Does Detailed Areal Distribution of Snow Cover Improve the Utility of a Hydrological Model for Watershed Management?

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ABSTRACT

This paper illustrates how the form used for areal snow cover in a watershed model influences calculations of streamflow and sediment load. The Areal Snow Accumulation-Ablation Model and the Guelph All-Weather Sequential-Events Runoff model were used with snow cover modelled as single block, and distributed over different land-cover types. Results showed that the distribution of snow cover used in calculations influenced model results for streamflows and suspended sediment loads, particularly during late winter and early spring months. Differences in monthly totals were as high as 40% for streamflows, and 165% for sediment loads.The results demonstrate that changes in land use that alter the areal distribution of snow could create noticeable changes in temporal patterns of streamflow and suspended sediment. To simulate these changes hydrological models would have to include explicit representations of the areal distribution of snow cover as influenced by land use/cover type.

INTRODUCTION

Recent studies conducted in Ontario to assess the impact on water resources of urban development within a watershed have shown the need for continuous modelling of streamflow and water quality (e.g. Charlton and Tufgar, 1991; Weatherbe et al., 1992). Completely continuous modelling of watershed hydrology requires the simulation of accumulation and ablation of snow cover during the winter and spring seasons, and accounting for the effect of winter snow storage on streamflow patterns in subsequent seasons.

In the modelling of hydrological process on the watershed scale there is always a choice in the extent to which areal variations in processes are "lumped". In this paper we examine the effect of "lumping" of snow cover on calculated streamflow and water quality.

Variations in amounts of snow cover among and within varying landscape units is readily observable and generally recognized (Adams, 1976; Schroeter and Whiteley, 1986; Burkard et al., 1991). Most continuous streamflow models used in eastern North America in the past did not incorporate these variations in their snow accumulation and ablation calculations (Huber, 1983; Cumming-Cockburn and Marshall Macklin Monaghan, 1988). Moreover, calculations in the models did not treat the contribution to areal variability created by redistribution of snow by wind after each snowfall (Schroeter et al., 1991).

The areal snow accumulation-ablation model (ASAAM) explicitly accounts for areal distribution and redistribution of snow by wind (Schroeter and Whiteley, 1987a,b; 1990). It gives continuous representation of snow cover for the entire winter for individual landscape units using daily meteorological observations.The practical capabilities of ASAAM have been demonstrated by its use in preparing operational flood forecasts (Schroeter et al, 1991).

A simplified form of ASAAM's spatial distribution algorithm has been installed in the Guelph All-Weather Sequential-Events Runoff (GAWSER) model (V6.0), an existing watershed model adapted recently for continuous streamflow and water quality simulations (Ghate and Whiteley, 1982; OMNR, 1989, Weatherbe et al., 1992).

For this study we used the ASAAM and GAWSER models to assess the influence of degree of detail in areal representation of snow cover on calculated streamflow and sediment yield. The paper begins with a brief overview of the computational procedures in ASAAM and GAWSER. Then, we present the sensitivity of simulated streamflows and suspended sediment loads to two representations of snow cover distribution: a) the snow cover modelled as a single block (lumped case), and b) the snow cover modelled in a distributive manner according to different land cover types. The paper concludes with an assessment of the practical implications of the results for continuous snow cover modelling for water management studies.

OVERVIEW OF COMPUTATIONAL PROCEDURES IN ASAAM AND GAWSER

Areal Snow Accumulation-Ablation Model (ASAAM)

ASAAM provides spatially-distributed estimates of snow cover amounts (snow depth, equivalent water content, and the extent of bare ground) for each day of the season of snow cover. Thus ASAAM gives the required start-up values to allow a streamflow-generation model to simulate any and every streamflow event during the winter. A complete description of ASAAM has been given by Schroeter and Whiteley (1987a,b; 1990) and Schroeter et al.(1991). Distinctive features of the model are outlined below.

In ASAAM (and also GAWSER), watersheds are divided into 'zones of uniform meteorology' (ZUMs) with one set of meteorological data applied within each ZUM. Differences in meteorological inputs among ZUMs account for the spatial variability in sequences of rainfall, snowfall, air temperature and wind speed across the watershed. Each ZUM usually comprises one or more subwatersheds, depending on the prevailing weather patterns in a watershed and the availability of meteorological measurements.

Each ZUM is partitioned among 'blocks of equivalent accumulation' (BEAs) to account for the spatial variation in average amounts of snow cover found among differing land cover units. BEAs are either 'areal' blocks, extensive in both length and width (e.g. fields and forests), or 'linear' blocks which represent long 'thin' land features with significant capacity to store snow (e.g. roadway ditches, forest-field edges, fence lines, and river valleys).

Spatial variation in snow retention characteristics occurs within in each cover-type block, because of topographic ridges, depressions and varying height of roughness . To represent this each BEA is divided into 'cells' with varying capacity to hold snow and capture blowing snow. Linear blocks have physically-based capacity patterns for their cells based on cross-section measurements (Schroeter and Whiteley, 1986), while areal blocks have a pattern of holding capacity determined from the statistical distribution of snow depth for that land cover type (see Burkard et al., 1991).

ASAAM operates on a daily basis using readily available meteorological inputs: maximum and minimum air temperature, daily new snow amounts (as depths, and equivalent-water content when available), daily rain amounts, mean wind speed, and prevailing wind direction. Ten processes are considered in the model: refreeze, sublimation, compaction, rain deposition, snowmelt, basal layer development, release of liquid water, new snow deposition, erosion and redistribution.

Snowmelt and refreeze are computed using a temperature index approach. In calculations where a single block represents the snowcover on the watershed the melt-factor used is an average for the various cover types actually present. When a distributed representation is used with differentiation of cover types into different blocks a separate melt-factor is set for each cover type. This allows for recognition of the higher melt rates that occur in open areas compared with those in coniferous forest blocks.Sublimation is small in comparison to major melt rates and is set at a fixed daily amount, applied on days with below-freezing temperatures with no rain.

Snowpack compaction is calculated using a one-dimensional consolidation equation, and the capacity of the snow to retain liquid water is computed as a fixed proportion of the available pore space. In lumped representation of the snowpack over area the "average" liquid-holding capacity used is sufficient , at maximum snowpack accumulation, to retain appreciable amounts of rain or snowmelt. In contrast the shallower depths of snow (and the bare ground) that occur in some blocks in a distributed representation of snow distribution give rise to overland flow and/or infiltration to soilwater storage from even very small amounts of rain and snowmelt. The susceptibility of new snow and the resistance of older snow to erosion is represented by division of the pack into five layers.The top two layers are new snow (today's and yesterday's) available for redistribution.The next layer is older compacted snow and the bottom two layers are saturated snow and a basal ice layer; the lower three layers are not effected by wind erosion.

New snow is distributed initially to all blocks and cells. The model then redistributes snow from those cells and blocks with low storage capacity, whose capacity depth has been exceeded, to units with a higher capacity; this occurs whenever there is sufficient wind within two days of a new snowfall. Redistribution is done first for cells within each block. Then, if any eroded snow cannot be held within a block, it is moved to linear blocks with higher storage capacity. The wind direction and the orientation and exposure of linear blocks are used to identify which blocks will participate in the erosion and redistribution calculations for a given time step.

Guelph All-Weather Sequential-Events Runoff (GAWSER) model

GAWSER is a deterministic hydrologic model, based on the HYMO format (Ghate and Whiteley, 1982), that is used to predict the total streamflow resulting from inputs of rainfall and snowmelt. It is applied widely in Ontario for planning, design, real-time flood forecasting, and evaluating the effects of physical changes in the drainage basin (e.g. Ecologistics Ltd., 1988; Weatherbe et al, 1992; Schroeter et al., 1992). As noted earlier GAWSER was modified recently to operate in a continuous simulation mode, and to predict pollutant accumulation, washoff and transport.

GAWSER can operate at variable time steps from as low as one minute to 24 h, depending on the availability of meteorological inputs for the selected time interval. Readily available daily maximum and minimum temperatures are fitted to an assumed sinusoidal diurnal pattern to develop the temperature inputs for each time step. Daily snowfall depths are distributed evenly among time steps where the air temperature is less than 0°C, and a constant value for new snow relative density is applied to estimate the new snowfall equivalent water contents.

GAWSER calculations are based on representation of eight hydrological processes: snow accumulation and ablation, infiltration, storage in soilwater, evapotranspiration, overland flow routing, subsurface and baseflow routing, stream channel routing, and reservoir routing (with operations). These procedures are outlined briefly below, but are fully described in the GAWSER Training Guide and Reference Manual (OMNR, 1989). The form of GAWSER used for continuous simulation and water quality modelling is described by Weatherbe et al. (1992).

The GAWSER snow accumulation and ablation sub-model is a simplified form of ASAAM, that uses one cell for each 'block of equivalent accumulation.' Redistribution of snow after each snowfall is handled by assuming that all new snow deposited in each block in excess of its holding capacity is available for redistribution to linear edge blocks. This assumption is valid only where blowing snow is common during and immediately following each snowfall (as in southern Ontario). No redistribution is done for snow in forest blocks.

Areal variability in infiltration rates, percolation rates within the soil, and rates of generation of overland runoff are accounted for by conducting separate calculations within each subwatershed for one impervious and up to four pervious areas. The Green-Ampt equation is used in the infiltration calculations with allowance for the recovery of infiltrability between events.

Overland routing uses area/time versus time relationships. The baseflow from subsurface and groundwater storage is simulated using a single linear reservoir. Channel routing is done by the Muskingum-Cunge method (see Schroeter and Epp, 1988). The reservoir routing is by Puls method with controlled releases allowed.

The dry-weather accumulation of pollutants is represented by an exponential build-up function (see Alley and Smith, 1981). The washoff and transport of up to four pollutants is modelled using the 'Equivalent Solids Reservoir' (ESR) approach developed by Schroeter and Watt (1989). This method requires sediment characteristics (particle size and relative density) as inputs to the sediment washoff/transport calculations.

Seasonal changes in model parameters (e.g. effective soil hydraulic conductivity, or snowmelt/refreeze factor) are specified on a monthly basis during long-term simulation periods.

SAMPLE APPLICATION FOR UPPER SPEED RIVER

Procedures

In this section, we show the sensitivity of simulated streamflows and sediment loads to varying representations of snow cover distribution for the

1985-86 water year (Nov 1, 1985 to Oct. 31, 1986) in the upper Speed River watershed (Figure 1). The winter season in this year was quite typical of southern Ontario winters over the past ten years, having significant thaws (mid-January and February) which creates partial snow cover conditions prior to the final melt period (March 15 to 31).

Two cases are considered: 1. the snow cover modelled as a single block (lumped case), and 2. the snow cover modelled in a distributive manner according to different land cover types.

We first applied the full distributed ASAAM to the sample watershed, and checked its output against available snow survey observations as outlined in Schroeter et al. (1991). This was done to set the parameters in GAWSER's snow accumulation and ablation sub-model. Next, GAWSER was run twice, once with the snowpack modelled as a lumped block, and a second time with the distributed blocks as calibrated in the ASAAM run. The two outputs were compared qualitatively using histogram plots of the simulated mean monthly discharge and the simulated monthly sediment loads.

Test Data

The upper Speed River watershed us agricultural with a drainage area of 167 km^2. It is located in southern Ontario about 70 km west of Toronto. The gauging station at the outlet is about 4 km upstream of Guelph Lake (Figure 1), one of the three major multi-purpose reservoirs operated by the Grand River Conservation Authority (GRCA).

Watershed soils are predominantly coarse, about 85% loamy tills, fine sands and gravel. About 70% of the area grows small grains, row crops and pasture with the remainder mostly forest with small areas for farmsteads, roads, and watercourses (Ecologistics, 1988).

Snow surveys are conducted at the GRCA Rockwood course (Figure 1) on the 1st and 15th of each month from December 1 to April 15. Supplementary surveys are made when necessary. This snow course samples two landscape units, a south-facing forest-field edge and a coniferous forest lot.

Daily temperature and precipitation are available at five Atmospheric Environment Service (AES) stations surrounding the watershed: Fergus Shand Dam, Fergus MOE, Hillsburgh, Elora Research Station, and the Guelph Arboretum. Additional daily climate information is available at the GRCA's Guelph Dam. Hourly rainfall amounts are recorded automatically at the Shand Dam, Elora Research Station, Guelph Dam, and Guelph Arboretum for the period April 1 to October 31. Some hourly rainfall amounts are available for certain events during the winter months at the GRCA's Shand and Guelph Dams. Wind speed and direction information were taken from the Elora Research Station.

The Water Survey of Canada (WSC) has maintained two streamflow gauges in the watershed (Figure 1), one on the main stem of the Speed River near Armstrong Mills (02GA040, drainage area 167 km^2) and the other on Lutteral Creek near Oustic (02GA033, drainage area 63 km^2). Hourly flow data are available for the open water periods only (usually April 1 to December 1). Sediment samples are collected on an event basis at the Armstrong Mills gauge, but data are not sufficient to establish a load rating curve.

The hydrologic model parameters throughout the year were established from application of GAWSER (and ASAAM) in forecast mode for the whole Grand River basin over the last four years (GRCA, 1988; Schroeter et al., 1991; 1992). For snow cover modelling, a 10 block ASAAM set-up for the upper Grand River valley was used, with the block areas adjusted to reflect conditions in the upper Speed River. Due to a lack of event-specific sediment data for model calibration, published values for the ESR parameters (Schroeter and Watt, 1989) were used directly to estimate sediment transport.

Simulation Results and Discussion

The simulation results are summarized in Figures 2 to 4. Figure 2 presents a time-series plot of the simulated snow depth and equivalent water content from both ASAAM and GAWSER for a forest and fence line edge block for the period Dec. 1, 1985 to March 31, 1986. The discrete snow course observations from the Rockwood course are noted in Figure 2 for the forest block only. Note that the ASAAM and GAWSER results are almost identical, and they agree quite well with the observations (Target achievement measures of greater than 60%).

The single-cell blocks used in GAWSER showed the snowpack completely gone two days ahead of the date given by ASAAM calculations using multiple cells, (up to 10 cells), for each distribution block.

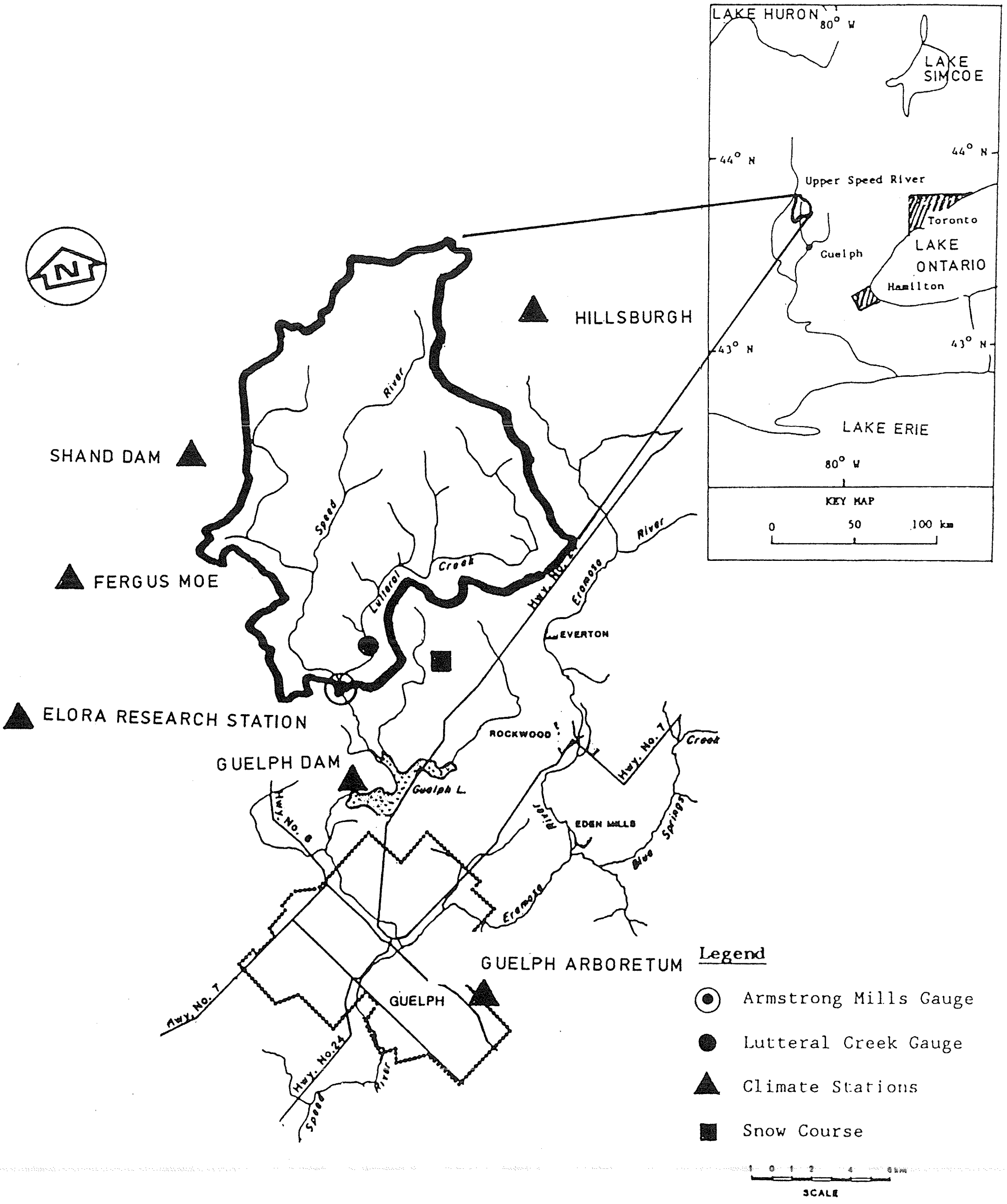


Figure 1. Upper Speed River Watershed

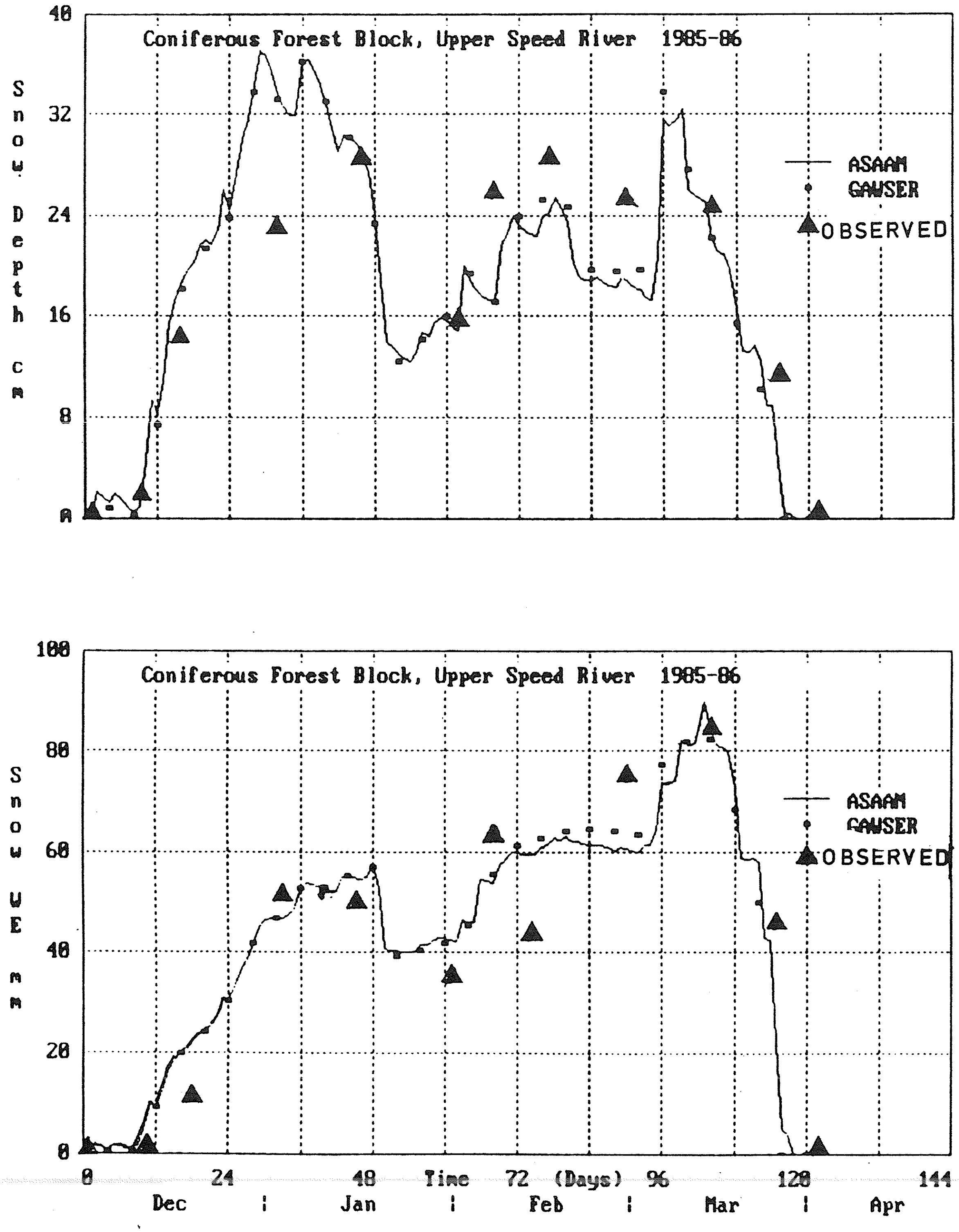


Figure 2(a). Time-series plots of mean snow depth and water equivalent for coniferous forest block, Upper Speed River Watershed 1985-86.

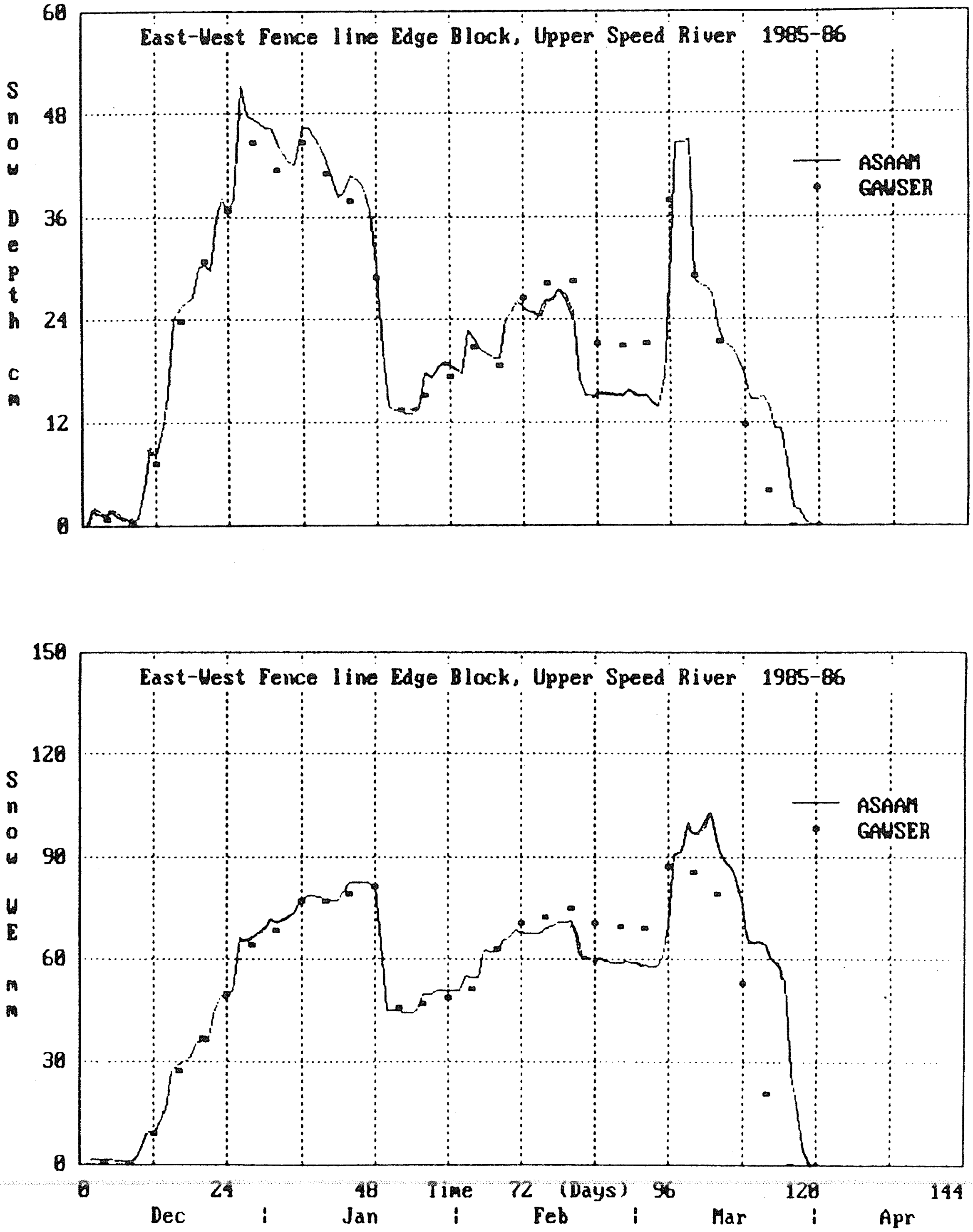
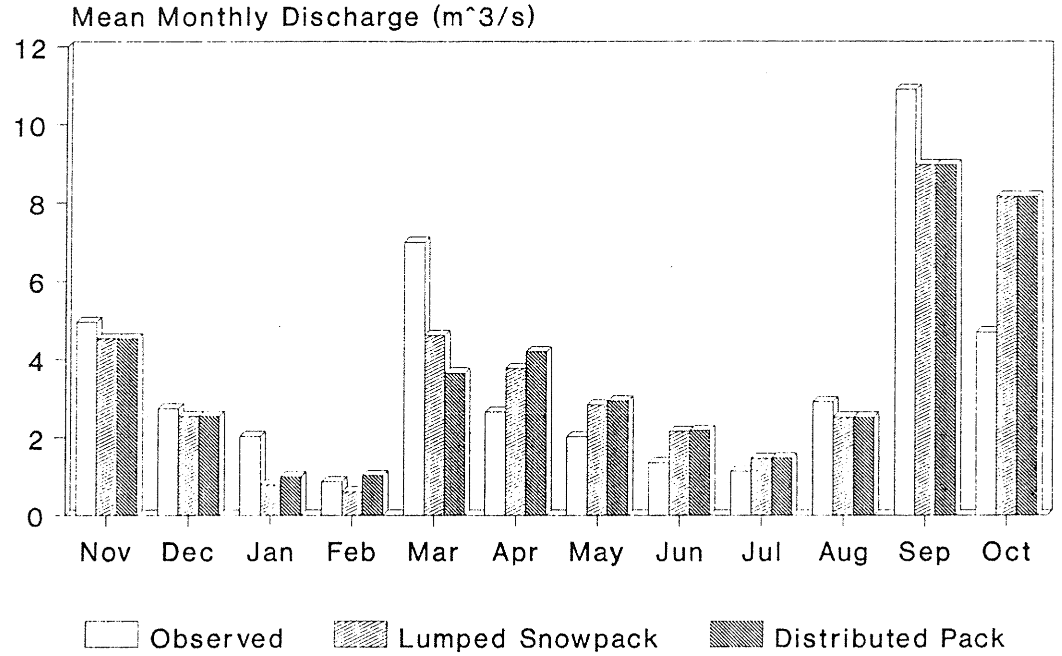


Figure 2(b). Time-series plots of snow depth and water equivalent for a east-west fence line edge block, Upper Speed River Watershed 1986-86.

Monthly Total Discharge 1985-86
Speed River near Armstrong Mills



Monthly Total Discharge 1985-86
Lutteral Creek near Oustic

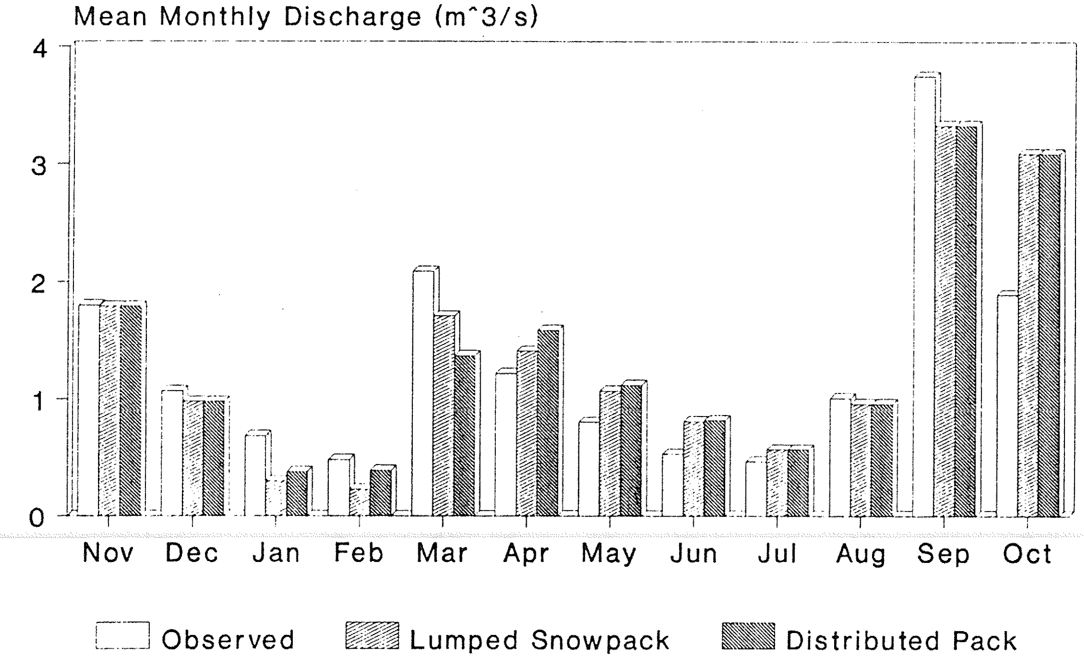
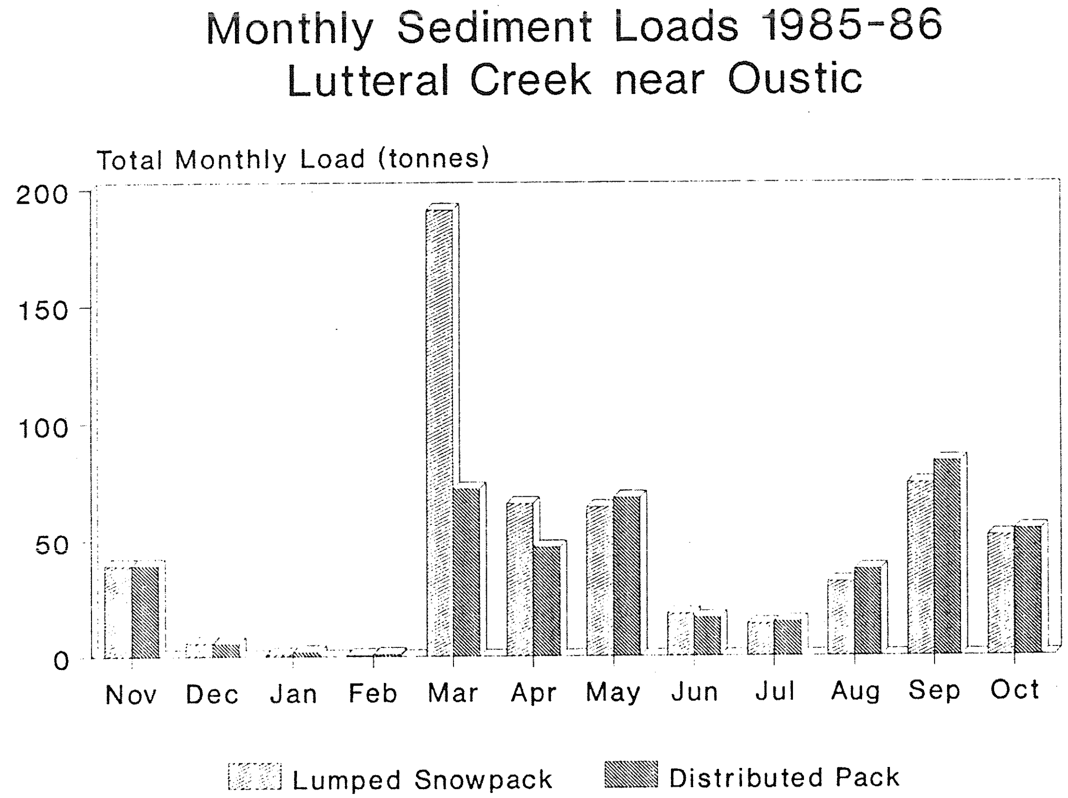
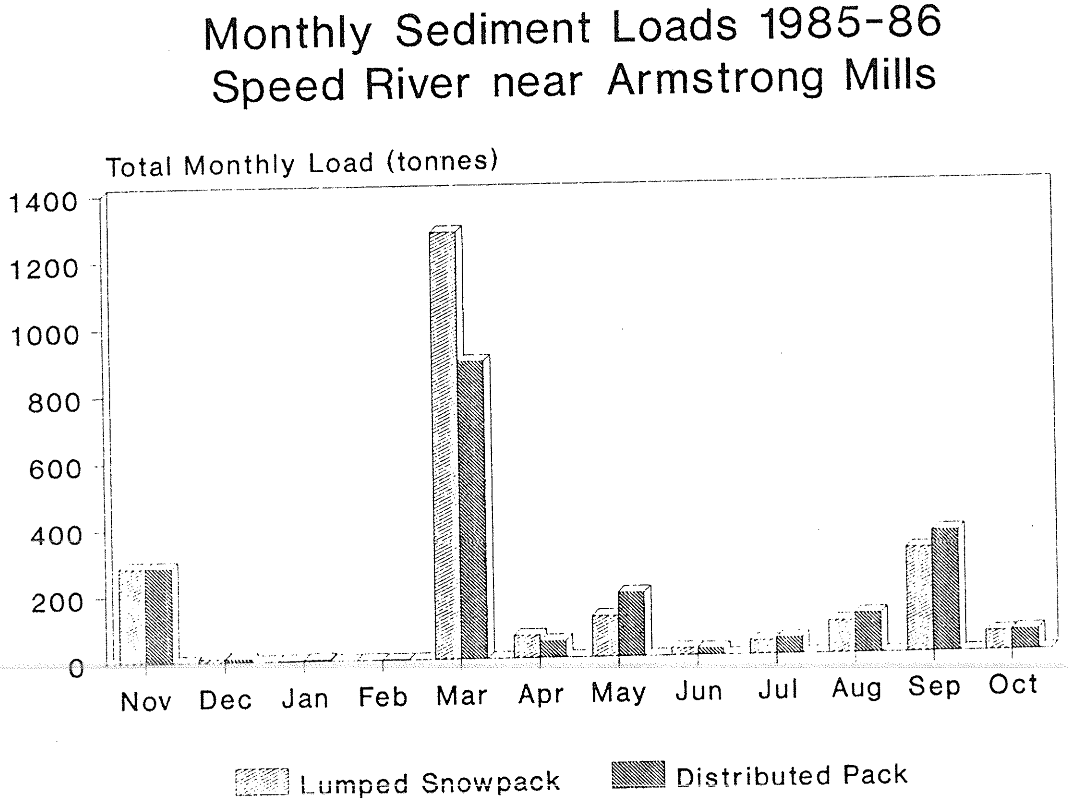


Figure 3. Monthly discharge for the Upper Speed River Watershed for calculations using differing representations of areal distribution of the snowpack.



Monthly Sediment Loads 1985-86
Lutteral Creek near Oustic



Monthly Sediment Loads 1985-86
Speed River near Armstrong Mills

Figure 4. Monthly sediment loads for the Upper Speed River Watershed for calculations using different representations of areal distribution of the snowpack.

A comparison of predicted mean monthly total flows for both the lumped and distributed snowpacks are depicted in Figure 3, together with the observed values for the Armstrong Mills and Lutteral Creek gauges. Both snowpack representations produced simulated flows that matched the observed values, both in terms of total annual flow (agreement within ±1%) and in month-to-month pattern of flows. This indicates that on the whole the measured inputs and outputs are reasonably accurate.

The agreement between observed and modelled flows for individual months was not always good, with the biggest disparities in March, April and October, and the best agreements for November, December, August and September. These discrepancies are believed to be attributed to: a) inadequate calibration of model parameters for some periods (we are still learning to use the model in continuous mode), b) using monthly average parameter values that may not provide adequate variation for some parameters during the final snowmelt period, c) inaccurate model input data, particularly the hourly rainfall amounts during the winter months (which are estimated for most events), d) inadequate models for some processes (e.g. temperature index may be unsuitable for snowmelt during foggy weather as on March 13 and 14), and e) measured flows for days with breakup of ice cover may not be accurate.

The difficulties specified above are present in the same way in the simulations done with the two different areal representations of snow cover. The difficulties do not interfere with an assessment of the differences in model output created by the difference in representation of snow cover distribution.

Appreciable differences are visible in Figure 3 between the flows calculated using different model treatments of areal variation in snow cover. As expected, there are no large disagreements (that is greater than ±10%) for November, December, and May to October, because these seven months have little or no snowmelt. The differences for the last four winter months are readily observable (Figure 3), with deviations greater than ±10% for each month at either gauge. The largest differences are noticeable for February (40%) and March (25%).

In general, the calculations with distributed snowpack produced larger flows than for the lumped case in January and February when the actual condition of the watershed was partial snow cover; the lumped model simulates full snow cover during these months. The lumped case yielded higher flows during March and the distributed case higher flows in April.

The higher flows from the distributed snowpack in January and February are the result of the presence in the calculation of some areas of shallow snow and of bare ground. These areas release water from small events of rain and snowmelt, water that is held within the deeper "average " depth of the lumped snowpack. In March this greater stored amount is released, giving rise to the higher flows from the lumped model during the major snowmelt. In April the distributed snowpack has snow in linear snowbanks and in the coniferous forest that contributes to streamflow when the lumped model shows all snow exhausted. Also in the distributed snowpack representation, the melt rates are slower for some of the blocks and the melt over longer times generates little overland flow, with meltwater directed to soilwater and groundwater storage.

We compared the computed sediment loads to estimates by Wall et al. (1982) (see Table 1). The two sets of estimates agree within an order of magnitude, which suggests that our predicted sediment loads are plausible. Furthermore, the monthly distribution of the simulated loads agrees with the patterns reported for several Ontario streams (Dickinson and Green, 1988) with more than 70% of the total annual load generated during the spring months.

Table 1 Comparison of computed annual unit sediment loads with previous estimates for Ontario agricultural watersheds

Gauge Station	Unit Sediment Loads (t/km^2)		
	Snowpack Representation		
	Lumped	Distributed	Wall et al. (1982)#
Lutteral Creek	8.8	7.0	5.9
Armstrong Mills	13.8	12.2	8.4

Note: # Load (t/km^2) = -20.4 + 0.79 (% Row crop area) + 1.1 (% clay area).

The monthly total sediment loads estimated for each areal snowpack representation are plotted in Figure 4.

The differences in the calculated monthly sediment loads produced by the two different representations of areal snowpack are quite evident. These deviations are as high as 165% , much higher than for streamflows. Furthermore the snowpack representation influenced the computed sediment loads for each month of the year, not just months with snow cover. This occurs because sediment washoff/erosion is a supply-based process, which means that if more sediment is washed-off during a given event, less sediment is available for subsequent events. Here, the lumped snowpack case eroded considerably more sediment in March (43% for Armstrong Mills) than the distributed one, and so less sediment remained available for transport later in the year.

CONCLUSIONS: IMPLICATIONS FOR WATERSHED MANAGEMENT STUDIES

The conclusions we have reached from these initial assessments are summarized below. We also include remarks on the implications these findings could have for watershed management studies.

1. The degree of detail used in a watershed model to represent the areal distribution of snow cover influences the calculations of streamflow during the mid- winter to mid-spring months when partial snow cover exists. This effect will likely be the greatest in watersheds with a variety of land cover types, and where blowing snow exerts a significant control on the snow cover patterns (as in southern Ontario). Further model applications to other years (and watersheds) is required to verify the preliminary findings we report and to ascertain whether snow cover distribution influences the long-term water balance.

2. The influence of snow cover distribution is even more pronounced in calculations of water quality as indicated here by the results for sediment loads. Differences in degree-of-detail in snow-cover representation change calculated monthly sediment results for the whole year. This is an important finding for watershed management studies, because sediment loading estimates are an integral part of the procedures for assessing the environmental impacts of any development within a basin. Numerous contaminants in runoff water are known to be associated with and carried by sediment (e.g. see Dickinson and Green, 1988). Moreover, sediment loads are required in fish habitat assessments (Weatherbe et al., 1992).

3. Choice of strategies for watershed management, including curbing the impacts of development, involve comparisons-for-effectiveness of various land-use/land-cover options. Land cover features are known to exert a strong influence on snow-cover-distribution patterns and our modelling results show that changes in snow-cover pattern influence model results for flowrate and water quality. Watershed models used for prediction of effects of changes in landuse on streamflow and stream quality should include explicit representation of the areal distribution of snow cover.

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REFERENCES

Adams, W.P. 1976. Areal differences of snow cover in east central Ontario. Water Resources Research, 12(6): 1226-1234.

Alley, W.M. and. P.E. Smith. 1981. Estimation of accumulation parameters for urban runoff quality modelling. Water Resources Research, 17(6): 1657-1664.

Burkard, M.B., H.R. Whiteley, H.O. Schroeter, and D.R. Donald. 1991. Snow depth/area relationships for various landscape units in southwestern Ontario. Proc. of the 48th Annual Meeting of Eastern Snow Conference. 51-65.

Charlton, D.L. and R. Tufgar. 1991. Integrated watershed management approach for small southern Ontario rural/urban watersheds. Canadian Water Resources Journal, 16(4): 421-432.

Cumming-Cockburn and Marshall Macklin Monaghan. 1988. Snow Hydrology Guidelines, Snow

Hydrology Study Phase VI Final Report, submitted to the Ontario Ministry of Natural Resources, Toronto, Ontario.

Dickinson, W.T. and D.R. Green. 1988. Characteristics of sediment loads in Ontario streams. Canadian Journal of Civil Engineering, 15(6): 1067-1079.

Ecologistics Ltd. 1988. Speed and Eramosa Rivers floodline mapping study: Hydrology. Submitted to the Grand River Conservation Authority, Cambridge, Ontario, under the Canada/Ontario Flood Damage Reduction Program.

Ghate, S.R. and H.R. Whiteley. 1982. GAWSER - A modified HYMO model incorporating areal-variable infiltration. Trans. ASAE, 25(1): 134-142.

Grand River Conservation Authority (GRCA). 1988. Grand River Hydrology Study- Phase I: Final Technical Report. A study funded under the Canada/Ontario Flood Damage Reduction Program. Cambridge Ontario.

Huber, A.L. 1983. A comparison of several snow accumulation and ablation algorithms used in watershed modelling. Proceedings of the 51st Annual Meeting of the Western Snow Conference, pp. 76-89.

Ontario Ministry of Natural Resources (OMNR). 1989. Guelph All-Weather Storm- Event Runoff Model (GAWSER) Version 5.4: Training Guide and Reference Manual. Toronto Ontario.

Schroeter, H.O., D.K. Boyd, L.L. Minshall, and H.R. Whiteley. 1992. Grand River Integrated Flood Forecast System (GRIFFS): development and real-time application. Proc. of the 2nd Canadian Conference on Computing in Civil Engineering, CSCE, Carlton University, Ottawa, Ont. pp 782-793.

Schroeter, H.O. and R.P. Epp. 1988. Muskingum-Cunge: a practical alternative to the HYMO VSC Method of channel routing. Canadian Water Resources Journal, 13(4): 68-89.

Schroeter, H.O., D.K. Boyd and H.R. Whiteley. 1991. Areal Snow Accumulation- Ablation Model (ASAAM): experience of real-time use in southwestern Ontario. Proc. of the 48th Annual Meeting of Eastern Snow Conference, June 6-7, 1991, Guelph, Ont., pp.25-37.

Schroeter, H.O. and W.E. Watt. 1989. Practical simulation of sediment transport in urban runoff. Canadian Journal of Civil Engineering, 16(5): 704-711.

Schroeter, H.O. and H.R. Whiteley. 1986. Distribution of snow cover as influenced by landscape units in southwestern Ontario. Proc. of the 43rd Annual Meeting of Eastern Snow Conference, pp. 32-44.

Schroeter, H.O. and H.R. Whiteley. 1987a. SAAM - an operational snow accumulation-ablation model for areal distribution of shallow ephemeral snowpacks. Proc. of the 8th Canadian Hydrotechnical Conference, Montreal, Quebec, pp. 481-500.

Schroeter, H.O. and H.R. Whiteley. 1987b. Application of a snow accumulation- ablation model for areal distribution of shallow ephemeral snowpacks. Proc. of the 44th Annual Meeting of Eastern Snow Conference, pp. 129-143.

Schroeter, H.O. and H.R. Whiteley. 1990. Simulating snow cover distribution in a watershed using the Areal Snow Accumulation-Ablation Model (ASAAM). Proc. of the Flood Plain Management Conference, March 12-14, 1990, Toronto, Ont., pp. 339-350.

Wall, G.J., W.T. Dickinson, and L.J.P. van Vliet. 1982. Agriculture and water quality in the Canadian Great Lakes Basin: II. Fluvial sediments. Journal of Environmental Quality, 11: 482-486.

Weatherbe, D.G., H.O. Schroeter, D.W. Draper, and H.R. Whiteley. 1992. Modelling of changes in surface water quality for watersheds undergoing urbanization. Chapter 6 in New Techniques for Modelling the Management of Stormwater Quality Impacts, (W James Ed.) Lewis Publishers Inc., Chelsea, Michigan pp 123 -147.