Soil moisture storage in mature and replanted sub-humid boreal forest stands

J. A. Elliott, B. M. Toth, R. J. Granger, and J. W. Pomeroy

Environment Canada, National Hydrology Research Institute, 11 Innovation Boulevard, Saskatoon, Saskatchewan, Canada S7N 3H5, e-mail: Jane.Elliott@ec.gc.ca. *Received 11 April 1997, accepted 29 November 1997.*

Elliott, J. A., Toth, B. M., Granger, R. J. and Pomeroy, J. W. 1998. **Soil moisture storage in mature and replanted sub-humid boreal forest stands**. Can. J. Soil Sci. **78**: 17–27. Soil moisture profiles at two mature forest sites (Pine and Mixed-Wood) and two plantations (1981 Pine and 1992 Mixedwood) in central Saskatchewan were studied in conjunction with soil properties, precipitation, interception and evapotranspiration. Sampling locations within each stand were chosen to highlight differences in soil moisture due to interception, evapotranspiration and soil physical properties.

Soil moisture storage to 1-m depth was greatest on the 92-Plantation where transpiration and interception of precipitation were less than the other sites. Moisture storage in the 81-Plantation was similar to that in the mixed-wood stand. The Pine stand had the lightest textured soils and stored least water to 1-m depth. Variability in moisture storage was also observed within stands and was associated with canopy structure and density, water extraction patterns and mechanical site preparation. In the furrows at the 92-Plantation, wet soils in combination with low infiltration rates and transpiration may have lead to the generation and channelling of rainfall runoff during a major rainfall event.

Key words: Boreal forest, hydrological pathways, soil moisture, infiltration, interception, evapotranspiration

Elliott, J. A., Toth, B. M., Granger, R. J. et Pomeroy, J. W. 1998. **Profil hydrique du sol sous peuplement exploitable ou sous nouvelle plantation dans la forêt boréale subhumide**. Can. J. Soil Sci. **78**: 17–27. Nous avons étudié les profils hydriques du sol à deux stations forestières d'âge exploitable (pin et peuplement mixte) et dans deux jeunes plantations (pin 1981 et peuplement mixte en 1992) dans le centre de la Saskatchewan, relativement aux propriétés du sol, aux précipitations, à l'interception et à l'évapotranspiration. Des sites d'échantillonnage dans chaque peuplement étaient choisis de façon à mettre en lumière les différences d'état hydrique dues à l'interception des précipitations par la frondaison, à l'évapotranspiration et aux propriétés physiques du sol. Les réserves hydriques du sol jusqu'à la profondeur de 1 m atteignaient les valeurs les plus élevées dans la plantation de 1992 où les déperditions par transpiration et l'interception des précipitations étaient moins importantes. Dans la plantation installée en 1981, les réserves d'eau étaient du même ordre que dans le peuplement mixte établi. C'est le peuplement de pin qui avait le sol le plus léger et qui par conséquent, contenait le moins d'eau jusqu'à la profondeur de 1 m. La teneur en eau du sol variait également à l'intérieur d'un même peuplement selon la structure et selon la densité de la frondaison, selon le profil d'extraction de l'eau et selon la préparation mécanique du terrain. Dans les sillons de la plantation de 1992, l'état détrempé du sol combiné à des taux d'infiltration et de transpiration faible aurait durant un épisode pluvieux important, créé une situation de canalisation des eaux de ruissellement pluviales.

Mots clés: Forêt boréale, voies hydrologiques, eau du sol, infiltration, interception, évapotranspiration

The western Canadian boreal forest regulates surface climate and water supply through the influence of its canopy on microclimate and the response of its water use to soil water supply, temperature and radiation (Bonan 1990; Granger and Pomeroy 1997; Pomeroy and Granger 1997). Harvesting disrupts the sequence, rate and pattern of hydrological processes operating in the ecosystem (Granger and Pomeroy 1997; Pomeroy et al. 1997) and the recovery of these processes during forest regrowth has been suggested as one indicator of ecosystem recovery in plantation forests. Quantifying hydrological processes in mature and disturbed forests provides a basis for identifying hydrological characteristics that are influenced by forest canopy and soils, and for assessing both the impacts of disturbance and the capacity of the forest to recover. This knowledge may contribute to the development of management strategies for reforestation which will promote regeneration of productive and self-sustaining stands.

Many effects of changes in the hydrological processes in a forest stand are integrated in the soil water system. Available soil moisture has been identified as a principle factor limiting reforestation of clear-cut sites in British Columbia (Fleming et al. 1994) and Oregon (Youngberg 1955). Despite this, the impacts of harvesting or replanting on soil moisture have rarely been examined and not in the context of the hydrological cycle. The soil moisture regime is directly affected by harvesting and replanting through the impacts of logging and mechanical site preparation on soil physical properties. Compaction during harvesting has been shown to reduce water infiltration through most of the cut stand especially on skid roads (Steinbrenner and Gessel 1955; Huang et al. 1996). The effects of compaction can persist more than 10 yr on sandy soils (Greacen and Sands 1980). Mechanical site preparation prior to replanting may improve soil conditions for seedling establishment. Fleming et al. (1994) reported an increased supply of soil water after three different site preparation treatments but did not relate their findings to soil physical properties. Harvesting indirectly affects soil moisture by reducing evapotranspiration (Granger and Pomeroy 1997). Removal of understory vegetation during site preparation prior to planting can also reduce transpiration losses (Marston 1962; Fleming et al. 1994). In mature forest stands, interception reduces the amount and intensity of rainfall reaching the soil surface (Gash et al. 1980; Hormann et al. 1996). Removal of the canopy through clear-cutting eliminates interception and as the forest regenerates canopy interception again begins to play a significant role in the hydrological cycle.

This paper examines differences in the soil moisture regimes between mature and regenerating forests with respect to the underlying processes in an area where annual moisture deficits suggest that tree growth may be water-limited in some situations. Natural and management-induced variability is studied on four sub-humid boreal forest stands in central Saskatchewan at both within-stand and between-stand scales. Specifically, the objectives are to quantify differences in soil moisture status between and within forest stands and illustrate the effects of soil properties, canopy interception and forest management (clear-cutting and replanting) on hydrological processes during a drought period and a major rainfall event.

MATERIALS AND METHODS

Site Description

Four experimental sites were established in the Prince Albert Model Forest which encloses approximately 1600 km^2 of Prince Albert National Park and a similar area of commercial forest (Weyerhaeuser Forest Management License Area). The Model Forest is in the Mixedwood Section of the Boreal Forest Region (Rowe 1972) about 70 km north of Prince Albert, Saskatchewan. Two mature forest sites were chosen in the national park and two replanted, clear-cut sites at different stages of regeneration were selected in the commercial forest.

PINE. The pine site (53°52.23′N, 106°07.75′W) is within a mixed-age stand of mature jack pine (*Pinus banksiana* Lamb). The trees are mainly 60 and 80 yr old and the stand density is around 2400 trees ha^{-1}. Heights range from 16 to 22 m and the average **diameter at breast height** (**DBH**) is 175 mm. There is a sparse understory of deciduous bushes. The soils were classified as Orthic Eutric Brunisols (Agriculture Canada Expert Committee on on Soil Survey 1987) developed on glaciofluvial parent material and had a 50 mm LF layer. Soil moisture was monitored under dense canopy (closed), in an area of relatively open canopy (open) and at an intermediate location (mid).

MIXED-WOOD. Approximately 75% of the land area at the mature mixed-wood site (53°53.56′N, 106°07.24′W) is covered by aspen (*Populus tremuloides* Michx.) and the remainder by white spruce (*Picea glauca* [Moench] Voss). The stand is 80 yr old. The density of aspen is 1000 trees ha^{-1} with heights ranging from 15 to 22 m and an average DBH of 245 mm. Spruce trees are present in the stand at a density of 150 trees ha^{-1}, are 15 m tall or less and have an average DBH of 455 mm. Grasses and deciduous bushes make up the understory at this site. The soils were developed on silty wind-blown parent material and had an LF layer around 50 mm thick. They were classified as Orthic Gray Luvisols. Soil moisture was monitored under a spruce tree (spruce), under an aspen tree (aspen) and on an open grassed area (open).

81-PLANTATION. The 81-Plantation (54°02.30′N, 105°54.87′W) was established at a site of a natural jackpine stand that been harvested by chain saw and skidder between 1980 and 1982. Soon after harvest, a blade was used to remove the debris and the site was mechanically replanted using a C&H mechanical planter. The planter created trenches 2 m apart that were 0.3 to 0.4 m wide and 0.2 to 0.3 m deep. Jackpine were planted every 2 m along the trench. Some natural regeneration of jack pine has also taken place resulting in a density of 3600 trees ha^{-1}. In 1994 most trees in the stand were less than 3 m tall and had an average DBH of 50 mm. Grasses and deciduous bushes were also well-established at the site. These soils were also developed on silty wind-blown parent material and classified as Orthic Gray Luvisols. The shaping effects of mechanical replanting on the soil surface were no longer prominent but soil moisture was monitored at two locations with paired ridge and furrow measurements. One pair of ridge and furrow soils (site 1) had an LF layer and dense understory vegetation but there was no understory vegetation or LF layer in either the ridge or furrow at the other monitoring location (site 2).

92-PLANTATION. The 92-Plantation (53°59.10′N, 105°54.79′W) was established at a former mixedwood site. The stand was mechanically harvested in 1991. The trees were delimbed at the roadside and the debris spread over the cut area. Three-year-old white spruce seedlings were planted with 2 m spacing in 1992 following mechanical site preparation with a TTS Delta disc trencher. The spruce trees mainly grow at the bottom of furrows which range from 0.3 to 1 m deep. On the surrounding ridges natural regeneration of aspen has occurred and although a few deciduous bushes and grasses are growing most of the soil surface is still exposed. In 1994 the aspen were around 1 m tall and the spruce trees were less than 0.3 m. The soil was classified as a Brunisolic Gray Luvisol developed on silty wind-blown parent material. Soil moisture was monitored at replicate ridge and furrow locations. Both of the ridge locations had thick (50–100 mm) LF layers but there was no organic layer at the furrow locations. The regenerating aspen at the site were thinned to release the spruce from competition in mid-June 1996.

Experimental Methodology

At each soil moisture monitoring site, the soil profile was described and classified (Agriculture Canada Expert Committee on Soil Survey 1987). Samples were taken for particle size analysis by the pipette method (Sheldrick and Wang 1993). Hydrogen peroxide pre-treatment was used to remove organic matter prior to analysis. Core samples were used to measure bulk density (Culley 1993) and total porosity was calculated from the ratio of bulk density to particle density (assumed to be 2.65 Mg m^{-3}). In June 1995, the rate of water infiltration was measured at the sites using a single ring infiltrometer (Bouwer 1986). The diameter of the ring was 1 m and the head of water was maintained at 75 mm. Measurements were made for at least 1 h and were continued until a constant (final) infiltration rate was obtained. Replicate measurements were made at each of the soil moisture monitoring sites at the Pine and Mixed-Wood sites but only one measurement was made at the monitoring sites in the 81-Plantation and 92-Plantation.

Effective **leaf area index** (**LAI**) was measured during a full leaf period (11 September 1996) using a LI-COR LAI-2000 Plant Canopy Analyser. The LAI-2000 was calibrated to sky brightness above the canopy on a clear day, using a 90° view-limiting cap to shield measurements from the operator and the sun. Measurements were taken at ground level within 2 min of the calibration readings with the same view cap and orientation. Four measurements were made at each of the monitoring locations at the Pine and Mixed-Wood sites and at one location in the 81-Plantation.

Volumetric soil water content (**VWC**) was measured by **time domain reflectometry** (**TDR**) to 1.6-m depth (Topp 1993). Buriable waveguides (0.2 m long) were installed horizontally at 0.05-, 0.1-, and 0.2-m depths and vertically at 0.3- to 0.5-m, 0.7- to 0.9-m and 1.4- to 1.6-m depths at each monitoring location. Most probes were in dominantly mineral soil and the standard TDR calibration between **dielectric constant** (**Ka**) and VWC was used (Topp et al. 1980) but in the organic layers Ka was measured and a custom calibration was used to obtain VWC (Herkelrath et al. 1991). TDR readings were taken once every two weeks in the summer of 1995 and every week in 1996. Moisture profiles were obtained by interpolating between measured depths.

Precipitation was measured at the top of the canopy using standard and tipping bucket raingauges except at the 92-Plantation site where water collected in a **standard raingauge** (**SRG**) in a Nipher snow shield was used to estimate above-canopy precipitation. At the mature forest sites, SRGs were placed at each of the monitoring locations. A SRG was also placed at ground level in the 81-Plantation and 92-Plantation stands. The water in the SRGs and Nipher gauge was measured when TDR readings were taken.

Evapotranspiration (**E**) was estimated from **net radiation** (**R_n**), **soil heat flux** (**Q_g**), **temperature** (**T**), **vapour pressure** (**e_a**) and **windspeed** (**u**) measurements using the GD method (Granger and Gray 1989). This method extends Penman's (1948) equation to non-saturated conditions using a parameter termed **relative evaporation** (**G**).

$$E = [\Delta G(R_n - Q_g) + \gamma G E_a]/(\Delta G + \gamma) \quad (1)$$

where Δ is the slope of the saturation vapour pressure against T curve, γ is the psychrometric constant and E_a is the drying power.

$$E_a = f(u)\,(e^* - e_a) \quad (2)$$

where e^* is saturation vapour pressure and $f(u)$ depends on u (m s^{-1}) and surface roughness (z_0):

$$f(u) = a + bu \quad (3)$$

where:

$$a = 8.19 + 0.0022 z_0 \quad (4a)$$

$$b = 1.16 + 0.0008 z_0 \quad (4b)$$

An average roughness height (m) was determined from aerodynamic considerations and eddy correlation measurements for each for the four stands. G was obtained from a dimensionless relationship with the **relative drying power** (**D**).

$$G = 1/(0.793 + 0.2\, e^{4.902D}) + 0.006D \quad (5)$$

where:

$$D = E_a/(E_a + R_n - Q_g) \quad (6)$$

Q_g was measured at 50-mm depth as an average of three REBS soil heat flux plates at each stand. Unreplicated measurements of R_n, T, e_a and u were made 2 m above the canopy in each stand. R_n was measured using REBS net radiometers, T and e_a were measured by Vaisala HMP35CF temperature/relative humidity gauges and Weathertronics 2032 cup anaemometers measured u. Output from these instruments was recorded every 30 min. Estimates made using the GD method agreed very well with eddy correlation measurements made at the stands during the study period (Pomeroy et al. 1997).

Net precipitation delivery to the soil surface was calculated as a fraction of precipitation at the top of the canopy using all 1995 and 1996 SRG data. The Rutter interception model (Rutter and Morton 1977) was used to calculate interception and evaporation from the canopy so that within-stand variability in the water balance could be assessed. The above-canopy SRG and tipping bucket (or Nipher gauge in the 91-Plantation) were considered to be measures of **gross rainfall** (**P_g**) and the below-canopy standard raingauge measurements at each site were used as **net rainfall** (**P_n**). Incident rainfall either falls freely through the canopy (free throughfall) or is intercepted. Intercepted water may drip to the soil surface or be evaporated from the canopy. The rainfall reaching ground level consists of free throughfall and drip. In the Rutter model, rainfall is partitioned into throughfall, drip and evaporation by estimating the **canopy storage capacity** (***S***) and **throughfall coefficient** (***p***). Graphical methods developed by Leyton et al. (1967) were used to determine S and p. If evaporation is assumed to be negligible, after the canopy is saturated all incident rainfall will be delivered to the soil surface as either throughfall or drip. Therefore, the slope of a plot of P_g against P_n for large rainfall events should be unity and the y-axis intercept is S. For small rainfall events, drip is negligible and P_n/P_g is p. Stand evapotranspiration estimates were used to calculate evaporation from the canopy. We assumed that evaporation was satisfied first from canopy water storage and then through transpiration or evaporation from the soil surface. Although stem flow was measured at the aspen location it was omitted

Table 1. Percentages of sand and clay and dry bulk densities (Mg m^{-3}) for the four forest sites. Standard deviations are given in parentheses

Soil depth (m)	Pine		Mixed-Wood		81-Plantation		92-Plantation	
Sand								
0–0.05	79		50	(8)	45	(3)	65	(6)
0.05–0.1	76	(12)	51	(15)	46	(12)	61	(7)
0.1–0.2	70	(14)	51	(13)	52	(12)	61	(2)
0.3–0.5	65	(15)	52	(7)	53	(2)	61	(6)
0.7–0.9	73	(6)	45	(3)	57	(4)	52	(8)
1.4–1.6	93	(2)	43	(2)	57	(0)	56	(3)
Clay								
0–0.5	6		8	(4)	9	(1)	7	(1)
0.05–0.1	4	(1)	7	(3)	10	(3)	8	(2)
0.1–0.2	8	(4)	10	(2)	12	(7)	10	(4)
0.3–0.5	14	(9)	18	(5)	18	(1)	13	(1)
0.7–0.9	11	(2)	25	(5)	17	(0)	23	(5)
1.4–1.6	4	(1)	24	(3)	16	(1)	18	(2)
Bulk density								
0–0.05	1.07	(0.08)	1.03	(0.14)	1.03	(0.02)	1.08	(0.11)
0.05–0.1	1.11	(0.10)	1.15	(0.17)	1.12	(0.11)	1.21	(0.17)
0.1–0.2	1.45	(0.14)	1.34	(0.10)	1.35	(0.01)	1.43	(0.14)
0.3–0.5	1.56	(0.10)	1.35	(0.08)	1.41	(0.15)	1.65	(0.02)
0.7–0.9	1.67	(0.07)	1.43	(0.07)	1.54	(0.05)	1.63	(0.09)
1.4–1.6	1.79	(0.05)	1.65	(0.07)	1.71	(0.09)	1.69	(0.17)

Table 2. Final infiltration rates for locations and sites

	Final infiltration rates (mm h^{-1})										
	Pine		Mixed-Wood			81-Plantation			92-Plantation		
Closed	27	(21)^z	Aspen	9	(6)	Site 1	82	(46)	Ridge	41	(15)
Open	33	(8)	Open	35	(10)	Site 2	4	(1)	Furrow	10	(7)
Mid	15	(13)	Spruce	38	(32)	Ridge	16	(36)			
						Furrow	20	(82)			
Mean	**24**		Mean	**22**		Mean	**18**		Mean	**20**	

^{z}Geometric means and standard deviations.

from these analyses as it delivered water to the roots directly beneath the tree trunk and did not appear to affect moisture contents at the monitoring location.

Statistical Analysis

Since the infiltration data are log-normally distributed, geometric means were used in the analysis. All the other soil property data are normally distributed. Standard deviations have been included in tables and figures to describe the variability of the data. Since p is the slope of a regression line, variability was described by the standard error of the slope. Spearman rank correlation coefficients (Steel and Torrie 1980) were used to test for significant correlation between LAI and the canopy parameters, S and p.

RESULTS AND DISCUSSION

Soil Characteristics

The results of the particle size analysis are shown in Table 1. The textural classification for the soil at Pine site is loamy sand over sand, the Mixed-Wood site is sandy loam over loam, the Plantation sites generally have sandy loam textures. The surface soil texture is quite variable at all sites except the 92-Plantation where the recent mixing has resulted in a more uniform spatial distribution of soil material. Soil textures found at the Mixed-Wood and 81-Plantation sites are similar. The 92-Plantation has slightly more sand and the Pine is much sandier and has less clay than the other sites.

Dry bulk densities for the four sites are also shown in Table 1. Bulk densities are generally greater for the Pine site and 92-Plantation than the other sites. This reflects the high sand content at these sites but there may also have been some compaction during harvesting and replanting at the 92-Plantation. From these densities we estimate that total porosity ranged from 61% at the surface of the Mixed-Wood and 81-Plantation sites to 32% at 1.4- to 1.6-m depth at the Pine site.

The measured final infiltration rates and geometric means for the sites are shown in Table 2. Mean infiltration rates were slightly lower on the plantation sites than the mature forest sites. On the 92-Plantation site, final infiltration rates in the furrows were lower than those on the ridges. Gravity acting on the precipitation incident on the steeply sloping sides of the furrows may cause runoff into the furrows even if the infiltration capacity of the ridges has not been met. Since infiltration rates in the furrow bottoms are low, there is potential for runoff along the furrows during rainstorms. There were no differences between ridges and furrows at the 81-Plantation site but there did appear to be differences between sampling locations. Site 1 (LF layer) had higher mean infiltration rates than the site without an organic layer. At the

Table 3. Leaf area index, net precipitation fraction, throughfall coefficient and canopy storage capacity calculated for 1995 and 1996 data

	Leaf area index	Net precipitation fraction	Throughfall coefficient (*p*)	Canopy storage capacity (*S*) (mm)
Pine				
Open	1.99 (0.00)[z]	0.92	0.81 (0.05)[x]	0.89 (0.16)[z]
Closed	2.20 (0.01)	0.61	0.54 (0.05)	5.08 (0.75)
Mid	2.01 (0.01)	0.84	0.63 (0.06)	1.67 (0.27)
Mixed-Wood				
Open	1.72 (0.00)	0.83	0.77 (0.07)	1.05 (0.27)
Aspen	1.79 (0.01)	0.87	0.84 (0.02)	0.91 (0.24)
Spruce	2.90 (0.02)	0.42	0.42 (0.08)	5.71 (0.77)
81-Plantation	1.92 (0.01)	0.80	0.72 (0.04)	2.05 (0.24)
92-Plantation		0.89[y]		

[z]Mean and standard deviation.
[y]Calculated as standard raingauge (soil surface)/Nipher gauge (above canopy).
[x]Slope and standard error of slope.

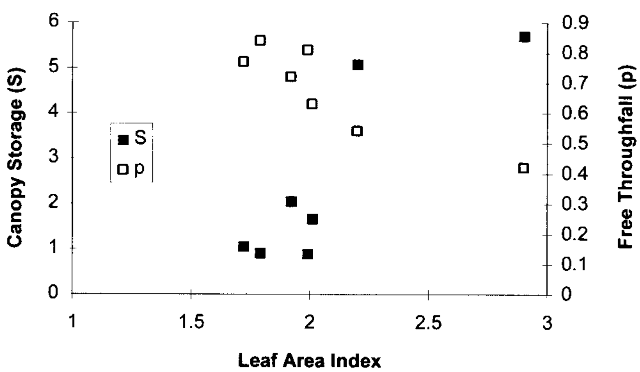

Fig. 1. Throughfall coefficient (*p*) and canopy storage (*S*) in relation to leaf area index.

Table 4. Estimated seasonal evapotranspiration (May to September) for the four sites

	Seasonal evapotranspiration (mm)	
Site	1995	1996
Pine	407	371
Mixed-Wood	359	322
81-Plantation	302	280
92-Plantation	288	259

Mixed-Wood site, final infiltration rates under the aspen tree were generally less than at the other two monitoring sites. There was no significant within-site variability at the Pine.

Canopy Characteristics

Net precipitation delivery to the soil surface, LAI, the throughfall coefficient (*p*) and canopy storage capacity (*S*) are shown in Table 3. The three canopy densities at the Pine site show the expected trend as interception increases with LAI. Although the LAIs are very similar for the open- and mid-canopy locations, the values for net precipitation fraction, *p* and *S* are quite different. The spruce location at the Mixed-Wood site had the smallest fraction of precipitation reaching the soil surface and the greatest LAI of all the locations studied. Although *S* was similar for the spruce location and the closed canopy in the Pine, *p* was larger for the latter site and therefore a greater fraction of precipitation reached the soil. There was more interception at the open location at the Mixed-Wood site than beneath the aspen tree despite a slightly higher LAI at the aspen site. Since the aspen canopy was not very dense, wind during rainfall could have caused greater apparent interception at the "open" location. The net precipitation fraction for the 81-Plantation was less than the mid- or open-canopy locations at the Pine site. As expected *S* showed the inverse trend, but *p* was more at the 81-Plantation than at the mid-canopy location. The LAI for the 81-Plantation was less than all locations at the Pine site. The similarity between the Pine site and the 81-Plantation indicates that the canopy was beginning to develop at the 81-Plantation site but did not yet have the structure of a mature stand. At the 92-Plantation site, there was little interception of precipitation.

The *S* and *p* coefficients for all sampling locations are plotted against LAI in Fig. 1. The inverse correlation between LAI and p was significant at $P = 0.05$ (Spearman $R = -0.82$) but the relationship between LAI and *S* was not significant. LAI appears to be a reasonable indicator of throughfall but storage is affected by structural features of the canopy which are not fully described by LAI measurements.

Evapotranspiration

Seasonal evapotranspiration, estimated by the GD method, is given for 1995 and 1996 in Table 4. Evapotranspiration estimates for the four sites averaged 30 mm less in 1995 than in 1996. The mature forest sites had greater evapotranspiration than the plantations. Evapotranspiration was greatest from the Pine site and least from the 92-Plantation. In both years, the Pine site lost almost 50 mm more than the Mixed-Wood site and approximately 100 mm more than the 81-Plantation.

Soil Moisture Storage

BETWEEN-SITE VARIABILITY. Stored soil moistures for the 0- to 1-m depth at the four sites in 1995 and 1996 are shown in Fig. 2. Throughout 1995 and 1996 the stored moisture in the 92-Plantation site was consistently greater than that on the other sites. The effect became even more pronounced after 14 June 1996 when the regenerating aspen at the site were thinned as part of a forest management practice. Moisture

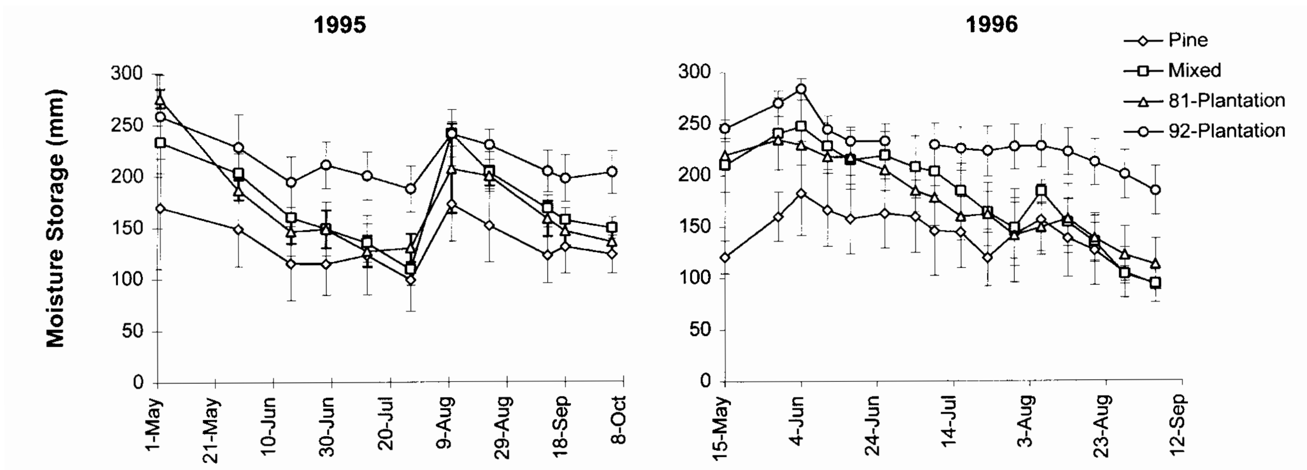

Fig. 2. Soil moisture storage to 1 m for the forest stands in 1995 and 1996. (Error bars show standard deviations.)

Table 5. Average soil moisture storage to 1 m (and standard deviations) during 1995 and 1996 for the sampling locations and the four stands

	Soil moisture storage to 0.5 m (mm)										
Pine			Mixed-Wood			81-Plantation			92-Plantation		
Closed	103	(20)	Aspen	175	(46)	Site 1	158	(46)	Ridge	217	(32)
Open	155	(27)	Open	166	(37)	Site 2	189	(39)	Furrow	229	(27)
Mid	159	(31)	Spruce	197	(54)	Ridge	171	(46)			
						Furrow	175	(45)			
Mean	**139**		Mean	**179**		Mean	**174**		Mean	**224**	

storage remained nearly constant in the 92-Plantation for about 6 wk after stand thinning while water contents decreased at the other sites. Moisture storage at the Pine site was generally less than at the other sites but the effect was not consistent during the measurement period. When the soils were relatively dry, the moisture stored in the Pine was similar to that in the Mixed-Wood and 81-Plantation.

The greatest moisture storage was measured in the spring of both years and on 10 August 1995 after a major rainfall event. At each site the moisture stored at these times was reasonably constant; 250 mm for the 92-Plantation, 230 mm for the Mixed-Wood site, 200 mm for the 81-Plantation and 170 mm for the Pine site. These values are probably reasonable estimates of profile field capacity. There is no evidence that wilting point (on a profile and stand basis) was reached, as the lowest measured moisture storage values were not repeated on consecutive sampling dates, but the declining decrease in stored moisture during dry periods at the Pine site may indicate that most of the available water was being removed.

The low soil moisture storage at the Pine site was probably partly due to the low field capacity of the sandy soil and interception of precipitation (Table 3). Although the soil at the 92-Plantation is lighter textured than the Mixed-Wood or 81-Plantation, its estimated field capacity was greater. Estimated seasonal evapotranspiration (Table 4) and interception of precipitation (Table 3) were lower on the 92-Plantation than the other sites. These factors in combination appear to have led to greater moisture storage.

WITHIN-SITE VARIABILITY. To summarize within-site variability, average soil moisture storage to 1-m depth from May to September of 1995 and 1996 was calculated for each monitoring location (Table 5). Within the Pine site, moisture storage to 1 m was less at the closed canopy location than at the open- or mid-canopy locations in both 1995 and 1996. Part of the difference is due to greater interception of rain and snow by the closed canopy but there was probably also some influence of root uptake and soil variability. Soil moisture storage at the open- and mid-canopy sites was similar although the mid-canopy site was slightly wetter in both years.

At the Mixed-Wood site, the spruce location was wetter than the other two locations. Soil moisture under the spruce tree was considerably greater after snowmelt than at the aspen or open locations but for the rest of the year moisture storage was similar for the three locations. The high spring moisture contents may have resulted from meltwater being channelled into the relatively snow-free area under the spruce canopy. During the rest of the year, low evapotranspiration withdrawals from the soils under the spruce canopy may have compensated for the high interception of precipitation (Table 3) to maintain soil moisture storage.

The furrow location at the 81-Plantation site stored only slightly more water to 1 m in 1995 and 1996 than the ridge location (Table 5). However, site 1 which had developed an LF layer and understory vegetation was drier than the more barren site 2 from mid-June to the end of the measurement period in each year. The differences were more pronounced in 1996, when incident precipitation was less than in 1995 and probably reflect evapotranspiration from the understory.

At the 92-Plantation there was a pronounced effect of ridge and furrow location on moisture storage to 1 m (Table 5). The furrow locations consistently stored 10 to 20 mm

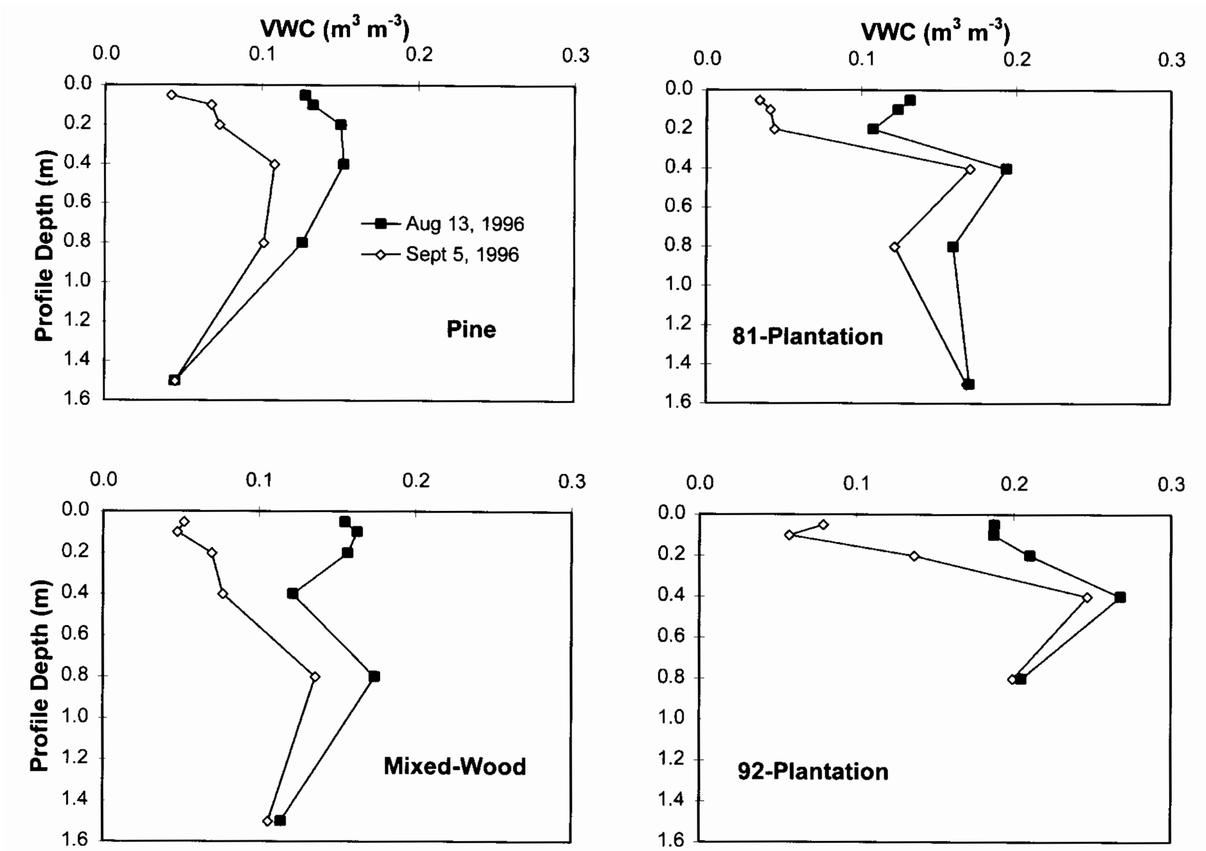

Fig. 3. Change in VWC at the study sites between 13 August and 5 September 1996.

more water than the ridges through 1995 and 1996. The greater moisture storage in the furrows could be a result of more incident water (due to gravity-induced runoff from the ridges), shading and less vegetative growth.

Water Use in a Drought Period

To identify differences in water use, between and within stands, changes in soil moisture were assessed by applying a water budget during a drought period. The water budget can be summarised by the simplified continuity equation:

$$P - E - D_p - R - \Delta S = 0 \quad (7)$$

where P is precipitation, E is evapotranspiration, D_p is drainage, R is runoff (or shallow subsurface horizontal flow) and ΔS is change in soil moisture storage. In a closed system, there is no drainage or horizontal flow and the change in soil moisture (corrected for incident precipitation) will be a measure of water-use at that location. When the water-use is averaged over the stand it should equal evapotranspiration.

Between 13 August and 5 September 1996, less than 10 mm of rain was measured at the SRGs under the forest canopy at all four sites. At the Pine and Mixed-Wood sites no significant precipitation was received in the week prior to this period but rain fell at the other sites (25 mm at the 81-Plantation and 10 mm at the 92-Plantation). The moisture profiles for the four stands at the beginning and end of the drought are plotted in Fig. 3. The overall change in soil moisture storage, stand evapotranspiration and below-canopy precipitation during the common drought period are shown in Table 6. Since this was a drought period, evaporation from water stored on the canopy was assumed to be

Table 6. Change in soil moisture storage (0 – 1.6 m), stand evapotranspiration (GD method) and below canopy precipitation (standard raingauge) for the drought period between 13 August and 5 September 1996

	Precipitation below canopy (mm)	Evapotranspiration (mm)	Change in soil moisture (mm)
Pine	7	58	**–45**[z]
Open	7		–53
Closed	7		–23
Mid	8		–60
Mixed-Wood	7	52	**–64**
Open	4		–68
Aspen	9		–34
Spruce	8		–78
81-Plantation	3	52	**–48**
Location 1			–43
Location 2			–54
92-Plantation	7	41	**–38**
Ridge			–42
Furrow			–33

[z]Bold numbers are averages of the sites within the stand.

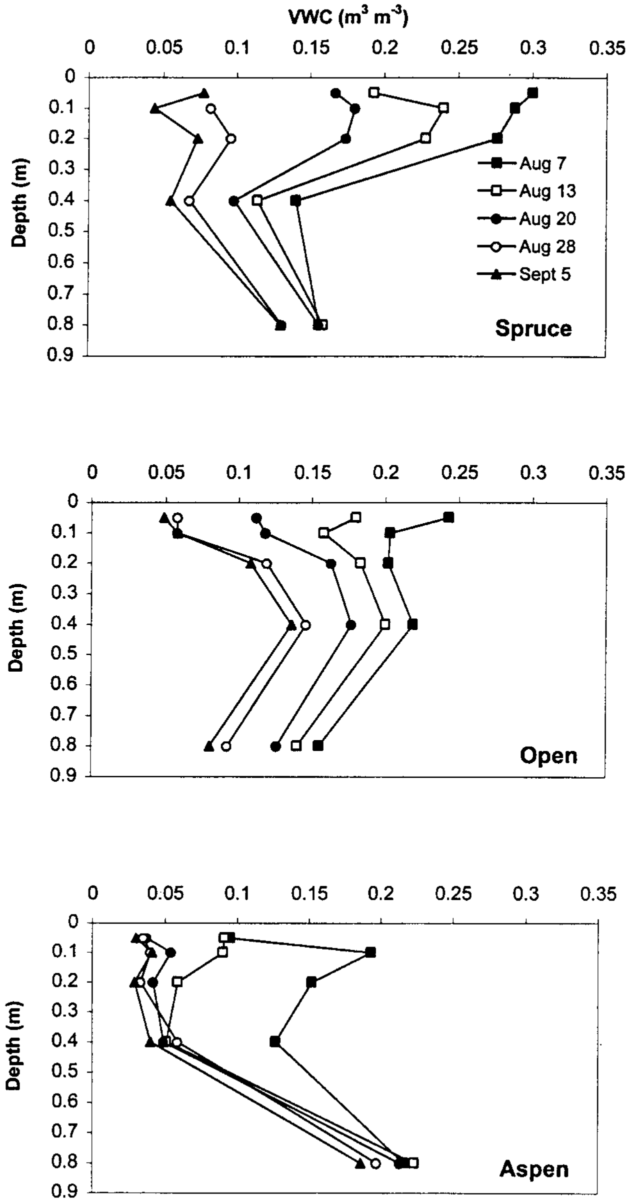

Fig. 4. Change in VWC within the Mixed-Wood site between 7 August and 5 September 1996.

negligible. Evapotranspiration followed the same pattern as seasonal evapotranspiration and was greatest from the Pine site, followed by the Mixed-Wood and 81-Plantation and then the 92-Plantation. On the Pine, Mixed-Wood and 81-Plantation sites water was extracted to a depth of 0.9 m during the drought period but at the 92-Plantation there was only a small decrease in moisture content at 0.3- to 0.5-m depth and no change at 0.7- to 0.9-m depth (Fig. 3). Since there still appears to be available water at 0.2 m in the 92-Plantation at the end of the drought period, it appears that the surface soil (0–0.2 m) has been able to satisfy the low evapotranspiration demand at this site. However, it is possible that root penetration and water extraction have been limited by the high bulk density at 0.3- to 0.5-m depth (Table 1).

At the 81-Plantation and 92-Plantation sites the change in water storage was balanced by below-canopy precipitation and stand evapotranspiration. Change in moisture was variable within stands at both sites. At the 92-Plantation there was more water-use on the ridge, where the aspen were growing, than in the furrows, where the white spruce were planted. There were no differences between ridges and furrows at the 81-Plantation site but water-use was less at site 1 than site 2. At the 81-Plantation water-use decreased in each week of the drought period indicating that water availability may have limited evapotranspiration. The decrease in soil moisture was similar for each week in the 92-Plantation.

At the mature forest sites, the average change in water storage was not balanced by evapotranspiration and precipitation. Since within-site variability was large in the mature forest (Table 6) a simple average of change in soil moisture may not be appropriate. At the Mixed-Wood site, an average of water use at the three locations overestimates stand evapotranspiration. Since aspen dominates this stand, the average water use should likely be weighted toward the low value obtained at the aspen location. If the average is weighted to account for the aspen covering 75% of the stand, the change in moisture storage would be 50.5 mm which nearly closes the balance. Stand evapotranspiration is likely underestimated by average water use at the Pine site because the small change in soil moisture measured at the closed canopy location is not representative of one-third of the site. If the closed canopy location is assumed to cover a realistic value between 15 and 20% of the site the water balance closes.

Within the Mixed-Wood stand, the pattern of water depletion varied considerably between locations (Fig. 4). At the spruce location, soil water contents decreased at a relatively constant rate throughout the drought period. Despite lower initial moisture contents at the open location, water storage declined steadily until the last week of the drought when withdrawals were less. The aspen location was driest at the start of the drought and most of the decrease in water content occurred in the first week of the drought period. Aspen have greater transpiration rates per unit of leaf area than spruce or pine trees (Peterson and Peterson 1992) and this may have translated to greater initial water-use at the aspen location than the spruce. Water-use later in the drought period appears to have been limited by low moisture availability.

Moisture content at 0.8-m depth declined only slightly during the drought at the spruce and aspen locations but decreased by 0.075 m^3 m^{-3} at the open location (Fig. 4). Apparently the grass roots were able to remove water from deeper in the profile than the tree roots. At the end of the drought period, moisture contents to 0.4-m depth at the aspen location were less than 0.05 m^3 m^{-3} but were still more than 0.15 m^3 m^{-3} at 0.8-m depth. This moisture appears to have been unavailable to the aspen roots. Van Rees (1995) found aspen roots densely concentrated in the upper 0.15 m and although some roots extended to 1-m depth, root activity at 0.9 m was low.

In the Pine site, available water at the closed canopy site was low at the start of the drought period. If water was not limiting, water-use at the closed and mid locations would likely be similar. From 7 to 13 August soil moisture declined 18.1 mm at the open location, 25.3 mm at the

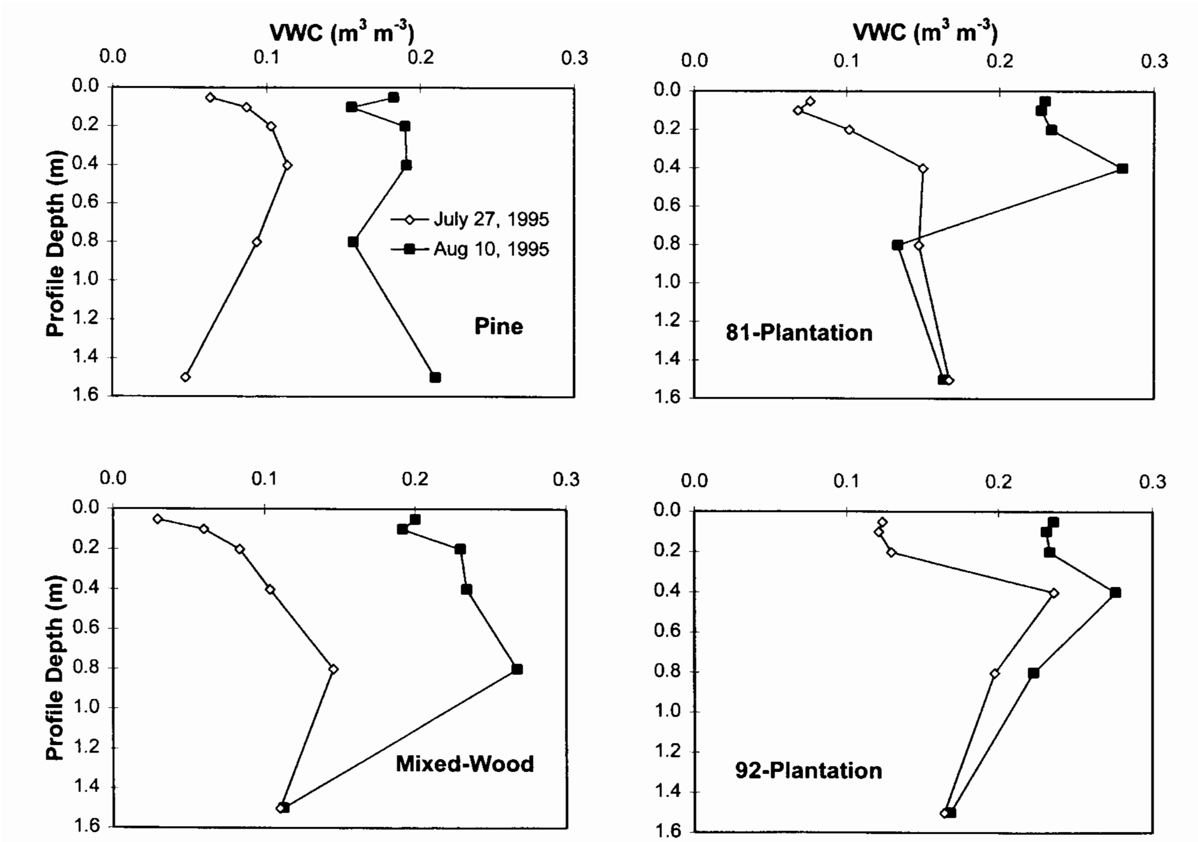

Fig. 5. Change in VWC at the study sites between 27 July and 10 August 1995.

Table 7. Water balance for forest stands between 27 July and 10 August 1995, during and following a major rainfall event

	Sub-canopy precipitation	Evapotranspiration[z]	Change in soil moisture to 1.6 m	Runoff
	(mm)			
Pine	**132**	**24**	**150**[y]	0
Open	137	27	81	
Closed	126	21	261	
Mid	133	24	107	
Mixed-Wood	**128**	**22**	**120**	0
Open	132	24	103	
Aspen	132	25	113	
Spruce	119	16	145	
81-Plantation	105	19	**67**	19
92-Plantation	111	19	**57**	35
Ridge			69.3	
Furrow			43.7	

[z]Stand evapotranspiration less evaporation of intercepted precipitation.
[y]Bold values are averages of measurements made at site.

closed location and 24.8 mm at the mid location. High water use appears to be part of the reason for low water contents observed at the closed canopy location in 1995 and 1996 (Table 5) but interception and soil factors are also involved.

Response to Intense Summer Rain

On 8 and 9 August 1995, more than 100 mm of precipitation was received at all four sites. The maximum intensity of the rainfall was 22 mm h^{-1} for a 30-min period early in the event. Although infiltration rates early in the event were likely to be greater than the steady-state rates, it is still interesting to compare the maximum intensity to the measured final infiltration rates. The maximum rainfall intensity was within the range of measured final infiltration rates (Table 2) and higher than a number of the measured rates including the furrow at the 92-Plantation, site 2 at the 81-Plantation and the aspen at the Mixed-Wood. The mature forest stands are in the Beartrap Creek basin, which is dominated by mature stands. No increase in streamflow was noted in the Beartrap Creek as a result of this event, but streamflow did increase in an adjacent basin with notable clear-cut portions (Pomeroy et al. [1997] data courtesy of Monitoring Operations Division, Water Survey of Canada).

The change in VWC at each site between 27 July and 10 August 1995 is plotted in Fig. 5. All sites gained moisture to 0.5-m depth but no increase in water storage occurred below this depth at the 81-Plantation site. At the Pine site, water entered the entire profile and drained to groundwater. No increase in moisture content was observed at 1.4 m in the Mixed-Wood and 92-Plantation sites and only a small increase in moisture content was measured at the 0.7- to 0.9-m depth in the 92-Plantation site.

Table 7 shows precipitation delivery to the soil surface, estimated evapotranspiration adjusted for evaporation from the canopy, the change in soil moisture to 1.6 m and runoff calculated from the water balance for the period between 27 July and 10 August 1995. On average, runoff only occurred at the two regenerating sites. Runoff losses from the 92-Plantation were almost double those from the 81-Plantation. Within the 92-Plantation site, soil moisture gains were greater on the ridges than the furrows. Prior to the event, moisture contents in the furrows were greater and therefore sorptivity and unfilled pore space would be less. Since the measured final infiltration rate for the furrows at the 92-Plantation site was exceeded during the storm, runoff losses may also have contributed to the relatively low recharge.

Antecedent moisture conditions also appear to have affected moisture gains in the Mixed-Wood stand. The greatest change in storage was found at the spruce location that received least precipitation before and during the storm and had the lowest soil moisture stored to 0.5 m on 27 July. At the Pine stand, the closed canopy location gained considerably more water than the other locations but most of the gain occurred at the deepest TDR waveguide. More than 40 mm of water were gained between 1.4- and 1.6-m depth suggesting that water may have flowed preferentially to that location from directly above and laterally.

SUMMARY AND CONCLUSIONS

The water stored in the soils of boreal forest stands reflects complex interactions between soil, canopy and vegetation water-use characteristics. Soil moisture storage at the pine site was less than at the other sites due to a combination of sandy soils, a dense canopy and high vegetation water-use. The sandy soil resulted in low porosity, low field capacity and free drainage below the sampling depth. Interception of precipitation by the pine canopy was generally high and evapotranspiration was 10 to 30% more than the other sites. Both interception and water use were greatest at the closed canopy location within the stand.

Average soil moisture storage and evapotranspiration at the Mixed-Wood site were intermediate between the Pine site and the 92-Plantation. However contrasting canopy types and vegetation water-use patterns resulted in notable within-site variability. Although the spruce canopy intercepted more precipitation than any of the other covers in the study, the average water storage was more than at the aspen or open (grass) locations. Preferential recharge during snowmelt and conservative water-use by the spruce tree appears to have sustained soil moisture. During a 4-wk drought period most of the available water at the aspen location was used in the first week and neither the spruce or aspen withdrew much water from below 0.5-m depth.

At the 81-Plantation, average soil moisture storage was similar to that at the Mixed-Wood site. Although canopy storage and interception were comparable to the Pine site the LAI indicates that the canopy was still not fully developed. Evapotranspiration was less than at the mature sites and a water balance of an extreme rainfall event indicated that there would have been some runoff from the 81-Plantation. The sampling location within the 81-Plantation with understory vegetation was drier than the other location but moisture storage was similar at ridge and furrow locations.

A combination of low evapotranspiration and interception of precipitation resulted in more water storage at the 92-Plantation than the other sites. The sandy-textured soil and low porosity did not appear to have affected moisture storage but high bulk densities could have contributed to somewhat lower infiltration rates. Runoff generated during a major rainfall event probably resulted from high initial moisture contents, low porosity and relatively slow infiltration rates. The runoff problem is intensified by the prominent ridges and furrows left by mechanical site preparation. Gravity acts to channel water into the furrows where soil moisture contents were higher and infiltration rates lower.

ACKNOWLEDGEMENTS

We thank D. Bayne, N. Hedstrom, K. Best, E. Richardson, K. Dion, J. Parviainen and D. Schill for technical assistance, the staff of the Prince Albert National Park and Weyerhaeuser for their co-operation and the Prince Albert Model Forest Association for their financial support.

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian System of Soil Classification. 2nd ed. Agriculture Canada, Ottawa, ON. Publ. 1646. 164 pp.

Bonan, G. B. 1990. Carbon and nitrogen cycling in North American boreal forests. I. Litter quality and soil thermal effects in interior Alaska. Biogeochemistry **10**: 1–28.

Bouwer, H. 1986. Intake rate: Cylinder Infiltrometer. Pages 635–662 *in* A. Klute, ed. Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA, SSSA, Madison, WI.

Culley, J. L. B. 1993. Density and compressibility. Pages 529–539 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL.

Fleming, R. L, Black, T. A. and Eldridge, N. R. 1994. Effects of site preparation on root zone soil water regimes in high-elevation forest clearcuts. For. Ecol. Manage. **68**: 173–188.

Gash, J. H. C., Wright, I. R. and Lloyd, C. R. 1980. Comparative estimates of interception loss from coniferous forests in Great Britain. J. Hydrol. **48**: 89–105.

Granger, R. J. and Gray, D. M. 1989. Evaporation from natural nonsaturated surfaces. J. Hydrol. **111**: 21–29.

Granger, R. J. and Pomeroy, J. W. 1997. Sustainability of the western Canadian boreal forest under changing hydrological conditions. II. Summer energy and water use. Pages 243–250 *in* D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz, and P. Rasmussen, eds. Sustainability of water resources under increasing uncertainty. International Association of Hyrological Sciences Publ. No. 240, IAHS Press, Wallingford, UK.

Greacen, E. L. and Sands, R. 1980. Compaction of forest soils: A review. Aust. J. Soil Res. **18**: 163–189.

Herkelrath, W. N., Hamburg, S. P. and Murphy, F. 1991. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resour. Res. **27**: 857–864.

Hormann, G., Branding, A. Clemen, T. Herbst, M. Hinrichs, A. and Thamm, F. 1996. Calculation and simulation of wind controlled canopy interception of a beech forest in Northern Germany. Agric. For. Meteorol. **79**: 131–148.

Huang, J., Lacey, S. T. and Ryan, P. J. 1996. Impact of forest harvesting on the hydraulic properties of surface soil. Soil Sci. **161**: 79–86.

Leyton, L., Reynolds, E. R. C. and Thompson, F. B. 1967. Rainfall interception in forest and moorland. Pages 527–543 *in* W. E. Sopper, and H. W. Lull, eds. International Symposium on Forest Hydrology, Pergamon Press, Oxford, UK.

Marston, R. B. 1962. Influence of vegetation cover on soil moisture in southeastern Ohio. Soil Sci. Soc. Am. Proc. **26**: 605–608.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. (Lond.) **A193**: 120–145.

Peterson, E. B. and Peterson, N. M. 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces, Canada. Special Report 1, Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, AB.

Pomeroy, J. W. and Granger, R. J. 1997. Sustainability of the western Canadian boreal forest under changing hydrological conditions. I. Snow accumulation and ablation. Pages 237–242 *in* D. Rosjberg, N. Boutayeb, A Gustard, Z. Kundzewicz, and P. Rasmussen, eds. Sustainability of water resources under increasing uncertainty. International Association of Hydrological Sciences Publ. No. 240, IAHS Press, Wallingford, UK.

Pomeroy, J. W., Granger, R. J., Pietroniro, A., Elliott, J. A., Toth, B. and Hedstrom, N. 1997. Hydrological pathways in the Prince Albert Model Forest. National Hydrology Research Institute Contribution Series No. CS-97004, Environment Canada, Saskatoon, SK. 154 pp.

Rowe, J. S. 1972. Forest regions of Canada. Canadian Forest Service Publ. No. 1300. 170 pp.

Rutter, A. J. and Morton, A. J. 1977. A predictive model of rainfall interception in forests, III. Sensitivity of the model to stand parameters and meteorological variables. J. Appl. Ecol. **14**: 567–588.

Sheldrick, B. H. and Wang, C. 1993. Particle Size Distribution. Pages 499–511 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL.

Steel, R. G. D and Torrie, J. H. 1980. Principles and procedures of statistics: A biometrical approach. 2nd ed. McGraw-Hill Book Company, New York, NY.

Steinbrenner, E. C. and Gessel, S. P. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Am. Proc. **19**: 372–376.

Topp, G. C. 1993. Soil water content. Pages 541–557 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL.

Topp, G. C., Davis, J. L. and Annan, A. P. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. Water Resour. Res. **16**: 574–582.

van Rees, K. 1995. Rooting patterns of boreal tree species. A report submitted to the Prince Albert Model Forest Association.

Youngberg, C. T. 1955. Some site factors affecting the success of reforestation and afforestation activities in the Willamette Valley Foothills. Soil Sci. Soc. Am. Proc. **19**: 368–372.