2.6 ANNUAL WATER BALANCE OF HIGH ELEVATION FOREST AND CLEARCUTS

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1. INTRODUCTION

Forest cover influences the balance between input of water (precipitation) and output (evaporation and above and below-ground runoff) from the soil. Precipitation is intercepted by and evaporated from the forest canopy. Water also returns to the atmosphere by transpiration from the vegetation and evaporation from the soil surface. The forest cover reduces the rate at which snow melts and infiltrates into the soil (Adams *et al*. 1998, Spittlehouse and Winkler 2002, Winkler et al. 2005). The net effect of removing forest cover through harvesting, fire or defoliation is an increase in water content of the soil (Ziemer 1964, Hart and Lomas 1997, Adams *et al.* 1991, Elliott *et al.* 1998, Bahatti *et al.* 2000), an increase in the amount of water available for runoff, and a change in the timing of snow melt (Troendle and Reuss 1997, Winkler *et al.* 2005). Detailed studies of the various processes of the forest water balance are need to quantify these changes and to provided data to calibrate and test hydrologic models (Thyer *et al.* 2004).

This paper presents the annual water balances for forest and clearcut sites for November 2002 to October 2005. Measurements of snow accumulation and melt, evaporation and interception and soil characteristics were used in combination with a daily soil water balance model in a high elevation watershed in the Southern Interior of British Columbia, Canada.

2. METHODS

2.1 *Site Description*

The research took place in the 240 and 241Creek watersheds of the Upper Penticton Creek Watershed Experiment (49° 39’ 25”N, 119° 24’ 10”W) at 1620 to 1670 m elevation (Winkler *et al.* 2003). The watershed is typical of headwater streams in the drier Engelmann Spruce – Subalpine Fir Zone (Lloyd *et al.* 1990) on the Okanagan Plateau, southern interior of British Columbia. The snow pack starts to develop between late October and early November and disappears between mid May and early June depending on the elevation and year. Peak snow pack water equivalent ranges from 250 to 450 mm. The forest consists of 125-year-old lodgepole pine with Englemann spruce ((*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt). Dominant and co-dominant trees are 15 to 22 m tall, stand density is 750-1000 stems ha^{-1}, canopy cover 40 to 50%. The forest floor is partially covered with a layer of lichens, moss, grouseberry and woody debris that is less than 0.2 high and with rhododendron bushes on wetter sites. The clearcuts were harvested in the winter of 2003/04 and had negligible plant cover for the three years of measurements. A large amount of coarse woody debris was left on the sites after harvest. Measurements in the three forest clearcut pairs (Sites A, B, C) in the lower half of the 241 Creek watershed started in May 2003. A fourth forest site (P7) has been monitored since 1997 in the 240 Creek watershed and is included in this analysis. All sites are on flat to gently rolling terrain except site C which is on a 15% slope.

Hemispherical photography was used to estimate plant area index (PAI) of the forest sites. Ten colour photographs were taken in each stand using a Nikon Coolpix camera. They were analysed using an interactive package to determine threshold for the cyan, magenta and yellow bands. A 45º cone around the zenith was used to determine PAI. No correction is made here to account for stems and branches to obtain leaf area index because the PAI is used for a relative comparison between sites. Canopy cover and plant area index were also determined at P7 using radiation penetration techniques based on the ceptometer (Fassnacht *et al.* 1994). Stand density and tree height was measured in a 50x50 m plot. The fraction of the surface covered by the understory (UAI) was determined from line transects (Groenevald 1997) using four 10-m transects with intersection points every 0.1 m.

Two soil pits were dug in each site to determine root zone depth, soil texture and stone content. Soils are coarse textured with high coarse fragment content (Cf) and a compacted layer or bedrock at 0.5 to 0.6 m. Hydrologic characteristics (soil water retention and saturated hydraulic conductivity) were determined on cores taken at 0.1-m-depths. The soil retention data were fit to the function $\psi = \psi_e \ (\theta/\theta_r)^{-b}$ where ψ is soil water potential (MPa), ψ_e is the air entry potential (MPa), θ is the average soil water content of the root zone (=W/z), W is mm water, z is the depth of the root zone (mm), θ_r is saturated water content (= soil porosity) and b is a function of the soil water retention curve (Campbell 1974, 1985).

2.2 *Weather Measurements*

The project weather stations consist of a forest and open pair at the base of 240 Creek watershed and a similar pair near the top of 241 Creek watershed. Air temperature and humidity, snow depth and snow and soil temperatures are measured at all sites and solar radiation, wind speed and direction and precipitation are measured in the open. A summer rainfall station was installed near two of the forest/clearcut pairs. Data were

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recorded as hourly averages and totals and as daily summaries using electronic data loggers. Precipitation as snow was obtained from hourly readings of the clearcut snow depth sensors (CSI UDG01 and SR50) and a snow density of 0.1 Mg m^{-3}. A third weather station about 5 km away from the main site had a large standpipe precipitation gauge with pump and pressure sensor, snow depth sensor and air temperature measurements. It provided measurements of precipitation during rain on snow events and was used to verify the snowfall data from the depth sensor at the main weather station in 240 Creek.

2.3 *Snow interception and snowmelt*

Snow interception by the forest sites was determined from 32-point snow surveys with a Federal snow tube over 0.5 ha (Spittlehouse and Winkler 1996) in the 240 Creek forest and adjacent open area. Snow melt during spring in the clearcut was determined from two snow melt lysimeters (Spittlehouse and Winkler 2004, Winkler *et al.* 2005). Snow melt in the forest was calculated from changes in snow depth from the depth gauge and the snow density from the snow surveys. In this case, conservation of mass is maintained for the pack as depth fall and precipitation occurs until a density of 0.38 is reached at which time snowmelt begins. The manufacturer suggests an accuracy of ±10 mm for the depth measurement. Our experience indicates that with careful quality checking an uncertainty of ±2.5 mm in daily melt can be achieved at peak densities. An error of 0.01 Mg m^{-3} in snow density results in an uncertainty of 2.5% in snow water equivalent, less than ±1 mm on the daily melt rate at peak melt. Combined measurement errors in depth and density likely result in an uncertainty of ±3 mm d^{-1} in melt. Any errors change the timing of melt peaks not the total amount of snow melt. The snow melt data from the 240 weather station were assumed to apply to all the clearcuts and those for the 240 forest to all forest sites. The melt rates were confirmed using snow melt modelling following Spittlehouse and Winkler (2004).

2.3 *Radiation Balance*

Albedo, radiation transmission and longwave radiative flux were measured at two forest stations during 2002 to 2004 using Kipp and Zonen CNR1 radiometers (Spittlehouse and Winkler 2004). This instrument separately measures the incident and reflected solar radiation and the longwave radiation from the sky and the surface. Downward longwave radiation (Epply pyrgeometer) and albedo (Epply pyranometer) was measured at a clearcut site during 2002 to 2004. These radiation instruments and the weather station solarimeter were inter-compared during early summer 2003 with the CNR1. The same albedo was used for the forest floor of all forests sites and another for the clearcuts. Hemispherical photography was used to determine the solar transmission and longwave view factors for modelling the radiation regime below the stands (Spittlehouse and Winkler 2004). Ten hemispherical photographs were taken in each stand and average transmission and view factors determined for the stands. Photographs were also taken at the location of the detailed radiation measurements at Upper Penticton Creek, combined with other data for different canopy covers (Spittlehouse unpublished data) and analyzed for transmission and view factor. These data compared well with the measured values from the CNR1.

Daily net radiation (Rn, MJ m^{-2} d^{-1}) of the forests is calculated with the following equations

$$Rn = S_g - a_f S_g + L_d - L_u \qquad [1a]$$

$$L_d = \varepsilon_s \sigma T^4 \qquad [1b]$$

$$L_u = 0.98\sigma T_a^4 \qquad [1c]$$

$$\varepsilon_s = (1 - 0.84n)\varepsilon_{clear} + 0.84n \qquad [1d]$$

$$n = (1 - S_g/S_{gclear}) \qquad [1e]$$

$$\varepsilon_{clear} = (0.53 + 0.206e_a^{0.5}) \qquad [1f]$$

$$S_{gclear} = 18.9 + 12.7(\sin[0.0172(DoY - 80)]) \qquad [1g]$$

where S_g is the solar radiation (MJ m^{-2} d^{-1}), a_f is the albedo (=0.12 for the forest), L_d is the downward longwave radiation (MJ m^{-2} d^{-1}), L_u is the upward longwave radiation (MJ m^{-2} d^{-1}) at the daily mean air temperature (T_a, K), ε_s is the sky emissivity, σ is the Stefan-Boltzman constant (4.9x10^{-9} MJ m^{-2} d^{-1} K^{-1}), T is the mean daily air temperature (K), n is the fraction of cloud cover, ε_{clear} is the clear-sky emissivity, S_{gclear} is the maximum clear-sky radiation at the ground for the day, DoY is the day of the year, the sine is in radians and e_a is the mean daily vapour pressure assumed equal to the saturated vapour pressure at the minimum air temperature.

Below canopy net radiation is calculated with S_g adjusted using a transmission coefficient (τ) derived from hemispherical photographs and varying through the year similar to equation 1g. Downward long wave (L_{ds}) is the sum of longwave from the sky and longwave from the canopy assumed to be at air temperature (L_{dc} =equation 1c), i.e., $L_{ds}=L_d(1-V_f)+L_{dc}V_f$, where V_f is the longwave view factor obtained from the hemispherical photographs.

2.4 *Rainfall Interception*

Interception loss is the difference between above-canopy rainfall and the sum of throughfall and stemflow. Five V-shaped throughfall troughs (6x0.1 m) and 5 stemflow collectors were continuously monitored using a data logger (Spittlehouse 1998) at two forested sites (P7 and site A). The P7 site has been monitored since 1997 and site A was installed in May 2004 adjacent to the forest water content measurements. Daily interception loss (I_i, mm d^{-1}) was calculated with

$$I_i = f\,(1-\exp(-gP)) \qquad [2]$$

where P is the daily rainfall (mm) and f and g are determined by fitting to the measured interception.

2.5 *Soil Water Content*

Biweekly measurements of soil water content were made during the snow-free season with time domain reflectometry. There were ten samples per treatment along a 100-m transect measuring the water content in the 0-0.5 m layer of the soil. A compact layer at 0.5 m restricts deep installation of the TDR wave guides rods and root distribution. Two of the forested sites (P7 and site C) and one clearcut (site C) also had ten 0-0.3 m measurements. Wave guides were 3 or 5 mm diameter stainless steel rods, 30 mm apart, with a shorting diode at the surface (Spittlehouse 2000). They were monitored with an Environmental Sensors Inc. MP917. Measurements of soil water content were made at the P7 forest in late March 2003, 2004 and 2005 prior to the start of the main period of snow melt.

2.6 *Site Water Balance*

The water balance equation links soil water content (W), precipitation (P), interception (I), infiltration (F=P-I), drainage from the root zone (D), evaporation from the soil surface (E_s) and plant transpiration (E_t):

$$\Delta W = F - E_t - E_s - D \qquad [3]$$

ΔW is the change in soil water content (mm) over time. During the winter period there is a delay in infiltration (P-I) until snowmelt, E_s is zero and water content changes depends only on D except where tree transpiration occurs during snow melt (Spittlehouse 2002). Values of E_s, E_t, and D were determined by modelling the water balance. The model was evaluated by matching simulated and measured water content during the snow-free season for all sites. There are periods when drainage dominates and others when evaporation dominates. The evaporation component of the model is calibrated during mid summer period when drainage is negligible. The drainage model is then calibrated for late spring/early summer with evaporation simulated with pre-calibrated evaporation model. This process is constrained by the fact that similar drainage and evaporation characteristics have to be used for all seven sites because they are all coarse textured stoney soils. The main differences between sites are the amount of vegetation cover (forest or bare clearcut) and coarse fragment content of the soil. The same characteristics must be used each year for a site.

The water balance model operates on a daily time step using solar radiation, air temperature and humidity, wind speed, snowmelt, rainfall and rainfall interception as input. The rainfall interception model (equation 2) was used for times outside of the measurement period and for stands with no measurements. Evaporation of interception was calculated with the Penman-Monteith equation (Monteith and Unsworth 1990, Spittlehouse 2003). Rain remaining on the canopy at the end of the day reduces interception for the next day.

Direct measurements of forest transpiration were made at the P7 forest site during 2000 and 2001 using sap flux sensors (Spittlehouse 2002). Daily tree transpiration was related to the daily maximum vapour pressure deficit (vpd_x) and fraction of extractable water in the root zone (θ_e) to give a function for modelling tree transpiration (E_t):

$$E_t = E_{tx} = 1.6/(1+18^*(\exp(-3^* vpd_x)) \qquad \theta_e>0.35 \qquad [4a]$$

$$E_t = E_{tx}{}^*(\theta_e/0.35)^2 \qquad \theta_e\leq 0.35 \qquad [4b]$$

$\theta_e = (\theta - \theta_r)/(\theta_{fc} - \theta_r)$ where θ_{fc} is the root zone water content (θ) at a soil water potential of 0.01 MPa. This function was adjusted to different stands by multiplying by the ratio of the plant area index of the stand to that for P7.

Evaporation from bare soil is calculated using an energy/soil water content limited model. In this model evaporation depends on the fraction of extractable water (θ_e) of a 50 mm surface layer. For $\theta_e > 0.9$, E_s equals the lesser of the daily potential evaporation and 3 mm d^{-1}. Below this value E_s declines exponentially to 0 at $\theta_e = 0$. Daily potential evaporation is calculated using the Priestley-Taylor equation, i.e., $E_p = \alpha(s/(s+\gamma)(Rn-G)$, where s and γ are the slope of the saturation vapour pressure curve (kPa $°C^{-1}$) and the psychometric constant (kPa $°C^{-1}$) at the daily air temperature, soil heat flux (G) is a function of net radiation (Rn) and α=1.26 for bare soil (Spittlehouse 1989). Water movement between this surface layer and the soil below is calculated using $k = k_r (\psi_1 - \psi_2)/0.05$, where ψ is the water potential (m of water) of the upper and lower layers (subscripts 1 and 2 respectively) (Campbell 1985). The maximum water content of the upper layer is constrained to minimise the instability that can occur in the water flow equation under high rainfall situations when using a daily time step.

Evaporation from below canopy vegetation (E_u) is the lesser of the daily potential evaporation and a soil limited rate equal to $\beta\theta_e$ (Spittlehouse 1989). In this case, α=1, θ_e is determined for the whole root zone and β= 5 for these coarse texture soils.

Daily drainage from the root zone (mm d^{-1}) is calculated as a function of soil water content (Spittlehouse and Black 1981), i.e.

$$D = k_{rd} (\theta/\theta_r)^m \qquad [5]$$

where k_{rd} is a reference hydraulic conductivity (mm d^{-1}), and m=2b+3 is a function of the soil water retention curve (Campbell 1974). When the soil is wet drainage must be calculated on a time step shorter than a day.

3. RESULTS

3.1 *Weather Conditions*

The annual water balance is determined for the period November 1 to October 31. This period was chosen because the snow pack in each year started in late October. Snow accumulating in late October is applied to the subsequent year's water balance. For the purposes of the water balance comparisons it is assumed that the clearcuts were in place in the fall of 2002 and they had October soil water content appropriate for a clearcut. This was obtained by simulating the 2001/2002 water balance for a clearcut. The three years in this analysis had different precipitation regimes (Table 1). The main snow season (November to April) was close to normal in all three years. The snowpack disappeared in early to mid May in 2004 and 2005 and by late May in 2003. The big difference between the years was in the summer rain season. 2003 had 63% of normal rain and had the earliest starting and longest summer dry period measured at the site over the last decade. It was also the warmest summer in the last decade with daily maximum air temperatures regularly in the high 20's. In contrast, 2004 was one of the wetter summers on record with 27% above normal rain. 2005 was close to normal.

Table 1. Precipitation (mm) during the measurement period and the average for 1992 to 2005. Precipitation for November to April is snow and for May to October is mainly rain.

	02/03	03/04	04/05	92/05
November-April	355	328	345	333
May-October	229	446	338	350
Total	584	774	673	683

Snow depth peaked at 1 to 1.4 m in the clearcuts and 0.8 to 1.0 m in the forest depending on the year. The main melt period began during early to mid April and the clearcut areas were usually free of snow by the middle of May. The forested sites were free snow about one week later.

2.2 *Forest Water Balance*

The water balance model was able to track the measured water content in the forest (Figure 1). This was consistent among sites and years. Differences in the forest water balances are due differences in water storage capacity and drainage characteristics of soils and canopy cover (Table 2). Winter interception by the forest varied 10 to 20% of the snowfall depending on the year. Rainfall interception was more consistent ranging from 28 to 30% of the rain (Tables 3 and 4). Water loss through vegetation transpiration and evaporation for the forest floor was 30 to 35% of the annual precipitation. Drainage produced the greatest loss of water ranging from 33 to 45% depending on the precipitation regime of the year.

Table 2. Vegetation and site characteristics used for modelling the forest site water balances. Symbols explained in the text.

	Site A	Site B	Site C	Site P7
PAI	2.5	2.6	3	2.4
UAI	0.7	0.5	0.3	0.5
V_f	0.86	0.85	0.9	0.82
τ_1	0.14	0.11	0.1	0.19
τ_2	0.07	0.07	0.06	0.08
f	5.5	5.5	6	5.5
g	0.09	0.09	0.09	0.09
z	600	500	550	600
Cf_1	0.08	0.07	0.1	0.07
θ_{r1}	0.68	0.72	0.59	0.7
B_1	3.4	3.4	3.4	3.3
ψ_{e1}	0.001	0.001	0.001	0.0008
k_{r1}	370	300	100	500
Cf_2	0.2	0.29	0.1	0.33
θ_{r2}	0.48	0.4	0.54	0.3
b_2	3.2	3.2	4.0	3.1
ψ_{e2}	.001	0.001	0.001	0.0012
k_{r2}	370	300	100	500
k_{rd}	200	500	100	500

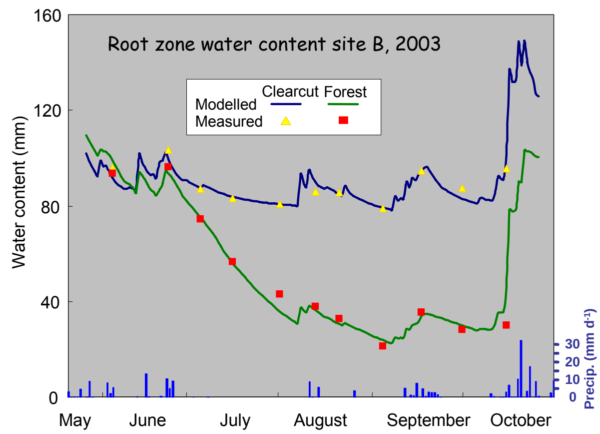

Figure 1. Measured and modelled soil water content for the site B forest and clearcut.

Table 3. Site water balance for November 2004 to October 2005 for the forest sites. Totals are in mm of water, I_{sn} is snow interception, I_r is rainfall interception, E_t is tree transpiration, E_s is soil evaporation, E_u is understory transpiration, and D is drainage. Totals do not sum to precipitation due to changes in storage of water in the root zone.

	Site A	Site B	Site C	Site P7
I_{sn}	46	24	46	46
I_r	95	94	102	98
E_t	175	150	210	126
E_s	24	33	40	45
E_u	45	29	14	44
D	299	275	265	284

Evaporation and drainage do not usually add up to the precipitation for the period. This is because there are changes in water storage in the root zone over the year. For example, the root zone was quite moist at the end of October 2004 The low fall rain in 2005 meant that the forest site root zone was quite dry with about 50 mm less stored water than the previous year. Consequently the water loss for 2004/05 is greater than precipitation. Clearcut soils are usually close to field capacity so that they are close to balancing on an annual basis.

Table 4. Average forest water balance (mm) for the 2002/03, 2003/04 and 2004/05 water years. Symbols explained in Table 4. Totals do not sum to precipitation for any one year due to changes in storage of water in the root zone.

	2002/03	2003/04	2004/05
P	584	774	673
$I_{sn} + I_r$	136	181	144
$E_t + E_s + E_u$	200	249	234
D	211	360	301

2.2 *Clearcut Water Balance*

As with the forest sites, the water balance model was able to track the measured water content quite well (Figure 1). Site soil physical and hydrologic characteristics (Table 5) influenced the partitioning of precipitation between evaporation and drainage (Table 6 and 7). As expected the clearcuts do not dry as much as the forests and remain moist even in dry summers (Figure 1). Evaporation accounts for 35 to 40% of the precipitation and drainage 60 to 65%.

Table 5. Site characteristics used for modelling the clearcut site water balances. Symbols explained in the text.

	Site A	Site B	Site C
z	500	550	500
Cf_1	0.08	0.07	0.1
θ_{r1}	0.68	0.72	0.56
B_1	3.4	3.0	3.4
ψ_{e1}	0.001	0.002	0.001
k_{r1}	370	100	500
Cf_2	0.29	0.29	0.22
θ_{r2}	0.46	0.39	0.39
b_2	3.2	3.2	3.2
ψ_{e2}	.001	0.001	0.001
k_{r2}	370	100	500
k_{rd}	30	300	50

3.3 *Evaporation from Forest and Clearcut*

Forests and clearcuts can have similar average evaporation rates when the soil surface is wet (Figure 2). Clearcut evaporation decreases as the soil surface dries, but increase substantially during rainy periods. Average forest evaporation rates were 1.5 to 2.3 mm d^{-1} when the soil was moist. The higher total evaporation from forest sites A and C is due their greater soil water storage capacity which can maintain maximum evaporation longer during the drier part of the summer. The forests lost about 50 mm more water than the clearcuts through evaporation.

Table 6. Site water balance for November 2004 to October 2005 for the clearcut sites. Totals are in mm of water, S is sublimation of snow, E_s is soil evaporation, and D is drainage. Totals do not sum to precipitation due to changes in storage of water in the root zone.

	Site A	Site B	Site C
S	13	13	13
E_s	279	216	255
D	388	405	381

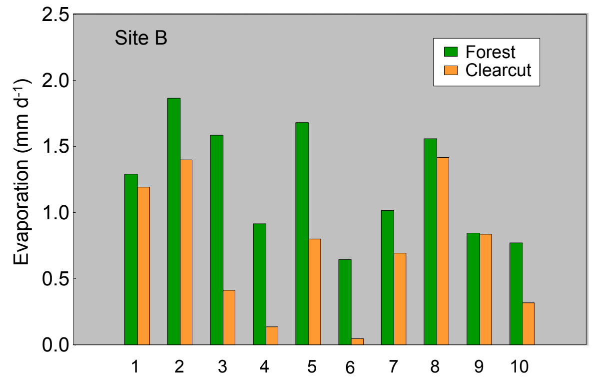

Figure 2. Mean daily evaporation from the site B forest and clearcut during 2003. The numbers on the x-axis indicate 10 to 14 day periods corresponding to the TDR measurements. They start at the beginning of June

Table 7. Average forest water balance (mm) for the 2002/03, 2003/04 and 2004/05 water years. Symbols explained in Table 6. Totals do no sum to precipitation for any one year due to changes in storage of water in the root zone.

	2002/03	2003/04	2004/05
P	676	648	648
S	8	7	22
E_s	166	293	250
D	394	501	391

The cumulative loss for the snow free period from mid May and late October 2003 is shown in Figure 6 for the forest and clearcut sites. In this dry summer, evaporation from the soil surface was suppressed.

3.2 *Annual Water Balance*

Figure 4 illustrates the partitioning of the water flows for a forest and clearcut. Evaporation from the soil surface of the clearcut is not that different from vegetation transpiration plus below-canopy soil surface evaporation. It is the reduction in interception that results in more water being available for drainage. Over the three years this averaged 138 mm per year, a 48% increase in drainage. The increase varied with the annual weather conditions, being 184 mm in 2002/03, 171 mm in 2003/04 and 111 mm in 2004/05, respectively 87, 39 and 30% increase in drainage. The high drainage loss in the driest year is a result of a higher snowfall and fall drainage conditions. The forest soil dried out and fall rains that replenished this water were not sufficient to produce drainage in the forest. However, only the near-surface layer dried in the clearcut so that drainage occurred when it rained in the fall.

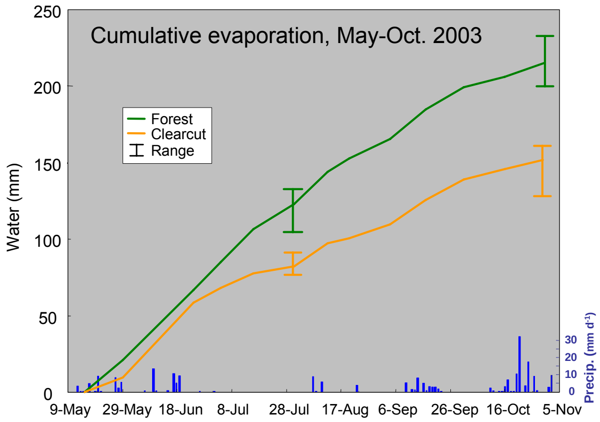

Figure 6. Cumulative evaporation (interception plus transpiration and/or soil evaporation) for forests, and clearcuts from late May to mid October 2003. Daily precipitation is also shown. The forest values are the mean of the four sites and the clearcut a mean of the three sites. The bars indicate the range of these values.

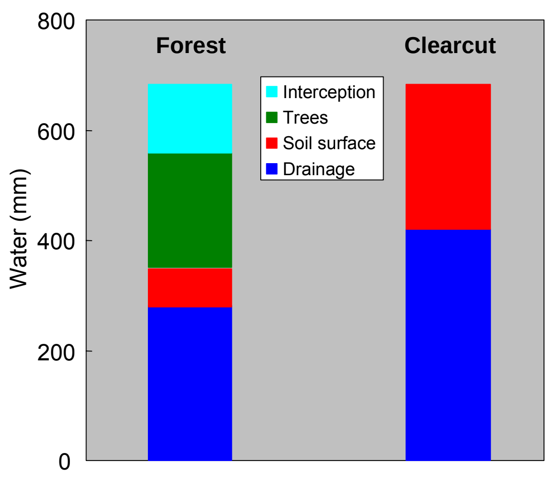

Figure 4. Annual water balance for a forest and clearcut. Data are averages for all sites for all three years.

4. CONCLUSIONS

Interception of precipitation by a forest reduces the amount of water reaching the forest floor by 20 to 25% depending on canopy cover and weather conditions. Over the summer, evaporation of intercepted water and transpiration from a forested surface exceeds evaporation from a recent clearcut by up to 30%. Consequently, removal of forest cover increases the amount of water available for surface and subsurface runoff to streams by 30 to 87% depending on weather conditions. Snow melt occurs at a higher rate in the open than in the forest under the same weather conditions resulting in a more rapid supply of water to the soil surface and a shortening of the snowmelt season by one to two weeks.

5. ACKNOWLEDGMENTS

This project was funded by the BC Ministry of Forests and Range (MoFR) and the Forest Investment Account through the BC Forest Science Program. Rita Winkler, MoFR, supplied the snow survey data and she and Graeme Hope, MoFR, provided invaluable help in site installation and data collection.

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