Pre-Operational Determination of Snow Water Equivalent (SWE) Using RADARSAT Data

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ABSTRACT

For the 1998-1999 winter, we have demonstrated the *operational feasibility* of using RADARSAT data to estimate the spatial distribution of Snow Water Equivalent (SWE) in a large hydroelectric complex managed by Hydro-Québec: the La Grande River watershed. The algorithms and procedures developed in this project have been implemented within a MapInfo™ application that has been named *EQeau*. It allows mapping of the spatial distribution of the estimated SWE at the desired level (pixel, square grid, sub-watershed). *EQeau* has been used successfully in a pre-operational mode using Wide beam images (W1). The algorithm has given results similar to the SWE values derived from Hydro-Quebec snow transects. Also, the SWE increase measured from January to March is clearly detected on the maps. The next steps in this pilot project will be the evaluation of the ScanSAR images and the demonstration of the economic advantages of using RADARSAT data in a hydrological forecasting system.

Key words : RADARSAT, Snow Water Equivalent, SAR

INTRODUCTION

In the last few years, we have studied the use of RADARSAT-1 data (C band-HH) for snow monitoring in the La Grande River watershed, a large hydroelectric complex in northern Quebec (184 000 km^2) managed by Hydro-Québec. Calibrated RADARSAT images have been acquired within the ADRO program of the Canadian Space Agency in Standard beams S1 (20-27°) and S7 (45-49°) as well as in ScanSAR mode (not calibrated). Those acquisitions were made in conjunction with field campaigns (snow lines, snow pits, air and soil temperature, etc.) in November, February, and March during two winter seasons, 1996-1997 and 1997-1998. Then, an empirical algorithm was developed to estimate the spatial distribution of the Snow Water Equivalent (SWE) using data from Standard beams and field measurements over the LG4 sub-watershed (Bernier *et al.*, 1998).

Considering that our approach for SWE estimation is based on the temporal changes of the dielectric characteristics of the soil related to the snow thermal resistivity (Bernier and Fortin, 1998), the S1 mode (low incidence angles) was considered to be more appropriate than the S7 mode. The RADARSAT algorithm for the SWE estimation is similar to the one developed previously for ERS-1data (Bernier *et al.*, 1999a), but the parameters (m,b) of the regression between the thermal resistivity of the snowpack and the ratio of the backscattering coefficients of a winter scene over a fall scene have been adjusted. The RADARSAT estimations of the mean SWE on the experimental sites are comparable to the values measured at the field sites. The standard deviations of the estimated values (+/- 17 to 26 mm) are also comparable to the standard deviations (+/- 15 to 24 mm) obtained from field measurements.

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The final objective of those studies being the operational use of RADARSAT data within the Hydro-Québec hydrological forecasting system, the algorithms and procedures have been implemented within a MapInfo™ application. This software named *EQeau,* jointly developed by Viasat Géo-technologie Inc. and INRS-Eau, allows mapping of the spatial distribution of the SWE estimated from RADARSAT data. It can also resample a map according to a square grid integrating many pixels or calculate the mean SWE on a sub-watershed.

Last winter, we demonstrated the operational feasibility of using RADARSAT data to estimate the spatial distribution of the Snow Water Equivalent (SWE) in the La Grande River watershed. This demonstration is part of a pilot project financed by Hydro-Québec and the Earth Observation Pilot Project Program of the Canadian Space Agency, which is administrated by the Canadian Centre for Remote Sensing. To gradually integrate the RADARSAT technologies within Hydro-Québec's hydrological forecasting system, the methodology was optimized for the *LG4* sub-watershed (30 000 km^2) in the winter of 1998 and then applied to three sub-watersheds (*LG4*, *Laforge* and *Canapiascau)* in the winter of 1999, covering more than 77 000 km^2 (Figure1). Up to 1998, RADARSAT Standard beam data were used. However, beams covering larger areas are necessary to operationally monitor large watersheds. So, acquisition of one ScanSAR image (500 km X 500 km) and three Wide images (165 km X 165 km) were scheduled for November 1998, January 1999 and March 1999 (Figure 1).

This paper presents the application of the *EQeau* software in a pre-operational mode to determine the SWE over the upstream half of the La Grande River watershed. We describe the RADARSAT data used in this demonstration, the methodology, the results of the application of the EQeau software and the SWE maps produced for the winter of 1999.

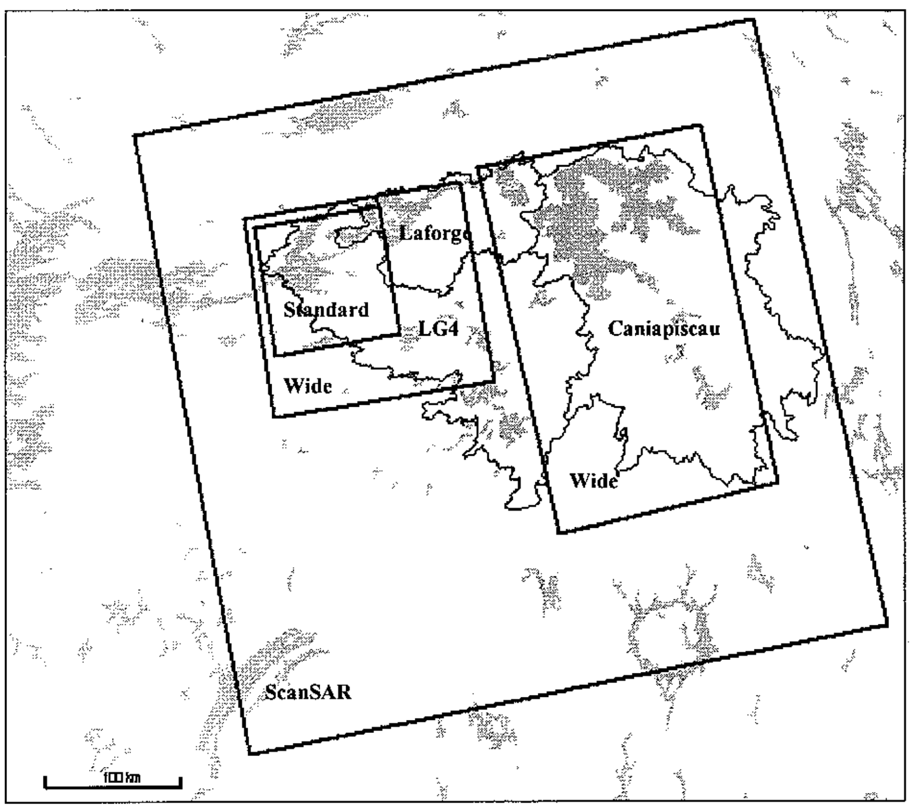

Figure 1: Coverage of the RADARSAT SAR images

DATA DESCRIPTION

Table 1 lists the RADARSAT data acquired last winter, both Wide (beam W1) and ScanSAR (beam W1, W2, W3 and S7) images. The plan was to acquire three Wide beam images from two ascending orbits at three different periods during the winter: November, January and March. However, a technical problem on the satellite prevented the acquisition of a W1 image on March 14, 1999.

Table 1: RADARSAT images acquired during the winter of 1998-1999

Date	Beam	Coverage	Incidence angle	Covering
7 November 1998	ScanSAR Wide	500 X 500 km	20°-49°	LG4, LA1, Caniapiscau
11 November 1998	Wide 1	150 X 150 km	20°-31°	Caniapiscau North
11 November 1998	Wide 1	150 X 150 km	20°-31°	Caniapiscau South
14 November 1998	Wide 1	150 X 150 km	20°-31°	LG4 ouest, LA1
18 January 1999	ScanSAR Wide	500 X 500 km	20°-49°	LG4, LA1, Caniapiscau
22 January 1999	Wide 1	150 X 150 km	20°-31°	Caniapiscau North
22 January 1999	Wide 1	150 X 150 km	20°-31°	Caniapiscau South
25 January 1999	Wide 1	150 X 150 km	20°-31°	LG4 ouest, LA1
7 March 1999	ScanSAR Wide	500 X 500 km	20°-49°	LG4, LA1, Caniapiscau
11 March 1999	Wide 1	150 X 150 km	20°-31°	Caniapiscau North
11 March 1999	Wide 1	150 X 150 km	20°-31°	Caniapiscau South

For each acquisition period, a ground campaign (Gauthier *et al.*, 1998) was done mainly in the LG4 sub-watershed. The November campaign allowed us to measure the soil dielectric constant, the depth of the soil frost and the soil surface temperature at a few sampling sites. The same measurements were made in January and March, and about forty snow transects (snow depth, snow density, SWE) and five vertical profiles (snow pits) representative of the snow conditions of the region (snow density and depth of each layer, grain size and type, dielectric constant, temperature) were undertaken.

Table 2 gives a summary of the three ground campaigns. Between January 28 and March 8 1999, there is a 50 mm increase of the SWE due to new snow precipitation and a decrease of the Thermal Resistance (Th.Res.) of the snowpack due to its densification.

Table 2: Summary of the ground campaigns for winter 1998-1999

Period	Snow cover characteristics (mean values)				Soil (mean values)	
	Depth [cm]	SWE [mm]	Density [kg/m³]	Th. Res. [°Cms/J]	T°C	Dielectric Constant
9 – 12 November 1998	10	-	-	-	0.2	8.4
25 - 28 January 1999	100	210	211	8.0	-0.7	3.5
8 - 11 March 1999	111	261	236	7.3	-1.1	3.2

Figure 2 shows the evolution of the meteorological parameters (air temperature, soil temperature, snow depth) during the winter of 1998-1999. First, we notice the thermal isolation effect of the snow cover on the soil temperature starting at the end of November. Secondly, the air temperature during the week preceding the RADARSAT image acquisitions of late January and at the beginning of March is characteristic of mid-winter conditions for this region ($T°_{air} < -15°C$). Thirdly, the maximum snow depth (126 cm) is also the normal snow depth for this region but is higher than the previous two winters (70 to 80 cm as shown in Figure 3). Fourthly, the soil is frozen but the soil temperature at the snow/ground interface is a bit warmer then the last two years. Finally, there was an additional accumulation of 10 cm of snow between the two RADARSAT acquisitions of January 22 and January 25, 1999.

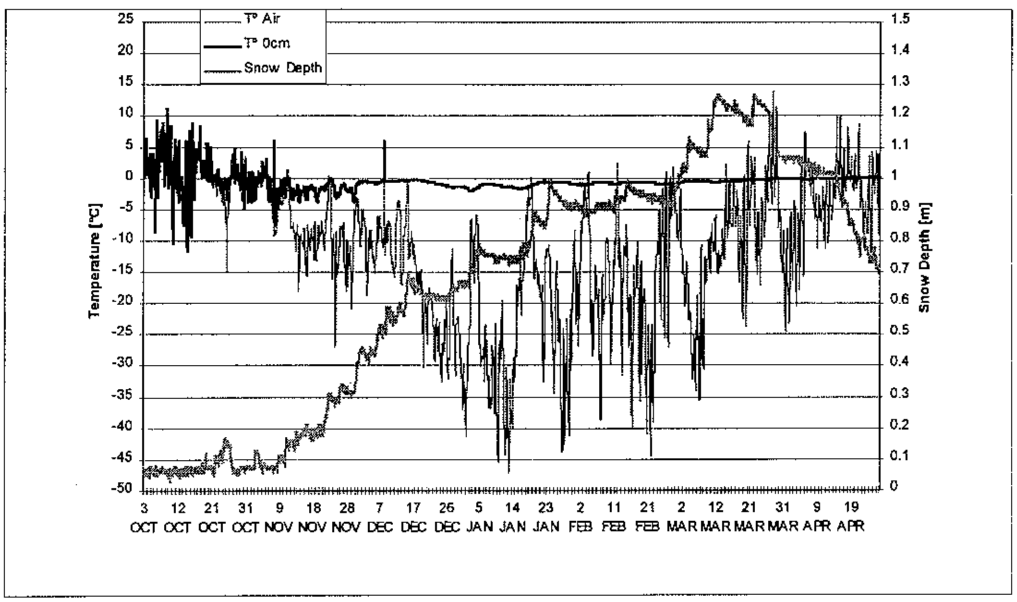

Figure 2 : Data for the winter of 1998-1999 from an automatic meteorological station installed on the LG4 sub-watershed (test site #2).

Also, a land cover map of the three sub-watersheds was made from five Landsat-TM images. There are six distinct land cover classes: forest, open forest, open land, burned forest, bare soil/rock and water. This map has been integrated into the *EQeau* software where a mean snow density is attributed to each land cover class. Furthermore, since the algorithm was developed for land only, all water pixels will receive the mean snow water equivalent value calculated over land.

IMAGE PROCESSING

All calibrated Wide (W1) images were processed by VIASAT Géo-Technologie Inc. using both their own geometric correction software and the EASI/PACE image analysis software. The main steps for processing the RADARSAT SAR images are: inversion of the Look-up table (Altrix Systems, 1998), tranformation of DN into power values, geometric correction using a DEM, image filtering and computation of the backscattering coefficient (σ^o_i) for each pixel. Then, the image can be imported into *EQeau,* where the backscattering ratio between the winter image and the reference (snow-free) image are calculated. This ratio (σ^o_w - σ^o_r) is used to reduce the impact of vegetation and topography.

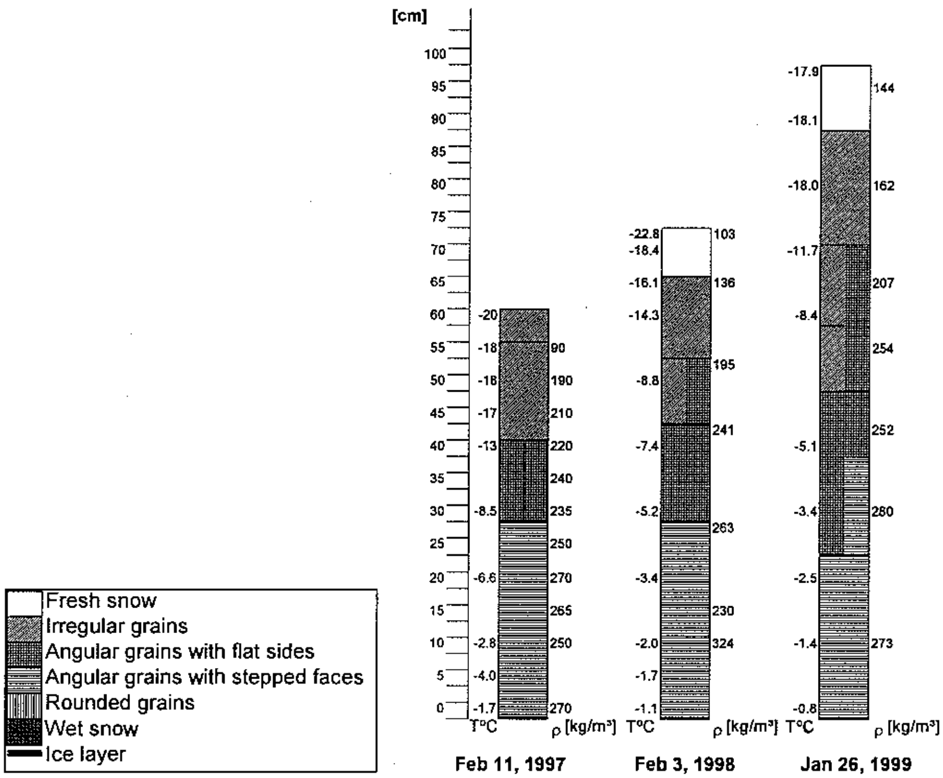

Figure 3 : Comparison of snow profiles measured on test site #2 in 1997, 1998 and 1999

VALIDATION OF THE ALGORITHM

The algorithm is based on studies conducted by INRS-Eau in a southern Québec agricultural area (Bernier and Fortin 1998) and in northern Québec (LG4 sub-watershed) with ERS-1 images (Bernier *et al.,* 1999a). The physical principles are the following:

- The snow cover characteristics (Thermal Resistance) influence the underlying soil temperature.
- The dielectric constant of the soil varies with the soil temperature under 0°C. The colder is the soil, the lower is the dielectric constant.
- The radar signal is influenced by the soil dielectric constant and the penetration depth of the frost in the soil.
- Consequently, the snow cover characteristics influence the signal recorded by the SAR sensor .

To recover the SWE from RADARSAT SAR data, the algorithm uses two equations (Bernier and Fortin 1998). The first one, is the linear relationship between the backscattering ratios and the snowpack thermal resistance. As mentioned earlier, the colder the soil and the deeper the frost, the lower the backscattering ratio (Figure 4).

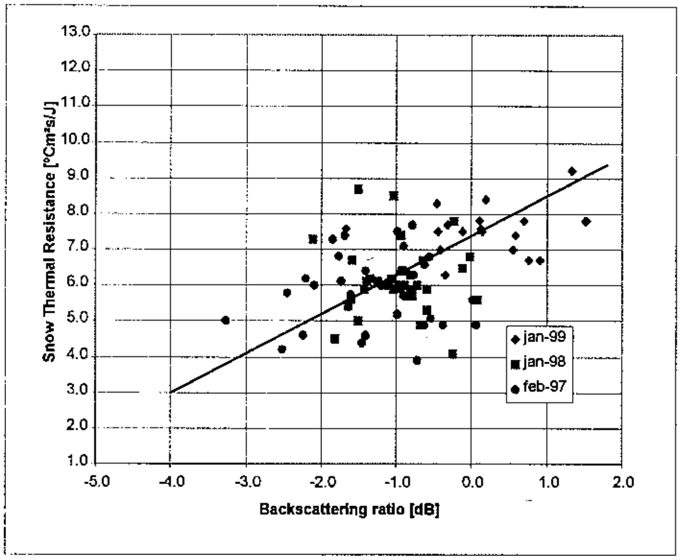

Figure 4 : Relationship between the backscattering ratios and the Thermal Resistance of the snow cover

The second equation infers the SWE from the estimated thermal resistance (derived from the first relationship) and the snow density (obtained from snow lines or snow models). The relationship between the SWE and the thermal resistance, as a function of density, is illustrated in Figure 5.

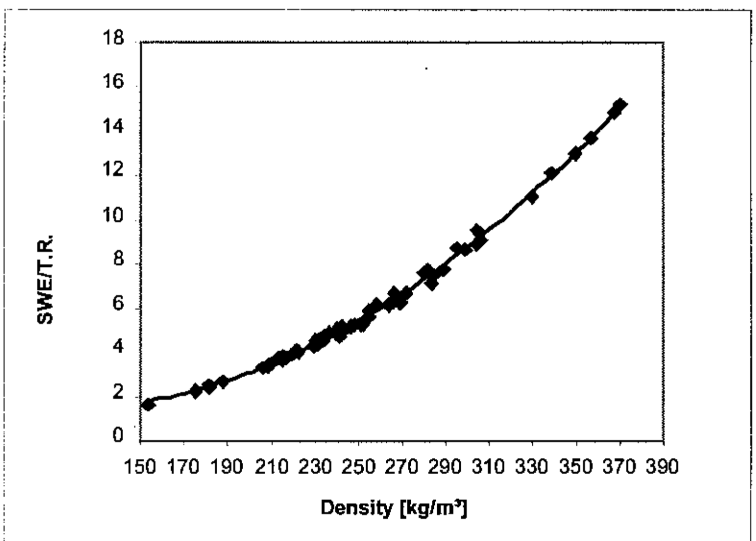

Figure 5 : Relationship between the SWE and the thermal resistance of the snow cover, as a function of density

For RADARSAT images acquired in mid-winter conditions, the first part of the algorithm has been developed previously from Standard images acquired in February 1997 and January 1998. The Thermal Resistance of the snow cover was computed from field measurements for about 20 homogeneous sites. Those values have been related to the mean backscattering ratio of each homogeneous site extracted from the two Standard images (Figure 4). Then, the backscattering ratios of the sampling sites extracted from the Wide images acquired in January 1999 (table 1) and the corresponding thermal resistance of the snow cover, measured on site, were added to Figure 4 to confirm the previously established relationship (Bernier *et al.*, 1998).

The refined algorithm was first tested on the backscattering ratios extracted from the Wide images of January 1999, over the sampling sites. The resulting mean SWE, for those sampling sites, is 219 mm with a standard deviation of 25mm. Those values are similar to the mean SWE measured by snow transects for the same sampling sites during the field campaign (mean of 213 mm, standard deviation of 18 mm).

SWE MAPPING

Using the *EQeau* sofware, the algorithm was then applied to the three Wide images acquired in January 1999 in order to map the SWE over the three sub-watersheds (*LG4*, *Laforge* and *Caniapiscau)*. The resultant maps are presented in Figure 6. There is a noticeable difference between the SWE estimated for the East images acquired on January 22 (Caniapiscau) and the West image acquired on January 25 (LG4). An analysis of the January 25 image revealed abnormally high backscattering coefficients at the lowest (18-24°) and highest (28-31°) incidence angles resulting in the overestimation of the SWE (250+ mm) for those areas (Bernier *et al.*, 1999b). However, the SWE estimated for the central part of the image is consistent with the values measured during the field campaign (~200 mm). On the Caniapiscau sub-watershed, the highest SWE values (201 to 250 mm) correspond to higher elevations the sub-watershed boundaries. The lowest SWE values (101 to 150 mm) can be found near the Caniapiscau reservoir.

The mean SWE over each sub-watershed was also computed by *EQeau*. Table 3 compares these values to the mean SWE derived from interpolation of the Hydro-Québec regular snow transects. The over-estimated SWE for a part of the LG4 image has affected the mean value calculated for that watershed. For the Caniapiscau watershed, it is important to note that the two Wide images were acquired a week before the HQ snow transects. A snow precipitation (SWE ~15-20 mm) was recorded during the interval and is the cause for the under-estimation seen in Table 3.

Table 3: Comparison of the estimated SWE and the measured SWE for January and March 1999.

Sub-watershed	Snow Water Equivalent	
	RADARSAT Images	**Hydro-Québec Survey**
	January 22 and 25	**January 22 through January 30**
LA1	216 mm (87% of the watershed)	213 mm
LG4	225 mm (74% of the watershed)	214 mm
Caniapiscau	189 mm (89% of the watershed)	215 mm
	March 11	**March19 through March 21**
Caniapiscau	312 mm (89% of the watershed)	331 mm

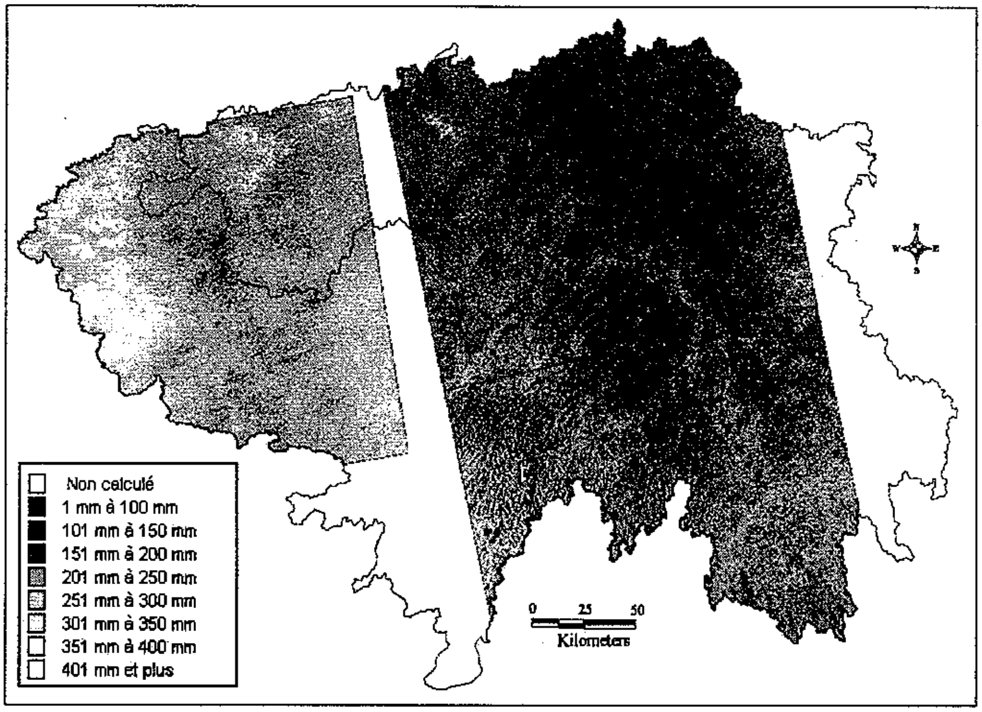

Figure 6 : SWE map derived from RADARSAT images acquired on January 22 and 25, 1999

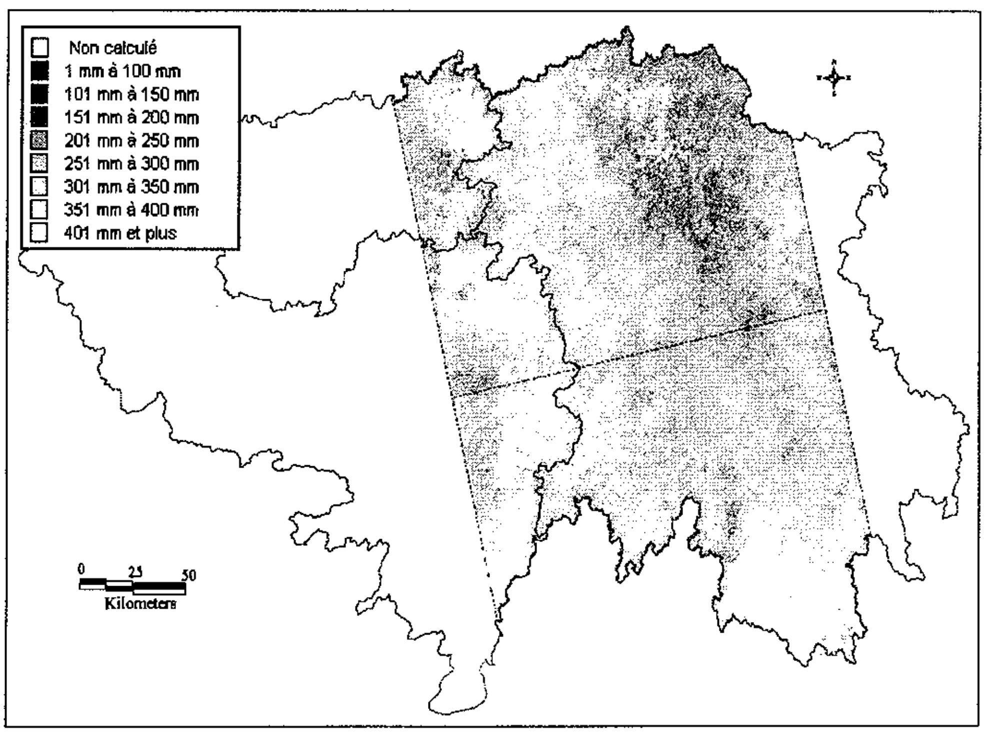

Figure 7 : SWE map derived from RADARSAT images acquired on March 11, 1999

The same algorithm (mid-winter conditions) has been applied by *EQeau* to the two Wide images acquired on March 11, 1999. The SWE map are shown on Figure 7. An important increase of the SWE was noticed and measured during the March field campaign (table 2). This increase is also apparent on the map produced by *EQeau*. Again, the highest SWE is found on the hills and the lowest SWE near the Caniapiscau reservoir. The mean SWE over the Caniapiscau sub-watershed was also computed by *EQeau* . The result is shown on table 3. Again, the snow transects were done a week after the RADARSAT overpass.

CONCLUSION

The *EQeau* software was used successfully in pre-operational mode during the winter of 1999.

The RADARSAT algorithm has performed well either under normal snow cover conditions (1999) using Wide (W1) images or under snow conditions below normal (1997-1998) using Standard images (S1). The increase of the measured SWE from late January to the beginning of March is clearly detected on SWE maps produced by *EQeau*. The mean estimated SWE on each sub-watershed is comparable to values obtained by the interpolation of Hydro-Québec field surveys. However, there is an uncertainty on both methodologies used to derive the mean SWE. We are presently working on the determination of these uncertainties for the RADARSAT approach.

Since the calibration of the ScanSAR images was not confirmed by the Canadian Space Agency until February 1st 1999, calibrated data were not used for this analysis. Results with the ScanSAR data sould be available soon. Following this analysis, we will be able to assess the uncertainty on SWE estimations from both Wide and ScanSAR images. Then, knowing the corresponding economic advantages of these RADARSAT products (Martin *et al.*, 1999), we should be able to make recommendations to Hydro-Québec managers concerning the type of data which is best suited for an operational use of *EQeau* on the La Grande watershed. The approach described in this study was developed for a watershed dominated by open forest and open land and should work for any similar environment, as long as the soil freeze during the snow season.

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