COMPARISON OF WATER EQUIVALENT OF SNOW COVER DETERMINED FROM AIRBORNE MEASUREMENTS OF NATURAL GAMMA RADIATION AND FROM A SNOW COURSE NETWORK

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INTRODUCTION

Natural gamma radiation emitted from the ground can be measured with a small portable detector on the surface or with high-sensitivity equipment from an airborne platform. The count rate of the detector decreases with height and depends on the mass of air between the ground and the detector. Since water is an effective absorber of gamma radiation, measurements of the radiation before and after the ground is covered with snow can be used to calculate the water equivalent of the snowpack.

The first experiments using this technique, were carried out in the USSR in 1963 (Kogan et al., 1965). Snow surveys over large areas of the Soviet Union have been reported and evaluated, up to 1969, by Vershinina and Dimaksyan (1969). Dmitriev et al. (1973) report that gamma-ray surveys are now being carried out in the USSR on an operational basis to map the water equivalent of the snowpack. Research in this field has also been done in Norway (Dahl and Ødegaard, 1970) and the U.S., (Peck et al., (1971)

During the winter of 1972 - 1973 airborne gamma-radiation surveys were carried out over Southern Ontario using a spectrometer flown in a Short Skyvan aircraft, operated by the Geological Survey of Canada (GSC). Each survey covered 1850 km (Figure 1). The flight lines were laid out approximately perpendicular to the average snow-water equivalent isolines, which are strongly influenced by the Great Lakes, and covered as many existing snow courses as possible. Thirty-nine snow courses were located on or near the flight lines.

In this paper the data from these courses are compared with the results of the airborne gamma-ray spectrometer surveys. Information on all ground measurements taken by federal and provincial agencies, operating the snow course network, is given in a report by Loijens and Grasty (1973).

An evaluation of the accuracy of the airborne method using ground measurements from experimental snow courses, laid out under the flight track after the survey lines were established, has been given by Grasty et al. (1974).

THEORY

The relation between the detector count rate N and the flying height H for an infinite homogeneous half-space emitting mono-energetic gamma radiation is given by Godby et al., (1952).

$$N = N_o E_2 (\mu_a H) \qquad (1)$$

E_2 is the exponential integral of the second kind, μ_a is the linear absorption coefficient of air at the energy concerned and N_o is the count rate at ground level. N_o is dependent on the radioactive concentration and absorption coefficient of the ground, soil moisture content, and various physical parameters of the detector system.

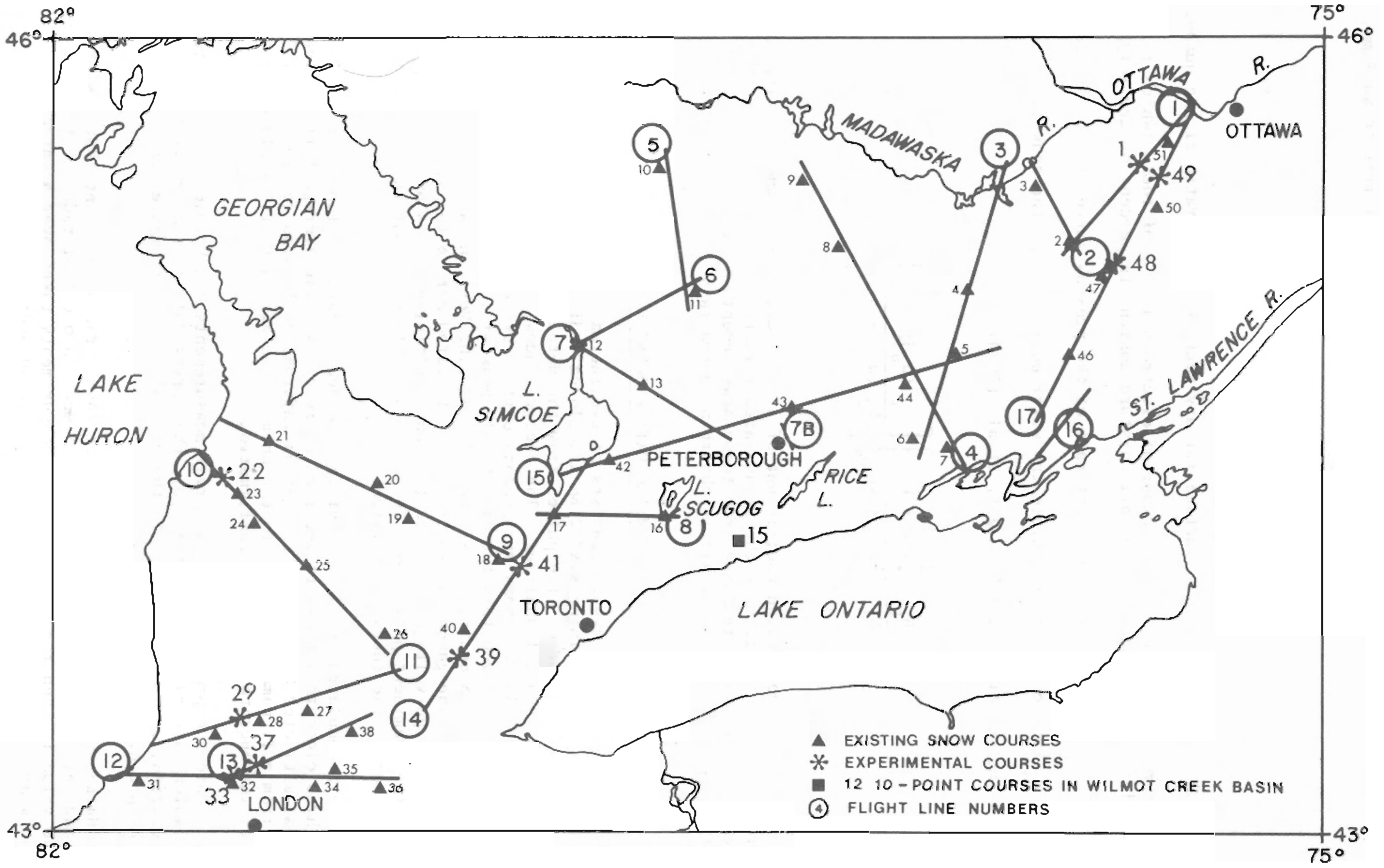

Figure 1. Flight lines and snow courses.

Kogan et al. (1969) give the following relation of count rate to soil moisture:

$$\frac{N_o}{N_d} = \frac{100}{100 + k\omega} \qquad (2)$$

where N_d is the count rate at the surface for dry rock, k is the ratio of the number of electrons in 1 g of water to the number of electrons in 1 g of rock, (which for most rock material is 1.11), and ω is the soil moisture content in percent of dry weight.

The ratio of the detector count rate of the presnow survey N_{ps} to the snow cover survey N_s can be used to calculate the water equivalent of the snow layer according to the following equation given by Grasty et al. (1974):

$$\frac{N_{ps}}{N_s} = \left[\frac{100 + k\omega_s}{100 + k\omega_{ps}}\right]\left[\frac{E_2\ (\mu_a H)}{E_2\ (\mu_a H + \mu_w D)}\right] \qquad (3)$$

The linear absorption coefficient of air was determined experimentally over a uniform radioactive test strip in the Ottawa area (Grasty, 1973). The linear absorption coefficient of water was calculated from these measurements because water is 1.11 times as effective as the same mass of air in absorbing gamma-rays.

AIRBORNE GAMMA-RAY SPECTROMETER SYSTEM AND DATA PROCESSING

The GSC detector system consists of two thermally-insulated boxes to minimize spectral drift, each containing six 22.86 x 10.16 cm sodium iodide (thallium activated) crystals, maintained at 38°C. The pulses from the detectors are sorted in four energy windows using a 128-channel analyzer. The energy windows are: *potassium* (1.37 - 1.57 MeV) which monitors the 1.46 MeV gamma-ray photons emitted by potassium-40; *uranium* (1.66 - 1.86 MeV) which monitors the bisumth-214 peak at 1.76 MeV; and *thorium* (2.41 - 2.81 MeV) which monitors thallium - 208 at 2.62 MeV; and an *integral count window* (0.41 - 2.81 MeV). The gamma-ray spectrum is calibrated before the start of each survey by adjusting the high-voltage supply to the photo multiplier tubes by monitoring the position of the prominent potassium - 40 peak. Normally no adjustments of the spectrum are required during the course of a flight.

The accumulated integral count is recorded on magnetic tape every 0.5 s while that from the three elements windows is recorded every 2.5 s. The average terrain clearance from a radar altimeter and Doppler navigation information is also recorded every 2.5 s. The image from a TV camera, mounted in the nose of the aircraft, is displayed on a screen in front of the operator for track confirmation.

Before the presnow and snow survey measurements can be used to calculate snow-water equivalent according to equation (3), the survey data must be corrected for *background radiation*, *Compton scattering* in the crystals, and differences in the *density of air* for the presnow and snow survey.

Background radiation originates from cosmic radiation, contributions from the aircraft and its equipment, and bismuth-214, a decay product of radon in the air. One background value is used for each line from measurements taken over a large lake, before the start of each flight and from values found over lakes along the line.

A fraction of the high energy photons impinging on the detectors are incompletely absorbed due to the finite size of the detectors and appear as counts in a lower energy window. The fraction of counts in a higher energy window that appears in a lower energy window is known as the Compton scattering coefficient or stripping ratio. The Compton coefficients α (uranium counts/thorium count = 0.35), β (potassium counts/thorium count = 0.33, and γ (potassium counts/uranium count = 0.56) have been determined experimentally by using uniform radioactive slabs of known composition (Grasty and Darnley, 1971).

Background and stripping corrections are carried out using the following equations:

$$Th_c = Th - Th_b \tag{4}$$

$$U_c = U - U_b - \alpha \, Th_c \tag{5}$$

$$K_c = K - K_b - \beta \, Th_c - \gamma \, U_c \tag{6}$$

where Th_c, U_c and K_c are the corrected thorium, uranium and potassium count rates; Th, U and K the uncorrected total counts Th_b, U_b and K_b the background counts.

Because the count rate of the detector at the flight height H_s depends on the mass of air between the ground and the detector, the data must be corrected for temperature and barometric pressure. For this survey only temperature corrections have been made. The effective flying height at 273°K was calculated from

$$H_e = H_s \frac{273}{T} \tag{7}$$

where T is the absolute air temperature in °K registered by a thermometer outside the aircraft. The count rate is adjusted to the nominal survey height of 150 m using an exponential function with parameters derived from flights over a uniform test strip.

A coordinate position was assigned to each data point using the Doppler navigation information and radiation profiles were plotted for visual checking of the data. However, each data point, representing a length of 135 m on the ground at an aircraft speed of 192 km h^{-1} cannot be used reliably to calculate the snow-water equivalent due to counting statistics. By accumulating counts over 16 km good counting statistics are obtained (Table I). Errors introduced by not duplicating the flight track also decrease with increasing line length.

TABLE 1 Average, corrected ground radiation at the 150 m level

Survey	Average Radiation (counts/5 min)(*)		Statistical Error (%)	
	Integral	Potassium	Integral	Potassium
Presnow	236,985	21,245	0.2	0.7
January	157,110	12,055	0.3	0.9
February	202,783	15,430	0.2	0.8

(*) A 5 min interval represents a distance of 16 km at a speed of 192 km h^{-1}

SNOW COURSE DATA

Snow-water equivalent is measured in a similar way on all courses, although the number of sample points varies. The Ontario Ministry of Natural Resources (OMNR) and the Ontario Ministry of the Environment (OME) operate 10-point courses covering a length of 275 m (900 ft) while Ontario Hydro (OH) courses cover a total length of 900 m (3,000 ft, 31 points). Snow observations by the Canals Branch of the Department of Indian and Northern Affairs (INA) cover a length of 600 m (2,000 ft, 21 points). The Federal sampler (Ø = 3.77 cm) is used by OMNR and OH; the Meteorological Services of Canada (MSC) (Ø = 7.05 cm) by OME; and INA uses a sampler of its own design.

All courses are being surveyed twice monthly, on the 1st and 15th, except for the INA courses which are measured once each year in late winter. The airborne surveys were planned to coincide with the dates on which the snow course measurements were taken. However, weather conditions did not always permit flying; especially, during the January survey, lengthy delays were incurred due to adverse weather conditions and snow squalls off the lakes. The actual dates on which the aerial survey was carried out are given in Table 2 and the courses which were used for the comparison of determinations are listed in Table 3. Precipitation data from nearby climatological network stations of the Atmospheric Environment Service were used to adjust the snow course measurements to the date of the airborne survey.

TABLE 2 Airborne survey dates of flight lines

Presnow Survey 1972		Snow Surveys 1973			
Date	Lines	Date	Lines	Date	Lines
October 31	1-7	January 9	1-7	February 13	1-7B
November 1	7B-13	13	7B-12	14	8-12
3	14	17	13-17	16	13-17
5	15-17				

RESULTS

A detailed evaluation of the natural gamma-ray spectrometer technique for measuring the snow-water equivalent by Grasty et al. (1974) showed that the root mean square error between potassium window and ground data was 1.2 cm compared to a value of 1.7 cm for the integral airborne data. Grasty's et al. potassium results, with and without soil moisture correction, are shown in Figure 2. The effect of soil moisture on the calculated snow-water equivalent is well illustrated in Figure 2 and Table 4. The increase in soil moisture between the fall and January survey corresponds to an equivalent water layer of 1.4 cm on the soil surface. It is also interesting to note that the moisture content of the soil continues to increase and by the time of the February survey the difference is 2.2 cm.

The ground measurements and the airborne results over the nearest 16-km line section are listed in Table 5. Potassium window results are plotted in Figure 3. Soil moisture values for correction of the airborne measurements, according to equation (3), are given in Table 6.

Soil samples taken along the existing snow courses showed a large variation in moisture content (Loijens and Grasty, 1973). The values in Table 6 reflect the general increase during the winter and are consistent with the results from experimental courses (Grasty et al., 1974).

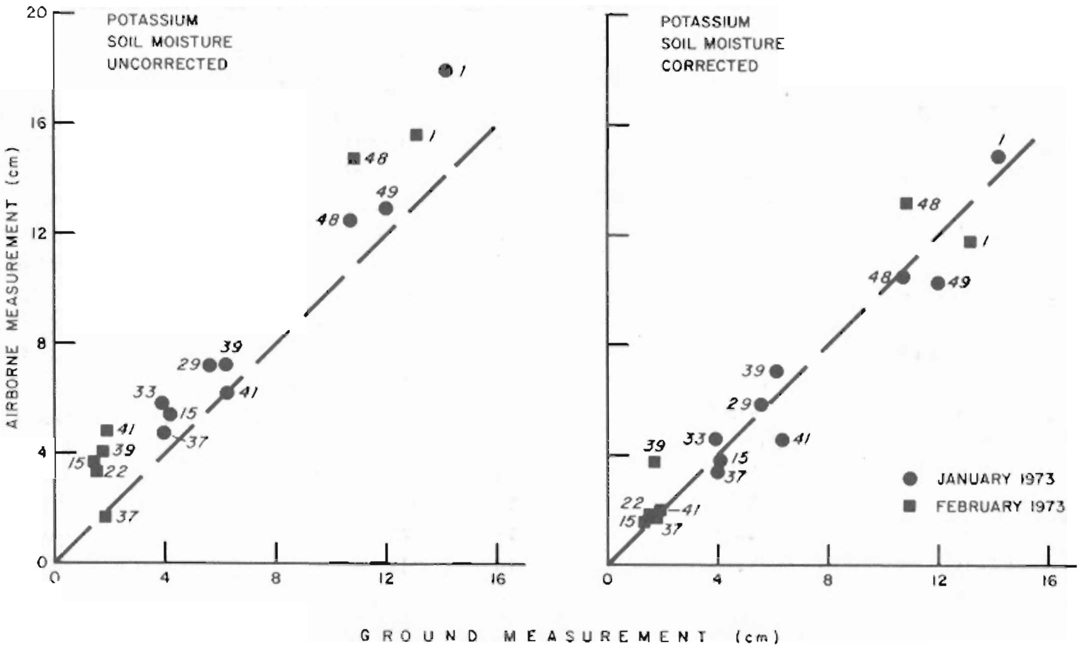

Figure 2. Airborne vs. ground measurements of snow-water equivalent on experimental courses.

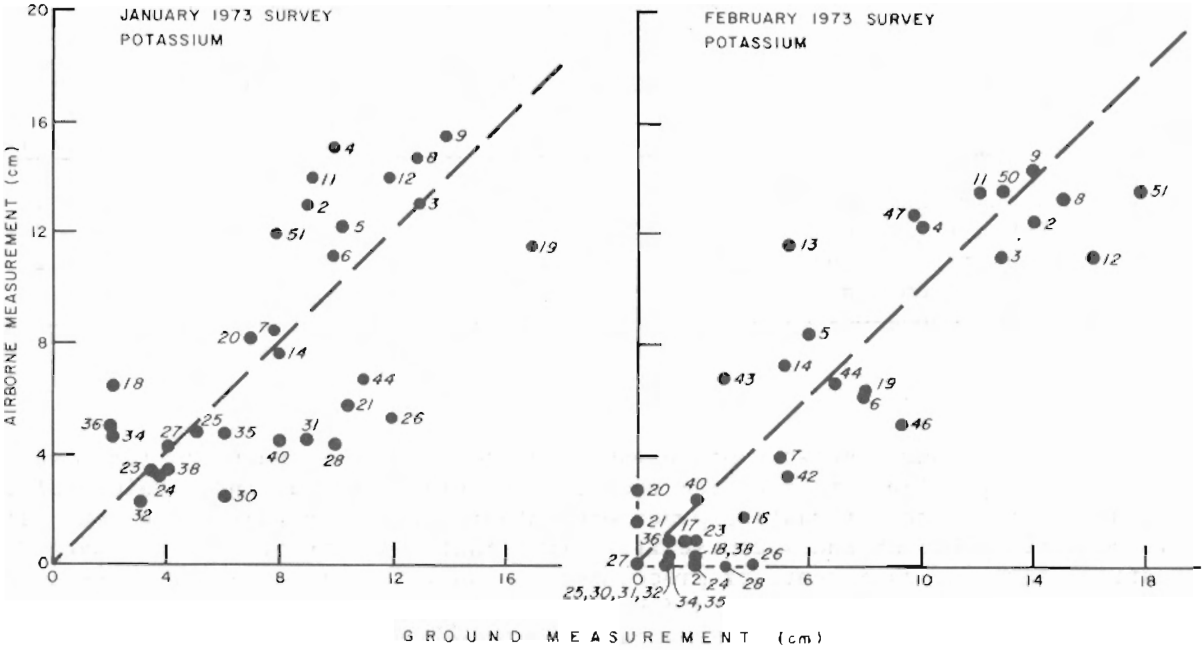

Figure 3. Airborne results vs. data from snow-course network.

TABLE 3 List of snow courses

Course No..	Name	Agency	Course No.	Name	Agency
1	ALMONTE	DOE/WRB	27	Sebringville	OMNR
2	High Falls	OH	28	Fullerton	OMNR
3	Barrett Chute	OH	29	FARQUHAR	McMaster
4	Cloyne	OH	30	Morrison Dam	OMNR
5	Actinolite	OMNR	31	Thedford	OMNR
6	Stirling	OMNR	32	Lucan	OMNR
7	Plainfield	OMNR	33	GRANTON	McMaster
8	Bancroft	OH	34	Embro	OMNR
9	Princess Lake	OH	35	Woodstock	OMNR
11	Minden	OH	36	Cathcart	OMNR
12	Wasdell Falls	OH	37	WILLBURN	McMaster
13	Kirkfield	INA	38	Tavistock	OMNR
14	Peterborough	Trent	39	BLUE SPRINGS CREEK	Guelph
15	WILMOT CREEK	OME	40	Terra Cotta	OMNR
16	Port Perry	INA	41	COLD CREEK	DOE/AES
17	Bradford	INA	42	Wilfrid	INA
18	Tottenham	OMNR	43	Warsaw	OMNR
19	Corbetton	OMNR	44	Madoc	OMNR
20	Flesherton	OMNR	46	Godfrey	OMNR
21	Tara	OMNR	47	Bathurst	INA
22	PAISLEY TRAVERSE	DOE/AES	48	PERTH	DOE/WRB
23	Paisley	OMNR	49	CARLETON PLACE	DOE/WRB
24	Walkerton	OMNR	50	Ashton	INA
25	Harriston	OMNR	51	Huntley	OMNR
26	Canagagigue	OMNR			

TABLE 4 Summary of ground and airborne (potassium count) results for the experimental snow courses (water equivalent, cm).

	Ground Survey	Airborne Survey Soil Moisture	
		Uncorrected	Corrected
January survey	7.4	8.8	7.2
February survey	4.6	6.8	5.1
January & February surveys combined	6.2	8.0	6.2

DISCUSSION

The snow course network was established for a special purpose, i.e., snowmelt runoff forecasting. The data from the courses are merely used as index values of snow water equivalent in the forecasting procedure rather than actual values representative of a larger area. For an index course it is important that any bias in the data due to location, sampling equipment, or procedures is consistent from year to year and for each survey. Some courses were up to 3 km off the flight track and, consequently, the data may not be representative of the area measured by the airborne method.

It should be noted that different snow samplers are in use by various agencies. McKay and Blackwell (1961) and Work et al. (1965) report that the Federal (Mount Rose) snow sampler overestimates the actual water equivalent of a homogeneous pack by about 10%

TABLE 5 Airborne and ground data* for snow course network using average soil moisture values (cm)

	January 1973 Survey			February 1973 Survey		
Course	Ground	Potassium	Integral	Ground	Potassium	Integral
2	9.	13.1	15.0	14.	12.5	14.6
3	13.	13.1	14.4	13.	11.3	12.1
4	10.	15.3	14.2	10.	12.1	15.4
5	10.	12.5	9.2	6.	8.5	8.4
6	10.	11.4	9.0	8.	6.2	5.0
7	8.	8.6	6.4	5.	4.0	2.4
8	13.	14.9	10.6	15.	13.3	11.3
9	14.	15.7	13.0	14.	14.4	12.0
11	9.	14.1	14.9	12.	13.5	10.9
12	12.	14.1	14.5	16.	11.2	9.5
13	-	16.1	14.1	5.	11.6	14.1
14	8.	7.7	9.1	5.	7.3	5.7
16	-	6.9	8.0	4.	1.8	8.0
17	-	4.4	6.2	2.	0.9	6.2
18	2.	6.5	8.2	2.	0.4	0.5
19	17.	11.6	13.6	8.	6.3	5.9
20	7.	8.3	10.4	0.	2.7	2.2
21	11.	5.8	6.6	0.	1.6	0.9
23	4.	3.4	3.0	2.	0.9	0.2
24	3.	3.3	3.8	2.	0.0	0.0
25	5.	4.9	5.6	1.	0.0	0.0
26	12.	5.3	6.7	4.	0.0	0.0
27	4.	4.4	3.4	0.	0.0	0.0
28	10.	4.4	3.4	3.	0.0	0.0
30	6.	2.6	1.6	1.	0.0	0.0
31	9.	4.7	4.7	1.	0.0	0.0
32	3.	2.4	1.7	1.	0.0	0.0
34	2.	4.8	4.9	1.	0.2	0.0
35	6.	4.8	4.9	1.	0.2	0.0
36	2.	5.1	5.2	1.	0.8	0.0
38	4.	3.5	5.3	2.	0.1	1.5
40	8.	4.6	5.0	2.	2.4	1.1
42	-	5.5	4.8	5.	3.2	0.0
43	-	8.2	5.1	3.	6.9	4.2
44	11.	6.7	6.0	7.	6.6	5.2
46	-	6.1	4.8	9.	5.1	2.2
47	-	11.0	9.8	10.	12.7	11.3
50		11.4	10.1	13.	13.7	11.8
51	8.	12.1	10.1	18.	13.7	12.2

* The ground data were adjusted to the date of airborne survey

TABLE 6 Soil moisture content (percent of dry weight) used for correction of airborne data.

Survey Lines	Presnow	January	February
1-4; 15-17	29	43	47
5-7	30	45	50
7B-14	30	48	52

and the MSC sampler, with larger diameter, by 5%; however, no extensive testing has been carried out for MSC sampler. A recent comparison of the two samplers in the Ottawa area, indicated that the Federal sampler gave values 6.3% higher than the MSC sampler.

The condition of the snowpack itself is another variable influencing the accuracy of the snow tube measurement. Especially, when ice layers are present in the pack, clogging of the tube opening will result in an underestimation of water equivalent (snow density). Turcan and Kozlik (1970) using a small diameter sampler (Ø =3.57) in Czechoslovakia showed that clogging and compaction of snow had considerable effect on the density measurement.

The results of ground and airborne surveys in January 1973, plotted in Figure 3, show two distinct groups of points. One group falls in the lower part where ground measurements are higher than the airborne results. Most of these courses are located between Lake Ontario and Lake Huron, an area characterized by farmland and small bushes where snow courses were generally established in protected areas. The data suggest that the courses are not representative of the area surveyed by the aircraft. This is also indicated by the February results. Snow is retained longer on the courses than on the survey lines. The other group of points for the January survey falls in the upper part of Figure 3, where the airborne results are higher than the ground measurements. These courses are located on the Canadian Shield in the northern part of the survey area. There is no apparent reason for this phenomenon other than the difference in survey dates, which was about 6 days in January (Table 2), although the ground data has been adjusted to the airborne survey date.

Errors associated with the airborne gamma-ray technique may be caused by:

1. variability in soil moisture content and measurement errors
2. variation in background radiation along a flight line
3. statistical errors associated with the random nature of the count rate
4. equipment stability and duplication of flight track
5. variation of the linear absorption coefficient due to inhomogeneity in ground radioactivity
6. variations in atmospheric pressure.

Soil moisture variations, background radiation, and statistical count errors have been quantified by Grasty et al. (1974) using average data over the survey area, (Table 7). Significant errors are believed to be associated with the duplication of the flight lines: however, this source of error is difficult to evaluate directly. The results

TABLE 7 Errors in airborne gamma-ray spectrometer technique over the survey area (in water equivalent, cm)

	Potassium	Integral
Soil moisture	0.8	0.8
Background	0.6	0.8
Statistical	0.2	0.1

given by Grasty et al. (1974) suggest that the experimentally determined linear absorption coefficient for the potassium window over a uniform radioactive test strip in the Ottawa area remained constant over the survey area. By not taking into account atmospheric pressure variation between presnow and snow surveys, the maximum error in the calculation of snow water equivalent is not expected to exceed 0.3 cm.

SUMMARY AND RECOMMENDATIONS

Gamma-ray spectrometer measurements of snow-water equivalent over southern Ontario in the winter of 1972-73 have been compared with data from the existing snow course network. The large scatter is believed to represent actual differences in snow accumulation measured by the two different techniques because earlier work has shown that the average water equivalent can be measured with a root mean square error of 1.2 cm using the potassium window counts and 1.7 cm using total radioactivity count. The airborne technique may be used advantageously to establish the areal representativeness of snow courses in a river basin.

The largest errors in the airborne technique are due to the lack of accurate soil moisture measurements and variation in background radiation along the line. The moisture content of the soil, between the fall and February survey, increased by an amount equivalent to a water layer of 2.2 cm on the ground surface, according to the gamma radiation measurements. The combined measurement of water storage in the snowpack and the topsoil by the airborne technique could be used to advantage in snowmelt runoff forecasting because the fall moisture conditions are not representative for the spring freshet period in southern Ontario.

The airborne measurements were compared with "ground truth" data from measurements with snow samplers of various design. The instrument error of these samplers has not been established for the snow conditions in Ontario, which vary from homogeneous to extensively ice-layered packs. It is therefore difficult to establish the accuracy of the gamma technique by comparing with these measurements.

The difference due to the sampling equipment should be eliminated by determining the measurement accuracy of the snow samplers in use by various agencies. This is especially important for hydrologic studies where data from several sources are used to obtain the actual water storage in the snowpack.

Background radiation and line duplication errors may well be reduced by laying out easily navigable lines which pass over sufficient lakes to ensure that enough background readings are taken. More research should be carried out to determine why the integral radioactivity count, which is ten times as high as the potassium count, is inferior to the potassium information for snow-water equivalent measurement. If the integral count could be used reliably, gamma surveys would become financially much more attractive. Duplication of the flight track should be checked using a tracking camera, especially in the initial stages of a survey when the navigation crew is not familiar with the area.

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