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THE DROUGHT CODE COMPONENT OF THE CANADIAN FOREST FIRE BEHAVIOR SYSTEM

by

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Résumé en français

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ABSTRACT

Development of the Drought Code component of the Canadian Forest Fire Behavior System is described. The scale of available moisture used in the original Stored Moisture Index developed for coastal British Columbia was transformed to one of cumulative drying and incorporated as a component of the National Index. Drought Code values are related to availability of surface water, and to fire behavior and effects. Procedures are developed for improving estimated starting values, taking into account the carry-over of drought from the previous season.

RÉSUMÉ

L'auteur décrit la composante "mise au point du code de sécheresse" du Système canadien de comportement des incendies de forêt. L'échelle d'humidité disponible utilisée pour l'Indice d'humidité accumulée mis au point pour la Colombie-Britannique côtière fut transformée en échelle de séchage cumulatif et fut incorporée au système national. Les valeurs du Code d'indices de sécheresse sont mises en rapport avec la disponibilité d'eau en surface et avec les effets et le comportement du feu. L'auteur met aussi au point des marches à suivre pour améliorer les points d'inflammation estimés, tenant compte du reliquat de sécheresse de la saison précédente.

INTRODUCTION

Difficulties experienced in forest-fire control have consistently been related to deficiencies of rainfall over some preceding period (Ludwig, 1923; Foley, 1947; Haines and Sando, 1969) lasting for months or even years. Danger rating systems, integrating preceding weather conditions, are widely used (Turner *et al.*, 1961). Some of these, such as the original Drought Index of the Canadian Danger Rating Systems (Beall, 1947), reached their upper limits too quickly to be useful where summer drought is a factor. Others, such as Nesterov's index (Zhdanko, 1960) or Cromer's Hygrothermographic Index (Foley, loc. cit.), were capable of reflecting extended drought periods but, because of their empirical nature, were not readily interpreted in any physical terms under such conditions.

After the development of provisional forest fire danger tables for British Columbia (Anon., 1961), the existing Drought Index with its upper limit of 25 drying days was inadequate for areas where more extended periods of summer drying were common (Foster, 1963). At that time, it became evident that an index was required of the available moisture in deep duff and rooting layers of standing timber adjacent to areas of slash. Such an index could alert forest managers to potentially troublesome escape situations and indicate when additional precautions might be required for prescribed burning.

The Stored Moisture Index (SMI) was developed[1,2] as an indicator of extended drought, incorporating suggestions from Robin (1957) and Nelson (1959). This was used successfully as an aid for slash burning in Coastal British Columbia. Specific guidelines for prescribed burning, in terms of SMI classes, were prepared by Muraro and Lawson (1970).

Development of the Canadian Forest Fire Behavior System transformed the SMI from a scale of available moisture to one of cumulative drying, and incorporated it into the system as the Drought Code (DC) (Anon., 1970).

STRUCTURE OF THE STORED MOISTURE INDEX

The system was designed to model the variations in moisture content in upper layers of forest soil, specified only by their ability to hold 8 inches of available water. This figure was assumed to be the amount that could be held by some shallower forest soils on Vancouver Island. The actual value was not expected to be of absolute significance because of the extreme

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[1]Mortimer, H.A. (Student assistant working under direction of the author.) 1966. The estimation of moisture stored in forest soils. Unpublished typescript. 6 pp & Tables.

[2]British Columbia Forest Service. 1966. The Stored Moisture Index/A Guide to Slash burning. Mimeo 4 pp.

variability of soil moisture regimes[3] but, in general, this was a reasonable value of the available moisture in the rooting zone of Vancouver Island Douglas-fir stands. It was not intended to represent the moisture content in any specific class of fuel. The SMI is augmented by the effective rainfall, which was assumed to be the amount available for storage after interception by the canopy. This value (r_d) is assumed to be related to the measured rainfall in the open (r_o) according to the relationship:

$$r_d = 0.83\ (r_o - .06) \qquad (1)$$

This is based on Rothacher (1963), by equating the daily rainfall amount to Rothacher's "Storm size".

Evidence for subtracting the intercepted rainfall is found in Goodell (1969), who indicates that this is a true loss, and does not give a compensating reduction in transpiration.

This stored moisture model is depleted daily by an estimated evapotranspiration loss (AE). Following Thornthwaite and Mather (1955), this loss is assumed to be related to the potential evapotranspiration (PE) by the relationship:

$$AE = PE \times \frac{SMI}{800} \qquad (2)$$

where SMI is the amount of available moisture (in units of .01 inch). The PE, by definition, refers to a level surface uniformly covered by vegetation, and is limited only by the available energy. The upper limit of 800 for SMI is never exceeded, corresponding to the assumption that excess moisture is lost as run-off.

According to the system of Thornthwaite and Mather, the daily estimate of PE is a function of the daily mean temperature, the time of year, and the latitude. Such estimates bear little relationship to reality on a day-by-day basis, but are meaningful when averaged over a week or more.

Simplified tables were prepared for estimating the daily moisture loss according to the following procedure:

1. Mean daily values of PE were calculated by months, from published climatic normals for 32 stations distributed throughout British Columbia.
2. For each summer month, the mean daily PE was plotted against the corresponding mean daily maximum temperature T_x (F), and the linear regression was obtained for each month (April to September). No strong relationship between the coefficient of regression and the season was evident (Table 1).

[3]The major variability is in the depth of organic horizons capable of holding about 3 inches per foot as opposed to underlying sandy loam holding 1.0 to 1.5 inches per foot.

TABLE 1

Potential Evapotranspiration as a function of daily maximum temperature and month*

Month	Regression Coeff. (0.01"/10F)	Avg Max Temp (F)	Avg PE (0.01"/day)
April	1.97	53.6	5.3
May	1.69	62.7	10.0
June	2.21	67.3	12.8
July	2.25	72.8	14.6
August	1.74	71.7	13.0
September	1.16	65.6	9.2
October	1.93	53.9	4.8

* Based on mean monthly records from 32 British Columbia climatic stations.

After rejecting the value for September as an outlying observation at the 5% level (Proschau, 1953), the mean value of the regression coefficient was equal to 0.0196 inches per 10F; this value, rounded off to 0.02 inches, was accepted as the slope applicable to all months.

3. The final method for estimating the PE/temperature relationship for each month was determined by the straight line of slope 0.02 inches per 10F passing through the point representing the average values for that month of daily maximum temperature and daily PE (Table 1).

The relationship between PE and daily mean temperature, (Thornthwaite and Mather, loc. cit.), is not linear, but exponential. However, over the range of monthly mean maximum daily temperatures encountered in British Columbia, the regressions for the summer months are essentially linear. Extrapolation of these linear relationships over the larger range of daily values provides unbiased estimates of the PE over periods of a month or more (*i.e.*, the mean of the PE values calculated from the daily temperatures is the same as the value of the PE calculated from the monthly mean temperature). Daily values estimated from these regressions will not necessarily agree with daily estimates according to Thornthwaite and Mather, but these daily estimates are of doubtful value and are not the prime concern here. Table 2 presents a comparison of the two methods for selected 10-day periods.

Williams (1954) has indicated that this suppression of the effect of daily temperature variations is not a serious deficiency. He concluded that variations in the level of the water table at Whiteshell, Manitoba could be modelled satisfactorily by using long-term average values of temperature, rather than observed daily values.

TABLE 2

Comparison of estimates of potential evapotranspiration

(Average daily value in inches)

Date	SMI	Thornthwaite & Mather
July 1-10	.12	.11
11-20	.15	.16
21-31	.16	.18
Aug. 1-10	.14	.15
11-20	.14	.14
21-31	.12	.12

In summary, the SMI is calculated by assuming a starting value of 800 at some known or estimated time when the soil is saturated. For each day thereafter, the index calculation consists of two steps:

(i) $(SMI)_r = (SMI)_o + 83\ (r_o - .06)$ . . . . (3)

Subject to the restriction that $(SMI)_r \not> 800$. ;

(ii) $SMI = (SMI)_r - \frac{(SMI)_r}{800} \times PE$; . . . . (4)

where: $(SMI)_o$, $(SMI)_r$ and SMI are, respectively, values of the SMI from the previous day, SMI after adjustment for rain and final value of SMI for the current day; r_o is the rainfall in the open; PE is related to maximum daily temperature T_x by the relationship:

$PE = 1/5\ (T_x - 32) + S$ (in units of .01") . . . . (5)

and S is the seasonal correction according to Table 3.

TABLE 3

Seasonal Adjustment[4]

	April	May	June	July	Aug.	Sept.	Oct.
S	0.9	3.8	5.8	6.4	5.0	2.4	0.4

[4]Calculated by substituting the mean values of PE & T_x for the month in equation (5). These values have been recalculated on the Hewlett Packard 2114A Digital Computer and differ slightly from values published previously, which were determined graphically.

THE DROUGHT CODE TRANSFORMATION

During development of the Canadian Fire Weather Index (FWI), the existing SMI was incorporated as the indicator of "long-term" drought. In order that the Drought Code module (DC) would be consistent in form with the intermediate Duff Moisture Code (DMC) developed by Van Wagner (1970b), the following transformations were employed:

$$(DC)_o = 400 \ln\{800/(SMI)_o\} \quad \ldots \quad (6)$$

$$(SMI)_o = 800\exp\{-(DC)_o/400\} \quad \ldots \quad (7)$$

$$(DC)_r = (DC)_o - 400 \ln\{1 + 83(r_o - .06)/(SMI)_o\} \quad \ldots \quad (8)$$

where $(DC)_o$, $(DC)_r$ and DC and the drought code values for the previous day, the value after adjustment for rain, and the final value for the current day, respectively. For each rainless day, the DC is merely increased by ½ the value of the PE.

Because the calculations for the FWI are based on weather observations at noon local standard time (LST), and the SMI was based on maximum temperature, an appropriate adjustment for the calculation of the PE was developed. Mean values of the 1200 LST temperatures, by months, were extracted from Cudbird (1964) for 22 stations distributed across Canada and compared with the daily maximum values (Appendix). The average differences were consistent and showed little evidence of seasonal variation; therefore, in the interest of simplicity, it was assumed that $T_{12} = T_x - 5$, where T_{12} is the noon LST temperature (F). We may now write equation (5) in the form:

$$PE = 1/5\ (T_{12} - 27) + S \quad \ldots \quad (9)$$

where S is the same as before.

CALIBRATION AND USE OF THE DROUGHT CODE

(a) Water Table Level

Data presented by Fraser (1962) indicates that there is a good correlation (over 16 years) between the water stored in the soil for different regimes and the depth to the water table. The disappearance of surface water in shallow depressions is related to the level of the DC; however, owing to the variability in soil characteristics, it is not possible to assign absolute value to this relationship.

The Drought Code could be expected to provide a useful indication of the availability of surface water for fire control purposes. Published water-level measurements (Anon., 1962) for Somenos Lake, B.C. (48°47'N, 123°41'W) were compared with the SMI values calculated for an adjacent climatological station for the 1961 season (Fig. 1). This lake was chosen

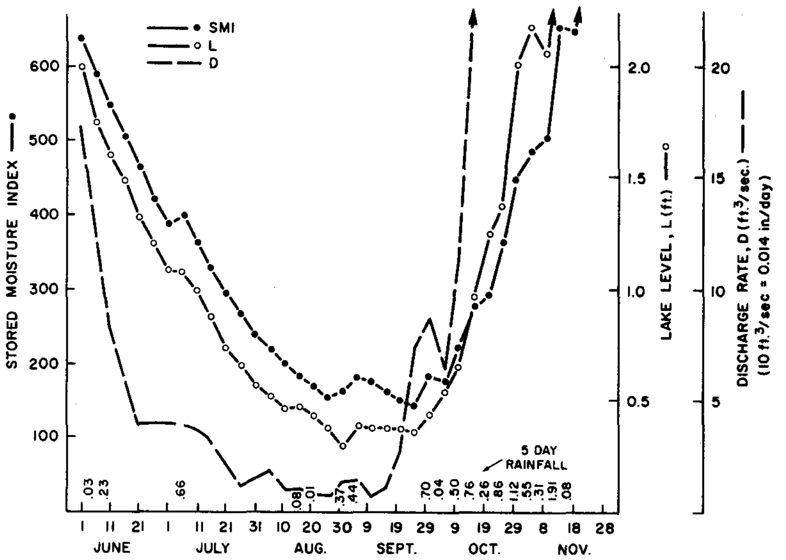

Figure 1. Seasonal variation in lake level and discharge rate for Somenos Lake (1961) with corresponding value of SMI.

because it was a relatively shallow depression, rain-fed from a 27 square-mile drainage area. The only discharge, from a small creek, averaged less than 0.006 inches/day over the drainage area from mid-June to mid-September, which was an order of magnitude less than the estimated evaporative loss over the same period. Unfortunately, subsequent years were not suitable for comparison, owing to a marked increase in water use for irrigation.

(b) Fire Behavior

Any hypothesis relating Drought Code to fire behavior assumes that the amount of fuel readily available for combustion is directly related to the DC value. Such parameters as depth of organic material removed and percentage of mineral soil exposed should relate well to values of DC. In a series of experimental burns in spruce-fir logging slash in Interior British Columbia, Muraro (personal communication) found these to be strongly correlated.

More recently, Lafferty[5] presented data from six experimental burns in cedar-hemlock logging slash in coastal British Columbia, indicating a linear relationship between total energy released per unit area and DC value in the range 75-175.

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[5]Lafferty, R.R. (1972). Regeneration and plant succession related to fire intensity on clear-cut logged areas in coastal cedar-hemlock type: an interim report. Canadian Forestry Service. Internal Rep BC-33.

Large fires may result from strong winds and dry aerial fuels reacting to several days of severe drying, usually in the early spring, and often with soils in a state of near saturation. During the remainder of the year, large fires are usually associated with increased amounts of available fuel resulting from extended periods of drying.

Figure 2 illustrates this latter relationship, giving the probability of a fire reaching 10 acres or more, as a function of the Drought Code value on the day of origin, based on July to September data for the years 1957-66.

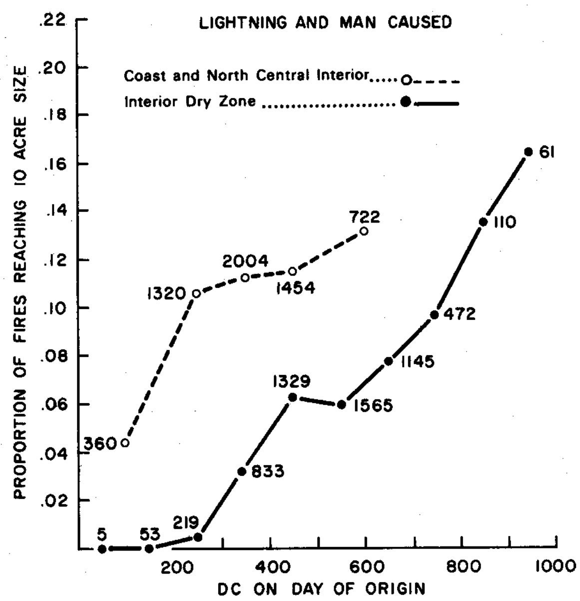

Figure 2. Relationship between proportion of fires reaching ten acres and Drought Code on day of origin for two regions in B.C. (July-Sept., 1957-66). (Figures refer to number of fires in DC class.)

Separate curves are given for the interior dry regions of B.C. and for the remainder of the province. The smaller probability of fires greater than 10 acres in the dry interior relative to the rest of the province is primarily the result of differences in fuel type between the two regions, although differences in levels of detection organization may be a contributing factor.

(c) Estimates of Starting Values

The Drought Code, by design, integrates past weather over a longer period than other components of the Canadian Forest Fire Behavior System. Several days of heavy rains or equivalent snow melt are necessary to reduce the DC to zero. The drying process is much slower, and Van Wagner (1970a) has estimated the exponential drying-rate time constant for the DC to be about 52 days.

This built-in "memory" makes it essential that some procedure be established for determining a realistic date for initiating fire weather observations and for starting DC calculations in the spring. There is also a necessity for a method of making a realistic estimate of DC where it is not possible to start making observations early in the season.

The normal starting instructions, as defined in the Canadian Forest Fire Weather Index tables (Anon., 1970), suggest a starting value of 15 to be used on the third day after the area is essentially free of snow or, where snow is not a factor, on the third day after the end of "spring run-off". If these conditions can not be met, calculations should be started on the third successive day that noon temperatures of 55F or higher have been observed. At this time, calculations should be started with a value of the DC equal to five times the number of days since the last preceding measurable rainfall.

For the purpose of calculation from climatological records, Simard (1972) has assumed a starting date on the third successive day after April 1 that the noon dry bulb temperature was equal to or greater than 48F, which he states agrees with the average date of snow melt in Eastern Canada.

In practice, it may not always be practical to obtain daily fire weather information from some locations until the fire season is well advanced. If observations are available from a nearby representative climatological station, these may be used, with adjustments for known differences between the two sites. As an aid in estimating mid-season starting values, changes in DC values to be expected in April, May and June were obtained as a function of monthly rainfall (Table 4 and Fig. 3).

TABLE 4

Mean Monthly Increase in Drought Code by

Rainfall Classes

(183 station-years for 20 B.C. stations)

Monthly Precip. (inches):	0 - .49	.50 - .99	1.00 - 1.99	2.00 +
Apr:	96(33)	96(52)	56(48)	27(44)
May:	150(20)	121(34)	55(33)	54(47)
June 1:	196(16)	163(31)	121(62)	54(71)

(Figures in brackets are station-months in class)

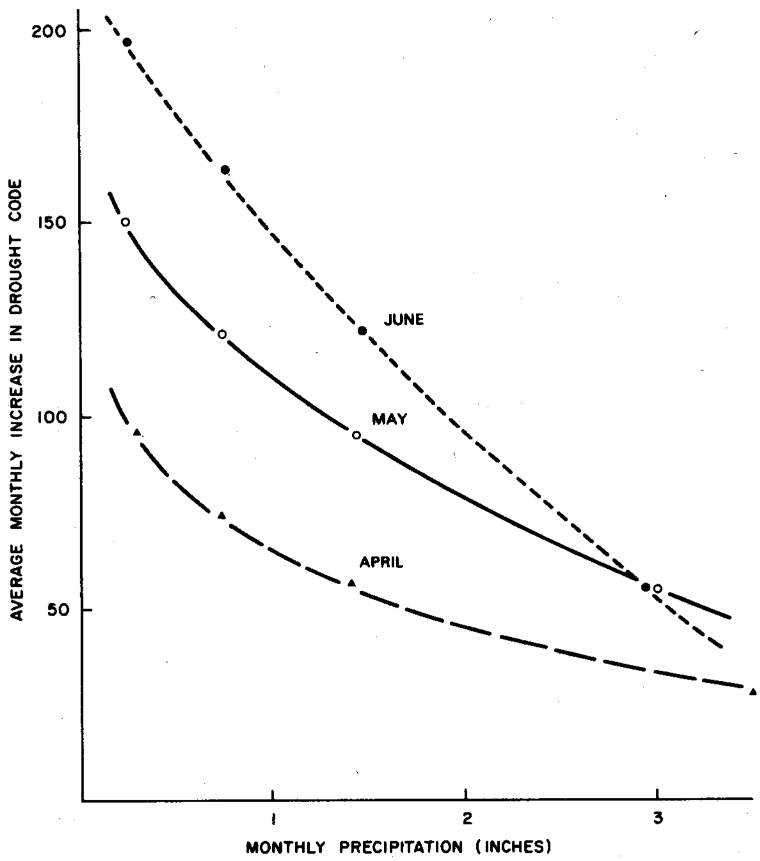

Figure 3. Increase in Drought Code by Monthly Precipitation for 20 B.C. stations.

To illustrate the use of this relationship, consider a station having rainfall of 0.80 inches in April, 1.10 inches in May and 1.60 inches in June. From Fig. 3, these correspond to average increases in DC value of 70, 106 and 115 units. Assuming a value of zero at April 1, this gives an estimate of the DC at July 1, of 70 + 106 + 115 = 291. (Simple rules of thumb, based on more limited information, have appeared as Supplement BC-4 to the Canadian Forest Fire Behavior System.)

(d) <u>Carry-Over of Moisture Deficiency from Previous Season</u>

As use of the Drought Code spread beyond the coast of British Columbia, the original assumption that it was automatically reduced to zero at the beginning of each fire season was no longer valid, due to deficient winter precipitation and overwinter losses in some regions.

The effect of deficient overwinter precipitation and various drying processes on the available moisture is less known for forested areas than it is for some agricultural soils.

Fig. 4 presents data from three separate investigations for agricultural soils (Staple *et al.*, 1960; Ferguson *et al.*, 1964; Hobbs and Krogman, 1971), in which the available moisture in the spring is plotted

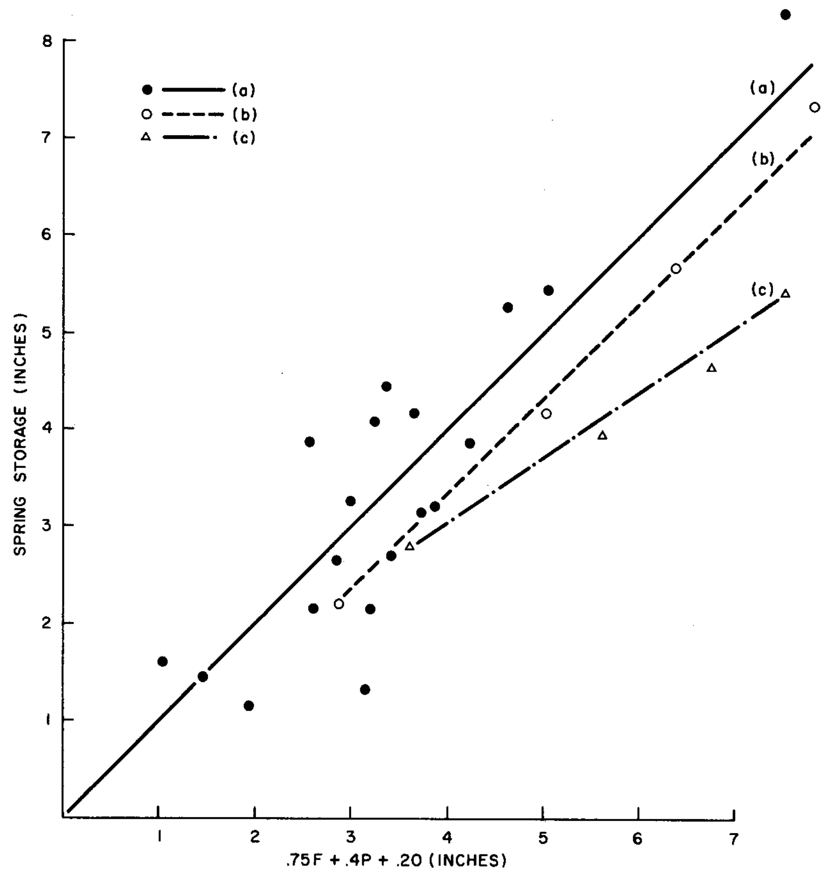

Figure 4. Stored moisture at planting time as a function of fall moisture (F) and overwinter precipitation (P).

(a) Staple et al. *(1960) Individual years--stubble-Saskatchewan*

(b) Ferguson et al. *(1964) Individual plots--hoed soil-Montana*

(c) Hobbs and Krogman (1971) Irrigation treatments--fallow soil-Alberta

against a function of the fall moisture content and overwinter precipitation derived from a regression found by Staple and his collaborators.

The function used was:

$$(SMI)_s = \{.75\ (SMI)_f + P\} \qquad (11)$$

where subscripts s and f refer to spring and fall values of SMI, and P is the overwinter precipitation in hundredths of an inch.

The proportion of the fall moisture carried over is assumed to be the same as for the agricultural soils. However, the percentage of overwinter precipitation contributing to the spring moisture is increased from .4 to .75.[6] This is in recognition of the more permeable "honeycomb" frost structure present under most forest stands, referred to by Pelton *et al.* (1967). (Interception losses are assumed to be included in the 25% lost.)

The consequences of such a model for overwinter adjustment of the DC may be judged by Table 5.

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[6]Multiplying the SMI by .75 is equivalent to adding 115 to the DC. Over roughly a 6-month "winter period" this is equivalent to 115/180 or 0.64 units/day corresponding to an average daily PE of .013".

TABLE 5

Overwinter Precipitation and Drought Code

According to Proposed Model

Fall Value DC	(SMI)	Precipitation (in inches) necessary for: (a) Maintaining Fall Value	(b) Saturation
0	(800)	2.67	2.67
115	(600)	2.00	4.67
277	(400)	1.50	6.67
555	(200)	0.67	8.67
832	(100)	0.33	9.67

("Fall" as used above refers to the freeze-up date or November 1, whichever is earlier, while "Spring" refers to the starting date as indicated above.)

This model is presented as a consistent method of allowing for carry-over of drought from one season to the next, with values of coefficients subject to adjustment. An alternative method has been developed by the staff of the Northern Forest Research Centre for use by the Alberta Forest Service (Kiil, A.D., personal communication).

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APPENDIX

Differences between mean daily maximum temperatures and the mean temperature at local standard noon for 22 stations across Canada.

$T_x - T_{12}$ (F)

	Apr	May	Jun	Jul	Aug	Sep	Avg.
Abbotsford, B.C.	4.9	5.1	4.0	4.5	4.8	4.7	4.7
Ft. St. John, B.C.	5.0	7.0	4.8	4.6	3.9	6.0	5.2
Penticton, B.C.	6.0	5.8	3.6	6.7	5.8	5.6	5.6
Prince George, B.C.	5.3	5.2	4.9	4.7	5.1	5.9	5.2
Vancouver, B.C.	3.8	4.2	4.7	4.5	4.6	3.6	4.2
Victoria City, B.C.	4.2	4.8	4.3	5.1	4.9	4.2	4.6
Whitehorse, Y.T.	2.4	5.0	4.9	4.1	4.3	4.4	4.2
Yellowknife, N.W.T.	7.4	5.7	3.2	4.1	3.6	4.0	4.7
Calgary, Alta.	7.7	6.3	3.5	5.9	5.6	5.9	5.8
Edmonton, Alta.	7.4	6.1	4.8	5.8	5.4	6.5	6.0
Regina, Sask.	5.9	6.1	2.9	5.4	3.7	5.7	5.0
Churchill, Man.	6.0	4.7	5.1	5.2	4.5	2.7	4.7
Winnipeg, Man.	6.6	6.2	4.0	5.8	4.5	6.4	5.6
Lakehead*, Ont.	4.2	4.8	4.3	5.2	4.0	4.9	4.6
Toronto, Ont.	3.0	3.7	3.9	4.9	3.7	3.8	3.8
Windsor, Ont.	4.0	4.4	5.2	4.1	4.3	3.6	4.3
Montreal, Que.	3.7	4.0	4.1	4.9	3.0	3.0	3.8
Sept Isles, Que.	2.4	5.0	5.4	5.5	5.3	4.2	4.6
Moncton, N.B.	4.2	4.7	4.5	5.8	4.0	4.1	4.6
Halifax, N.S.	3.6	5.7	7.2	8.5	4.1	3.0	5.4
Gander, Nfld.	3.0	4.9	4.0	5.9	4.8	4.1	4.5
Goose Bay, Nfld.	3.1	3.6	4.8	5.8	3.8	4.1	4.2
Average	4.7	5.2	4.5	5.4	4.4	4.6	

*Now Thunder Bay