AIRBORNE SNOW WATER EQUIVALENT MEASUREMENTS OVER A FORESTED ENVIRONMENT USING TERRESTRIAL GAMMA RADIATION

by

Thomas R. Carroll and G. Dane Vose

Airborne Gamma Radiation Snow Survey Program
National Weather Service
6301 - 34th Avenue South
Minneapolis, Minnesota 55450

ABSTRACT

The National Weather Service makes operational airborne snow water equivalent measurements over much of the agricultural areas in the upper Midwest. Two research flight line networks have recently been established in the Lake Superior basin and in the Saint John River basin in northern Maine, New Brunswick, and Quebec to assess the capability of the airborne measurement technique over forested regions. Airborne and ground snow water equivalent data are analyzed for one season in the Saint John basin and for two seaons in the Lake Superior basin. Approximately 200 depth and density samples are collected on each of 72 calibration flight lines in both research basins and compared with the associated airborne snow water equivalent measurements. Results from the last two snow seasons indicate airborne snow water equivalent measurements can be made in a forested environment with a Root Mean Square error of 2.3 cm.

The airborne snow water equivalent measurement technique requires some estimate of soil moisture in the upper soil zone at the time airborne radiation data are collected. A procedure is developed to simulate soil water for the upper 15 cm using temperature and precipitation data. Soil water, temperature, and precipitation data from northern Minnesota taken during a four year period are used to develop a model to simulate soil water for the upper soil zones of a forested environment. Preliminary results suggest it is possible to simulate soil water with an Root Mean Square error of 0.30 cm of available water for the upper soil zone.

INTRODUCTION

The Office of Hydrology developed and maintains an operational Airborne Gamma Radiation Snow Survey Program in the upper Midwest (Peck, et al., 1980). The technique uses the attenuation of natural terrestrial gamma radiation to make airborne snow water equivalent measurements over agricultural environments with a Root Mean Square error of 0.8 cm (Carroll, et al., 1983). Two flight line networks have recently been established in the Lake Superior basin (Minnesota, Wisconsin, Michigan, and Ontario) and the Saint John River basin (Maine, Quebec, and New Brunswick) to assess the capability of the airborne snow water equipment measurement technique in forested areas.

This paper discusses two of the major sources of error associated with airborne snow water equivalent measurements in forested areas which are: (1) derivation and calibration of the cosmic radiation, aircraft radiation, and mass attenuation coefficients required for the greater snow water equivalent values found in forested areas, and (2) estimation of ground soil mositure for the upper 20 cm over each flight line at the time of airborne radiation data collection. This paper gives a comparison of ground and airborne snow water equivalent measurements using new cosmic and aircraft radiation constants and new mass attenuation coefficients required for the comparatively deep snowpacks of the forested basins. Additionally, the paper summarizes a procedure to estimate fall soil moisture for the upper 15 cm in a forest environment using maximum daily temperature and precipitation data. The estimated soil moisture values are compared with observed values.

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AIRBORNE SNOW WATER EQUIVALENT MEASUREMENTS

The physics and calibration of the National Weather Service airborne gamma radiation spectrometer were developed under contract by EG&G, Inc. in Las Vegas and have been described by Fritzsche (1979, 1982). A procedure to make airborne soil moisture measurements was developed by Carroll (1981). Results of recent airborne snow water equivalent and soil moisture measurements made in an agricultural environment have been reported by Jones and Carroll (1983), Carroll and Jones (1982), and Carroll et al. (1983).

Gamma Radiation Attenuation Technique

The gamma radiation flux near the ground originates primarily from the natural ^{40}K, ^{238}U, and ^{208}Tl radioisotopes in the soil. In a typical soil, 96 percent of the gamma radiation is emitted from the top 20 cm (Zotimov, 1968). After a measure of the background (no snow cover) radiation and soil moisture is made over a specific flight line, the attenuation of the radiation signal due to the snow pack overburden is used to calculate the amount of water in the snow cover over approximately 6 km^2. Three snow water equivalent values are calculated by measuring the attenuation of the gamma radiation flux using data from the K window (1.36-1.56 MeV), the Tl window (2.41-2.81 MeV), and the gross count (GC) energy spectrum (0.41-3.0 MeV). The potassium photopeak is consistently the strongest in the energy spectrum and has been used successfully to measure snow water equivalent in Canada and in the U.S. (Glynn and Grasty, 1980; Peck et al, 1980). The gross count window accumulates an order of magnitude more counts than the K and Tl photopeak windows. Consequently, gross counts are useful when measuring the variability of snow cover along a flight line or a snow cover with an excess of 20 cm of snow water equivalent.

Airborne measurements of terrestrial radiation are complicated by radon gas contributions. Radon (^{222}Rn) is a daughter of ^{226}Ra in the ^{238}U chain. Radon is a gas with a 3.8 day half-life and can diffuse out of the soil into the atmosphere. Its daughters are gamma emitters that emanate from both the ground and the atmosphere. The airborne radon and daughters are highly variable in concentration, so they contribute a varying amount to the gamma spectrum count rate. Their contribution can range from zero to more than 100 percent of the terrestrial fraction. Radon is a heavy element; consequently, the gas tends to concentrate close to ground. Because the spectral shape of radon is similar to that of uranium, an independent measurement is required to distinguish the two sources of radiation.

Details of the airborne detection package have been described by Carroll and Vadnais (1980) and Fritzsche (1979, 1982). The system consists of five down-looking 10.2 x 10.2 x 40.6 cm NaI (Tl) scintillation detectors; two 10.2 x 10.2 x 20.3 cm up-looking detectors; a Pulse Height Analyzer; and a HewlettPackard 9826 computer used to reduce and record the output date onto magnetic disk. The up-looking and down-looking detectors are used to assess the radon gas contribution to the terrestrial radiation spectrum. The up-detector is shielded from the ground by lead and the down-detector; consequently, it measures primarily the airborne radon. The downdetector measures both terrestrial radiation and radon. The data are then available to write two equations in two unknowns to obtain the ground count rate and the radon count rate (Fritzsche, 1982).

The principal sources of error in calculating snow water equivalent or soil moisture values using the gamma attenuation technique are: (1) the ground measurement of mean areal soil moisture used to calibrate a flight line, (2) the measurement of air mass (i.e., temperature, pressure, and radar altitude), (3) radiation counting statistics, and (4) the accurate assessment of the radon contribution. In areas where the terrestrial radiation count rates are substantially reduced due to forest cover and deep snowpacks, significant errors can be introduced by: (1) the use of cosmic radiation constants derived at a higher altitude and lower latitude, (2) aircraft contribution constants derived using a different aircraft, and (3) mass attenuation coefficients derived for a snowpack with a maximum water equivalent of 30 cm. These sources of error generate insignificant errors in airborne snow water equivalent measurements over agricultural areas where the count rates are relatively high. In forested and deep snow areas, however, count rates are typically 70 percent less than over snow-free agricultural areas, and errors in the cosmic, aircraft, and mass attenuation constants can introduce a significant error in the final snow water equivalent measurement. The following describes the effort to derive new cosmic, aircraft, and mass attenuation coefficients for use with the airborne radiation data collected over the Lake Superior and Saint John River basin.

Radiation Spectrum Stripping Equations

A typical radiation spectrum is given in Figure 1 showing the windows used in the procedure to "strip" the extraneous sources of radiation from the measured windows giving the pure, uncollided radiation count rates. The specific equations used to strip the contribution of the Compton tails associated with the peaks of higher energy, the cosmic component, and aircraft contribution are given as:

$$U = U_w - \alpha T - \phi K - U_a - U_c \tag{1}$$

$$T = T_w - \rho U - T_a - T_c \tag{2}$$

$$K = K_w - \gamma U - \beta T - K_a - K_c \tag{3}$$

$$GC_g = GC_d - GC_r - GC_{da} - GC_{dc} \tag{4}$$

where:

T,U,K = the unscattered ^{208}Tl, ^{238}U and ^{40}K count rates,

T_w,U_w,K_w = total count rate in the windows used to obtain the uncollided peak count rates,

ρ = ratio of ^{238}U counts in window T_w to window U_w,

α = ratio of ^{208}Tl counts in window U_w to window T_w,

ϕ = ratio of ^{40}K counts in window U_w to window K_w (generally small),

γ = ratio of ^{238}U counts in window K_w to window U_w,

β = ratio of ^{208}Tl counts in window K_w to window T_w,

T_a and T_c = aircraft and cosmic count rates in window T_w,

U_a and U_c = aircraft and cosmic count rates in window U_w,

K_a and K_c = aircraft and cosmic count rates in window K_w,

GC_d = total gross count rates in the gross count window of the down detector,

GC_r = gross count due to airborne radon daughters in the down detector,

GC_g = gross count due to terrestrial gammas in the down detector,

GC_{da} = gross count due to the aircraft background in the down detector, and

GC_{dc} = gross count due to cosmic rays in the down detectors.

It is possible to derive the aircraft and cosmic components of equations 1-4 from data collected over water (to assure the absence of terrestrial radiation) on a no-Radon day (to assure the absence of atmospheric radiation). Multiple flights were conducted over Lake Superior on a no-Radon day at multiple altitudes from 30 m to 1524 m. To derive the cosmic components of the above equations, all of the windows (Figure 1) for the lower spectrum (collected at 30 m) are subtracted from the associated windows for the higher spectrum (collected at 1524 m). The subtraction eliminates the constant aircraft radiation component and gives only the contribution of the cosmic component in each of the spectral windows. The cosmic component in each window is represented as the ratio of the cosmic counts in that window (derived from the subtraction) to the counts in the cosmic window (C_w). Consequently, the cosmic contributions in equation 1-4 are calculated as the product of the cosmic constant for each window and the counts in the cosmic window (C_w) (Table 1). The cosmic radiation flux is, in part, a function of altitude and latitude (NCRP, 1975). Consequently, it is reasonable to expect a significant difference between the cosmic constants derived in Las Vegas at altitudes of 4267 m and 5182 m and those constants derived over Lake Superior at altitudes of 30 m and 1524 m. It may be more appropriate to use those constants derived over Lake Superior because the altitude and latitude used for the calibration correspond more closely with the altitudes and latitudes of a typical snow measurement survey. Table 1 gives the results of the cosmic constants derived over Las Vegas and Lake Superior.

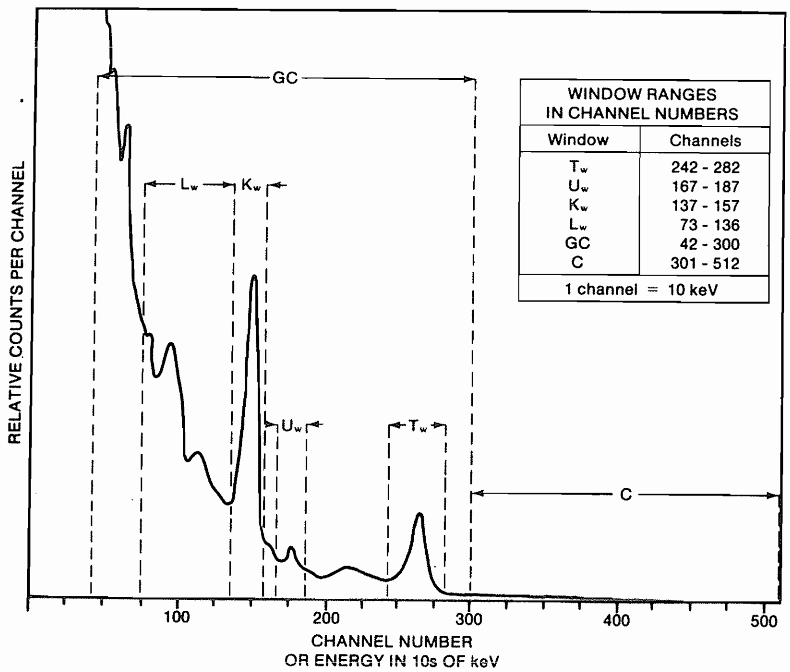

Figure 1. The Gamma Energy Spectrum. (After Fritzsche, 1982)

TABLE 1.

COSMIC CONSTANTS WHICH RELATE

THE C_W COUNT RATE TO THE

COSMIC CONTRIBUTION TO OTHER WINDOWS

WINDOW	TERMS OF EQUATION 1-4	CONSTANTS, ξ LAS VEGAS	LAKE SUPERIOR
U_W	$U_c = \xi_u C$	0.22	0.28
T_W	$T_c = \xi_t C$	0.27	0.28
K_W	$K_c = \xi_k C$	0.28	0.32
GC_d	$GC_{dc} = \xi_{cd} C$	4.45	5.26
C	$C = \xi_c C$	1.00	1.00

The contributions to the radioactivity of each window by the aircraft, detection package, and pilots are typically found by subtraction. The appropriate values of the aircraft constants in equations 1-4 are those which force the respective stripped window counts to zero over water on a no-Radon day. Because new cosmic constants have been derived, it is necessary to calculate new aircraft contributions. Table 2 gives the results of the aircraft constants for the Las Vegas and Lake Superior calibration.

TABLE 2.

AIRCRAFT ENERGY WINDOW

COUNT RATES

WINDOW	TERM IN EQUATION 1-4	COUNT RATE (min^{-1}) LAS VEGAS	LAKE SUPERIOR
U_w	U_a	145	58
T_w	T_a	115	54
K_w	K_a	445	486
GC_d	GC_{da}	4400	3498
C	-	0	0

Mass attenuation coefficients. Airborne snow water equivalent measurements are made using the following relationships:

$$SWE(^{40}K) = A_k \left[\ln \frac{K_0}{K} + \ln\left(\frac{1 + 1.11\ M_0}{1 + 1.11\ M}\right) \right] G/CM^2 \qquad (5)$$

$$SWE(^{208}Tl) = A_t \left[\ln \frac{T_0}{T} + \ln\left(\frac{1 + 1.11\ M_0}{1 + 1.11\ M}\right) \right] G/CM^2 \qquad (6)$$

$$SWE(GC) = A_g \left[\ln \frac{GC_{g0}}{GC_g} + \ln\left(\frac{1 + 1.11\ M_0}{1 + 1.11\ M}\right) \right] G/CM^2 \qquad (7)$$

where:

K_0, T_0, GC_{g0} = pre-snow ^{40}K, ^{208}Tl and GC_g count rates.

K,T, and GC_g = the over-snow unscattered ^{208}Tl, ^{40}K count rates, and gross count due to terrestrial gammas in the down detector.

A_k, A_t, A_g = ^{40}K, ^{208}Tl and GC_g inverse attenuation coefficients in water, g/cm^2.

M_o, M = pre- and over-snow soil moisture fractions. Fractional soil moisture is soil sample moisture weight divided by soil dry weight for the upper 20 cm.

With new cosmic and aircraft constants in the stripping equations, it is necessary to recalculate the mass attenuation coefficients (A_k, A_t, and A_g) used in the snow water equivalent equations 5, 6, and 7. The values of the attenuation coefficients which describe the attenuation of the terrestrial radiation in each of the three windows (K, T, and GC) can be derived from airborne radiation data collected over a single flight line at multiple altitudes. Figure 2 gives the results of the log of the count rates versus air mass. The air attenuation coefficient is represented by the slope (α) of the least squares exponential fit for each of the three windows. The atomic cross section of water (i.e., snow) is 1.11 times that of air per unit mass over the gamma energy range of interest (Adams and Dams, 1970). Consequently, the inverse mass attenuation coefficient in water can be calculated as:

$$A = \frac{1}{1.11\alpha} \tag{8}$$

where:

A = inverse attenuation coefficient in water (g/cm^2) and

α = air attenuation coefficient (cm^2/g).

Table 3 gives the inverse of the attenuation coefficients derived in Las Vegas and over Minnesota flight line MN508C.

TABLE 3.

INVERSE WATER ATTENUATION

COEFFICIENTS (g/cm^2)

WINDOW	LAS VEGAS	MN508C
K_W	14.34	17.25
T_W	18.85	21.57
GC_W	17.73	18.36

It is now possible to reprocess the background and over-snow radiation data using the new aircraft and cosmic constants and new attenuation coefficients. Airborne snow water equivalent measurements using the new coefficients should be a reasonable estimate of the true mean areal snow water equivalent along a particular flight line.

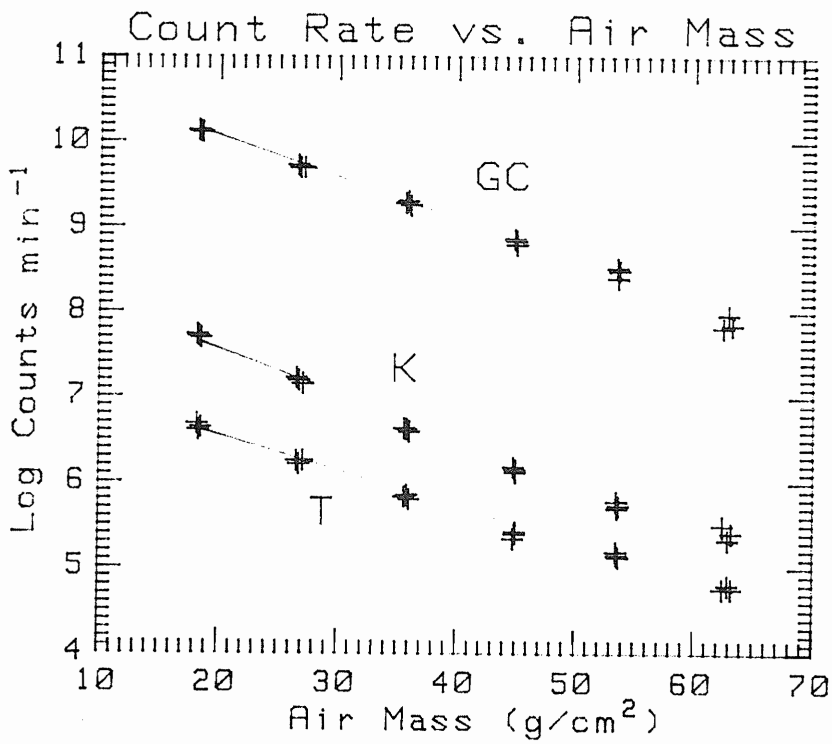

Figure 2. Log of count rates versus air mass for the K, Tl, and GC windows.

Results from Lake Superior and Saint John Airborne Surveys

Eighty five flight lines have been established in the Lake Superior basin, 22 of which are calibration flight lines. Fifty flight lines have been established in the Saint John River basin, eight of which are calibration flight lines. Airborne data were collected over Lake Superior in 1983 and 1984 and the Saint John basin in 1984. Ground snow and soil moisture data were collected on each of the calibration flight lines at the time airborne data were collected. Approximately 200 snow depth measurements, 20 snow density measurements, and 20 soil moisture samples were collected from approximately 10 representative sampling sites evenly distributed along the length of each calibration flight line. Figure 3 summarizes the results of 72 flight lines in the two forested basins. Table 4 summarizes the airborne and ground snow water equivalent results by basin and year using the new calibration coefficients.

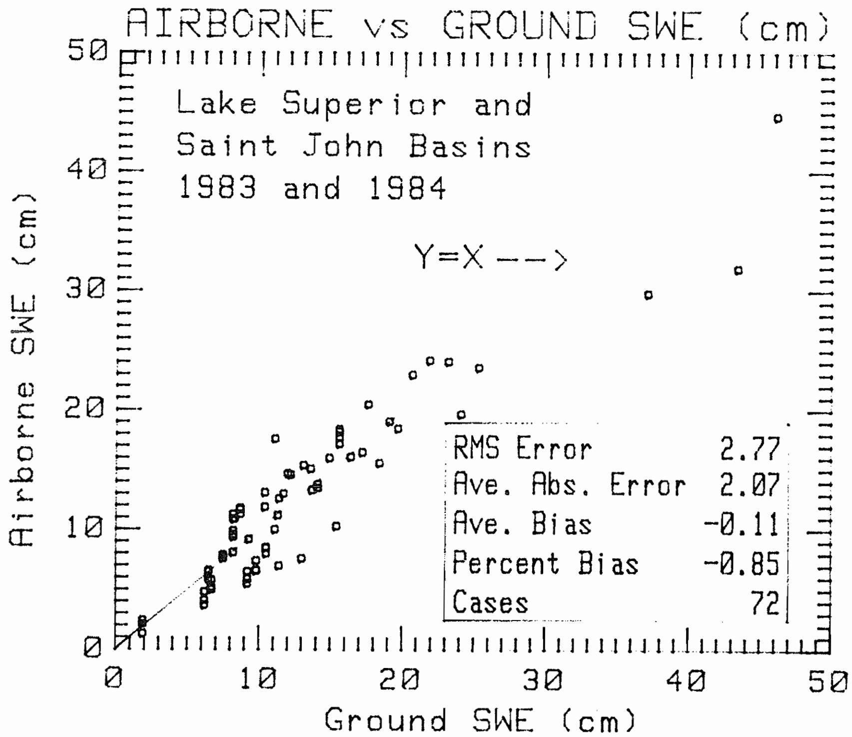

Figure 3. Airborne and ground snow water equivalent measurements for the Lake Superior and Saint John River basins.

TABLE 4.

SUMMARY OF AIRBORNE

SNOW WATER EQUIVALENT ERRORS

USING NEW AIRCRAFT, COSMIC, AND ATTENUATION COEFFICIENTS

ERROR	LAKE SUPERIOR 1983	1984	SAINT JOHN 1984	TOTAL 1983 & 1984
Root Mean Square Error (cm)	1.96	2.87	4.95	2.77
Average Absolute Error (cm)	1.64	2.28	3.51	2.07
Average Bias (cm)	-0.09	0.47	-2.01	-0.11
Percent Bias	-0.99	3.44	-6.80	-0.85
No. of Flight Lines	39*	25	8	72

*Note: Each of 13 flight lines flown 3 times

Table 5 gives the same error results using the aircraft, cosmic and mass attenuation coefficients derived in the Las Vegas calibration (Fritzsche, 1982). A comparison of Table 4 with Table 5 indicates the new calibration is more appropriate.

TABLE 5.

SUMMARY OF AIRBORNE SNOW

WATER EQUIVALENT ERRORS USING LAS VEGAS

AIRCRAFT, COSMIC, AND ATTENUATION COEFFICIENTS

ERROR	LAKE SUPERIOR 1983	LAKE SUPERIOR 1984	SAINT JOHN 1984	TOTAL 1983 & 1984
Root Mean Square Error (cm)	2.12	2.81	6.06	3.04
Average Absolute Error (cm)	1.78	2.12	4.01	2.14
Average Bias (cm)	-0.90	-1.20	-3.18	-1.26
Percent Bias	-10.52	-8.80	-10.76	-9.94
No. of Flight Lines	39*	25	8	72

*Note: Each of 13 flight lines flown 3 times

Ground-based snow water equivalent measurements. A major problem in the interpretation of Table 4 is the assumption that ground snow cover data sampled from an area less than 2 m^2 is representative of an area 8 to 10 km^2 -- or over 5,000,000 times as large as the sample area. Ground snow data collected on flight lines in forested areas cannot reasonably be expected to sample more than 200 parts per BILLION of the total area. As a result, mean areal snow water equivalents estimated from ground snow cover data may not, in fact, accurately reflect the true mean areal snow water equivalent for a particular flight line.

A second problem with ground snow water equivalent data is estimating the error or standard deviation when the mean snow water equivalent is estimated as the product of two means (depth and density) each with its respective variance. Because the depth measurements are highly correlated, the traditional calculation of the variance of two means (which assumes independent measurements for each variable) cannot be used as a measure of the variance for the mean snow water equivalent value. The mean and variance of both the depth and density, however, can be used in a Monte Carlo simulation to calculate the standard deviation of the snow water equivalent for each flight line. The coefficient of variation can be calculated for each flight line along with the range and mean for the data set. The range of the coefficient of variation is from 110.7 percent to 7.9 percent with a mean of 25.0 percent. On average, ground estimates of mean snow water equivalent for a forested flight line have a coefficient of variation of 25 percent. This estimate is substantiated by snow cover data collected by the U.S. Geological Survey in Maine. On each of two flight lines in the Saint John basin, 200 direct snow water equivalent measurements were made (not derived as the product of depth and density). The resulting coefficients of variation were 15.4 percent on line SJ141C and 25.5 percent on SJ139C.

Problems with the ground data not withstanding, the data given in Table 4 appear reasonable for Lake Superior. The Saint John data, however, seem to have a bit of a problem. The airborne data underestimate the ground snow water equivalent data on lines SJ121C and SJ129C in the Saint John basin by 7.1 cm and 11.3 cm, respectively (Figure 3).

In retrospect, it seems that the two flight lines are not in good locations. They follow a road along a narrow valley bottom. Two potential problems can arise in such a situation. One, it is possible the ground data were collected from areas of deeper snow near the road along the valley bottom while the aircraft data were collected further up the valley side where snow may accumulate to a lesser extent. Two, vertical rock outcrops from the snow-free valley side could conceivably contribute radiation to the airborne spectra. This would consequently tend to generate an underestimate of the airborne snow water equivalent measurement. This appears to be the particular case with flight line SJ129C. As a result, it is useful to recalculate the errors in Table 4 for the Saint John basin and for the total data set including all but the data for the two suspect calibration flight lines. The associated errors are:

ERRORS	SAINT JOHN 1983	TOTAL 1983 & 1984
Root Mean Square Error (cm)	1.74	2.31
Average Absolute Error (cm)	1.62	1.87
Average Bias (cm)	0.38	0.15
Percent Bias	1.46	1.28
No. of Flight Lines	6	70

Summary

Airborne and ground snow data collected on 70 flight lines in the Lake Superior and Saint John River basin indicate that it is possible to make airborne snow water equivalent measurements in forested areas with a Root Mean Square Error of 2.31 cm when compared to the ground snow data. Sources of snow water equivalent measurement error include: (1) limited counting statistics due to increased attenuation of the radiation signal by tree cover and deeper snow packs, (2) air mass measurement errors caused by rough terrain, (3) inability to accurately determine background and over-snow soil moisture (M_o and M in equations 5, 6, and 7), (4) errors in the system calibration (principally the air attenuation coefficients for each of the three windows), and (5) errors in the ground snow water equivalent data used to assess the airborne measurements.

ESTIMATION OF SOIL MOISTURE FROM TEMPERATURE AND PRECIPITATION DATA

Percent soil moisture in the upper 20 centimeters appears in the snow water equivalent equations (Eq. 6, 7, and 8) as M_o and M. Collecting ground soil moisture data is both time consuming and expensive. As a result, it is desirable to accurately assess Mo and M without resorting to direct measurements. An estimated value is useful as a measure of background soil moisture (M_o) on those lines for which it is not feasible to obtain ground data. Additionally, a rough estimate of the winter soil moisture (M) can also be obtained.

Based on work by Thornthwaite (1948), Keetch and Byram (1968) developed a drought index model for forest fire control which uses estimated values of evapotranspiration (ET) derived from maximum daily temperature data. The accounting method suggested by Thornthwaite and used by Keetch and Byram, along with a procedure to estimate ET similar to that proposed by Nelson (1959), can be incorporated into a conceptual model to estimate available soil water based on daily maximum temperature and precipitation data. Available soil water can then be converted to percent soil moisture (M_o or M).

Soil Moisture Model

The model described generates a daily accounting of available soil water in centimeters in a 105 cm soil column. Water is added as net precipitation from rainfall and subtracted as a result of evapotranspiration determined from maximum daily temperature:

$$SM_1 = SM_0 + \text{Net Precip} - ET \qquad (9)$$

Beginning soil water (SM_0) and net precipitation are known; thus, it is necessary only to calculate a value for ET to obtain a new soil water (SM_1). Evapotranspiration is estimated as:

$$ET = m * EXP(bT) \tag{10}$$

where:

ET = evapotranspiration in centimeters of water,

T = maximum daily temperature in degrees F, and

m and b = constants.

This approach makes four assumptions. One, a satisfactory estimate of evapotranspiration can be calculated solely on the basis of daily maximum temperature (Nelson, 1959). Two, vegetation density (and hence the rate at which the vegetation can remove moisture from the soil) is a function of mean annual rainfall (Keetch and Byram, 1968). Three, 0.5 cm of cumulative rainfall is intercepted by the forest canopy. The difference between measured precipitation and intercepted rainfall is net precipitation. Four, there is a constant relationship between the available water held in a column of soil 105 cm deep and the available water held in the top 15 centimeters of that column. (The SWE equation uses a measure of soil moisture in the upper 20 cm; however, soil water data were obtained in the upper 15 cm. It seems reasonable to assume percent soil moisture in the upper 20 cm is equal to that in the upper 15 cm.)

The relationship of soil water in the upper 15 cm to soil water in the 105 cm column can be expressed as:

$$SM_{15} = A + B * SM_{105} \tag{11}$$

where:

SM_{15} = soil water in the surficial 15 cm,

SM_{105} = soil water in the 105 cm column, and

A and B = constants.

When the amount of water measured in the top layer of soil was regressed on the total available water in the soil column, the following relationship was derived:

$$y = .04 + .17x \tag{12}$$

where:

y = the available water in the surface layer (cm), and

x = the available water in the total column (cm).

The data used to derive equation 12 indicate the following:

Root Mean Square error = .20 cm available water

Average Absolute error = .15 cm available water

Correlation Coef. = .97

*Number of Cases = 18

* Note: Each case is the average of eight point measurements.

Simulation Results

The USDA Forestry Sciences Lab at Grand Rapids, Minnesota has accumulated daily temperature, precipitation, and periodic soil water data at its Experimental Forest since 1969. Soil water measurements were taken at each of eight sites for the top 15 cm of soil, and then in 30 cm horizons to a depth of 105 centimeters. Four years of record were considered for this study. Soil water values used for the analysis are the averages of the eight point observations obtained at each measurement. Soil water measurements were made eighteen times over the four year period.

Estimated Evapotranspiration. By rearranging Equation 9, evapotranspiration can be expressed in terms of soil water and precipitation:

$$ET = SM_0 + \text{Net Precip} - SM_1 \qquad (13)$$

Over certain intervals of time during the four year period, beginning and ending values for soil water, as well as precipitation amounts, are known from direct measurement. An estimated value of actual evapotranspiration can be calculated for these intervals of time (Eq. 13). A simulated value for evapotranspiration expressed in terms of daily temperature can also be obtained for each interval of time (Eq. 10). Values for the constants m and b in equation 10 are obtained by trial and error substitution. A comparison of "observed" ET (Eq. 13) to simulated ET (Eq. 10) where m = .000061 and b = .106 is provided in Figure 4.

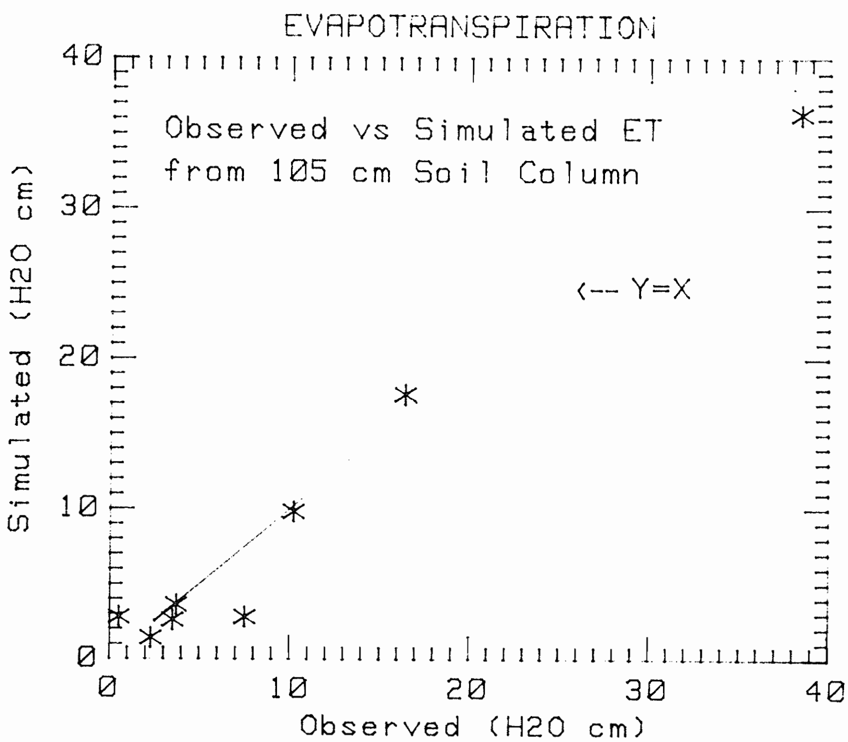

Figure 4. Observed versus simulated evapotranspiration over eight intervals of time

Simulated Soil Water in 105 cm Column. The amount of available water held in soil is bounded by field holding capacity and the wilting point. To accurately calculate ET using of Equation 13, soil water must not exceed the boundary values during the interval of time over which the calculations are made. Accordingly, the ET comparisons represented in Figure

4 were determined using intervals where the boundary values were not exceeded. By defining boundary values for field holding capacity and wilting point, however, it is possible to predict soil water during intervals of time where additions from precipitation or deductions from evapotranspiration would otherwise be excessive. The boundary values for the Grand Rapids data were determined by making calculations over a range of values for field holding capacity and wilting point, and then selecting values which produce the lowest RMS error. Using this technique a field capacity of 16 cm of water, and a wilting point of 2 cm of water were obtained. These values compare favorably to data presented by Nelson (1959). Observed soil water versus simulated values using these boundary conditions in combination with Equations 9 and 10 (m = .000061, b = .106) are given in Figure 5.

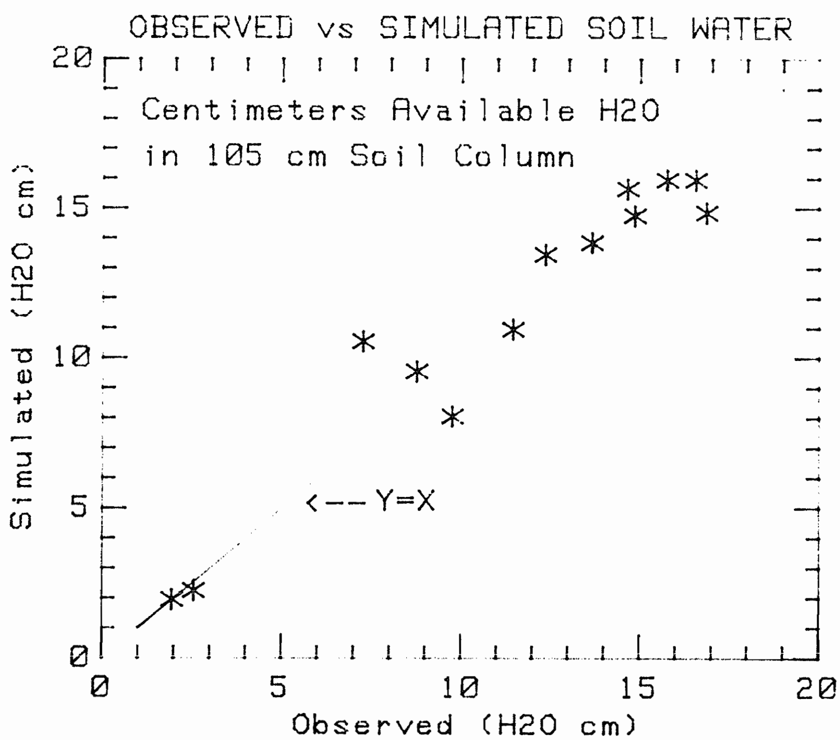

Figure 5. Observed versus simulated soil water content of a 105 cm column of soil at the end of thirteen intervals of time.

Simulated Soil Water in Upper 15 cm. The values obtained for soil water in the 105 cm column can now be used in Equation 12 to give the simulated value for soil water in the upper 15 cm. The comparison of observed to simulated soil water in the upper 15 cm is given in Figure 6.

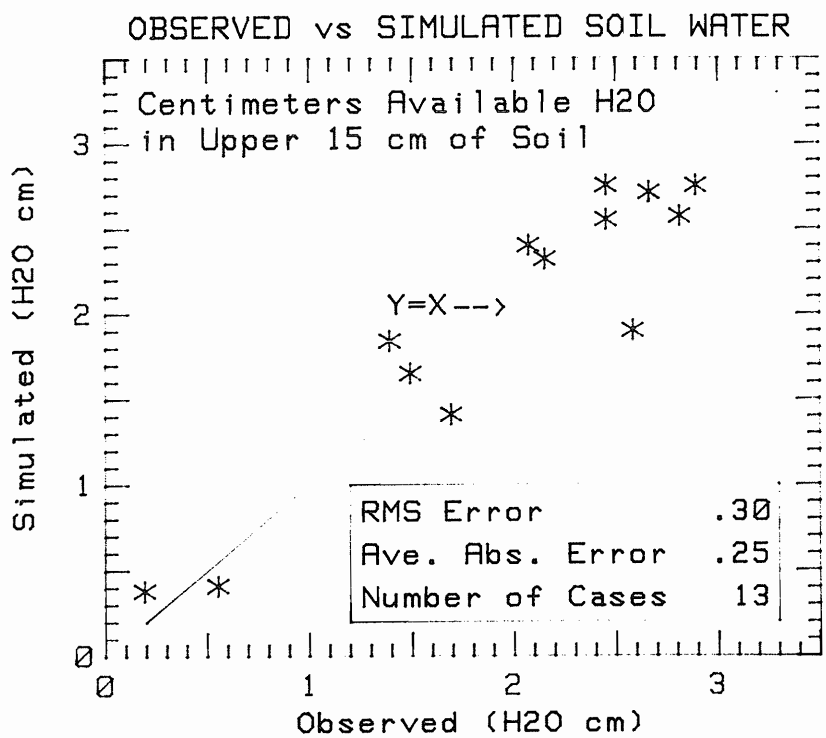

Figure 6. Observed versus simulated soil water content of the upper 15 cm of a 105 cm column of soil over thirteen intervals of time.

Errors of the simulated and observed soil water values are:

Root Mean Square error = .30 cm available water

Average Absolute error = .25 cm available water

Average Bias = .02 cm available water

Percent Bias = 1.06%

Number of Cases = 13

CONCLUSION

The RMS error obtained for soil water simulations in the upper 15 cm was .30 cm of available water. An error of 0.30 cm in soil water translates to an error of 2 percent soil moisture given a typical bulk density of 1.2. This, in turn, results in an error of 0.30 cm in the calculation of snow water equivalent using equations 5, 6, & 7. The overall error in snow water equivalent measured over a forested area is 2.3 cm using field measurements of soil water. Thus, a soil water value estimated to the level of accuracy described by this technique would introduce minimal error in the airborne snow water equivalent measurement. The technique to estimate surficial soil water appears promising. Work will continue to incorporate the procedure into operational airborne snow water equivalent measurements.

ACKNOWLEDGEMENTS

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