Combined use of VEGETATION and RADARSAT data for updating areal distribution and water equivalent of snow cover, in the HYDROTEL hydrological forecasting model

by

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INTRODUCTION

Accurate forecasting of snowmelt in Spring is a very important component of any flood prevention strategy. Yet, the use of remotely sensed data and even hydrological models is far from being a daily practice in most forecasting agencies, for various reasons mostly related to a strong reluctance to change. Other agencies, like Hydro-Québec, are prepared and willing to make the necessary steps.

In the meantime, researchers at INRS-Eau have been working for many years on the development of both application of remote sensing to hydrology and distributed hydrological models able to use remotely sensed and GIS data. Within the framework of the VEGETATION Preparatory Program, we have developed a snow mapping methodology at the sub-pixel level as well as a reflectance estimation of individual land use classes from the Vegetation data. Concurrently, in the framework of similar RADARSAT programs, we have developed a software package called EQeau, for the distributed estimation of the water equivalent of a dry snowpack. Also, the HYDROTEL hydrological model has been adapted to hydrological forecasting.

In this paper, we will first explain why hydrological models do need updating of their state variables for more accurate streamflow forecasts. The approach used to permit updating of state variables using VEGETATION and RADARSAT data will follow. Finally, we will conclude with comments on the interest of using remotely sensed data for hydrological forecasting.

NEED FOR UPDATING OF STATE VARIABLES

As shown in Figure 1, the HYDROTEL model (Fortin et al., 1995) is a distributed hydrological model whose spatial structure allows simulation of the vertical water budget on very small sub-basins built up using small cells from a digital elevation model. Figure 1 shows the complete basin as well as a zoom on a few sub-basins close to the outlet of the basin. Flow direction from cell to cell can be seen. The available simulation options for the vertical water budget are also shown on the figure. Water available at each time step is routing downstream using kinematic equations. As long as there is snow on the ground, the model simulates the variation with time and space of the water equivalent (SWE) of the snowpack in three main land use classes: open areas, deciduous forests and coniferous forests. Figure 2 shows a map of SWE in those classes on March 31, 1988. As the available meteorological data used as input to a model may not be always accurate or representative and no model is perfect, differences between the simulated and measured SWE at different locations within the basin may appear. For instance, it is shown in Figure 3 that the simulated SWE fits very well with the measured values at the Vallée-Junction station throughout the snow season whereas it is well above the measured values at the Saint-Etienne station. An analysis of the meteorological stations responsible for those values showed indeed that they were not representative at the beginning of winter. Also, there are only eight snow survey stations, on that basin that covers more than 6000 km², and SWE measurements are taken only five or six times during the season. Updating of the snowpack using snow survey data can improve streamflow
simulations as long as the measured values are representative of the distribution of SWE on the basin (Figure 4), but remote sensing appears to be a very valuable complementary source of data because it furnishes already distributed information on the snowpack and can be integrated with ground data.

UPDATING PROCEDURE USING VGT AND RADARSAT DATA

During winter and with below zero temperatures, the snow is dry. Then, VGT data allows monitoring of snow surface albedo, a very important variable that controls solar energy input to the snowpack. A procedure for reflectance estimation in various land use classes based on spectral mixture theory and using VGT data, is proposed in Fortin et al. (2000).

While monitoring albedo with VGT data in the absence of clouds, it is also possible to monitor SWE using RADARSAT data (Bernier et al., 1999) without being affected by clouds. Snow is essentially transparent in C-band. However, snow acts as a thermal insolation for the underlying ground. Then, for given meteorological conditions over a large region, the areal distribution of snowpack characteristics will affect the temperature and liquid water content of the ground underneath and, thus, the dielectric constant of the surface layer of the ground. Then, the spatial distribution of the dielectric constant of the ground will result in a spatial distribution of the backscattering coefficient from different surfaces within that region, which will be a function of the thermal resistance of the snowpack through its effect on the ground characteristics. As surface roughness also affects the backscattering coefficient, the backscattering ratio between a snow covered image and a snowfree image is compared to the thermal resistance of the snowpack rather than the snow covered image alone, in order to minimize the effect of surface roughness on the relation. This relation can be written:

\[ R_{est} = m \left( \frac{\Phi_{B_w}}{\Phi_{B_r}} \right) + b \]  

(1)

where:
\( R_{est} \) = thermal resistance of the snowpack;
\( m \) = slope of the relation;
\( \Phi_{B_w} \) = backscattering coefficient over snow covered ground;
\( \Phi_{B_r} \) = reference backscattering coefficient over snowfree ground;
\( b \) = ordinate at the origin.

Since the thermal resistance of the snowpack for each layer of density \( \Delta \) is proportional to its thickness \( h \) and inversely proportional to its thermal conductivity \( k(\Delta) \), whereas the SWE is proportional to both the thickness \( h \) and the density \( \Delta \), there is a direct relation between the thermal resistance of a snow layer \( R_{est} \) and its SWE:

\[ \text{SWE} = R_{est} \cdot k(\Delta) \cdot \Delta \]  

(2)

The total SWE equivalent of a snowpack is naturally the sum of the SWE of the individual layers. In practice, a mean density is assumed and it is possible to obtain an estimation of SWE by first estimating the thermal resistance of the snowpack from equation 1 and then using equation 2 to estimate the SWE equivalent corresponding to the estimated thermal resistance of the snowpack, knowing the mean snow density on the day on which the winter image was taken. For a particular region, this value can be estimated from ground measurements, \( R_{est} \) past records of snow density as a function of time or from simulation of the snowpack by an hydrological model.

As the monitored basins in Northern Québec are very large (greater than 30 000 km\(^2\)), ScanSAR images (500 km width) have been preferred to Wide Mode images (150 km width), since they could cover much larger regions. Figure 4 shows SWE maps obtained for three watersheds in the James Bay region on the
January 18 and March 7, 1999. The increase in SWE is clearly seen. For comparison purposes, the results obtained with Wide Mode images also appear on that image. Snow survey stations also exist in Northern Québec, but the network is rather sparse and the stations must be reached by helicopters. So, it is interesting to notice on Figure 6 that, with due care for the number of days between estimations and the types of data, the estimations made by the RADARSAT images on the three watersheds at three different dates in the 1998-1999 winter do agree with the ground surveys. However, with RADARSAT data, we do get the spatial distribution of SWE whereas, with the sparse snow survey network, we only get information at a few locations on that vast region. Then, RADARSAT data becomes an interesting new source of information to obtain better estimations of the areal distribution of SWE at different dates during the snow season.

Figure 7a shows that it is first possible to update the spatial distribution of SWE simulated by the HYDROTEL model using snow survey data a few times in the snow season, when there are surveys. SWE maps prepared with the EQeau software (Bernier et al., 1999) can also be used, with density values coming from the HYDROTEL model. Finally, there might be the possibility that snow survey data and SWE maps are available on the same day or a few days apart. They can then be used together to update the simulated SWE.

During the melt period, liquid water content prevents the estimation of SWE using RADARSAT data as the radar signal is strongly absorbed by the wet snow. However, the darker areas on the image will indicate where the snow is melting. Also, provided the sky is clear, the VGT data will show a lowering of reflectance indicating ripe snow. The VGT data will also allow estimation of snow cover at the sub-pixel level, as explained by Fortin et al. (2000). Figure 7b shows that this information can be used to update the areal distribution of snow cover during the melt period, whereas Figure 8 presents the percentage of snow cover remaining on each area corresponding to a VGT pixel on April 2 and April 11, 1999, in Southern Quebec. Weather permitting, daily snow cover maps could be available to update the snow cover simulated by the model, if necessary. The information on melting snow can be very useful to verify if the model is making the proper distinction between hydrological units on which melt has begun and those on which snow is still dry. Also, the information on the spatial distribution of snow cover at the sub-pixel level can be used to make any necessary correction to the snow cover area as simulated by the model.

CONCLUSION

We have shown that both VGT and RADARSAT data can be used routinely to furnish complementary information and make the needed updating of state variables. Of course, VGT images of snow cover can be obtained only during daylight hours, which may be a problem in the more northerly regions in winter, and for clear days, which may be a problem in Spring during the period in which they would be the most useful. As for RADARSAT images, they will be most useful over dry snow covers lower than one to 1.5m and for low to non forested areas. Faster access to the data and shorter processing times will also have to be obtained.

However, because meteorological data are not always representative of the variation with time and space of the meteorological phenomena affecting watersheds, hydrological models may simulate streamflow data that can be in error by a certain percentage. In the case of snow cover, it is possible to update the state variables of the model and, hence, obtain more accurate simulations, using snow survey data. But, only a few surveys are made during the snow season and at a few stations, particularly in northern regions. Then, remotely sensed data, as it is already spatially distributed, represent a very valuable complementary type of information.
REFERENCES


FIGURE 1: Modelled processes at the sub-basin level. a) The Chaudière basin divided into sub-basins b) Zoom showing flow structure in the sub-basins c) Available simulation options.

FIGURE 2: Water equivalents of the snowpack as simulated by the Hydrotel model on March 31, 1988.

FIGURE 3: Simulated (green line) and measured (red squares) water equivalents of the snowpack at eight snow survey stations on the Chaudière basin for the 1989-1990 winter.

FIGURE 4: Improvement of the streamflow simulations after snowpack updating from snow survey data a) For the Chaudière river at St-Lambert (5820 km²) b) The Famine river (691 km²) and c) The Beaurivage river (709 km²), both at the confluence with the Chaudière river.
FIGURE 5: Spatial distribution of the water equivalents of the snowpack, as estimated from RADARSAT ScanSAR and WIDE mode data, by the EQeau software, on the LG4, LA1 and Caniapiscau sub-basins of the La Grande River (Québec, Canada). a) January 18, 1999 b) March 7, 1999.

FIGURE 6: Comparison between ScanSAR, Wide mode and in situ estimations at the sub-basin level.

FIGURE 7: Updating procedure of the snowpack in Hydrotel a) using snow surveys and RADARSAT data b) using snow surveys and VEGETATION data.
FIGURE 8: Spatial distribution of the snowpack in Southern Quebec as estimated from VEGETATION data at the sub-pixel level. a) April 2, 1999 b) April 11, 1999.