Precipitation in Northern Quebec and Labrador: An Evaluation of Measurement Techniques

B. F. FINDLAY[1]

ABSTRACT. A testing of published maps of precipitation normals for a continental subarctic area using hydrological techniques suggests a systematic annual error of 6 inches (152 mm.) The scope of the analysis is subcontinental, but point values for a central climatological station are used to elucidate indirect techniques available for the adjustment of precipitation gauge data. These methods include snow surveying, stream gauging, interception and evapotranspiration calculations and watershed rain gauge networks. All hydrological parameters are characterized by inherent errors in measurement and short periods of record. Consequently, the results of this investigation should be considered speculative.

RÉSUMÉ. *Les précipitations dans le nord du Québec et au Labrador: évaluation des techniques de mesure.* La vérification, au moyen de techniques hydrologiques, des cartes publiées de hauteur moyenne des précipitations pour une région continentale subarctique révèle une erreur annuelle systématique de 6 pouces (152 mm). L'analyse a une portée subcontinentale, mais on utilise les valeurs d'une station climatologique centrale pour éclairer les techniques indirectes servant au rajustement des données pluviométriques. Ces méthodes comprennent les mesures d'épaisseur du manteau nival et des débits fluviaux, le calcul de l'interception et de l'évapotranspiration, et l'établissement de réseaux pluviométriques de bassin. Tous les paramètres hydrologiques se caractérisent par des erreurs inhérentes de mesure et par de courtes séries de données. Conséquemment, les résultats de cette enquête doivent être considérés comme spéculatifs.

РЕЗЮМЕ. *Выпадение осадков в Северном Квебеке и Лабрадоре — оценка методики измерения.* Проверка гидрологическими методами опубликованных карт нормальных осадков в континентальном субарктическом районе указывает на существование систематической годовой погрешности в 152 мм. Анализ охватывает субконтинентальный район, но в то же время применяются отдельные измерения для центральной климатологической станции с целью разъяснения имеющейся косвенной методики обработки данных, полученных при помощи осадкомеров. Эта методика включает снежную съемку, наблюдения над реками, расчеты по задержанию и эвапотранспирации осадков, а также применение системы дождемеров на водоразделах. Все гидрологические параметры характеризуются неизбежными погрешностями в измерении и кратковременностью наблюдений. В силу этого, результаты данных исследований следует считать предварительными.

INTRODUCTION

The surface of Quebec and Labrador lying north of 50° latitude and covering an area of 1,450,000 km^2. is exceedingly rough and has been accessible only in recent times. For economic and administrative reasons an accurate precipitation map for the area is desirable. Recent precipitation maps pertinent to this area have been produced by the Canada Department of Transport (1967) and by

[1]Meteorological Branch, Canada Department of Transport.

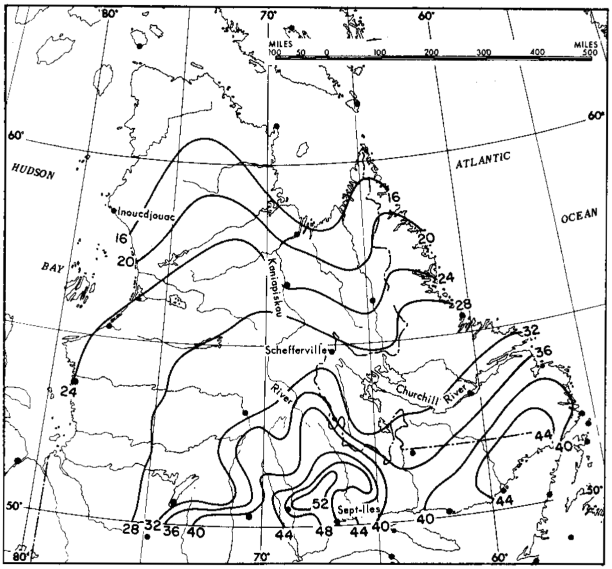

FIG 1. Annual precipitation (inches). (After Gagnon and Ferland 1967). Dots show positions of permanent meteorological stations.

Gagnon and Ferland (1967). However, within this entire area there are only 23 permanent meteorological stations with data suitable for analysis and most of these are coastal stations. Moreover, the period of record is generally short. These maps were based upon the normal period 1931 to 1960, and they appear similar in overall pattern although the positioning of isolines varies in detail. Considerable skill has been employed in the construction of each of these maps, but since those of Gagnon and Ferland are accompanied by an explanatory text and, in addition, show the amount of residual precipitation following run-off, their study has been selected for particular discussion here (see Figs. 1 and 2).

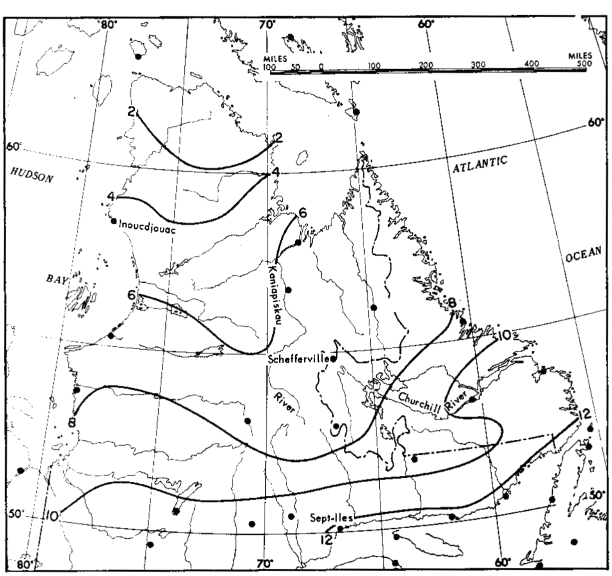

FIG. 2. Annual residual precipitation after run-off (inches). (After Gagnon and Ferland 1967 — Déficit d'Ecoulement). Dots show positions of permanent meteorological stations.

The processing of climatological data has been streamlined in recent years. However, we still must contend with errors produced by short period and intermittent records, the subjective positioning of isolines on small-scale provincial or national maps, scattered sampling stations, imperfect instruments and sampling techniques, as well as observational and recording errors. This paper is particularly concerned with systematic errors perpetrated by our sparse station network, the selection of representative samples, and instrumentation. Some of our greatest problems in this respect were experienced in Labrador-Ungava.

CLIMATE

Most of the area experiences a continental climate, for the land surface rises quickly away from the sea on all sides of the peninsula and moderating characteristics of marine air masses are adjusted to comply with inland temperature and moisture régimes. Marine influences do, however, occur even in the remote interior. Temperatures rarely fall below −45°C. or rise above +25°C. Precipitation varies from over 1,300 mm. a few kilometres north of Baie Comeau, to less than 400 mm. in the northwest. Summers are cool and skies are cloudy from July to January in interior locations. Once Hudson Bay becomes frozen over in January, cool, dry air masses can enter the area without much modification. Hare (1951) has shown that most precipitation is cyclonic in origin and is brought from the west and southwest. Occasionally, however, a northeasterly circulation brings mid-winter rain and fog. The high frequency of atmospheric disturbances is notable and over the whole peninsula precipitation occurs often; the amount of fall during each event decreases from southeast to northwest with the exception of local orographic variation. On the average, winds are northwesterly and moderate in all seasons.

PROBLEMS IN MAPPING

As there are only 23 suitable point values available within this large, heterogeneous area, the task of interpretation and interpolation will be readily recognized. Moreover, the period and length of record varies considerably from station to station. The plotting of isohyets on maps is largely based upon elevation variation, for our knowledge of slope and aspect effects is limited. The physiography has been mapped at a scale of 1:500,000, but published versions are available only at smaller scales (Hare 1959). Gagnon and Ferland (1967 p. 11) note another vexing problem:

> Total precipitation diminishes toward the north whereas the variability increases. Physically, this means that for an observation period of equal length, the means are known with greater precision in the south than in the north because the probable error of the mean is directly related to the variability. [Translation.]

In the north a longer period of record is necessary to realize a normal value. While Gagnon and Ferland constructed a rainfall variability map, one was not attempted for snowfall, for the preliminary values computed were too large in the north to be significant when considering the short period of record. During 17 years of measurement at Inoucdjouac (Port Harrison), for example, the annual snowfall varied from 182.7 inches (4,641 mm.) to 27.4 inches (696 mm.).

PRECIPITATION MEASUREMENT PROCEDURES

Rainfall is measured in Canada with a cylindrical gauge 9 cm. in diameter which is emptied daily or every 6 hours depending upon the type of station. The gauge is mounted unshielded in an open area with the orifice 30 cm. above the ground. Inaccurate measurements have been experienced in rough terrain and during windy periods (see McKay 1965).

Two methods are commonly used to measure snowfall. At principal stations the Nipher shielded snow gauge has been in official use since 1960. At all other stations newly fallen snow is probed with a ruler, and the water equivalent determined by dividing by ten. The inadequacies of ruler measurements have been known for many years and the gauge is an effort to increase our knowledge of this extremely variable parameter. Wind tunnel tests show that the Nipher shield inhibits a considerable amount of the turbulent air flow which may occur near the gauge orifice. It is in this respect superior to the Alter shield, often used on storage gauges; but snow does pile up on the upper horizontal surface and may subsequently blow into the gauge. The receptacle is cylindrical with a 12.7 cm. orifice, mounted 160 cm. above the snow surface. The catch is melted and the water equivalent measured on the same schedule as for rainfall. Less than 0.005 inches (0.125 mm.) is not a recordable value. Authorities have reported catch errors greater in magnitude than those for rain gauges, but less than those for unshielded gauges.

Using the ruler method, a representative site near the station must be selected. This is often very difficult since most stations are located near airstrips which are necessarily in very exposed situations. The assumed density of 0.10 for newly fallen snow in a climatically heterogeneous country like Canada is somewhat fallacious, and authors such as Potter (1965) have attempted to introduce modifications. Potter simultaneously compares the water equivalent values from the two methods and notes in Labrador-Ungava that immediately north of the St. Lawrence River the differences are small, but:

> there then appears to be an abrupt change near the height of land as illustrated by the ratios of 0.72 at Nitchequon (ratio of gauge to ruler water equivalent) and 0.77 at Indian House Lake . . . Between the height of land and the shores of Hudson Bay, there are no reporting stations and, unfortunately, useful data were not available from the stations on the east shore of Hudson Bay (Potter 1965, p. 10).

Potter's results imply, for example, that the snowfall water equivalent at Schefferville as calculated by the ruler method is approximately 25 per cent too high. Whereas the density of newly fallen snow in this region may well be less than 0.10 on many occasions, the accuracy of Potter's working data is reduced by:

a) the difficulty in selecting representative sites for ruler measurements, b) the problem of estimating accumulation during windy periods, c) good evidence of gauge catch errors in upland and exposed regions, d) the rigid 6 hour observation schedule (now modified) which fails to document the accumulation and movement of snow on the ground and which allows *traces* to be noted every six hours during light snowfall when the total fall over a longer period could be assigned a value.

Moreover, the watershed yield investigation described below does not indicate such a surplus. In fact, it suggests that for some places the ruler method, biased and unscientific as it may be, is (fortuitously perhaps) a better estimate than the gauge receipts.

INDIRECT EVALUATION OF SNOWFALL

In regions where mid-winter thaws are infrequent or of short duration, the snow sampler can be a useful tool to evaluate the performance of a precipitation gauge. Most samplers are elongated tubes which cut a vertical section through the pack which is then weighed and the water content deduced. A late winter sample gives a cumulative seasonal precipitation value which includes rainfall re-frozen in the snow pack. Sampling errors can be sizable during windy periods, during periods when there is a great thermal difference through the pack profile which causes the sample to jam in the tube, and on occasions when inexperienced surveyors choose sampling sites and handle the equipment. Useful evaluations of samplers have been prepared by Work *et al.* (1965) and McKay and Blackwell (1961).

TABLE 1. Snow depth and water storage in various cover types, Schefferville 1965.

Cover class	*Open lichen woodland scrub, lichen scrub*	*Close lichen woodland*	*Open lichen woodland*	*Lakes and swamps*	*Total*
Per cent watershed	45	19	12	24	
Mean depth (cm.)	114	135	140	53	
No. of samples	138	67	57	65	327
Water equivalent (cm.)	30	28	39	16* (13)	
No. of samples	43	26	25	11	105
Water equivalent of white ice (cm.)				10	
Interception (cm.)		6			
Sublimation (cm.)	3	3	3	3	
Weighted synthetic precipitation (cm.)					32.6
Accumulated Nipher Gauge (cm.)					23.8

*16 cm. is the arithmetic mean of 11 samples. The value 13 cm. is calculated from the following formula (Shaw 1964). As the formula utilizes a greater number of survey samples, the 13 cm. value is considered preferable.

$$\rho_s = \frac{a_w \rho_w - a_i \rho_i}{a_s}$$

Where: ρ_s is the snow density; ρ_w is the water density; ρ_i is the ice density; a_w is the height of water in a drill hole; a_i is the ice thickness; a_s is the snow depth

At Schefferville in March 1965 a traverse 19 miles (30.6 km.) in length and generally perpendicular to the wind was undertaken by two parties with snow samplers (Adirondack and Mount Rose types). All principal vegetation and slope types within the vicinity were sampled (Table 1). According to Hare (1959), and from personal observation, the landscape features near Schefferville are not greatly different from widespread areas of Labrador-Ungava.

The studied area was a watershed of 35 $km.^2$ which drained into Knob Lake, and thence by irregular stream courses to the Kaniapiskau River. The winter precipitation was estimated by averaging the amount of snow water within each vegetation type and summing the weighted values on an areal importance basis. The forest values were corrected for estimated interception losses and all areas were given a small increment to offset sublimation losses. Particular attention was given to the lakes in conjunction with an ice survey. It was possible to estimate the amount of snow which had been converted to white ice. A comparison of the synthetic value with the cumulative Nipher gauge figure at the Schefferville station suggested that the overall gauge catch deficiency was about 37 per cent. After an inspection of snow survey and gauge data for other winters, it became apparent that the catch error was directly related to the seasonal wind speed. The synthetic precipitation value was subjected to further hydrological analysis, and it was found that it was a much more realistic estimate than the gauge provided.

KNOB LAKE RAIN GAUGE NETWORK

Six standard rain gauges were set out in various locations within the watershed during 1965. The gauges were read weekly and after a 10-week period it was calculated, by measuring Thiesson polygons, that the watershed precipitation was 6 per cent higher than that indicated at the main station. All gauges were placed in well-exposed, physiographically different locations. The literature indicates that the overall catch deficiency corresponding with the mean wind speed experienced at Schefferville is about 10 per cent (McKay 1965). The conclusion is that rainfall is undermeasured at Knob Lake by 15 to 16 per cent. Again this supposition was checked by hydrological techniques.

WATERSHED YIELD

The exchange of water between the atmosphere, land surface and oceans is roughly cyclical, and can be evaluated in a manner similar to an accounting balance sheet. The continuum equation effectively describes the balance within a controlled area, i.e. a tight watershed.

$$P = R + ET + \Delta GW + \Delta SM$$

where:

P is the precipitation
R is the run-off
ET is the evapotranspiration
ΔGW is the ground water storage change
ΔSM is the soil moisture and surface water storage change

The ground water and soil and surface detention terms fluctuate seasonally, but usually approach equilibrium at the end of a hydrological year. If the average annual precipitation, run-off, and evapotranspiration are used for a study, the storage terms can be safely omitted. Thus any of the three parameters can be calculated by knowing the other two. Streamflow is usually the unknown factor. For example, Cavadias (1961) estimated the mean annual flow for the Koksoak, Rupert, Romaine and St. Maurice Rivers from precipitation figures and estimates of evapotranspiration (Thornthwaite technique). From existing run-off records and the Turc formula (Turc 1954) he deduced that evapotranspiration calculations were too high. His technique assumed precipitation to be the stable parameter. However, flow records from the Churchill and Outardes Rivers which have been collected for some time now indicate a surprisingly large discharge when compared with contemporary precipitation figures and it becomes obvious that the error cannot be attributed entirely to evapotranspiration estimates. Hare (1966) has argued from radiation data and signs of dessication on trees that evapotranspiration in Labrador-Ungava takes place at the potential rate. Even though the widespread lichen surface effectively arrests the upward movement of water vapour from the soil, isolated spruce clumps transport water to the atmosphere at an excessive rate. He points to the abundance of heavy cumulus clouds in the summer sky as evidence that a considerable amount of solar energy is available for atmospheric heating as well. Bruce and Weisman (1967) have produced *Provisional evaporation maps of Canada*. Evaporation here means free water or reservoir evaporation. However, the authors relate this to potential evapotranspiration:

> Although there is still some controversy, most recent work suggests that potential evapotranspiration is approximately equal to 'free water' evaporation from small lakes and reservoirs since both are limited by radiative and sensible heat exchanges with the atmosphere (Bruce and Weisman 1967, p. 1).

Evaporation was calculated from class A pan data, the Penman equation at radiation stations and Mateer's formula at sunshine stations. These established procedures are explained in detail by the authors. As with many authorities on this subject, the effect of vegetation type on potential evapotranspiration was considered minimal. The Labrador-Ungava portion of the map is shown in Fig. 3.

By way of comparison, Gagnon and Ferland's map of residual precipitation (Fig. 2) is based upon watershed yield principles and, accordingly, is an account of average annual actual evapotranspiration. The concept is based upon the Turc formula.

$$E = \frac{P}{\left(0.9 + \frac{P^2}{L(t)^2}\right)^{1/2}}$$

where: $L(t) = 300 + 0.05t^3$

t is the mean annual air temperature (°C.)

P is the mean annual precipitation (mm.)

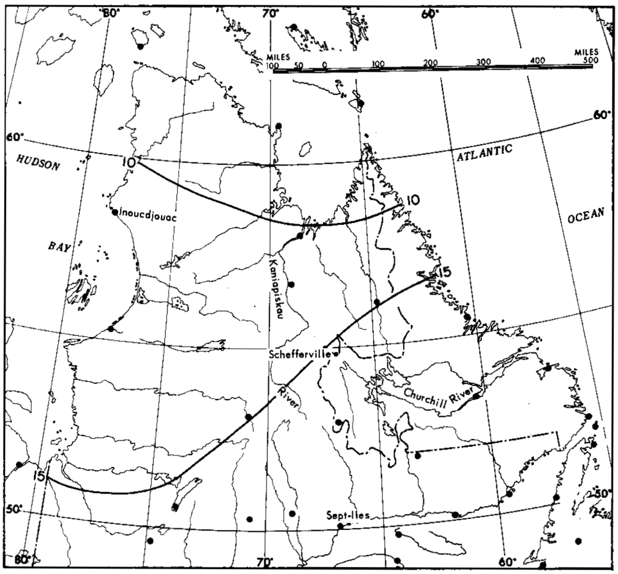

FIG. 3. Annual free water evaporation (inches). (After Bruce and Weisman 1967). Dots show positions of permanent meteorological stations.

The formula was developed following a statistical analysis of precipitation — run-off relationships in 254 watersheds in all world climatic regions. Cavadias (1961) reports good results from this formula on a national basis. Its usefulness is, however, governed by the accuracy of the precipitation values utilized.

If Hare is correct in stating that evapotranspiration in Labrador-Ungava takes place at approximately the potential rate, it would seem that Bruce and Weisman's map should represent the actual average conditions of water vaporization. On the other hand, if evaporative opportunity is not available and radiative and sensible energies are directed toward atmospheric and soil heating, the true value may be closer to that deduced by the Turc formula. Streamflow data may assist in answering this question.

RUN-OFF IN NORTHERN QUEBEC AND LABRADOR

The stream-gauging record is short and of an intermittent nature in much of the region. However, since a run-off measurement indicates the average flow throughout the entire upstream area, it has the stability and greater weight of an areal as opposed to a point value. Moreover, the accuracy of a good gauging station is said to be within approximately 5 per cent, although winter flow conditions are difficult to evaluate. Thus a run-off map can be constructed with greater confidence from a shorter record period than with precipitation. Nevertheless, the map presented here can only be considered tentative, particularly with respect to the position of the northerly isolines (Fig. 4). This map was constructed from streamflow records published by the Canada Department of Energy, Mines and Resources, and the Québec Ministère de Richesses Naturelles. The specific reports are listed in the bibliography. Run-off does not decline in absolute value toward the northwest at the same rate as precipitation and evapotranspira-

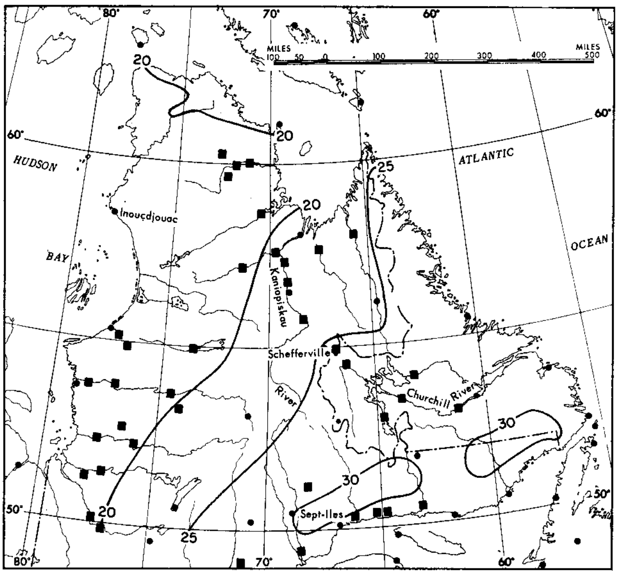

FIG. 4. Annual run-off (inches). Compiled from stream gauge records published by the Canadian and Quebec Governments (see bibliography). Dots show positions of permanent meteorological stations and squares show hydrometric stations.

tion. This probably is a result of the increasing importance of direct run-off which is promoted by frozen ground and the rapid release of snow water to the streams during late spring.

THE WATER BALANCE

To compute a water balance for the Quebec-Labrador peninsula the isopleths of the precipitation, run-off and the two evaporation maps were planimetered. The results are presented in Table 2. Initially it would appear that the Turc value is within the correct order of magnitude. However, it is interesting to note the similarity of some of the mean areal values to the mean point values as measured at the geographically central station Schefferville. The average precipitation at Schefferville since 1948 has been 29.40 inches (747 mm.). Run-off from both small (35 km.^{2}) and large (19,070 km.^{2}) watersheds averages 24 to 25 inches (610 to 635 mm.). Evaporation has been measured for several years from a free water surface (class A pan and black porous disc atmometer), and from the lichen surface within the forest (simple evapotranspirometer). There is a considerable difference between the land and water surface values (Findlay 1966). The com-

TABLE 2. Average Annual Hydrological Parameters

Mean precipitation	28.27 inches (718 mm.)
Mean run-off	23.09 inches (486 mm.)
Mean actual evapotranspiration	7.48 inches (Gagnon and Ferland) (189 mm.)
Mean potential evapotranspiration	13.72 inches (Bruce and Weisman) (348 mm.)

$\overline{P}-\overline{R}=5.18$ inches (132 mm.)

puted Turc value corresponds closely with the measured land value. However, since 25 per cent of the area is a free water surface, the Turc figure is too low. Nebiker and Orvig (1958) noted that since the lichen is a non-vascular plant it probably does not transpire, and in effect its morphology resembles a mulch, which inhibits soil evaporation. This is a plausible explanation for the difference between the two evaporation figures. A realistic actual evapotranspiration estimate for the Schefferville area would be about 11 inches (280 mm.) and it is contended on the basis of vast areas of physiographic and phytogeographical similarity that this would also be a reasonable average value for Labrador-Ungava.

Therefore, on a water yield basis, the average precipitation could be 34 inches (864 mm.), or 6 inches (152 mm.) greater than the existing records would indicate. Inadequacies of present precipitation measurement practices can give rise to systematic errors, particularly in wind-swept locations where most of our climatological stations are situated. In addition, we have very limited information on the precipitation régime in remote highland areas such as the Torngat Massif, the Kaniapiskau Massif, the Mealy Mountains and the Laurentide Massif north of Sept-Iles and Baie Comeau. In view of our limited areal knowledge of the phases of the hydrological cycle, and our rather crude methods of measurement and estimation, the results presented here must be regarded as being more conceptual than absolutely accurate. Therefore, it is not considered feasible to present a precise precipitation map at this time.

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