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Application of SAR Snowcover Mapping to Hydrological Modelling of Snowmelt Runoff in Southern Ontario

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ABSTRACT

In this experiment WATFLOOD, a distributed hydrologic model, was set up for the 1991 spring snowmelt event on the Grand River watershed to investigate the possibility of using airborne nadir C-band Synthetic Aperture Radar (SAR) imagery to update the model by providing snowcovered area (SCA) information. WATFLOOD parameters were first derived using only atmospheric and ground data, the model was then run again to derive parameters using the SAR imagery to update the model. The results showed that model appeared to simulate the river flow better when updated using the SAR imagery. It was concluded that the present WATFLOOD optimization, which deals solely with river flows, allows for unrealistic values for snowmelt. This can be corrected by separate optimization of snowmelt parameters to known snowcover characteristics and of snowpack hydraulic characteristics to streamflow.

INTRODUCTION

The simulation of snowmelt runoff in low-relief regions is complicated by the presence of shallow discontinuous snowcover. The development of hydrological models, spatially discretized on the basis of Grouped Response Units (Kouwen et al., 1993) or Hydrologic Response Units (Leavesley and Stannard, 1990), can incorporate distributed snowcover information, such as percent snowcovered area at different locations in the watershed, into the algorithms. Hence distributed snowcover information can be used for model calibration and/or validation. WATFLOOD uses the Grouped Response Unit approach (Kouwen *et al.*, 1993) for computational elements and provides snowcovered area estimates on a landcover basis within each response unit.

Visible-band imagery has proven useful in alpine regions (Rango and Martinec, 1979) but the utility of visible band satellite imagery in regions such as southern Ontario is limited by the frequent cloud cover during the spring period. Active microwave sensors such as the proposed RADARSAT can penetrate cloud cover and will be able to provide frequent high resolution imagery for use in hydrological applications (St. Pierre, 1989). Matzler and Shanda (1984) discussed the potential for watershed-wide mapping of wet snowcover using Synthetic Aperture Radar (SAR) imagery and Donald *et al.* (1992) indicate that the classification accuracy of the snow covered and bare field mapping for sensors such as RADARSAT may be on the order of 80%. Other reports have discussed microwave measurement of snowpack properties on small test areas, for example Stiles *et al* (1981), however do not compare SAR imagery of snow to ground reference data.

In this paper the hydrological model WATFLOOD (Kouwen, 1992) is used to simulate snowmelt runoff for the 1991 spring melt event in the northern Grand River watershed. The estimated snowcovered area derived from the model is then compared to snowcovered area estimates from concurrent airborne SAR C-HH imagery.

WATFLOOD SIMULATION

WATFLOOD is an integrated set of computer programs to forecast flood flows for watersheds having response times ranging from one hour to several weeks. Through the use of Grouped Response Units (GRUs), WATFLOOD is able to preserve the distributed nature of a watershed's hydrologic and meteorologic condition. Using this approach, regions with hydrologically similar response within each GRU are grouped together, regardless of location, and each group is treated separately for runoff calculations. The sum of the runoff from each type of region within a GRU becomes the total runoff from the GRU that is available for stream flow routing. Groups within each GRU are usually assembled by vegetation type.

The processes and components of the hydrologic budget included in WATFLOOD are: precipitation, interception, depression storage, infiltration, upper zone storage and runoff, surface runoff, groundwater runoff, baseflow and channel routing. The model also includes the ability to optimize certain parameters that are not easily evaluated, such as ground roughness, permeability and upper zone storage depletion. WATFLOOD is summarized in Kouwen *et al.* (1993) and a detailed description is in Kouwen (1992).

WATFLOOD was originally designed for non-winter conditions but was modified by Donald (1992) to include a snowmelt process model. This model includes the additional hydrologic budget components; precipitation as snow, snowpack distribution, snowpack energy budget and snowmelt runoff. A temperature index approach to the snowpack energy balance is used in the model and is defined by the equation:

$$M_i = MF_i \, (T_a - T_{oi})$$

where:

M_i = snow meltwater generated (mm/hr)
MF_i = melt factor (mm/hr/°C)
T_a = atmospheric temperature (°C)
T_{oi} = base temperature for melt occurring (°C)
i = land class.

The melt factor and base temperature are optimized parameters. The melt factor relates the amount of snow meltwater generated to the atmospheric temperature and the base temperature is the lowest temperature at which melt occurs.

Donald (1992) also investigated the use of Snowcover Depletion Curves (SDCs) in WATFLOOD. These are micro-scale representations of snow coverage, relating the average basin snow water equivalent or snow depth to the percent snowcovered area. The research demonstrated that small improvements in distributed snowmelt modelling can be made through the use of straight-line land cover based SDCs. Thus using snowcovered area as input into the model would be useful in improving the model.

Seglenieks (1993) enhanced the model, by allowing the SCA to be output for all grid squares for any hour of the simulation. The overland flow roughness parameter was also separated into 2 components: bare ground and snowcovered ground. These are to account for the lag which occurs when snow meltwater reaches the ground surface and creates a basal ice layer.

THE 1991 SPRING MELT EVENT

The Grand River watershed is located in south-western Ontario. WATFLOOD was set up for the 1991 spring snowmelt event on this basin using 10x10 kilometre square GRUs. In this study the upper unregulated portion of the watershed was used. This section of the watershed (Figure 1) has a drainage area of 1552 km^2 and five streamflow gauges operated by the Grand River Conservation Authority. Within the Grand River watershed the following hydrologically significant land classes occur: open field, forest, crop and marsh.

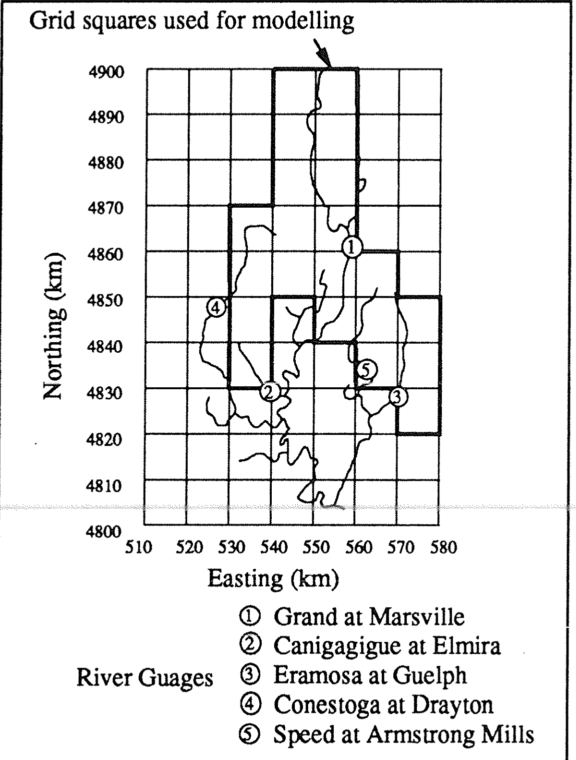


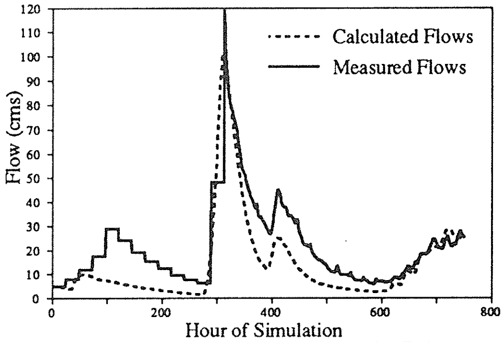
Figure 1: WATFLOOD grid squares used in modelling

Table 1: Summary of S Criterion for Grand River watershed melt events

River Gauge	1975	1980	1985	1988	1991	1991
					Original	Updated
Grand at Marsville	0.527	0.441	0.344	0.495	0.400	0.419
Eramosa at Guelph	1.668	0.778	0.510	0.398	0.212	0.204
Conestogo at Drayton	0.721	0.601	0.375	0.359	0.337	0.363
Speed at Armstrong Mills	1.411	0.552	0.330	0.698	0.565	0.575
Canigagigue at Elmira	1.891	1.593	0.632	0.651	1.258	1.267
Average S value	1.244	1.593	0.438	0.520	0.554	0.566

In this region the snowpack is usually established by late-November to mid-December and can last until late March to mid-April. The combination of shallow discontinuous snowcover and variable winter temperatures allows the snowcover to partially or completely disappear and re-establish any time from early winter through late spring. Generally high river flows are caused by a combination of snowmelt, spring rainfall and frozen ground conditions, which frequently occur during partial snowcover (Donald, 1992). Since the studied portion of the watershed is unregulated, the snowmelt and rainfall input will dominate modelled stream flow output.

Optimization using original parameters



Optimization using SCA data from SAR image

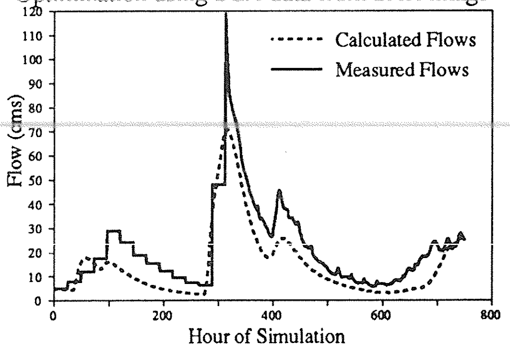


Figure 2: Flow simulation for river gauges covered by SAR image

WATFLOOD was run on the 1991 spring melt event to optimize four parameters: bare ground roughness, snowcovered ground roughness, melt factor and base temperature. The other non-snow parameters were taken from Donald (1992). The derived and measured hydrographs for the streamflow gauge Grand at Marsville (see Figure 1 for location) are shown in Figure 2.

The 1991 event was then evaluated using the S criterion, defined as the ratio of the root mean squared error of the estimated flows to the mean observed discharge for the simulation period. This criterion was shown to be particularly useful in evaluation of snowmelt runoff models (WMO, 1986), however they also suggest the most important criterion is the visual inspection of simulated and observed hydrographs.

Use of the S criterion also allowed comparison with four other melt events in the Grand River watershed studied by Donald (1992). The average S values for these events were 1.244, 0.793, 0.438 and 0.520 for 1975, 1980, 1985 and 1988, respectively, with the values for the individual sub-basins summarized in Table 1. For the 1991 melt event, the average S value was 0.554 which compares well to the previous melt events.

Maps of the SCA estimated by WATFLOOD were produced for specific days of the melt cycle. In particular, SCA maps were output for the portion of the watershed covered by the SAR image for dates on and after the imagery was acquired (Table 2).

CLASSIFICATION OF THE SAR IMAGE

On March 15 and 16, 1991 an experiment was conducted in which airborne nadir mode C-HH SAR imagery was acquired by the Canada Centre for

Table 2: Snow covered area calculated by WATFLOOD for grid squares covered by SAR image

	March 16		March 17		March 18		March 19	
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Original Model	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Parameters	100.0	100.0	100.0	100.0	100.0	91.9	75.1	57.5
	*****	100.0	****	100.0	*****	100.0	*****	65.3
	100.0	100.0	100.0	77.7	65.2	35.7	42.5	24.0
	22.0	21.5	12.0	9.1	3.4	2.7	4.9	3.5
Updated Model	22.4	15.0	11.0	7.4	3.1	1.8	4.5	2.3
Parameters	8.7	5.7	3.3	3.1	0.8	0.7	1.1	1.2
	*****	5.8	*****	2.2	*****	0.5	*****	1.1
	17.9	16.8	7.5	8.2	1.5	1.6	2.7	2.2
	16.3	19.5	A*	B	* Square location in Figure 3 ***** - Luther Marsh			
From Classified	19.6	20.7	C	D				
SAR C-HH Image	19.3	14.9	E	F				
	*****	6.8	*****	H				
	24.5	8.0	I	J				

Remote Sensing (CCRS) CV-580 System (Livingstone et al., 1988). The objective of the experiment was to compare the snowcovered area derived from SAR imagery taken on March 16 to coincidental aerial photography taken on March 15 at two sites each approximately 5 km^2. A full description of the experiment is given in Donald *et al.* (1992). Classification accuracies were above 80% for open areas with most of the errors a result of confusion over wet soil and wet snowcover.

This study used the same SAR imagery collected on March 16, 1991, however here snowcovered area was derived for the entire image of approximately 850 km^2. The image fully covers 4 grid squares in the WATFLOOD simulation and partially covers 6 more (Figure 3) with the partially covered squares each at least 50% within the image. Eight of these squares are upstream of the Grand at Marsville river gauge.

In order to remove the speckle inherent in all radar imagery, an adaptive filter was used to smooth the image data without removing edges or sharp features. The filter used by the software is the Frost filter which is an exponentially damped convolution kernel that adapts itself to features using local statistics. The adaptive filter computes a set of weight values for each pixel within the filter window surrounding each pixel (PCI, 1992). A filter size of 7 by 7 pixels was used on the entire image. Pixels have ground footprints of 6m by 6m.

The image was georeferenced using over 50 ground control points and a third order transformation. The georeferenced image was then split into separate data files each corresponding to a single grid from the WATFLOOD simulation. For each of these, the useful portion of the image within each site was visually determined and this part used for further analysis.

Training sites were chosen for the image in three categories; forest or scrub, snowcovered field, and bare field. Because of the change in incidence angle, the western portion of the image had a lower return than the eastern portion, hence different training sites were chosen in each portion of the image for the forest or scrub and bare field landcover classes.

Table 3: Summary of Classification Results for Grid Squares Covered by SAR Image

Land Class	Grid Square (percent of each class)								
	A*	B	C	D	E	F	H	I	J
Forest or Scrub	29.3	36.7	35.1	24.2	34.2	27.2	19.5	13.1	13.2
Snow Covered Field	11.5	12.3	12.7	15.7	12.7	10.8	5.5	21.5	6.9
Bare Field	59.1	51.0	52.2	60.1	53.1	61.9	75.0	65.4	79.9

* grid square location in Figure 3

From the statistics gathered at the training sites (Figure 4) snow had the lowest return and the forest and scrub had the highest return. The low return of snow is because the water in the snow acts as a specular reflector of radar waves while the high return from forest or scrub is a result of the trees acting as a group of volume scatterers composed of a large number of discrete plant components (Lillesand and Kiefer, 1987). A maximum likelihood classifier was then used to classify the image using the training site statistics.

The results of this classification are summarized in Table 2. The grid square containing Luther Lake and Luther Marsh was dropped from the classification as the low return of the lake and marsh areas were difficult to distinguish from wet snowcover. Visual inspection of the SAR derived classification and the coincidental visual photography indicated a good match between the two. No attempt was made at quantifying this comparison. As in the study by Donald *et al.* (1992), most of the error in classification is probably caused by confusion in detecting the difference between wet soil and wet snowcover.

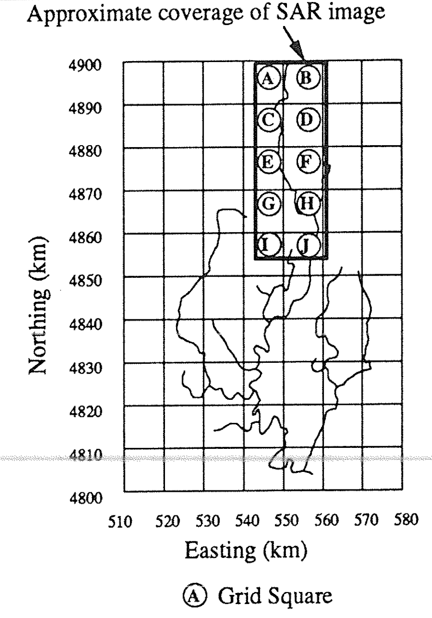


Figure 3: Coverage of SAR image on Grand river watershed

COMPARISON OF WATFLOOD AND SAR DERIVED SCA

The values of SCA for the open fields predicted by WATFLOOD did not match well with the values derived from the SAR imagery. However the SCA values from WATFLOOD for the days after the date of the SAR imagery predict that the melt occurred quickly after the date of the experiment. This is confirmed by snow depth measurements taken by Grand River Conservation Authority.

The discrepancy in the March 16 SCAs is understandable considering that the algorithm for optimizing the parameters in WATFLOOD finds the minimum error in the computed flows without reference to SCA.

Another problem for the running of WATFLOOD is the lack of initial snowcover information for different land covers in the Grand River watershed. For this simulation it was assumed that the snow depth was constant for all types of landcover, however snow depth has been shown to vary depending on land type (Adams, 1976).

Part of the experiment was to determine whether the model could be updated using the information gathered during the melt event. To do this, the snowmelt factor and base temperature parameters of the open areas were manually adjusted so the model would better simulate the snowcover information from the SAR image. Snowmelt parameters for other

Table 4: Summary of parameters derived from WATFLOOD optimization

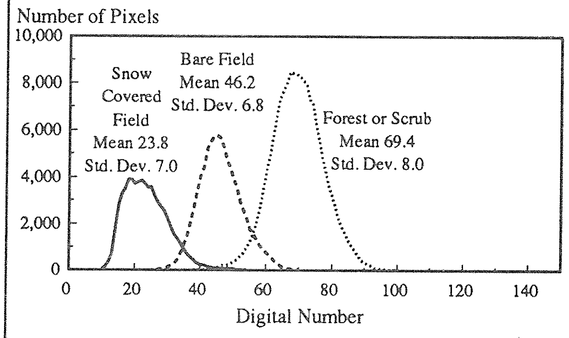
Land Cover	Melt Factor		Base Temperature		Snow Covered Field Roughness		Bare Field Roughness	
	Original	Updated	Original	Updated	Original	Updated	Original	Updated
Open	0.50	0.68	1.0	0.3	7	12.2	20	9.8
Forest	0.35	0.35	-0.3	-0.5	30	30	9.9	9.9
Crop	0.05	0.05	-7.5	-8.0	93	93	20	20
Marsh	0.07	0.007	3.5	3.0	67	67	8.9	8.9

landcover types were left unchanged. The optimization criterion chosen was the total squared error between the SCA estimates from the model and the SAR image for the nine grid squares. The SCA from this optimization for the grid squares covered by the SAR image is summarized in Table 3. The melt factor increased from 0.50 to 0.68 and the base temperature decreased from 1.0 to 0.3 (Table 4) for the open landcover class. Each of these changes would cause increased snowmelt.

The updated snowmelt and base temperature parameters for open areas were then held constant and the model was then run to optimize all other parameters. For this run, the bare ground roughness parameter for the open class decreased to 9.8 from 20.0 while the snowcovered ground roughness parameter increased to 12.2 from 7.0 (Table 4). This indicates the model compensated for the increased snowmelt by making it harder for the additional snowmelt to reach the river. The updated values for the open areas did not cause changes in the optimized values of the roughness coefficients for the other landcover types.

The S factor for these runs went up slightly to 0.565, a change of only 1.9%, indicating that the addition of more realistic snow parameters does not seriously affect the quality of the flow routing. But, visual inspection of the hydrographs (Figure 2) indicates that the flow may have been estimated better over most of the simulation period, only failing to adequately predict the peak flow. This incorrect peak flow estimate caused an overall increase in the S factor.

Training Area Data on Western Part of Image



Training Area Data on Eastern Part of Image

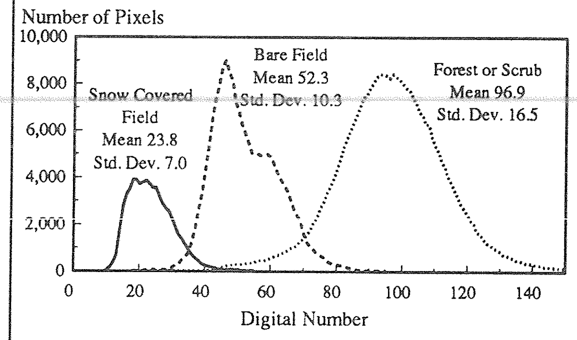


Figure 4: Training area statistics for SAR image

CONCLUSIONS AND DISCUSSION

From this experiment, it has been shown that the present optimization of WATFLOOD, which deals solely with river flows, allows for unrealistic values for snowmelt which are compensated for by decreased overland flow resistance. This can be corrected by separate optimization of snowmelt parameters to known snowcover characteristics and snowpack hydraulic characteristics to streamflow.

The separation of the statistics of the major land classes in the SAR C-HH imagery allow it to be used for mapping of the areal extent of wet snowcover in open fields to provide a data set for such separate parameter optimization. These images could also be used to update distributed hydrologic models such as WATFLOOD operationally.

Several limitations are apparent for operational application of the SAR imagery. The high return of forest or scrub areas masks the effects of snowcover on the ground surface requiring other sources to obtain SCA information. Possible solutions to this is the use of different wavelengths and incidence angles 8of the radar which may allow for greater penetration of the radar signal in rough vegetation.

Also, application of the imagery is limited to periods when the surface of the snowpack is wet. As a consequence, SAR imagery would have to collected during a time of day when surface melt has occurred.

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