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Application of Weather Radar to Model the Snow Hydrology of Southern Ontario

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ABSTRACT

Weather radar is used to approximate the accumulation of snow over the winter season as input to hydrologic watershed modelling for estimation of hydrographs. The hydrologic modelling is accomplished using a coupling of WATFLOOD, a distributed hydrologic model developed at the University of Waterloo, and CLASS, the Canadian Land Surface Scheme developed by Environment Canada. Good estimates of snowfall are provided by weather radar when compared with data from three Nipher-shielded Belfort precipitation gauges, especially when the radar images are adjusted for scale removal and for temperature during mixed-precipitation events. The modelled snow water equivalences are greater than measured snowcourse SWE for the 1993 winter, however, the model snow accumulates at the same rate as observed. The computed spring snowmelt hydrographs matches the observed streamflow well for the 1993 winter season across the Grand River basin in southern Ontario.

Key words: snowpack, hydrologic modelling, weather radar, southern Ontario

INTRODUCTION

Since the creation of the Stanford Watershed Model in 1966, numerous models have been developed to simulate various hydrologic processes. The combined increases in computer accessibility and power, automated observation and remote sensing, and environmental accountability have fuelled the advance of hydrologic models as tools for water resources management and prediction. Today's models incorporate most components of the hydrologic cycle reasonably well, in their attempt to integrate physical properties with physical processes to estimate water quantities. A demanding task for a hydrologic model is the simulation of winter processes, in particular those related to snow.

In regions that are snow-covered for part of the year, the largest streamflows often occur as a result of spring snowmelt. Continuous hydrologic modelling is difficult through the winter due to uncertainties in snowfall, as well the complexities of the snow processes (eg., Pomeroy *et al.* 1998). Often the prediction of the spring hydrograph through hydrologic modelling is simplified by concentrating on the snowmelt period, through assessment of the state of the snowpack at the onset of melt.

The objective of this paper is to present progress in modelling hydrologic conditions throughout the winter season using weather radar as the precipitation input. Modelling of the snowpack provides continuous estimates of the snow state variables, water/moisture movement and storage for spring streamflow simulation. This also provides important feedback for atmospheric modelling.

The steps in the modelling procedure are: using weather radar to approximate snow accumulation over the winter, modelling the snowpack using a coupled hydrologic-land surface scheme model, and routing snowmelt to gauged locations in a watershed. This is part of a larger project to incorporate hydrology into atmospheric models using a soil-vegetation atmospheric transfer (SVAT) scheme. The hydrologic model is based on WATFLOOD and the SVAT is an adaptation of the Canadian Land Surface Scheme (CLASS).

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The progress is demonstrated by the following comparisons: i) snowfall estimation by precipitation gauge measurement to weather radar accumulations; ii) snowpack development by measured properties to modelled results; and iii) measured streamflow, as a watershed integrator, to simulated hydrographs.

BACKGROUND

Radar precipitation estimation

Radar has been used for 50 years to estimate rainfall rates by relating reflectivity of falling particles (Z) to precipitation rate (R). The Z-R relationship, initially developed by Marshall and Palmer (1948) for rainfall, is based on observations in individual storms and theoretical analysis, related in part to drop size distributions. Numerous Z-R relationships have been developed for snowfall, however most are based on individual storm events and involve comparisons to precipitation gauges. The analysis by Sekhon and Srivastava (1970) concluded that snow particle size distribution increases rapidly with precipitation rate. At present the Z-R relationship developed by Sekhon and Srivastava is widely used for the cold weather season precipitation estimation.

Weather radar has been used to estimate rainfall across watersheds in numerous studies, including an early study by Kouwen and Garland (1989), however, no references have been found in the literature that use radar to estimate snowfall for hydrologic modelling.

Hydrologic modelling

For this research, the WATFLOOD and CLASS models are used to simulate the streamflow and snowpack, respectively. The lateral water movement and streamflow routing is performed using the WATFLOOD distributed hydrologic model developed at the University of Waterloo. It uses the Grouped Response Unit approach (see Kouwen *et al.* 1993) that incorporates land cover heterogeneity within grid elements. The grid elements are normally square and are usually 2 to 50 kilometres in length. Up to 15 different land covers types can exist within each grid element, each of which has different soil and vegetative properties.

The CLASS model, developed by Environment Canada (Verseghy 1991) provides physical modelling of the vertical water and energy budget. Snow is accumulated into a single layer pack and budgeting is performed using heat and moisture transfer. At present, CLASS incorporates the following snow processes: surface albedo, snowpack density, effective thermal conductivity, snow heat capacity, short-wave radiation density fluxes, sublimation, snowmelt, and meltwater evaporation (Verseghy 1991).

APPLICATION

Study Area

This research is undertaken in the area of central south-western Ontario covered by the Atmospheric Environment Service King Radar (Fig. 1a). The radar is located near King City, Ontario (43° 57' 50"N, 79° 34' 27"W). The installation is primarily a C-band radar (5.2 cm), although it has X-band capabilities. It provides a conventional radar image with a 2 x 2 km grid over a scanning radius of 200 km. The hourly precipitation accumulation maps are rates in millimetres of water. These radar maps are prepared from 10 minute Constant Altitude Plan Position Indicator images, based on the radial hit closest to centre of the square grid pixel. For the warm season, the power law reflectivity-precipitation rate relationship developed for southern Ontario by Richards and Crozier (1983) is used, and for snow the Sekhon and Srivastava relationship is used (Crozier *et al.* 1991). A comparison of these two sets of coefficients illustrates that for the same return signal, there would be 4.06 times as much water falling in the summer than in the winter.

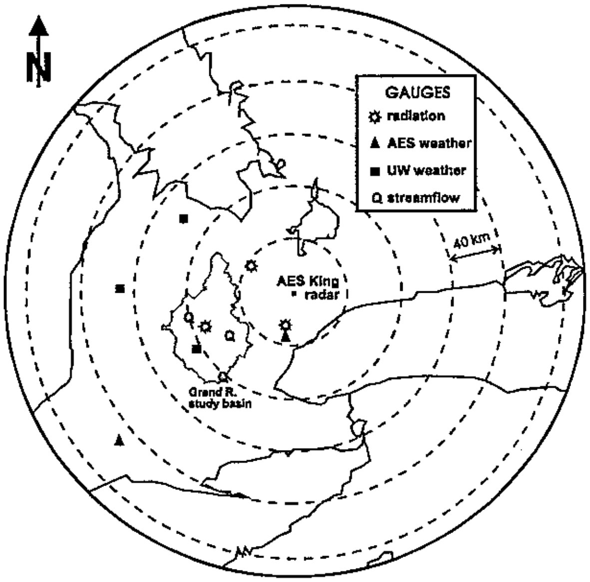

Figure 1a. Map of central south-western Ontario illustrating the AES King City Radar coverage and the Grand River study basin.

The focus of this paper is the Grand River watershed (Fig. 1b), modelled using 10 by 10 km grid elements. Most of this watershed is covered by crops and low vegetation (59%), with smaller regions of wetland (18%) and mixed deciduous-coniferous forest (14%). The remainder of the watershed comprises bare (8%) and impervious (1%) areas. The terrain in this portion of southern Ontario is glacial material, composed primarily of clayey till. The three hydrometric stations that will be used are the outflow of the basin at Galt and two smaller sub-basins, the Speed River above Armstrong Mills and the Conestogo River above Drayton. In total eight snowcourse locations are sampled on a bi-weekly basis in the study basin, four in the northern section and four in the southern section. The snowcourses were located in crop and low vegetation land classes.

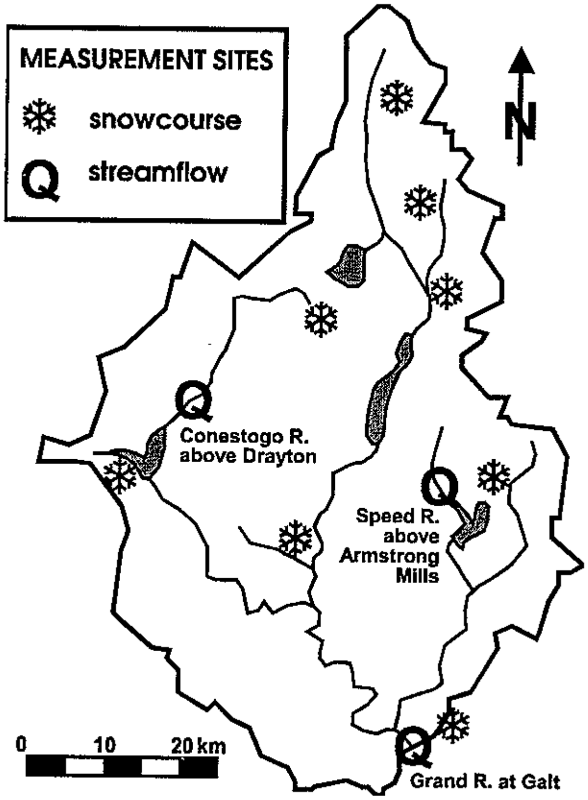

Figure 1b. Map of the Upper Grand River basin showing the location of snowcourses and streamflow gauges.

Meteorological gauges

The snowfall accumulations were measured using Belfort precipitation gauges with Nipher shields. Goodison (1978) has shown that even with the use of a Nipher Shield, the under-catch of solid precipitation can be significant when the wind speed at the mouth of the gauge is greater than 2 m·s^{-1} when compared to the octagonal vertical double fence shielded Tretyakov gauge. The gauges used in this study were located in wind sheltered areas and the wind speed at the gauge mouth was always less than 3 m·s^{-1} during a snowfall event. When the gauge data were adjusted using the correction derived by Goodison *et al.* (1997), the monthly accumulations were altered by less than 2%. Although there are other errors associated with the use of a Nipher-shielded Belfort, as illustrated by Goodison (1981), the precipitation accumulation collected by this gauge is used as the ground truth. For the gauge-radar comparison, three precipitation gauges are used (Fig. 1a). The 3 radiation stations and 2 standard meteorological stations (temperature, wind speed, barometric pressure and humidity) that are used in this modelling effort are located in Figure 1a.

Radar Data Adjustment

Since solid precipitation accumulates over an entire winter in colder climates, the quantity of snow that falls in a single storm event is less significant in a hydrological sense than the seasonal accumulation. Although the characteristics of an individual snowfall are important to snowpack modelling, operationally, multiple event accumulation can be used with metamorphosis, redistribution, and sublimation routines to estimate the state of the pack, in particular the quantity of water remaining in the pack at the onset of spring melt. Therefore to illustrate the usefulness of radar for snowfall estimation, monthly radar and gauge accumulation estimates will be compared, as well as seasonal accumulations.

Scaling

A simple problem that may cause overestimation, especially for conventional radar, is forced over-scaling. This is a function of the discretization of the precipitation rates. For the King City Radar product used in this research, there are 27 intervals at a minimum of 0.5 mm per increment. Forced over-scaling occurs when anomalous propagation is present that produces a return signal that is larger than the maximum rate (13.5 mm) at the lowest rate increment (0.5 mm). This forces an increase in the scaling intervals to 1 mm, 2 mm or greater. This scaling increase may be appropriate for summer precipitation events, however, winter storms rarely produce hourly accumulation rates greater than 13.5 mm. To overcome the forced over-scaling, the radar data was reprocessed using only the lowest increment of 0.5 mm.

Mixed Precipitation

Radar detection of mixed precipitation can produce underestimates of the precipitation rate when the solid precipitation Z-R relationship is used at air temperatures near or above freezing. To compensate for this radar error, the images can either undergo a different Z-R transformation during processing, or post-processing can be applied to images derived from the standard Z-R relationships. Since the state or condition of mixed precipitation is localized, the spatial distribution of temperature across the radar window is required for adequate adjustment of the mass of precipitation. It would be difficult to adjust the Z-R relationship based on temperature as the precipitation map is being produced and archived, since the temperature data are often not available in real-time. Instead, post-processing of the images can be performed once both the radar precipitation has been reviewed and the temperature field has been developed across the desired domain. For hydrologic modelling, the precipitation-temperature adjustment can be undertaken during runtime, since both temperature and precipitation are model input.

The probability of snow versus temperature curve derived by Auer (1974) is used to adjust the radar images for underestimation due to mixed and liquid precipitation. Ideally a relationship could be developed between percentage snow in the precipitation versus radar precipitation rate adjustment, however, the Z-R relationship has only been established for solid precipitation and for liquid precipitation. Since relationships only exist up to the two boundaries of mixed precipitation, a linear relationship has been assumed between percent snow or solid precipitation and reflectivity adjustment across the temperature domain of mixed precipitation. Therefore the probability of snow versus temperature curve is used directly to estimate the adjustment to the precipitation rate. Although the precipitation rate is 4.06 times greater for rain than for snow at a given reflectivity, the authors have found that the King City radar often overestimates rainfall by a factor of two when weather radar is used as input for hydrologic modelling. Therefore, a factor of 2.03 will be used to increase the precipitation rate for precipitation that is 100% rain.

Use of the dewpoint temperature was considered to appraise the effects of vapour pressure deficit in conjunction with temperature. Matsuo *et al.* (1981) considered relative humidity and temperature for the distinction between precipitation types, however, distributions were presented. In this research the dewpoint temperature is used to adjust the radar images for modelling, however it was not used for the monthly comparisons since humidity data were not available at all radar-gauge comparison sites.

RESULTS

Radar snowfall estimation

Research into the use of radar to estimate snowfall has been driven by forecasting and measurement efforts for specific events, however, snowfall estimation from radar for specific events in southern Ontario is not reliable. Figure 2 illustrates a sample month-long comparison that shows a large differences between gauge and radar accumulation for many of the individual events, yet, the seasonal accumulations are within five percent. The monthly comparisons for three Belfort gauges (from January 1993 to March 1997) shows a reasonable correlation for unadjusted data, with the exception of four large radar overestimations (up to 150% greater) and five large radar underestimations (Fig. 3a). Nevertheless, the monthly **r**^{2} value for the raw data is only 0.247.

The removal of scale from all the radar images results in a significant improvement for the four overestimated monthly accumulations (Fig. 3b), with the monthly **r**^{2} value increasing to 0.634. The adjustment for underestimation during mixed precipitation, applied after the scale removal, increases underestimated monthly accumulation (Fig. 3c). However, as some monthly totals become more overestimated, in comparison to scale removal only, the monthly **r**^{2} value decreases slightly to 0.607.

For seasonal accumulations, the **r**^{2} value increases from 0.301 for the raw comparison (Fig. 3d) to 0.727 for the scale removal adjustment (Fig. 3e), to 0.762 for the combination of the two adjustments (Fig. 3f).

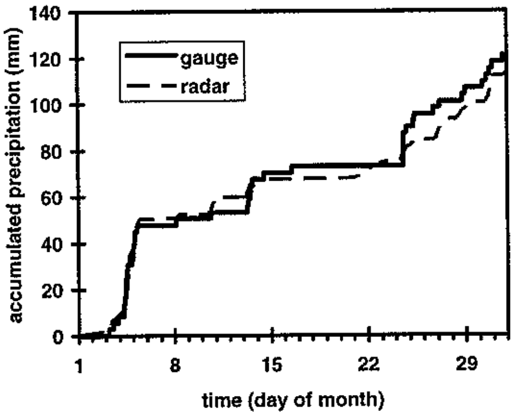

Figure 2. Snowfall radar-gauge comparison at Wormwood Nipher-shielded Belfort precipitation gauge site for January 1993.

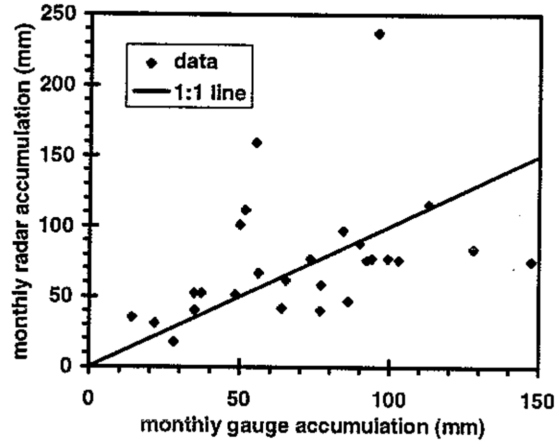

Figure 3a. Monthly snowfall accumulation comparison of raw radar versus three University of Waterloo Nipher-shielded Belfort gauges (r^2 = 0.247).

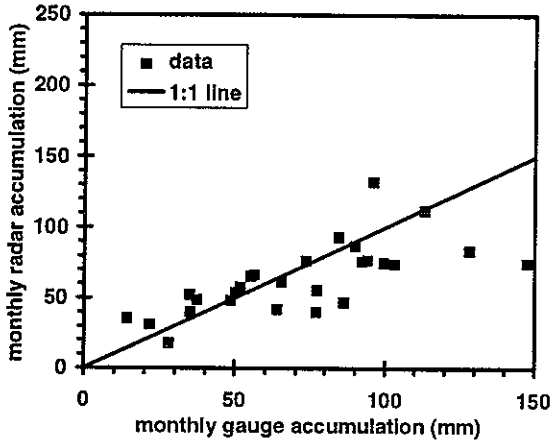

Figure 3b. Scale adjusted monthly radar-gauge snowfall comparison (r^2 = 0.634).

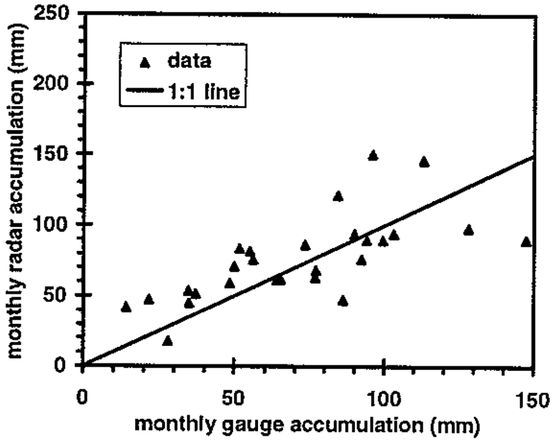

Figure 3c. Temperature and scale adjusted monthly snowfall radar-gauge comparison (r^2 = 0.607).

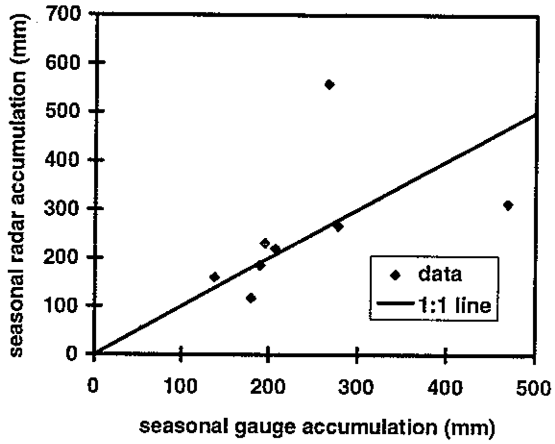

Figure 3d. Seasonal snowfall accumulation comparison of raw radar versus three University of Waterloo Nipher-shielded Belfort gauges (r^2 = 0.301).

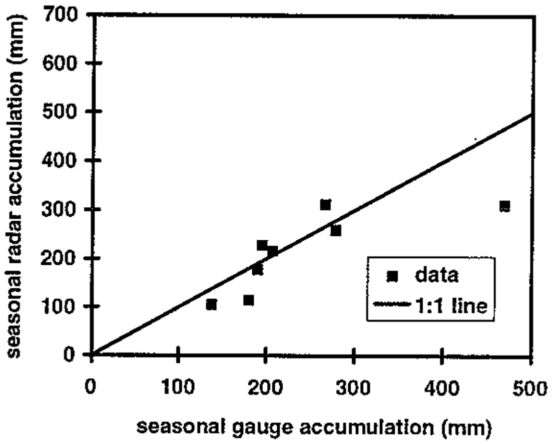

Figure 3e. Scale adjusted seasonal radar-gauge snowfall comparison (r^2 = 0.727).

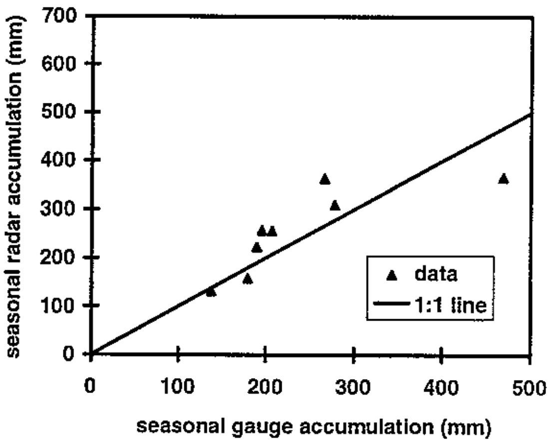

Figure 3f. Temperature and scale adjusted seasonal snowfall radar-gauge comparison (r^2 = 0.762).

Snowcourse comparison

The average observed and simulated snow water equivalent (SWE) values at snowcourse locations are compared at the north and the south sites in Figure 4. For both areas, the simulated SWE is too large at the time of the first observed snowcourse SWE. As illustrated in Figures 5a through c, the January peak in each hydrograph is not matched well; the simulated flow is much less than the measured flow. The larger computed snowpack thus corresponds to less computed flow, since the rain on snow event that occurred is not modelled correctly and snow that is predicted to remain is overestimated.

The computed average rate of increase in the SWE is however, almost the same as the measured increase, illustrating that the model is accumulating snow appropriately. For the southern snowcourse sites, the melting of the pack is simulated well, as indicated by the decrease in SWE, with the exception of one site. At the northern sites, the pack is modelled to melt twice as fast as observed. This is a consequence of the meteorological data used by the model, which is based on data only from southern locations. The temperatures, and hence the long wave radiation are thus estimated to be higher than actually occurred, resulting in a melt that is too rapid.

Hydrograph comparison

For the melt period in 1993, the modelled streamflow matches the observed streamflow (from Environment Canada 1997) for the Grand River at Galt hydrometric station well (see Figure 5a). At Galt the largest flow occurred in early January as the result of a rain on snow event. During the event, the snow was quickly depleted, then the ground refroze and became impervious, and all the rainfall entered the stream channels. For the Speed River and the Conestogo River stations (Figures 5b, and 5c, respectively), this early peak is even less well matched than at the Galt station since the Grand River at Galt integrates all of the hydrologic activity in the watershed. Similarly, the modelled spring snowmelt peak matches the observed streamflow at Galt better than at the other two locations. These results, while not excellent, illustrate that weather radar can be used to estimate snowfall accumulation for hydrologic modelling.

DISCUSSION

Since gauge data are used to provide all the meteorologic inputs except precipitation, it might be

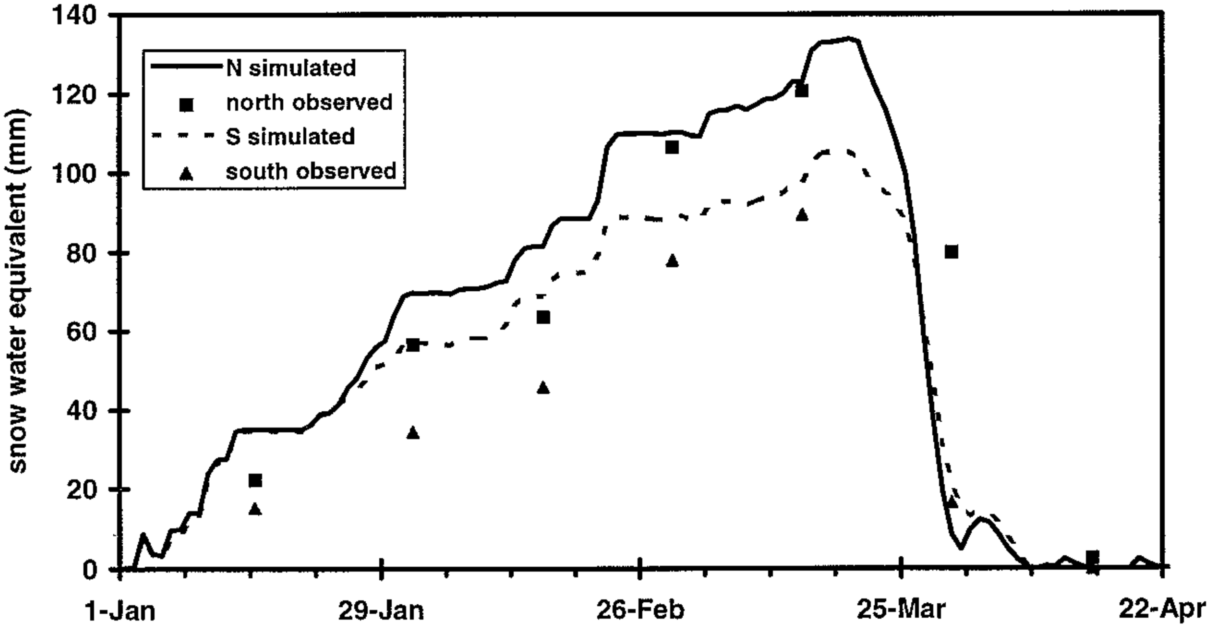

Figure 4. Average observed snowcourse SWE and modelled SWE during the winter of 1993, across the north and south sections of the Upper Grand River basin (typically measured in low vegetation land class at 2 week intervals).

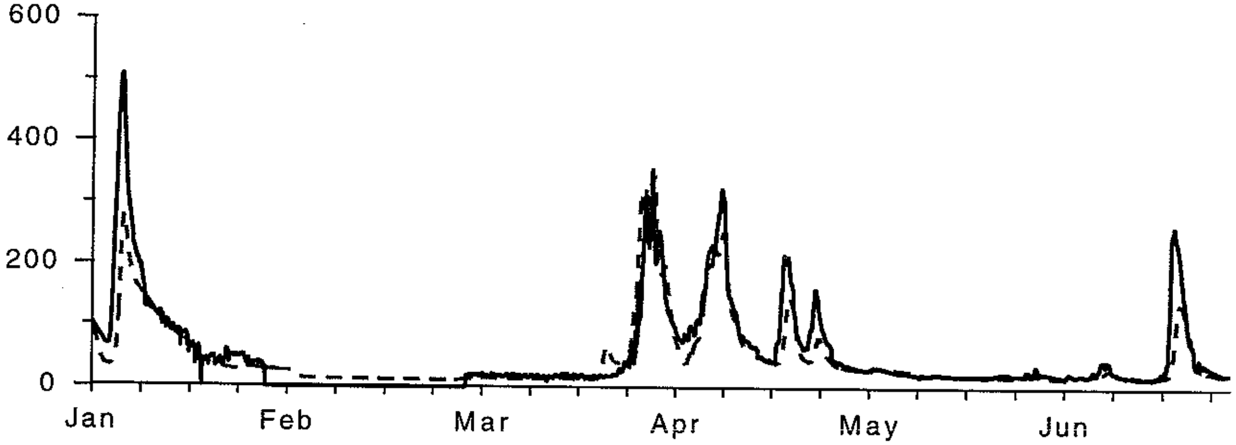

Figure 5a. Observed (solid line) and simulated (dashed line) hydrographs for the Grand River at Galt streamflow gauging site from January to June 1993.

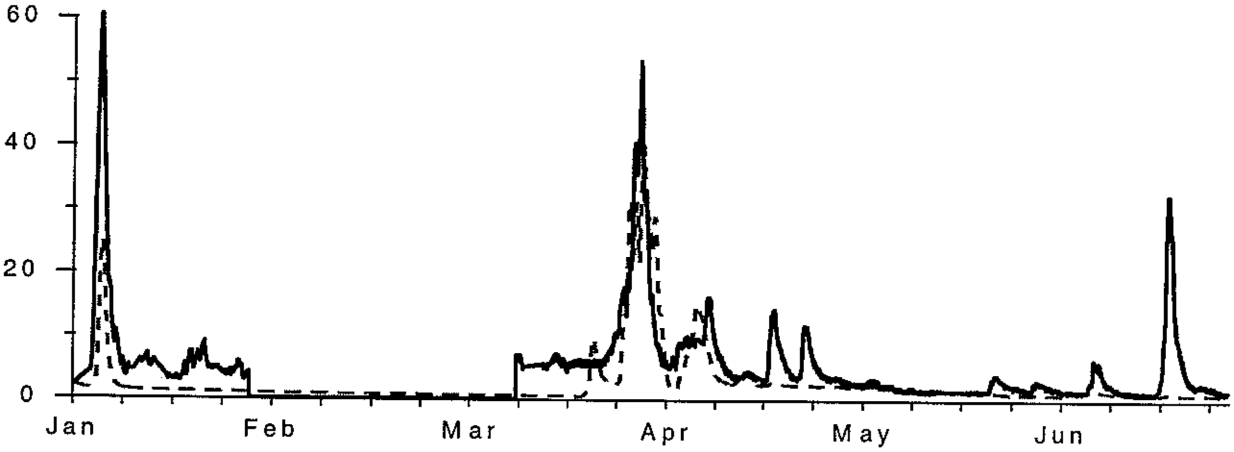

Figure 5b. Observed (solid line) and simulated (dashed line) hydrographs for the Speed River above Armstrong Mills streamflow gauging site from January to June 1993.

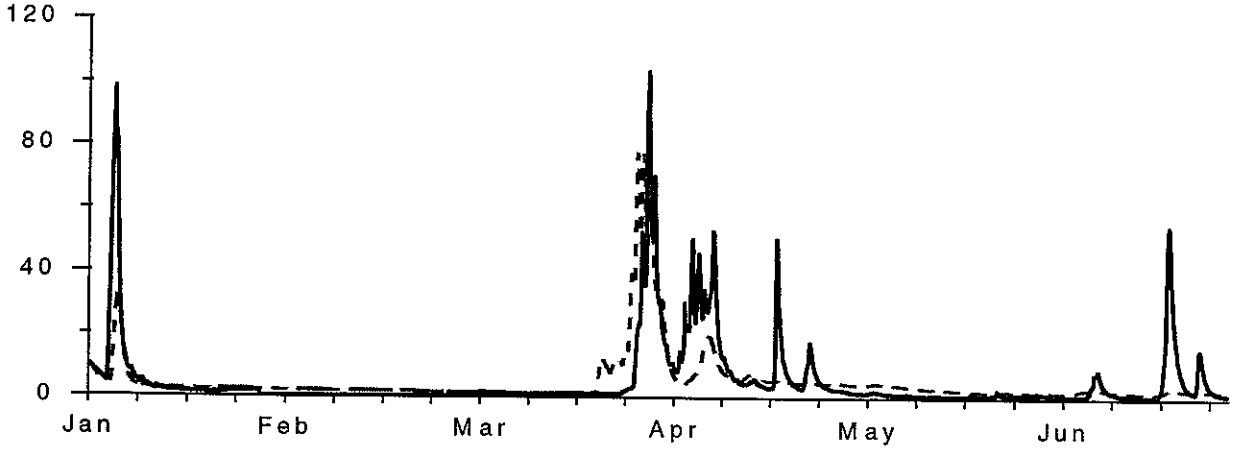

Figure 5c. Observed (solid line) and simulated (dashed line) hydrographs for the Conestogo River above Drayton streamflow gauging site from January to June 1993.

argued that gauge data could also be used for precipitation input. However, the variability of precipitation across southern Ontario is usually much larger than the variation in other meteorologic parameters, such as temperature. Temperature does vary across the study area, with the north being cooler than the south, but there is often a linear relationship between conditions at northern and southern locations. Although not discussed in this paper, the variation in precipitation that can be captured by weather radar is especially true for convective summer storms that frequently occur in southern Ontario.

Snowcourse property estimates will be improved by integrating more representative datasets that consider the northern variation in weather across the area. The problems with snowcourse data are the temporal and spatial limitations. Since the snowcourses are only sampled on a 14 day interval, any intermittent pack changes cannot be detected. The spatial problem is the same as the point estimation problem for a precipitation gauge. Redistribution of snow in the vicinity of the snowcourse may be a problem, however the averaging of 10 samples usually eliminates this issue. The snowcourses are assumed to be in areas modelled as low vegetation or crop, however, snowcourses may be in locations that are not represented by a particular modelled land class.

As discussed by Pomeroy *et al.* (1998), the CLASS model, that represents the physical hydrologic processes, needs several significant additions to fully represent snow processes. At present, the soil heat flux is averaged between bare and snow-covered areas during partial snowcover. This is being corrected by the authors by separating the bare and snow covered areas into distinct sub-elements. Although transport of snow and the associated blowing snow sublimation is not yet modelled, this is not important for southern Ontario since most fields are too small to provide the fetch length necessary for transport lengths that are associated with blowing snow sublimation. Snow redistribution does occur in Southern Ontario especially from bare and low vegetation areas to the edge of forests. Work is ongoing to model this transport using a simplified redistribution routine.

There are three other snow processes that should be improved in CLASS. First, pack densification, which at present has a maximum of 300 kg.m^{-3} for all land cover types, should be set to other maximum density limits based on the vegetation types. Second, snowfall canopy interception, which currently uses rainfall interception and does not consider sublimation, CLASS should use the routines developed by Hedstrom and Pomeroy (1997). Third, with no infiltration of meltwater into frozen soil, the routines developed by Zhao *et al.* (1997) that enable partial infiltration should be considered for implementation into CLASS.

Even considering the above-mentioned potential improvements in the WATFLOOD/CLASS model, the results are very encouraging, and it can be seen that weather radar can be used as the precipitation input for distributed hydrologic modelling of the snowpack.

CONCLUSIONS

Weather radar provides adequate estimates of monthly snowfall accumulation, comparable to estimates from precipitation gauges, and the radar estimates are improved by scaling removal and mixed-precipitation temperature adjustments. The SWE estimates computed by WATFLOOD/CLASS are adequate for streamflow simulation, and improvements in the data and representation of processes in the model should improve SWE estimates. The computed hydrographs match the observed streamflow reasonably well, especially for the spring freshet. Weather radar provides a good estimate of precipitation as input into the hydrologic model WATFLOOD/CLASS for the 1993 winter season across the Grand River basin. The model is evolving and the datasets are improving and together better estimates of SWE and streamflow should result.

FUTURE WORK

The coupled WATFLOOD/CLASS model is currently under development to include decoupling of soil parameters for bare and snow-covered areas during periods of partial snowcover, and simple redistribution of snow from exposed areas. These routines will be applied to other watersheds in southern Ontario for the period from 1993 to 1997. Further development of the snow processes in the CLASS model is also ongoing, however, these changes will provide only limited improvements for the hydrological snowpack modelling of the Southern Ontario area.

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REFERENCES

Auer, A.H., Jr. (1974) The rain versus snow threshold temperatures. *Weatherwise*, **27**:67.

Crozier, C.L., P.I. Joe, J.W. Scott, H.N. Herscotvitch and T.R. Nichols (1991) The King City operational Doppler radar: development, all season applications and forecasting. *Atmosphere-Ocean*, **29**:479-516.

Environment Canada (1997) *1995 HYDAT Hydrometric Data CD-ROM*. Water Survey of Canada, Ottawa, Canada.

Goodison, B.E. (1978) Accuracy of Canadian snow gauge measurements. *Journal of Applied Meteorology*, **17**:1542-1548.

Goodison, B.E. (1981) Compatibility of Canadian snowfall and snow cover data. *Water Resources Research*, **12**(4):893-900.

Goodison, B.E., J.R. Metcalfe and P.Y.T. Louie (1997) Annex 5 National Reports of Analysis and Results. Annex 5A: Canada. In, *WMO Solid Precipitation Measurement Intercomparison Final Report*, WMO, Geneva, 15pp. In Press.

Hedstrom, N.R. and J.W. Pomeroy (1997) Accumulation of intercepted snow in the Boreal Forest: Measurements and Modelling. In *Proceedings of the 54th Annual Eastern Snow Conference*, Joint meeting with the 65th Annual Western Snow Conference, Banff, Alberta, May 4-8, 1997.

Kouwen, N. and G. Garland (1989) Resolution considerations in using radar rainfall data for flood forecasting. *Canadian Journal of Civil Engineering*, **16**:279-289.

Kouwen, N., E.D. Soulis, A. Pietroniro, J.R. Donald and R.A. Harrington (1993) Grouped response units for distributed hydrologic modelling. *ASCE Journal of Water Resources Planning and Management*, **119**(3):289-305.

Marshall J.S. and W.M. Palmer (1948) The distribution of raindrops with size. *Journal of Meteorology*, **5**:165-166.

Matsuo, T., Y. Sasyo and Y. Sato (1981) Relationship between types of precipitation on the ground and surface meteorological elements. *Journal of the Meteorological Society of Japan*, **59**, 462-476.

Pomeroy, J.W., D.M. Gray, K.R. Shook, B. Toth, R.L.H. Essery, A. Pietroniro and N. Hedstrom (1998) Modelling snow processes for land surface modelling. In *Proceedings of the 55th Annual Eastern Snow Conference*, Jackson, New Hampshire, June 3-5, 1998.

Richards, W.G. and C.L. Crozier (1983) Precipitation measurement with a C-band weather radar in southern Ontario. *Atmosphere-Ocean*, **21**: 125-137.

Sekhon, R.S. and R.C. Srivastava (1970) Snow-size spectra and radar reflectance. *Journal of Atmospheric Sciences*, **27**:299-307.

Verseghy, D.L. (1991) CLASS-A Canadian Land Surface Scheme for GCMs. I. Soil model. *International Journal of Climatology*, **11**:111-133.

Zhao, L., D.M. Gray and D.H. Male (1997) Numerical analysis of simultaneous heat and mass transfer during infiltration into frozen ground. *Journal of Hydrology*, **200**:345-363.