Hydrologic Recovery of Aspen Clearcuts in Northwestern Alberta

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Abstract—*A 3-year study of evapotranspiration from aspen clearcuts 1 to 14 years of age indicated the following: (1) The annual evapotranspiration from 1- to 5-year-old clearcuts ranges from 0 to 143 mm less than a mature forest on the same site. Evapotranspiration is highly dependent upon the amount of precipitation. (2) These effects can vanish in as few as 2 years with low precipitation (300 mm) or persist for 40 to 45 years with high precipitation (600 mm). These results were confirmed by data from the Spring Creek experimental watershed. Simulated water yield increase from the harvested catchment averaged 16 mm, compared with 16.3 mm estimated from the paired watershed data. In planning harvesting scenarios on flood-prone watersheds, full hydrologic recovery should be assumed to occur 45 years after harvest. Harvesting sequences designed using this approach should not cause a measurable increase in flooding levels or flood frequency.*

Introduction

Clearcutting generally increases water yield (Anderson et al. 1976; Hibbert 1967; Swanson and Hillman 1977; United States Environmental Protection Agency 1980). This is a logical consequence of the removal of trees and a reduction in water loss by transpiration. In windy environments, clearcutting can be accompanied by removal and rearrangement of the winter's snowpack (Tabler and Schmidt 1972; Troendle and Meiman 1984), which can alter the duration of snowmelt and the quantity of snowmelt water. In coniferous stands in the Rocky Mountains, the combined effects of these processes may last for 80 to 120 years (Leaf 1975). Similar effects on snow accumulation and melt have been noted in aspen stands (Swanson and Stevenson 1971). The duration of water yield increases from clearcuts in aspen stands is reportedly shorter, approximately 9 to 14 years (Verry 1987) and somewhat uncertain in Alberta (Swanson et al. 1998). Our purpose in the study reported here was to determine how long these processes were operating to affect water yields from aspen harvest on the Keg River watershed in northwestern Alberta, Canada.

Flooding of Homes and Fields

Forest clearcutting has generally been dismissed as a factor in major flooding events (Hewlett 1982), but there is some evidence to the contrary in the Keg River watershed in northwestern Alberta. About 13% of the Keg River watershed area was cleared for agriculture (Delta Environmental Management Group Ltd. 1989; W-E-R Engineering Ltd. 1990). The Keg River area was settled as a ranching community in the early 1930s. According to the Delta report, between 1957 and 1987, most of the coniferous timber stands from the Naylor Hills portion of the Keg River watershed were removed, with the result that yearly spring flooding and high water table levels are now a common hydrological feature of the area. According to the WER report, "Since

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settlement of the area, overbank flows along the Keg River and its tributaries have been a frequent occurrence. As a result, any activities in the watershed which may influence flood conditions in this area are of vital concerns to the local residents."

Much of the upper portions of the Keg River watershed contains mature deciduous forest. Daishowa Marubeni International, Ltd. (DMI), which has the cutting rights in this area, proposed to start harvesting aspen in the winter of 1991/1992. DMI has been sensitive to the concerns expressed by residents on farm and ranch lands downstream from their proposed harvests and commissioned the report by W-E-R Engineering Ltd. (1990) to evaluate the potential hydrologic impacts of their harvests. Their report concluded that the hydrologic effects of any single aspen harvest would essentially vanish in 2 to 3 years. To mitigate flooding concerns, the report recommended that "harvesting activities should be scheduled over two or more years in sub-watersheds which will be extensively harvested or where channel erosion is a significant concern."

DMI questioned the validity of the 2- to 3-year estimate for the effects of aspen harvesting to vanish. Verry (1987) reported a significant increase 14 years after aspen harvest in Minnesota. In southern Alberta, a harvest of aspen from 50% of the area above a small spring in the Streeter Basin experimental watershed produced increases in water yield greater than 25 mm for the 7 years of measurement following harvest (Swanson et al. 1986). (Water yield is defined as the depth that would result if all of the streamflow for a defined period and from a defined watershed were spread evenly over the watershed area. Water yield in millimeters equals streamflow volume in cubic decameters divided by watershed area in square kilometers.) Extrapolation of the Streeter results (figure 1) in time indicated that the effects of the harvest would vanish in about 30 years (Swanson et al. 1998). DMI chose to design its initial harvesting scenarios in accordance with the recommendation of the WER

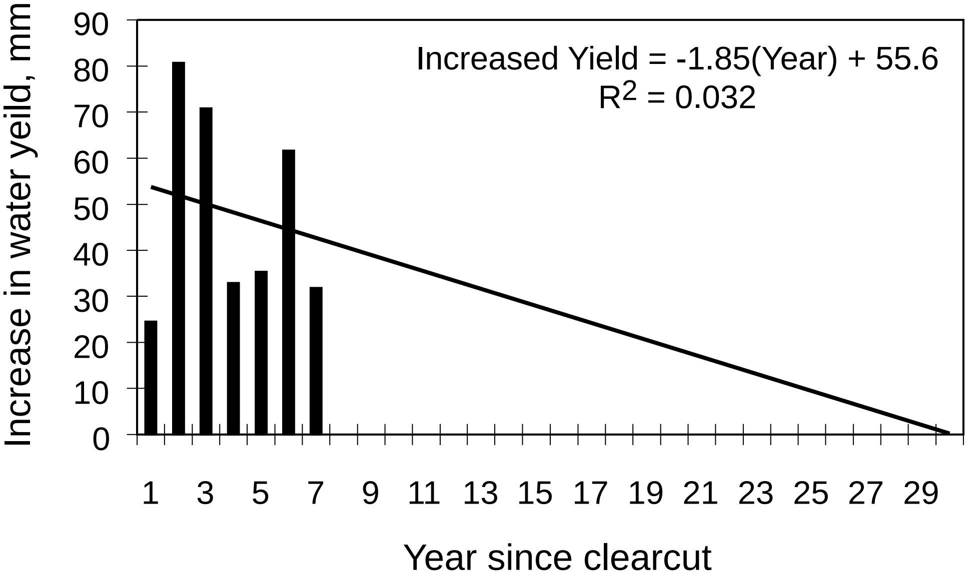

Figure 1—Decline in annual increases in generated runoff from an aspen watershed after clearcutting. Unpublished analysis of data from the Streeter Experimental Basin, Alberta. Aspen forest was harvested in 1976 and water yield data collected through 1982.

report but used simulations with the WrnsHyd[2] version of the WRENSS procedure (United States Environmental Protection Agency 1980) and the Streeter Basin results to ensure that water yield increases remained well within the 15% of average water yield bounds set by Alberta Environmental Protection (John Taggart, Alberta Environment, Edmonton, Alberta, personal communication). Because of the uncertainty in the length of the recovery period, the study reported here was funded by DMI and the Canadian Forestry Service's Partnership Agreements in Forestry program (in our case, a project funded jointly by the Government of Canada, the Province of Alberta, and DMI).

Objectives

Our first objective was to better define the period during which aspen clearcuts could significantly affect water yield and the potential for flooding. We assumed that: (1) a reduction in evapotranspiration (ET) would result in an increase in generated runoff[3] (GRO) of the same magnitude, and (2) annual increases of 10 mm or less in GRO would be considered insignificant.

Our second objective was to incorporate tree growth equations within the WRENSS procedure (United States Environmental Protection Agency 1980) so that it could be driven by forest inventory information and used by forest managers to relate cumulative areal and temporal harvests to water yield change. These would enable the use of the WRENSS procedure for evaluation of existing harvests and to plan future harvests in order to minimize any detrimental effects on water users, either instream or downstream.

Scope of Investigations

The study was to be conducted over 3 years commencing the first year after instrumentation was installed (1993). All of our investigations were conducted on existing harvested cut blocks 0 to 10 years old (in 1993), 20 to 40 ha in size, and in deciduous forests in northwestern Alberta. We initially sought all of our sites within the Keg River watershed. However, there was only one age class available, those harvested in the winter of 1991–1992 (our site Kg92). And, since aspen had not been harvested to any great extent in the past in Alberta, there were few sites to choose from anywhere in northwestern Alberta. Most of those in which aspen regeneration had occurred had been treated either mechanically or with herbicides to discourage deciduous growth and to favor that of coniferous plantings. We located 5- and 10-year-old sites (Gp88 and Gp83) south of Grande Prairie, Alberta, that were suitable. A mature and a second newly logged site (SpMat and Sp94) were found on the Spring Creek experimental watershed, near Valleyview, Alberta.

The Spring Creek experimental watershed was started in 1966 with stream gauges on all sub-basins and a comprehensive network of weather stations. The watershed study was deactivated in 1986 before any experimental treatment was done. Alberta Environment proposed reactivation of the watershed and that DMI harvest one of the sub-basins in 1994 to complete a portion of the original purpose of the experimental watershed. Alberta Environment reactivated the stream gauge on Bridle Bit Creek, the 21 km^2 control watershed, and on Rocky Creek, the 15.3 km^2 watershed that DMI would harvest. Sp94 was located on the Rocky Creek watershed. The two sub-basins, monitored since 1994, provided data for a paired watershed comparison. The Spring Creek paired watershed study serves an excellent complement to, and check on, the data derived from the evapotranspiration measurements and model simulations.

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[2] WrnsHyd is an MS-DOS implementation of the hydrology chapter on the WRENSS (United States Environmental Protection Agency 1980) handbook. WrnsHyd was programmed by the Canadian Forestry Service and made available to any interested user in 1990. It is currently available by ***email only*** (rswanson@expertcanmore.net), free of charge from R.H. Swanson.

[3] Generated runoff (GRO) is that increment of water added during a given time interval that will eventually leave a catchment. All onsite losses have been deducted but the water has not passed through the stream gauging point. It is correctly defined as precipitation-evapotranspiration. This definition is in agreement with that proposed by the U.S. Army Corps of Engineers (1956), which states that generated runoff is water in transitory storage in the soil, groundwater, or stream channel.

Plan of Attack

Our plan was to obtain the data necessary to estimate the change in generated runoff through time from new clearcuts in the Keg River watershed to mature aspen stands. Initially we thought that measured precipitation and the estimates of annual evapotranspiration from microclimate and soil moisture measurements obtained at each age might be sufficient to define an age:generated-runoff relationship. However, we soon realized that the sites had sufficiently different climates to render direct comparisons of evapotranspiration magnitude impossible. We anticipated this and planned to simulate generated runoff with a microclimate and vegetation model in addition to the direct measurements. The direct measurements of ET were to serve as control values for simulated ET on the same sites.

The BROOK90 model (Federer 1995) was used to integrate all of the site information including winter and summer precipitation and to simulate the change in generated runoff from the time of initial harvest to 60 years. The Spring Creek paired watershed results were used to verify the BROOK90 simulations of increased water yield from Sp94. The results obtained from the BROOK90 simulations were then incorporated into WrnsDmi, a version of the hydrology section of the WRENSS (United States Environmental Protection Agency 1980) procedure for use by DMI within its allotted area to evaluate existing harvests and prescribe future ones to maintain water yield increases within acceptable bounds, presently set by Alberta Environment at 15% of average annual yield. The value of 15% was chosen through unit hydrograph analysis, which indicated that increases in annual yields of this magnitude would not increase the magnitude of instantaneous or daily peak flows.

Measurements

The data necessary to calibrate and use the BROOK90 model (Federer 1995) to simulate change in generated runoff were taken at each site. The BROOK90 model requires daily values of air temperature, vapor pressure, solar radiation, wind speed, and precipitation. Leaf area index (LAI) and tree height (TH) are required to describe the vegetation on a site. Site latitude, initial water content of the snowpack, and the amount of water in groundwater storage are used to initialize a simulation run. Soil water can be drawn from one to 10 layers. Various combinations of output variables are available. We chose to view daily, monthly, and annual ET, generated runoff and soil moisture, and calibrated the model at each site on 1994 climate, LAI, TH, and soil moisture data. We did not attempt simulation of actual streamflow because the BROOK90 model does not include a storage routing routine or storage parameters. Spring Creek's streamflow is highly dependent upon withdrawals from and replenishment of soil, groundwater, and surface storage during years of low and high precipitation as is the streamflow of most watersheds in northwestern Alberta.

An instrument tower was installed at each site (10 m tall at Kg92 and Sp94, 15 m tall at Gp83 and Gp88, 30 m tall at SpMat). All were identically instrumented (table 1) with the wind sensors approximately 10 m above the canopy. Hourly-averaged climate data was collected at each site with a Campbell Scientific (CSI) CR10 data logger programmed to read all sensors at 1-second intervals. The soil moisture and soil temperature sensors were read every 4 hours. Both climate and soil moisture/temperature data were taken year-round.

Snow depth and density were measured at all sites in February or March 1994, 1995, and 1996. If available, an adjacent newly harvested clearcut and a mature stand were also sampled. No permanent snow courses were established.

Table 1—Aspen study sites in northwestern Alberta, locations, and instrumentation.

Location, harvesting, and instrumentation dates						
Nearest town	**Identifier**	**Latitude**	**Longitude**	**Elevation**	**Harvested**	**Instrumented**
				m	*Year*	*Mon/Year*
Keg River	Kg92	57:46:00N	117:55:00W	513	1992	04/1993
Grande Prairie	Gp83	54:54:50N	118:47:30W	610	1983	07/1993
	Gp88	54:54:45N	118:56:00W	610	1988	07/1993
Valleyview	Sp94	54:58:20N	117:45:00W	730	1994	03/1994
	SpMat	54:55:30N	117:42:45W	700	Unharvested	04/1993

Continuous observations taken at all above sites from 1994 through 1996			
Type of data			
Climate	Air temperature	CSI[a] HMP35C (Fenwal[b] UUT51J1 Thermistor sensor)	°C
	Relative humidity	CSI HMP35C (Vaisala[c] capacitor RH sensor)	%
	Short wave radiation	SKYE[d] SKS 1110 Pyranometer	W/m^2
	Wind speed	RM Young[e] 05103 Propeller Anemometer at 10 m.	km/h
	Wind direction	RM Young 05103 Potentiometer Vane at 10 m	0–360
	Soil mmoisture and temperature	MC363[f] Fibreglass Moisture and Temperature Cells at 15 and 40 cm depths (15 and 30 cm at Kg92)	mm & °C

Periodic observations taken at all sites from 1994 through 1996		
Rainfall 1 May to 31 October	CSI TE525MM Tipping Bucket	mm
Snow accumulation February to March	USDA-SCS snow tube, 10 point snow course approximately 100 m long.	mm SWE[g]
Bowen's Ratio 1 May to 31 October	Temperature Gradient. Unshielded 0.08 mm Chromel/Constantan Thermocouples, approximately 2 m separation, CSI 10TCRT Reference.	°C
	Vapor Pressure Gradient. Air was drawn over a centrally mounted Vaisala sensor alternating every 30 seconds between top and bottom vents collocated with the thermocouples.	kPa
	Net Solar Radiation. CSI Q-6 (REBS[h] Net Radiometer).	W/m^2
	Soil Heat Flux. CSI HFT3 (REBS soil heat flux sensor).	W/m^2

[a] Campbell Scientific (Canada) Corp., 11564–149 St., Edmonton, AB T5M 1W7.
[b] Fenwal Electronics Group, 500 Narragansett Park Drive, Pawtucket, RI 02861-4325.
[c] Vaisala, Inc., 100 Commerce Way, Woburn, MA 01801-1068.
[d] Skye Ltd., Unit 5, Ddole Industrial Estate, Llandrindod Wells, Powys, UK LD1 6DF.
[e] R.M. Young, 2801 Aero-park Drive, Traverse City, MI 49684.
[f] Hoskins Scientific Ltd., 239 East 6th Ave, Vancouver, BC V5T 1J7.
[g] SWE = Snow Water Equivalent.
[h] Radiation & Energy Balance Systems, Ins., P.O. Box 15512, Seattle, WA 98115-0512.

At each site a starting point at least 100 m from the forest edge was selected and 10 measurements made at 10 m intervals.

The soil moisture sensors at each depth (table 1) were calibrated against gravimetric measurements at those same depths during each month of the 1994 growing season (dry weight basis every month, volumetric measurements made in June only). The volumetric moisture contents were converted to mm of water in each soil layer.

The data to calculate Bowen's ratio were taken at periodic intervals in 1994 and continuously from 1 May to 31 October in 1995 and 1996. During 1994, we attempted to use the CSI Bowen Ratio instrumentation but it proved unsatisfactory for use over forest canopies because the length and construction of the sensor mounting arms made it almost impossible to move them or to repair or replace the thermocouple sensors while mounted on the towers.

We constructed Bowen's ratio apparatus that functioned similarly to CSI's using readily available 2-inch diameter white ABS pipe. Two 1 m lengths of pipe were fastened to opposite ends of a central chamber containing a CSI HMP35C sensor. The resulting rigid structure allowed easy mounting on a tower with supports placed at any convenient position on the tower. Thermocouple sensors (0.08 mm diameter) were mounted on 1 mm diameter 10 cm long ceramic arms extending outward near each air intake. The bottom sensor's temperature and the difference between the upper and lower sensors temperature were read at 1-second intervals and averaged over 30 or 60 minutes as desired. Vapor pressure gradient was obtained by drawing air over the HMP35C sensor alternately from the upper and lower vents. Air was drawn from the upper vent for 10 seconds to flush the central chamber, and then vapor pressure was recorded for 20 seconds. This procedure was then repeated with air drawn from the lower vent. This sequence was repeated every 60 seconds.

Leaf area indices and tree heights were obtained during 1993 and 1994 by harvesting all of the leaves from plots or representative trees (three each 9 m^2 plots at Kg92, four each 1 m^2 plots at Gp83 and Gp88, three representative trees at SpMat). Sampling was done in late June and July following full leaf expansion. The trees were felled and all green foliage collected and bagged for laboratory analysis. The area of 15 to 20 subsamples of the leaves from each site was measured. An equation was derived for leaf area as a function of oven dry weight (in a forced air oven at 40 ^oC for 24–48 hours). The total oven dry weight of all of the leaves was used to estimate total leaf area for the plot or tree(s). The LAI obtained by averaging the data from the plots was considered the LAI for that stand. The LAI from the individual trees at SpMat was scaled up by multiplying the average leaf area per tree by the number of trees per hectare in that stand. The heights and diameters of the trees at breast height and at the root collar were measured. Estimates of stocking (stems/ha and basal area) in the mature stand were obtained by counting all of the trees in two randomly established 0.01 ha plots. The heights of the trees in each plot or sample were averaged and considered representative of the stand from which they were obtained.

Results

Snow Accumulation

Snow accumulation in the clearcuts and in the uncut forest was approximately the same from 1994 through 1996. Average winter wind speed at 10 m at the Spring Creek or Keg River clearcut sites was generally less than 2 km/h, considerably less than the 24 km/h that Tabler and Schmidt (1972) indicate as the threshold velocity for transporting snow particles from a snowpack. In addition, the regeneration height in the clearcuts at the end of the first-year's growing season averaged 1 to 1.5 m, which provided sufficient aerodynamic roughness to protect the shallow snowpacks in these areas from wind erosion or transport (Swanson 1994).

Leaf Area Indices and Tree Heights

There were no replicates of age classes because of the lack of suitable sites, particularly in the 5- and 10-year age groups. The LAI's that we obtained were plotted against age (figure 2) and a logarithmic curve was fitted to the data (equation 1). The tree heights were plotted as a linear function of age (equation 2).

These equations were used to estimate the LAI's and tree heights at each age used in the BROOK90 simulations (table 2).

$$LAI = 1.665 \mathrm{Ln}(Age) - 0.0712 \tag{1}$$
$$TH = 0.261(Age) + 0.88 \tag{2}$$

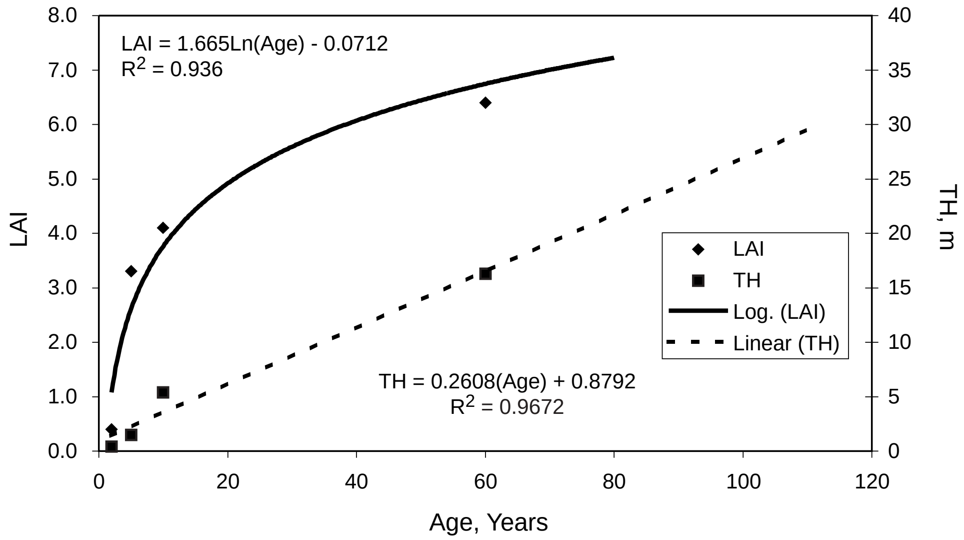

Figure 2—Leaf area index (LAI) and tree height (TH) as a function of aspen age in northwestern Alberta.

Table 2—Annual evapotranspiration as simulated with the BROOK90 model at LAI and tree height at site age versus that simulated using SpMat vegetation data (Age 60, LAI = 6.7, TH = 16.5 m) on the same site.

Age (year)	LAI at age	Height	Precipitation	ET (at age)	ET (mature)	ET (decrease)
	m^2/m^2	*m*	- - - - - - - - - -	- - - - *mm*	- - - - - - - -	- - - - - - - - - -
Gp88 Grande Prairie site, clearcut in 1988						
6 (1994)	2.9	2.4	507	412	445	33
7 (1995)	3.2	2.7	605	427	499	72
8 (1996)	3.4	3.0	591	410	447	37
Average			**568**	**416**	**464**	**47**
Gp83 Grande Prairie site, clearcut in 1983						
11 (1994)	3.9	3.7	507	377	421	44
12 (1995)	4.1	4.0	577	392	446	54
13 (1996)	4.2	4.3	677	428	496	68
Average			**587**	**399**	**454**	**55**
Kg92 Keg River site, clearcut in 1992						
3 (1994)	1.8	1.7	379	298	346	48
4 (1995)	2.2	1.9	312	277	277	0
5 (1996)	2.6	2.2	407	346	375	29
Average			**366**	**307**	**333**	**26**
Sp94 Spring Creek site, clearcut in 1994						
1 (1994)	.8	1.0	462	275	418	143
2 (1995)	1.1	1.4	457	307	373	66
3 (1996)	1.8	1.7	616	349	462	113
4 (1997)[a]	2.2	1.9	500	363	430	67
5 (1998)	2.6	2.2	387	307	320	13
Average			**484**	**320**	**401**	**80**
Average decrease in ET area-weighted over Rocky Creek watershed						**16**

[a]Temperature, vapor pressure, and solar radiation data from SpMat used for 1997 and 1998 simulations at Sp94.

Evapotranspiration Estimates From Soil Moisture Data

Evapotranspiration can be estimated from soil moisture changes over the growing season. The water balance equation (3) was used to make these ET estimates (Johnston et al. 1969):

$$Q = P - ET - I - \Delta G - \Delta S \tag{3}$$

where Q = water yield, P = precipitation, ET = evapotranspiration, I = Interception, ΔG = change in groundwater storage, and ΔS = change in soil moisture storage.

$$ET = P - \Delta S \tag{4}$$

To calculate ET from the soil moisture data collected during this study, we assumed that surface runoff, interception, and percolation to groundwater were negligible. Under these assumptions, calculations (table 3) with equation (4) indicate that during 1994–1996, the ET from the younger Gp88 site averaged 442 mm, 2 mm less than the 444 mm at the older Gp83 site. Evapotranspiration at Gp88 was higher than at Gp83 for 2 of the 3 years of data, which tends to confirm observations of DeByle (1985) that for stands reproduced from root suckers “within 10 or 20 years, the sprout stand will probably consume as much water as its parent trees did.”

During this same time period, the ET at the newly clearcut site on Spring Creek (Sp94) averaged 318 mm, 64 mm less than the 382 mm at the mature Spring Creek (SpMat) site. Evapotranspiration at the Keg River site (Kg92) averaged 254 mm. We had no ET data from a mature site at Keg River to compare with that from the clearcut.

Evapotranspiration Estimates From Bowen’s Ratio Data

The Bowen’s ratio method uses a form of the energy balance equation (5) to estimate ET (Oke 1987).

$$Q^* = Q_H + Q_E + Q_G \tag{5}$$

Table 3—Seasonal water use from aspen sites as estimated from soil moisture depletion and precipitation, 1 May to 30 September (Kg92, 1996, 1 May to 31 August).

Site	Age	Year	Precipitation	Water use
	years		- - - - - *mm*	- - - - -
Gp83	11	1994	328	390
	12	1995	394	472
	13	1996	474	473
Average				**444**
Gp88	6	1994	328	406
	7	1995	431	509
	8	1996	388	412
Average				**442**
Kg92	3	1994	212	244
	4	1995	196	220
	5	1996	239	297
Average				**254**
SpMat	60+	1994	293	368
	60+	1995	266	346
	60+	1996	421	431
Average				**382**
Sp94	1	1994	293	400
	2	1995	266	220
	3	1996	421	336
Average				**318**

where Q^* = net all wave solar radiation, Q_H = sensible heat, Q_E = latent heat, and Q_G = heat conduction to or from the underlying soil. The Bowen's ratio, b, equation (6) is defined as the ratio of sensible to latent heat (Oke 1987), where C_A is specific heat of air, L_V is latent heat of vaporization, and T_1, T_2, V_{P1}, and V_{P2} are air temperature and vapor pressure at levels 1 and 2, respectively.

$$\beta = Q_H / Q_E = C_A(T_1 - T_2)/L_V(V_{P1} - V_{P2}) \qquad (6)$$

Evapotranspiration can be calculated with equation (7) by rearrangement of equation (5) and substitution of β.

$$ET = [(Q^* - Q_G)/(1 + \beta)]/L_V \qquad (7)$$

Bowen's ratio can be determined with very accurate measures of air temperature and vapor pressure at two levels above the canopy. In order to meet all of the assumptions inherent in the derivation of Bowen's ratio, stringent fetch and height constraints must be met. In general, one can assume that the fetch requirement is met if the distance to the nearest obstacle to wind flow over the site is 40 times the height of the lowest air temperature and vapor pressure sensor set (measured from above the canopy). This fetch requirement was met at all but the Gp83 site.

The placement of the lower sensor cannot be specified exactly and will always involve some trial and error. In our case, we started with the lower sensor set 2 m above the tallest vegetation and with a 2 m separation between the lower and upper sensor sets. This spacing and placement appeared to give satisfactory readings. The spacing between the upper and lower sensors was not changed but at the three newest clearcut sites (Gp88, Kg92, and Sp94), the lower sensor was moved to 2 m above the canopy before leaf-out each year.

We found it difficult to maintain the complete Bowen's ratio measurements at all sites over a full growing season. Although the instruments were checked monthly, data logger program failures, broken temperature sensors, and holes pecked by birds in the shields of the net radiometers rendered much of the data suspect. The 1996 data sets at all sites are the most complete because all of the temperature and vapor pressure data were valid. However, birds were particularly bothersome in 1996 with the result that most of the net radiation data was unusable. Therefore, we estimated net radiation by subtracting a fixed value for albedo (0.18) from direct solar radiation readings.

The results for 1996 (table 4) indicate that growing season ET from the Sp94 site, where the regeneration was in its third year, was 410 mm, 40 mm less than that (450 mm) from the mature SpMat site. The monthly values of ET simulated by the BROOK90 model for 1996 are shown for comparison with the

Table 4—Monthly evapotranspiration in 1996 as estimated from Bowen's ratio data and BROOK90 simulations at one of the Grande Prairie sites, the two Spring Creek sites, and the Keg River site.

	Bowen's Ratio				BROOK90			
Site	**Sp94**	**Kg92**	**Gp88**	**SpMat**	**Sp94**	**Kg92**	**Gp88**	**SpMat**
Age, years	3	5	8	60+	3	5	8	60+
Month	mm	mm	mm	mm	mm	mm	mm	mm
May	29	31	31	53	23	26	34	30
June	101	101	112	87	84	76	112	86
July	120	114	142	126	93	100	128	108
August	120	91	132	136	91	86	59	98
September	41	—	49	49	44	—	61	54
Season	410	337	465	450	334	288	393	376

Bowen's ratio data. The Bowen's ratio ET show similar trends to those of the BROOK90 simulations, but their magnitudes were not sufficiently comparable to use as control data for the model.

Generated Runoff Estimates From Model Output

Complete data sets for the BROOK90 model were either taken or estimated for the years 1994 through 1996 for all five sites. The model was calibrated for each site on the soil moisture in the top 40 cm. (The data taken gravimetrically at monthly intervals from 26 April to 9 September 1994 at each depth [table 1] were depth-weighted and combined into one measurement for a 40 cm thick soil layer.) We considered the model to be calibrated for a particular site when it simulated the soil moisture within 5 mm of that measured on 1 May and 31 August with the 1994 weather data from that site. For all sites except Sp94, several months of weather data were available for 1993, and these data were used to initialize the contents of the storage compartments within the model for simulation of the 1994–1996 data sets. On Sp94, the 1994 data was entered twice and the model storage components initialized on 1994 data before simulation of the 1994–1996 data sets.

We used the watershed results from Spring Creek as a check on the simulated generated runoff change. Regression analysis of Rocky Creek versus the Bridle Bit Creek control indicated a high correlation ($R^2 = 0.9732$) between their flows during the pre-harvest period. Measured flows during the post-harvest period, 1994–1998, are consistently above the pre-harvest regression line (figure 3), even when the data from a storm on 28–31 May 1996[4] are left out. In 1999, the estimated change in water yield is on or slightly below the regression line for the first time.

The average water yield increase for 5 years, 1994–1998, obtained from the paired basin regression analysis was 16.3 mm. The increase in generated runoff simulated with the BROOK90 model for these same years for the clearcut and area-weighted with the uncut portion of Rocky Creek was 16 mm (table 2). We take this close correspondence for the years 1994–1998 as reasonable verification of the simulations with the BROOK90 model.

The increase in generated runoff from each site was simulated with LAI and TH as estimated for the years 1994 through 1996 (table 2). These simulations were compared with simulations as if trees at each site were the same as those at SpMat (LAI = 6.7, TH = 16.5 m) for each of those same years. The increase in GRO ranges from a low of 0 mm in 1995 at the Keg River site to a high of 143 mm in 1994 at the Spring Creek clearcut site. In general, greater increases in generated runoff occur in high precipitation years, e.g., 1996.

We simulated generated runoff increases at the Keg River and Spring Creek clearcut sites through 60 years using the highest and lowest precipitation that occurred during the period 1994 through 1996. The simulations for the Keg River site (figure 4) indicate that the effect of harvest on GRO increase would be insignificant (<10 mm) at 25 years with high precipitation and at 2 years with low precipitation. On the Spring Creek site where precipitation during the study years was higher than at Keg River, the effects of harvest on GRO increase would be about 10 mm at 40–45 and 25–30 years with high and low precipitation, respectively (figure 5).

Alberta Environment indicated that they could detect no change in peak flows following the harvest on Rocky Creek. This is consistent with similar findings for coniferous harvested areas on the Weldwood forest management area near Hinton, Alberta (RH Swanson & Associates 1997). Swanson estimated that the maximum change in any one-day's peak-generated runoff could

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[4] A beaver dam failed on 28 May 1996 resulting in the highest flow on record for Rocky Creek. Alberta Environment recommended that the streamflow from the entire month of May be excluded from the analysis of the harvest effect. We saw no reason not to include the streamflow data prior to the failure of the dam, nor for excluding that after the hydrograph returned to pre-failure level. We therefore excluded only the streamflow data for 28–31 May 1996 from both the control and treated watersheds. We also cannot rule out the possibility that the increased yield resulting from the harvest was a factor in the dam failure.

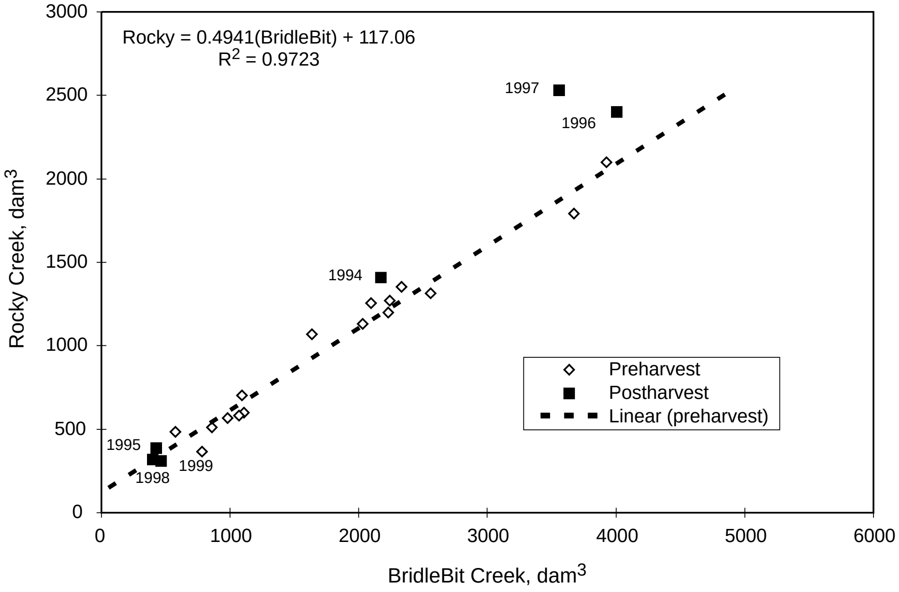

Figure 3—Effect of the 1994 clearcut harvest of approximately 20% of the area of Rocky Creek on annual water yield. Data for 1996 excludes the storm of 28–31 May; it could be somewhat higher because at least part of the runoff during that storm was due to the harvest. Note that the water yield for all of the years since harvest (except 1999) are above the pre-harvest regression of Rocky Creek on Bridle Bit Creek.

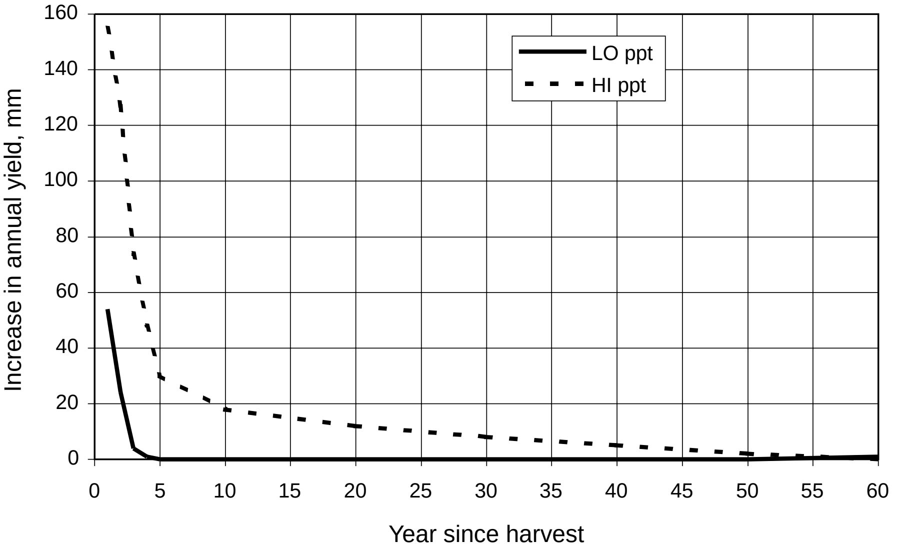

Figure 4—Change in annual generated runoff at Keg River with age of clearcut. Simulations with BROOK90 model using the climate data from the lowest (LO ppt; 312 mm) and highest (HI ppt; 407 mm) precipitation years that occurred from 1994–1996 at the Keg River site.

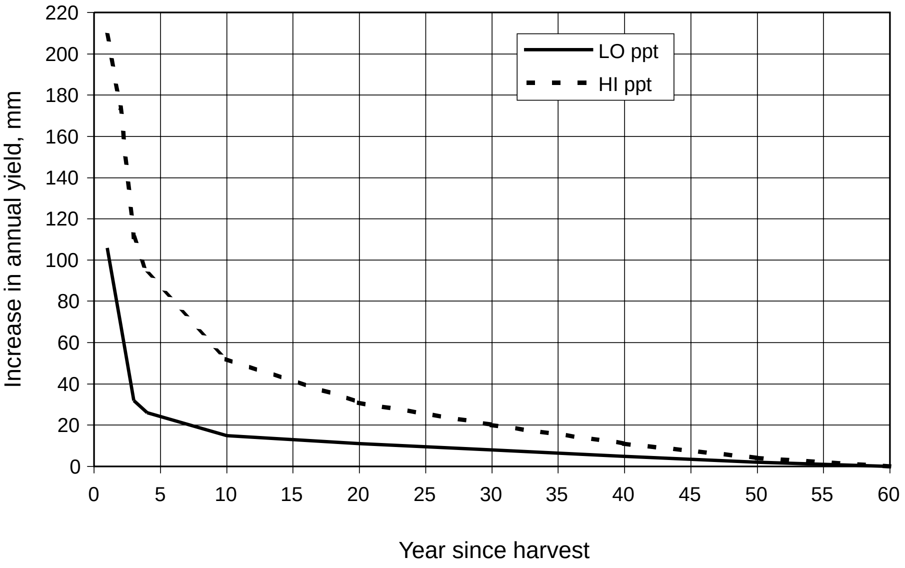

Figure 5—Change in annual generated runoff at Spring Creek with age of clearcut. Simulations with BROOK90 model using the climate data from the years with the lowest (LO ppt; 457 mm) and highest (HI ppt; 615 mm) precipitation at Spring Creek.

not exceed the potential evapotranspiration for that day. The maximum potential evapotranspiration for 1 day in this portion of Alberta is about 6 mm. If all 6 mm were added to a day's streamflow as a result of harvest, there would be a significant increase in peaks recurring at a frequency of every 2 years, but little or no change in the peak magnitude of those recurring at a frequency of 5 years or greater. We simulated daily additions to peaks with the BROOK90 model for 1996, the year with the highest precipitation at Rocky Creek, and found that the maximum increase in one day's generated runoff was 6.5 mm on the clearcut area (figure 6). This is approximately 1.3 mm when area weighted over the cut and uncut portions of the watershed. One should not expect to detect a change this small in maximum daily or instantaneous peak streamflow.

Interpretation of Results

The evapotranspiration values calculated from soil moisture or Bowen's ratio data were useful in a general sense in that they confirm that water yield increases cannot be reliably estimated solely from the age of a clearcut. Differences in precipitation masked the comparison of ET obtained from soil moisture at Gp88 and Gp83 or from Bowen's ratio data at Gp88 with that at the mature SpMat site. Both soil moisture data (64 mm difference over 3 years) and Bowen's ratio (42 mm difference during the 1996 growing season) at Sp94 and SpMat indicated higher values of evapotranspiration at the mature site and the decrease in ET on the clearcut site was reasonably comparable to GRO increases simulated with BROOK90. However, the soil moisture and Bowen's ratio data did not answer our question about how long it takes until the decrease in ET from aspen clearcuts becomes insignificant. The BROOK90 simulations gave us an answer, providing the duration of effects for use in the WrnsDmi procedure.

An increase in generated runoff in the hydrology section of WRENSS (United States Environmental Protection Agency 1980) is dependent upon the cover density of vegetation in a clearcut. In the hydrology section of the WRENSS procedure, the effect of any given clearcut generally vanishes when the cover density in that clearcut reaches half the maximum cover density anticipated for that particular stand. Cover density is defined in the hydrology section of WRENSS as an empirical function of basal area for each species in a WRENSS region (figure 7). Maximum cover density is assumed to occur at

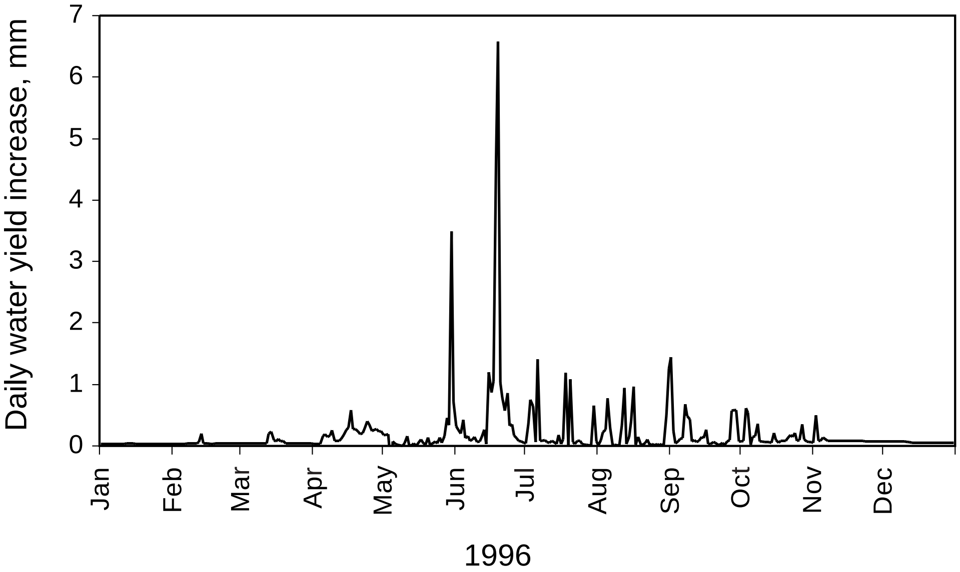

Figure 6—Simulated change in daily generated runoff for clearcut area. Maximum increase in one-day GRO is 6.5 mm on clearcut; area-weighted, 1.3 mm on watershed.

maximum basal area. WrnsDmi, our implementation of a computerized version of the hydrology section of the WRENSS procedure specific to the DMI forest management area in northwestern Alberta, contains basal area and tree height growth equations specific to deciduous stands in northwestern Alberta, considered by us to be in WRENSS region 1, "New England/Lake States" (figure 8). These growth equations are normalized curve shapes that can be programmed to reach a maximum value at any given stand age.

Prior to obtaining the results of this study, we assumed that the hydrologic effects of aspen harvest in northwestern Alberta would vanish at approximately 30 years (Swanson et al. 1998), so we programmed the aspen regrowth equations in WrnsDmi to reach maximum basal area at age 60 for "medium

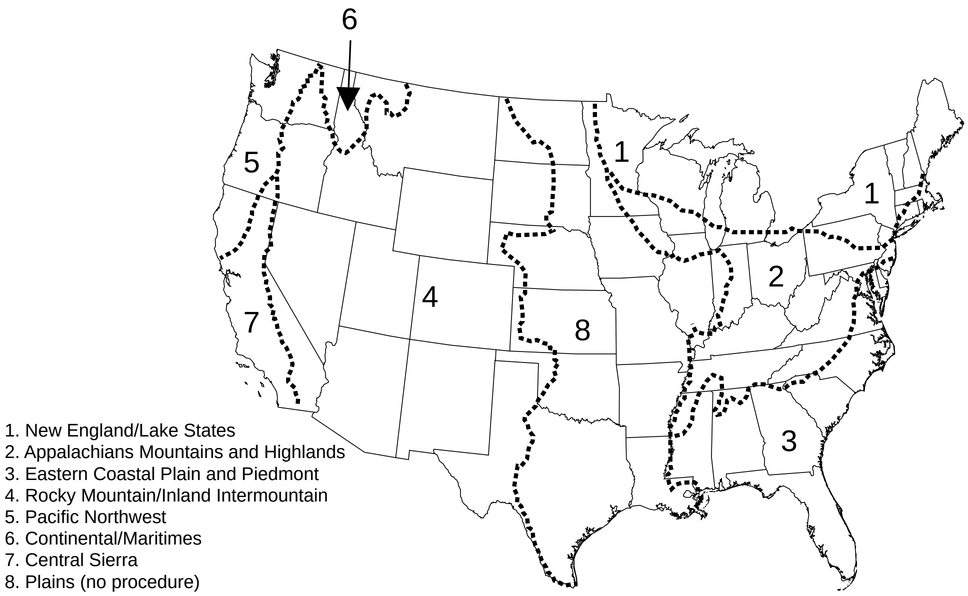

Figure 7—WRENSS regions of the United States.

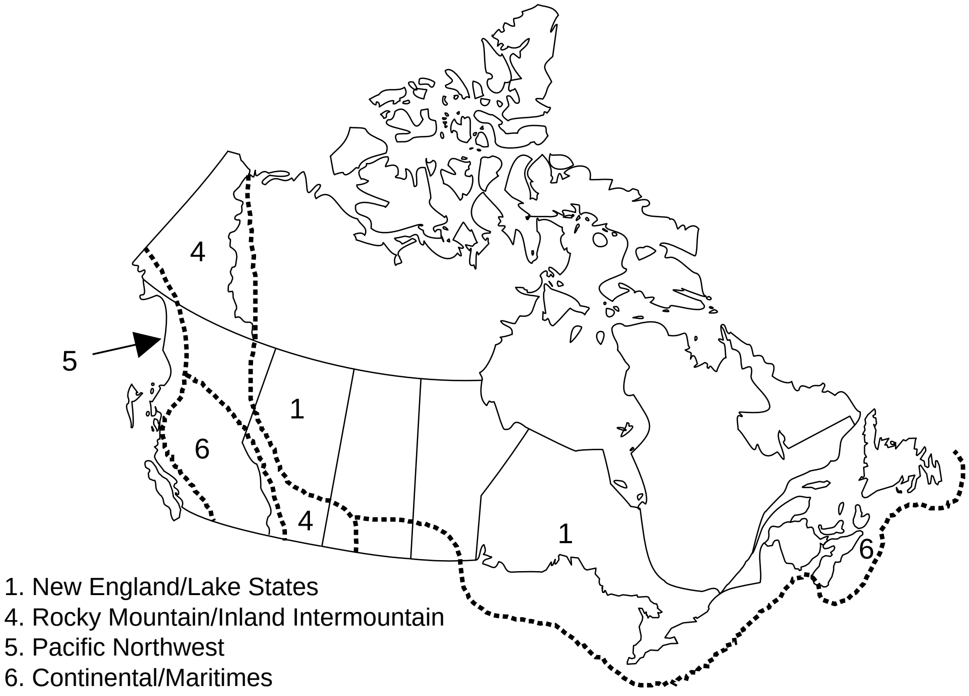

Figure 8—WRENSS regions extrapolated into Canada.

sites" (site index 16 m at 50 years, breast height age). Although 60 years was a reasonable approximation, our results from this study suggest a longer time in wetter years.

The precipitation measured at Kg92 during 1994 to 1996, and used to simulate the change in ET over 60 years, appears to be considerably lower than average. Annual precipitation from a nearby (57:45:00N, 117:37:00W, Elevation 405 m) Alberta Forest Service (AFS) weather station range from 376 to 670 mm (average 468 mm) during the period 1984 to 1997. The highest precipitation that we measured at Kg92 from 1994 to 1996 was 407 mm—less than the average at the AFS site.

The simulations of duration at the Spring Creek clearcut site (Sp94) for the year with 457 mm precipitation (slightly less than the average at the Keg River AFS site) indicate that the effect of harvest will be 10 mm or less at approximately 25 to 30 years and will not vanish until year 55 (figure 5). The simulations with 615 mm precipitation, which is closer to the maximum (670 mm) recorded at the Keg River AFS weather station, suggest a longer time period—i.e., an increase in GRO to less than 10 mm at 40 to 45 years and vanishing at 60 years (figure 5).

The results of this study were intended to be used to limit water yield increases in flood-prone areas. The water yield and any water yield increase caused by harvest is highest in years with most precipitation. Therefore, years with the highest precipitation are the most likely to be associated with flooding. We feel that the most conservative result we obtained should be used in planning harvesting sequences on flood-prone watersheds. In accordance with this conservative approach and our assumption that an increase in GRO of 10 mm or less is not significant, we recommend that the regrowth equations in WrnsDmi be programmed for full hydrologic recovery at 45 years, i.e., maximum cover density at 90 years after harvest. Harvesting sequences designed using this approach should not cause a measurable increase in flooding levels or flood frequency.

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