Preliminary Estimate of Evapotranspiration from Black Rock Forest, 1994

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Introduction

The Black Rock Forest experimental site presents an ideal opportunity for the Columbia community of scientists to study chemical, physical and biological dynamics in a "pristine" watershed near New York City. A number of potential research subjects have been investigated ranging from alterations in stream chemistry as related to atmospheric deposition, to the potential for the introduction of cryptosporidium in NYC's drinking water, to estimating the size of the potential carbon sink related to eastern hardwood forests. Many of these studies require fairly accurate estimates of various components of watershed hydrology, such as the amount of incoming precipitation lost to evapotranspiration or the decrease in tree carbon uptake due to water stress. Dynamic simulation models are the best tools we have for making these estimates using commonly measured meteorological variables. This report is the result of a preliminary attempt to model the hydrology of the watershed at Black Rock Forest for 1994. Observed streamflow data for two catchments within the watershed provide a basis for assessing the accuracy of the simulations. Comparison of observed and modeled data, and discussion of areas requiring improvement are presented.

Materials and Methods

Climate and Evapotranspiration

An estimate of potential and actual evapotranspiration, deep drainage and surface runoff for 1994 at the Black Rock experimental forest was made using the GAPS simulation environment (Riha et al, 1994). The GAPS model is designed to simulate hourly energy balance, water flux and growth of a homogeneous plant canopy, and was originally intended for crop growth and yield simulation. A number of different equations are available for estimating evapotranspiration and soil water flux, depending on data availability and model appropriateness. We chose the Priestley-Taylor method (Priestley and Taylor, 1972) of modeling evapotranspiration (ET), which assumes that ET is proportional to net radiation and uses an empirical coefficient to account for plant-dependant surface resistances. In the case of smooth, well-watered crop canopies, the Priestley-Taylor performs quite well, but it is generally less appropriate for tall, rough forest canopies. Our model presents the option of using the more-physically based Penman-Monteith equation for modeling ET (Monteith, 1981) which includes the surface resistances explicitly, but requires that the aerodynamic resistance of the plant canopy either be calculated (requiring wind speed) or input and that the plant minimum stomatal resistance also be known. We felt that lack of measured parameters necessary to use the Penman model made it inappropriate for this preliminary study. Results will be discussed in this context.

Daily on-site precipitation values for 1994, with daily maximum and minimum temperature and solar radiation from the near-by site of Millbrook, were used as model inputs.

Forest Characterization

Using the Priestley-Taylor equation for estimating evapotranspiration, the only surface characteristic taken into account is leaf area index (LAI), which is used to partition ET into soil evaporation and plant transpiration. Two plant cover types were modeled which represent the forest types in the two test catchments. For the Cascade Brook catchment, we used plant input parameters representative of a pure deciduous hardwood cover which was assumed to leaf out instantaneously on day 130 with a leaf area index (LAI) of 5 m^2m^{-2}. Leaf fall occurred on day 295. These dates are the mid-points of the periods of observed leaf out and leaf fall in 1994. For Canterbury Brook, we modeled a mixed hardwood deciduous (2/3) and coniferous (1/3) forest with hardwoods maintaining an LAI the same as in the pure stand and conifers averaging an LAI of 2.5 m^2m^{-2} throughout the year. Thus, the effective LAI at Canterbury Brook during the summer months was 7.5 m^2m^{-2}.

Soil Profile and Water Flux

The soil was defined as a shallow glacial till with layer characteristics based on data from records of soil excavations performed previously in the watershed. The model soil was divided into 9 layers and reached 0.61 m. Bulk density and occurrence of coarse fragments increased with depth. Although most of the watershed at Black Rock is probably underlain with impermeable bedrock, our model assumes that the soil is free draining at the bottom. In reality, contributions to streamflow travel considerable distance laterally through and across the landscape, whereas our model only simulates water and energy fluxes in the vertical dimension. We therefore summed runoff and modeled drainage from the bottom of the profile for our estimate of streamflow contributions. A capacitance-type, or "bucket" model of soil water flux was used for these simulations. This model assumes that water movement from one soil layer to the next is a function of soil texture and water holding capacity as defined by saturated water content, field capacity or a drained upper limit, a lower limit extractable by plant transpiration, and rate-limiting drainage coefficients (Jones and Kiniry, 1986). This simple model was chosen over the more complex numerical approach using the Richards equation because of uncertainty in parameterization of soil characteristics as well as the likelihood that the capacitance approach is satisfactory in a thin, rocky, fast-draining soil such as that found at Black Rock (Corwin et al, 1991; Radulovich et al, 1992).

Simulations and Observed Data

Simulations were run with a one-hour timestep, assuming precipitation was distributed evenly across each 24-hour period during days in which there was rain. The observed streamflow data for Cascade and Canterbury Brooks was converted from weekly observations of cubic feet per second to the mm day^{-1} equivalent over each square meter of the 135 ha and 266 ha of landscape in each catchment, respectively, that would have produced this volume of flow. Results presented are all in units of mm day^{-1} for ease of comparison.

Results

Model Comparison with Observed Streamflow Data

Modeled streamflow is under predicted in early spring at both the pure deciduous and mixed forest sites (Fig. 1a & 1b). This may be related to melting of the snow pack although records indicate that the snow pack was gone by the time of the first stream observations at week 16. At present, GAPS does not handle snow as a separate storage and this may be critical for accurate estimates of spring hydrology at Black Rock. Summing the total daily streamflow from week 22 forward which avoids the early spring period, predictions at Cascade Brook underestimate the observations by roughly 18%, while the Canterbury Brook predictions are more than 40% lower than observed (Table 1). This implies that the simulations are overestimating evapotranspiration which is the sum of rainfall intercepted by the canopy, plant transpiration and soil evaporation. There is indication that the observed streamflow values, particularly at Canterbury Brook, may be high based on the fact that precipitation over this same period is only 998 mm. If the streamflow values are correct, it would mean that 73% of the precipitation falling on the Canterbury Brook catchment is recovered in streamflow while only 27% is lost to ET. For a forested catchment with summer rainfall this would be highly unusual. It is also contrary to expectations that the streamflow per unit of catchment area is considerably higher in the catchment with conifers which intercept rainfall and contribute to transpiration year-round as opposed to the deciduous forest catchment. None the less, there appears to be no pattern to the discrepancies, with both sites displaying both over and under predictions in both moderate and extreme events, based on precipitation (Fig. 2).

Table 1

Total Streamflow Equivalent (mm)
Week 22 to 52
Period Precipitation = 998 mm

	Observed	Modeled
Cascade Brook	581	476
Canterbury Brook	728	434

be dependent on canopy architecture, leaf type, and particularly, rainfall intensity and duration (Leonard, 1967; Dunin et al, 1985). Assumptions used in the model with respect to this process need further validation and refinement. However, the results presented here are in line with commonly observed losses due to interception (Stewart, 1977).

Discussion and Conclusions

Comparisons of observed and modeled streamflow in two catchments at the Black Rock Forest indicate that simulations may overestimate evapotranspiration from the catchments. Discrepancies between observed and modeled data, as well as further analysis of observed data bring into question the accuracy of the observed streamflow rates or possibly catchment delineation. The current method of measuring streamflow at Black Rock is somewhat primitive and calculations indicate that streamflow may be overestimated, particularly at the Canterbury Brook site. This suggests that improved measurement methods may be necessary in the future. However, without further observations, we will assume that the error lies in the simulations.

The poorest agreement between model and observed data occurs in early spring when snowpack may be influencing runoff. This important component of the water budget will have to be incorporated into the model for accurate predictions. Excluding the period of obvious snow influence, the largest discrepancies still occur in late spring and early fall before and after the period when the canopy has complete leaf cover. This is the period when soil evaporation dominates at the deciduous site, Cascade Brook, where soil surface is exposed before and after canopy development. At the mixed deciduous and coniferous site, soil evaporation is low, but rainfall interception by the conifers in spring and fall may be over estimated. One factor in both the estimates of soil surface evaporation and canopy interception losses is the duration of the rainfall event during the day. If the canopy remains wet all day with a gentle rainfall, evaporative losses will be greater than if the rainfall event is short and heavy. Our precipitation data does not include this information but there may be ways of estimating rainfall duration from historical data.

As was discussed earlier, the Priestley-Taylor equation used to calculate hourly ET does not take the surface aerodynamic characteristics into account. It has been found that under dry conditions, using the Priestley-Taylor method with an α value of 1.27, the value commonly used in estimates of ET from smooth crop surfaces, ET is overestimated in coniferous forests because surfaces resistance tend to be very high in forests compared to crops. When the canopy is wet, ET is greatly underestimated (Stewart, 1977; Shuttleworth and Calder, 1979). We used an α value of 1.1 on the assumption that the canopy will predominantly be dry. In our data, the period with the greatest difference in modeled and observed streamflow correspond to the periods of low rainfall in 1994. Again, this analysis is dependent on rainfall distribution and the number of days when the canopy is wet, rather than absolute amounts. However, it supports the necessity of investigating rainfall intensity and distribution with respect to soil and canopy evaporation.

Ten-day running means of daily modeled streamflow were used to smooth the weekly values shown in Figures 1a and 1b, since our model does not account for the time necessary for runoff and drainage to reach the brook. It appears that further smoothing of the modeled results would improve the prediction, but this may be handled more explicitly in the model. It is unclear what the source of the peak in observed streamflow data seen at both sites around week 44 may be. Precipitation events remained low and even during this time. Leaf fall took place between about week 40 and 44 and leaf litter on the soil surface may have inhibited water infiltration, increasing runoff for a short period.

Partitioning of Water Budget

The amount of water leaving the catchment as evapotranspiration versus runoff and deep drainage by month is shown for the two forest types in Figures 3a & 3b. The pattern is similar at the two sites but it can be seen that ET increases earlier and stays higher later in the season at Canterbury Brook, the catchment with some conifers which maintain transpiring leaf area all year. Similarly, streamflow in spring and fall is decreased as a result of increased losses from the catchment when conifers are present. Looking at the fraction of precipitation that leaves the catchment as evapotranspiration (Fig. 4), the general pattern is to increase as atmospheric demand increases toward the summer months. But when summer rainfall exceeds demand, excess water leaves the catchment as streamflow, decreasing the fraction leaving as ET.

Forest cover type influenced the partitioning of ET into soil evaporation, plant transpiration and water evaporating directly from the canopy during rainfall events. At Cascade Brook, the catchment with deciduous cover, ET was distributed approximately equally to each of the three components (Table 2). At Canterbury Brook, where some coniferous cover is present to intercept rain and transpire year-round, soil evaporation was reduced to less than half its value at the deciduous site, and transpiration and interception were increased to 40% and 47% of total ET, respectively. Canopy interception of rainfall, and its contribution to total ET, is known to

Table 2

Components of Annual Evapotranspiration (mm)

	Cascade Brook (pure deciduous)	Canterbury Brook (mixed deciduous and conifer)
Soil evaporation	240.5	105.5
Plant transpiration	243.0	326.8
Canopy Interception	215.2	384.6
Sums	698.7	816.9

Further improvement in model estimates of ET are likely to be gained by applying the Penman-Monteith model of ET, which considers canopy characteristics. This would entail making some representative measurements of stomatal conductance on the various tree types at Black Rock. In conjunction with this more mechanistic approach, more detailed data on leaf area indices with gradual canopy develoment, variation in soil characteristics and rooting habit, and further refinement of vegetation types in each catchment would improve our estimates. Other improvements in our model which will be necessary for year-round estimates of water balance are the inclusion of snow as a discrete storage compartment on the soil profile, and aspect of the catchment.

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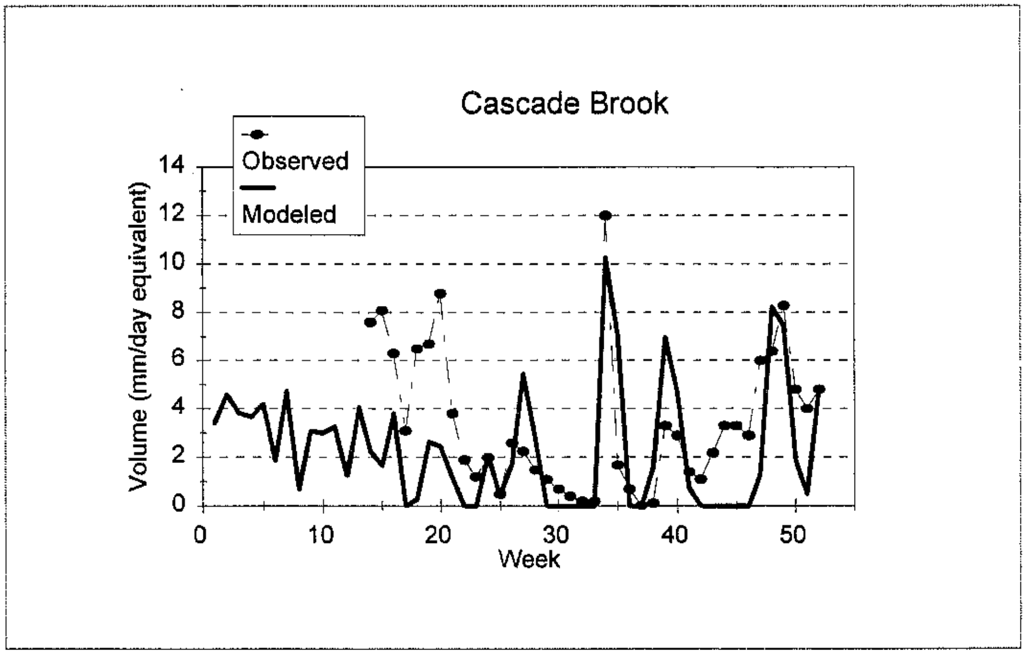
1a



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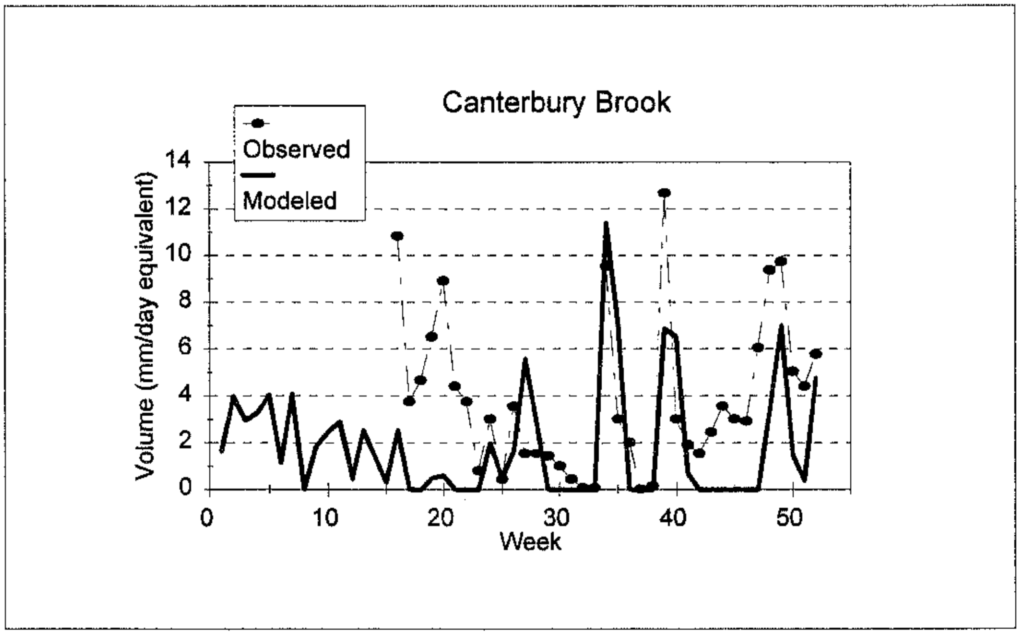


Figures 1a & 1b: Observed streamflow versus modeled streamflow for two catchments at Black Rock Forest in 1994

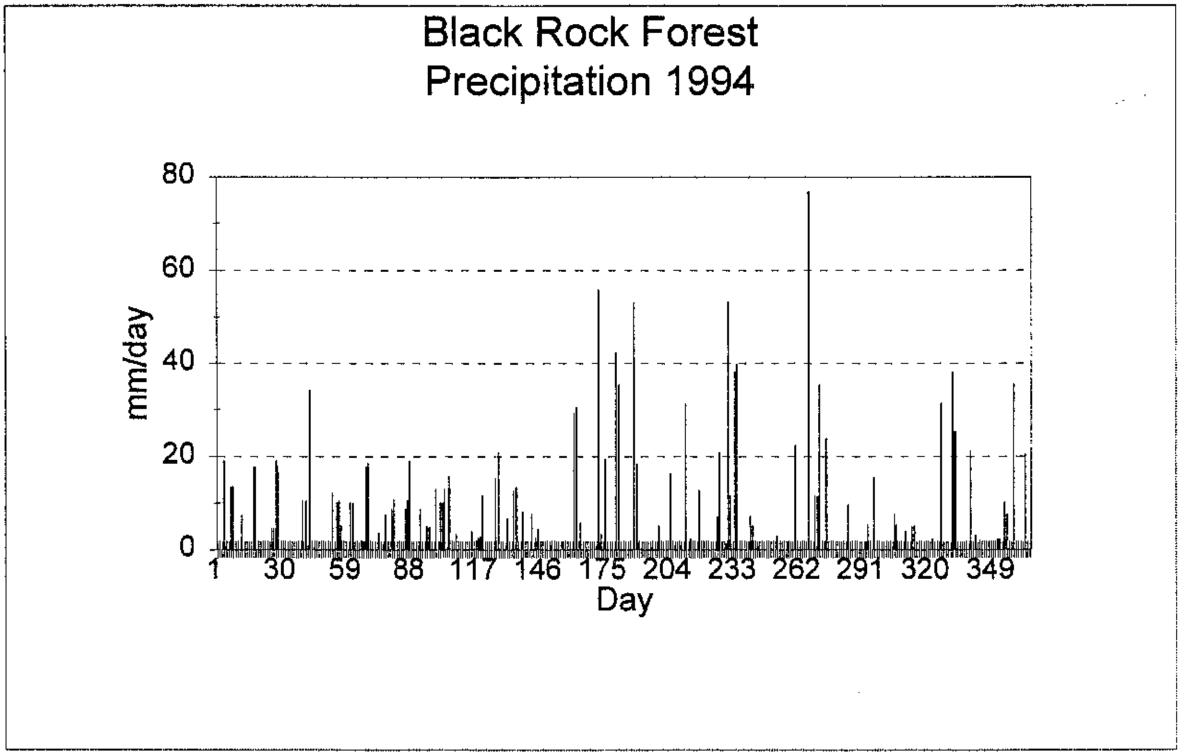
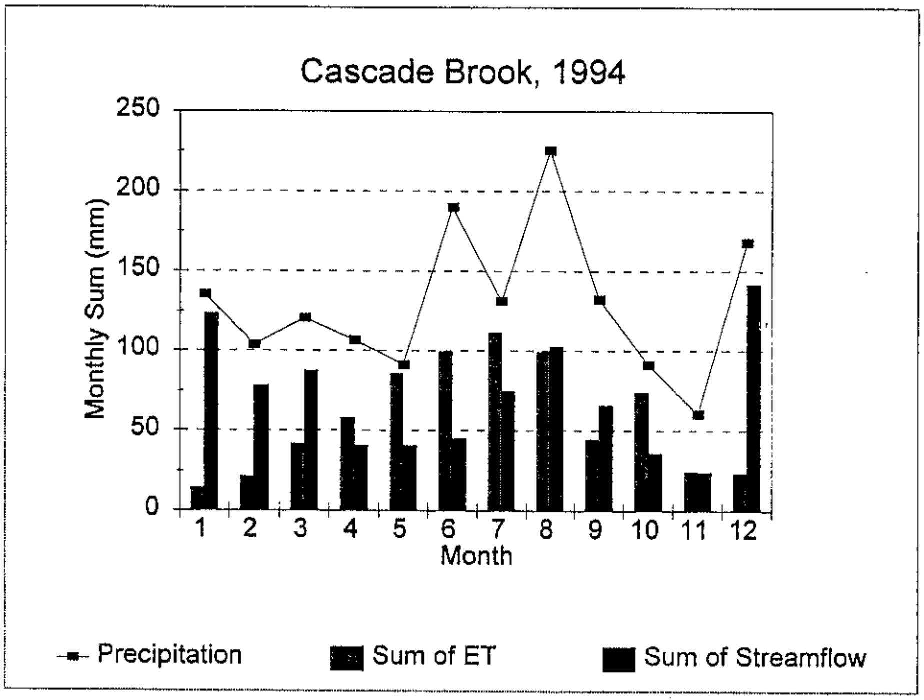
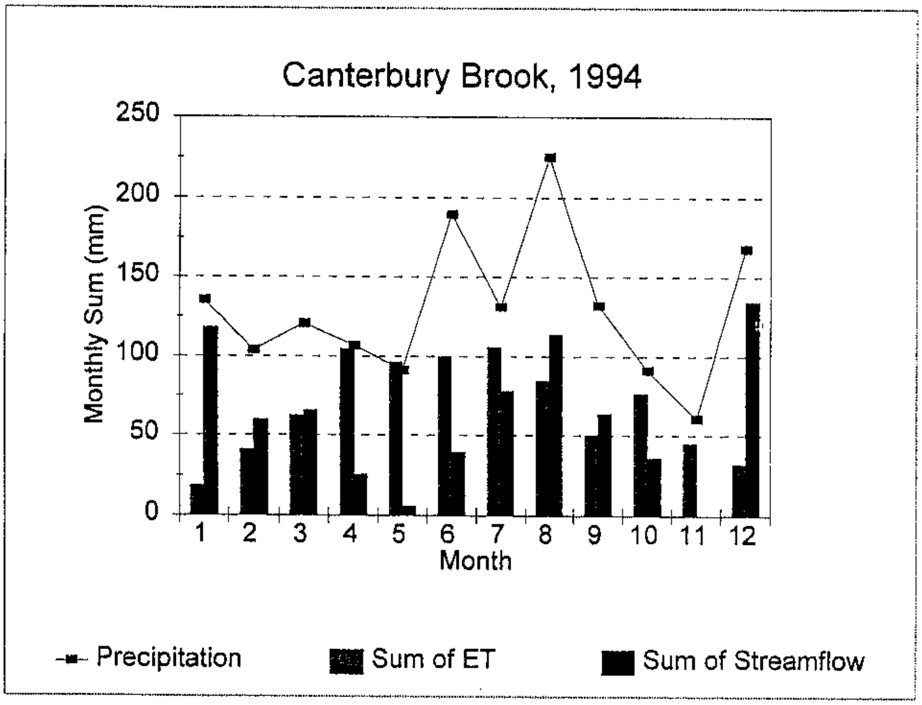


Figure 2: Daily Precipitation measured at Black Rock Forest for 1994



3a



3b

Figures 3a & 3b: Modeled partitioning of water budget into evapotranspiration and streamflow for 2 catchments at Black Rock Forest

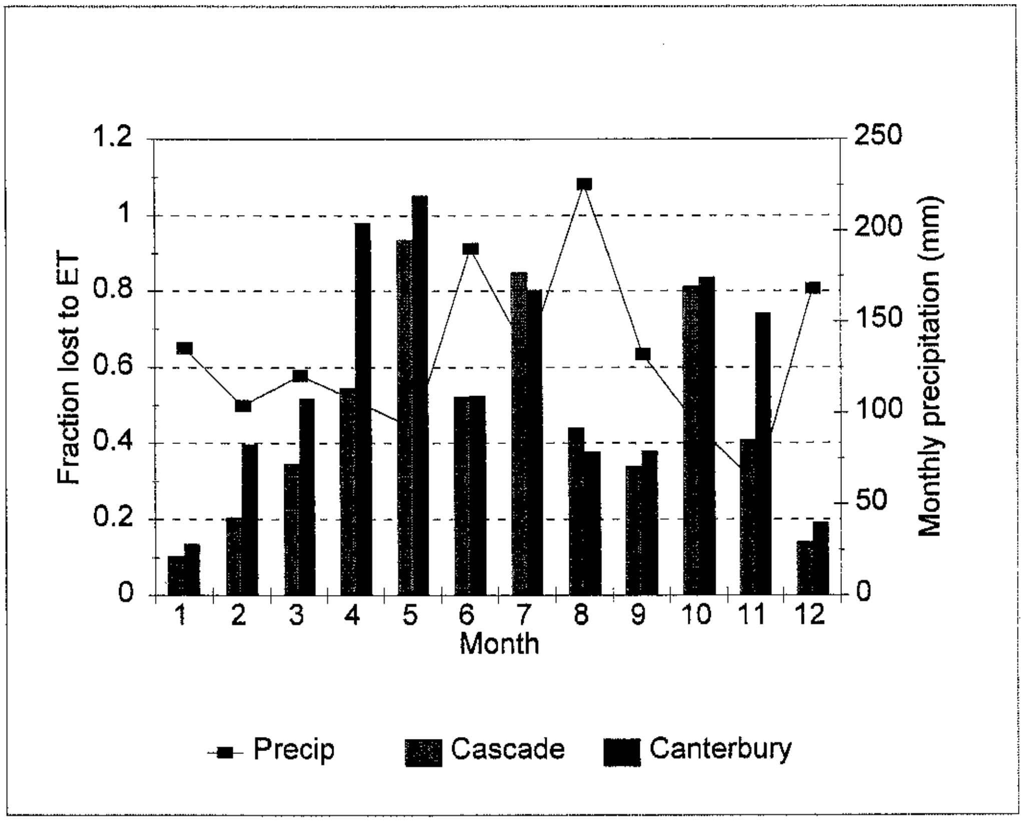


Figure 4: Fraction of incoming precipitation lost to evapotranspiration in two catchments at Black Rock Forest

Canterbury Brook
Monthly sums (mm)

month	PotEV	ActEV	PTrans	ActTrans	Precip	Drain	Runoff	WCC	WIn	Canopy Interception
1	5.3	5.3	1.8	1.8	135.6	92.4	25.6	-1	98.7	11.336
2	11.8	11.3	15.3	15.3	103.9	46.5	13.3	2.9	76	14.6
3	18.7	18.7	17.3	17.3	120.7	46.9	18.8	-8.2	75.4	26.5
4	33.4	19.2	37.9	37.7	106.7	21.1	4.5	-23.1	54.5	47.7
5	15.2	12.1	47.5	37.8	91.4	0	6	-11.2	39.1	46.3
6	3.2	2.7	92.4	34.5	190.0	12.8	26.8	50.4	100.7	62.5
7	3	3	99.5	71.5	131.3	16.3	62.1	-52.8	38.2	31.0
8	2.5	2.5	53.9	34.3	225.6	27.2	86.7	26.6	90.9	48.0
9	2.4	2.2	60.8	31.8	132.3	16.4	47.4	18.2	68.6	16.3
10	6.8	6.8	24.3	24.3	91.4	31.1	5	-21	41	45.4
11	13.3	12.4	15.7	15.5	60.7	0	0	15.1	43.5	17.2
12	9.3	9.3	5	5	168.148	102.9	31.5	1.6	118.8	17.8
Annual Sum	124.9	105.5	471.4	326.8	1557.714	413.6	327.7			384.614

Cascade Brook
Monthly sums (mm)

month	PotEV	ActEV	PTrans	Act Trans	Precip	Drain	Runoff	WCC	WIn	Canopy Interception
1	14.2	14.2	0	0	135.6	98.4	25	-1.7	111.2	0
2	33.2	20.6	0.3	0.3	103.9	68.6	9.7	4.7	93.8	0.386
3	54.6	41.4	0.3	0.3	120.7	66.4	21.1	-8	100.4	0
4	96	55.2	0.9	0.9	106.7	36.6	4.4	7.2	100.1	2.18
5	40.8	20.4	29.6	29.6	91.4	28.2	12.8	-35.1	43	35.64
6	11.7	6.7	92.3	47.3	190.0	19.8	25.5	45.2	119.1	45.392
7	12.4	9.4	99.4	71.1	131.3	19.5	55.3	-55	45.1	30.918
8	9.3	9.3	58.7	40.7	225.6	37.5	65.2	23.7	111.2	49.152
9	7.7	3.4	58	29.7	132.3	29.6	36.4	21.1	84.1	11.772
10	14.4	11.4	23.1	23.1	91.4	32.5	3.7	-18.8	48	39.734
11	39.2	24.8	0	0	60.7	24.1	0	11.7	60.7	0.006
12	25.9	23.7	0	0	168.148	119.9	22.08	2.4	146.2	0
Annual Sum	359.4	240.5	362.6	243	1557.714	581.1	281.18			215.18

WCC = Change in profile water content
WIn = Water entering the soil profile