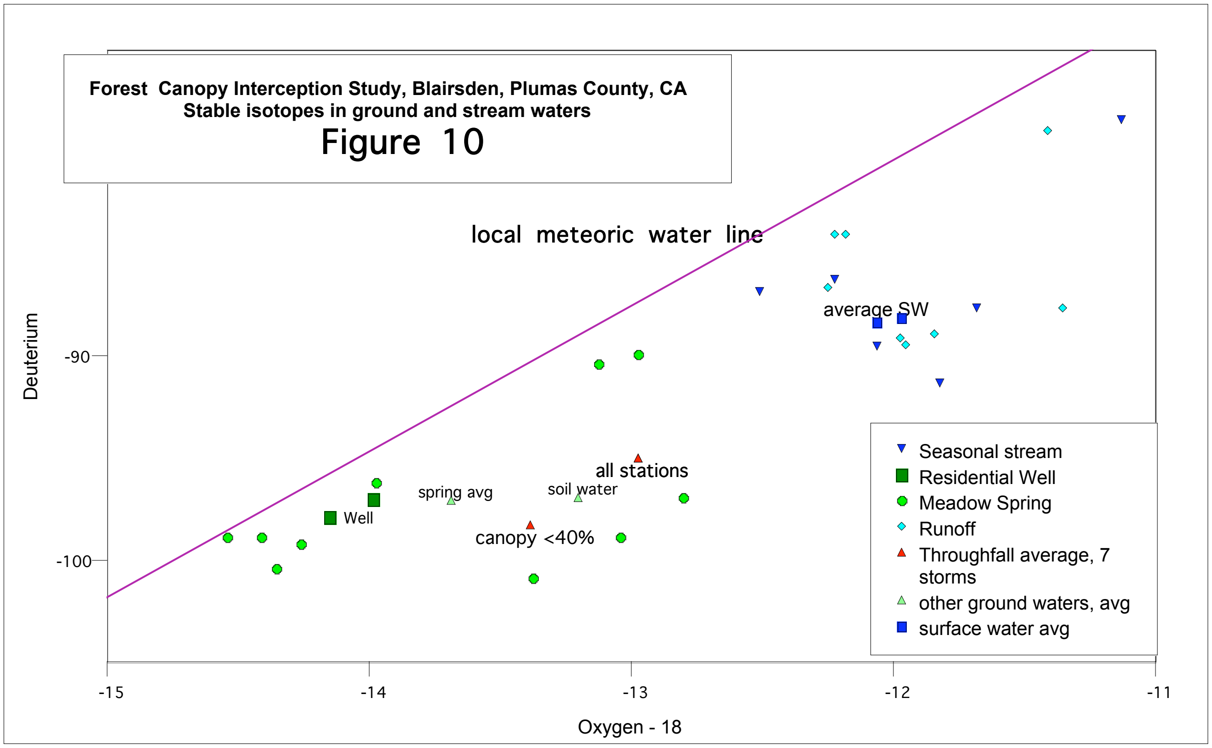
For comparison, the data are plotted in Figure 10, together with ground and stream waters.

Table 3: Throughfall isotope data summary

Measured storms									
	19-Dec	01-Jan	25-Mar			19-Dec	01-Jan	25-Mar	
storm depth, cm	8.2	14.6	16.1			8.2	14.6	16.1	
Storm type - % of total:	Snow	Rain	Rain			11%	19%	21%	
	Oxygen-18, per mil:					**Deuterium, per mil:**			
average all stations	**-11.2**	**-15.2**	**-12.4**			**-73.0**	**-119.7**	**-87.4**	
Station avg CD<40%	**-11.6**	**-15.3**	**-13.2**			**-75.8**	**-121.0**	**-92.7**	
Isotope shift, per mil	0.39	0.13	0.76			2.79	1.23	5.30	
Station averages for entire season, weighted by storm depth:									
	Season average, 3 storms measured:			**Extrapolated, 7 storm average:**			**Soil water, 10 station average:**		
	O-18, per mil	D, per mil		O-18, per mil	D, per mil		O-18, per mil	D, per mil	
Storm dates included	19-Dec, 01-Jan, 25-Mar			19-Dec, 01-Jan, 25-Mar, 22-Dec, 03-Jan, 22-Jan, 26-Feb					
all station avg	**-13.2**	**-96.7**		**-13.0**	**-94.9**		**-13.2**	**-96.9**	
canopy <40% avg	**-13.6**	**-100.0**		**-13.4**	**-98.3**				
Isotope shift, per mil	0.4	3.4		0.4	3.4				
Lab measurement precision, per mil	+/- 0.05	+/- 1.0							

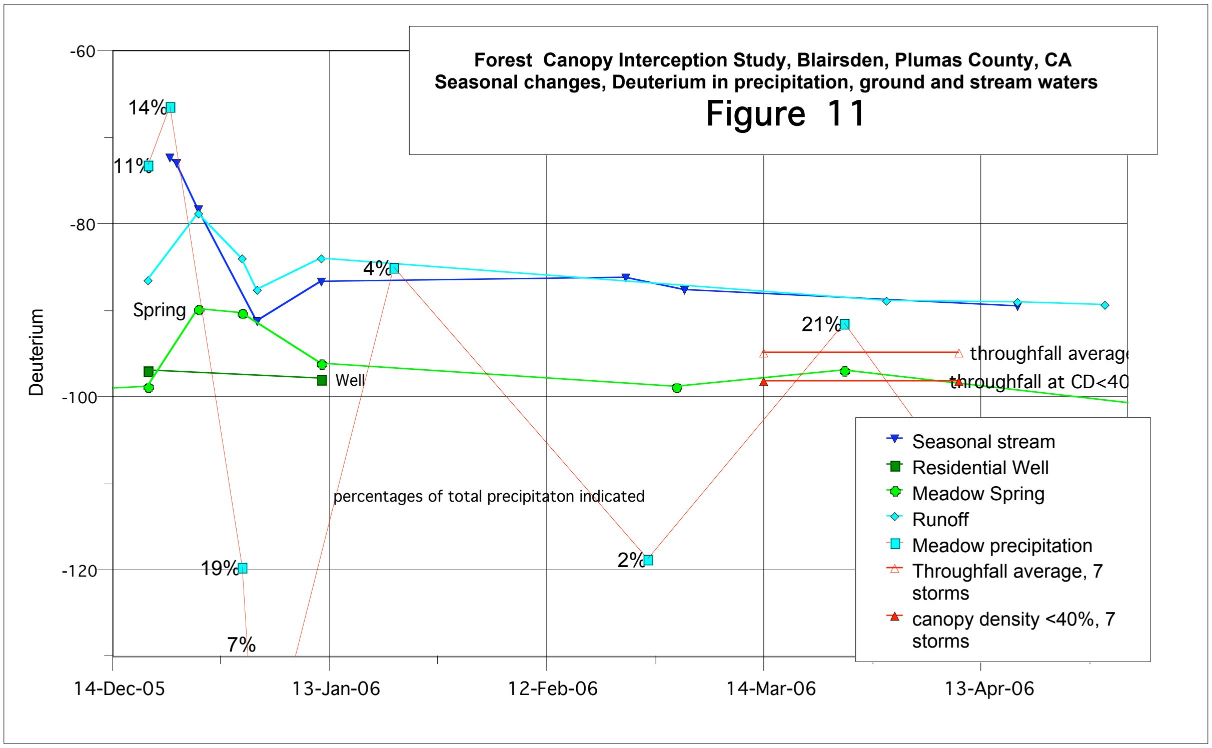
Isotope composition of stream and ground water

Figure 10, Stable isotopes in ground and stream waters



1. This is a standard isotope plot of ground water, runoff and average throughfall.
    a. Throughfall and precipitation data are plotted in red.
    b. Ground water data are plotted in green.
    c. Stream and runoff data are plotted in blue.
2. The ground waters and throughfall data plot in the same range, suggesting a link between throughfall and ground water recharge.
    a. The soil water average is almost the same as the three-storm station average, and differs from the seven storms extrapolated average.
3. Stream and ground waters make two distinct groups, each with a wide range. Although the significant scatter may suggest no systematic trends, nevertheless, as can be seen in the next diagram, the data are subject to systematic seasonal changes in response to precipitation,.

Figure 11 - Seasonal changes, deuterium in precipitation, ground and stream waters



1. This diagram shows the connection between precipitation events, throughfall, stream water and ground water. Shown here are the changes of deuterium over time.
2. Storm precipitation data collected in the meadow are plotted in red. Ground water data are plotted in green. Stream and runoff data are plotted in blue.
   a. Storm deuterium fluctuates most widely early in the season,. The fluctuations diminish later in the year. Each storm's depth is indicated in percentages of the total for all eight storms.
   b. Early in the season both ground and surface water changes mimic the storms, however, the response is significantly dampened. Over the long range stream and ground water composition remains much more stable.
   c. Runoff from the forest floor and the seasonal stream are almost identical, indicating the immediate influence of precipitation.
   d. Response by surface water bodies to precipitation would be expected to result in isotope fluctuations of a similar range as in the concurrent storms. But since stream water is also affected by ground water the impact of precipitation in a stream is only muted.
   e. More so, ground water responses are much more muted due to mixing in a larger reservoir (shallow aquifer). Nevertheless these data are a strong indication of how precipitation enters the stream channel: either as open meadow precipitation or throughfall into the soil, into ground water and then into the stream channel.

Discussion

The observations made in the previous two diagrams have useful implications for using isotopes to study stream response to forest canopy changes.

The long term average deuterium level in the spring is -99 per mil, and is the same as in the well. This increased up to -90 per mil after the first major storm, only to return to the long term average within 30 days. Presumably ground water composition is determined by the long term average recharge composition, in this case forest canopy throughfall.

The spring is perennial and is presumably fed by a larger aquifer system, probably the same as the well.

The long term average spring O-18 and deuterium is -13.82 and -99.16, which is significantly lower than the seasonal throughfall averages in Table 3. On the other hand, the stream and runoff averages are significantly higher. In other words:

1. The spring discharges a mixture of ambient ground water and new seasonal recharge. Given the large aquifer volume, the long term ground water composition is relatively stable (samples between March 2005 and June 2006), however, in the early storm season it is affected significantly by precipitation (infiltration).
2. Deuterium in the seasonal stream and runoff is for the most part also relatively constant around -89 per mil, except for the temporary increase early in the season. Presumably the stream channel is affected by ground water and due to its much smaller 'volume' its composition is much more susceptible to precipitation.

The estimated changed isotope composition for only those stations with less than 35% canopy density are plotted in Figure 10 and Figure 11. The observed 3 storm station average is indicated as a horizontal red line in Figure 11 (far left). As expected it fairly closely coincides with the average ground water composition. The observed deuterium from the stations less than 35% is shown as a purple horizontal line. To identify the effect canopy thinning to ground and stream water isotope signature would encompass to convincingly demonstrate a change of that magnitude in a spring, well or stream.

To accomplish this one would have to collect at least one years' worth of ground water and baseflow data before and after treatment. Since the estimated isotope shift is well outside the lab measurement error in Table 3, it is conceivable that the shift can be detected. In larger watersheds it may require more than one year's worth of post-thinning data due to greater subsurface water travel times. Hopefully, this can be demonstrated in ongoing thinning projects, if not areas affected by wildfires.

Recommendations for further research

While the data analysis conducted so far is adequate for the interim a number of further steps are beneficial:

1. Further data analysis:
    a. Storm depth data measured in the meadow are probably too low, and should be corrected via double-mass-plot using precipitation gauge data collected at the Mohawk Ranger Station.
    b. One important further step will be non-parametric statistical testing of correlation (Spearman's or Kendall's rank correlation) to verify increasing significance of canopy interception with storm depth.
    c. Lab analysis of the remaining four storm's throughfall samples is recommended since it may shed considerable light on the evaporation process during interception of snow.
    d. Sample and analyze tree tissue. Water in tree tissue is derived form the unsaturated zone that the tree's root tap into. In other words by obtaining isotope signatures from tree tissue at each station it is expected that thereby one can determine a long-term seasonal average for each station.
2. Further field data:
    a. Part of this watershed has been logged as part of fire safety thinning operation. It would be interesting to continue stream and ground water isotope data for pre- and post-logging comparison.
    b. Correspondingly an effort should be expended on collecting isotope data from stream and springs with capture zones under extensive thinning or burn areas. Considering that isotope data are comparatively cheap, most expenditure would be associated with traveling. On the other hand, automated samplers may significantly ease access problems during the winter.
    c. Identify improved means of determining canopy densities. Though the connection between canopy densities, throughfall depth and isotope enrichment has been established the confounding factors are not understood at this point.
3. Conduct a literature search. So far this work is in its entirety a field study. But the results need to be tied into other researchers' work by means of literature search.
4. The findings made in this study should be tested in other areas, preferably in areas slated for thinning projects, if not areas affected by wildfires.

Bibliography

Bohm, B., 1997: Precipitation Loss due to Tree Canopy Interception and Evaporation in a Pine Forest, Eastern Plumas County, California. Field Measurements and Data Analysis. Technical Summary Report prepared by Burkhard Bohm, Plumas Geo-Hydrology. July 26, 1997.

J.M. Bosch and J.D. Hewlett, 1982, a review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55 (1982) 3-23, 3.

Attachment A: Measured throughfall depths

Canopy interception in a coniferous forest in eastern Plumas County, California

Throughfall data. Table entries are depths given in cm.

Date, sampling		19-Dec-05	22-Dec-05	30-Dec-05	01-Jan-06	03-Jan-06	22-Jan-06	26-Feb-06	25-Mar-06	Rain, aver.	Snow, aver	Total Throughfall	% meadow precip
	time	13:45	22:00	16:25	10:30	14:15	11:30	15:30	09:30				
Storm type:		S/R	R	R	R	S	S	S	R				
isotope data?		yes	yes	no	yes	no	no	no	yes				
	Can. density	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	TF, cm	
Storm depth of total		11%	14%	22%	19%	7%	4%	2%	21%	77%	23%	100%	
Meadow	10%	8.2	10.8	16.6	14.6	5.1	2.8	1.2	16.1	13.3	3.0	**75.4**	100%
G	26%	7.4	9.5	13.9	12.7	3.8	3.8	1.1	6.9	10.1	2.9	59.2	78%
M	27%	6.8	7.9	11.7	11.0	3.9	2.7	1.7	8.7	9.2	2.8	54.5	72%
H	41%	6.1	8.6	13.0	11.3	4.3	3.4	0.8	11.4	10.1	2.8	58.8	78%
I	42%	6.9	7.4	12.6	12.1	5.2	4.7	0.9	12.5	10.3	3.6	62.4	83%
F	47%	9.7	9.2	13.8	13.5	6.5	6.9	1.7	12.1	11.6	5.0	73.3	97%
P	52%	6.6	6.7	*9.0*	9.7	4.2	3.3	1.9	11.7	8.8	3.2	53.2	71%
Q	53%	5.9	8.7	*13.1*	11.0	5.2	4.3	0.8	12.1	10.2	3.4	61.2	81%
B	58%	5.0	7.6	10.1	10.3	3.9	5.4	0.7	11.1	8.8	3.4	54.1	72%
K	58%	5.9	8.8	13.0	11.9	4.8	3.9	0.3	11.9	10.3	3.0	60.5	80%
C	59%	8.6	***7.4***	10.1	12.4	9.4	2.8	1.6	10.4	9.8	4.6	62.6	83%
J	61%	7.0	8.8	12.5	11.9	4.1	2.4	0.7	10.8	10.2	2.4	58.2	77%
N	63%	7.2	9.6	12.0	12.1	4.7	2.4	0.6	11.3	10.4	2.6	59.8	79%
L	65%	4.9	6.2	9.3	8.2	3.2	3.6	0.8	11.6	8.0	2.5	47.8	63%
R	67%	6.1	6.0	8.4	8.4	3.4	2.1	1.2	10.9	8.0	2.2	46.6	62%
T	80%	5.8	8.0	*12.4*	12.2	4.2	3.4	1.0	12.1	10.1	2.9	59.2	78%
A	81%	5.9	6.1	8.2	8.9	2.9	1.7	1.5	10.0	7.8	2.0	45.2	60%
O	86%	6.7	7.9	10.4	10.9	3.8	4.5	1.5	10.3	9.3	3.3	56.1	74%
S	87%	5.8	8.2	12.4	11.6	4.4	3.6	0.2	13.2	10.2	2.8	59.5	79%
E	89%	7.7	7.3	10.1	10.2	3.8	1.0	1.6	9.7	9.0	2.2	51.5	68%
D	91%	6.4	5.7	7.9	9.3	3.1	0.6	1.1	8.2	7.5	1.6	42.3	56%
Average/station:	**62%**	6.7	7.9	11.4	11.2	4.5	3.3	1.1	11.1	9.7	3.0	57.2	
TF Range per storm, cm		4.8	3.9	6.0	5.3	6.4	6.3	1.7	6.4	4.2	3.4	33.1	
station avg/Meadow, %		82%	73%	69%	77%	88%	118%	88%	69%	73%	97%	76%	
			total in meadow								75.4	cm	
			total average throughfall in stations								56.3	cm	
			meadow versus forest								134%		

Attachment B: measured stable isotope data from throughfall stations.

Forest Canopy Interception Study, Blairsden, Plumas County, CA

Isotopes in water data, Oxygen-18 and Deuterium.

					total:				
Storm depth, cm	8.2	10.8	14.6	16.1	49.7				
% of all 8 storms	11%	14%	19%	21%	66%				
Date sampled	19-Dec	22-Dec	01-Jan	25-Mar		19-Dec	22-Dec	01-Jan	25-Mar
storm type	S	R	R	R		S	R	R	R
Station	O-18	O-18	O-18	O-18		D	D	D	D
Meadow	-11.34	-9.47	-15.1	-13		-73.2	-66.4	-119.6	-91.4
G	-11.57	-9.43	-15.3	-13.63		-76.3	-67.1	-120	-95.8
M	-11.79	-9.54	-15.62	-12.83		-78	-68.4	-123.3	-90.8
H	-11.3	-9.73	-15.02	-13.3		-73.5	-68.8	-118.9	-93.5
I	-11.27	-9.71	-15.26	-12.38		-72.5	-66.5	-120.3	-87.2
F	-11.96	-9.45	-15.07	-12.54		-79	-63.6	-118	-87.4
P	-11.87	-9.59	-15.36	-12.11		-77.7	-63.8	-121.3	-87.1
Q	-10.45	-9.62	-15.12	-11.98		-65.5	-67.4	-120.1	-85.8
B	-10	-9.64	-14.66	-13.09		-65.3	-66.2	-115.6	-90.7
K	-10.35	-9.44	-15.21	-12.49		-66.4	-67.2	-119.7	-88.8
C	-11.9	-9.53	-15.56	-11.77		-79.7	-65.4	-120.1	-82.3
J	-11.1	-9.55	-15.26	-12.28		-71.5	-66.1	-120.5	-87.1
N	-10.96	-9.62	-14.9	-12.02		-71.9	-66.6	-118.2	-85.8
L	-11.14	-9.56	-14.82	-13.15		-71.7	-66.8	-116.6	-92.9
R	-11.37	-9.49	-15.91	-12.18		-74.9	-66.1	-124.9	-86.3
T	-10.6	-9.35	-15.07	-11.75		-68.3	-66.6	-118.9	-82.4
A	-11.3	-9.72	-15.1	-12.02		-75.4	-68.1	-117.8	-84.8
O	-10.57	-9.46	-15.16	-12.33		-69.9	-66	-120	-84.1
S	-9.84	-9.47	-15.55	-12.31		-63.6	-66.4	-122.4	-87.6
E	-12.13	-9.72	-15.39	-11.88		-80	-65.4	-120.6	-83.8
D	-11.9	-9.42	-15.04	-11.15		-79.6	-64.6	-117.6	-79.1
average per station	-11.17	-9.55	-15.22	-12.36		-73.04	-66.36	-119.74	-87.17
avg CD<40%	-11.6	-9.5	-15.3	-13.2		-75.8	-67.3	-121.0	-92.7
avg CD>40%	-11.1	-9.6	-15.2	-12.3		-72.6	-66.2	-119.5	-86.5
>40%/<40%	96%	101%	99%	93%		96%	98%	99%	93%

Attachment C: Canopy measurements

Canopy density measurements

Canopies were photographed with a wide angle lens on a digital camera, looking up. The camera was placed stationary and horizontal facing up to zenith, using a small contractor's level, arranged such that the top of the image faces north, and the right side to the west (!), etc.

Images were downloaded and processed with the Adobe Photoshop Elements 2.0 software. Total image size was 307200 pixels. The purpose of processing was to estimate canopy density for each station. This was accomplished by using the 'Magic Wand Tool', clicking either on the sky portion or on the canopy portion of each image. Pixels were counted using the 'image- histogram' feature. Tolerance levels were as a rule set to 10% when estimating percent blue sky, and 100% when relying on the dark color of canopy, branches, trunk, etc. However, tolerance levels had to be raised for the sky pixel counts when partial cloud cover occurred.

The pixel counts were entered into a spreadsheet to calculate the canopy densities for each station.

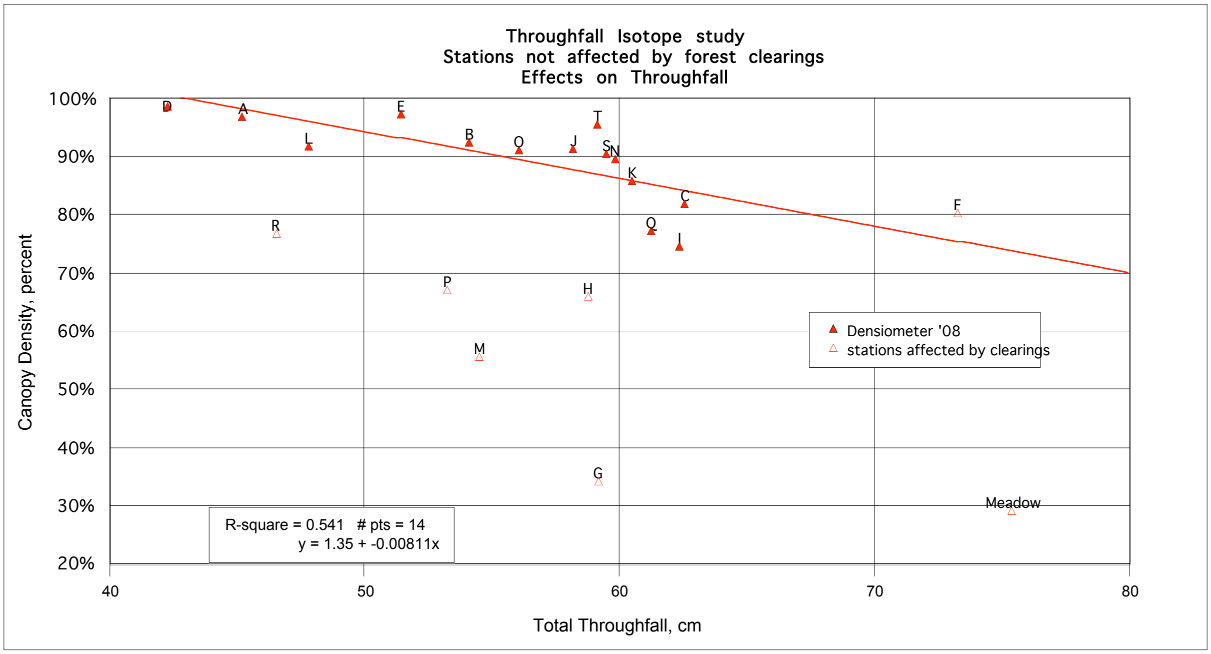
Attachment D: Canopy data

Canopy interception in a coniferous forest in eastern Plumas County, California

Canopy data

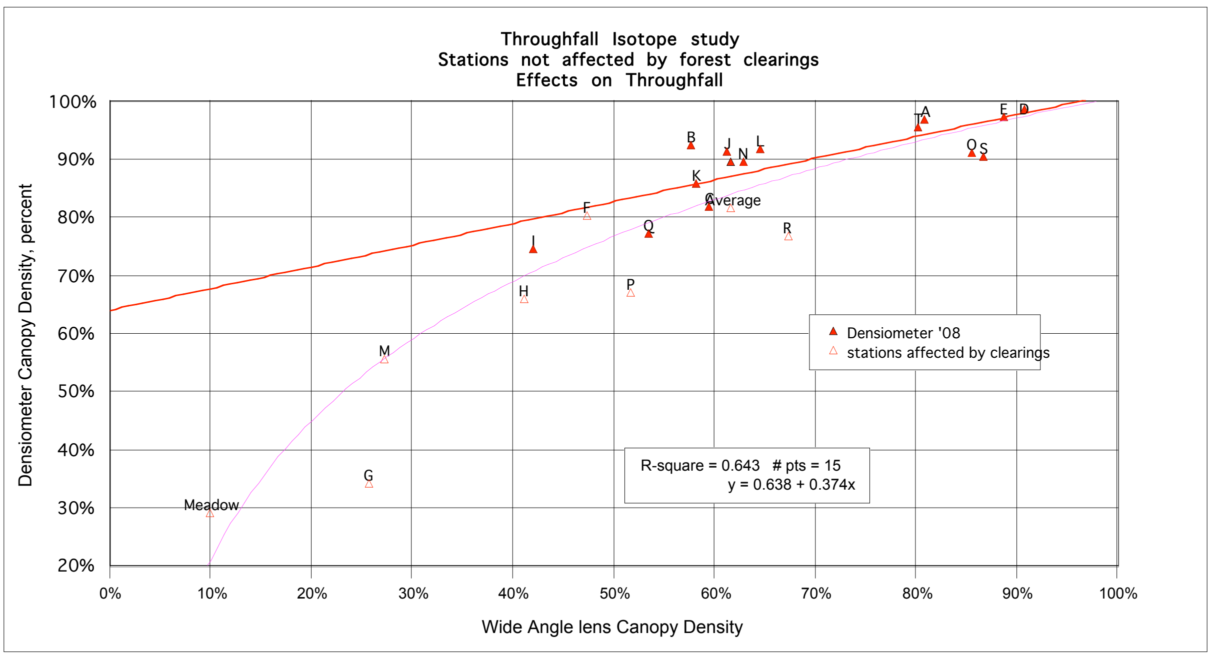
	Canopy densities										
Station	**regular lens**	**Wide-angle lens**	**Densiometer '08**	**aspect**	**clearing?**	**Rain, aver., cm**	**Snow, aver., cm**	**All aver., cm**	**Total Throughfall, cm**	**O-18, avg.**	**Deuterium, avg.**
Meadow	5%	10%	29%		yes	13.3	3.0	8.1	75.4	-12.23	-87.7
G	3%	26%	34%	N	yes	10.1	2.9	6.5	59.2	-12.48	-89.8
M	15%	27%	56%	N	yes	9.2	2.8	6.0	54.5	-12.45	-90.1
H	34%	41%	66%	N	yes	10.1	2.8	6.5	58.8	-12.34	-88.7
I	31%	42%	75%	N	no	10.3	3.6	7.0	62.4	-12.16	-86.6
F	44%	47%	80%	N	yes	11.6	5.0	8.3	73.3	-12.26	-87.0
P	40%	52%	67%	S	yes	8.8	3.2	6.0	53.2	-12.23	-87.5
Q	54%	53%	77%	S	no	10.2	3.4	6.8	61.2	-11.79	-84.7
B	71%	58%	92%	N	no	8.8	3.4	6.1	54.1	-11.85	-84.5
K	58%	58%	86%	N	no	10.3	3.0	6.7	60.5	-11.87	-85.5
C	50%	59%	82%	N	no	9.8	4.6	7.2	62.6	-12.19	-86.9
J	52%	61%	91%	N	no	10.2	2.4	6.3	58.2	-12.05	-86.3
N	57%	63%	89%	N	no	10.4	2.6	6.5	59.8	-11.88	-85.6
L	69%	65%	92%	N	no	8.0	2.5	5.3	47.8	-12.17	-87.0
R	55%	67%	77%	S	yes	8.0	2.2	5.1	46.6	-12.24	-88.1
T	68%	80%	95%	S	no	10.1	2.9	6.5	59.2	-11.69	-84.1
A	84%	81%	97%	N	no	7.8	2.0	4.9	45.2	-12.04	-86.5
O	71%	86%	91%	N	no	9.3	3.3	6.3	56.1	-11.88	-85.0
S	77%	87%	90%	S	no	10.2	2.8	6.5	59.5	-11.79	-85.0
E	76%	89%	97%	N	no	9.0	2.2	5.6	51.5	-12.28	-87.5
D	77%	91%	99%	N	no	7.5	1.6	4.5	42.3	-11.88	-85.2
Average	54%	62%	82%								
excl. meadow											

plot



Throughfall Isotope study
Stations not affected by forest clearings
Effects on Throughfall
100%
90%
80%
70%
60%
50%
40%
30%
20%
Canopy Density, percent
40
50
60
70
80
Total Throughfall, cm
D
A
L
R
E
P
B
M
O
J
T
S
N
H
G
K
Q
C
I
F
Meadow
Densiometer '08
stations affected by clearings
R-square = 0.541 # pts = 14
y = 1.35 + -0.00811x

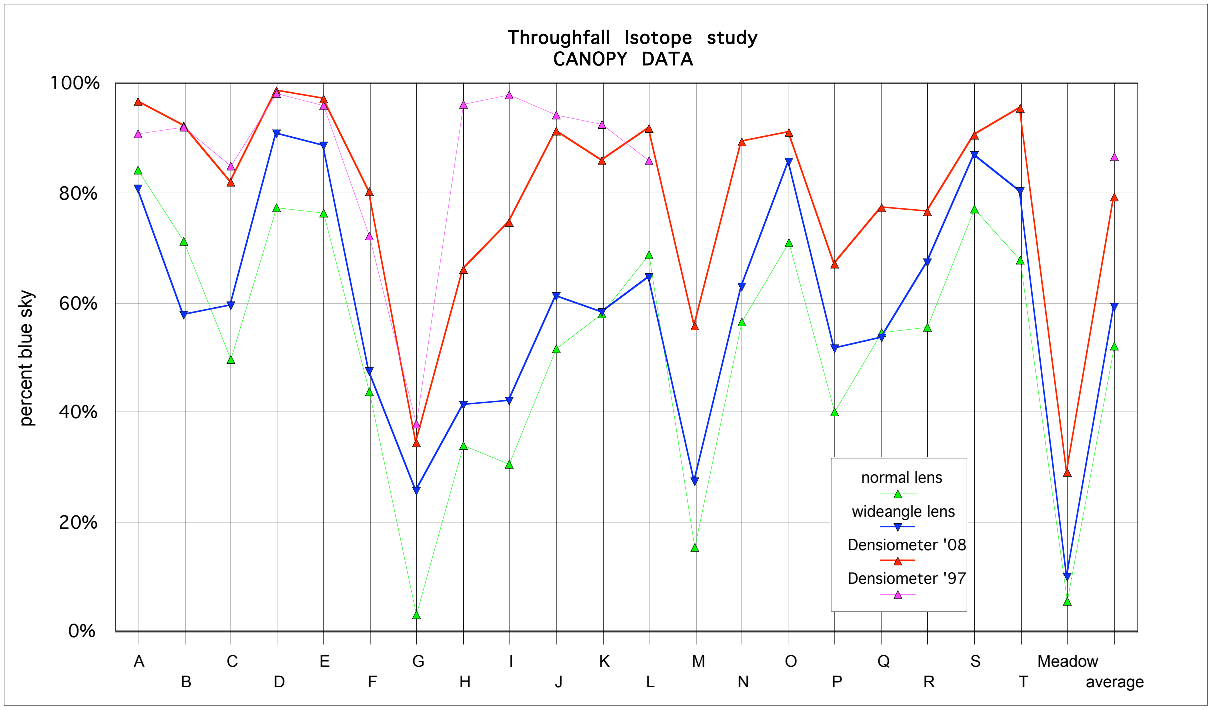
Plot



Throughfall Isotope study
Stations not affected by forest clearings
Effects on Throughfall
100%
90%
80%
70%
60%
50%
40%
30%
20%
Densiometer Canopy Density, percent
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Wide Angle lens Canopy Density
Meadow
G
M
H
I
F
P
Q
K
B
J
N
L
Average
R
T
A
O
S
E
D
Densiometer '08
stations affected by clearings
R-square = 0.643 # pts = 15
y = 0.638 + 0.374x

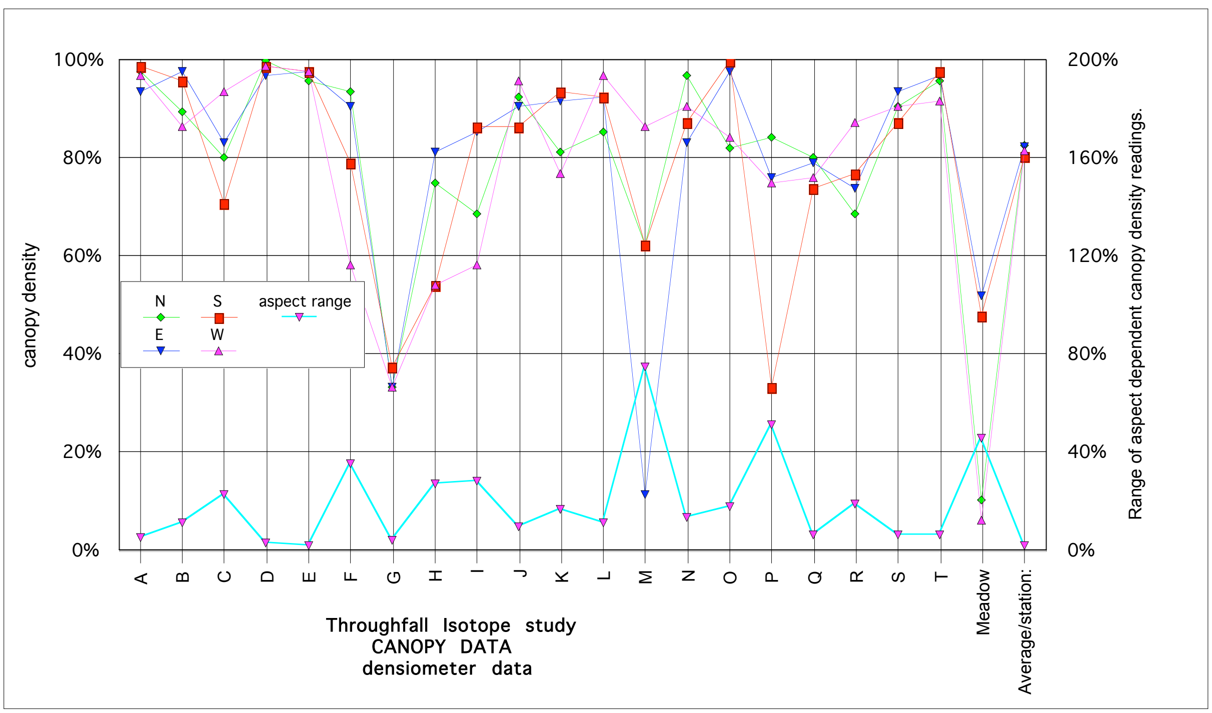
P

P



Throughfall Isotope study
CANOPY DATA
percent blue sky
100%
80%
60%
40%
20%
0%
normal lens
wideangle lens
Densiometer '08
Densiometer '97
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
Meadow
average

P



canopy density
100%
80%
60%
40%
20%
0%
Range of aspect dependent canopy density readings.
200%
160%
120%
80%
40%
0%
N
S
aspect range
E
W
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
Meadow
Average/station:
Throughfall Isotope study
CANOPY DATA
densiometer data