ESTIMATING EVAPOTRANSPIRATION ON A

REGIONAL SCALE

-By-

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ABSTRACT

The purpose of the study is to determine the most suitable means
of calculating evapotranspiration on a regional scale. A brief
review of factors involved and methods available is included. Tests
were carried out for seventeen stations throughout Canada.
Comparison of results from Turc's equation, Thornthwaite's climatic
water balance and a modified approach of the climatic water balance
found the latter method to give superior results.

ESTIMATING ACTUAL EVAPOTRANSPIRATION FROM CLIMATOLOGICAL
DATA FOR MAPPING PURPOSES

INTRODUCTION

The primary objective of the study was to evaluate different
methods of calculating actual evapotranspiration (AE) which may be
applied for climatic mapping purposes. Although the study was
restricted to Canada, it was hoped that the wide differences in
climatic and physiographic conditions which exist throughout our
Country permit evaluation of techniques under a number of diverse
conditions so that the results obtained from the study would have
general application - particularly to "Developing Nations". The
terms; actual evaporation or evapotranspiration as used herein, are
defined as the amount of water which is evaporated and/or transpired
from the soil and vegetative cover under prevailing meteorological
and soil moisture conditions. The importance of evapotranspiration as
a climatic variable is well-recognized because it plays a major role
in energy and moisture exchanges between the earth and the atmosphere.

Climatic indexing and water resource management and planning
studies require some insight of the magnitude of the evapotranspiration
component. Many other factors relating to these needs have been mapped
successfully on a regional scale. For example, maps are available for
temperature, precipitation, humidity, sunshine, runoff, radiation,
evaporation from free water surfaces and other variables. Thus, the
omission of evapotranspiration is most noticeable if attempts are to be
made to develop a general climatic map. The primary reason for this
omission stems from the fact that numerous variables, with their own

inaccuracies, are required to evaluate actual evapotranspiration. This parameter is affected by climatic inputs to the system, vegetal and soil properties.

FACTORS AFFECTING EVAPOTRANSPIRATION

The primary climatic factors which influence the amount of evaporation are the energy supply available to evaporate water, the transfer processes and those factors which affect the movement of the evaporated amounts in the overlying layer away from the soil-vegetation surface. These factors are readily reflected in the potential evapo-transpiration, PE term - which is the evapotranspiration required to satisfy atmospheric demands at the evaporating surface (assuming water supply to be non-limiting). Many equations, both theoretical and empirical, have been developed to estimate potential evapotranspiration. Radiation, temperature, humidity and wind speed are the primary climatic parameters used to determine potential evapotranspiration.

Although actual evapotranspiration is affected by many of the same variables which affect potential evapotranspiration; in calculating actual evapotranspiration over a period of time (e.g. weekly, monthly, seasonally or annually), the amount of precipitation which occurred within that time interval must be taken into account. At different times of the year, in many parts of the World, the amount of water available for evapotranspiration is limited and hence, precipitation becomes the controlling factor governing the actual evapotranspiration. The problem is further complicated by the nature of the precipitation; whether it is

in liquid or solid form. For example, in many parts of Canada infiltration from snow melt is an important input to ground water and soil moisture recharge. Calculations of actual evapotranspiration on an annual basis must take into consideration this input.

Although precipitation, either in the form of rain or snow, is the main parameter which determines the water available for evapotranspiration (certainly on a regional scale), soil and vegetal characteristics are probably of equal importance. The interactions that exist within the soil-moisture-vegetation complex have deterred the development of methods of estimating actual evapotranspiration.

The moisture holding capacity and the infiltration rate of a soil influence the amount of precipitation that enter the soil and is retained for evapotranspiration. These physical characteristics of a soil vary greatly in space and time and from one soil type to another. Similarly, the moisture withdrawal pattern from any given soil is usually not known. Some investigators consider that all soil moisture between field capacity and the permanent wilting point is readily available to the plant and evapotranspiration proceeds at the potential rate. A more accepted soil moisture withdrawal pattern is a modified exponential type of relationship in which the actual evapotranspiration decreases as the soil dries out (see Figure 1). In the figure, it is assumed that soil moisture is sufficient to satisfy potential demands from field capacity down to a certain soil moisture content then the withdrawal rate decreases rapidly as the soil dries. This curve tends
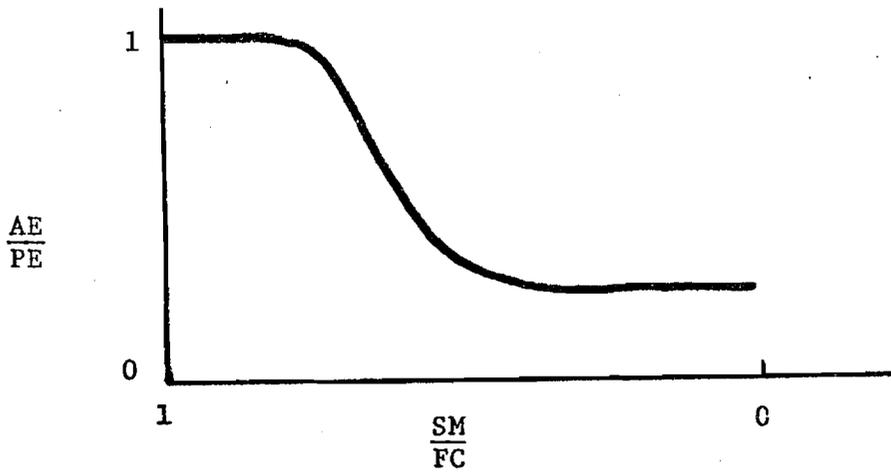
Figure 1. Schematic Drying Curve of a Soil

FC = Total Moisture Soil can Hold for Evaporation (Field Capacity).
SM = Actual Soil Moisture.

to shift position for different soil types and with different drying rates. In addition, the amount of water available between the limits of field capacity and the wilting point is a function of the rooting depth of the vegetation.

Vegetation influences actual evapotranspiration through its rooting habits, growing season, ground cover and others, and through its ability to absorb water from the soil and transpire it to the atmosphere.

Similarly, artificial (human) induced changes can alter actual evapotranspiration patterns by different land use practices. These effects are difficult to evaluate on a regional basis.

METHODS OF EVALUATING ACTUAL EVAPOTRANSPIRATION (AE)

Energy Balance

The energy balance is a theoretical approach that is used to evaluate potential evapotranspiration amounts from a land surface. The method is based on the conservation of energy.

$$ET = R_N - S - K - N - \text{Storage Terms} \tag{1}$$

ET = energy for evapotranspiration,

R_N = net radiation,

S = energy to soil heat,

K = sensible heat to the air, and

N = energy used by plants for photosynthesis.

if the terms, S, N and Storage are considered negligible, Equation 1 can be reduced to,

$$R_N = H = K + ET \tag{2}$$

H = heat budget

Equation 2 is limited in its "general" application because of the difficulties encountered in measuring the different components. In certain instances, a constant ratio between K and ET is assumed and this proportioning although minimizing the problem in certain cases creates others. For example, the ratio K:ET is neither constant with time nor space. Further, since one is working with potential evapotranspiration values the problem is further complicated in cases where the soil moisture conditions are insufficient to meet the potential demands.

In any event, the use of Equation 2 in establishing regional climatic maps of actual evapotranspiration demands would be very restricted in its application because of the lack of basic meteorological information available from those stations operated in a network. Perhaps the greatest value of this approach is to check the more simplified equations which have been developed to estimate actual evapotranspiration.

Mass Transfer

This method is based on the aerodynamic law presented by Dalton.

$$E = \frac{K\ f(u)(e_o - e_a)}{f(z_o)} \tag{3}$$

E = evaporation,

K = parameter to include the effects of air density and

pressure,

$f(u)$ = wind velocity function,

$e_o - e_a$ = vapour pressure difference; in which e_o is the saturated

vapour pressure at the temperature of the surface and e_a

is the actual vapour pressure of the water at the air

temperature, and

$f(z_o)$ = roughness parameter.

Sverdrup (1946) and Thornthwaite and Holzman (1939) have developed

workable forms of this equation but as in the case of the Energy

Balance they are not generally used for general mapping purposes because

of the unavailability of data.

Water Balance

$$P = E + R \pm \Delta S_m \pm \Delta G_w \tag{4}$$

R = runoff,

P = precipitation,

E = evapotranspiration,

ΔS_m = change in soil moisture storage, and

ΔG_w = change in ground water storage.

Of the theoretical methods, the Water Balance approach probably could

be applied with the most confidence and ease to estimate actual

evapotranspiration if adequate measurements of changes in soil moisture and ground water were available. However, the expense of measurement of changes; particularly in soil moisture and ground water storage, is usually very high and prohibits extensive measurements except at a few limited locations. Also, in many instances the measurement of soil moisture is made on a gravimetric basis rather than volumetric. As in the case of other techniques these factors tend to limit the use of the approach for purposes of regional scale mapping.

In certain cases, however, the Water Balance has been successfully applied in determination of actual evapotranspiration. The primary requirement for the success of this approach is that the sum of the changes in the water stored in an area in the form of either soil moisture or ground water approach zero within the time interval of study. Under favorable climatic conditions - humid or subhumid - the approach has been successful in calculation of annual evapotranspiration amounts. Also, in a few instances as at Katherine, Australia, it has been used for monthly calculations. The climatic conditions at Katherine are somewhat unique inasmuch as there is a distinct division between wet and dry seasons.

Others

Several other commonly-used techniques for measuring actual evapotranspiration are;

    1. Soil moisture depletion studies on small plots.

    2. Tank and lysimeter experiments.

3. Study of ground water fluctuations.

4. Empirical constants applied to tank evaporation

    measurements.

5. Soil moisture budgets.

All these methods are impractical for the purpose of the current study
due to their special applications and usual lack of data.

Empirical (Turc)

An empirical method was developed by Turc to estimate
evapotranspiration on a regional scale. Two equations were developed;
one for annual use and one for calculating evapotranspiration for a
ten-day period. These equations require measurements of temperature,
precipitation, radiation and some estimate of crop yield.

Annual Equation:

$$E = \frac{P}{\sqrt{0.9 + \dfrac{P^2}{L(t)^2}}} \tag{5}$$

E and P are evaporation and precipitation respectively in
units of mm.

$L(t) = 300 + 25t + 0.05t^3$

    t = mean annual air temperature in degrees C

    $E = P$ when $\dfrac{P^2}{L(t)^2} < 0.1$

Ten-day Period:

$$E \text{ mm/10 days} = \frac{P + a + V}{\sqrt{1 + (\frac{P + a}{\ell} + \frac{V}{2\ell})^2}}$$ (6)

a = drying term for a bare soil,

= 35 - Δ with a minimum of 1 and a maximum of 10,

V = drying term due to vegetation,

= the smaller value (not less than zero) of

$$(\Delta_o + 30 + 1.5 \text{ Mc } \frac{z}{Z}) - \Delta$$

or $$25 \frac{\sqrt{Mc}}{Z}$$

ℓ = function of temperature and solar radiation,

$$= \frac{(t + 2)\sqrt{I}}{16} ,$$

M = total dry matter harvested in q/ha,

Z = number of ten-day periods in the growing season

(intervals with ℓ < 10 are excluded; for then V = 0),

z = number of the ten-day period being considered,

c = coefficient of transpiration of the plant in question

relative to that of wheat,

Δ = deficit of soil moisture from the field capacity,

Δ_o = value of Δ at the start of the growing season,

I = insolation (ly/day),

t = average ten-day temperature in degrees C,

P = ten-day precipitation in mm.

Runoff occurs when the precipitation brings the soil moisture deficit to less than zero.

Climatic Water Balance

This method developed by Thornthwaite (1957) is based on the water balance equation,

$$P = E + R \pm \Delta S_m \pm \Delta G_w \tag{7}$$

In application of the method a soil moisture withdrawal pattern and soil moisture holding capacity are assumed or evaluated and a potential evaporation equation used to budget precipitation to soil moisture and evaporation. As in the Turc method, runoff occurs when the precipitation increases the soil moisture to a level greater than field capacity. No attempt is made to distinguish between surface runoff and additions to the groundwater. The method can be used with minimal measured data; namely precipitation and temperature.

The limitations of the different methods discussed above for calculating actual evapotranspiration; as they relate to the attainment of the project objectives of the study reported herein, are summarized in Table 1.

TABLE I.   Methods of Estimating AE for Regional Application

Method	Limitations
(1) Energy Balance	Lack of data for proportioning energy under less than optimum moisture conditions.
(2) Mass Transfer	Data required is too specific for regional application.
(3) Water Balance	Measurements of soil moisture lacking. Can be applied to annual norms in some cases.
(4) Measurements	Expense prohibits their use except in small local studies.
(5) Empirical (Turc)	Accuracy will be much less than more theoretical methods. Applicability to different climatic regions must be tested.
(6) Climatic Water Balance	Also a reduction in accuracy. Must be evaluated for different climatic regions and soil types.

From Table 1 it can be concluded that "Turc's Method" and the "Climatic Water Balance" are the only methods that can be more or less generally or universally used for calculating evapotranspiration amounts using data recorded at most climatic stations. The choice of an evapotranspiration equation for the water balance computation is also restricted by the available data.

The two methods; Turc's and Climatic Water Balance, were tested at different locations in Canada (see later discussions) in attempt to evaluate the applicability of each in estimating regional evapotranspiration patterns.

PROCEDURE

Before discussing the results of the studies, it is appropriate that the methodology followed in application of the pre-mentioned methods be briefly described.

Turc

Turc's annual equation (Equation 5) was not used in the study as it is well-known that the mean annual evapotranspiration may be very different for two regions having the same values of mean annual temperature and precipitation. This problem was indicated by Cavadias (1961) in applying the annual equation to conditions in Quebec.

To apply the ten-day equation, several terms must be evaluated. In applying the Turc equation, values for the dry matter harvested and the coefficient of transpiration were taken equal to those for a perennial crop such as grass. Accepting these criteria eliminated the necessity of obtaining specific cropping patterns. It was assumed these data would not decrease the accuracy of the computation significantly. Similarly, M - the total dry matter harvested was estimated. Although the length of the growing season usually varies from year to year, a constant value was assumed for a given location. Maps published in "The Canada Land Inventory - ARDA" (1963) were used to obtain estimates of the length of the growing season. Precipitation and temperature data were obtained from the Atmospheric Environment Service, Canada Department of Environment. The insolation values were interpolated from global solar radiation maps of Canada. The constants used in applying Turc's equation are given in Appendix A.

Climatic Water Balance

Basically the approach used for this method was the same as that used for the Thornthwaite's Climatic Water Balance. However, since the results from Thornthwaite's method have been published for many parts of Canada, several modifications were made to the technique.

The major modification to the method was the manner of using the precipitation data. Thornthwaite uses monthly values of precipitation budgeted towards potential evaporation. In the study it was assumed that the variability of precipitation at many of the selected locations warrants the use of a shorter time period in the analysis. Hence, a ten-day time period was chosen. For those months having thirty-one days; the last time period of each month used eleven days of data so as to keep monthly summations separate. Also, the fact that precipitation does not occur uniformily neither with respect to space or time over an area naturally infers non-uniform contributions to the soil moisture. Schematic descriptions depicting the differences in approaches are given in Figures 2 and 3.
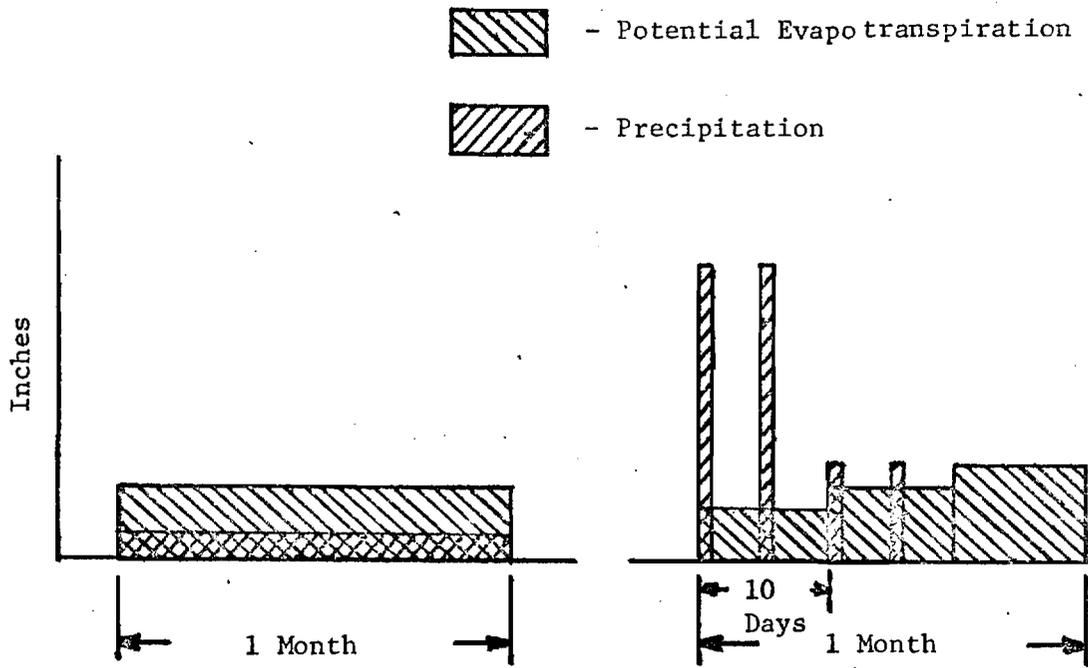
Figure 2. Thornthwaite Method of
Accounting for Precip-
itation Additions

Figure 3. Modified Approach to
Precipitation Additions

In comparing Figures 1 and 2 it is evident that the use of
precipitation data recorded on shorter time intervals provides better
representation of the manner which moisture is added to a soil under
natural storm events than when monthly totals are used. This increases
runoff. The effect is most noticeable during the snow melt period. In
the spring, large amounts of moisture may be added to the soil before
evapotranspiration begins. If the amount of water potentially available
from snow melt is distributed or applied to the soil over a period of a
month, the amount of evapotranspiration will probably be greater than
actual and runoff may be much less. Obviously, in the spring, the
addition of precipitation could result in both surplus and deficit
conditions occurring in the same month. Monthly analysis is incapable
of calculating both these moisture conditions (within any given month).

A study by Ferguson, O'Neill and Cork (1970) found the
Christianson-Mehta Equation to be superior to other methods in the
regional mapping of evaporation from open water bodies in Canada. This
equation was adopted for calculating potential evapotranspiration. The
Christianson-Mehta Equation is,

$$PE = 0.328 \ R \ C_T \ C_W \ C_H \ C_S \ C_E \ C_M \tag{8}$$

R = extra-terrestrial radiation in evaporation units,

$C_T = 0.1532 + 0.00874T + 0.0000546T^2$,

$C_W = 0.79 + 0.0037W - 0.00000333W^2$,

$C_H = 1.202 - 0.00353H - 0.0000381H^2$,

$C_S = 0.402 + 0.019S - 0.00028S^2 + 0.0000017S^3$,

$C_E = 0.9654 + 0.0362Z - 0.0016Z^2$,

C_M = monthly coefficient,

T = mean temperature in degrees F,

W = mean wind velocity at pan level in miles per day,

H = mean daytime relative humidity in percent,

S = percentage of possible bright sunshine,

Z = station elevation in units of thousands of feet.

In applying the equation in the work reported herein,

1. The values of the monthly coefficients, C_M, for the period from January - December were taken as; 1.20, 1.20, 1.20, 1.18, 1.13, 1.08, 1.05, 1.10, 1.15, 1.20, 1.20 and 1.20 respectively.

2. For stations where wind data was not available, the coefficient, C_W, was omitted from the equation.

3. Where humidity measurements were not recorded, C_H was assumed to be unity.

4. Calculation of the sunshine coefficient, C_S, was based on the mean value for a ten-day period obtained from the long-term averages listed in the Climatic Atlas of Canada and the total possible hours of sunshine given in the Smithsonian Meteorological Tables (1966). Values for extra-terrestrial radiation, obtained from the paper given by Christianson (1966) were also used in the calculation.

Although the soil moisture extraction pattern used by Thornthwaite (as shown in Figure 4) could have been used in computing the water balance by Equation 8, it was decided that an adjustment to this curve should be made so that it more closely follows the pattern shown in Figure 1. Thus, the crop root zone of the soil was divided into two zones. In this division, it was assumed that moisture was withdrawn from the upper zone at the potential rate. Moisture removal from the lower zone followed the relationship established in Thornthwaite's soil retention tables. This adjustment is schematically illustrated in Figure 5. The equation used to simulate Thornthwaite's tables is;

$$SM_2 = SM_1 - PE\left(\frac{SM_1}{FC}\right) \tag{9}$$

SM_2 = final soil moisture,

SM_1 = initial soil moisture, and

FC = field capacity (maximum water available for

evaporation in the complete soil profile - upper

and lower zones).

The equation must only be used with small values of potential evapotranspiration. In the computer program, withdrawal increments of 0.20 inches were used to apply the potential evapotranspiration to the lower zone. The actual evaporation from the lower zone was then the difference between the soil moisture at the beginning of the looping process and SM_2 at the end.
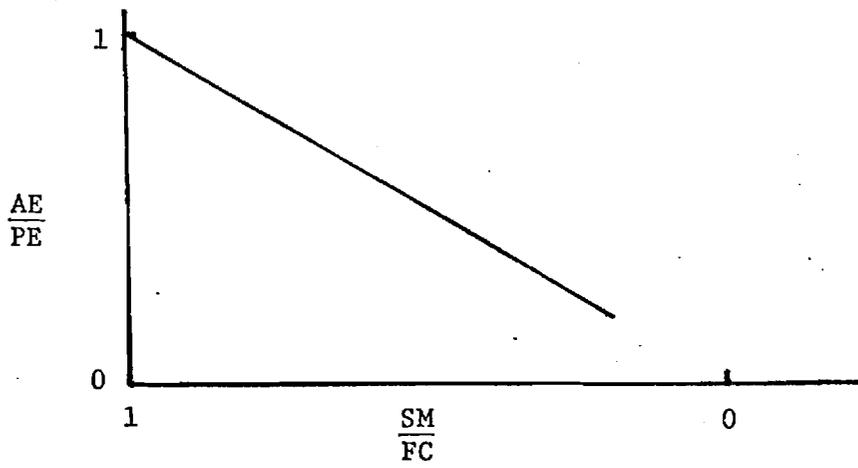
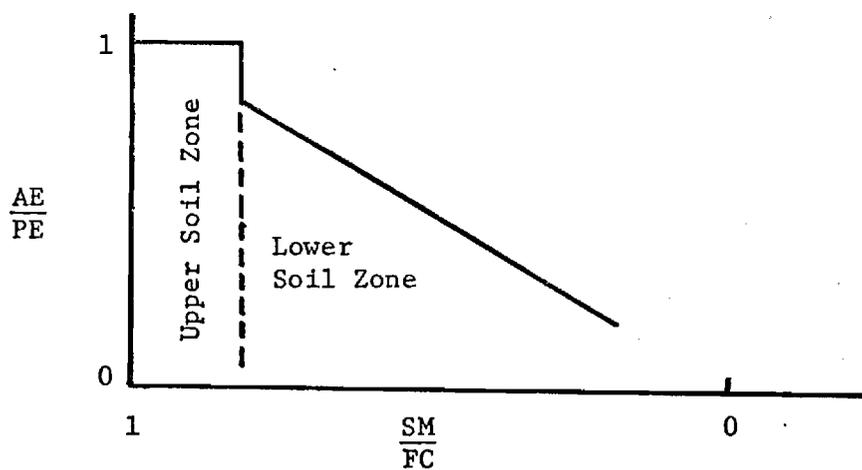Figure 4. Thornthwaite's Drying Curve

Figure 5.   Soil Drying Curve Used in Water
Balance Technique

One major advantage of this technique is that small amounts of precipitation that do not completely fill the upper zone are not subject to low evaporation rates - as would be the case if the soil were considered as one zone. This aspect is particularly critical for Prairie Conditions, where during the summer the soil usually becomes very dry, resulting in a low evapotranspiration rate. Water from a small rain at this time of the year would not penetrate to the lower soil moisture zone but would be held in the upper zone where it would evaporate very quickly.

An attempt to allow for vegetation influences was also included in modifications made to the water balance computation. The growing season was assumed equal to that established for Turc's equation. For those periods not falling within this growing season, it was assumed that the soil moisture was removed only from the upper soil zone.

The moisture holding capacities of the different zones for different soils were initially estimated and then refined after trial calculations had been carried out for each station.

In Canada much of the precipitation that supplies runoff is in the form of snow. In the procedure used, it was assumed that when the average ten-day temperatures were less than freezing then any precipitation within the period was snow. Snowfall values were accumulated until the ten-day temperature again increased above the freezing point. The accumulated snowfall was melted according to the empirical relationship,

$$M = 0.05 \ (T - 32) \ N \hspace{4cm} (10)$$

M = inches of snow melt,

T = mean temperature in degrees F during a period of N

    days, and

N = number of days considered in finding the mean

    temperature.

The amount of snow melt calculated during any given ten-day period was considered as part of the precipitation which occurred within the period. A simple bookkeeping of the amounts of snow (as water equivalent) and melt was used to obtain an estimate of the net supply (water) during the melt and accumulation periods.

The approach used to evaluate the different methods of computing actual evapotranspiration was to compare "calculated" runoff amounts with "measured" values.

Statistics

To properly assess the methods used it is necessary to have some measure of the "goodness-of-fit" of the runoff values. For this analyses, annual runoff values were used. No attempt was made, however, to apply a linear regression analyses to the data as it was not considered the intent of the study to develop "Prediction Equations" for each station but rather to test the application of different equations for determining AE under variable climatic and physiographic conditions. If a regression analysis were applied to the data, a different set of coefficients would be obtained for each location.

A brief discussion of some of the statistical parameters used in analyses of the data is given below.

Coefficient of Variation

$$CV = \frac{\sqrt{Var(Q_{meas})}}{\bar{Q}_{meas}}$$ (11)

CV = coefficient of variation of the measured annual runoff values, Q_{meas},

$Var(Q_{meas})$ = variance of the measured annual runoff,

$$= \frac{1}{n} \Sigma \ (Q_{meas} - \bar{Q}_{meas})^2, \text{ and}$$

$\bar{Q}_{meas}$ = mean measured annual runoff.

CV is the ratio of the standard deviation to the mean. Statistically and hydrologically it has been found to be an extremely useful parameter in that its magnitude is relatively insensitive - within a given region - to changes: other than sampling error. The parameter often is related to the "skewness" of frequency distributions. In many cases, CV can be used to differentiate areas with dissimilar hydrologic and climatic characteristics.

Correlation Coefficient

$$r = \frac{\Sigma (Q_{calc} - Q_{calc}/N)(Q_{meas} - Q_{meas}/N)}{[\Sigma (Q_{calc} - Q_{calc}/N)^2 \times \Sigma (Q_{meas} - Q_{meas}/N)^2]^{\frac{1}{2}}} \qquad (12)$$

Q_{calc} = calculated annual runoff, and,

N = number of events.

The correlation coefficient, r, common to both statistical and hydrologic literature provides a measure of the degree of association between two variables which are assumed to follow a bivariate normal distribution. For the purpose of the study it provides a quick and simple index of the relationship between measured and calculated annual flows. However, caution must be exercised in interpretation of the parameter in that; high values of the coefficient can be obtained between the variables in cases when the magnitude of one variate is either _consistently_ higher or lower than the corresponding paired variate and at many locations – particularly the Prairies – there may be a number of events of "zero" magnitude.

Standard Deviation of the Differences – between paired observations.

$$s_d = [\Sigma (Q_{calc} - Q_{meas})^2/N - (\Sigma (Q_{calc} - Q_{meas})/N)^2]^{\frac{1}{2}} \qquad (13)$$

s_d = standard deviation of the difference between calculated and measured annual runoff,

Q_{calc} = calculated annual runoff, and

N = number of paired comparisons.

The parameter, s_d, provides a statistical measure of the magnitude of the difference between calculated and measured values - and therefore a measure of the agreement between the two values. Obviously, the smaller the value of s_d; the better the relationship.

Ibbitt (1971)

$$P^2 = F^2/n \; \bar{Q}_{meas} \tag{14}$$

$$R^2 = \frac{Var \; (Q_{meas}) - (F^2/n)}{Var(Q_{meas})} \tag{15}$$

$$F^2 = \Sigma (Q_{meas} - Q_{calc})^2,$$

$$Var(Q_{meas}) = \frac{1}{n} \Sigma (Q_{meas} - \bar{Q}_{meas})^2, \text{ and}$$

n = number of evenly-spaced values in the record.

From Equation 14, it is obvious that the parameter, P, may be assumed analagous to the coefficient of variation. Obviously, as the difference, $(Q_{meas} - Q_{calc})$ approaches zero, P^2 approaches zero. Likewise, the coefficient, R^2, (Equation 15) is analagous to the coefficient of determination. As the difference between measured and calculated values decreases, R^2 approaches a limiting value of unity.

Both parameters are dimensionless but are only independent of length of the series if the effects of serial correlation are zero.

Whenever possible use was made of measured runoff from selected small basins having a climatic station in close proximity to the watershed. The purpose for this being to minimize or reduce the effects of the following factors in the "Balance" calculations.

1. Large scale spatial and temporal variations in precipitation, temperature or other important meteorological parameters.

2. Problems associated with delineation of groundwater and surface water (runoff and detention and depression storage).

3. The large runoff "lag factor" which may occur on large watersheds.

The climatic stations and stream gauging stations used for analyses are given in Figure 6 and Table 2, respectively.

Figure 6. Climatic Stations Used

TABLE II. Runoff Gauging Stations

Climatic Station	Runoff Gauge	River	Period of Record	Drainage Area (mi^2)
Swift Current	05HD031	Swift Current	1944-1954	760
	05HD036	Swift Current	1955-1966	575
Porcupine Plain	05LB002	Etomami	1955-1966	749
Vegreville	05EE001	Vermillion	1959-1967	2200
Brandon	05LL013	Whitemud	1961-1967	242
Guelph	02GA015	Speed	1951-1967	229
Montreal	030901	Chateauguay	1921-1962	967
Fredericton	01AK001	Shogomoc	1919-1940, 1944-1967	90.5
Fort Simpson	07SA003	Snare	1950-1962	5880
Yellowknife	07SA003	Snare	1950-1962	5880
Sept-Isles	072201	Rapides	1955-1967	214
Fort Chimo/Knob Lake	104001	Baleine	1963-1967	11200
White River	02BC004	White	1960-1967	1800
Duncan	08HA016	Bings	1962-1966	7.8
Abbotsford	08MH029	Sumas	1953-1967	57.6
Deer Park	08NE087	Deer	1959-1967	31.1
Vernon	08NM020	BX	1961-1971	21.5
Terrace	08EG011	Zymagotitz	1961-1967	142

All computations were programmed for computer calculation on an IBM 360. These programs, although not appended to the report, can be made available on request.

DISCUSSION OF RESULTS

An initial study was made using both the Turc and Climatic Water Balance for stations at Swift Current, Brandon, Guelph, Montreal, Fredericton and Fort Simpson. In manner of summary, the results of this preliminary investigation showed that,

> The results obtained using the Turc Equation were not found to be significantly better than those obtained using the Climatic Water Balance approach for any of the selected six stations - although in some cases it provided results of equivalent accuracy. For the Prairies the calculated runoff amounts obtained from the Turc Equation tended to be very unstable. Further, on extensive tests with this equation using data from Swift Current and Guelph, it was found that the equation was insensitive to large changes in the terms used in its solution. In certain cases, the term M - total dry matter harvested - may be adjusted to bring the computed runoff values to the same order of magnitude as the measured values. However, no correction was found to improve the correlation of runoff values. Another very weak point in the method is the soil moisture deficit term. This variable does not appear to have any physical limits.

On the basis of the preceding remarks, and the fact that the Turc Equation required greater computer time, etc., it was not utilized in calculating evapotranspiration amounts at other stations.

The statistics for the annual measured and computed flows are tabulated in Table III.

Consideration of the annual averages of measured and computed runoff given in Table III does not suggest significant differences in the values calculated by the two methods. The agreement in values

TABLE III – STATISTICAL ANALYSIS OF ANNUAL RUNOFF

Station	Measured Average $\bar{Q}m$	Computed Average $\bar{Q}c$	Correlation Coefficient r	Standard Deviation of Differences s_d	Coefficient of Variation of Measured Annual Flows CV	R^2	P^2
A. Water Balance Technique							
Swift Current	0.95	0.85	0.66	0.62	0.71	0.06	0.44
Brandon	0.56	1.92	-0.07	0.99	0.24	-178	8.87
Porcupine Plain	2.2	2.11	0.38	1.64	0.70	-0.28	0.58
Vegreville	0.29	0.17	0.58	0.23	0.93	0.07	0.80
Guelph	11.30	11.28	0.92	1.45	0.30	0.81	0.02
Montreal	16.30	15.14	0.42	4.13	0.25	-0.10	0.06
Fredericton	26.30	24.34	0.71	6.09	0.26	0.19	0.05
Sept Isles	36.70	28.89	0.75	6.37	0.19	-1.76	0.09
White River	14.30	16.03	0.67	2.53	0.13	-2.28	0.04
Fort Simpson	3.76	4.78	0.10	1.82	0.22	-5.57	0.30
Yellowknife	3.76	3.73	0.52	1.73	0.22	-3.52	0.21
Fort Chimo-Knob Lake	23.2	17.97	0.99	1.98	0.17	-1.38	0.05
Duncan	29.70	25.06	0.86	3.26	0.24	0.18	0.03
Abbotsford	25.70	40.90	0.41	7.40	0.28	-5.10	0.43
Deer Lake	14.30	5.23	-0.23	3.81	0.20	-12.50	0.47
Vernon	5.60	3.92	0.48	1.49	0.27	-1.52	0.16
Terrace	83.4	37.61	0.06	11.30	0.13	-20.35	0.31
B. Turc's Method							
Swift Current	0.95	0.98	0.54	1.25	0.71	-2.67	1.76
Brandon	0.56	3.12	0.49	0.84	0.24	- 458	22.80
Guelph	11.30	12.80	0.90	1.30	0.30	0.69	0.02
Montreal	16.30	17.09	0.50	4.17	0.25	-0.09	0.06
Fredericton	26.30	22.14	0.74	12.81	0.26	-2.08	0.24
Fort Simpson	3.76	3.44	-0.04	1.98	0.22	-5.09	0.28

obtained by the Turc method is slightly better at Swift Current, Montreal and Fort Simpson and the values computed by the water balance gives better agreement at Brandon, Guelph and Fredericton.

In comparing the statistics, r and s_d, for the water balance and Turc methods, it is evident that no definite conclusion may be reached as to which method is superior. A most notable feature is exhibited in the results obtained from Fredericton. At this station, use of Turc resulted in an increase in the correlation coefficient (0.71 -- 0.74) but at the same time s_d doubled (6.09 -- 12.81). This fact gives evidence to the use of the water balance over the Turc approach.

In considering the statistic, CV, there is evidence that the values for the Prairies are much higher than for other parts of the country. This result suggests that the Prairies may be considered a distinctly different hydrologic region; except in cases where streams are perennial and/or ground water flow forms a major part of the annual yield. Under these latter considerations the behaviour of the streams may be analogous to those which occur in more humid regions.

The statistics given in Table III are based on annual flows. Monthly trends, however, are also a major concern. A more detailed discussion of the annual and monthly results obtained from streams which occur within generalized geographical regions of Canada is presented subsequently.

Prairies

Swift Current

At Swift Current the agreement between the long-term averages of monthly and annual runoff computed by the Turc equation and the measured

values was reasonably good (see Fig. 7(a)). However, the prediction
of yearly variations using the Turc equation was poor (See Fig. 7(b)
and 7(c)). Runoff values calculated at a particular time were much too
high. Consequently, this period was followed by a series of zero values.
The water balance method depicted much better the year to year
variation in yield, although the long-term averages were not quite as
close (see Fig. 7(d), 7(e) and 7(f)). To obtain close agreement,
values obtained from the water balance method required inclusion of a
soil moisture capacity reduction term during the first ten days of
snowmelt. The necessity for including this correction could be due to
freezing in the upper soil zones which causes a subsequent reduction
in the infiltration rate. Swift Current may also be affected by
"chinook" activity which may cause melt prior to the main snowmelt
period. These melt periods usually are not evident when the ten-day
average temperatures are used in the calculations. Hence, the reduction
in the soil moisture holding capacity may correct for rapid melt periods
missed in analyzing temperature data. The drainage basis used in the
analysis would also influence the magnitude of a correction of this
type. Wind probably redistributes snow into areas of the basin so that
runoff occurs more from individual source areas than from the total
watershed. It is expected that this type of correction would be useful
only in the central prairie region. The more northerly stations chosen
in the prairies did not require any reduction in the soil moisture
capacity in the spring. For these stations, in the long-term water
balance (Equation 4), the sum of the changes in soil moisture storage
and groundwater storage can be assumed to approach zero. If this
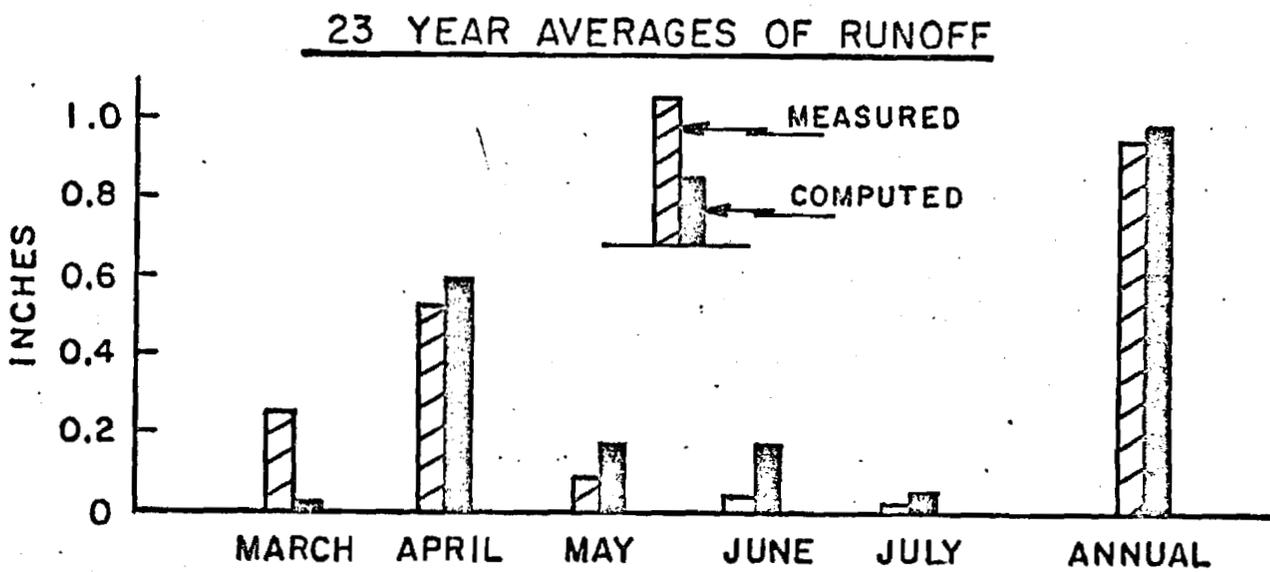
Fig. 7(a) Turc Runoff at Swift Current vs. Swift Current Creek
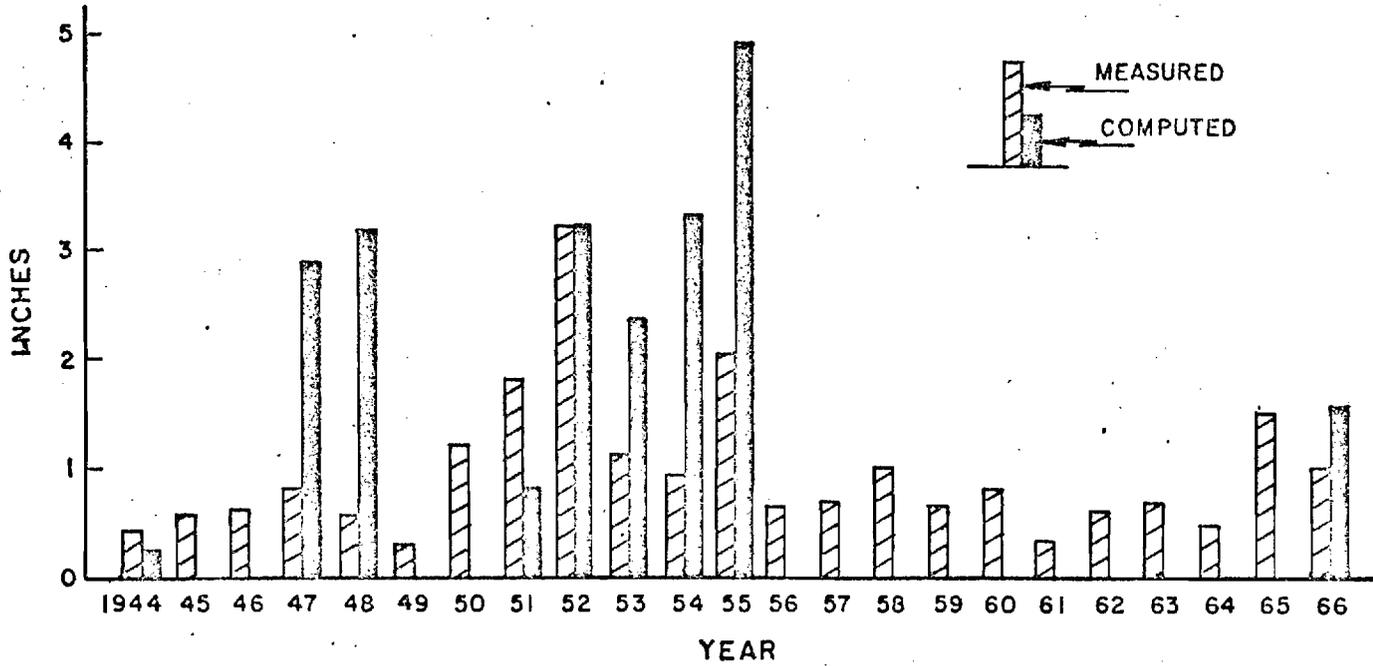
Fig. 7(b) Turc Annual Runoff at Swift Current vs. Swift Current Creek.
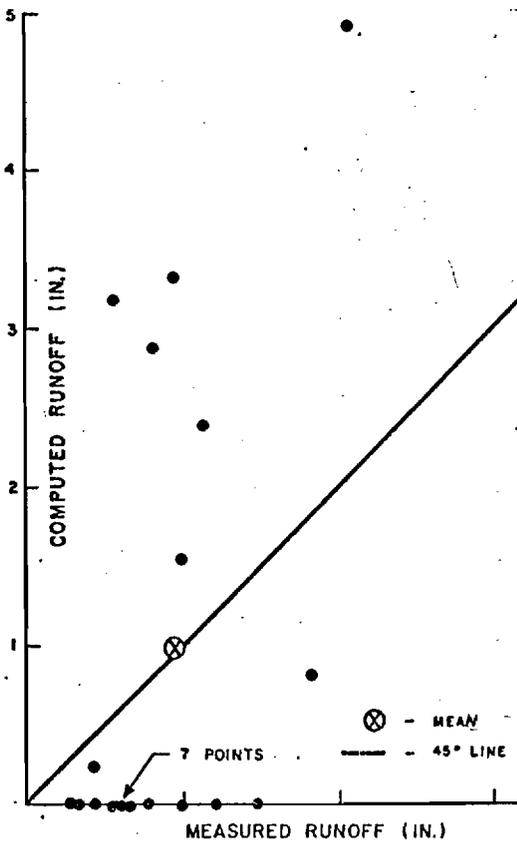
Fig. 7(c) Turc Annual Runoff at S. Current vs. Swift Current Creek
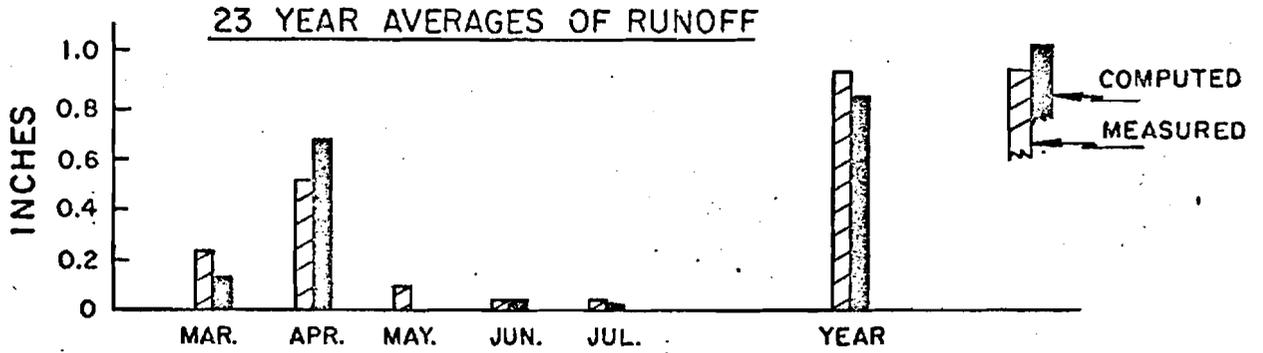
Fig. 7(d) Water Balance Runoff at Swift Current vs. Swift Current Creek
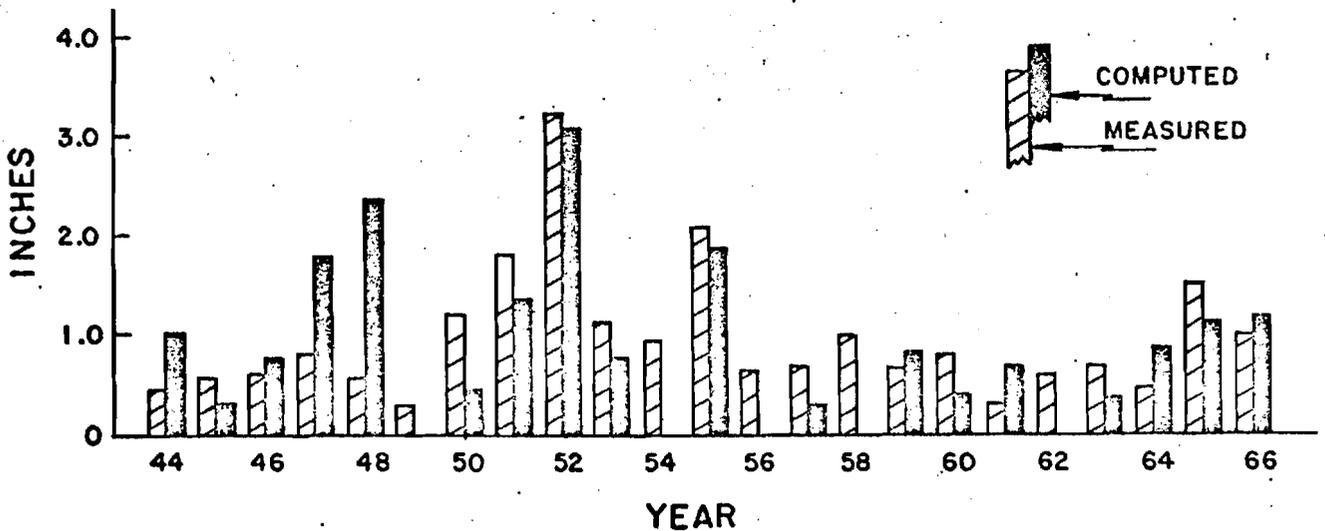
Fig. 7(e) Water Balance Annual Runoff at Swift Current vs. Swift Current Creek
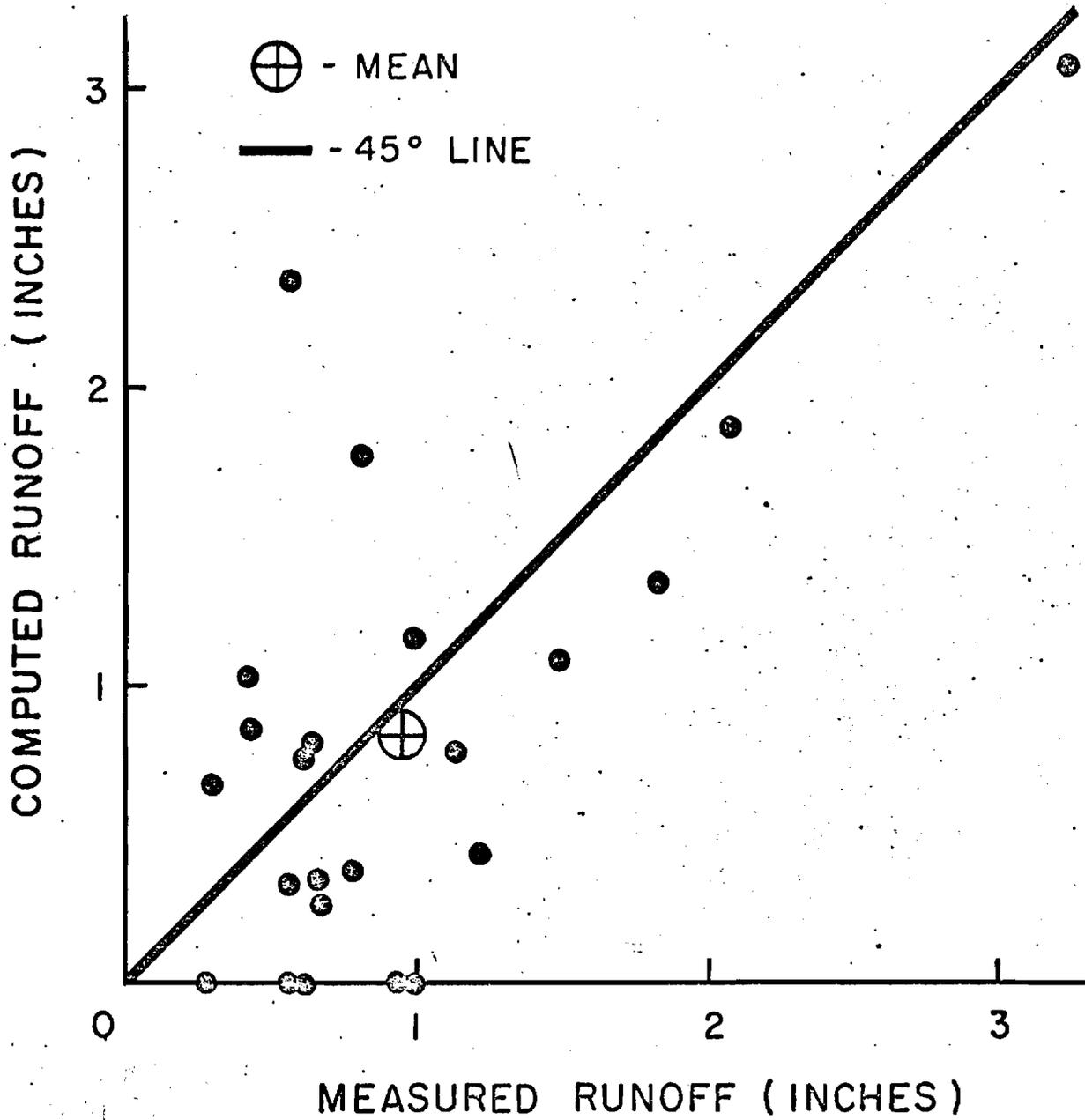
Fig. 7(f) Water Balance Annual Runoff at Swift Current vs. Swift Current Creek

assumption is made the average annual evaporation can be computed from precipitation and runoff. The calculated evapotranspiration at Swift Current differs by less than 1% from the actual value. Since surface runoff contributes such a small part of the water balance in this area, the use of the soil moisture capacity reduction term in the spring would not seriously affect the evaporation errors. The uncertainty, on any physical basis, of the requirement for using a correction for spring soil moisture capacity and its applicability does not support its inclusion in a climatic approach considering the small errors in evaporation calculations in the central prairie region.

Brandon

At Brandon the measured runoff shows very little variation from year to year (see Figs. 8(a) and 8(c)). This fact would suggest that groundwater plays a dominant role in the annual water yield. The water balance technique, although producing very poor results, was found to be better than the Turc method when comparing long-term averages (see Figs. 8(e) and 8(f)). However, neither method showed good correlation between calculated and measured values. The magnitude of the error in the calculated evaporation was still found to be within acceptable limits. The majority of the error in the calculations occurs during the snowmelt period.

Porcupine Plain and Vegreville

For water balance calculations at Porcupine Plain and Vegreville, the annual and monthly averages of runoff are quite good (see Figs. 9 to 10). Direct runoff in these areas constitutes a small part of the overall water balance.
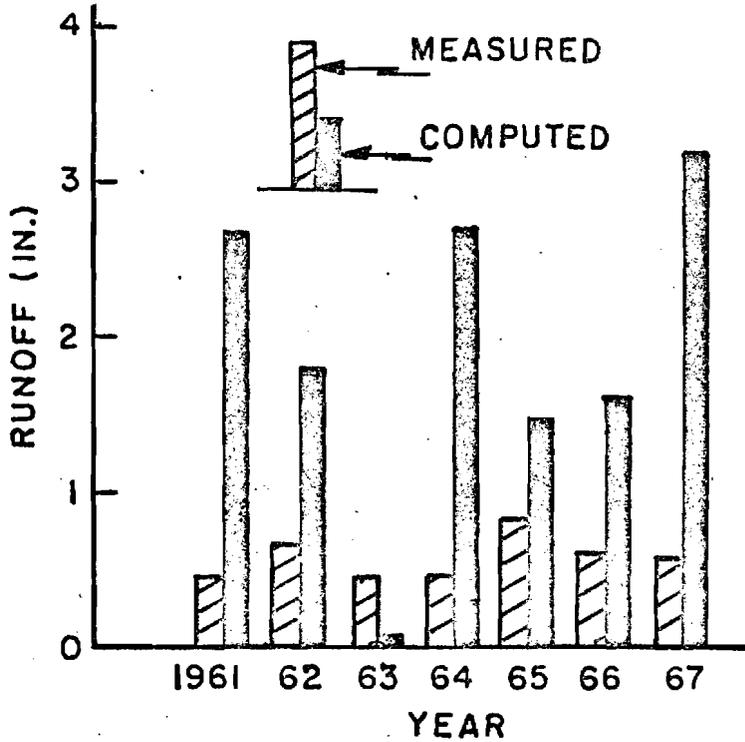
Fig. 8(a) Water Balance Annual Runoff at Brandon vs. Whitemud River
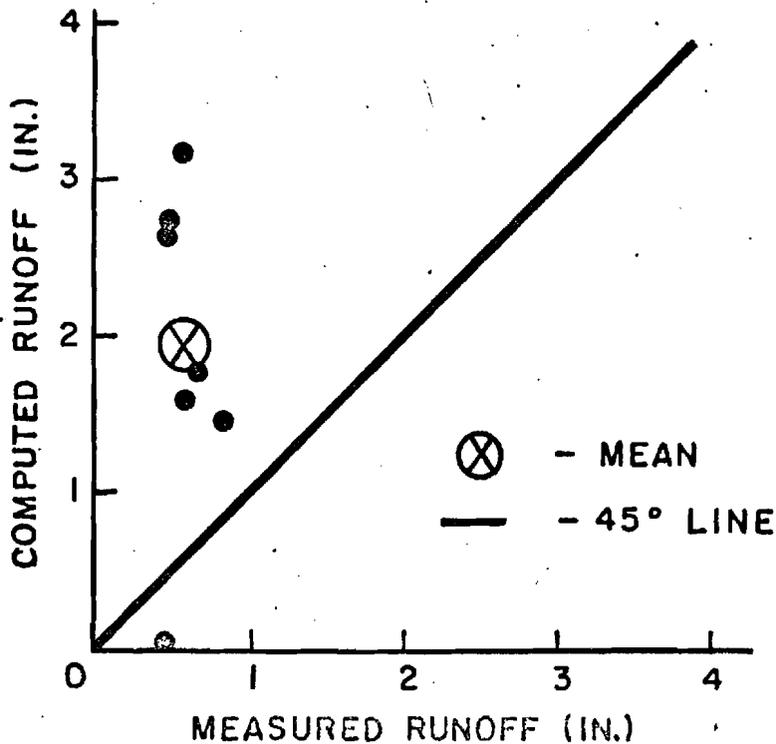
Fig. 8(b) Water Balance Annual Runoff at Brandon vs. Whitemud River
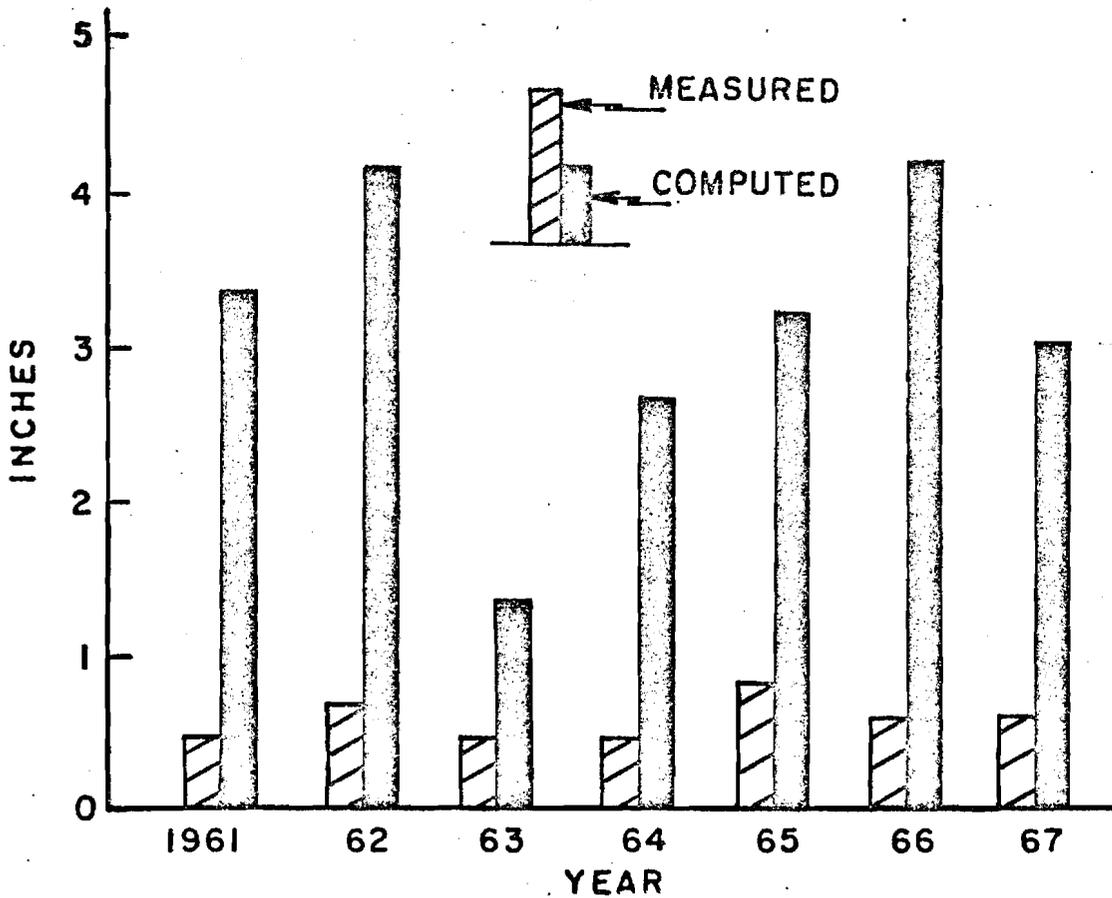
Fig. 8(c) Turc Annual Runoff at Brandon vs. Whitemud River
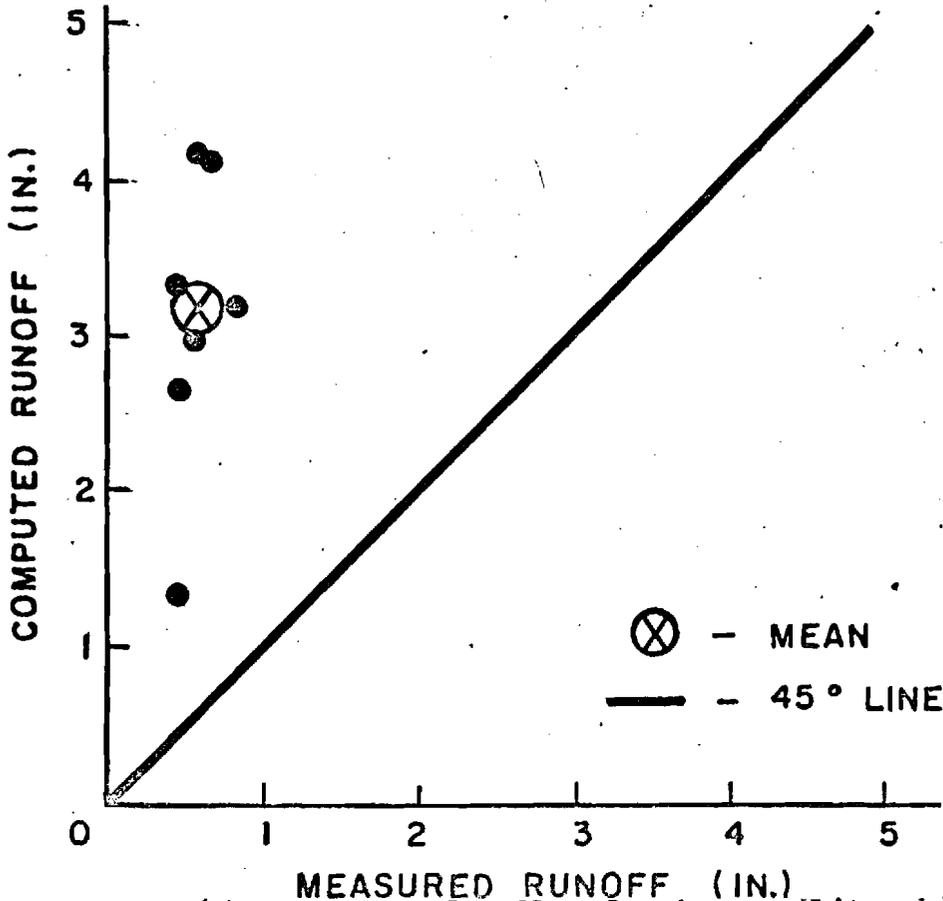
Fig. 8(d) Turc Annual Runoff at Brandon vs. Whitemud River
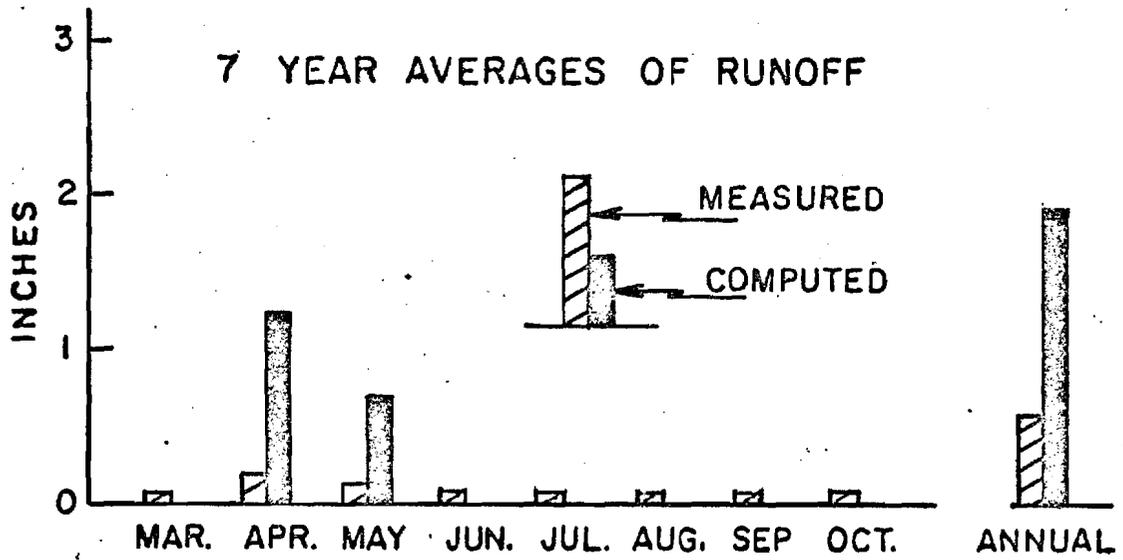
Fig. 8(e) Water Balance Runoff at Brandon vs. Whitemud River
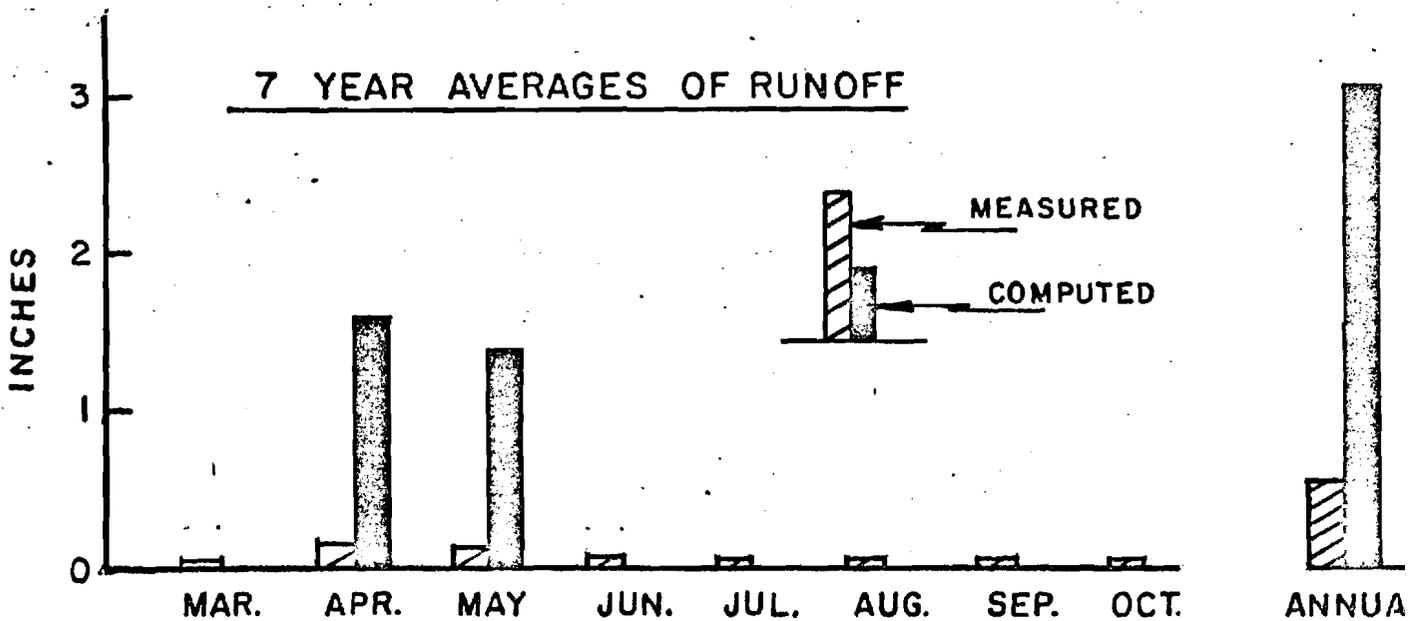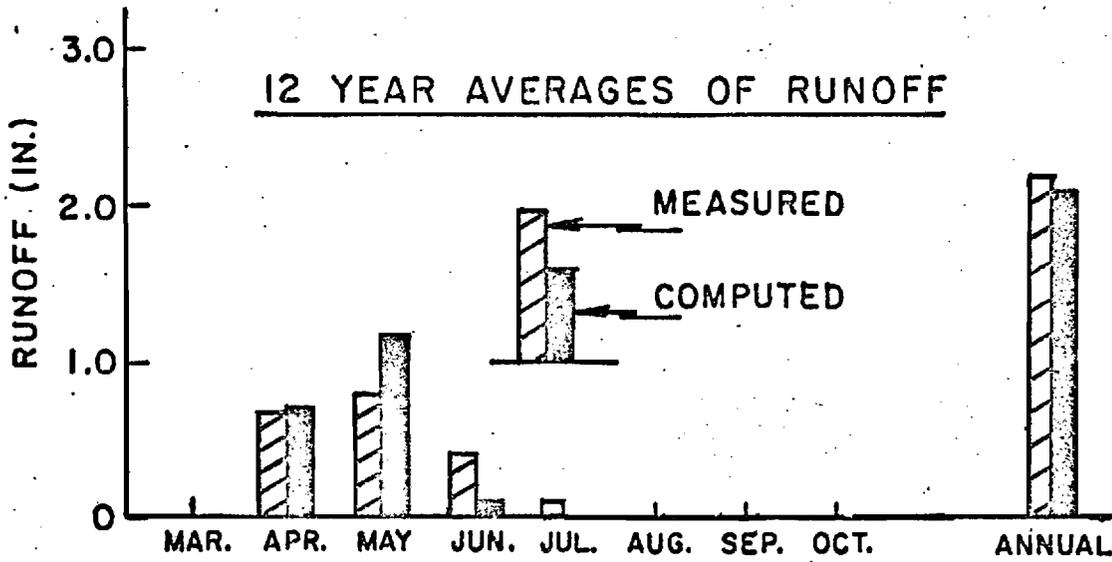

Fig. 8(f) Turc Runoff at Brandon vs. Whitemud River

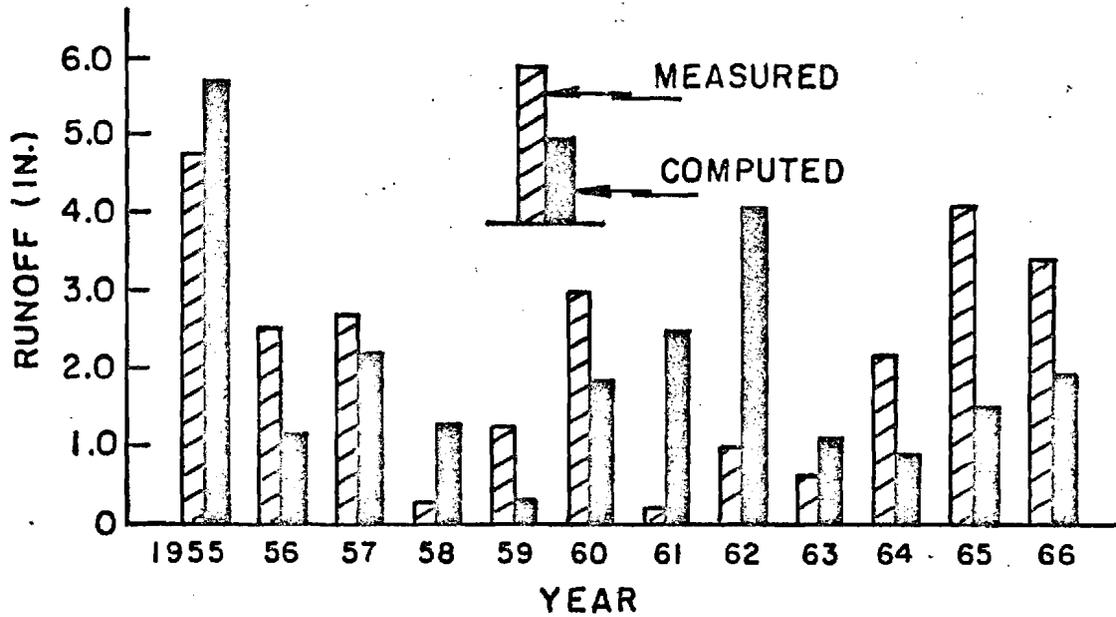Fig. 9(a)Water Balance Runoff at Porcupine Plain vs. Etomami River

Fig. 9(b) Water Balance Annual Runoff at Porcupine Plain vs. Etomami River
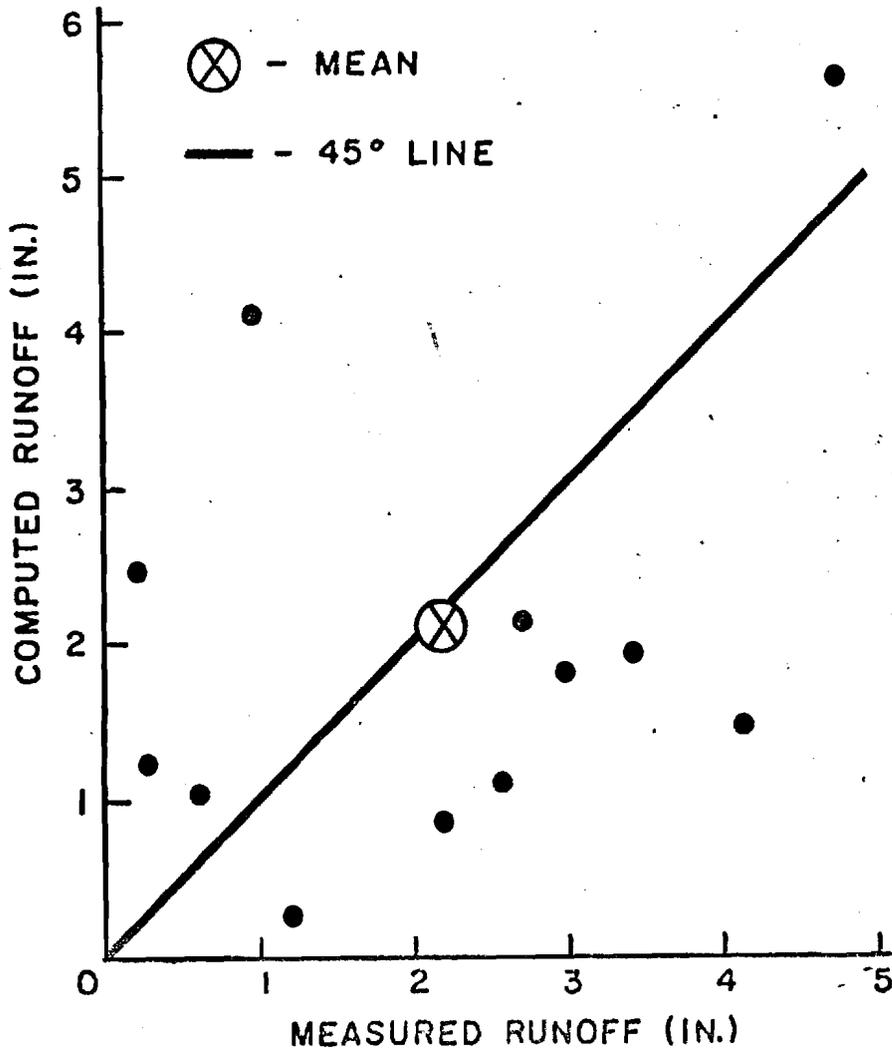
Fig. 9(c) Water Balance Annual Runoff at Porcupine River vs. Etomami River

9 YEAR AVERAGES OF RUNOFF
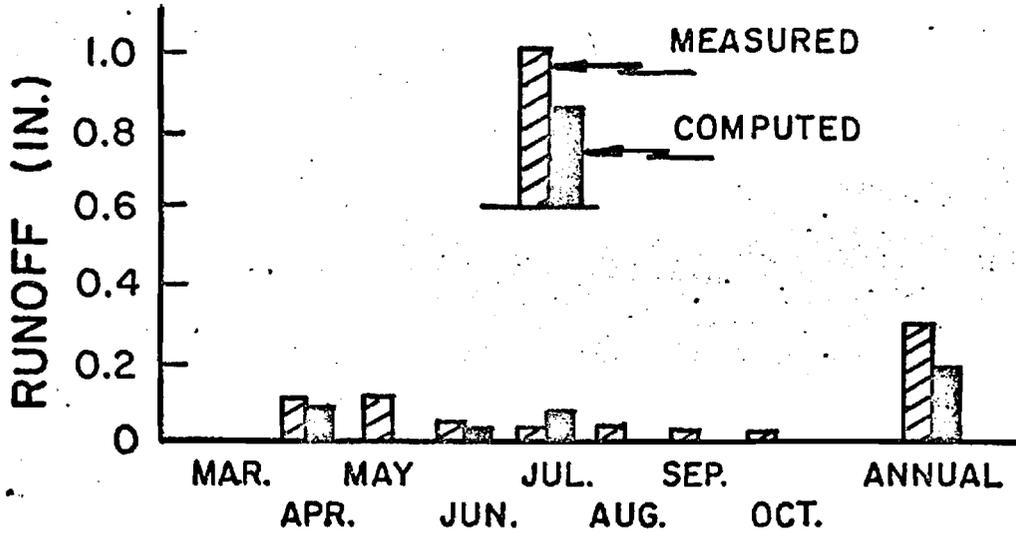
Fig. 10(a) Water Balance Runoff at Vegreville vs. Vermillion River
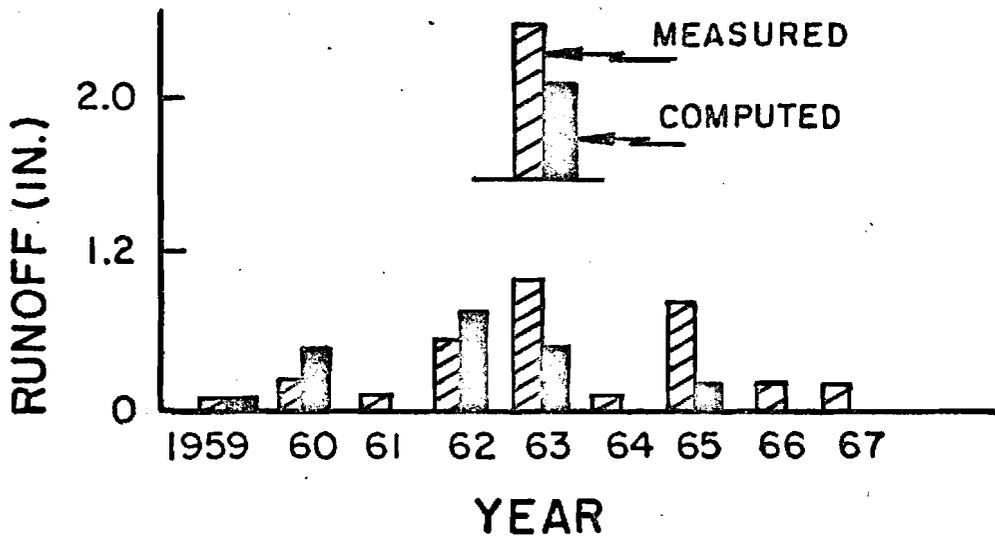
Fig. 10(b) Water Balance Annual Runoff at Vegreville vs. Vermillion River
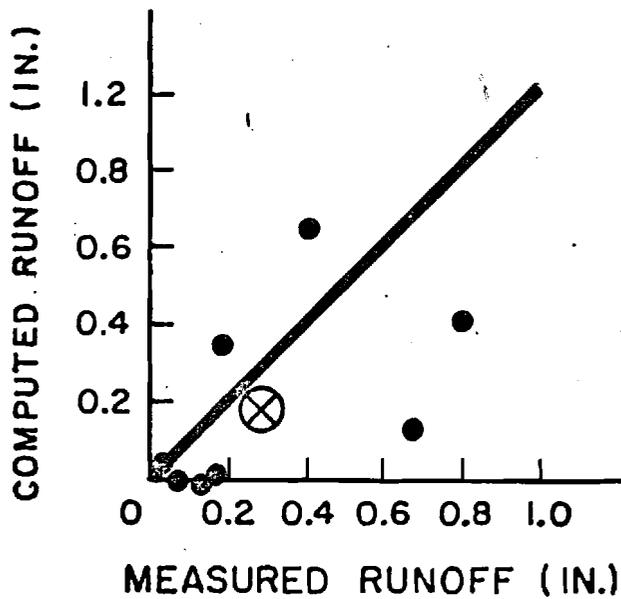
Fig. 10(c) Water Balance Annual Runoff at Vegreville vs. Vermillion River

In general the runoff values calculated during the period April-
May account for the largest errors in the Prairie region. Consideration
of lag times in the runoff would improve the comparisons of the runoff
hydrographs. This lag effect may be very significant on the prairies
where groundwater levels may fluctuate greatly over a period of time.
This fluctuation causes uncertainty as to the percent of a drainage
basin which is actually contributing to stream flow in any given year.
Similarly, the high spatial variability in precipitation (and the
"representativeness" of precipitation amounts to basin precipitation)
also affects the validity of the calculations in the Prairies.

Maritimes and Eastern Canada

Guelph

Both the Turc and water balance methods gave very good estimates
of water yield at Guelph. It was considered that the accuracy of the
results obtained from Guelph was the best of all the stations analyzed
(see Figs. 11(a) to 11(f)). In general the calculated values by the
water balance method gave better estimates of the measured average
values of runoff. The average annual runoff for 17 years of data
analyzed by the water balance was the same as the measured runoff over
the same period. The correlation coefficient between measured and
calculated yields obtained from both methods (Turc and water balance)
was greater than 0.9.

Montreal, Fredericton, Sept-Isles, White River

For Montreal there was very little choice between the two methods
used to calculate the runoff amounts. Both procedures gave fairly close
approximations of the trends of monthly and annual values of runoff
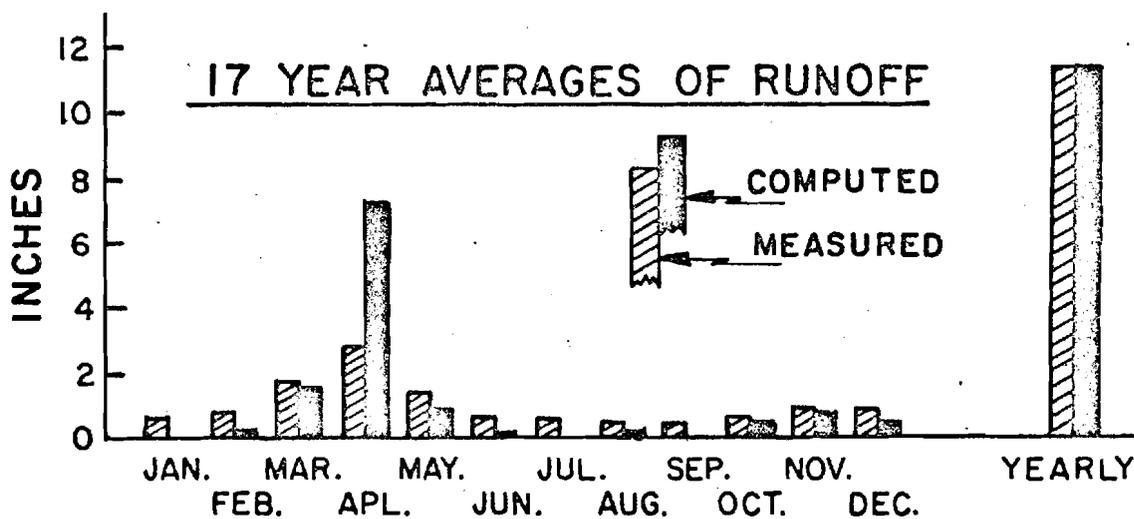
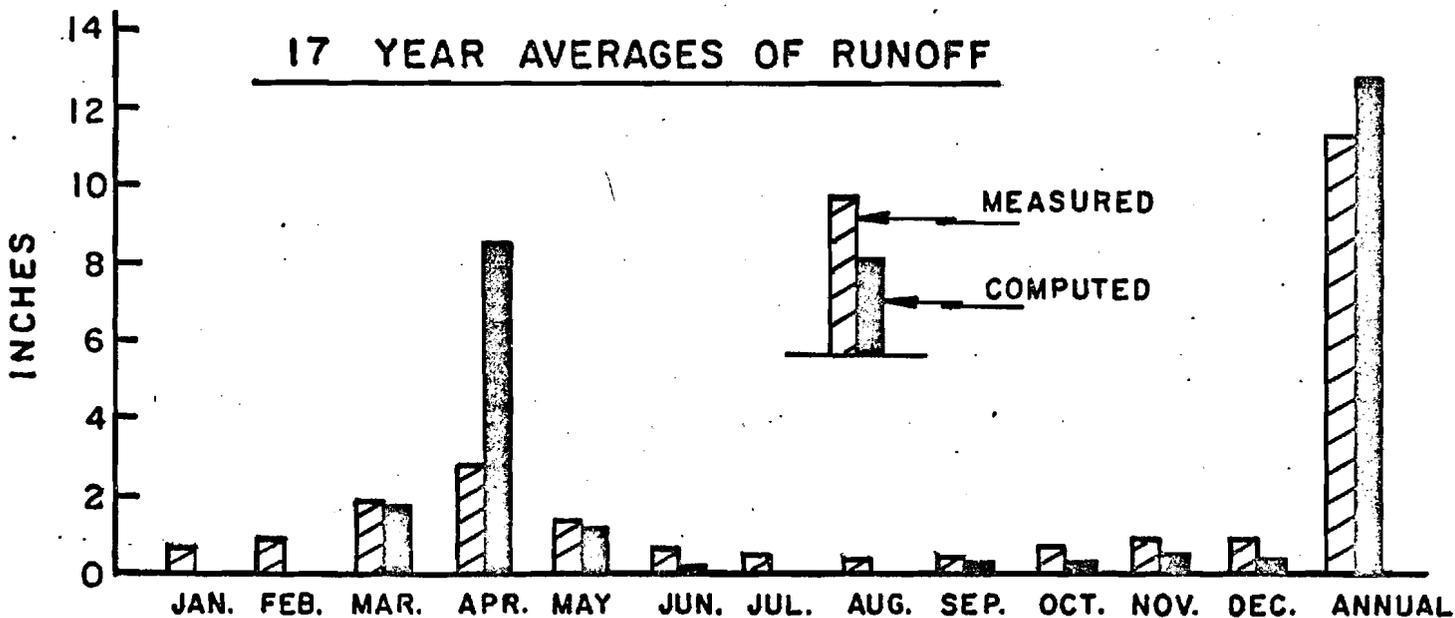Fig. 11(a) Water Balance Runoff at Guelph vs. Speed River
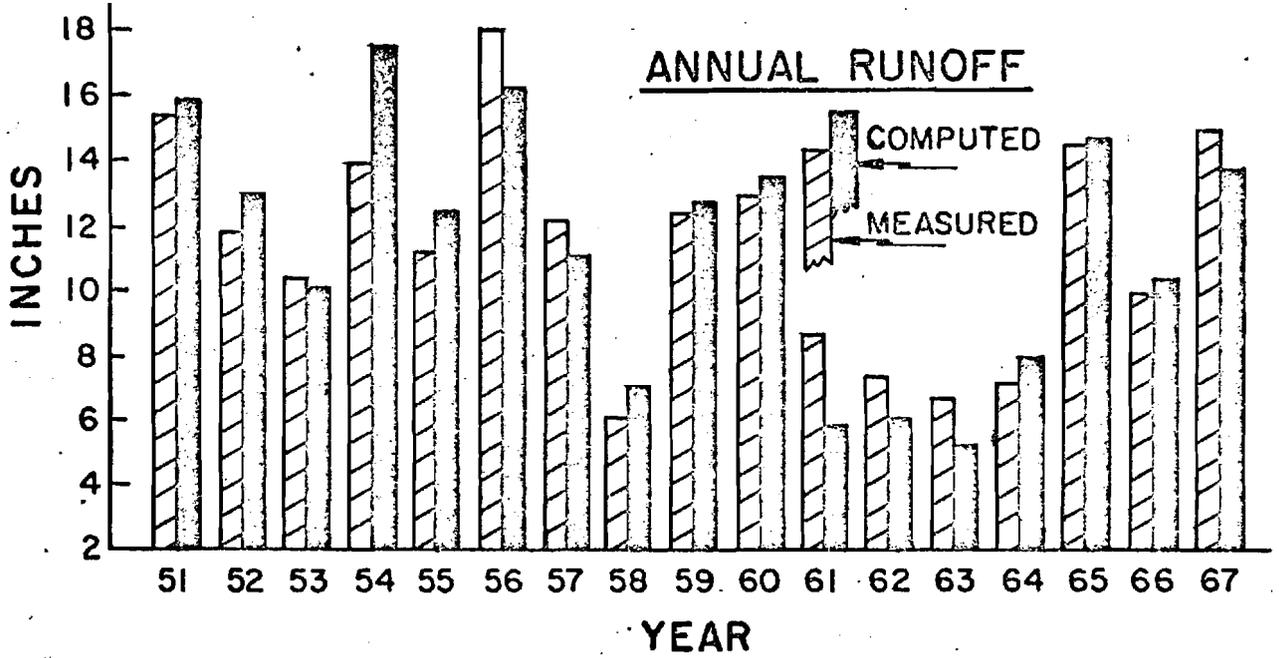

Fig. 11(b) Turc Runoff at Guelph vs. Speed River

Fig. 11(c) Water Balance Annual Runoff at Guelph vs. Speed River
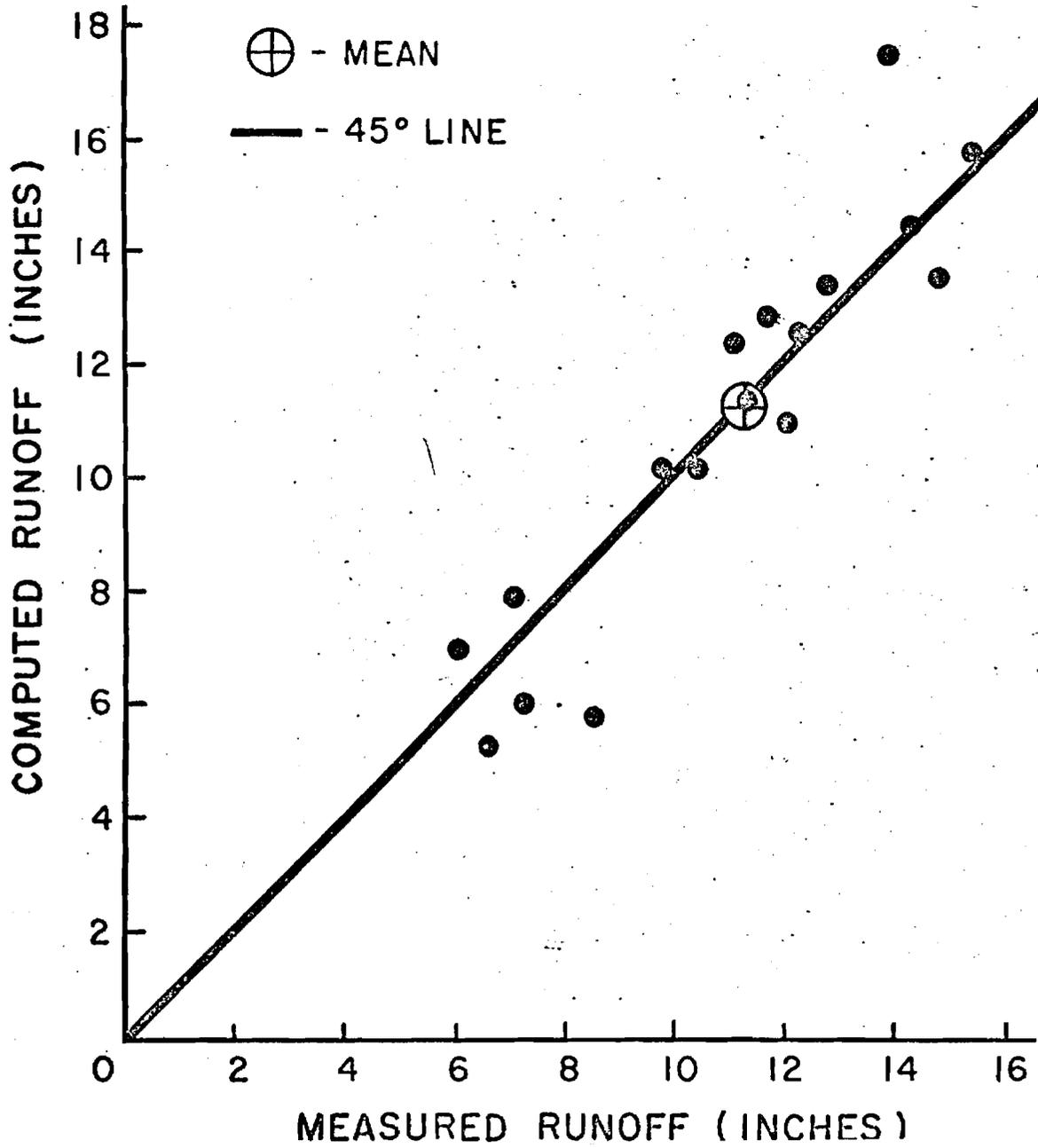
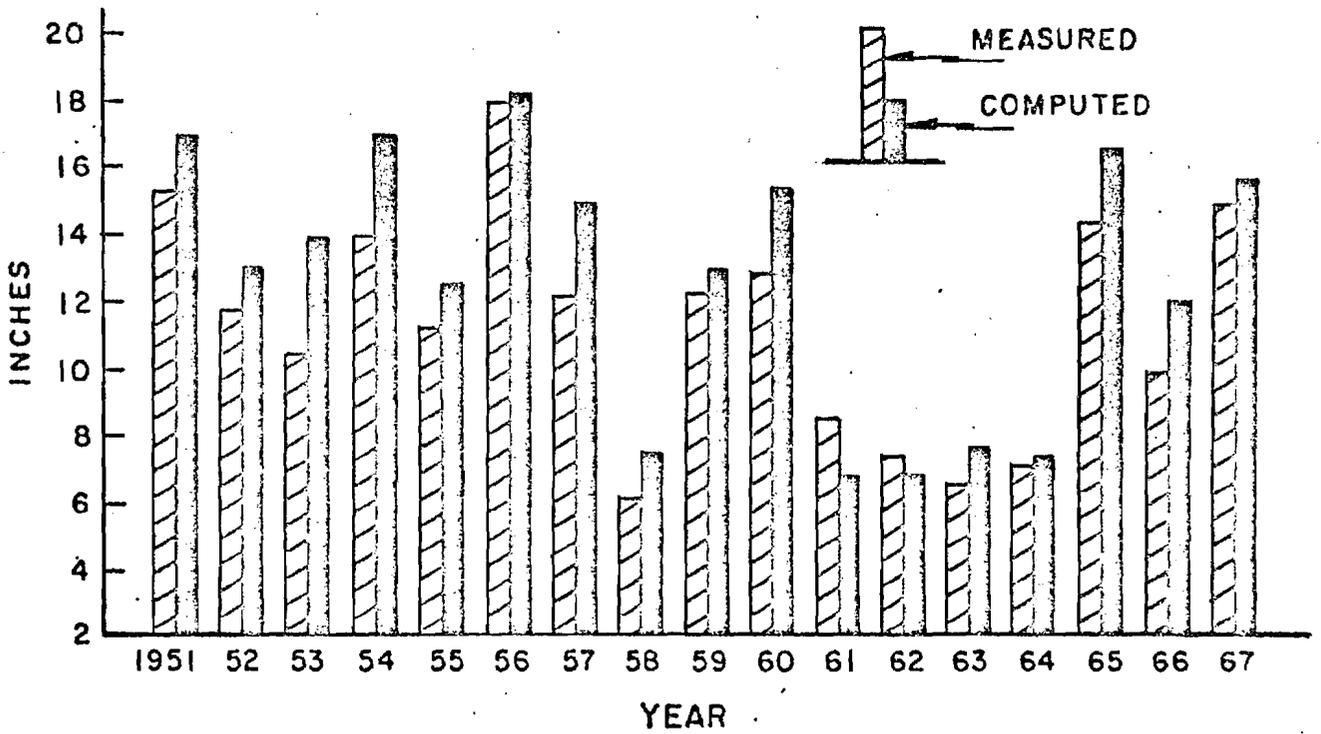Fig. 11(d) Water Balance Annual Runoff at Guelph vs. Speed River

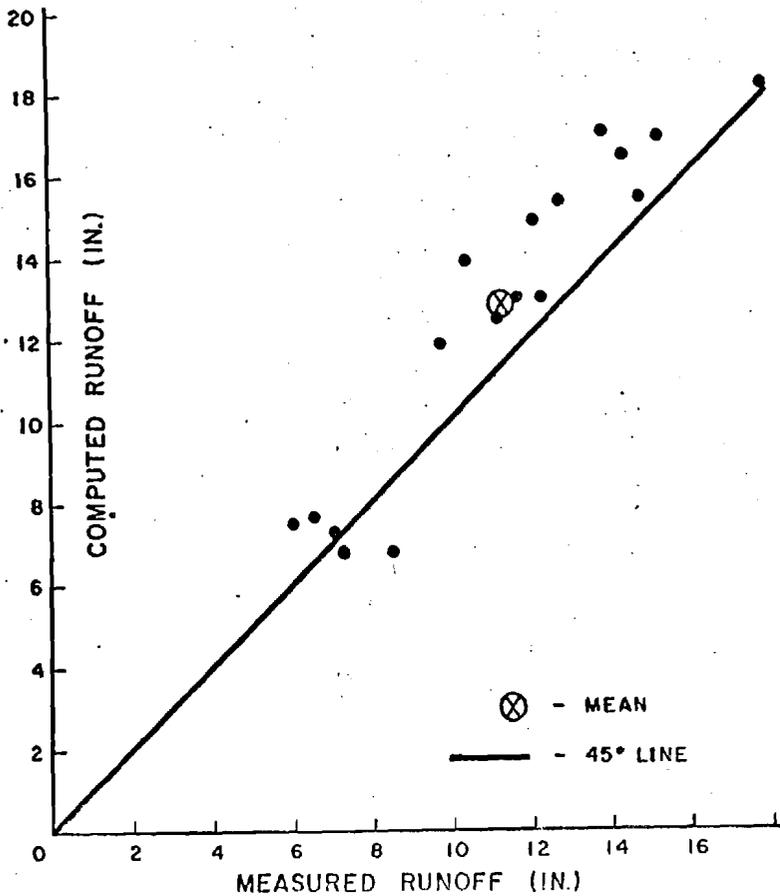Fig. 11(e) Turc Annual Runoff at Guelph vs. Speed River

Fig. 11(f) Turc Annual Runoff at Guelph vs. Speed River

(see Figs. 12(a) to 12(f)).

The water balance calculations at Fredericton agreed with the measured values better than those calculated by the Turc method (see Figs. 13(a) to 13(f)). Correlation coefficients and seasonal trends of runoff by the two methods were much the same.

At Sept-Isles the thirteen-year average of runoff obtained from the water balance technique was about 20% less than the measured amounts (see Figs. 14(a) and 14(b)). The seasonal trend of runoff compared quite favourably and the agreement with measured amounts was fairly high.

The water balance runoff was slightly higher than the measured values at White River (see Figs. 15(a) and 15(b)). At this station the runoff gauge is below a lake which may cause runoff records to be smoothed out more over the year.

Northern Canada

Fort Simpson and Yellowknife

Calculated runoff values from the Turc and water balance methods were very similar at Fort Simpson. For both methods the correlation coefficients were very low. The discharge records used in the analysis are those values calculated by the Northern Canada Power Commission and approximate natural outflow from Bigspruce Lake. "True" or "actual" runoff would then be the estimated runoff plus evaporation and ground-water losses from the lake. The lack of runoff data in the area necessitated the use of the same drainage basin for comparing Fort Simpson and Yellowknife values. Because of the different hydrologic and climatic regions in the two areas, the comparison is somewhat
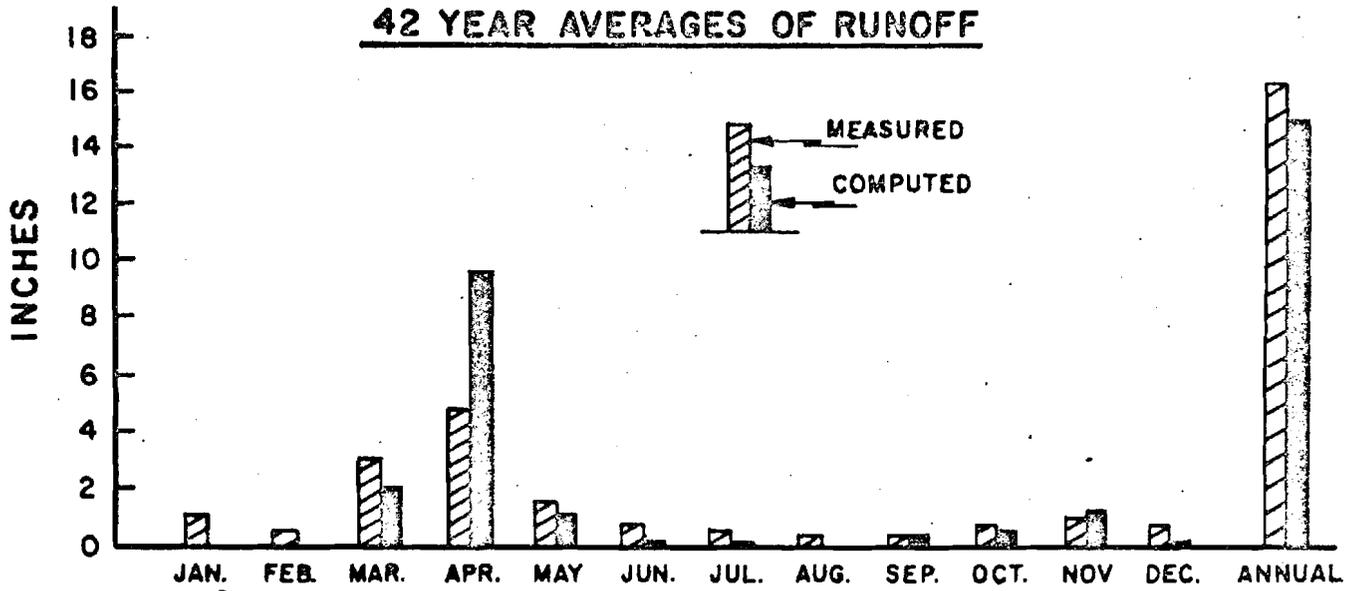
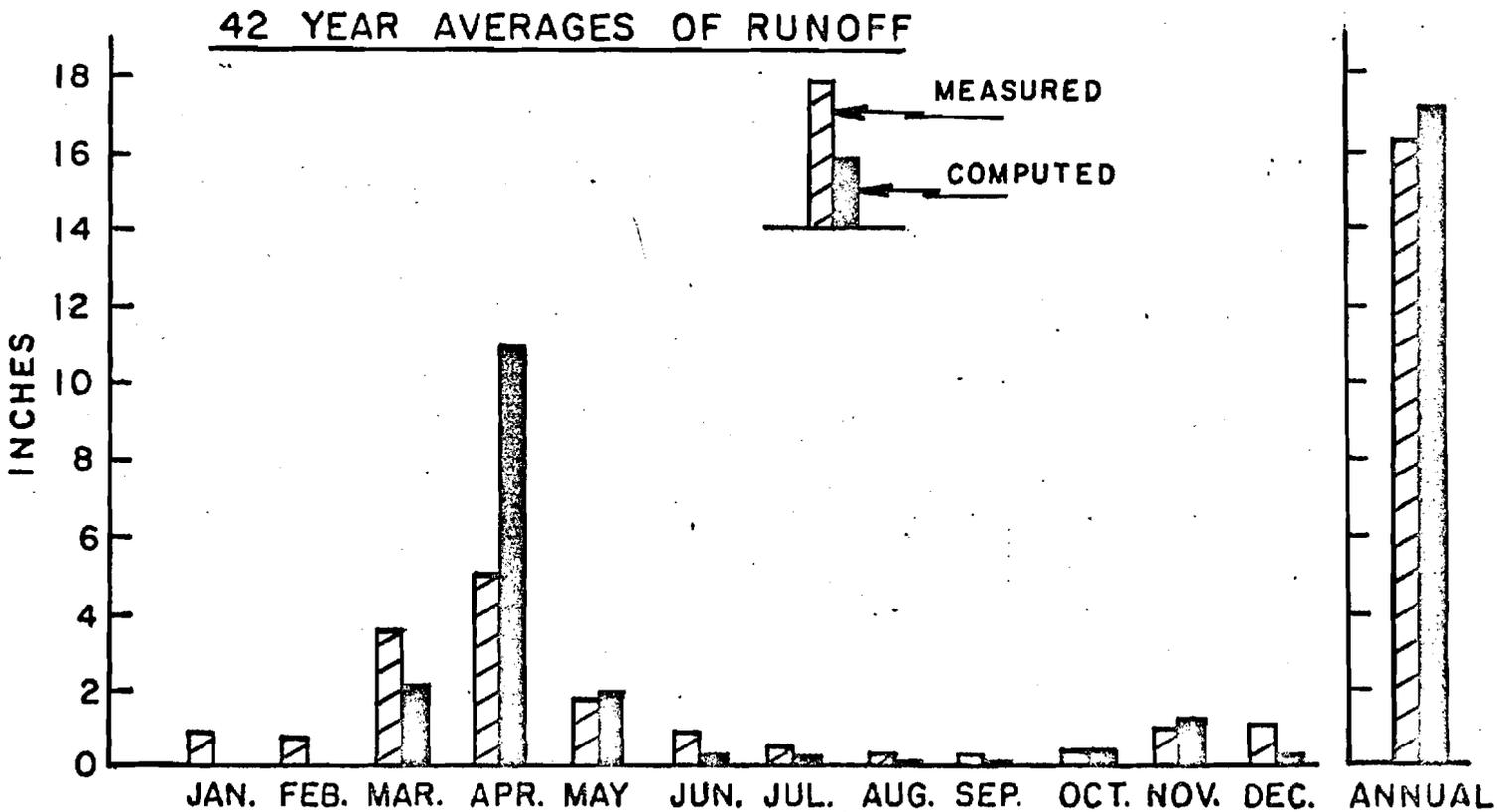Fig. 12(a)   Water Balance Runoff at Montreal vs. Chateauguay River

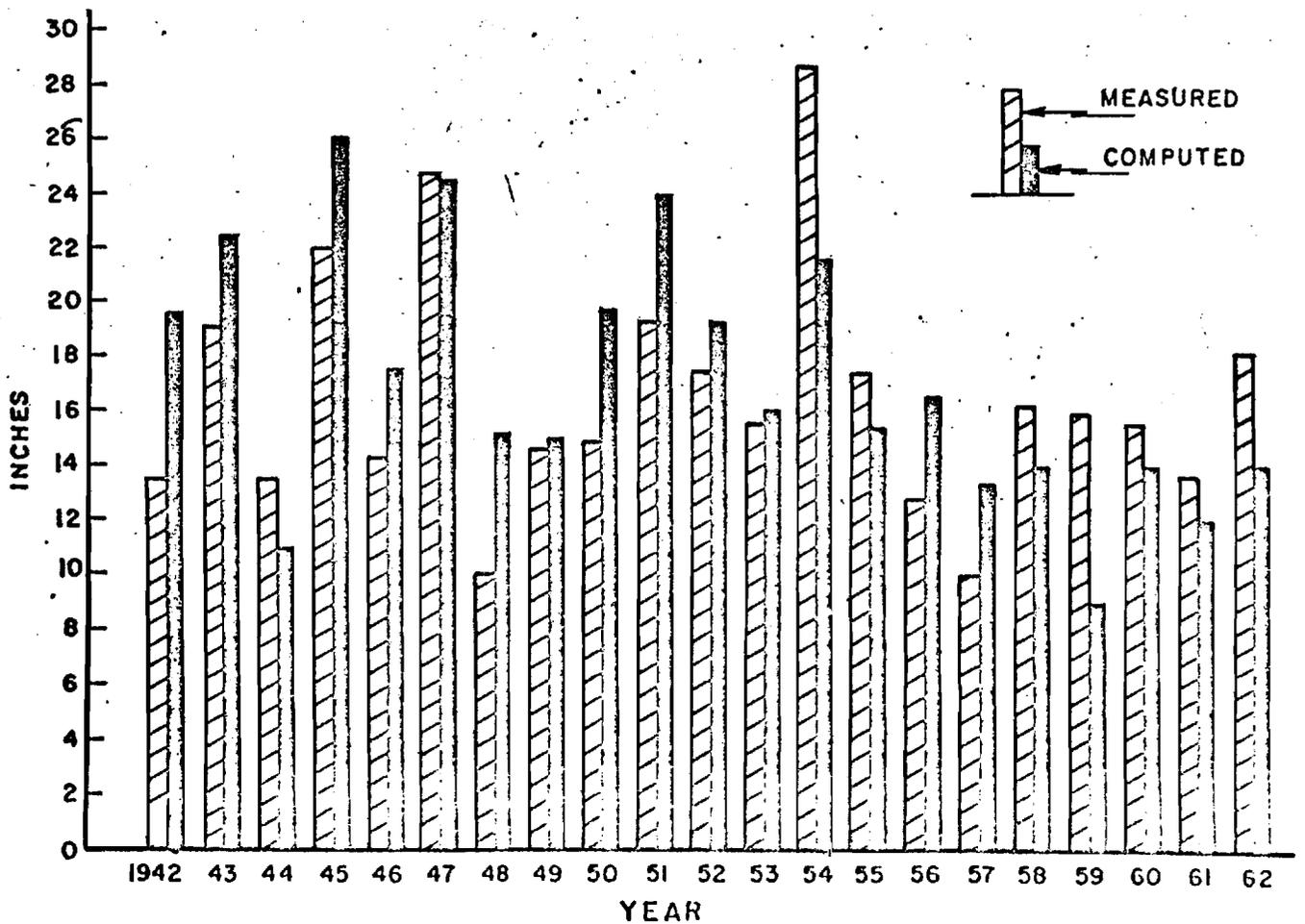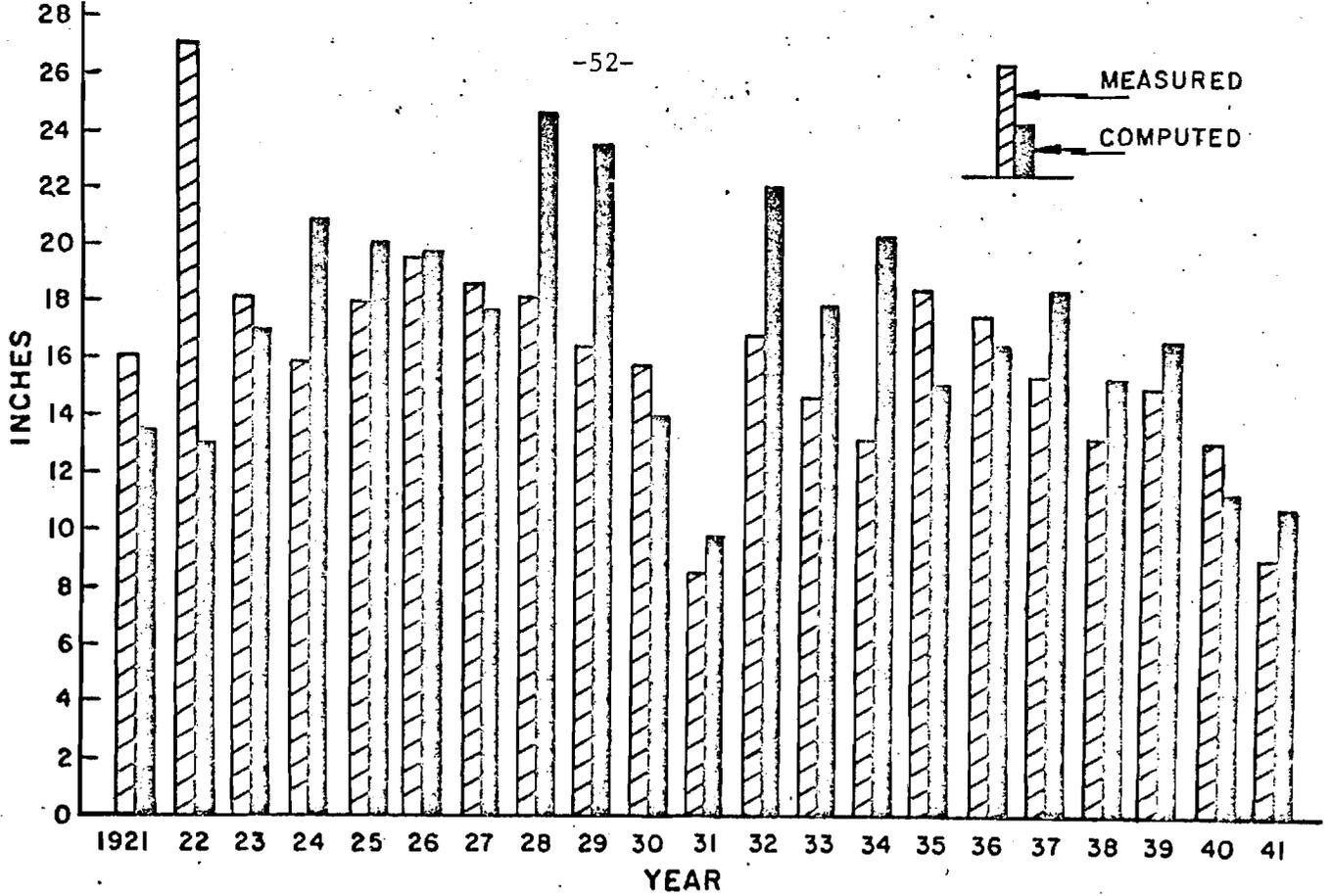Fig. 12(b) Turc Runoff at Montreal vs. Chateauguay River

Fig. 12(c) Water Balance Annual Runoff at Montreal vs. Chateauguay River
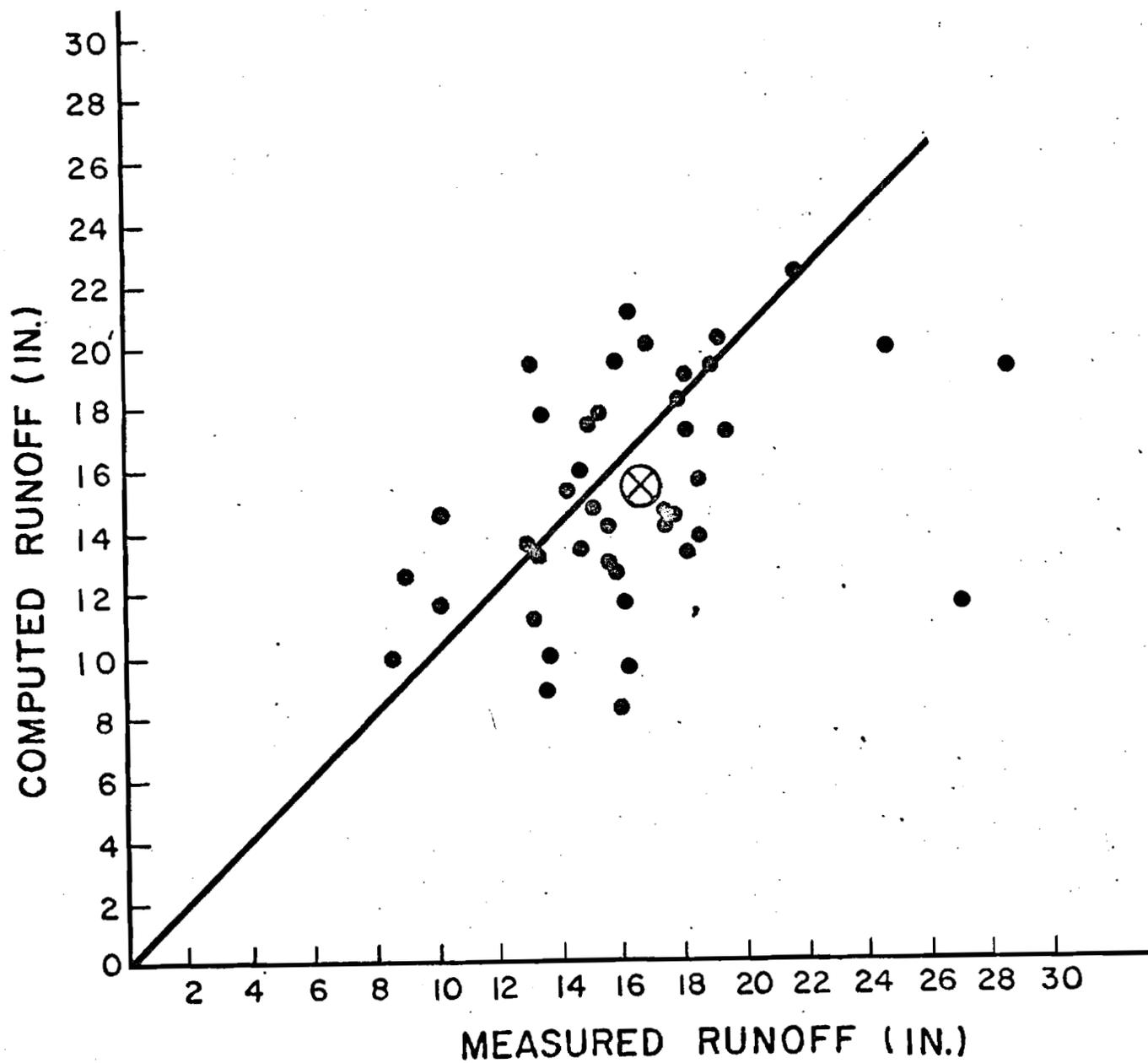
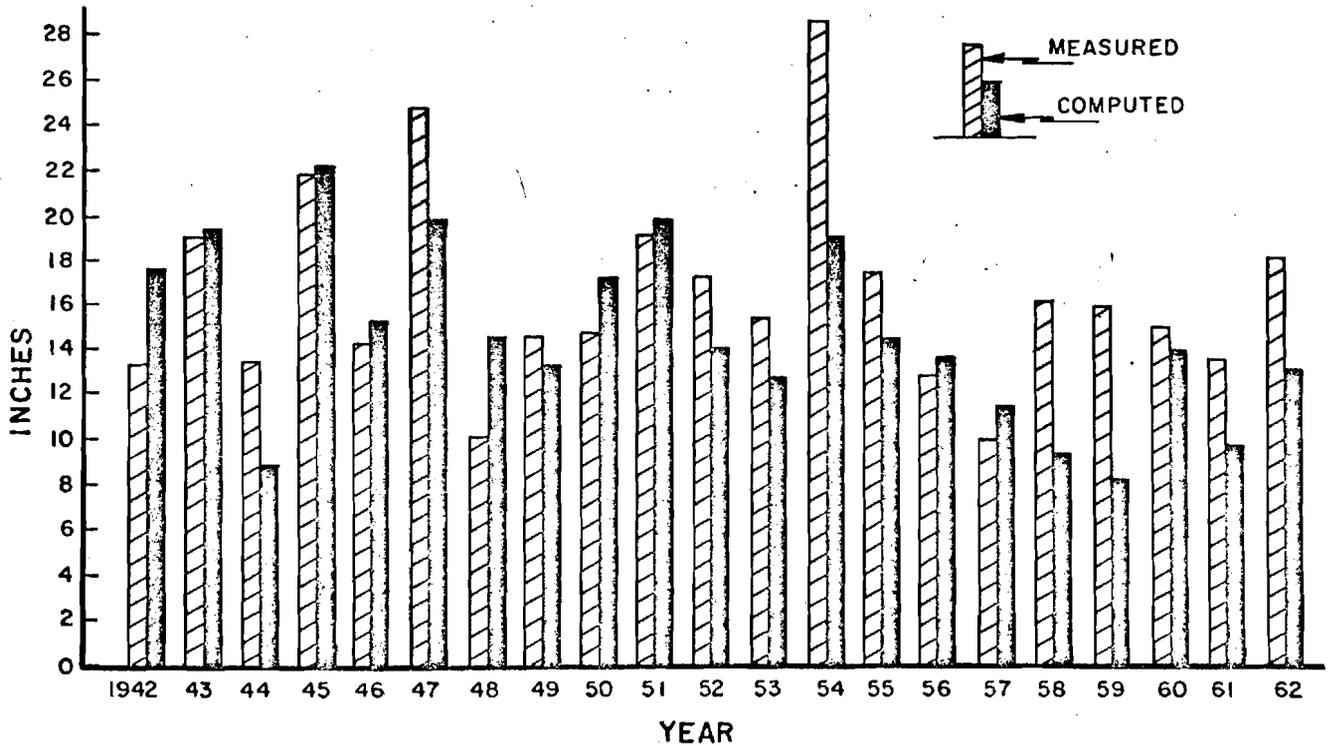Fig. 12(d) Water Balance Annual Runoff at Montreal vs. Chateauguay River

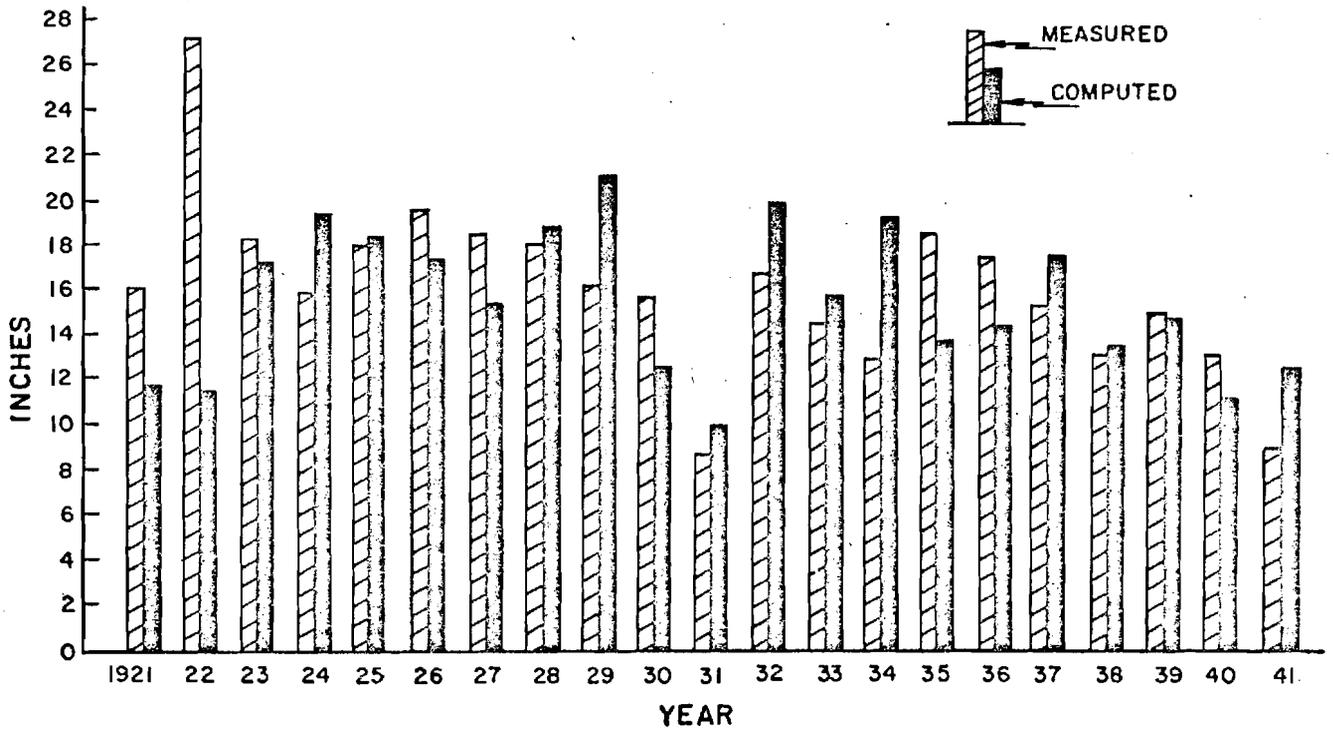Fig. 12(e) Turc Annual Runoff at Montreal vs. Chateauguay River
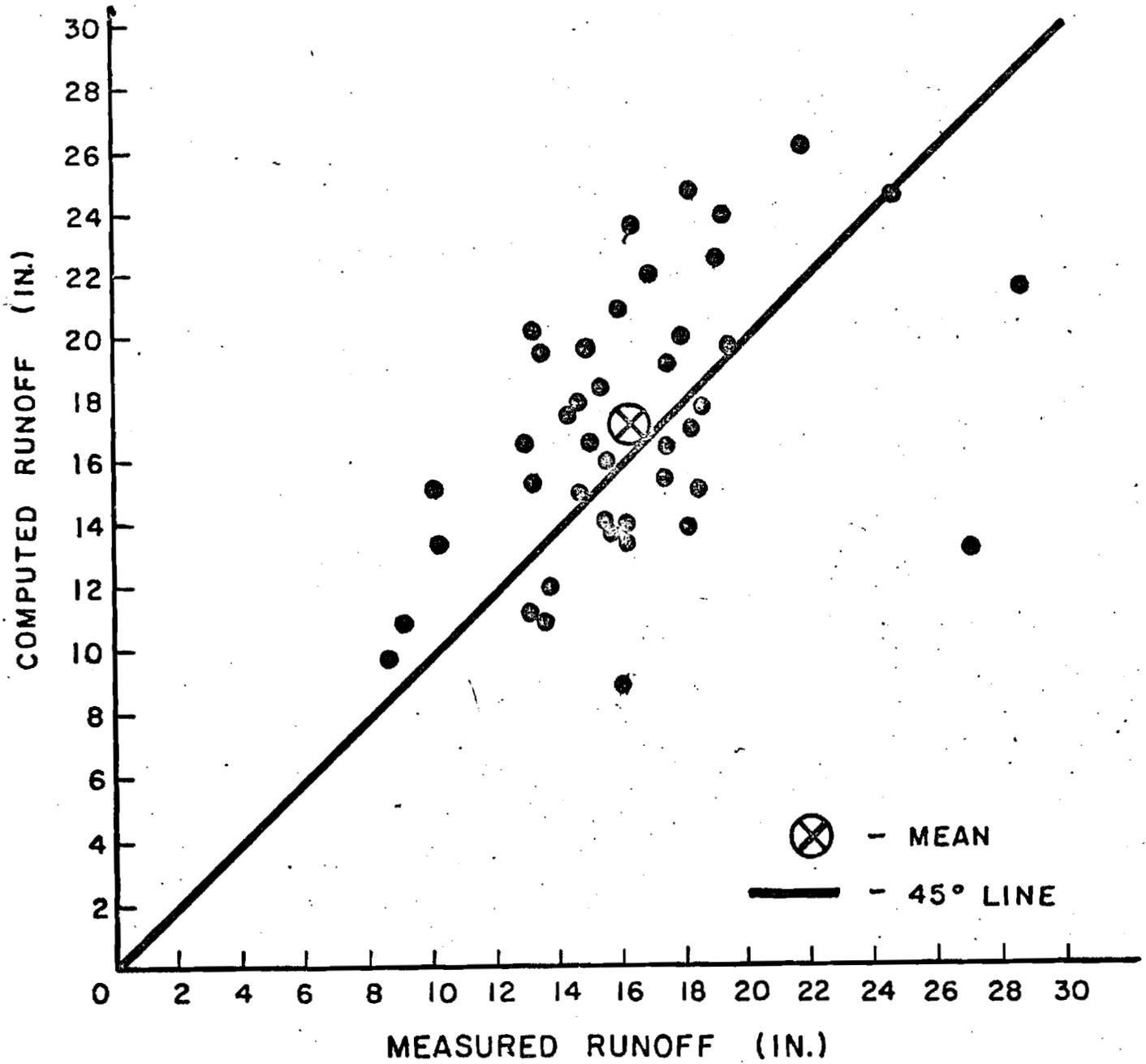
Fig. 12(f) Turc Annual Runoff at Montreal vs. Chateauguay River

Fig. 13(a) Water Balance Runoff at Fredericton vs. Shogomoc River

Fig. 13(b) Turc Runoff at Fredericton vs. Shogomoc River
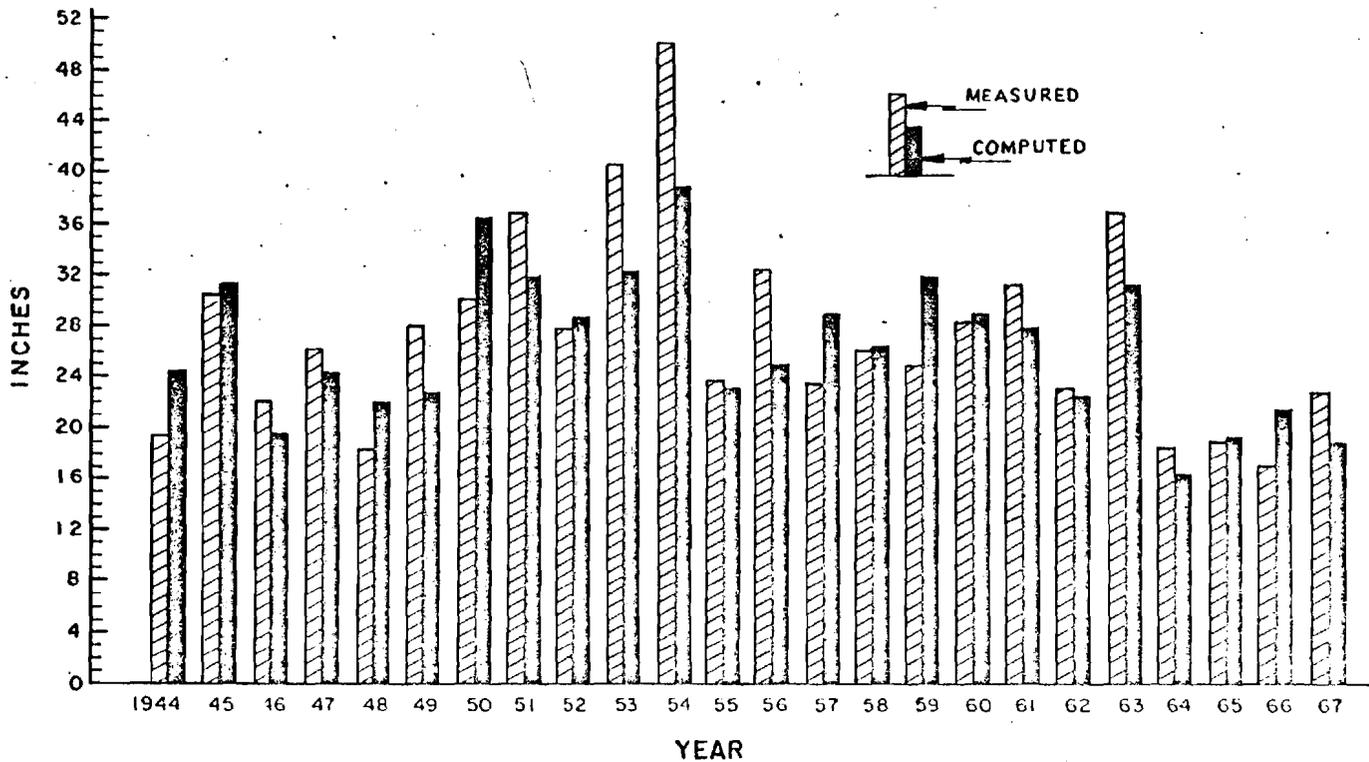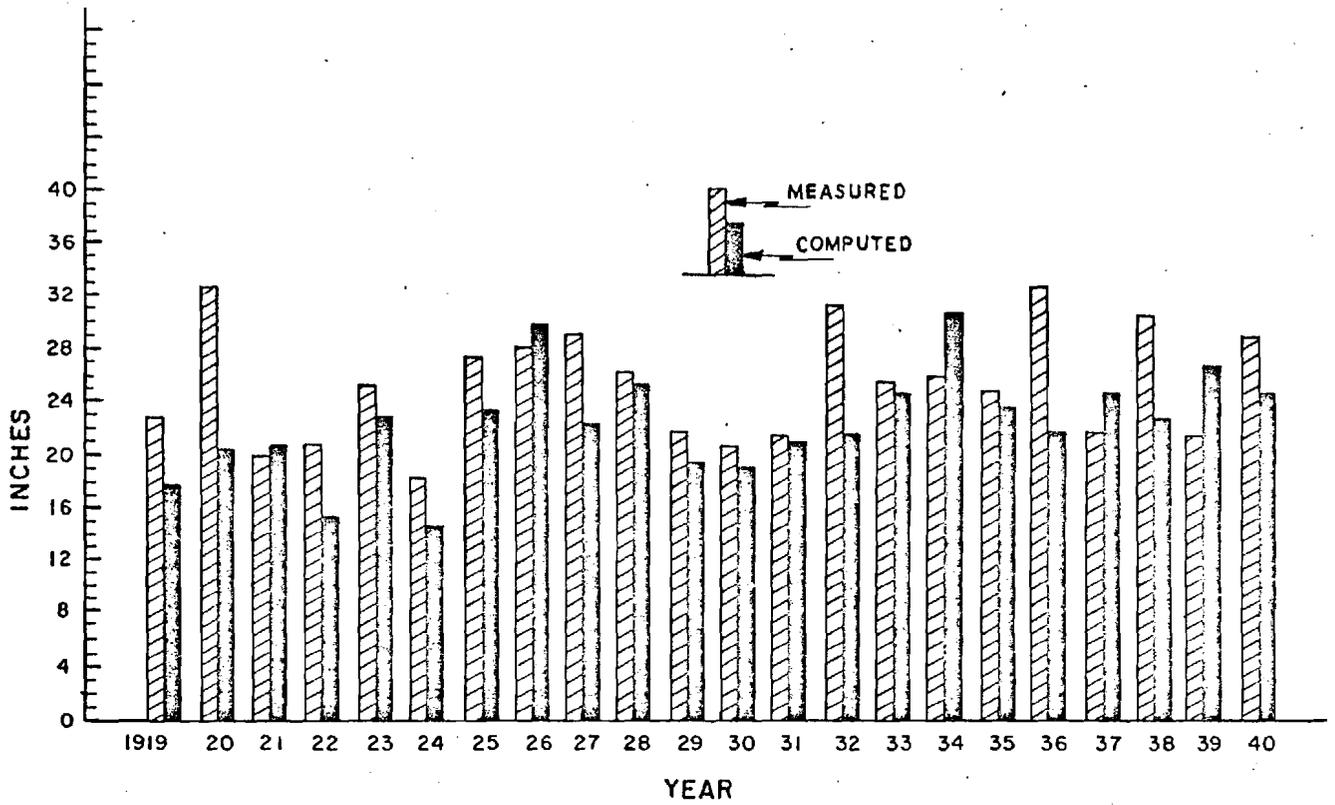
Fig. 13(c) Water Balance Annual Runoff at Fredericton vs. Shogomoc River
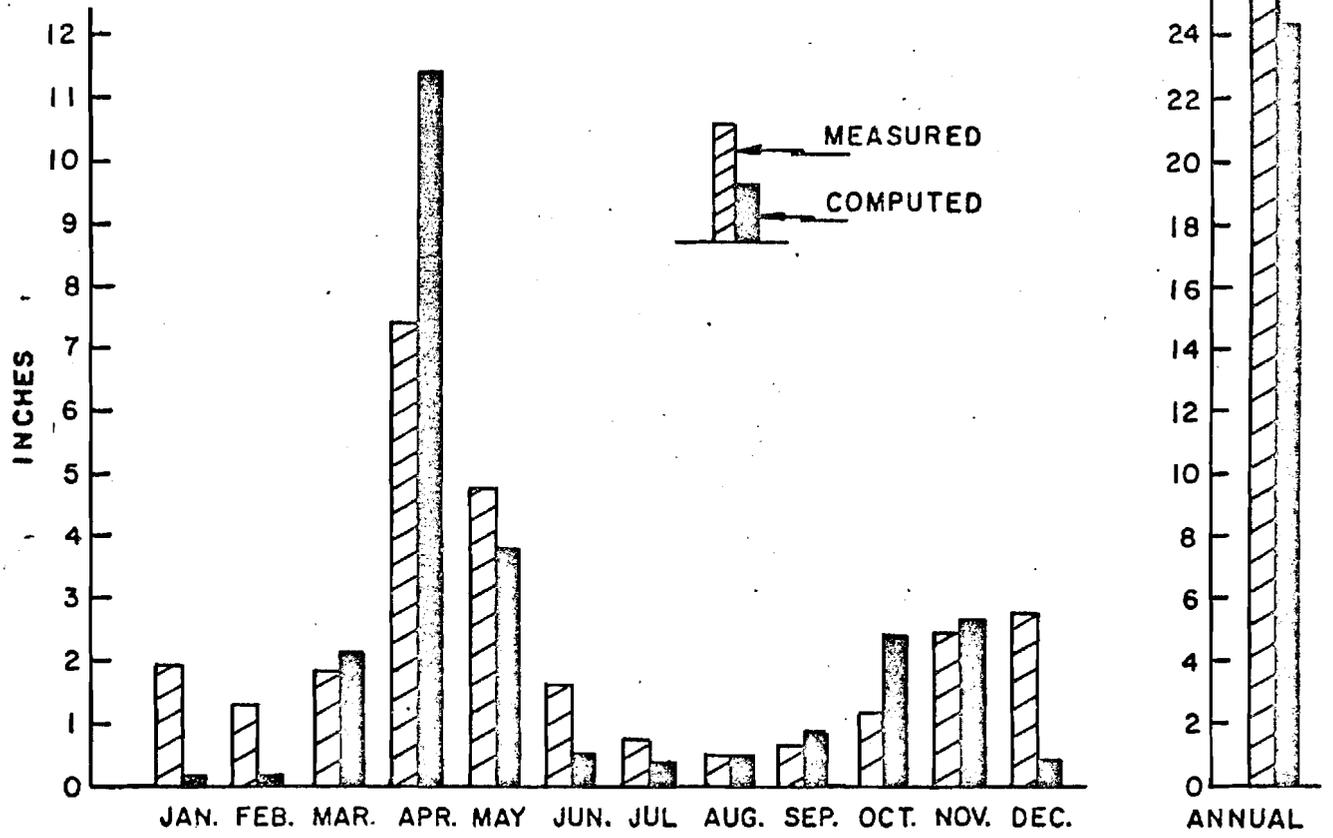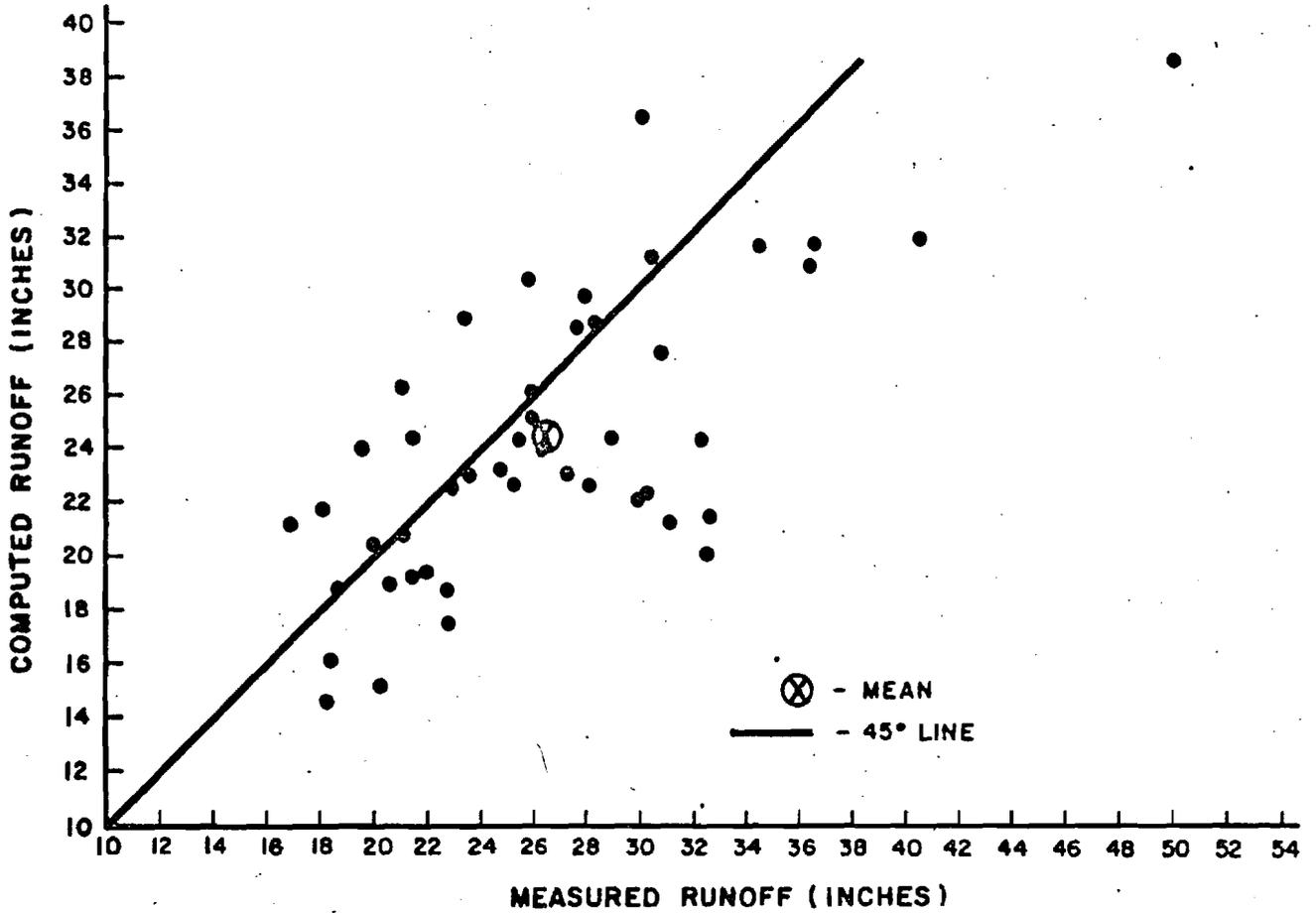
Fig. 13(d) Water Balance Annual Runoff at Fredericton vs. Shogomoc River

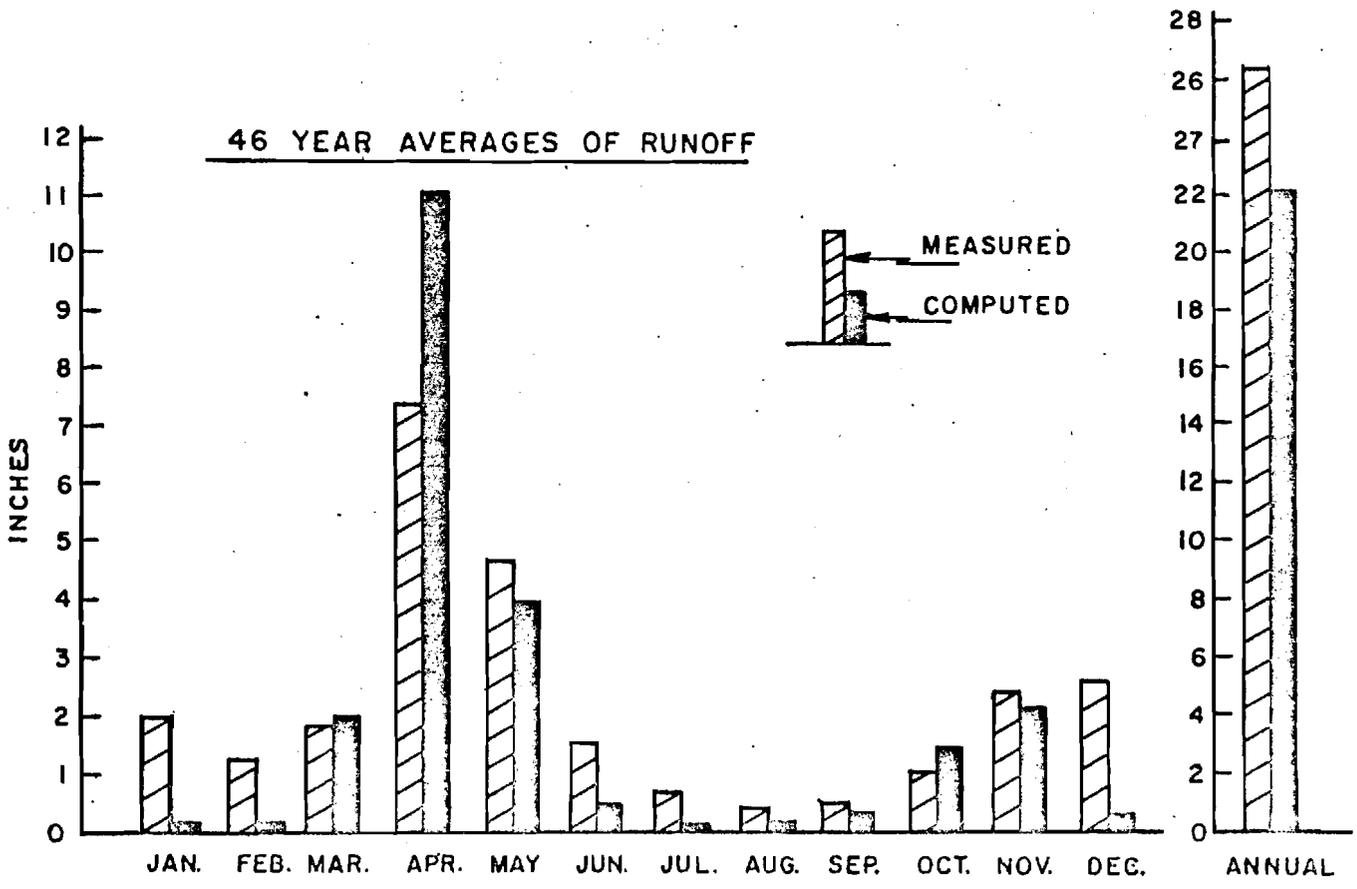Fig. 13(e) Turc Annual Runoff at Fredericton vs. Shogomoc River
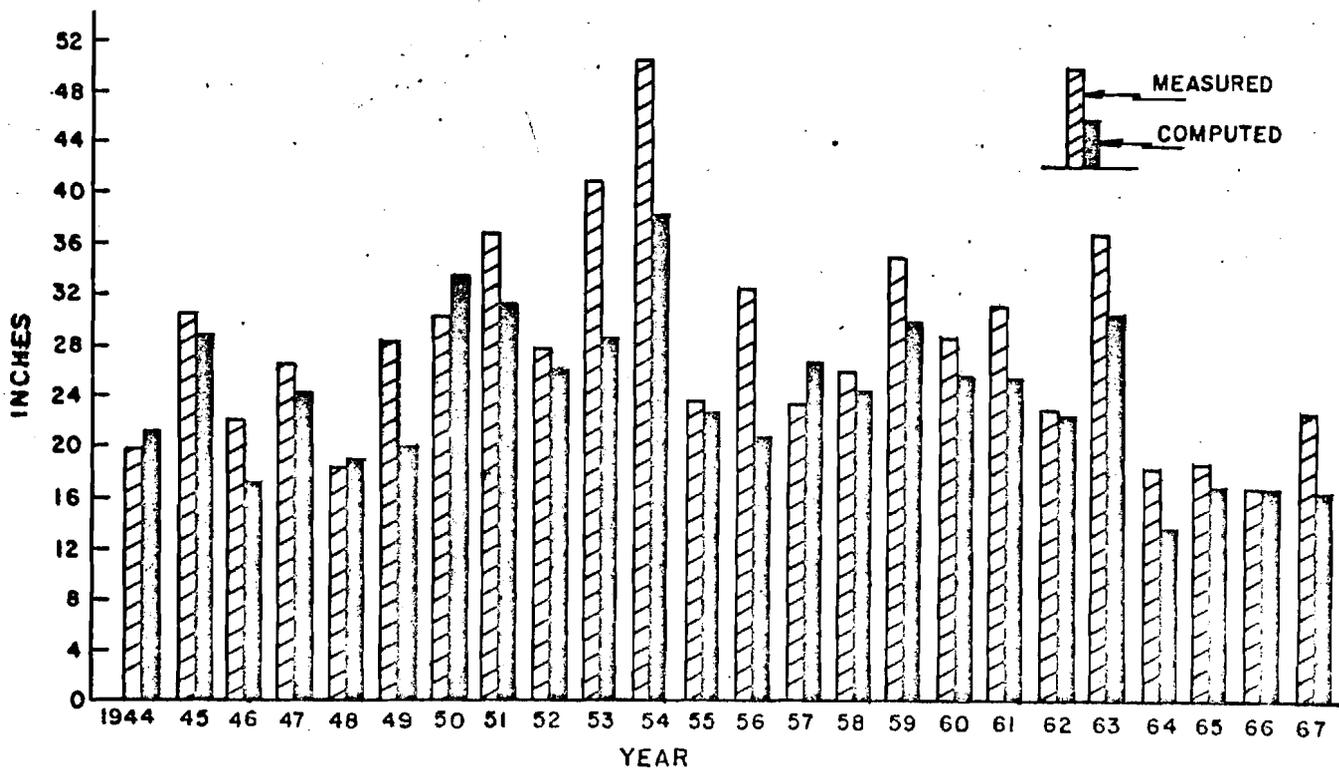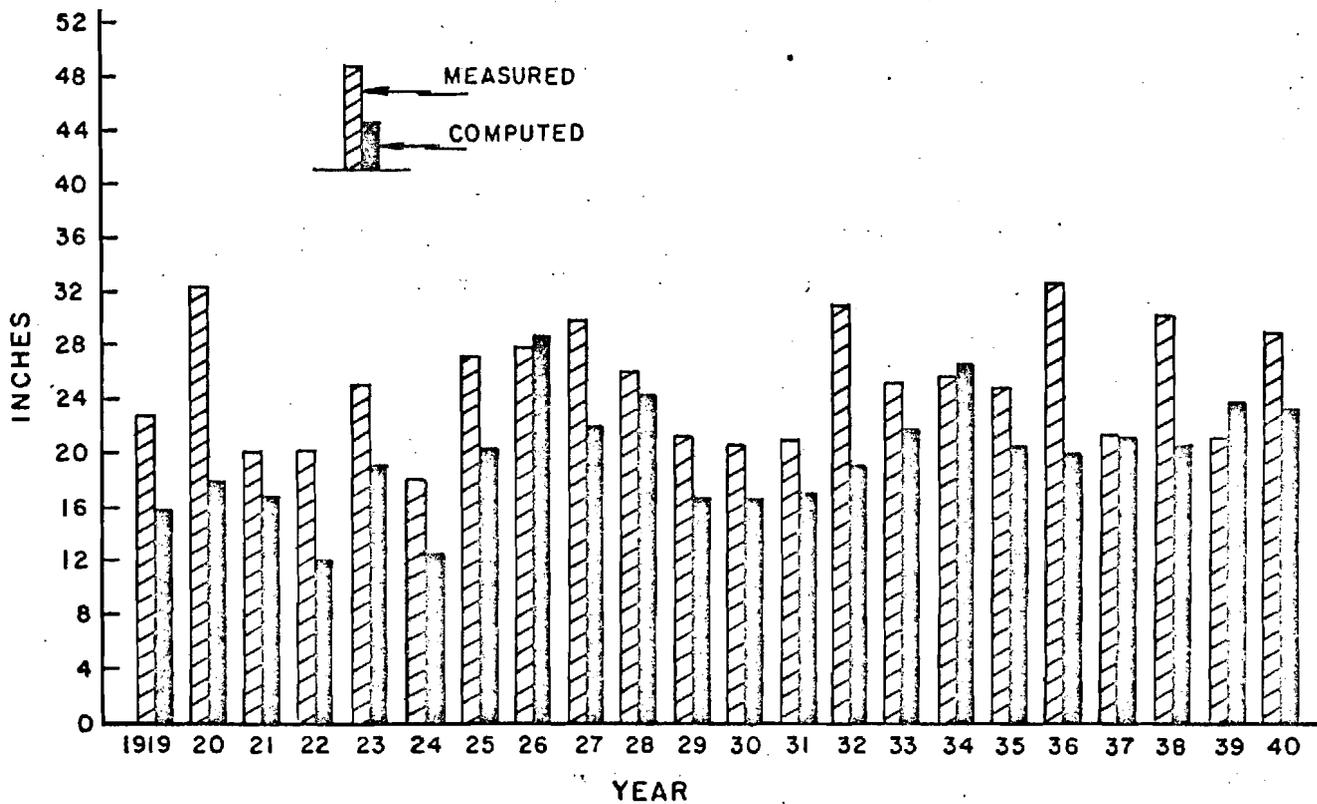
Fig. 13(f)   Turc Annual Runoff at Fredericton vs. Shogomoc River

Fig. 14(a) Water Balance Runoff at Sept-Isles vs. Rapides River

Fig. 14(b) Water Balance Annual Runoff at Sept-Isles vs. Rapides River

Fig. 14(c) Water Balance Annual Runoff at Sept-Isles vs. Rapides River

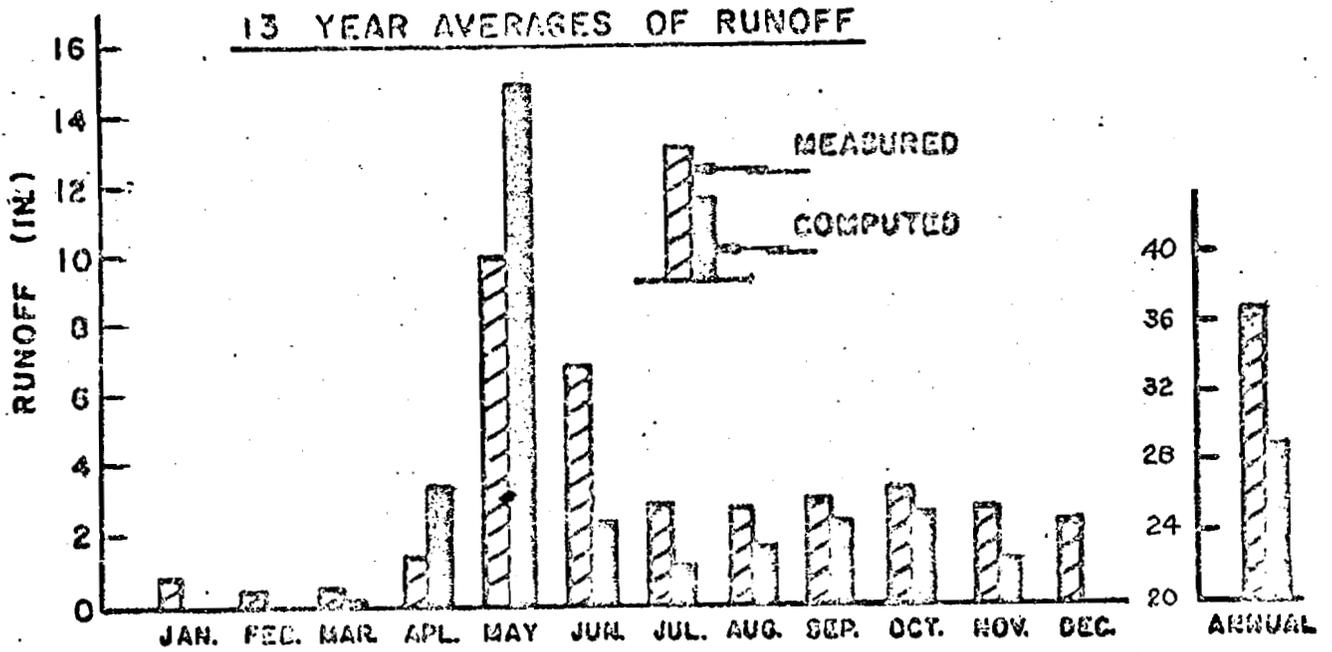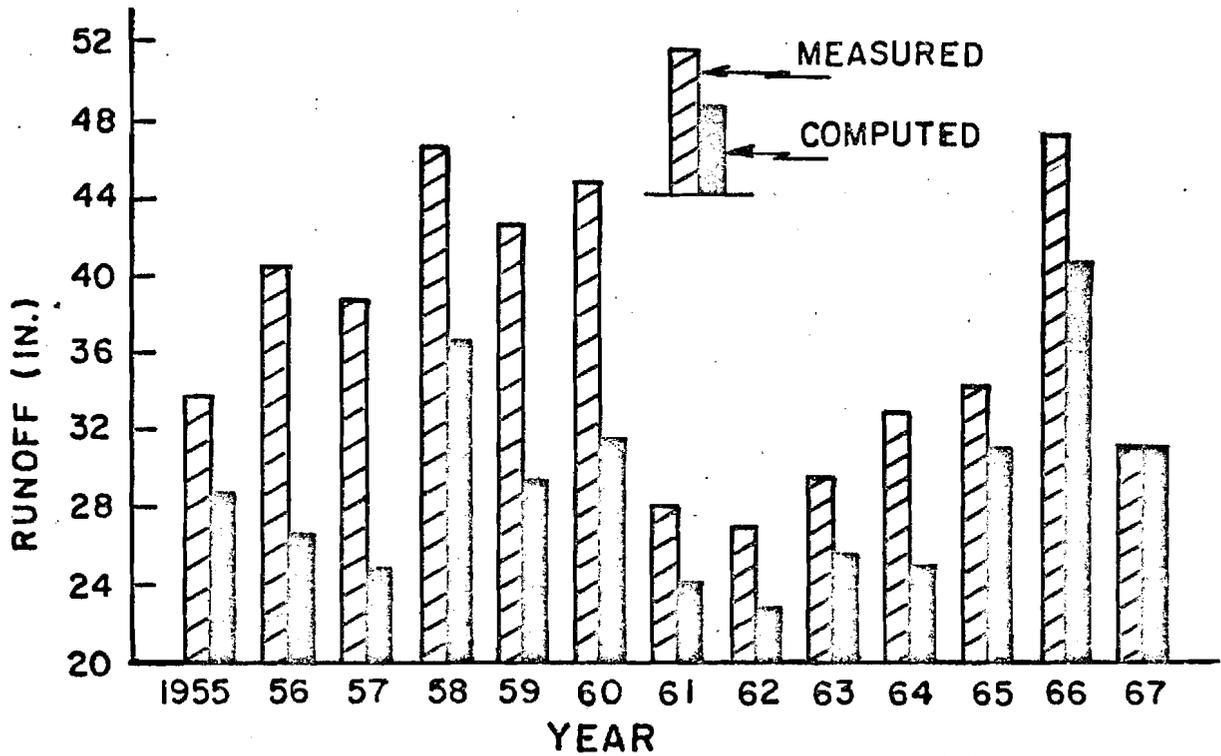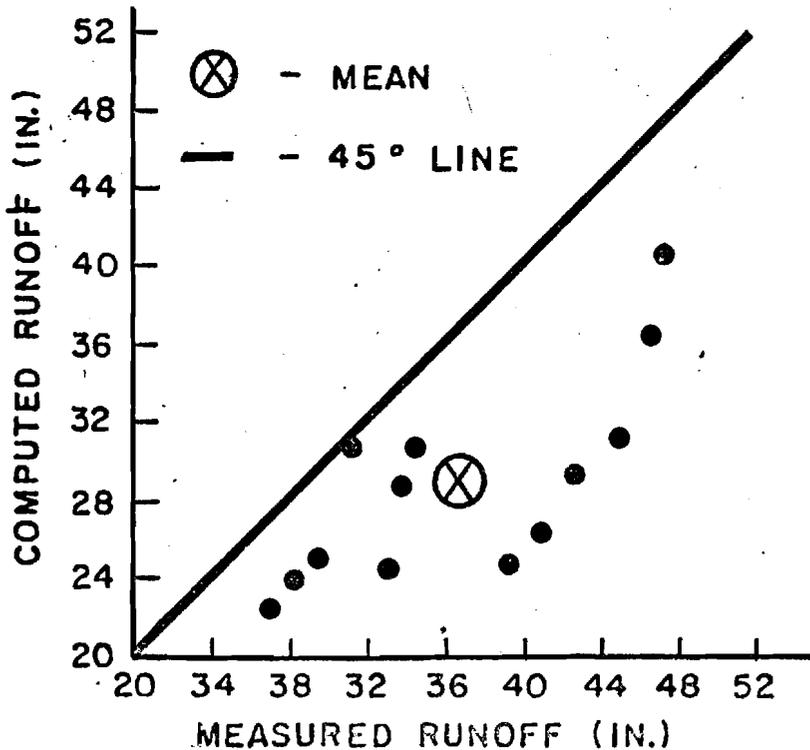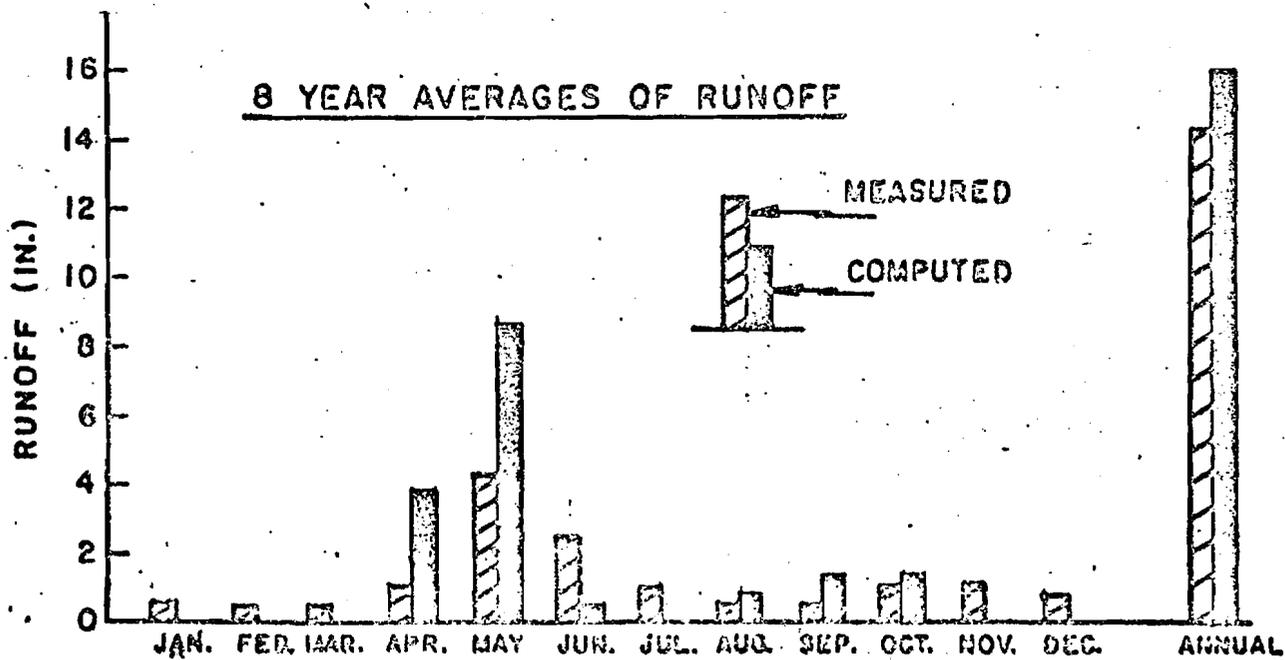Fig. 15(a)   Water Balance Runoff at White River vs. White River
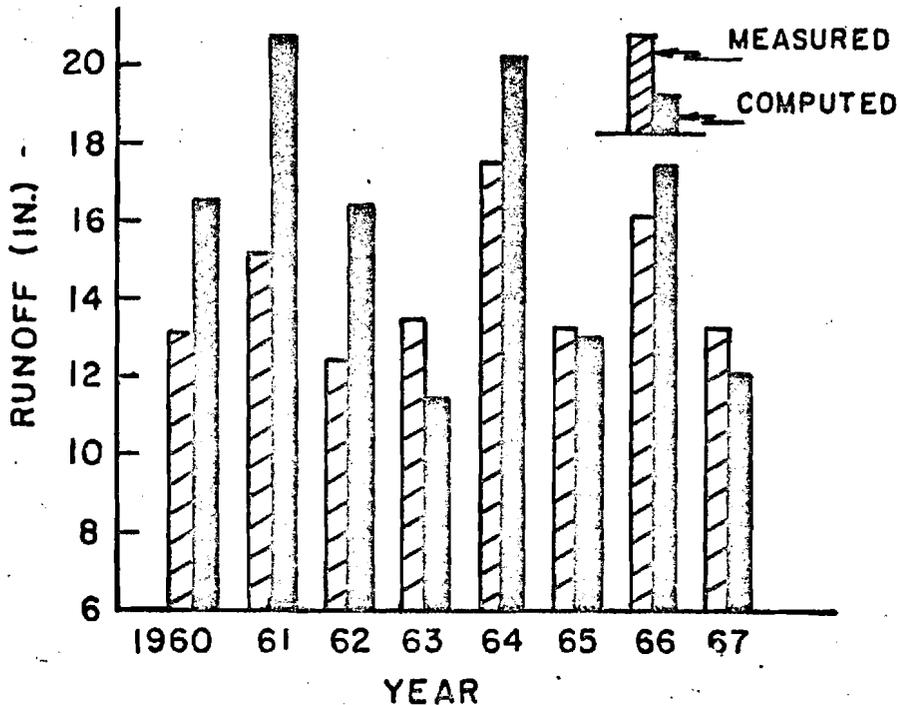
Fig. 15(b) Water Balance Annual Runoff at White River vs. White River
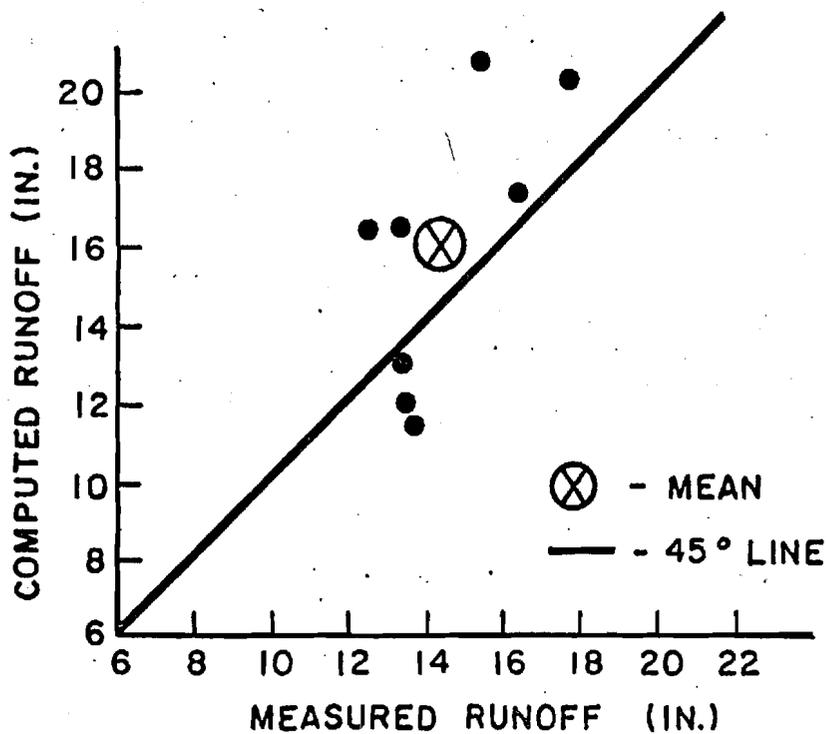
Fig. 15(c) Water Balance Annual Runoff at White River vs. White River

redundant. In spite of these limitations, a comparison of the values
for Fort Simpson using both methods and water balance calculations
at Yellowknife suggest the water balance technique to be superior.
The estimated runoff values obtained by the Turc method for Fort
Simpson are lower than the measured values and would be even lower for
Yellowknife. The water balance calculations at Yellowknife reproduce
the average measured values very well. Also, the correlation is much
improved from calculations at Fort Simpson. This may be expected as
Yellowknife is closer to the drainage basin than Fort Simpson.

Fort Chimo

At Fort Chimo problems were encountered because of the size of
the basin used. Precipitation decreases markedly from the south
towards the north coast of Quebec. The measured runoff from the basin
is comparable in magnitude to the recorded precipitation at Fort Chimo.
Since Knob Lake is situated at the southern end of the drainage basin
and Fort Chimo at the northern end, the average climatic values for the
two stations were used in the calculations. The comparison of water
balance runoff and measured values were very similar to those obtained
at Sept-Isles. The calculated annual and monthly variations were in
good agreement with measured values although the calculated values were
generally about 20% lower than the measured runoff. This station had
the highest correlation coefficient for annual values (r=0.99) of all
those used in the analysis.

The shield region of Canada contains many lakes and comparisons of
runoff are at times difficult due to the lag in runoff. The fact that
no "lag effects" were considered in the calculations must be recognized

and considered in the interpretation of the graphs of runoff from these
stations (see Figs. 16 to 18).

British Columbia

At Duncan the gauged stream had a very small drainage area (7.8 mi^2).
This is likely why the comparison of calculated and measured values at
this station were by far the best of any tests done in the mountain
region (see Fig. 19(a)). The errors in precipitation measurements that
are restrictive in the mountains would be much less critical on such a
small basin. The calculated annual runoff at this station is approxi-
mately 15% lower than the recorded values. The monthly trends are
quite favourable as is the yearly variation, indicated by the correlation
coefficient.

At Abbotsford the computed runoff is much higher than the measured
values (see Fig. 20(a)). It was learned later that the river chosen
for comparison is in quite an intensive irrigation area and hence the
poor agreement between predicted and recorded values. Comparison of
the computed annual average with isolines in the Hydrological Atlas of
Canada indicates that the computed runoff is a reasonable estimation.

The calculated runoff at Deer Park is very much lower than the
measured value. Also, the calculated runoff is coming from December
to March, whereas the major portion of measured runoff occurs from
April to July (see Fig. 21(a)). This would indicate that the
precipitation and temperature values as measured at the climatic
station are not representative of the climatic inputs over the basin.
The recorded pattern of runoff indicates that much of the precipitation
is falling as snow in the upper areas of the basin and hence cause the
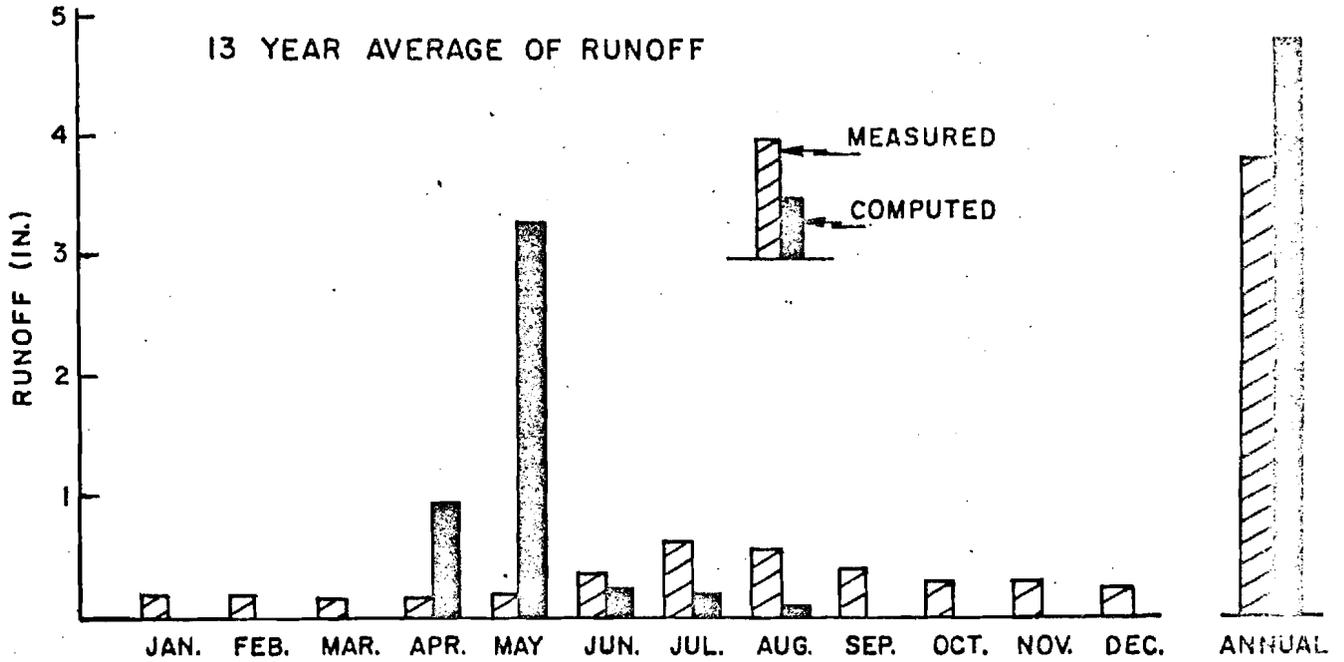
Fig. 16(a) Water Balance Runoff at Fort Simpson vs. Snare River
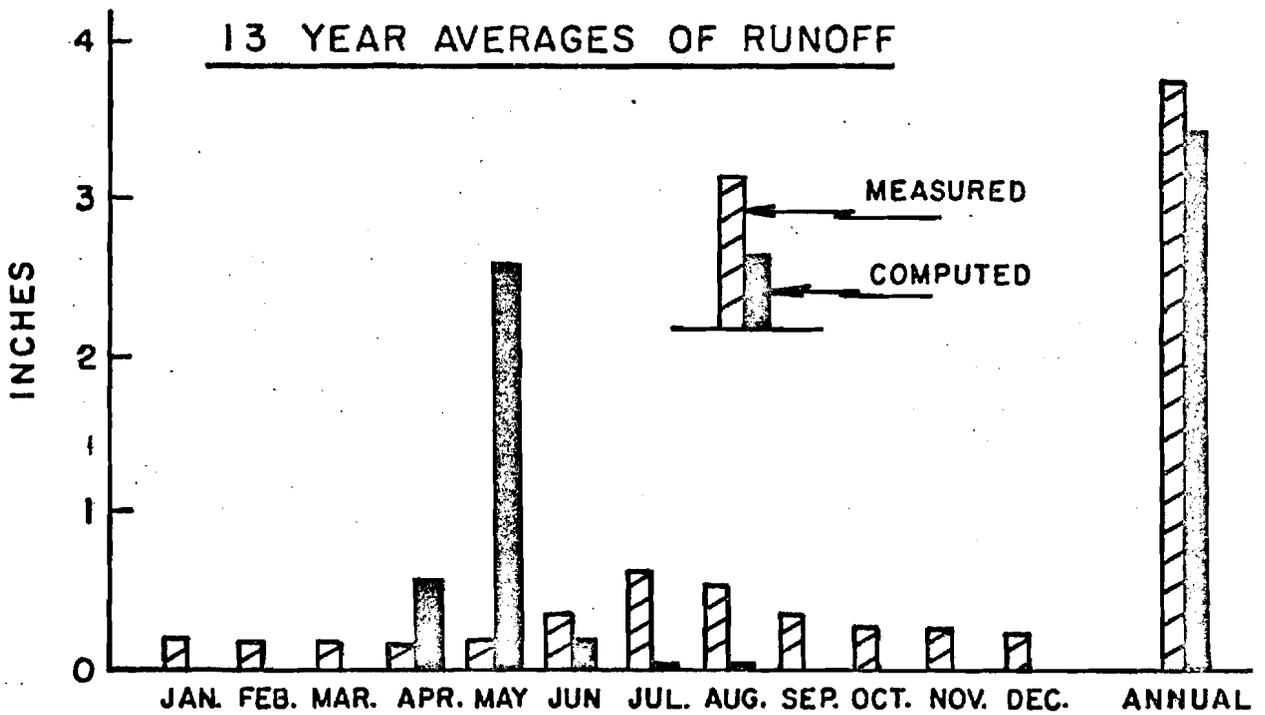
Fig. 16(b)   Turc Runoff at Fort Simpson vs. Snare River
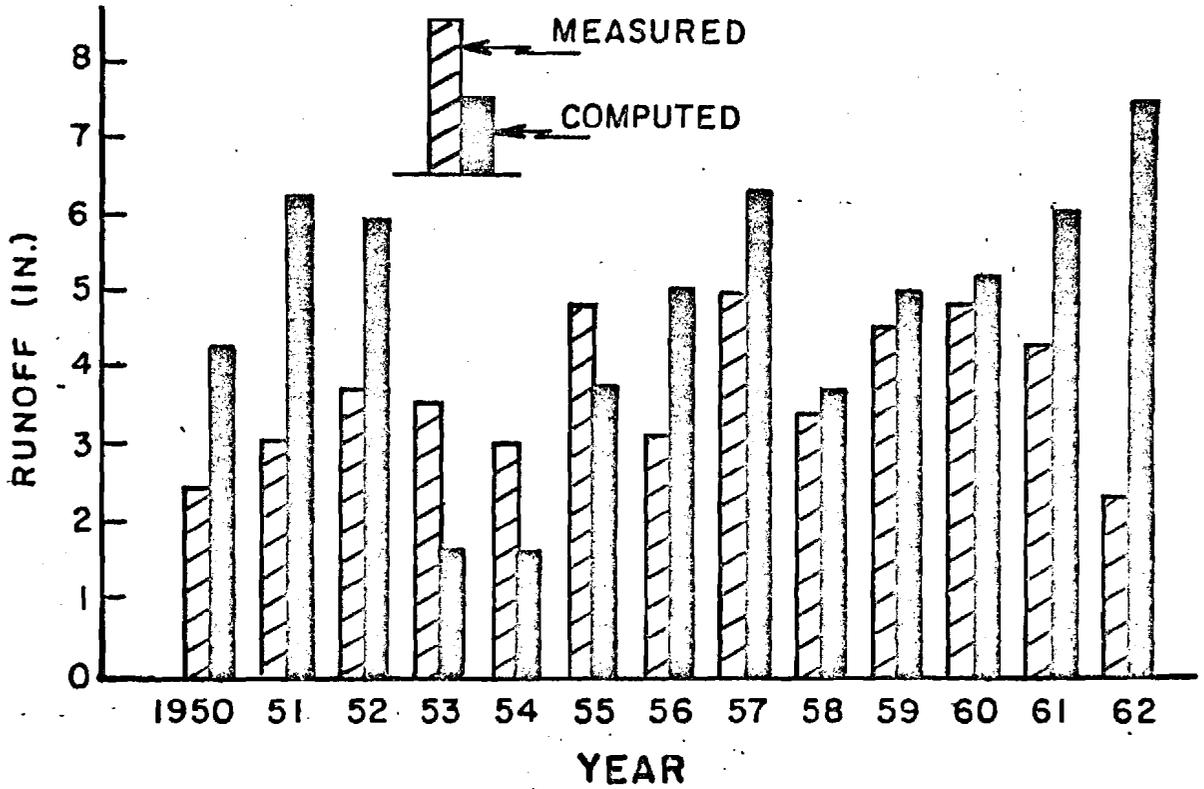
Fig. 16(c) Water Balance Annuan Runoff at Fort Simpson vs. Snare River
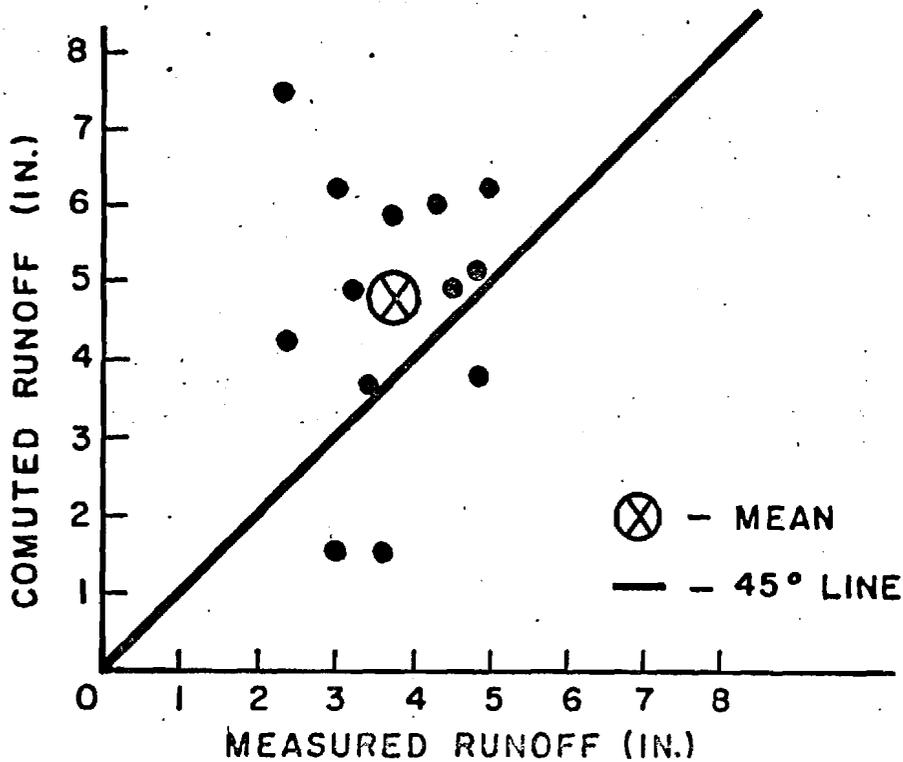
Fig. 16(d) Water Balance Annual Runoff at Fort Simpson vs. Snare River
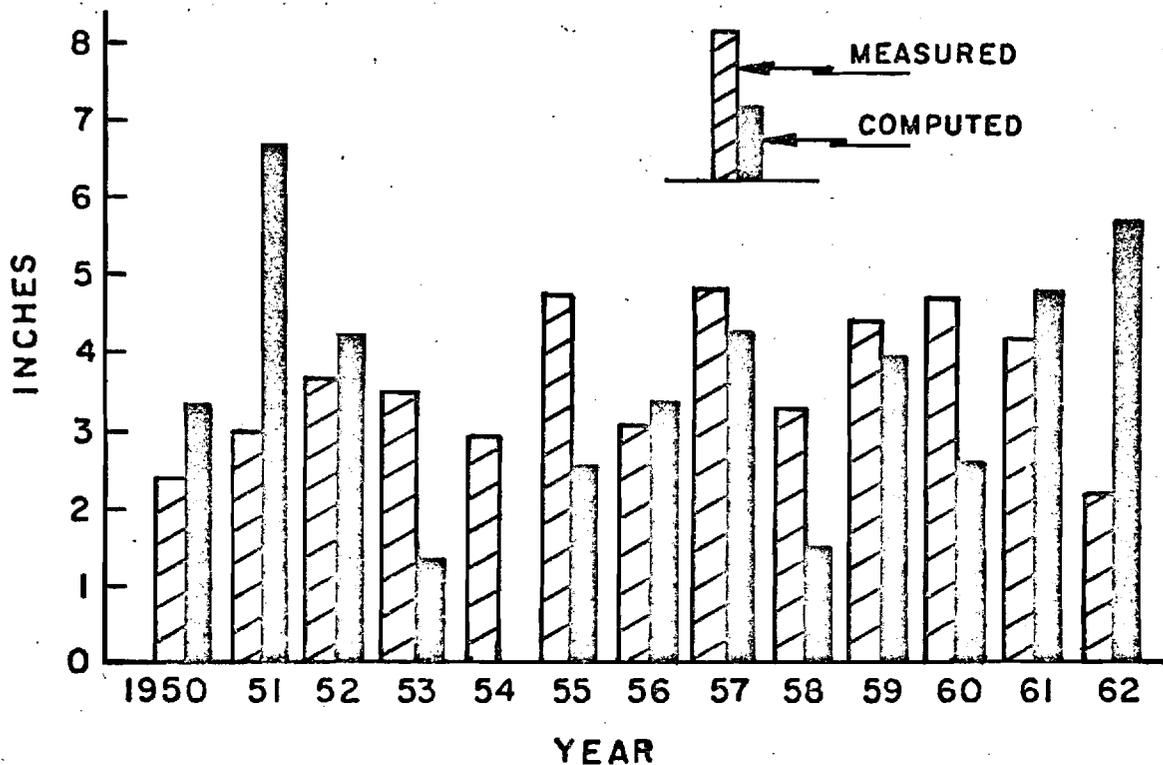
Fig. 16(e) Turc Annual Runoff at Fort Simpson vs. Snare River
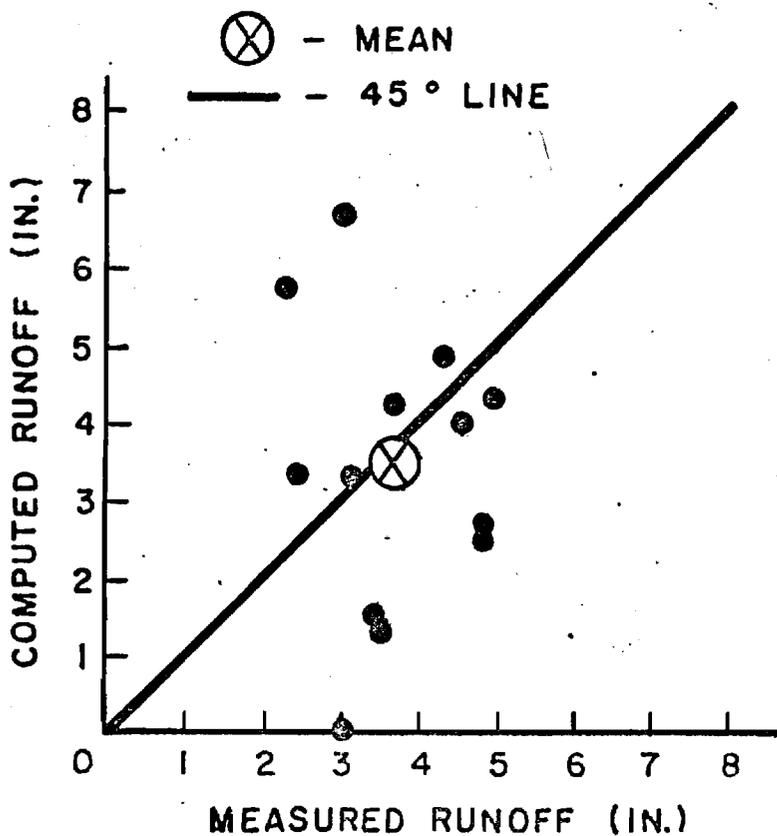
Fig. 16(f) Turc Annual Runoff at Fort Simpson vs. Snare River
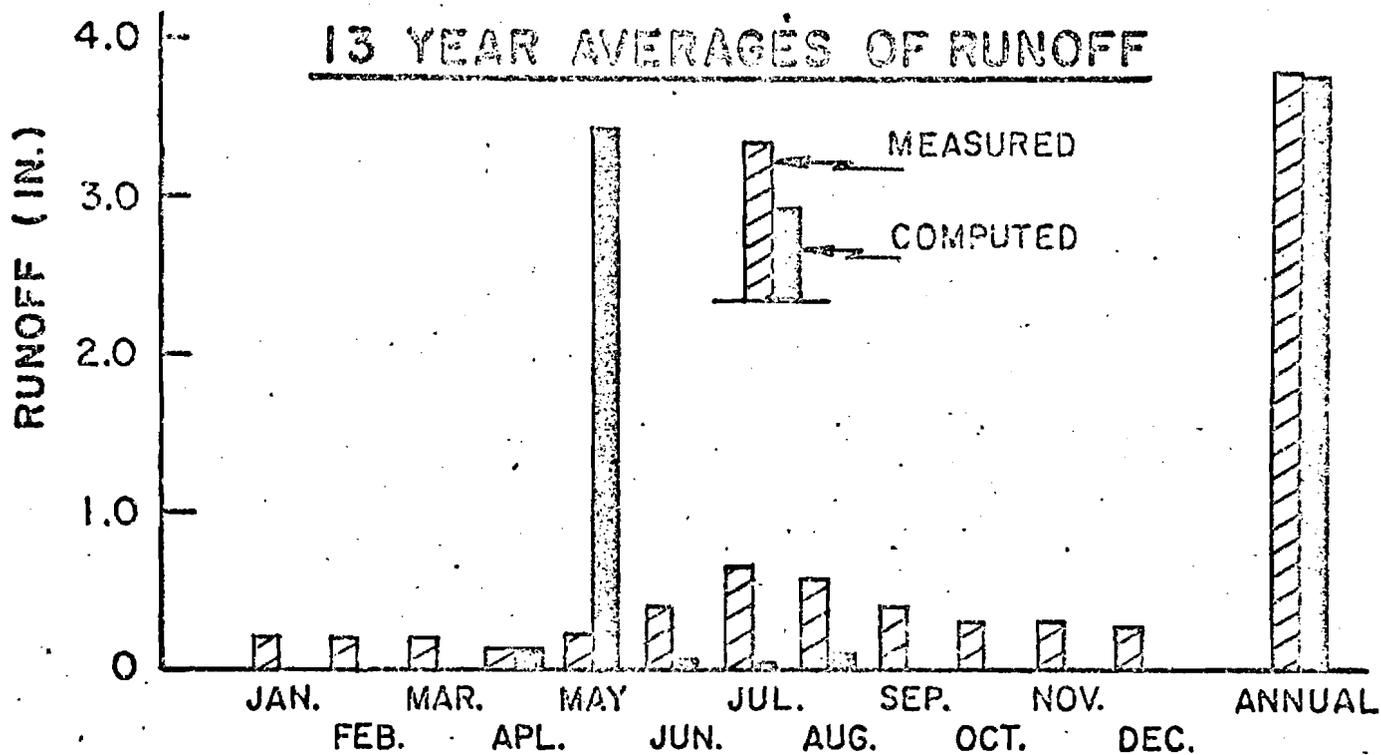
Fig. 17(a)   Water Balance Runoff at Yellowknife vs. Snare River
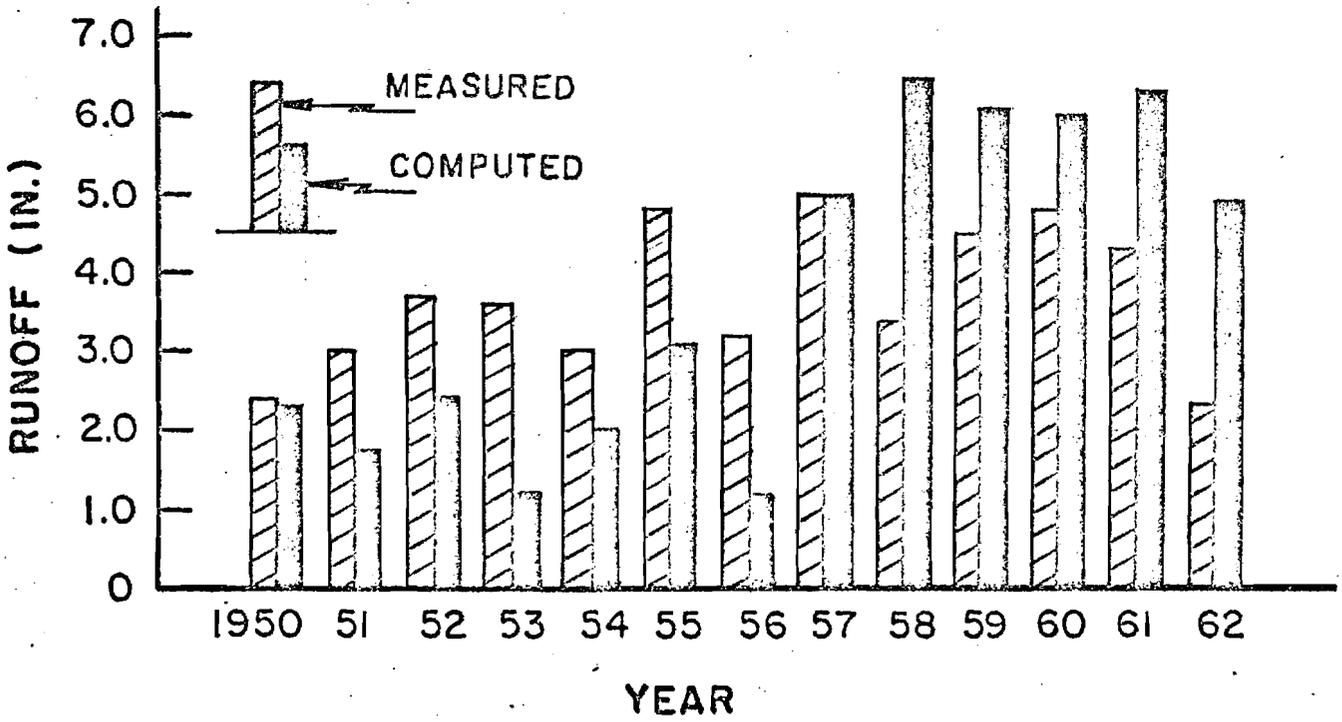
Fig. 17(b) Water Balance Annual Runoff at Yellowknife vs. Snare River

Fig. 17(c) Water Balance Annual Runoff at Yellowknife vs. Snare River

Fig. 18(a) Water Balance Runoff at Fort Chimo-Knob Lake vs. Baleine River
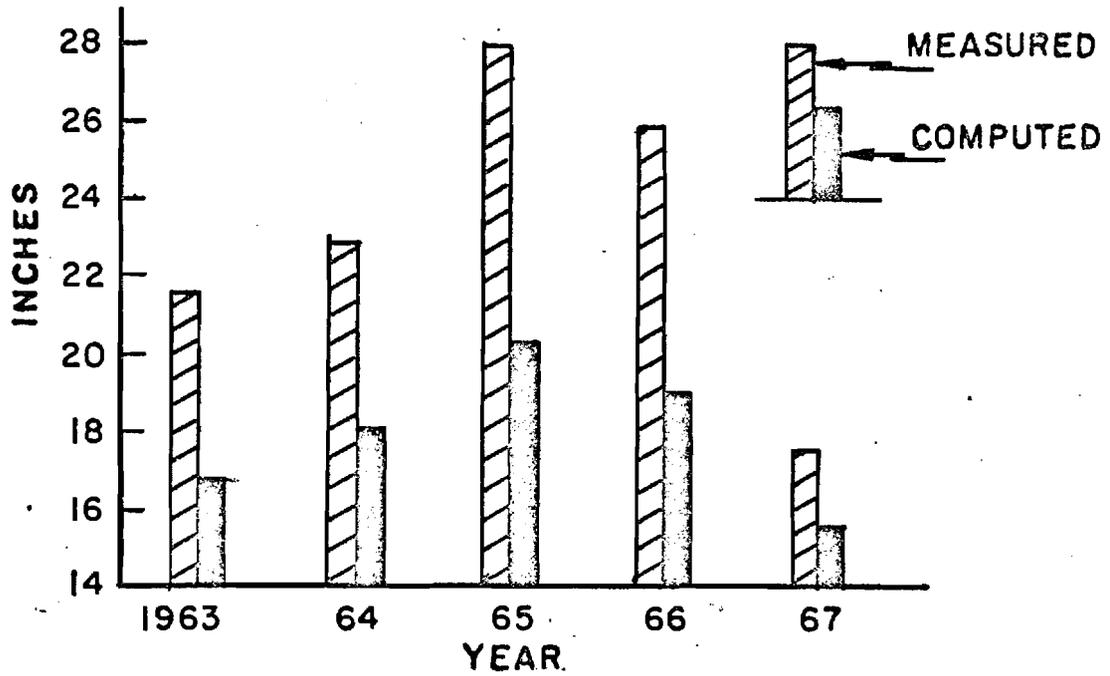
Fig. 18(b) Water Balance Annual Runoff at Fort Chimo-Knob Lake vs. Baleine River
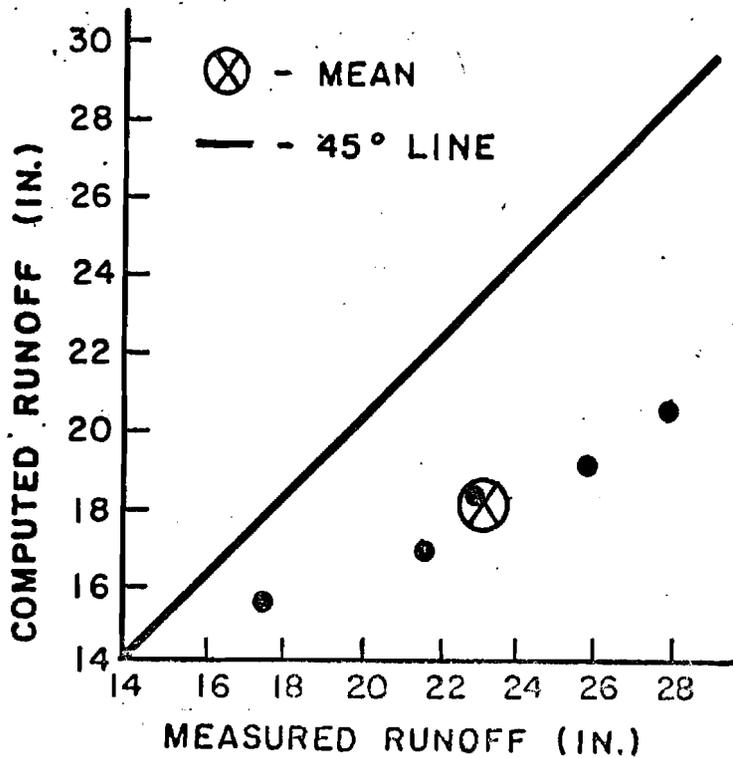
Fig. 18(c) Water Balance Annual Runoff at Fort Chimo-Knob Lake vs. Baleine River

5 YEAR AVERAGES OF RUNOFF
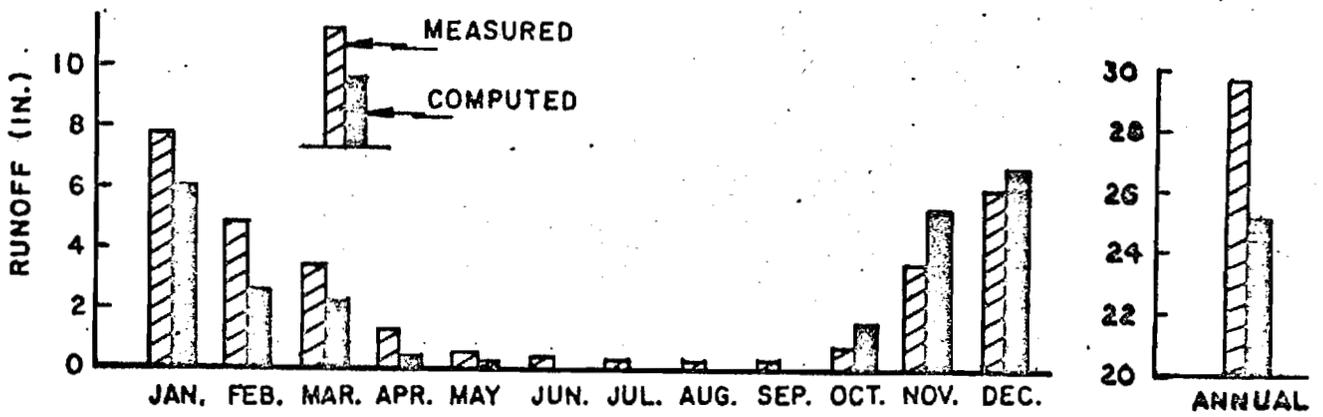
Fig. 19(a) Water Balance Runoff at Duncan vs. Bings Creek
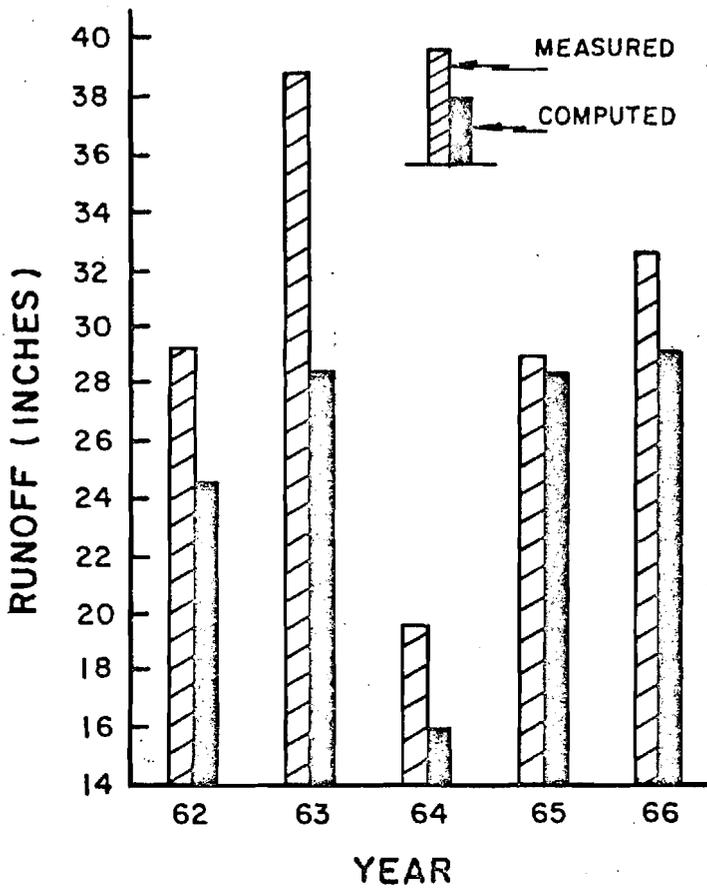
Fig. 19(b) Water Balance Annual Runoff at Duncan vs. Bings Creek
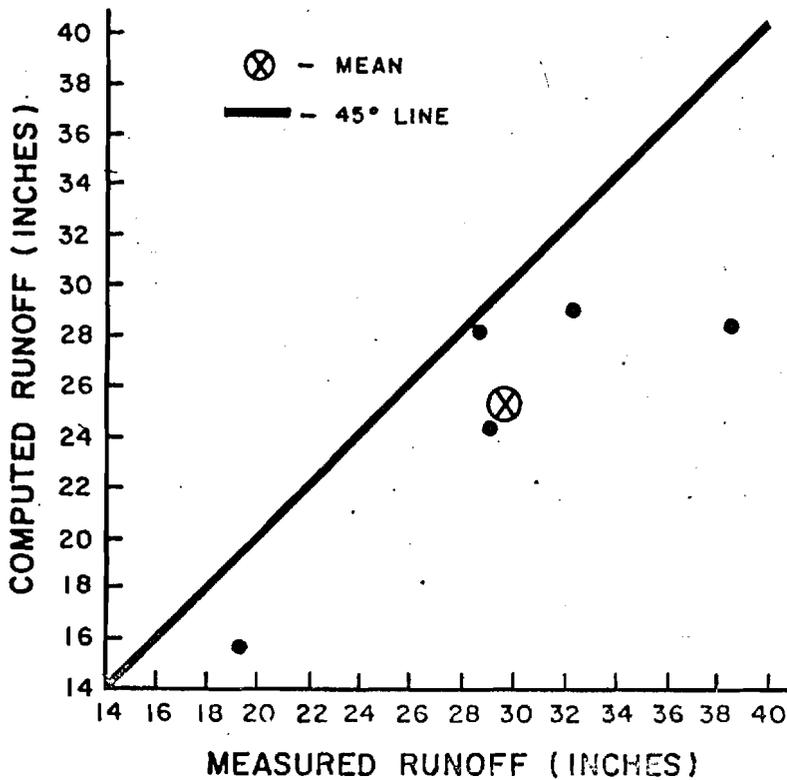
Fig. 19(c) Water Balance Annual Runoff at Duncan vs. Bings Creek

Fig. 20(a) Water Balance Runoff at Abbotsford vs. Sumas River
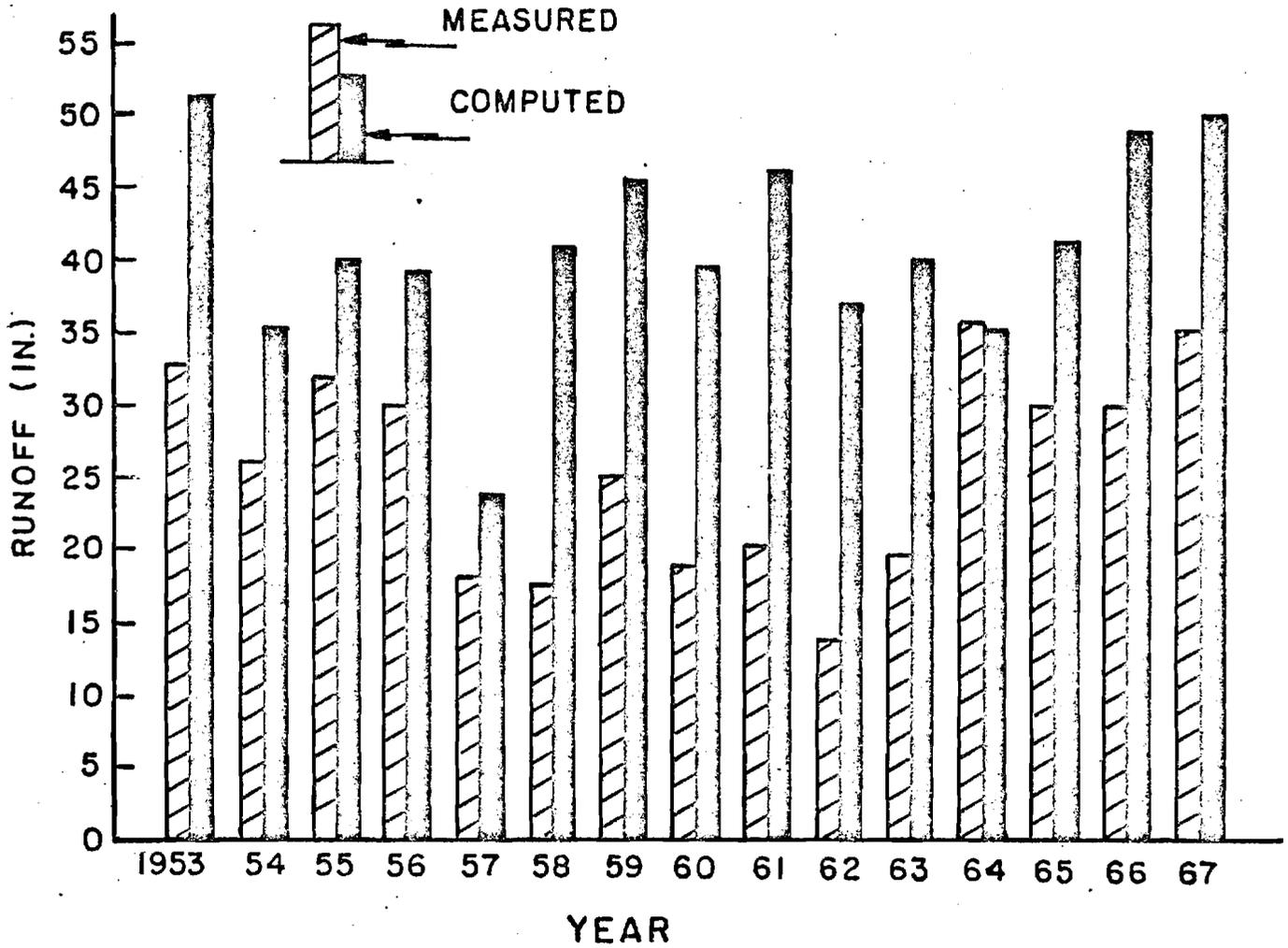
Fig. 20(b) Water Balance Annual Runoff at Abbotsford vs. Sumus River
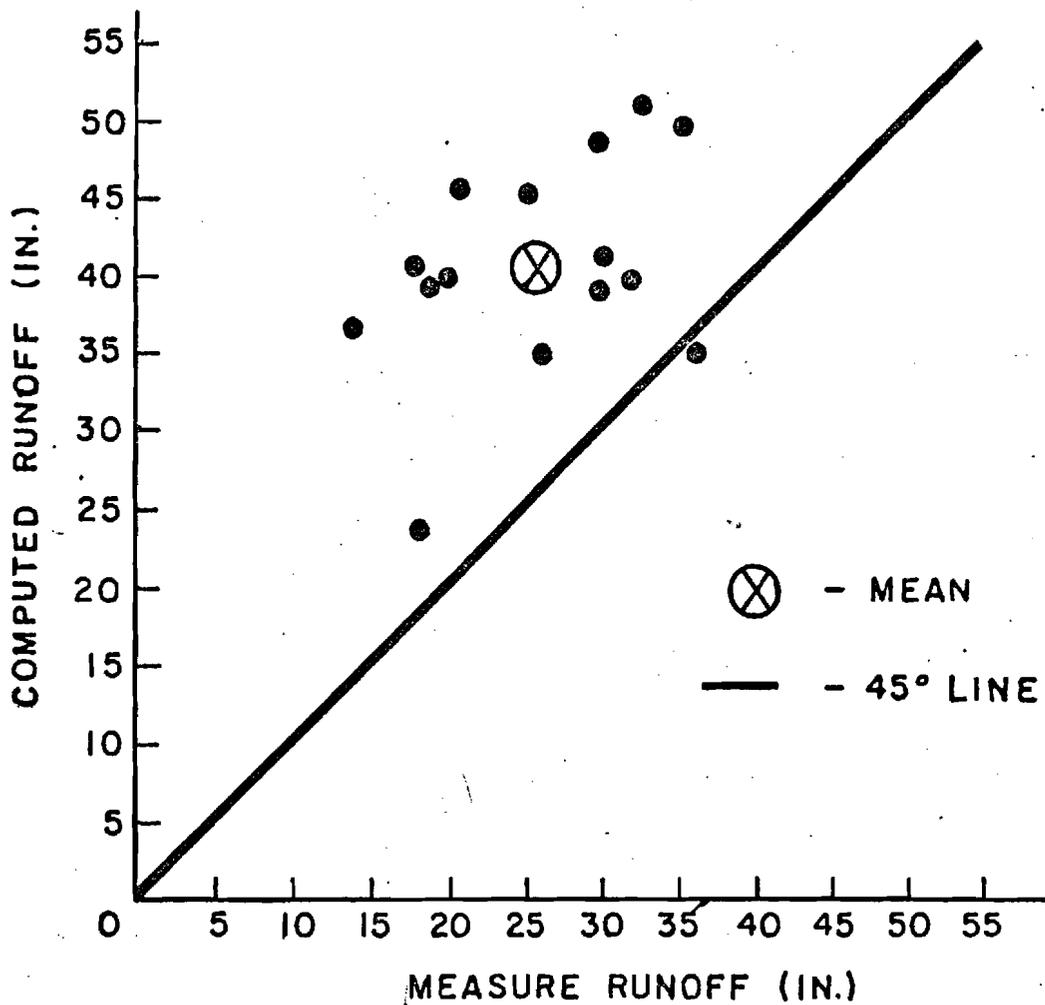
Fig. 20(c) Water Balance Annual Runoff at Abbotsford vs. Sumus River
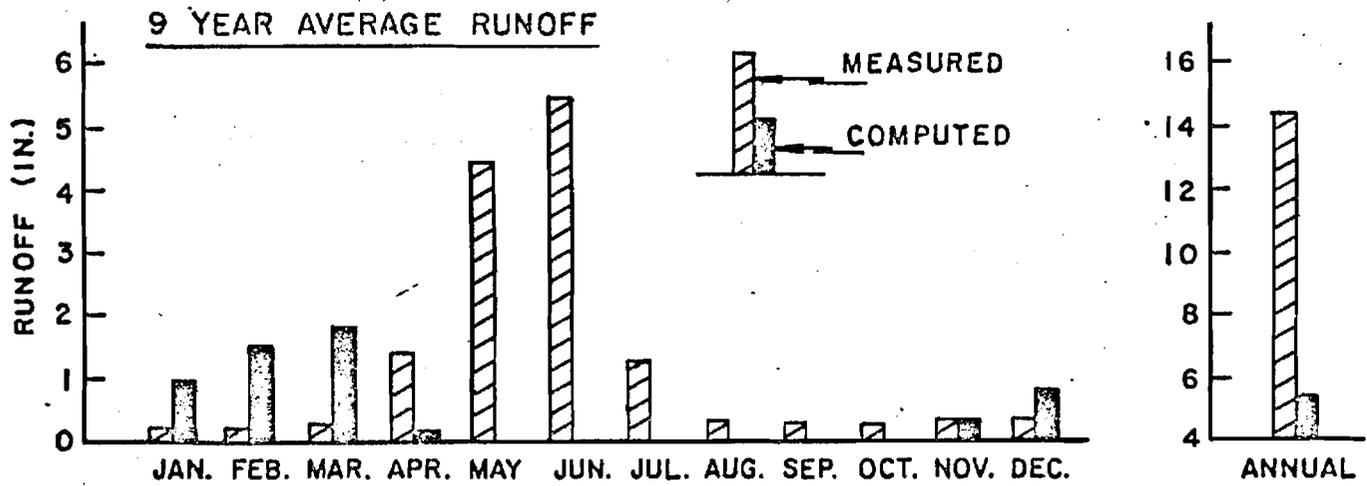
Fig. 21(a) Water Balance Runoff at Deer Park vs. Deer Creek
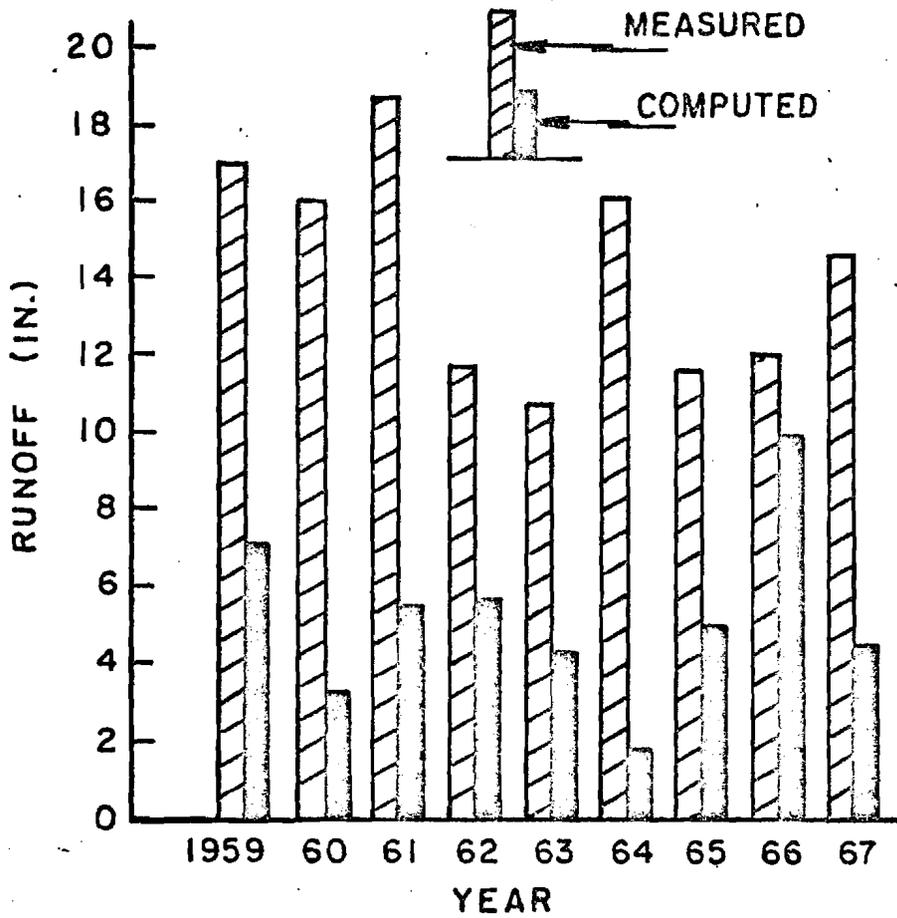
Fig. 21(b) Water Balance Annual Runoff at Deer Park vs. Deer Creek

MEASURED RUNOFF (IN.)

difference in measured and computed runoff curves. Also, this phenomena
would produce more runoff due to the geology of the upper area of the
basin and the fact that snow stores precipitation above ground and
releases it in a more intense fashion with regards to runoff. The
recorded temperatures at Deer Park did not indicate any major snowfall
accumulation during the winter months.

A similar problem can be noticed at Vernon in that calculated
peaks of runoff are coming prior to the measured ones (see Fig. 22(a)).
The problem is not as bad though due to the more northerly location of
the station and also the runoff gauge at Vernon measures a slightly
smaller drainage basin.

The calculated runoff at Terrace is completely unrepresentative of
the measured values (see Figs 23(a) to 23(c)). Similar to the comparison
at Deer Park the seasonal trend of measured runoff shows that it is due
mostly to snow accumulation at higher elevations. This amount of snow
accumulation is not indicated by temperature data at the climatic
station. As well the annual average of runoff is 164% of the recorded
precipitation. The lack of true precipitation values makes it
impossible to compare the calculations. The magnitude of the error in
precipitation readings at this station suggest that underestimation
of runoff at the other stations in the mountains is not as severe of
criticism of the method as one would first believe.

The problem of measuring precipitation and the geologic changes
between the lower and upper parts of the basin subject any resulting
evaporation calculations to question. The soil moisture capacities
used would have to be average values for the basin and would then
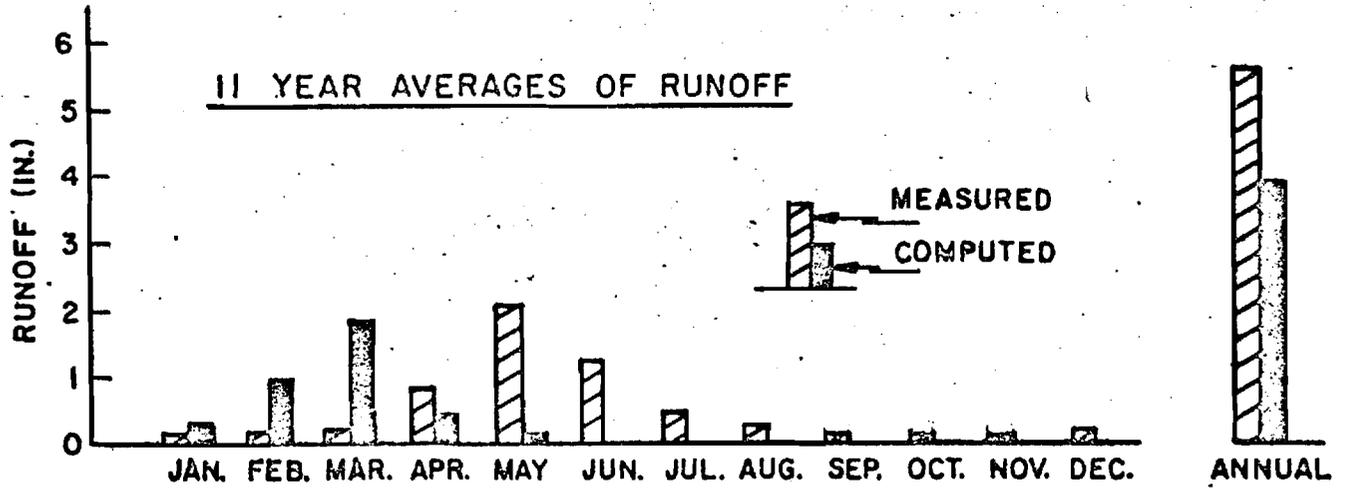
Fig. 22(a) Water Balance Runoff at Vernon vs. BX Creek
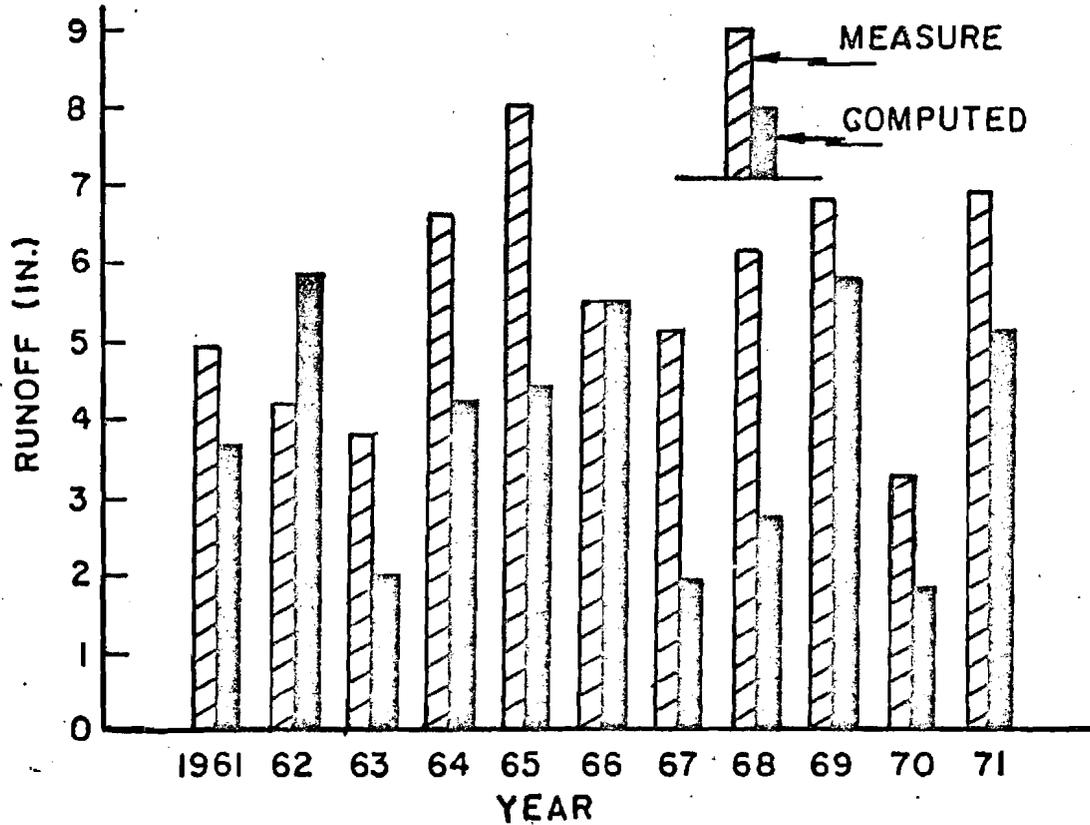
Fig. 22(b) Water Balance Annual Runoff at Vernon vs. BX Creek

Fig. 22(c) Water Balance Annual Runoff at Vernon vs. BX Creek

7. YEAR AVERAGES OF RUNOFF
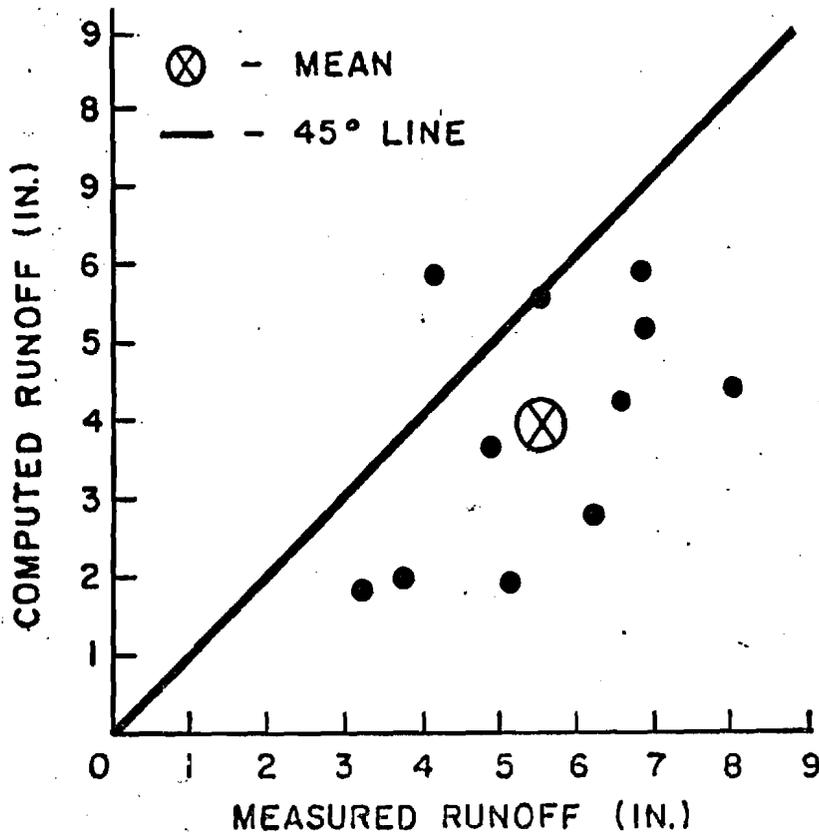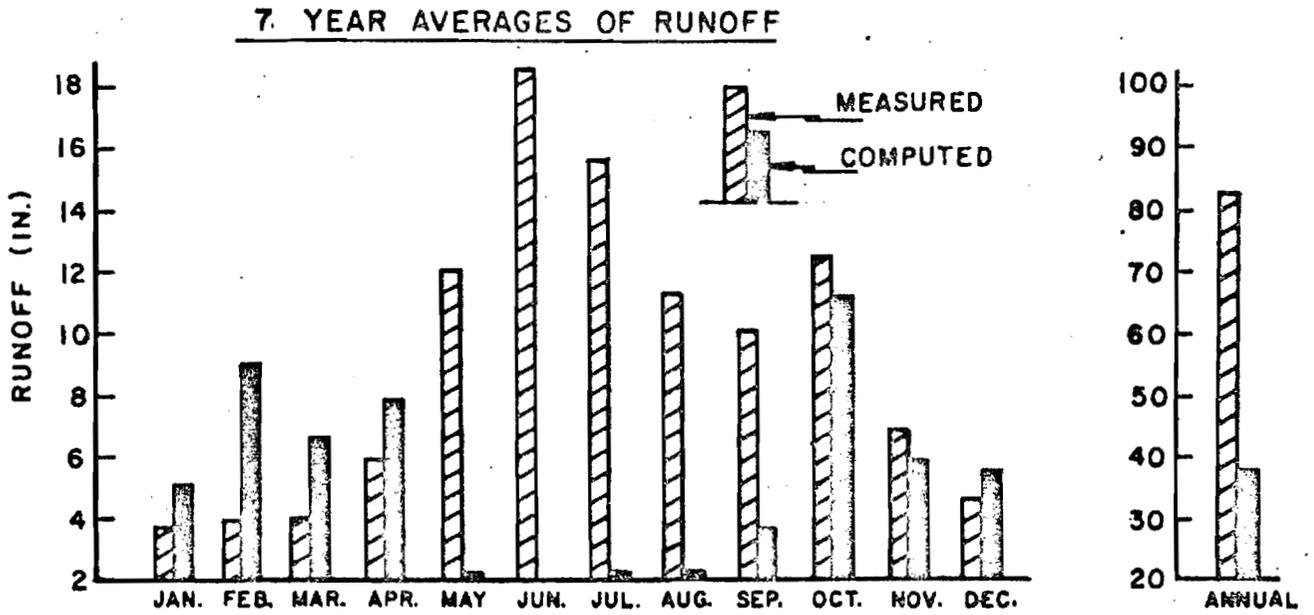
Fig. 23(a) Water Balance Runoff at Terrace vs. Zymagotitz River
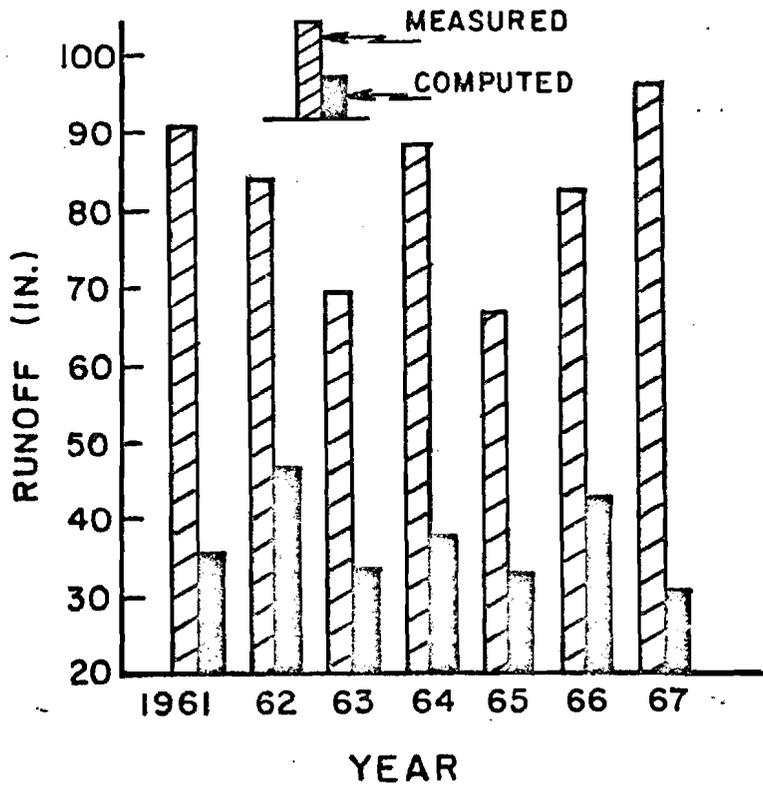
Fig. 23(b) Water Balance Annual Runoff at Terrace vs. Zymagotitz River
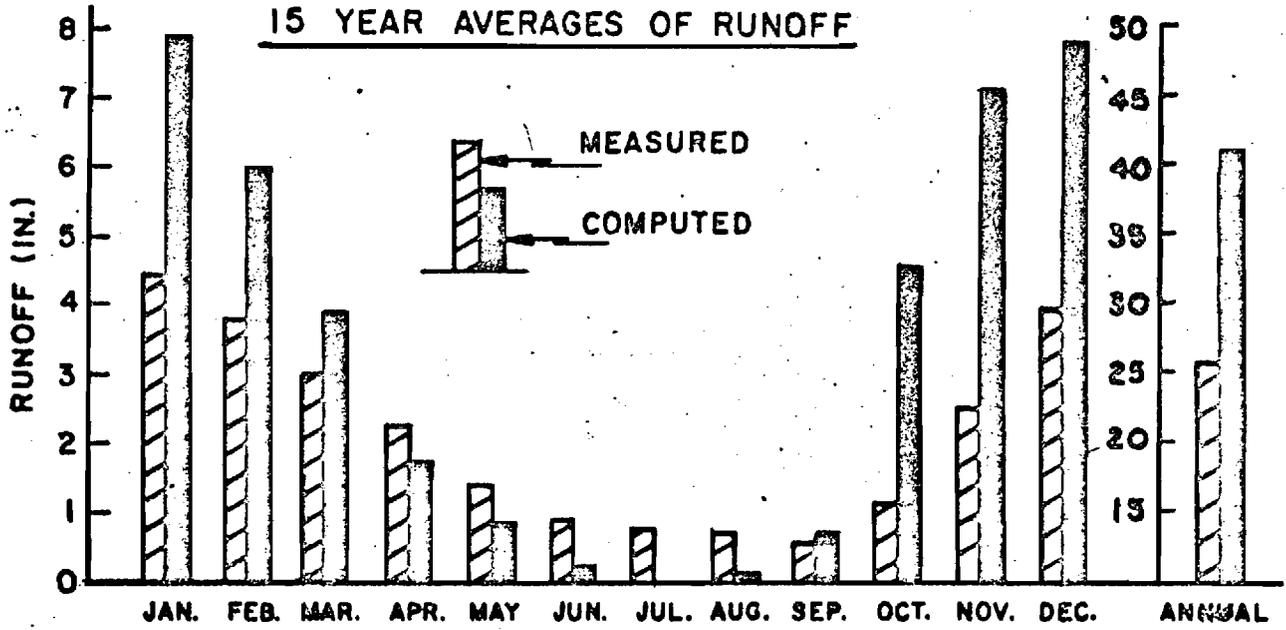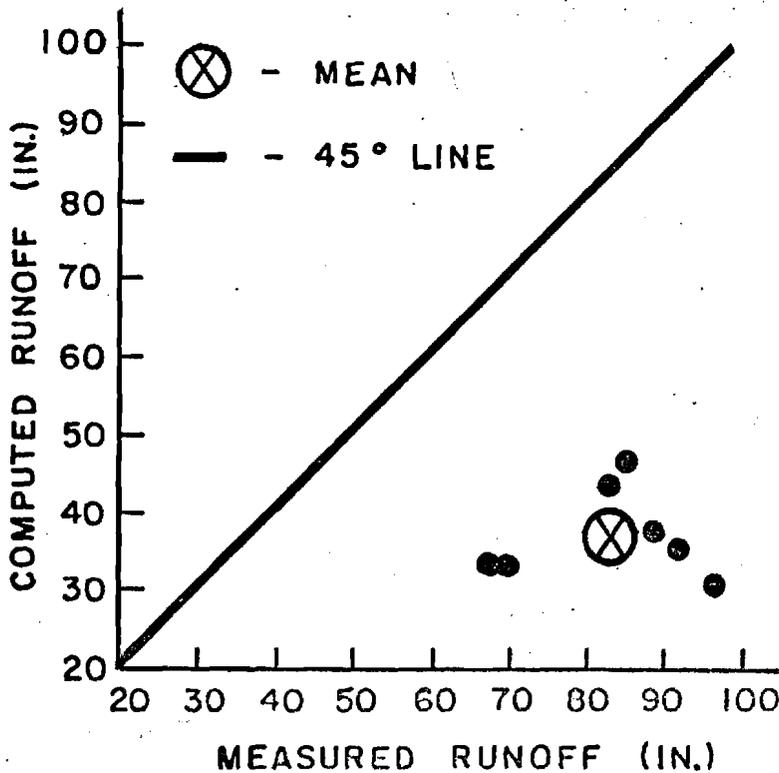

Fig. 23(c) Water Balance Annual Runoff at Terrace vs. Zymagotitz River

underestimate evaporation in the lower areas. The results at Duncan
would suggest that the calculations could be applied with reasonable
confidence only as a measure of evapotranspiration in the lowlands.

General

The calculations show that the climatic water balance, in addition
to being simpler to apply, gives generally superior results to those
given by the Turc equation. For the water balance method, in cases
where adequate data is available, runoff values may be predicted by this
method within the range of 0-25%. This excludes most of the stations
in the mountainous area because of the inadequacy of data. Except for
the mountains, in the majority of cases the errors in the evaporation
values will be less than the errors in runoff.

Published value for the Thornthwaite climatic water balance are
entered in Table IV. Direct comparison of these values with results
from the study are difficult because of the different number of years
of records analyzed. In general, the Thornthwaite method tends to give
lower values than the water balance approach used here or the measured
runoff values. However, the results are more compatible for Abbotsford,
Sept-Isles, Montreal and Fredericton. The Thornthwaite calculations tend
to be much lower in the more interior parts of the country.

In most instances the increase in computed runoff by the water
balance method can be attributed to the different manner of handling
precipitation inputs and snowmelt. These modifications are very
significant because the Christianson-Mehta equation and the soil
moisture extraction pattern used give a higher rate of evaporation than
the Thornthwaite climatic water balance. In summary, the application

TABLE   IV

Comparison of Thornthwaite Water Balance to Modified Water Balance

Station	Measured Annual Average	Years of Record	Calculated Annual Average From Water Balance	Years of Record	Published Annual Averages From Thornthwaite Water Balance[a]	Years of Record
Swift Current	0.95	23	0.85	23	0	?
Porcupine Plain	2.17	12	2.11	12	0[a]	10[b]
Vegreville	0.29	9	0.17	9	---	---
Brandon	0.57	7	1.92	7	0	?
Guelph	11.3	17	11.3	17	7.6	44
Montreal	16.3	42	15.1	42	17.8	55
Fredericton	26.5	46	24.3	46	21.5	67
Fort Simpson	3.8	13	4.8	13	0	42
Yellowknife	3.8	13	3.7	13	0	10
Sept-Isles	36.7	13	28.9	13	25.2	9
Fort Chimo/Knob Lake	23.2	5	18.0	5	4.1	10
White River	14.4	8	16.0	8	9.5	52
Duncan	29.7	5	25.1	5	15.1	?
Abbotsford	25.6	15	40.9	15	36.9	9
Deer Park	14.3	9	5.2	9	---	---
Vernon	5.6	11	3.9	11	0	20
Terrace	83.4	7	37.6	7	24.8	27

[a]From Average Climatic Water Balance Data of the Continents - Part VI

[b]Data for Hudson Bay, Saskatchewan

of precipitation to the soil rather than balancing precipitation against potential evaporation is the primary alteration to Thornthwaite water balance technique.

This method of applying precipitation requires that a shorter period of summation of the climatic terms be used. As indicated previously even with ten day totals, precipitation may be quite large and should be added in two storm events.

Figure 24 indicates the growing seasons used here. The division between zone 3 and 4 is not very critical. In the major agricultural areas the growing season is more important since potential evaporation rates can exceed the moisture capacity of the upper soil zone quite early. In the north the potential evaporation rates at the start of the assumed growing seasons are not as high. Figure 25 indicates the soil moisture capacities used. The divisions between different zones were determined by the results of the study with reference to a map of soil regions of Canada. No stations were calculated for the tundra region (Zone 9) and therefore the soil moisture capacities recorded for this area are estimated values only.

The results of the calculations of the water balance and comparison with Turc and published values for Thornthwaite's climatic water balance indicate that the method is a significant improvement. The choice of test stations in many different regions show the confidence with which the method can be applied for mapping of evapotranspiration. This report has emphasized the absolute values more than correlation coefficients since correlation of runoff values are not a very complete measure of the accuracy of the model. This is especially true when
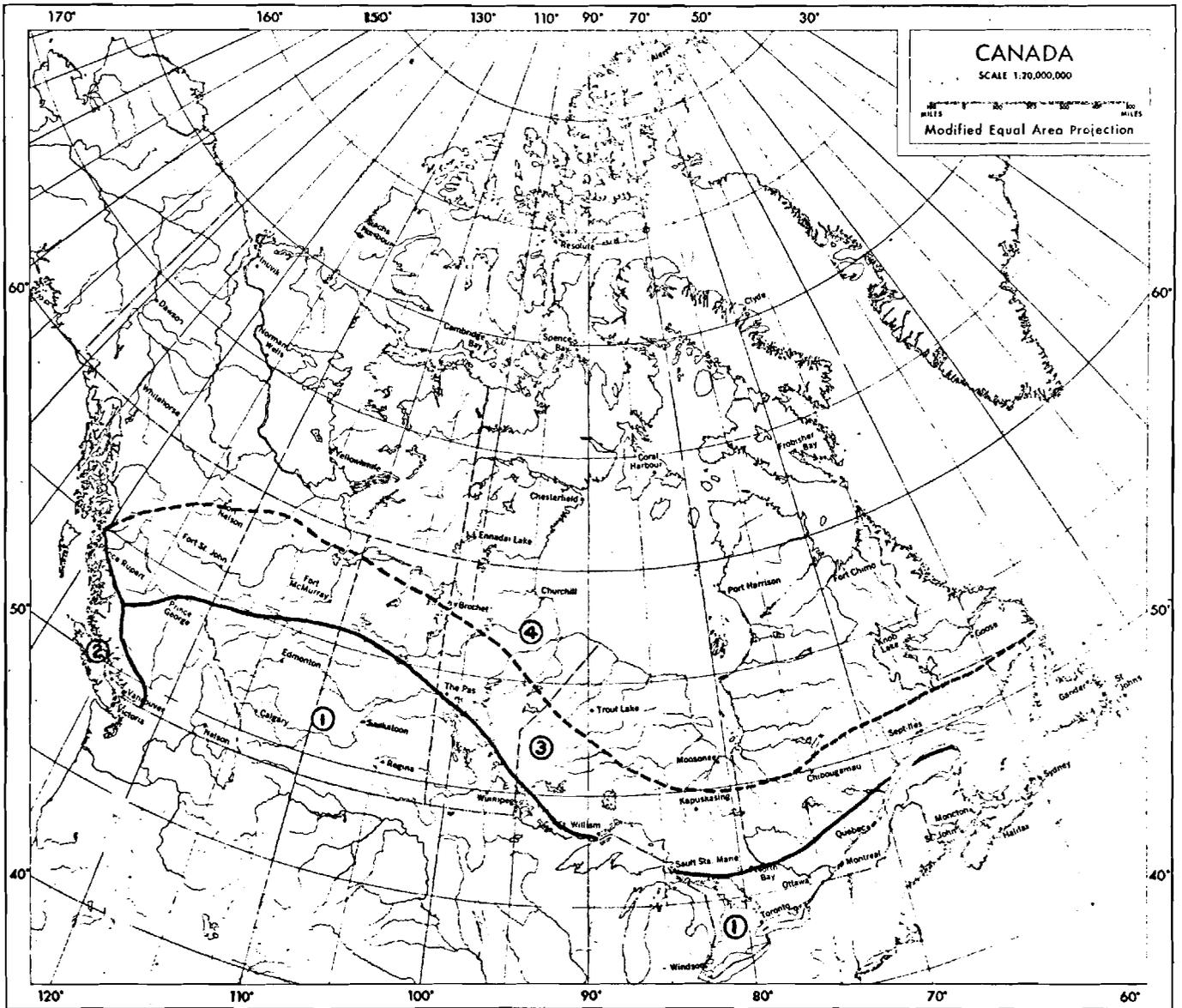
Figure 24. Growing Seasons

① - May 1 to September 30

② - April 1 to October 31

③ - May 10 to September 30

④ - May 20 to September 20
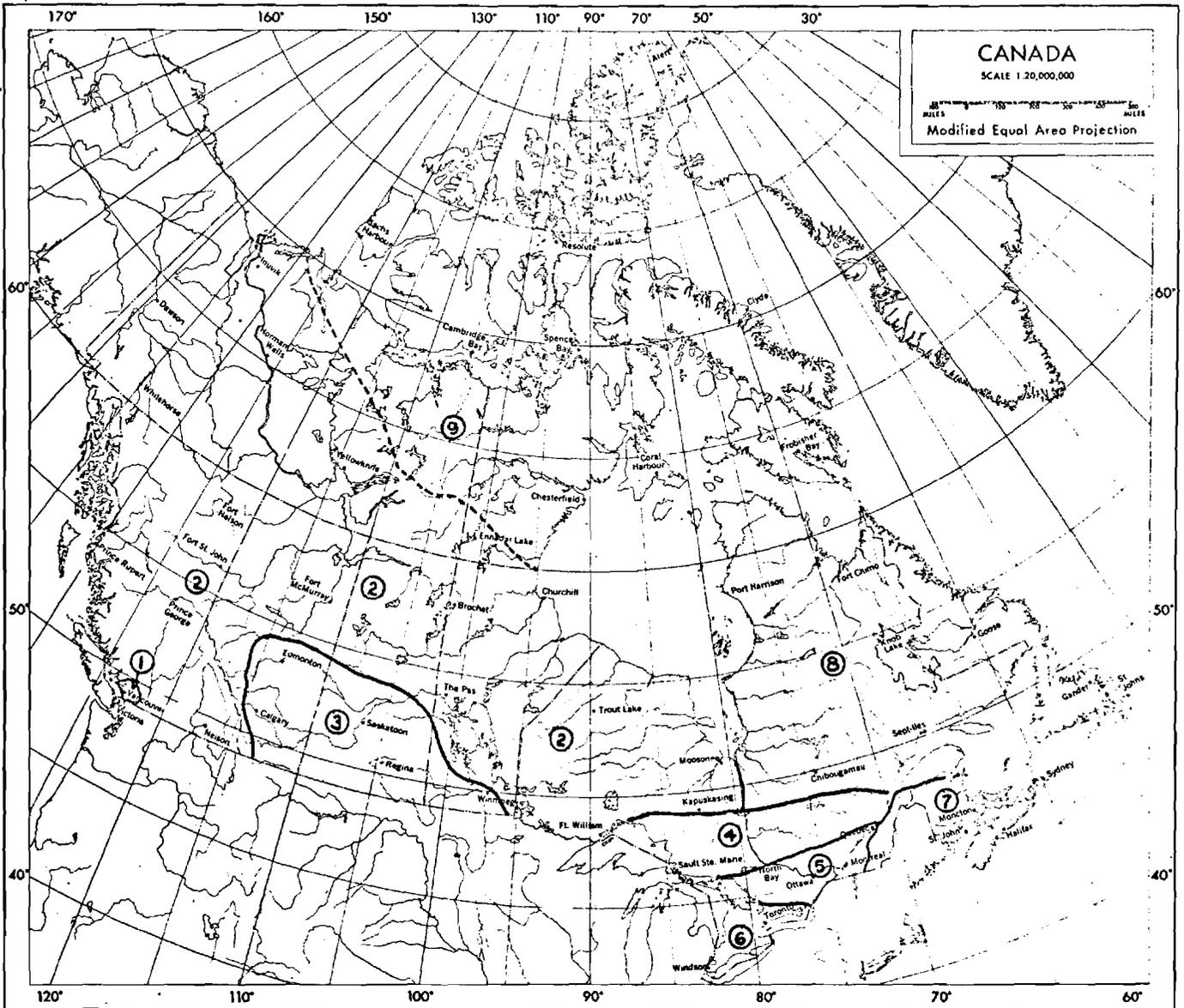
Figure 25. Soil Moisture Capacities

① - Upper Zone = 1", Lower Zone = 2"

② - Upper Zone = 0.5", Lower Zone = 1"

③ - Upper Zone = 1", Lower Zone = 3"

④ - Upper Zone = 1", Lower Zone = 1"

⑤ - Upper Zone = 1", Lower Zone = 1.5"

⑥ - Upper Zone = 1", Lower Zone = 2"

⑦ - Upper Zone = 0.25", Lower Zone = 1.75"

⑧ - Upper Zone = 0.25", Lower Zone = 0.75"

⑨ - Upper Zone = 0.25", Lower Zone = 0.75" (Estimate Only)

the method is to be used as a means of calculating long term averages
of monthly and annual evapotranspiration.

The procedure can readily be programmed for computer solution.
An outline of the steps in the procedure is included in Appendix C.
Quality checks on the data are a necessary precaution. No decisions
are required other than the soil moisture capacities and growing
seasons. These have been indicated in Figures 7 and 8.

EVAPOTRANSPIRATION ESTIMATES

The evapotranspiration amounts for each station, as calculated by
the water balance technique, are plotted in Figure 26. Of most
significance is that these graphs show the interaction between potential
evaporation and precipitation in determining the actual evapotranspiration.
At no time can the amount of actual evapotranspiration exceed the
potential evaporation or the available moisture supply although it
may exceed the precipitation in some periods.

For many stations (Swift Current, Brandon, Guelph, Montreal,
Fredericton) the evapotranspiration reaches a peak value in May or
June, which is at a later date than the occurrence of the maximum
available moisture supply from snowmelt yet before potential evaporation
is a maximum (in mid-summer). For Porcupine Plain, Vegreville, White
River, Fort Simpson and Yellowknife the evapotranspiration is relatively
uniform during the period from May to August. At Sept-Isles and
Fort Chimo-Knob Lake, the maximum occurs in July, indicating that
potential evaporation, not available moisture supply, may play the
more dominant role in these areas.

For the stations in British Columbia, evapotranspiration is

FORT CHIMO

5 YEAR AVERAGES OF A.E.

ANNUAL - 8.4 IN.

● KNOB LAKE

13 YEAR AVERAGES OF A.E.

ANNUAL - 10.9 IN.

● SEPT-ISLES

9 YEAR AVERAGES OF A.E.

ANNUAL - 13.7 IN.

● WHITE RIVER

● FREDERICTON

49 YEAR AVERAGES OF A.E.

ANNUAL - 16.9 IN.

● MONTREAL

42 YEAR AVERAGES OF A.E.

ANNUAL - 22.2 IN.

● GUELPH

17 YEAR AVERAGES OF A.E.

ANNUAL - 21.3 IN.

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
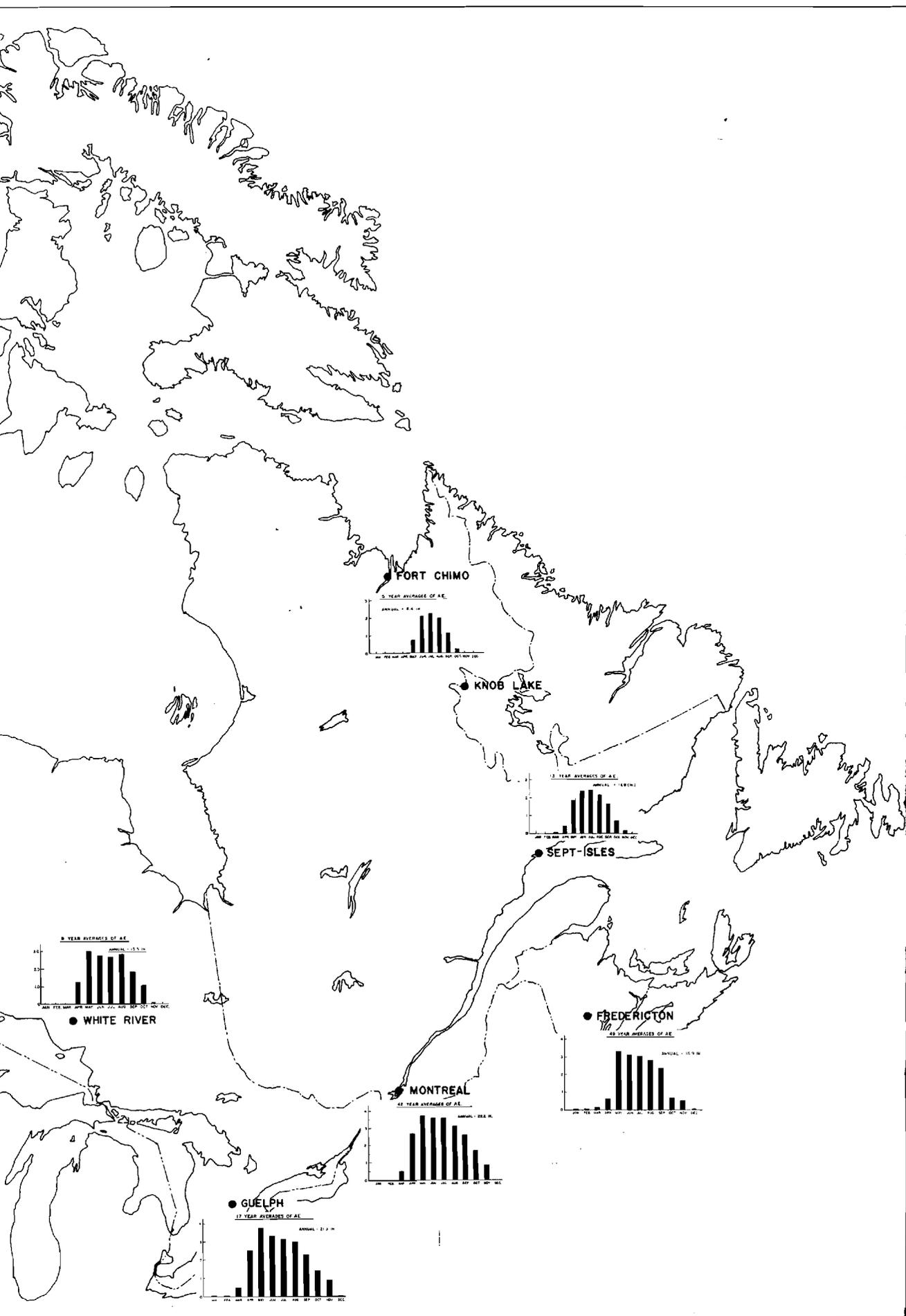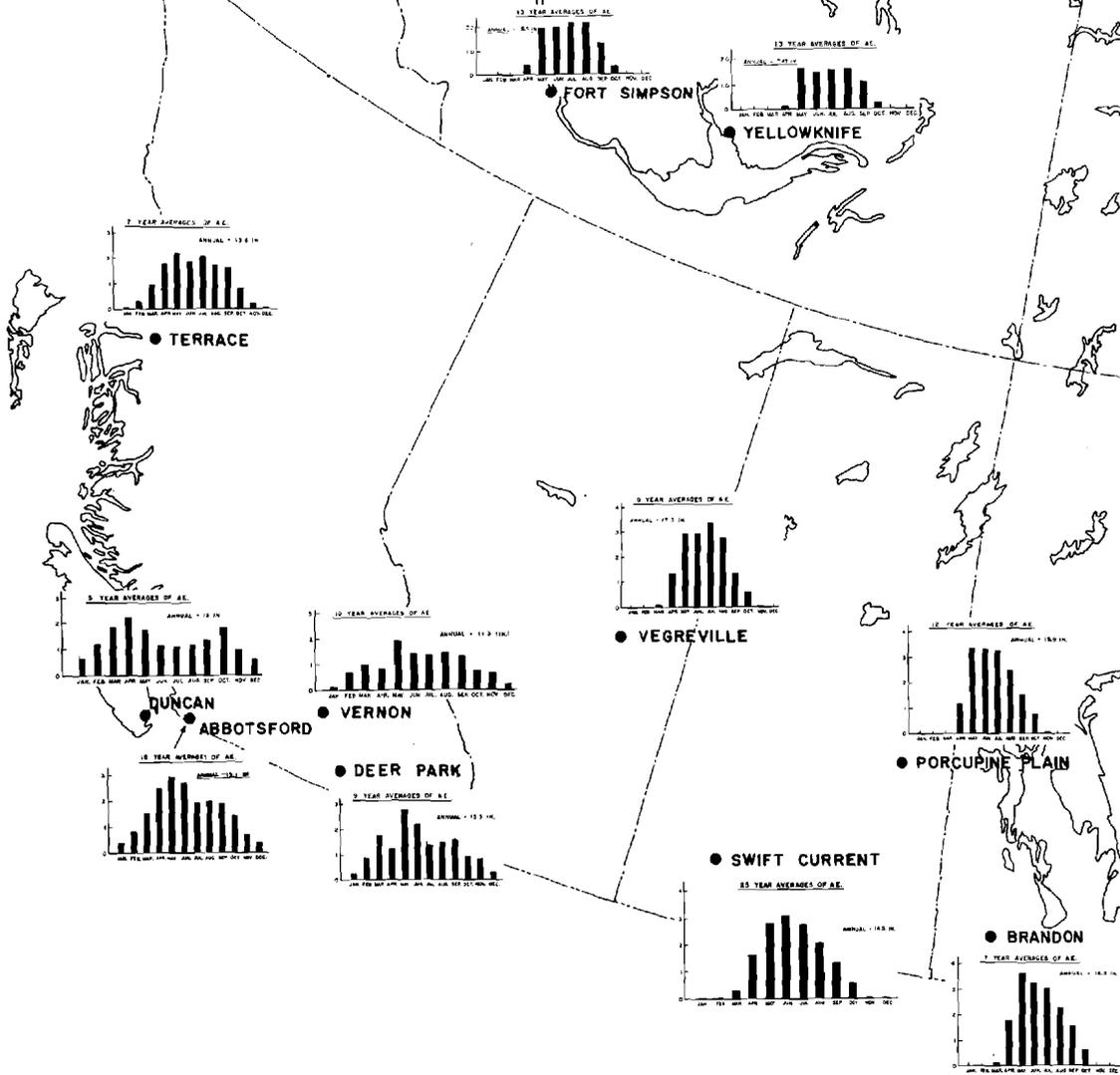
CANADA
MONTHLY ACTUAL EVAPOTRANSPIRATION IN INCHES
FROM THE CLIMATIC WATER BALANCE

Figure 26

significant for each month of the year. As indicated previously, this is likely true only in the low-lying valley areas from which the temperature and precipitation data were obtained. In British Columbia the monthly values tend to fluctuate more than at other areas of the country. Generally a relative minimum occurs in July when potential evaporation is a maximum and precipitation is low.

It must be recognized that these graphs are average values and may shift considerably for certain years both in magnitudes and times-of-occurrences of relative maximums and minimums.

The results obtained in the study are too incomplete in terms of geographical location for development of a generalized regional map of evapotranspiration amounts in Canada. To suffice this objective additional calculations would be required on a denser spatial scale. Nevertheless, the results do demonstrate some significant features which should be taken into consideration when considering climatological mapping of evapotranspiration regimes. For example, in semi-arid regions, such as those experienced in the Canadian Prairies, there is indication that the isolines of evapotranspiration may be more uniformly and widely spaced and the annual amounts are significantly less than experienced in the more humid regions of Eastern Canada. Further, mapping of monthly evapotranspiration amounts will require a smaller spatial resolution (as compared to annual values) because maxima and minima are reached at different times of the year in different regions. This spatial and temporal variability of monthly values is considered extremely important to the design of a regional network.

An approach similar to the climatic water balance technique must be used to evaluate monthly evapotranspiration amounts. Variable soil

moisture capacities and the time scale and manner of handling precipitation inputs, either as snow or rain, have been shown to be very important. The stations chosen for analysis have attempted to cover a wide range of climatic factors affecting the water balance. These initial calculations provide a base from which further climatic stations may be used to develop a map of evapotranspiration.

HYDROLOGIC IMPLICATIONS AND FUTURE STUDIES

Although the method is more applicable to climatic use, it does give quite a bit of information about the hydrology of an area. The use of this type of an approach would be useful in little known areas. It could also prove useful for extrapolating known stream records to ungauged streams nearby. Runoff and soil moisture indications may be the most valuable outputs from applying the method to hydrologic studies.

Further work on the model would vastly improve the knowledge and usefulness of this climatic approach to hydrology. Research should be conducted on a smaller time period of analysis. This would likely result in better monthly totals. The thought behind this is again concern for the variability of precipitation. A shorter time period would also detect chinooks and short duration snowmelt that the ten day averages of temperature do not.

In summary, knowledge gained by applying a climatic water balance is useful in hydrology. This insight into the water balance of an area would be further advanced by studies of a more local nature and more detailed consideration of the several variables involved in the water balance technique. Any improvements would benefit climatic application

as well since the fields of climatology and hydrology are linked very

closely in precipitation and evaporation studies.

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A P P E N D I X   A

CONSTANTS   FOR   TURC'S   EQUATION

AND

GROWING   SEASONS   AND   SOIL-ZONE   CAPACITIES   USED

Values Used In Turc's Ten-Day Equation For Evapotranspiration

Station	Z	M	c
Swift Current	15	50	1.1
Guelph	15	80	1.1
Fredericton	15	70	1.1
Montreal	15	70	1.1
Brandon	15	60	1.1
Fort Simpson	12	34	1.2

Growing Seasons And Soil Zones

Station	Growing Season		Upper Zone	Lower Zone
Swift Current	May	1 → Sept. 30	1.0	3.0
Guelph	May	1 → Sept. 30	1.0	2.0
Fredericton	May	1 → Sept. 30	0.25	1.75
Montreal	May	1 → Sept. 30	1.0	1.5
Brandon	May	1 → Sept. 30	1.0	3.0
Fort Simpson	May	20 → Sept. 20	0.5	1.0
Abbotsford	April	1 → Oct. 31	1.0	2.0
Deer Park	May	1 → Sept. 30	0.5	1.0
Terrace	May	1 → Sept. 30	0.5	1.0
Yellowknife	May	20 → Sept. 20	0.5	1.0
Vegreville	May	1 → Sept. 30	1.0	3.0
Porcupine Plain	May	1 → Sept. 30	1.0	3.0
White River	May	10 → Sept. 30	1.0	1.0
Fort Chimo	May	20 → Sept. 20	0.25	0.75
Sept-Isles	May	10 → Sept. 30	0.25	0.75
Duncan	April	1 → Oct. 31	0.5	1.0
Vernon	May	1 → Sept. 30	0.5	1.0

A P P E N D I X   B

TABULATED COMPARISON OF MONTHLY AND ANNUAL RUNOFF

Meteorological Station   Swift Current, Sask. (4028040)

Runoff Gauging Station   Swift Current Creek (05HD031 & 05HD036)

Record Interval   1944 to 1966

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	0	0	----	0	----
February	0	0	----	0	----
March	0.23	0.13	0.55	0.01	0.41
April	0.52	0.67	0.69	0.59	0.53
May	0.09	0	----	0.17	0.21
June	0.04	0.04	0.20	0.17	0.64
July	0.03	0.01	0.91	0.04	0.59
August	0.01	0	----	0	----
September	0.01	0	----	0	----
October	0.02	0	----	0	----
November	0	0	----	0	----
December	0	0	----	0	----
ANNUAL	0.95	0.85	0.66	0.98	0.54

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   <u>Brandon, Man. (S010485)</u>

Runoff Gauging Station   <u>Whitemud River (05LL013)</u>

Record Interval   <u>1961 to 1967</u>

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	0	0	----	0	----
February	0	0	----	0	----
March	0.03	0	----	0	----
April	0.19	1.24	0.24	1.65	0.37
May	0.11	0.67	0.06	1.38	0.49
June	0.07	0	----	0.09	0.87
July	0.05	0	----	0	----
August	0.03	0	----	0	----
September	0.04	0	----	0	----
October	0.04	0	----	0	----
November	0	0	----	0	----
December	0	0	----	0	----
ANNUAL	0.57	1.92	-0.07	3.12	0.49

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   <u>Porcupine Plain, Sask. (4086160)</u>

Runoff Gauging Station   <u>Etomami River (05LB002)</u>

Record Interval   <u>1955 to 1966</u>

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0	0	----
February	0	0	----
March	0.01	0	----
April	0.70	0.72	0.53
May	0.82	1.22	-0.09
June	0.38	0.12	0.88
July	0.14	0	----
August	0.03	0.05	-0.08
September	0.04	0	----
October	0.05	0	----
November	0	0	----
December	0	0	----
ANNUAL	2.17	2.11	0.38

[a] Computed runoff correlated with corresponding values of measured runoff

Meteorological Station <u>Vegreville, Alta. (3016761)</u>

Runoff Gauging Station <u>Vermillion River (05EE001)</u>

Record Interval <u>1959 to 1967</u>

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0	0	----
February	0	0	----
March	0.03	0.04	-0.25
April	0.10	0.08	0.73
May	0.09	0	----
June	0.03	0.02	0.90
July	0.02	0.06	0.24
August	0.02	0	----
September	0.01	0	----
October	0.01	0	----
November	0	0	----
December	0	0	----
ANNUAL	0.29	0.17	0.58

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Guelph, Ont. (6143083)

Runoff Gauging Station   Speed River (02GA015)

Record Interval   1951 to 1967

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	0.73	0	----	0	----
February	0.77	0.10	0.02	0	----
March	1.83	1.50	0.12	1.69	0.13
April	2.73	7.24	0.80	8.41	0.84
May	1.26	0.78	0.53	1.20	0.62
June	0.64	0.06	0.58	0.13	0.75
July	0.47	0.01	0.21	0.07	0.37
August	0.37	0.09	0.94	0.03	0.94
September	0.34	0.02	0.06	0.23	-0.11
October	0.57	0.44	0.93	0.24	0.89
November	0.75	0,69	0.59	0.53	0.56
December	0.82	0.37	0.23	0.29	0.43
ANNUAL	11.30	11.28	0.92	12.83	0.90

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   <u>Montreal, Que. (7024400)</u>

Runoff Gauging Station   <u>Chateauguay River (030901)</u>

Record Interval   <u>1921 to 1962</u>

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	0.93	0	----	0	----
February	0.71	0	----	0	----
March	3.28	1.79	0.55	1.87	0.56
April	4.90	9.60	0.48	10.82	0.45
May	1.73	1.32	0.37	1.82	0.47
June	0.81	0.16	0.09	0.25	0.36
July	0.49	0.16	0.08	0.22	0.09
August	0.40	0.02	0.02	0.06	0.06
September	0.35	0.27	0.47	0.10	0.37
October	0.63	0.54	0.65	0.57	0.79
November	1.04	1.08	0.68	1.16	0.75
December	1.00	0.20	0.01	0.22	0
ANNUAL	16.26	15.14	0.42	17.09	0.50

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Fredericton, N.B. (8101600)

Runoff Gauging Station   Shogomoc River (01AK001)

Record Interval   1919 to 1967 (1941 - 1943 missing)

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	1.98	0.09	0.30	0.05	0.52
February	1.22	0.07	0.08	0.07	0.08
March	1.78	1.99	0.75	1.96	0.74
April	7.44	11.36	0.60	11.16	0.59
May	4.73	3.69	0.69	4.01	0.70
June	1.57	0.43	0.65	0.45	0.69
July	0.73	0.28	0.30	0.11	0.43
August	0.40	0.44	0.60	0.15	0.64
September	0.54	0.75	0.54	0.32	0.61
October	1.09	2.39	0.75	1.42	0.78
November	2.38	2.55	0.53	2.12	0.73
December	2.66	0.30	0.59	0.33	0.58
ANNUAL	26.51	24.34	0.71	22.14	0.74

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Sept-Isles, Que. (7047960 & 7047910)

Runoff Gauging Station   Rapides (072201)

Record Interval   1955 to 1967

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0.81	0	----
February	0.37	0	----
March	0.53	0.20	0
April	1.34	3.21	0.56
May	9.92	14.85	0.78
June	6.76	2.17	0.68
July	2.76	0.95	0.43
August	2.81	1.49	0.87
September	3.04	2.40	0.78
October	3.30	2.55	0.75
November	2.74	1.06	0.70
December	2.30	0	----
ANNUAL	36.69	28.89	0.75

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   White River, Ont. (60S9475)

Runoff Gauging Station   White River (02BC004)

Record Interval   1960 to 1967

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0.66	0	----
February	0.45	0	----
March	0.42	0	----
April	1.01	3.92	0.15
May	4.30	8.65	-0.16
June	2.51	0.43	0.55
July	0.96	0	----
August	0.51	0.74	-0.05
September	0.49	1.21	0.13
October	1.11	1.09	0.66
November	1.08	0	----
December	0.87	0	----
ANNUAL	14.35	16.03	0.67

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Fort Simpson, N.W.T. (2202100)

Runoff Gauging Station   Snare River (07SA003)

Record Interval   1950 to 1962

Time	Measured Runoff	Water Balance		Turc	
		Runoff	Correlation Coefficient[a]	Runoff	Correlation Coefficient[a]
January	0.21	0	----	0	----
February	0.18	0	----	0	----
March	0.18	0	----	0	----
April	0.16	0.95	-0.13	0.58	-0.13
May	0.22	3.26	-0.47	2.60	-0.48
June	0.39	0.23	-0.30	0.21	-0.25
July	0.65	0.22	0.66	0.03	0.38
August	0.56	0.11	-0.42	0.03	-0.31
September	0.38	0	----	0	----
October	0.29	0.01	0.05	0	----
November	0.29	0	----	0	----
December	0.25	0	----	0	----
ANNUAL	3.76	4.78	0.10	3.44	-0.04

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Yellowknife, N.W.T. (2204100)

Runoff Gauging Station   Snare River (07SA003)

Record Interval   1950 to 1962

| Time | Measured Runoff (Inches) | Water Balance | |
		Runoff (Inches)	Correlation Coefficient[a]
January	0.21	0	----
February	0.18	0	----
March	0.18	0	----
April	0.16	0.13	-0.04
May	0.22	3.42	0.15
June	0.39	0.05	-0.19
July	0.65	0.02	0.14
August	0.56	0.08	-0.22
September	0.38	0.02	-0.38
October	0.29	0.02	-0.10
November	0.29	0	----
December	0.25	0	----
ANNUAL	3.76	3.73	0.52

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   <u>Fort Chimo, Que. (7112400) & Knob Lake, Que.</u>
(7113520)

Runoff Gauging Station   <u>Baleine (0104001)</u>

Record Interval   <u>1963 to 1967</u>

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0.39	0	----
February	0.24	0	----
March	0.20	0	----
April	0.21	0	----
May	2.15	3.04	0.84
June	8.10	8.87	0.81
July	2.88	1.31	0.69
August	2.49	1.77	0.48
September	2.32	1.64	-0.16
October	2.05	1.35	-0.17
November	1.40	0	----
December	0.74	0	----
ANNUAL	23.18	17.97	0.99

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Duncan, B.C. (1012570)

Runoff Gauging Station   Bings Creek (08HA016)

Record Interval   1962 to 1966

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	7.82	5.98	0.41
February	4.81	2.57	0.63
March	3.40	1.95	0.83
April	1.43	0.42	0.46
May	0.78	0.08	0.66
June	0.30	0	----
July	0.20	0	----
August	0.17	0	----
September	0.17	0	----
October	0.75	1.73	0.98
November	3.73	5.58	0.75
December	6.12	6.74	0.54
ANNUAL	29.69	25.06	0.86

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Abbotsford, B.C. (1100030)

Runoff Gauging Station   Sumas River (08MH029)

Record Interval   1953 to 1967

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	4.46	7.85	0.67
February	3.76	6.05	0.70
March	2.98	3.89	0.59
April	2.27	1.75	0.12
May	1.42	0.84	0.04
June	0.93	0.21	0.18
July	0.79	0.01	0.62
August	0.75	0.09	-0.01
September	0.65	0.70	0.63
October	1.13	4.45	0.51
November	2.56	7.23	0.66
December	3.94	7.82	0.57
ANNUAL	25.6	40.9	0.41

[a] Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   <u>Deer Park, B.C. (1142400)</u>

Runoff Gauging Station   <u>Deer Creek (08NE087)</u>

Record Interval   <u>1959 to 1967</u>

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	0.19	0.91	0.15
February	0.17	1.46	-0.11
March	0.26	1.71	-0.47
April	1.28	0.07	0.39
May	4.36	0.07	0.92
June	5.40	0	----
July	1.19	0	----
August	0.35	0	----
September	0.31	0	----
October	0.34	0	----
November	0.28	0.28	0.21
December	0.21	0.74	0.14
ANNUAL	14.31	5.23	-0.23

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station   Vernon, B.C. (1128554)

Runoff Gauging Station   BX Creek (08NM020)

Record Interval   1961 to 1971

| Time | Measured Runoff (Inches) | Water Balance | |
		Runoff (Inches)	Correlation Coefficient[a]
January	0.08	0.26	-0.35
February	0.08	0.90	0.01
March	0.17	1.79	-0.48
April	0.86	0.51	0.73
May	2.05	0.07	0.17
June	1.24	0	----
July	0.39	0	----
August	0.20	0	----
September	0.15	0.01	0.09
October	0.15	0	----
November	0.14	0.02	0.38
December	0.10	0.38	0.26
ANNUAL	5.60	3.92	0.48

[a]Computed runoff correlated with corresponding values of measured runoff

Meteorological Station <u>Terrace, B.C. (1068130)</u>

Runoff Gauging Station <u>Zymagotitz River (08EG011)</u>

Record Interval <u>1961 to 1967</u>

Time	Measured Runoff (Inches)	Water Balance	
		Runoff (Inches)	Correlation Coefficient[a]
January	1.75	2.89	-0.12
February	1.95	6.90	0.14
March	1.96	4.46	0.05
April	3.78	5.56	0.48
May	9.89	0.16	-0.61
June	16.37	0	----
July	13.35	0.09	0.78
August	9.09	0.06	0.49
September	7.75	1.51	0.88
October	10.32	9.07	-0.21
November	4.64	3.65	0.81
December	2.50	3.25	0.07
ANNUAL	83.37	37.61	0.06

[a]Computed runoff correlated with corresponding values of measured runoff

A P P E N D I X   C

OUTLINE OF CALCULATION PROCEDURE FOR WATER BALANCE

1. Set the growing season and upper and lower soil zone moisture capacities.

2. Initialize moisture conditions. If one can not assume soil is at field capacity then discarding the first years calculations will remove most of the error in the assumed moisture conditions.

3. Calculate the potential evaporation from the Christenson-Mehta Equation and sum the precipitation amounts recorded in the ten day period[a].

4. If the average temperature is below freezing then consider precipitation as snow and add the sum to any previous snow accumulation. Bookkeeping of snowfall is done with water equivalent values. Set AE equal to zero and proceed to next period (Step 3).

5. If average temperature is above freezing check for any snow remaining and if so determine the snowmelt (Equation 9). Add the snowmelt to precipitation for the ten day period.

6. Divide precipitation and PE by two so that precipitation can be added in two storm events.

7. Calculate the moisture deficits in each soil zone.

8. Add as much of the precipitation to the upper zone as this soil zone will hold.

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[a]For last period in each month the radiation values in Christenson-Mehta Equation are determined for the number of days left in the month (ten or eleven for all months but February). Precipitation and PE are then calculated for this number of days to keep monthly summations separate.

9. Any remaining precipitation is added to the lower zone.

10. If the moisture capacity of the lower zone is exceeded then the
    excess precipitation is runoff.

11. Determine soil moisture in each zone after precipitation has been
    added.

12. If the ten day period under consideration is outside the growing
    season apply PE only to the upper soil zone and at the PE rate.
    If the ten day period is within growing season then any remaining
    potential evaporation is applied to moisture in the lower zone at
    a reduced rate (Thornthwaites soil moisture retention tables -
    Equation 8 in report). Sum the evapotranspiration from each soil
    zone.

13. Reduce the soil moisture in each soil zone by the amount of
    evaporation taken from each.

14. Repeat from Step 7 if the second half of the ten day precipitation
    and PE has not been used.

15. Sum the evaporation from the two step to get the ten day values.

16. Return to Step 3 for next ten day period.