DETERMINATION OF SNOW WATER EQUIVALENTS BY USING NOAA-SATELLITE IMAGES, GAMMA RAY SPECTROMETRY AND FIELD MEASUREMENTS

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ABSTRACT

A method was developed to estimate snow water equivalents in the snow melt period in lowlands by using NOAA/AVHRR images, airborne gamma ray spectrometry and field measurements. The errors were 20 - 50 mm for satellite images and 5 - 10 % of the snow equivalent for gamma ray spectrometry. The results of field measurements can be combined with remotely sensed data. Because the cloud cover prevents the use of satellite imagery, a snow melt equation is used to estimate snowmelt in cloudy days.

1. INTRODUCTION

Weather satellite images have been used for a long time for mapping snow covered areas. In mountaineous regions correlation exists between the snow covered area and the magnitude of streamflow. This has been verified by many scientists in different parts of the world, e.g. Rango and Martinec (1982), Andersen (1984), Ramamoorthi (1985) and Baumgartner et al. (1985). In lowlands this kind of correlation is not possible and thus efforts have been made to estimate the amount of snow using the shape of the image histogram, Merry et al. (1985).

The cloud cover hampers the use of multispectral scanner images for snow mapping during the relatively short period of snowmelt if only cloudfree images are used. If cloudy areas could be interpreted and images after that rectified, partly cloudfree images could also be used in snow mapping. This would much increase the snow information available from satellite image.

The method of measuring the snow water equivalent using terrestrial gamma emission was originally developed in the USSR in the 1960's, Vershinina and Dimaskyan (1969). In this method the intensity of gamma emission is measured before snow accumulation in autumn and then during winter along the same line. The snow water equivalent can be inferred from the ratio between gamma emission from bare ground and emission from snow-covered ground. This gamma technique has also been studied and developed in many countries outside the USSR, Tollan (1979) Norway, Loijens (1979) and Grasty (1979) Canada, Fritsche (1979, 1982) and Carroll (1984) USA, Bergström and

Brandt (1984) Sweden, and Kuittinen et al. (1980, 1985) Finland.

A method to estimate snow water equivalent values directly from NOAA-images in lowland areas during the snowmelt period was developed in Finland in 1985-1987. A method to estimate snow water equivalents by airborne gamma ray techniques was developed to be operative and fast in 1981-1985. For cloudy days a method was developed to estimate daily snowmelt by using air temperature and satellite-based global radiation on the ground. Together these methods permit the daily estimation of the snow water equivalent over large areas.

2. ESTIMATION OF SNOW WATER EQUIVALENTS USING SATELLITE IMAGES

The density of the snow cover normally increases towards the spring. At the beginning of the snow melt, the snow water equivalent in northern Finland is about 260 kg/m3 and at the end of the snow melt it is about 329 kg/m3 in forest and 349 kg/m3 in open sites, Kuusisto (1984). In the latter part of the snow melt, when snow free areas already exist, the density of snow can be considered to be constant, 330 kg/m3. The rate at which snow pack melts varies from place to place, creating snowless areas quite early in the melting period. Figure 1 shows the relationship between the snow water equivalent and the percentage of the snow free area. In northern Finland the first snowless areas appear when the snow water equivalent is about 125 mm.

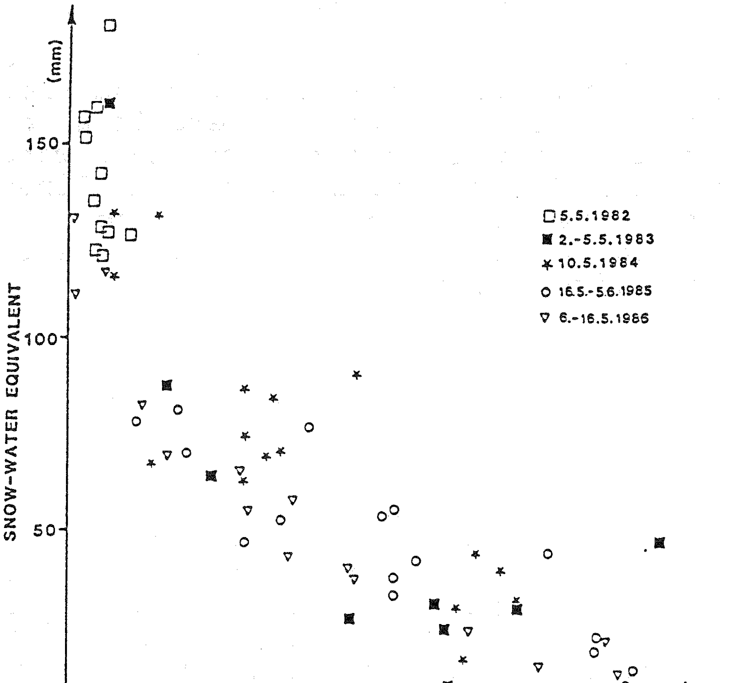

Figure 1. The relationship of the snow water equivalent and the snow free area in northern Finland.

The linear regression equation is the following:

$$y = -.813*x + 97.25 \qquad (1)$$

in which x is the snow free area (%)
y is the snow water equivalent

correlation coefficient was 0.889.

The thickness of the snow pack does not decrease as rapidly as the snowmelt suggests, because the melting occurs strongly around the snowless spots and thus the area of the snow cover decreases at the same time as the snow melts. The snow water equivalent can thus be estimated if the snow free area can be measured in the melting period. This is possible using satellite images, because the radiance from the ground decreases as the extent of the snow free area increases.

The NOAA/AVHRR scanner has 4 -5 channels, three of which are in the thermal region of the electromagnetic spectrum. Cloud and snow discrimination is possible in the area of 1.5 - 2.6 um, Bunting (1982). Because AVHRR does not have this channel, the only possible way to discriminate between clouds and snow is to use the thermal channels and/or the near infrared channel of the AVHRR.

The thermal channel is the most suitable for detecting clouds in spring because clouds are in most cases colder than melting snow and snowless ground. During winter this is not the case. This interpretation involves interactive image processing because treshold values are needed for every image.

If the albedos of snow and snow free ground are used as constants there is a linear relationship between the radiances measured by the AVHRR and the snow free area. There is also a good correlation between the snow free area and snow water equivalent, which can thus be estimated using a linear relationship. These two correlations permit the use of a linear regression equation in estimating the snow water equivalent gs(x,y) in satellite images:

$$gs(x,y) = ai*f(x,y) + bi \qquad (2)$$

in which f(x,y) is the pixel value of channel 1 of the AVHRR image and, ai and bi are constants.

Forest affects the radiance of the snow cover by decreasing the amount of radiation. To obtain reliable results, the correction must be made for this. This was done by computing regression equations for the major terrain types. The coefficients ai and bi of these equations were determined by comparing the snow water equivalents maesured by gamma ray spectrometry and the radiances of the same places measured by the AVHRR. Models were also constructed for north and south slopes, flat areas and snow water equivalent values of less than 125 mm. Altogether 69 measurements were used in determining the regression coefficients. The results for flat areas are presented in Table 1.

Table 1. Regression models for estimation of the snow water equivalent, correlation coefficients, standard errors and residual mean square errors of models.

Terrain type		ai	bi	s1	s2	r	rms(mm)
I and II	flat	1.37	-51.48	.071	9.13	.93	33.5
	flat/125	.958	-32.07	.063	5.21	.93	14.5
III	flat	1.32	-45.89	.096	12.44	.93	35.4
	flat/125	.868	-30.57	.063	4.89	.96	11.6
IV and V	flat	1.28	-55.19	.062	8.47	.93	29.3
	flat/125	.887	-31.16	.072	6.32	.91	17.7

Terrain types I and II as well as IV and V are combined because there were less than 5 observations in the classes I and V.

s1 = standard error for ai, s2 = standard error for bi

These models also permit correction for the effects of terrain topography in estimating the snow water equivalent, but this requires, however, the use of a digital elevation model. Table 1 shows that the accuracy of these models increases towards the end of snowmelt, due to the increase in the snow free area. In the case of new ealls of snow, this method does not work, because the snow on the trees and the disappearance of the snow free patches make the area equally white and thus no correlations exist between the snow depth and the radiance detected by the AVHRR scanner. New snow disturbs this method for only a few days, because melting soon restores the normal spring situation.

To obtain a similar computing method for all the images, correlations were made for the effect of the increased radiance in the midday images by using correction coefficients.

Terrain type	correction coefficient, ki
I and II	0.70
III	0.73
IV and V	0.75

After this correction the regression models are the following:

$$gs(x,y) = ki*[ai*f(x,y) + bi] \quad (3).$$

The changes in the declination of the sun can also be taken into account. As their affect is similar to that of the changes in the elevation of the sun these corrections have to be made for all terrain types. The reference date is 10 May. After these corrections the equations are:

$$gs(x,y) = hi*ki*[ai*f(x,y) + bi] \quad (4).$$

The values for hi were the following:

Period	hi
15.-20.4.	1.3
21.-30.4.	1.2
1.-10.5.	1.0
11.-20.5.	.9
21.-30.5.	.8

Just before the end of the snow melt the snow water equivalents measured by gamma ray spectrometry are about 10 mm higher than these measured by the gravimetric method due to the water which is always present in this time on the ground. To correct for this effect and to obtain a clear distinction between the snow and snow free areas, the models were modified by changing the coefficients ai and by determining the threshold values for every class. These threshold values were determined on the basis of snow free ground for different types of terrain. The final equations for estimating of the snow water equivalent are:

Terrain types I and II
$$gs(x,y) = hi*ki*[1.43*f(x,y) - 64.0], \text{ when } f(x,y) > 46 \quad (5)$$

Terrain type III
$$gs(x,y) = hi*ki*[1.38*f(x,y) - 58.2], \text{ when } f(x,y) > 43 \quad (6)$$

Terrain types IV and V
$$gs(x,y) = hi*ki*[1.33*f(x,y) - 67.9], \text{ when } f(x,y) > 52 \quad (7)$$

The accuracy of the method was evaluated in three different ways, by:

-analyzing the errors of the models
-comparing the results with results obtained by gamma ray spectrometry
-comparing the results with the results of the field measurements

The residual mean square errors of the models varied between 61.8 mm and 11.6 mm so that the smallest values were obtained for flat areas and snow water equivalents below 125 mm. The mean of errors of the flat area values was 32.7 mm and the corresponding value for snow water equivalents below 125 mm was 14.6 mm.

When the values determined from NOAA/AVHRR images were compared with the results obtained by gamma ray spectrometry, they varied between 0 and 103 mm having the mean 43 mm, which was 28 % of the average snow water equivalent. When compared with field measurements, the mean error was 20 mm. In this case the snow water equivalents were small, all below 159 mm and the mean was 40 mm.

3 DETERMINATION OF THE SNOW WATER EQUIVALENT BY USING GAMMA RAY SPECTROMETRY

The amount of water in the snowpack can be determined by using the following equations:

$$I_s = N_o \int_1^\infty \frac{e^{-(\mu_w \cdot w + \mu_a \cdot H)\cdot x}}{x^2}\, dx \qquad (8)$$

$$I_g = N_o \int_1^\infty \frac{e^{-\mu_a Hx}}{x^2}\, dx \qquad (9)$$

in which No is the number of gamma pulses above the ground (p/s)
H is the measuring altitude (m)
S is the soil activity (1/kg s)
Ao is the effective detector area (cm2)
μg is the soil absorption coefficient (cm2/g)
μa is the air mass absorption coefficient (cm2/g)
μw is the snow mass absorption coefficient (cm2/g)
W is the snow water equivalent (g/cm2)

Fritzsche (1984).

In general the E2- function is estimated by an exponential function, which however is not the optimum, because it is also possible to determine the snow water equivalents by the E2-functions in the following way, Kuittinen et al. (1985):

$$w = (H_e - H)/1.11 \cdot \frac{\rho_w}{\rho_a} \qquad (12)$$

$$H_e = 1.11 \cdot \frac{\rho_w}{\rho_a} + H \qquad (11)$$

in which He is the effective flight altitude (m)
H is the measured flight altitude (m)
ρw is the density of water (g/dm3)
ρa is the density of air (g/dm3)

In the effective flight altitude there are included air mass and the snow water equivalent.

The errors in snow water equivalent estimation in gamma ray spectrometry can be devided into two groups: 1) errors in calibrating the methods and 2) errors caused by measuring circumstances and navigation of the aircraft. In the first group the following sources of errors exist: absorption coefficient of air, measuring air mass and flight altitude, cosmic and background radiation and the statistical nature of gamma radiation. The effects of these are presented below:

Number of pulses measured (p/s)	Standard deviation (p/s) A	B	C	D
2000	27	1	4	28
1000	14	1	3	15
100	1	1	1	2
30	1	0	1	1

A absorption coefficient and effective flight altitude
B cosmic and background radiation
C statistics of gamma radiation
D combined variation of measured pulses

The errors of the second group appear when measurements are made over a long period (many snow courses in different places) and when the same snow course is measured many times. The sources of these errors are: variations in background radiation, which is mainly caused by the amount of radon in the air, incorrect navigation and the length of snow course. For a five-kilometer-long snow course these are:

Number of measured pulses (p/s)	Error (p/s)			Error smaller than presented	
	A	B	C	in 67% of cases (p/s)	in 95% of cases (p/s)
2000	60	32	10	69	302
1000	30	16	10	35	152
100	3	2	1	4	15
30	1	5	1	5	7

A error caused by navigation
B error caused by the length of snow course
C error caused by atmospheric radon

When varying gamma radiation intensities and the standard deviations presented are used, the following results are obtained, Table 3.

Table 3. Average errors of gamma ray spectrometry when snow water equivalents of 100 mm and 200 mm are measured.

Intensity of gamma radiation Snowless (p/s)	Snow 100mm (p/s)	Snow 200mm (p/s)	SNC1 (p/s)	SNC2 (p/s)	Error of snow water equivalent mm	mm
100	50	20	3.5	2.3		
500	200	150	16	8		
1000	600	270	35	20	a) 4.5	4.0
2000	1200	580	70	42		
100	50	20	15	10		
500	200	150	70	30		
1000	600	270	152	85	b) 16.5	14.0
2000	1200	580	300	180		

a) error smaller than this in 67 % of the cases
b) error smaller than this in 95% of the cases.

The above estimates are based on the precision of the method. If errors are evaluated by using the differences between ground measurements and gamma ray spectrometry, following results are achieved:

	Snow water equivalent 0-100 mm	101-150 mm	151-200 mm	over 200 mm
rms (mm)	18.7	15.5	25.6	38.9
rms (%)	31	12	15	16

Soil moisture changes are not corrected in these results and there an error of 5 - 10 mm in ground measurements is also.

4.A MODEL FOR DETERMINING DAILY SNOW WATER EQUIVALENT VALUES

When satellite images, gamma ray spectrometry and snow courses are used for measuring the snow water equivalent, and snow melt and precipitation are included, then the expression for the areal snow water equivalent in the evening of a certain day can be written:

$$g(x,y) = af*ff(x,y) + ag*fg(x,y) + asfs(x,y) + fp(x,y) - fm(x,y), \qquad (12)$$

in which $ff(x,y)$ is the snow water equivalent determined by the gravimetric method
$fg(x,y)$ is the snow water equivalent determined by gamma ray spectrometry
$fs(x,y)$ is the snow water equivalent determined by using satellite images
$fp(x,y)$ is the precipitation
$fm(x,y)$ is snow melt
af, ag and as are the weights. These are determined on the basis of the representativeness of the measurements.

The estimation of the snow melt is here based on two variables, the air temperature on the ground and the global radiation estimated from the AVHRR images. The relatioship between the satellite images and the global radiation were constructed in the following way:

At first the relationship were determined between the hourly global radiances and the daily global radiance. The correlations varied between 0.870 and 0.981. A linear model was constructed to convert from the hourly global radiation measured between 12.00 and 13.00 the daily global radiation. After that a model was constructed to convert the cloudiness interpreted from midday NOAA images to the daily clobal rsdiances. The equation was the following:

$$gh(x,y) = -2.15*(x1+x2) + 2524 \qquad (13)$$

in which $x1$ is the value of channel 1 of the AVHRR
$x2$ is the value of channel 2 of the AVHRR

This model was used only in cloudy areas. In cloudless areas constants depending on the declination of the sun were used.

Secondly a snow melt equation was determined. This is based on the degree-day factor and the daily clobal radiation.

$$gm(x,y) = k* \;\; T + h*gh(x,y) \qquad (14)$$

Because degree-day factors and the snow melt caused by global radiation vary in different terrain types, equations were determined for all types of terrain. The equations were:

Terrain type	k	h
I and II	2.7	.0006
III	3.3	.0012
IV and V	3.5	.0015

The errors of snow melt determined by these equations varied from 0.1 to 5.2 mm/d, having the mean 3.3 mm/d.

5. CONCLUSIONS

According to the cloud statistics determined in 1982-1987 from NOAA images in northern Finland about 40 % of the images are partly cloudy but useful and about 10 % totally cloudless. It is possible to obtain useful amount of snow cover data from NOAA images.

The error of developed satellite-based snow water equivalent estimation method is between 20 and 50 mm depending on the amount of snow. This method is not as good as gamma ray spectrometry, which has error between 13 and 17 mm for the areal averages of the snow water equivalent.

This method permits to use different types of snow water equivalent estimation techniques. The user has to decide on the basis of the cost, accuracy and rapidness, which ones he wants to use. The method permits to obtain the results of the measurements in near real time, which in this case means 12 hours from the measurements in Finnish circumstances.

By using one gamma ray spectrometry measurements, all satellite images available and about two ground based measurements of the snow water equivalent it is possible to keep the error of the estimate of the areal snow water equivalent smaller than 25 mm.

This method cannot be used in snow accumulation period. This is not a very serious disadvantage, because in northern latitudes snow information is mostly needed before and during snowmelt period. This method can be used in hydrological information systems, because the results are presented aslo as two dimensional functions, images, which are rectified and presented in some map projection.

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