COFRDA REPORT 3317

Hydrology of Drained and Undrained Black Spruce Peatlands: Streamflow and Hydrologic Balance

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1991

Canada-Ontario
Forest Resource Development Agreement
Entente sur la mise en valeur de la ressource forestière

Catalogue No. Fo 29-25/3317E
ISBN 0-662-18738-5
ISSN 0847-2866

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This report was produced in partial fulfilment of the requirements of Project 33029, "Effects of Forest Drainage on the Hydrology of Black Spruce Swamp and Low-ground Sites", under the Research, Development and Applications Sub-program of the Canada-Ontario Forest Resource Development Agreement. This work was also supported by the Federal Panel on Energy Research and Development (PERD), ENFOR Project P-328.

Berry, G.J. 1991. Hydrology of drained and undrained black spruce peatlands: streamflow and hydrological balance. For. Can., Ont. Region, Sault Ste. Marie, Ont. COFRDA Rep. 3317. 25 p.

ABSTRACT

Hydrological parameters were measured during the snowmelt and snow-free periods of 1987, 1988 and 1989 in forested drained and undrained peatland basins. Snowmelt was the major source of streamflow, contributing 42 to 72% of seasonal flows. In comparison with an undrained basin, drainage decreased snowmelt flows by 48% in one basin, and increased flows by 248% in another basin. Storm flows were decreased and increased, respectively, in the same way as snowmelt for the two basins. Drainage consistently increased lag time and hydrologic response. Drainage increased flow during the summer low period by between 23 and 245%. The major factors controlling these effects were the quantity of precipitation and soil moisture capacity before precipitation occurred. Whether drainage increased or decreased flows depended on the physical characteristics of the basins, such as total ditch length, and the orientation and position of surround ditches. Drainage increased storage of water and evapotranspiration when atmospheric conditions were dry. Actual evapotranspiration values for the undrained basins were from 17 to 76% less than potential evapotranspiration values.

RÉSUMÉ

Les paramètres hydrologiques ont été mesurés pendant des périodes de dégel et d'absence de neige en 1987, 1988 et 1989 dans des bassins de tourbières drainés et non drainés. La fonte des neiges représentait la principale source des débits d'eau, avec 42 à 72 % des débits saisonniers. Comparativement à un bassin non drainé, le drainage a entraîné une diminution de 48 % des débits de fonte dans l'un des bassins, et une augmentation de 248 % de ces débits dans un autre bassin. Les débits pluviaux ont augmenté et diminué de la même façon que les débits de fonte des neiges, et ce dans les deux bassins déjà mentionnés. Le drainage a systématiquement augmenté le temps de réponse et la réaction hydrologique. Le drainage a augmenté le débit de 23 à 245 % pendant la basse période estivale. Les principaux facteurs déterminant ces effets étaient la quantité de précipitations et la capacité en humidité du sol avant

les précipitations. Le drainage a augmenté ou diminué le débit selon les caractéristiques physiques des bassins, comme la longueur totale du fossé ainsi que l'orientation et l'emplacement des fossés alentour. Le drainage augmentait le stockage de l'eau et l'évapotranspiration lorsque le temps était sec. Les valeurs réelles d'évapotranspiration pour les bassins non drainés étaient de 17 à 76 % inférieures aux valeurs d'evapotranspiration possibles.

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INTRODUCTION

In Ontario, more than 8 million hectares of productive black spruce (*Picea mariana* [Mill.] B.S.P.) forest grow on peatland (Ketcheson and Jeglum 1972). Forest drainage can increase tree growth by lowering the groundwater table (Payandeh 1973, Stanek 1977, Heikurainen and Joensuu 1981, Dang and Lieffers 1989). Drainage can also affect the biotic and abiotic components of a peatland ecosystem by altering the moisture regime within the peat. One abiotic component is the hydrologic (or water) balance. In simple terms, this balance is comprised of inputs, such as precipitation (PPT), and outputs, such as streamflow (Q), interception (I), evapotranspiration (ET) and changes in storage (ΔS). In equation form:

$$PPT = Q + I + ET + \Delta S$$

Most research has concentrated on streamflow because of its importance within the balance.

Streamflow is the "residual" output, since the other outputs occur on-site. Hence, those factors affecting interception, evapotranspiration and storage also influence streamflow indirectly. For an undrained peatland, factors that affect outputs include: topography, location and area of the peatland within the landscape, type of peat, type of vegetative cover, amount and intensity of precipitation, and soil moisture conditions before precipitation (Starr and Päivänen 1986, Verry et al. 1988). Once a peatland is drained, outputs are also affected by the type of ditch and drainage intensity (Starr and Päivänen 1986). Because of interactions among these factors, the response of the outputs to drainage will vary according to the drainage prescription and the specific conditions of the site.

Lowering the groundwater table by drainage increases the soil moisture capacity (i.e., storage) of the upper peat layer and either increases or decreases evapotranspiration. Evapotranspiration is increased if the water table is maintained within reach of moss and tree roots and is decreased if the water table is lowered beyond their reach (Heikurainen and Joensuu 1981, Ahti 1987, Verry 1988). During dry periods, when evapotranspiration tends to decrease as a result of the lower water table, low flows from drained areas are 20 to 50% greater than from undrained areas (Seuna 1982, Lundin 1988, Vompersky et al. 1991). This is attributed to the interception of groundwater flow by the ditches. Peak flows are influenced by the moisture conditions before a rainfall (i.e., the position of the water table). For a given storm event, drainage will result in increased peak flow if the soil moisture capacity is low (i.e., a high water table), or decreased peak flow if the capacity is high (i.e., a low water table) (Boelter and Verry 1977, Heikurainen 1980, Fitzgibbon 1982).

As can be seen, the effects that drainage has on water balance are varied. The development of operational drainage guidelines requires research into the ecological and physical changes that drainage causes in peat environments. Drainage of forested peatlands to improve tree growth is being investigated in several regions of Canada (Hillman 1987). A project was initiated in 1984 by the Ontario Ministry of Natural Resources, in cooperation with Forestry Canada's Ontario Region, to study forest drainage and produce the necessary management guidelines (Koivisto 1985, Rosen 1986a, Jeglum 1991). This paper is one of a series dealing with the hydrological impacts of drainage at The Wally Creek Area Forest Drainage Project. Two papers have dealt with groundwater table profiles and fluctuations (Berry and Jeglum 1988, 1991a), and two with water quality (Berry 1991, Berry and Jeglum 1991b).

The objective of the present study was to examine the influence of drainage on the water balance of forested swamps of the main peatland site types, as determined from the Forest Ecosystem Classification (Jones et al. 1983). These site types, termed Operational Groups (OGs), are defined as landscape segments with mature forest that have an identified range of vegetational conditions, soil conditions and probable responses to specific management prescriptions.

METHODS

Study Area

The Wally Creek Area Forest Drainage Project is located 30 km east of Cochrane, Ontario (49°3' N, 80°40' W), in the Northern Clay Section of the Boreal Forest (Rowe 1972). Climatic data for Cochrane (Anon. 1982a,b,c) show that the area has a continental climate, with cold winters and warm, moist summers. The mean annual temperature is 2°C, with monthly means averaging between -18°C (January) and 17°C (July) and extremes of -45°C and 38°C. Approximately 66% of the total annual precipitation of 885 mm occurs as rain. More than 42% of the total (378 mm) occurs as rain from June through September. The remainder is evenly distributed throughout the other months. There is an average of 1328 degree-days (>5°C) per year and potential evapotranspiration (Thornthwaite's method) is estimated to be 490 mm/year (Anon. 1985).

The flat topography of the Wally Creek area, which generally has a slope of <0.3%, has a natural drainage towards the northwest. The depth of peat is variable (<30 to >300 cm) and overlies a heavy clay of lacustrine origin. The area is an uneven-aged (50 to 140 years, 8 to 17 m tall) black spruce (*Picea mariana* [Mill.] B.S.P.) upland and swamp that has been site-typed according to the Forest Ecosystem Classification (Jones et al. 1983). The main types are OG8 – Feathermoss – *Sphagnum*; OG11 – *Ledum*; OG12 – *Alnus* – Herb Poor; and OG14 – *Chamaedaphne*. These sites are characterized by a black spruce canopy with an understory variously dominated by *Alnus rugosa*, *Ledum groenlandicum*, *Vaccinium myrtilloides* and *Chamaedaphne calyculata*. The moss layer is composed of varying proportions of *Sphagnum nemoreum*, *S. fuscum*, *S. magellanicum*, *S. girgensohnii*, *Pleurozium schreberi* and *Ptilium crista-castrensis*.

Drainage Prescription

The ditches (Fig. 1) in the ca. 450 ha area north of the road were planned and installed in 1984 to Finnish standards, through the services of an experienced Finnish consultant and machine operators (Koivisto 1985, Rosen 1986b). Spacing of ditches was based on Finnish guidelines for sites equivalent to the OGs. The recommended spacings were from 30 to 50 m, to give an average water-table depth of from 40 to 45 cm between ditches. Actual spacings between ditches ranged from 19 to 75 m in order to verify the applicability of the Finnish recommendations under site and climatic conditions in northern Ontario. Almost 72 km of ditches were installed in 280 ha, giving a mean ditch density of 254 m/ha. In most of the area, side ditches averaged 90 cm in depth; collector and surround ditches averaged 120 cm in depth. In 1985, an additional 170 ha area were clearcut and 59 ha were drained. In total, 339 ha were drained.

Basin Description

Four basins were identified in the Wally Creek area (Fig. 1). Two of these basins were undrained controls (basins 1 and 2) and two were drained treatments (basins 3 and 4). One of the treatments consisted of an area almost completely drained (basin 4), whereas the second treatment contained a drained area within a larger undrained area (basin 3). In addition, a sub-basin between basins 1 and 3 was identified.

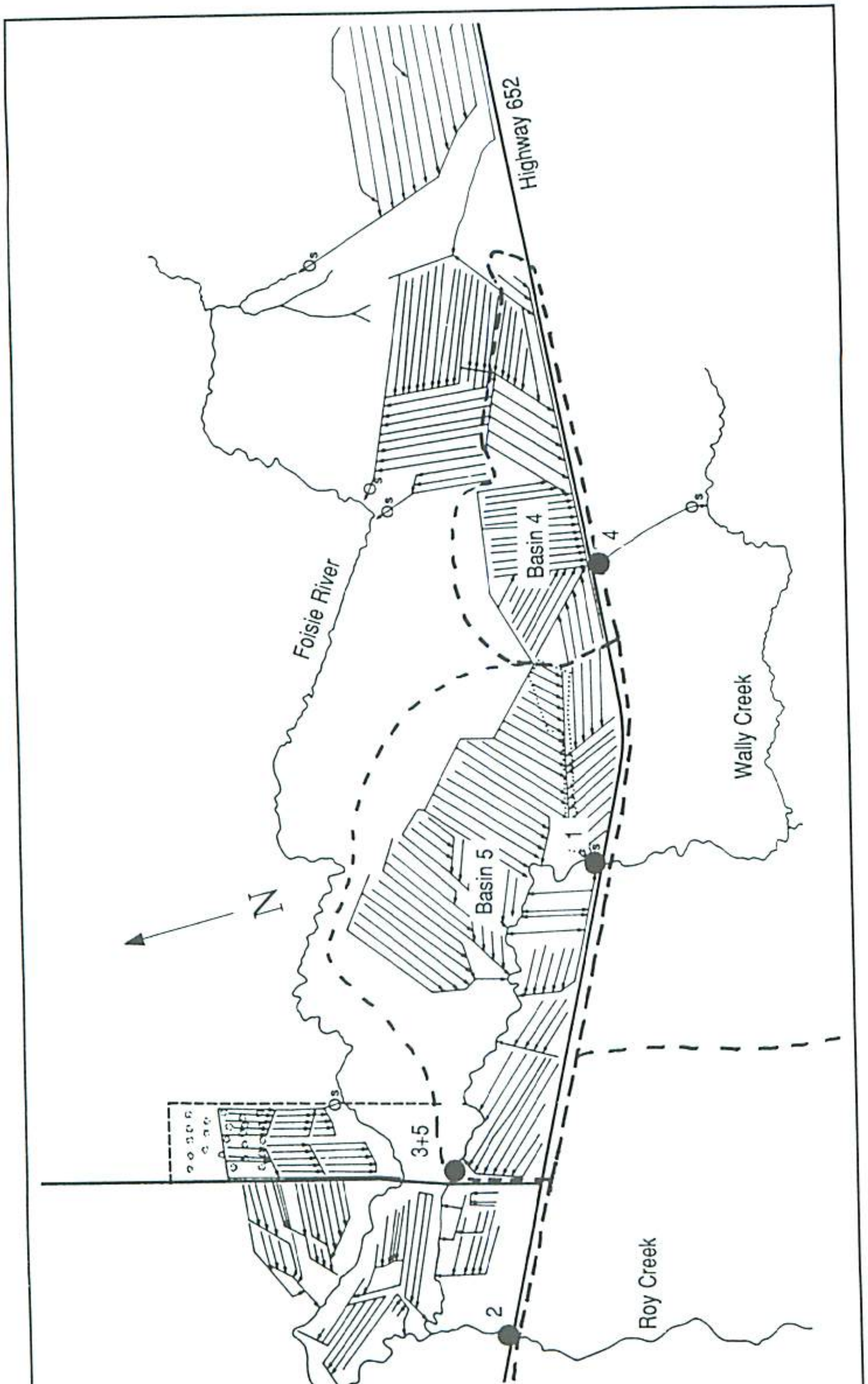

Figure 1. Map of drainage network, showing basin outlet gauging sites and drained basins 4 and 5.

This treatment basin (basin 5) is essentially the drained area within basin 3. It should be noted that this was not a paired-watershed design because of the lack of calibration (i.e., pretreatment) data. The effects of drainage on various hydrological parameters could only be inferred from the comparison of the drained and undrained basins. Basin boundaries are difficult to define in peatlands because of the indistinct phreatic divides (Boelter and Verry 1977). The boundaries in this study were determined from topographic maps and aerial photos. The morphology of the basins is described in Table 1. Although the collector ditch from basin 4 empties into Wally Creek upstream of the outlet to basin 1, the effects were assumed to be minimal as a result of the potential for much greater flow in Wally Creek, as indicated by the respective basin areas (12.97 vs. 0.67 km^2).

Measurement of Streamflow

The basin outlets were selected as flow-measurement sites. "Stilling" wells (vertical culverts) were established at each site and instrumented with Stevens Type-F water-level recorders. The usual chart speed was 1.5 cm/day, but this speed was increased to 24.0 cm/day immediately before anticipated storm events in order to increase the precision of the stage measurements. Streamflow at each site was measured with a Price AA-type current meter using standard metering procedures (Hewlett 1982). Measurements were taken 51 times over three field seasons (August to October in 1987; April to October in 1988 and 1989). Various flow rates were measured, including numerous storm flows, to establish the stage-discharge relationships required to transform the stage data (i.e., water levels) from the recorders into flow values.

Measurement of Precipitation, Throughfall and Storage

Hourly total precipitation was measured with a tipping-bucket rain gauge. Six "trough" throughfall gauges were placed randomly throughout the area. The long, narrow shape of the gauges (i.e., 10 cm x 150 cm) permitted an "average" (i.e., representative of exposed ground and ground beneath the canopy) throughfall to be collected

Table 1. Description of the basins.

Basin no.	Location	Area (km^2)	Length of stream (km)	Area drained (km^2)	Area drained (%)	Length of ditches (km)	Density	
							Ditches (m/ha)	Channels[a] (km/km^2)
1	Wally Creek – upstream of drainage – control	12.97	8.4	-	-	-	-	0.65
2	Roy Creek – upstream of drainage – control	4.66	2.1	-	-	-	-	0.45
3	Wally Creek – downstream of drainage – treatment	14.99	9.7	1.39	9	31.8	229	2.77
4	Collector ditch – treatment	0.67	0	0.58	87	16.2	279	24.18
5	Wally Creek – between basins 1 and 3 – treatment sub-basin	2.02	1.3	1.39	69	31.8	229	16.39

[a]"Channels" refers to natural watercourses and drainage ditches.

because each gauge was beneath the canopy as well as being beneath openings in the canopy. The gauges were maintained at their locations throughout the field seasons. The amount of throughfall was measured after each storm event.

The storage components of the water balance comprise surface storage, field (soil) moisture storage, groundwater storage and channel storage (Hewlett 1982). Of these, only groundwater storage was assumed to be significant over the course of a field season. Groundwater storage was determined by measuring seasonal fluctuations in the depth of the groundwater table below the peat surface. The depths were measured in representative drained and undrained areas within the basins by using water-table wells, described in Berry and Jeglum (1991a).

Data Analysis

Streamflow

The water-level records were interpreted for date, average daily stage, daily maximum stage, daily minimum stage, and times of maximum and minimum stages. Stage-discharge (h-Q) relationships for basins 1 to 4 were developed from stage and flow measurements. During the snowmelt event, flows from basins 1, 2 and 3 were very high. The stage-discharge relationships were best described by a linear function. For the non-snowmelt period in basins 1-3, and for the entire season in basin 4, the relationships were described by a logistic function (Swokowski 1975). The outlets of the basins were affected by the presence of culverts either upstream or downstream and the logistic function accounted for the fact that a culvert begins to impede flow when the stage approaches the mid-point of the cross-section of the culvert. The resulting equations were tested using a sub-set of the stage and flow data that was not included in the generation of the equation parameters. The parameters and r^2 values for the test data are given in Table 2. The equations were used to calculate continuous measurements of flow from the interpreted stage records. Streamflow for basin 5 was calculated as the difference in flow between basins 1 and 3.

The flow data were used to generate seasonal and storm hydrographs and flow-duration curves, and to calculate basin lag time and hydrologic response. Basin lag is the time from the centroid (time at which one half of the rain from a storm has fallen) of rainfall to peak flow and is a function of basin area and topography (Dunne and Leopold 1978). Smaller basins will have a shorter lag time because the water does not have to travel as far, whereas steeper basins have a shorter lag because the water is moving faster. The effect of drainage on lag time was determined in two stages. First, the effects of area were discounted using a regression equation based on time versus area (Dunne and Leopold 1978); the data from basins 1, 2 and 3 were applied to basin 4. Then, the predicted lag time for an undrained basin the same size as basin 4 was compared with the actual lag time to identify the drainage effect. Data from basin 3 could be included in the development of the equation because only a small portion (i.e., 9%) of the basin's area was drained.

Hydrologic response (R) is the ratio of stormflow to storm precipitation and is a function of soil moisture capacity (Hewlett 1982). It is therefore influenced by antecedent soil-moisture conditions. Stormflow was determined using a straight-line base-flow separation technique (Dunne and Leopold 1978). Paired t-tests using average daily flow per unit area (i.e., $m^3\ sec^{-1}\ km^{-2}$) and stormflow per unit area were performed to detect any statistically significant differences between the basins (Steel and Torrie 1980). For some analyses, such as those for seasonal total flows and water balance calculations, 1987 data were not included because data from that field season were incomplete. Seasonal hydrographs, time of snowmelt peak flows, and storm lag times for basin 5 were not calculated because flows from this basin were not explicitly measured.

Table 2. Stage – discharge equation parameters.

Basin no.	Flow period	Parameter K1	Parameter K2	Parameter K3	r^2
1	melt	0.0609	-6.34	n/a	0.99
	non-melt	1.7	6.42	-0.0630	0.96
2	melt	0.0346	-2.29	n/a	0.94
	non-melt	0.7	5.52	-0.0732	0.88
3	melt	0.0378	-3.52	n/a	0.98
	non-melt	2.0	5.31	-0.0476	0.97
4	melt + non-melt	0.16	4.50	-0.182	0.96

Form of equations: Melt period $Q = (K1 \times h) + K2$
Non-melt period equation – $Q = K1 / (1 + e\ )$
where $n = K2 + (K3 \times h)$, Q = flow (m^3/s) and h = stage (cm).

Precipitation, Throughfall and Storage

The precipitation data were analyzed to obtain storm, weekly and seasonal totals. The distribution of weekly totals was compared between years by using one year's results as a base value and subtracting it from values for the others. The differences were plotted to show periods of comparative wet and dry conditions. For comparison, the monthly 30-year norm precipitation values were also examined. The precipitation data for 1987 were not included in this examination because data for that field season were incomplete.

Interception was calculated by subtracting throughfall from precipitation and expressing the result as a percentage of precipitation. Values from the six gauges were averaged to give a mean value for the entire area.

Changes in the groundwater storage component of the water balance were calculated by expressing the seasonal fluctuations of the water table as an "area depth" of water in each basin. Area depth is the difference between average depths to water table measured in the water wells at the beginning and end of the snow-free season.

Water Balance

Water balances for the 1988 and 1989 field seasons were calculated using seasonal input and output totals. Evapotranspiration was the only component of the balance not directly measured. It was calculated as the residual of the balance (i.e., the remainder when all other measured components had been summed). For comparison purposes, potential evapotranspiration was calculated using meteorological data from Cochrane airport and Thornthwaite's (Dunne and Leopold 1978) and Holdridge's (1962) methods.

RESULTS AND DISCUSSION

Snowmelt-period Streamflow

The most prominent feature of the hydrographs for 1988 and 1989 (Fig. 2 and 3) was the dominance of snowmelt as a source of streamflow. The daily flows ranged from less than 0.2 $m^3\ sec^{-1}$ for basin 4 to more than 4.0 $m^3\ sec^{-1}$ for basin 3. The magnitude of flow increased with increasing basin size. The snowmelt contributed from 42 to 53% of total seasonal (April to October) flow in 1988 and from 47 to 72% in 1989 (Table 3). The drained basins had the lower percentages in 1988 and the lowest and highest in 1989. The 1989 values were higher because of drier post-snowmelt conditions. In both years, the snowmelt runoff period was short — about 28 days. The three peak occurrences in 1989 (Fig. 3) were the result of thawing and freezing weather patterns.

There were two factors that could account for the importance of snowmelt flow. First, the study area was in a snow-dominated climate, where a major portion of total annual precipitation was stored as snow for release during the snowmelt. Approximately one-half (46 to 52%) of the total precipitation was made available for flow during the snowmelt period (Table 3). Second, frost reduced the soil's moisture capacity to a minimum, which prevented infiltration of snowmelt and allowed more precipitation to become flow (Heikurainen 1976).

Because of the frost, soil moisture capacities of drained and undrained areas were not only minimal, but were also similar (Heikurainen 1976). Any differences in peak flow between drained and undrained areas were therefore due to the ditches and the size of the basins, and not soil moisture conditions. Where there was accelerated flow from a drained area, it was because the ditches provided easier movement of overland flow off the site. The melting of snow that accumulated in ditches also tended to increase peak flows, but only if the timing of ditch snowmelt was synchronized with snowmelt from the surrounding treed areas. This timing would depend on the energy regime along the openings in the forest created by ditching (Berry 1985).

Drainage did not appear to affect the magnitude of 1988 peak-melt flows. Flows from the three drained basins were from 92 to 102% of those from undrained basin 1 (Table 4). The 1989 peak flows from heavily drained basins 4 and 5 were 14 and 23% higher, respectively, than those from basin 1. Increases of this magnitude were noted by Seuna (1980, 1982). In each year, peak flows from basins 1, 2 and 3 occurred on the same day, while peak flows from basin 4 occurred one day earlier.

The differences between undrained basins 1 and 2 suggest that there was some variability in peak flows. Basin 1 was used for comparison instead of basin 2 because of its larger size (Table 1). The area of a large peatland basin can be

Table 3. Total snowmelt and non-snowmelt flow and total precipitation, expressed as an area depth (mm).

	Snowmelt period		Non-snowmelt period		Total		% of Total: Snowmelt period		% of Total: Non-snowmelt period	
Basin no.	1988	1989	1988	1989	1988	1989	1988	1989	1988	1989
1	303	306	307	236	610	542	50	57	50	43
2	344	276	301	134	645	410	53	67	47	33
3	315	367	325	242	640	609	49	60	51	40
4	223	158	303	179	526	337	42	47	58	53
5	392	759	441	281	833	1040	47	73	53	27
PPT[a]	468	305	440	354	908	659	52	46	48	54

[a] precipitation for snowmelt period estimated from Cochrane airport data and includes snow-water equivalent at onset of melt period.

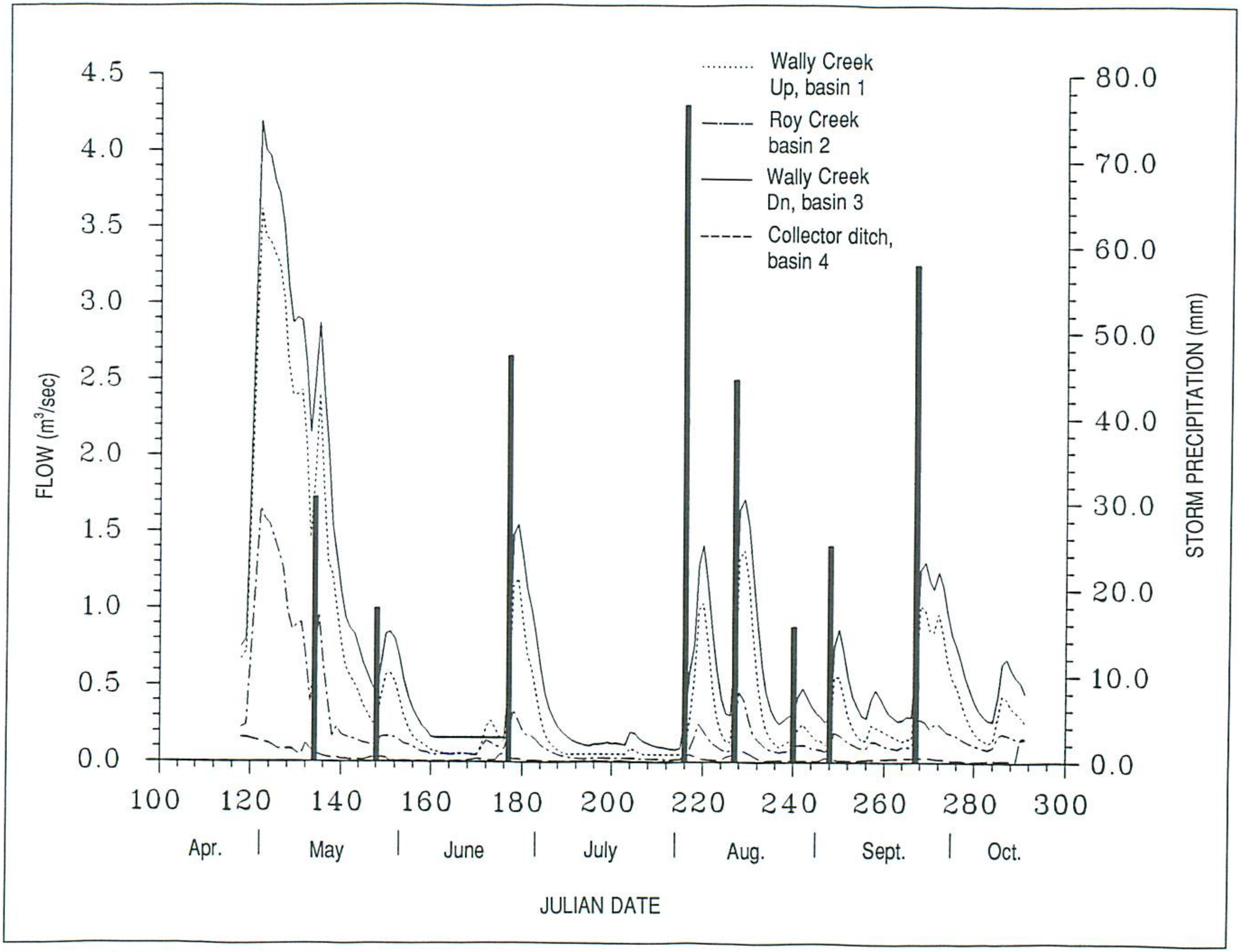

Figure 2. 1988 hydrographs for basins 1 to 4, showing storm events.

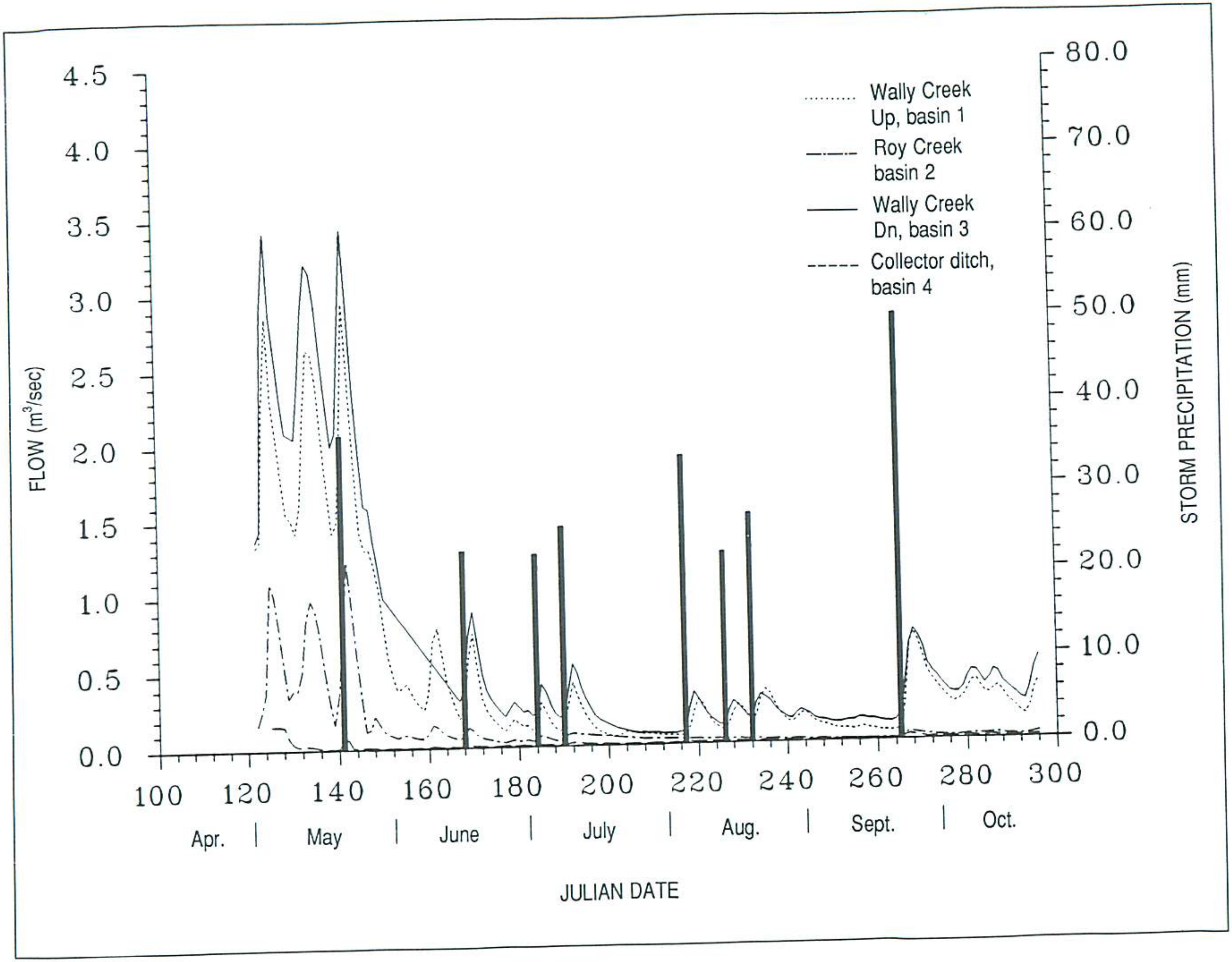

Figure 3. 1989 hydrographs for basins 1 to 4, showing storm events.

Table 4. Snowmelt period peak flows, expressed as $m^3 sec^{-1} km^{-2}$ and as ratio of basin 1.

Basin no.	$m^3 sec^{-1} km^{-2}$		Ratio	
	1988	1989[a]	1988	1989[a]
1	0.279	0.217	1.00	1.00
2	0.355	0.237	1.27	1.09
3	0.280	0.224	1.00	1.03
4	0.257	0.248	0.92	1.14
5	0.284	0.266	1.02	1.23

[a] 1989 flows calculated as average of the three peak-flow occurrences.

determined with a lower percentage of error than that of a small basin. The hydrographs show that although basin 4 did drain into basin 1, the effect in terms of absolute flow (i.e., $m^3 sec^{-1}$) was minimal.

Non-snowmelt-period Streamflow

Total Flow

Flows for the snow-free period (about 146 days) were from 47 to 58% of total seasonal flow in 1988 and 27 to 53% in 1989 (Table 3). All the basins had similar flows in 1988, except basin 5, which had substantially greater flows (Table 5). Flows from control basin 2 and drained basins 4 and 5 decreased significantly between 1988 and 1989 (Table 5). This decrease was probably due to a combination of lower precipitation in 1989 and differing basin characteristics. Flows from basin 3 were similar to those from basin 1 in both years.

Total non-snowmelt period precipitation for 1989 was 356 mm, compared with 490 mm in 1988, a 20% difference (Table 6). For the 4 months with complete records, 1989 precipitation averaged only 3% less than that in 1988 over the 30-years for which data was available. However, examining individual months showed that 1989 was drier in August and September, slightly drier in June, and wetter (but still less than normal) in July. On a weekly basis, differences between the years were even greater (Fig. 4). Out of 20 snow-free weeks, 1989 was drier in 13 weeks (Fig. 4c). Differences between total precipitation in 1989 and 1989 in dry weeks (i.e., dry in relation to 30-year means) totalled 204 mm; by comparison, the total difference in wet weeks totalled 124 mm. Not only was 1989 drier in terms of the quantity of precipitation, but it also was drier a greater amount of time. The 20% decrease in precipitation was reflected in 23 and 25% decreases in the flow ratios of basins 4 and 5, respectively (Table 5).

The 41% decrease in the flow ratio of control basin 2 between 1988 and 1989 (Table 5) was probably because of lower precipitation in 1989 and a smaller area than basin 1 (Table 1). The

Table 5. Total non-snowmelt period flow, expressed as a ratio of basin 1.

Basin no.	Non-snowmelt period	
	1988	1989
1	1.00	1.00
2	0.98	0.57
3	1.06	1.03
4	0.99	0.76
5	1.44	1.19

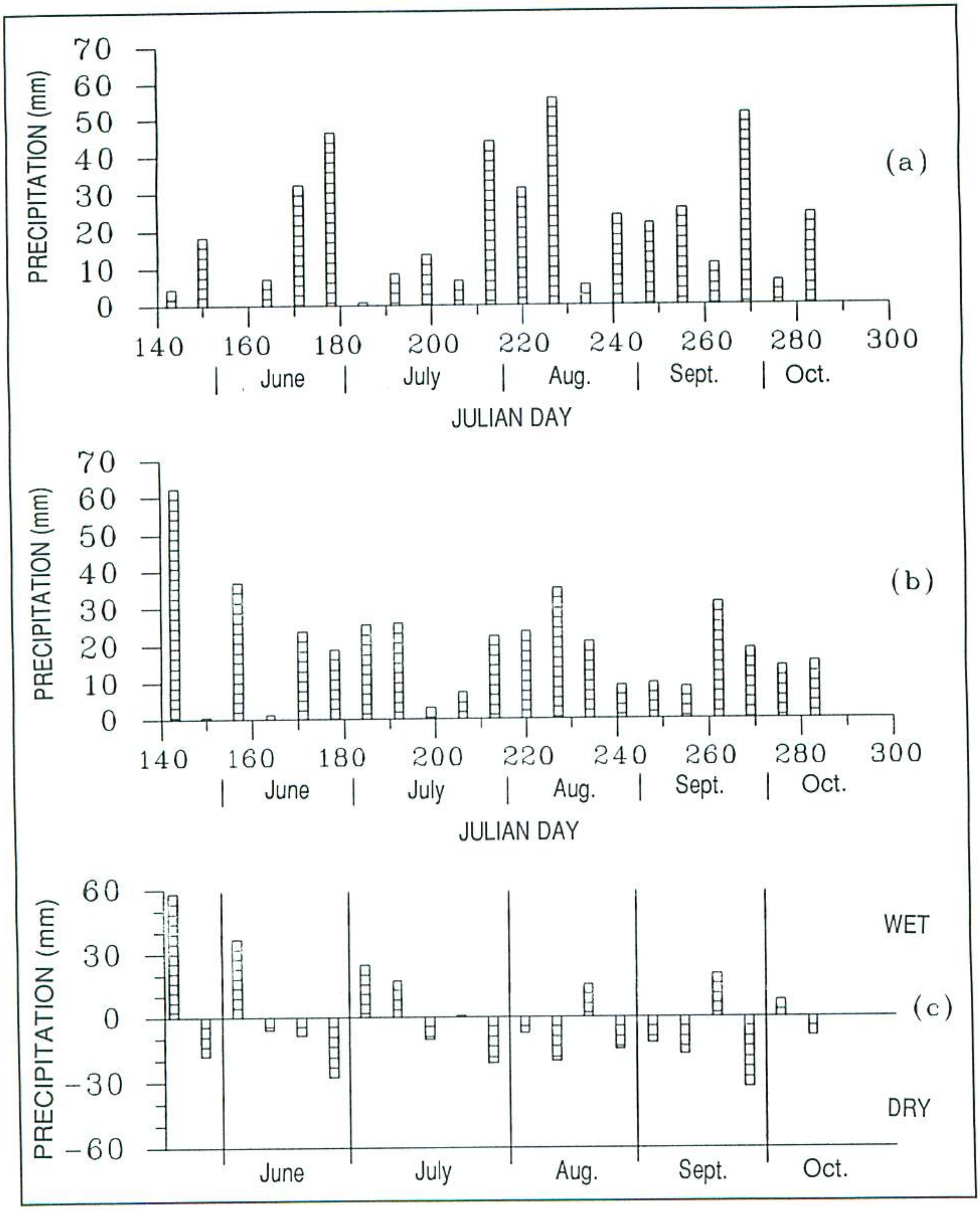

Figure 4. Weekly total precipitation: (a) 1988, (b) 1989 and (c) comparison of weekly total precipitation 1989 – 1988.

Table 6. Monthly and seasonal total precipitation (mm)[a].

Month	1988	% of norm	1989	% of norm
May	23	–	1	–
June	86	93	81	88
July	30	31	66	67
August	159	185	108	126
September	113	111	71	70
October	29	–	27	–
Total	440		354	
Average		91		88

[a] % of norm = % of monthly 30-year norm

larger area of basin 1 implies a greater volume of water in storage and, hence, potentially more water to be released during a dry year. The decreases in flow ratios of drained basins 4 and 5 were probably not affected by the areas of the basins, despite the fact that these basins were much smaller than basin 1, because of the ditches, which helped carry groundwater out of the basins.

Storm Flow

There were 19 storm events during the three field seasons. There were eight storms in each of 1988 and 1989, which are shown on the hydrographs (Fig. 2 and 3). Only storms with greater than 15 mm of precipitation generated a flow response. Lundin (1975) speculated that small precipitation events during the summer have a negligible effect on flow because the precipitation is retained within the large pore spaces of the peat, even when moisture conditions are near saturation. Average storm flow for the 19 events ranged from 0.045 $m^3\ sec^{-1}\ km^{-2}$ for basin 4 to 1.238 $m^3\ sec^{-1}\ km^{-2}$ for basin 5 (Table 7a). The paired t-test showed that flows from basins 1 and 2 were not significantly different, but that basin 4 had lower flows and basin 5 had higher flows (Table 7b). Flows from basins 2 and 3 were not different because of the variability of flows from basin 2. As with snowmelt flow, drainage appears to have both increased and decreased storm flow (basins 5 and 4, respectively). This situation will be discussed in the section on flow duration.

Average basin lag time for the 19 storm events in 1988 and 1989 ranged from 16.5 hours for basin 4 to 46 hours for basin 1 (Table 8a). The paired t-test showed that only basins 1 and 3 were not significantly different (Table 8b). The differences in lag time among the other basins were attributed to variations in basin area and channel density. Basin 2 was much smaller than basins 1 or 3 (Table 1) and, hence, had shorter lag times. Basin 4 had the shortest lag times, but also the smallest area and greatest channel density (Table 1). The regression equation, which accounted for area, estimated that the average lag time for basin 4 should have been about 7 hours. (The equation was quite accurate, with r = 1.000 and SE = 1.0 hour.) This result indicates that drainage actually increased lag time. A possible explanation for the increase is that the soil moisture deficit within this heavily drained basin was generally greater than that in the undrained basins. It took longer for this deficit to be satisfied and for the hydraulic

Table 7. Summary of (a) descriptive statistics and (b) probability values of paired t-tests for storm flow, where flow is $m^3\ sec^{-1}\ km^{-2}$.

(a)

	Basin no.				
	1	2	3	4	5
Mean flow	0.095	0.091	0.101	0.045	1.238
Standard Error	0.019	0.025	0.019	0.013	0.249
n	19	19	19	19	19

(b)

	Basin no.			
Basin no.	1	2	3	4
5	0.000[a]	0.000	0.000	0.000
4	0.013	0.065	0.006	
3	0.001	0.142		
2	0.522			

[a] e.g., flows from Basins 1 and 5 significantly different at p=0.000.

gradient to increase sufficiently to begin water movement into the ditches. However, if the soil moisture deficit at the onset of precipitation had been minimal in both the drained and undrained basins, then the drained basin would have been a shorter lag time due to the accelerated delivery of flow to the ditches (Mustonen and Seuna 1972, Starr and Päivänen 1986).

The average hydrologic response ratios for the 1988 and 1989 events ranged from 0.24 to 0.56 (Table 9). The paired t-test showed that the only significant differences (at the 95% level) were between basins 1 and 2 and between basins 2 and 5. Drainage appeared to have no effect on the hydrologic response value (basin 4), or to increase it only slightly (basin 5) (see Table 10). Hydrologic response was dependent on antecedent soil moisture conditions. Wet conditions (i.e., minimal soil moisture deficit) at the onset of a storm would result in a drained basin having a higher hydrologic response value than an undrained basin as a result of reduced losses from canopy interception and increased channel interception. The highest hydrologic response values from a single storm for all basins resulted from storm 8 in 1988. The values ranged from 0.42 to 1.35 (Table 9). These high values were caused by a large quantity of precipitation (57.9 mm, Table 11) and wet antecedent soil moisture conditions as a result of recent storms (Fig. 2).

Hydrologic responses and basin lag times varied among years and within each year. Precipitation events in 1988 were not only larger than in 1989 (an average of 40.7 versus 29.2 mm, Table 11), but also tended to occur when the soil moisture deficit was low (Fig. 2 and 3). Mean hydrologic response values for 1988 ranged from 0.26 to 0.76, and for 1989 ranged from 0.21 to 0.27 (Table 9). The decrease from 1988 to 1989 ranged from 32% for the undrained controls to 72% for basin 5. The decreases reflected the drier antecedent soil moisture conditions in 1989.

Table 8. Storm event basin lag times (hrs) (a) and probability values of paired t-tests (b).

(a)

	Basin no.							
	1		2		3		4	
Storm Event no.	1988	1989	1988	1989	1988	1989	1988	1989
1	22	21	20	15	24	21	13	3
2	68	45	12	21	68	43	3	21
3	30	17	12	9	36	23	3	1
4	92	39	70	37	98	41	66	25
5	34	70	16	–	38	40	–	1
6	28	80	14	–	30	50	–	–
7	31	66	12	–	36	30	4	–
8	34	62	26	30	42	64	10	30
Mean	42	50	23	22	47	39	17	16
Grand mean		46		22.5		43		16.5

(b)

	Basin no.		
Basin no.	1	2	3
4	0.000[a]	0.000	0.000
3	0.357	0.000	
2	0.001		

[a] e.g., lag times for basins 1 and 4 are significantly different at p=0.000.

Changes in lag times between 1988 and 1989 were not consistent for all basins. Lag times increased for basin 1, decreased for basin 3, and were unchanged for basins 2 and 4 (Table 8a). On a seasonal basis, lag time was not heavily influenced by moisture conditions.

The effect of antecedent soil moisture conditions on flow, hydrologic response and lag times is illustrated by comparing storms 2 and 4 in 1988 (Fig. 2). Storm 4 had 330% more precipitation than storm 2 (76.5 vs. 17.8 mm, Table 11), whereas increases in storm flow from basins 1 to 4 ranged from 3% (basin 4) to 251% (basin 3). Only the increase in flow (518%) from basin 5 exceeded the increase in precipitation. The smaller increases in flow compared with precipitation were reflected in the hydrologic respnse values, which decreased by between 19% (basin 3) and 76% (basin 4) (Table 9). The hydrologic response value for basin 5 increased by 43%. Basin lag times increased by between 35% (basin 1) and 733% (basin 4) (Table 8a). The decrease in hydrologic response values and increase in lag times, even though storm 4 was much larger, were as a result of differences in

Table 9. Storm event hydrologic response (R) values.

	Basin no.									
	1		2		3		4		5	
Storm event no.	1988	1989	1988	1989	1988	1989	1988	1989	1988	1989
1	0.21	0.25	0.30	0.60	0.13	0.19	0.50	0.34	–	–
2	0.51	0.36	0.25	0.07	0.54	0.34	0.67	0.18	0.76	0.23
3	0.66	0.08	0.35	0.07	0.58	0.10	0.43	0.16	0.10	0.24
4	0.34	0.28	0.21	–	0.44	0.28	0.16	0.53	1.09	0.28
5	0.50	0.16	0.21	–	0.50	0.15	–	0.11	0.47	0.07
6	0.12	0.13	0.12	–	0.17	0.10	–	–	0.45	–
7	0.32	0.21	0.21	–	0.43	0.13	0.35	–	1.10	–
8	0.77	0.43	0.42	0.06	0.85	0.36	–	0.28	1.35	–
Average	0.43	0.24	0.26	0.21	0.46	0.21	0.42	0.27	0.76	0.21
Grand average		0.33		0.24		0.33		0.34		0.56

Table 10. Probability values of paired t-tests for hydrologic response (R).

Basin no.	Basin no. 1	2	3	4
5	0.163[a]	0.013	0.162	0.347
4	0.859	0.129	0.798	
3	0.878	0.054		
2	0.047			

[a] e.g., R values of basins 1 and 5 are significantly different at p=0.163.

antecedent soil moisture conditions. Storm 2 occurred just after the snowmelt, when storage capacity was minimal. Precipitation at that time was rapidly translated into large storm flows. Storm 4 occurred after a 4-week drought, when storage capacity was very high. A large portion of the precipitation filled this storage; only after this had occurred could the excess become flow. The contrary reactions of basin 5 will be discussed in the following section on flow duration.

Flow Duration

The average daily flow for the combined field seasons ranged from 0.021 to 0.080 $m^3\ sec^{-1}\ km^{-2}$ (Table 12a). Although basins 1 and 2 had the same average flow, the paired t-test showed them to be significantly different (Table 12b). Indeed, virtually all the basins were significantly different. The differences in flows can be identified by comparing the flow-duration curves for the basins. All five basins had a curve form typical of groundwater-dominated peatlands, with almost flat slopes most of the time and steep slopes for lower percentages of time (Fig. 5) (Boelter and Verry 1977). This indicates that although low flows tended to be stable over the long term, high flows were of short duration.

The curves for the entire season showed that snowmelt flows (≤12% of the time) from basins 1 to 4 were quite similar, whereas flows from basin 5 were higher (Fig. 5). Peak flows in the

Table 11. Storm-event precipitation for the non-snowmelt period (mm).

Storm event no.	1988	1989
2	17.8	22.9
3	47.2	22.4
4	76.5	25.7
5	44.5	33.8
6	15.7	22.4
7	25.1	26.9
8	57.9	50.0
Total	284.7	204.1
Average	40.7	29.2

Note: Storm event #1 occurred during the snowmelt period.

non-snowmelt period were much less than those in the snowmelt period (Fig. 5 and 6): the flows from basins 1 to 4 were reduced to less than half of those in the snowmelt period. Again, the curves were similar for basins 1 to 4 and showed higher flow in basin 5. A closer examination of the non-snowmelt period showed that flows from drained basin 4 became greater than those from the undrained basins about 35% of time (Fig. 7). Drained basins 3 and 5 consistently had higher flows than the undrained basins.

High flows from undrained basin 2 were 23% lower than the flows from undrained basin 1 (Table 13). During the high-flow events, soil moisture deficits tended to be minimal, so flows were directly affected by other physical factors. Basin 1 was larger than basin 2 (Table 1), a condition that could yield proportionally greater flows (Dunne and Leopold 1978). High flows from heavily drained basins 4 and 5 were 27% less and 215% greater, respectively, than flows

Table 12. Summary of (a) descriptive statistics and (b) probability values of paired t-tests for average daily flow, where flow is m^3 sec^{-1} km^{-2}.

(a)

	Basin no.				
Average daily flow	1	2	3	4	5
Mean	0.036	0.036	0.043	0.021	0.080
Standard error	0.003	0.003	0.003	0.002	0.004
n	412	363	377	312	371

(b)

Basin no.	Basin no.			
Average daily flow	1	2	3	4
5	0.000[a]	0.000	0.000	0.000
4	0.000	0.004	0.000	
3	0.000	0.000		
2	0.001			

[a] e.g., flows from dasins 1 and 5 are significantly different at p=0.000.

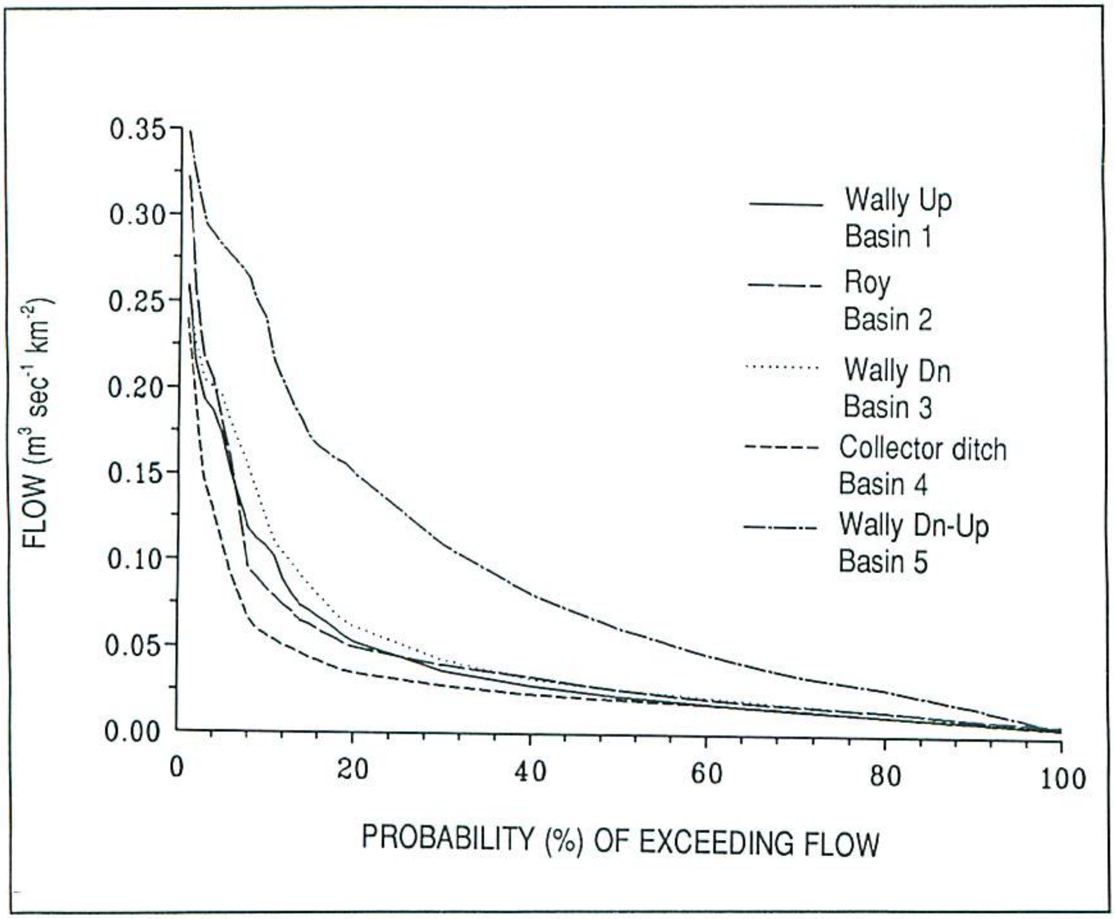

Figure 5. Flow duration for entire field season – combined 1987, 1988 and 1989 data.

from basin 1 (Table 13). High flows from lightly drained basin 3 were only 6% greater. The concept that drainage increases flows from storm events (Vompersky et al. 1991) seems to be supported by the results from basin 5, but not by results from basins 3 and 4. In contrast to the situation for high flows, all three drained basins had greater low flows than basin 1, with increases ranging from 23 to 245% (Table 13). Why drainage appears to both increase and decrease high flows, as well as to increase low flows with such a range of magnitude, is, in essence, a question of why and how basin 4 differs from basin 5.

Ratios of the flows from basin 5 versus basin 4 were determined for three flow conditions (Table 14). These ratios were all greater than 1.0, indicating that flows from basin 5 were greater than those from basin 4. The differences in flows were probably a result of differences in the physical characteristics of the basins for the time period described by each flow condition. Four characteristics of interest were the total length of all ditches, the length of surround ditches, and the orientation and position of the surround ditches in relation to the groundwater flow pattern.

Snowmelt peak flows from basin 5 were 1.9 times those from basin 4 (Table 14). Because the peat was frozen at depth during this time period, groundwater was unable to enter the ditches. Flows were dependent on surface runoff of snowmelt. This runoff became flow more readily when ditches were nearby. When the flow ratio was recalculated to account for the influence of all the ditches (i.e., using, for each basin, flow per km of total ditch length), the result was a ratio of 1.0, indicating that both basins reacted in a similar manner during the snowmelt.

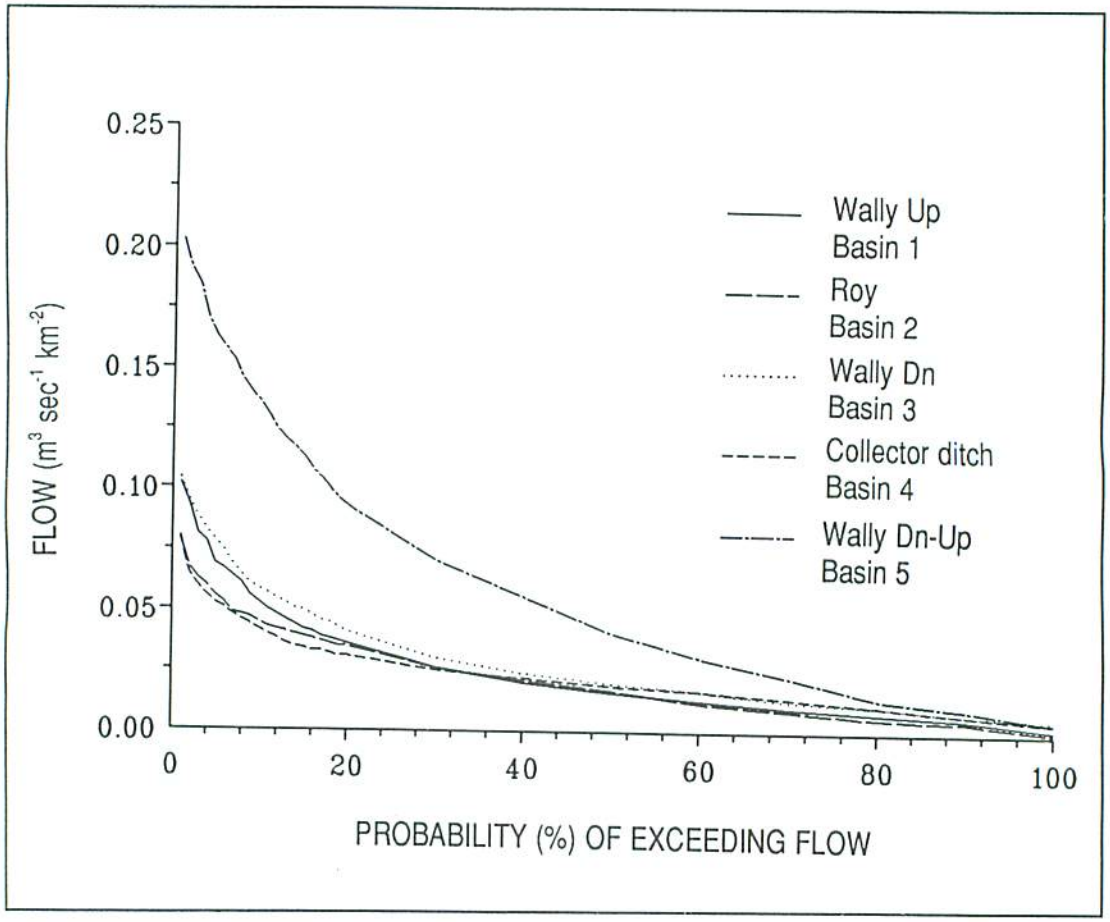

Figure 6. Flow duration for snow-free season - combined 1987, 1988 and 1989 data.

Non-snowmelt peak flows from basin 5 were 2.9 times those from basin 4 (Table 14). The ditch densities were similar (Table 1), suggesting that some other factor was influencing flow. During periods of peak-flow, peat in the undrained areas adjacent to the drained area tended to be saturated, allowing large quantities of subsurface storm runoff to flow from the undrained areas into the surround ditches. The ratio was recalculated using, for each basin, flow per km of total surround-ditch length; this yielded a value of 1.1. These results suggested not only a similarity of reaction, but also the strong influence of the entire surround-ditch length during peak flow (i.e., saturated) conditions.

Non-snowmelt periods of low flow (i.e., flows that occurred ≥35% of the time) from basin 5 were 2.0 times those from basin 4 (Table 14). During low-flow periods, the side ditches did not affect flows significantly. Flows were sustained by groundwater that was intercepted by the surround ditches while moving from undrained areas into drained areas. Unlike during peak flows, the orientation and position of the surround ditches became important under low-flow conditions. Surround ditches on the upslope side of a drainage network that were perpendicular to the groundwater flow pattern would have greater quantities of water entering them than ditches that were either parallel to groundwater movement or perpendicular on the downslope side (i.e., the upslope ditches intercepted water that would otherwise have reached the downslope ditches). The flow ratio was recalculated using, for each basin, flow per km of surround-ditch length of suitable orientation (i.e., not parallel to groundwater flow) and slope position (i.e., not downslope). The result was a value of 1.1, again indicating a similar reaction between ditches 4 and 5, and also showing the importance of the orientation

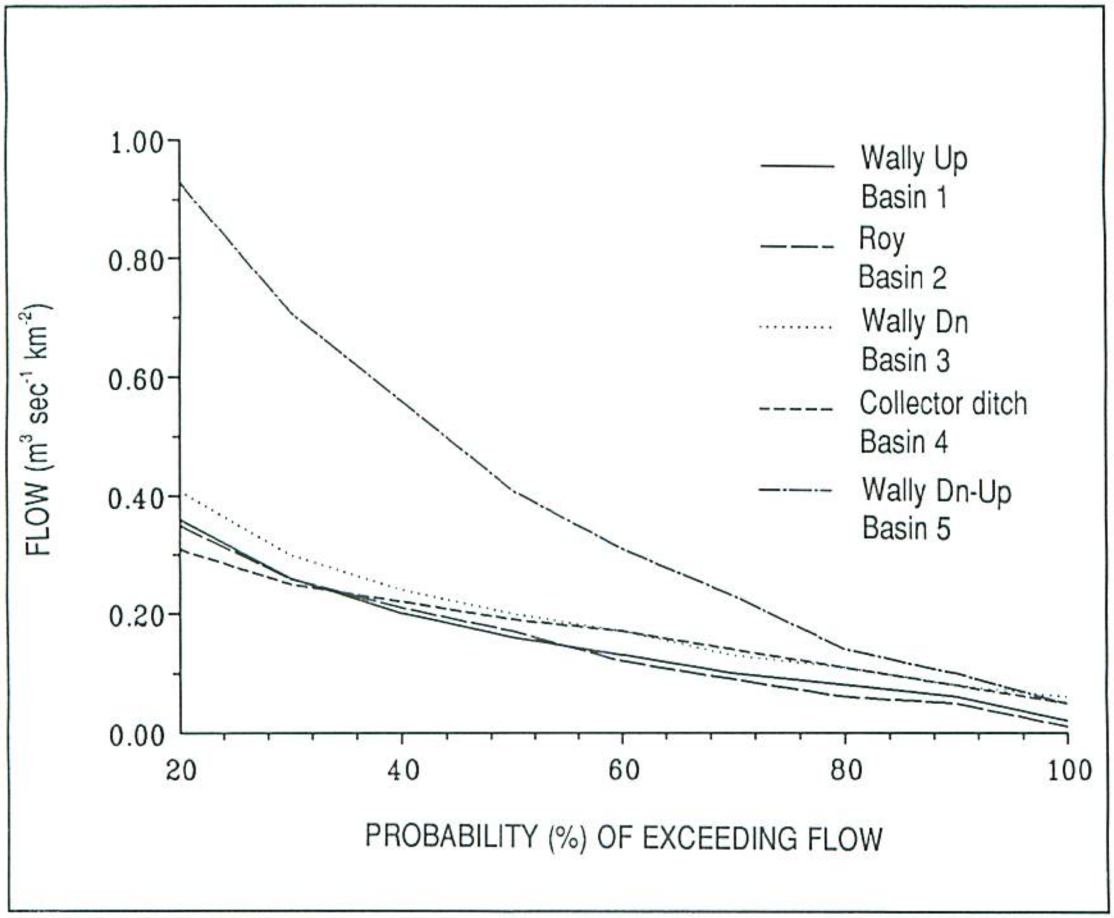

Figure 7. Flow duration for snow-free season (≥20% of time) – combined 1987, 1988 and 1989 data.

Table 13. High- and low-flow values for non-snowmelt period,expressed as ratios of the value for Basin 1 (from flow duration curves).

	Ratio	
Basin no.	High flow (≤5% of time)	Low flow (>35% of time)
1	1.00	1.00
2	0.77	0.96
3	1.06	1.28
4	0.73	1.23
5	2.15	2.45

and position of the surround ditches with respect to groundwater movement.

Examining basins 4 and 5 for these three flow conditions showed that although their flows differed significantly on a unit-area basis (i.e., $m^3\ sec^{-1}\ km^{-2}$), these differences could be explained in terms of the physical characteristics of the basins. On a unit-area basis, then, drainage may increase (basin 5, Tables 4 and 12) or decrease peak flow (basin 4, Tables 4 and 12), and may affect the magnitude of the increase in low flows (basins 4 and 5, Table 13), depending on physical characteristics such as ditch length and the orientation of surround ditches.

Water Balance

Components of the water balances for the 1988 and 1989 field seasons are presented in Table 15.

Table 14. Flow ratios for basin 5: basin 4 (from flow duration curves).

Event	Ratio
Peak flow – snowmelt period (≤5% of time)	1.9
Peak flow – non-snowmelt period (≤5% of time)	2.9
Low flow – non-snowmelt period (≥35% of time)	2.0

The 1988 streamflow value for basin 5 was greater than the precipitation value, indicating that there may have been movement of groundwater into the basin from the surrounding area. As stated previously, flows from fen peatlands were difficult to gauge because of indistinct phreatic divides (Boelter and Verry 1977). In each year, drained basins 4 and 5 had a greater decrease in storage during the year than undrained basins 1 and 2, illustrating the influence of the ditches in removing water. The differences between these drained and undrained basins were small, ranging from 8 mm in 1988 to 17 mm in 1989. Basin 3 had even smaller differences — 1 to 2 mm. All the basins had a greater decrease in storage in 1989 than in 1988 because of the lower precipitation in 1989.

Because precipitation, interception and storage were similar for all the basins in each year, any differences in flow depended on differences in evapotranspiration. The 1988 evapotranspiration values for basins 1 to 4 were quite similar. The negative evapotranspiration value for basin 5 was the result of inflow and the calculation of evapotranspiration as the residual within the water balance equation. The 1989 evapotranspiration values were greater and more variable than those in 1988, with values for basins 1 to 4 ranging from 25 to 99% higher. The basin 5 evapotranspiration value also increased significantly, from -4 mm to 122 mm. These increases were a consequence of the drier 1989 conditions. Mean relative humidity for May to October of 1988 was more than 80%. No relative humidity data for 1989 were available,

Table 15. Seasonal water-balance components for the non-snowmelt period.

		Component (mm)				
Year	Basin no.	Precipitation	Streamflow	Interception	Evapotranspiration	Storage
1988	1	440	307	62	122	-51
	2	440	301	62	128	-51
	3	440	325	62	105	-52
	4	440	303	62	136	-61
	5	440	441	62	-4	-59
1989	1	354	236	50	153	-85
	2	354	134	50	255	-85
	3	354	242	50	149	-87
	4	354	179	50	227	-102
	5	354	281	50	122	-99

Water balance equation: Precipitation = Streamflow + Interception + Evapotranspiration + Storage
e.g., for 1988, 440 = 307 + 62 + 122 - 51

but a lower value could be implied from the lower levels of precipitation. A lower relative humidity is an indication of a greater vapor-pressure gradient, which would allow higher rates of evapotranspiration to occur. During 1989, the water table was still within reach of root systems, so that evapotranspiration was not reduced in response to a water shortage.

The variability of the 1989 evapotranspiration values may be because the factors controlling evapotranspiration differ among the basins. But what factors control evapotranspiration? Boelter and Verry (1977) stated that, for an undrained peatland, actual evapotranspiration equalled potential evapotranspiration calculated by the Thornthwaite method. Seasonal potential evapotranspiration using the Thornthwaite method was more than 500 mm in each year (Table 16), compared with actual evapotranspiration values for the undrained basins of 122 to 255 mm (Table 15). Seasonal potential evapotranspiration using the Holdridge method was more than 300 mm in each year. The seemingly low actual evapotranspiration values may be partly the result of an overestimate of the streamflow values as a result of inclusion of some snowmelt flow. It should be noted that care was taken to accurately delineate the melt and non-melt periods through hydrographic analysis; however, the possible over-estimation of streamflow would still not be of sufficient magnitude to account for the large difference between actual evapotranspiration and potential evapotranspiration values. Alternatively, under some climatic conditions, actual evapotranspiration may not necessarily equal potential evapotranspiration. Verry (1988) suggested that in areas with large groundwater contribution, actual evapotranspiration may be only 10% of the input values.

The method of potential evapotranspiration calculation must also be considered. The Thornthwaite estimates may have been high because this method relies only on air temperature. The Holdridge estimates were

Table 16. Estimates of total evapotranspiration using the Thornthwaite and Holdridge methods.

	Evapotranspiration (mm)			
	Annual PET[a]		Seasonal[b] PET	
Method	1988	1989	1988	1989
Thornthwaite	518	579	506	579
Holdridge	372	362	307	307

[a] PET = potential evapotranspiration
[b] seasonal = May to October

possibly more realistic because this method uses both air temperature and humidity. However, Lee (1978) maintained that determinations of evapotranspiration based on meteorological data do not accurately quantify evapotranspiration because of the complexity of the "biospheric phenomenon" controlling evapotranspiration. He stipulated that only qualitative estimates were possible. This concept was supported by Calder (1982) and Morton (1984), who suggested that the vegetation itself was a modifier of evapotranspiration. The variable 1989 values were therefore the result of differences in the interactions within the "biospheric phenomenon". Over all, drainage had little effect on evapotranspiration in 1988, a wet year, and increased evapotranspiration by approximately 14% in 1989, a dry year, through the effects of a lowered water table.

CONCLUSIONS

Starr and Päivänen (1986) identified three models describing the effects of drainage on runoff from ditched areas such as basins 4 and 5. The models described combinations of increased or decreased peak and low flows. They differed because of different basin and precipitation characteristics. The present study has identified some of the characteristics, such as basin morphology and ditch orientation, that should be examined when a drainage program is contemplated. This study has also shown that drainage in the Clay Belt need not have adverse effects on streamflow, especially when the drainage network is only a small part of a catchment, as is the case for basin 3. Indeed, a secondary objective of drainage, after improved tree growth, could be the possible enhancement of hydrological conditions through decreased peak flows and increased summer low flows, especially since these two conditions are long-lived (Heikurainen et al. 1978).

ACKNOWLEDGMENTS

Appreciation for their advice and assistance is extended to J.K. Jeglum and S.J. Taylor of Forestry Canada, Ontario Region, and to G. Lee and S. Michelsky. This project was funded jointly by the federal Panel on Energy Research and Development (PERD) and the Canada-Ontario Forest Resource Development Agreement.

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