Area Snow Accumulation-Ablation Model (ASAAM)

Experience of Real-Time Use in Southwestern Ontario

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ABSTRACT

The areal snow accumulation-ablation model (ASAAM) estimates the spatial distribution of snow cover amounts (snow depth and equivalent water content) for individual cover types on a daily basis for the complete winter. The calculated distributions provide an improved basis for streamflow modelling during conditions of partial snow cover which occur for many large flood events in Ontario.

The model requires as input daily snowfall depth, rainfall amounts, air temperature, wind speed and direction. ASAAM can make direct use of the individual point values from routine snow course surveys for upgrading of its real-time monitoring of snowpack conditions.

ASAAM is in operational use at the Grand River Conservation Authority as part of their new Integrated Flood Forecasting System (GRIFFS). This paper gives a brief overview of the the computational procedures available in ASAAM, together with results of applying the model in real-time over the last three winters (1988-89, 1989-90 and 1990-1991) in the Upper Grand River Watershed. The paper concludes by summarizing the utility of model as an operational tool for water management.

INTRODUCTION

The variation from point to point of snow amounts among and within varying landscape units is readily observable and generally recognized. Most models for snow accumulation and ablation that have been used for forecasting of streamflows in eastern North America in the past did not incorporate this variation into their calculation algorithms (Huber, 1983; Cumming-Cockburn and Marshall Macklin Monaghan, 1988). The redistribution of snow by wind after each snowfall has also not been treated by the calculation procedures used in these models.

The areal snow accumulation-ablation model (ASAAM) explicity accounts for areal distribution and the redistribution of snow by wind (Schroeter and Whiteley, 1987a,b, 1990). The model 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 tested by its use in the preparation of flood forecasts. For this application, a data management program (EDSAM) was developed under the sponsorship of the Ontario Ministry of Natural Resources (OMNR, 1989). EDSAM provides for incorporation of real-time data into ASAAM calculations. The continuous daily estimates of snowpack conditions provided by ASAAM were entered as initial conditions for runs of the Grand River Integrated Flood Forecast System (GRIFFS) (GRCA, 1989; Smith and Boyd, 1990).

In this paper, we briefly outline the basic features of the computational procedures available in ASAAM, and then demonstrate its use as an operational tool for monitoring the snowpack status in the Upper Grand River watershed over the last three winters (1988-89, 1989-90 and 1990-91). The complete development, testing and initial application of the ASAAM is documented elsewhere (Schroeter and Whiteley, 1987a,b, 1990)

OVERVIEW OF THE COMPUTATIONAL PROCEDURES IN ASAAM

The ASAAM (areal snow accumulation-ablation model) is designed to provide areally-distributed estimates of the snowpack conditions (depth, equivalent water content, and the extent of bare ground) required as input to most streamflow generation models for the start of the simulation of an event at any time during the entire winter.

Representation of spatial variation in snow cover amounts

To account for the spatial variability in sequences of rainfall, snowfall, air temperature and wind speed, a watershed is divided into 'zones of uniform meteorology' (ZUM). Each ZUM is one or more subwatersheds for which one set of meteorological measurements is used. Typically, a ZUM may be from 100 to 350 km^2 (GRCA, 1989).

Each ZUM is partitioned among 'blocks of equivalent accumulation' (BEA) to account for the spatial variation in snow cover found within and among differing land cover units. Based on field observations (Dickinson and Whiteley, 1972; Stepphun and Dyck, 1974; Adams, 1976; Goodison, 1981; McKay and Gray, 1981; Schroeter and Whiteley, 1986), two types of BEAs are identified in the model. The first type, 'areal' blocks, are extensive in both length and width. The second type of BEA, 'edge' blocks, represent long 'thin' land features with significant capacity to store snow (e.g. roads with ditches, forest-field edges, fence lines with and without trees, and river valleys).

Spatial differences in retention of snow exist within each cover- type block because of topographic ridges and depressions and spatial variation in roughness height. This variation is represented in the model by subdividing each block into 'cells' with varying capacity to hold snow during drifting conditions. Cells for edge blocks have physically-based cell capacity patterns based on cross-section measurements while areal blocks have a pattern of holding capacity determined from the statistical distribution of snow depth for that land type.

Typically, ten cells are used to represent the maximum snow depth profile for edge blocks, where the cell widths range from 2 to 10 m. For areal blocks, five cells are usually used to define the capacity depth curve, each representing 20% of the total block area.

Model inputs and simulation of ablation processes

The model operates on a daily basis using readily available meteorological inputs: maximum and minimum air temperature, new snow amounts (as depths, and equivalent water content when available), rainfall amounts, mean wind speed, and prevailing wind direction.

Calculations are made within the model for changes in snow density with time (compaction), snowmelt and sublimation amounts, liquid water holding capacity, refreezing of liquid water during below freezing conditions, infiltration into the ground and overland runoff of liquid water when available.

Snowmelt and refreeze are computed using a temperature index approach. Sublimation is set as a fixed daily amount, applied on days with below freezing temperatures no rain. Snowpack compaction is calculated using a one-dimensional consolidation equation, and the liquid water holding capacity is computed as a fixed proportion of the available pore space.

The amount of meltwater that infiltrates into the ground is limited by one of two capacity limits, one representing unfrozen ground and the other frozen conditions, established from air temperature sequences and meltwater amounts. Meltwater that does not infiltrate or leave the pack by lateral flow remains in a saturated layer and during any subsequent refreeze, forms a solid basal ice layer. When an ice layer is present, meltwater infiltration is restricted to near zero. A complete description of the snow ablation computation is given by Schroeter and Whiteley (1987a).

Simulating snow cover erosion and redistribution

The aging of a snow cover in terms of its reduced susceptibility to wind erosion and drifting is represented by a five-layer snowpack. The top two layers are active for erosion and redistribution. The other three layers are not subject to redistribution by wind.

The model redistributes eroded snow from cells and blocks of low capacity to store snow to those with a high capacity whenever there is sufficient wind within two days of a new snowfall. Snow erosion is computed using an expression adapted from the sediment pick-up functions reviewed by van Rijn (1984).

Redistribution is done first for cells within each block. Then, if any eroded snow cannot be held within a block, it is moved to edge blocks with higher storage capacity. The wind direction and the orientation and exposure of edge blocks are used to identify which blocks will participate in the erosion and redistribution calculations for a particular time step.The snow cover erosion and redistribution procedures are described by Schroeter and Whiteley (1987b).

REAL-TIME APPLICATION RESULTS FOR UPPER GRAND RIVER

Assessment of the performance of a simulation model in real-time application is very different from the verification/validation testing associated with model development. In the latter case strigent testing procedures are required to establish the model's credibility in reproducing the complexity of behaviour of the systems the model represents. On the other hand, the objective in assessing a model for real-time applications endeavours to answer the question, 'Does the model get the job done?'

The assessment of ASAAM for overall simulation of the complex snow accumulation, ablation and redistribution processes has been presented elsewhere (Schroeter and Whiteley, 1987a,b, 1990). In this paper, we assess the performance of ASAAM in real-time flood forecasting for the Upper Grand River watershed for the last three winters.

In this application accurate simulation of the timing of snowmelt runoff events is the most critical feature with forecasts of specific quantities, such as mean basin snowpack equivalent water content or streamflow peaks and volume ranking next in importance.

Overview of real-time assessment procedures

In real-time application of snowpack modelling input data is sparse and output data for testing of results is limited to a few snow course locations for only a small number of dates during the winter (e.g. 9 or 10 dates). Moreover, most snow courses sample only one cover type, and so comprehensive evaluation of the model results as regards distribution among cover types is not possible in real-time.

There is also ambiguity in selecting which day's model results to compare with snow survey samples. Snow sampling is done in daylight hours between 9 am and 5 pm usually.The meteorological data are recorded at 8:00 am for most sites, with precipitation data back dated to the previous day. The daily simulation period for model calculations was chosen to run from midnight to midnight.A particular snow cover observation recorded on, say March 15th, may be best compared to the simulated value at midnight on the 14th or on the 15th, depending on the sequence of rain, snow or melting temperatures overnight and on the 15th.

Standard procedures for testing hydrologic models as outlined in the literature (e.g. James and Robinson, 1981; James and Burges, 1982) cannot be applied in a straightforward manner when the observed data set is sparse. Objective measures of model performance, such as the Nash-Sutcliffe (1970) model efficiency, are intended for comparative analysis with continuously recorded data (e.g. streamflow hydrographs), and can be extremely biased by single outlier values, and hence are inappropriate for use with comparisons based on a few discrete observations.

As a result of these considerations we evaluated model performance subjectively and through a target-achievement measure described below. The most important tools of assessment were time-series plots of the simulated mean snow depth and total water content for each block, on which the discrete measurements were noted. Viewing these plots one has the opportunity to scan the entire set of relationships between observations and model results. The subjective terms 'excellent', 'very good', 'good', 'fair', and 'poor' are defined as follows.

Percentage of observations in agreement with model output	Qualifying Level of agreement
> 80	Excellent
60 to 80	Very Good
40 to 60	Good
20 to 40	Fair
< 20	Poor

In hydrological practise corresponding simulated and measured values are said to be in agreement when their magnitudes differ by less than the level of error normally associated with measuring hydrologic variables, i.e.±10% for snow depth, snow water equivalent, precipitation depths, and streamflow. In keeping with the expectations of real-time performance our error band for agreement was increased to 20%, with a time difference of one day accepted for comparison.

Some errors in measuring early winter snowfall inputs lead to poor late season model results, although the temporal trend in the simulated output agrees with the observations throughout. If the overall trends agree for the whole winter, then the model performance was listed as as fair due to the conservation in trend even though the test of corresponding points gave a poor rating.

To quantify the assessment we defined a 'Target Achievement Measure' (TAM) computed as follows:

$$\mathrm{TAM} = (100/N) \sum_{i}^{N} T_i \qquad [1]$$

with $T_i = 1$ for $|Y_{oi} - Y_{mi}| < f_t * Y_{oi}$ and $T_i = 0$ otherwise.

where N is the total number of observations available, Y_{oi} and Y_{mi}, are the observed and modelled results respectively for sample i, f_t is a fraction representing the selected target level of achievement. To account for the lack of synchronization between model input data and snow cover measurements, T_i is calculated using the simulated values (Y_{mi}) for day before and after the observation date. The highest value of T_i is then used.

Taking account of the uncertainties in real-time snow cover observations as noted earlier, we selected our target achievement level as ±20%, and hence set f_t=0.2.

Test Data

The upper Grand River valley is an agricultural watershed with a drainage area of 683 km^2 in the headwaters of the Grand River near Marsville. The outlet of this watershed is about 12 km upstream of Lake Belwood (Fig. 1), one of the three major multi-purpose reservoirs operated by the Grand River Conservation Authority (GRCA).

With the watershed snow surveys are conducted at Corbetton, Jessopville and Waldemar (Fig. 1). These surveys are done usually on the 1st and the 15th of the month from December 1 to April 15. The means of the 10 snow depths and the 10 water equivalent measurements are reported on the survey day to the Authority's Flood Centre in Cambridge, Ontario. Supplementary snow course surveys are done between scheduled dates when this is necessary.

The snow course at Corbetton samples two cover types, natural grassland and a deciduous forest. At Jessopville, the snow course traverses a forest edge and coniferous forest. The Waldemar snow course is located entirely within a coniferous forest. In total, observed snow data are available from five different blocks.

Daily temperature and precipitation are available in real-time from two of the GRCA's dams, the one near Monticello (Luther Dam) and the Shand Dam on Lake Belwood. Additional data from more than 10 climate stations (see Fig. 1) are available for post-event evaluation or historical modelling. Wind speed and direction were taken from Waterloo-Wellington Airport located 70 km south of the watershed.

For real-time streamflow forecasting, the GRCA maintains three gauges located along the main stem of the river at Legatt, Waldemar and near Marsville (see Fig. 1). Real-time water level information is telemetered to the GRCA head office in Cambridge. These data are used to compare with the simulated output from the Authority's hydrologic forecast model (GRIFFS, see GRCA, 1989; Smith and Boyd, 1990), and hence can be used to indirectly test the output from the ASAAM.

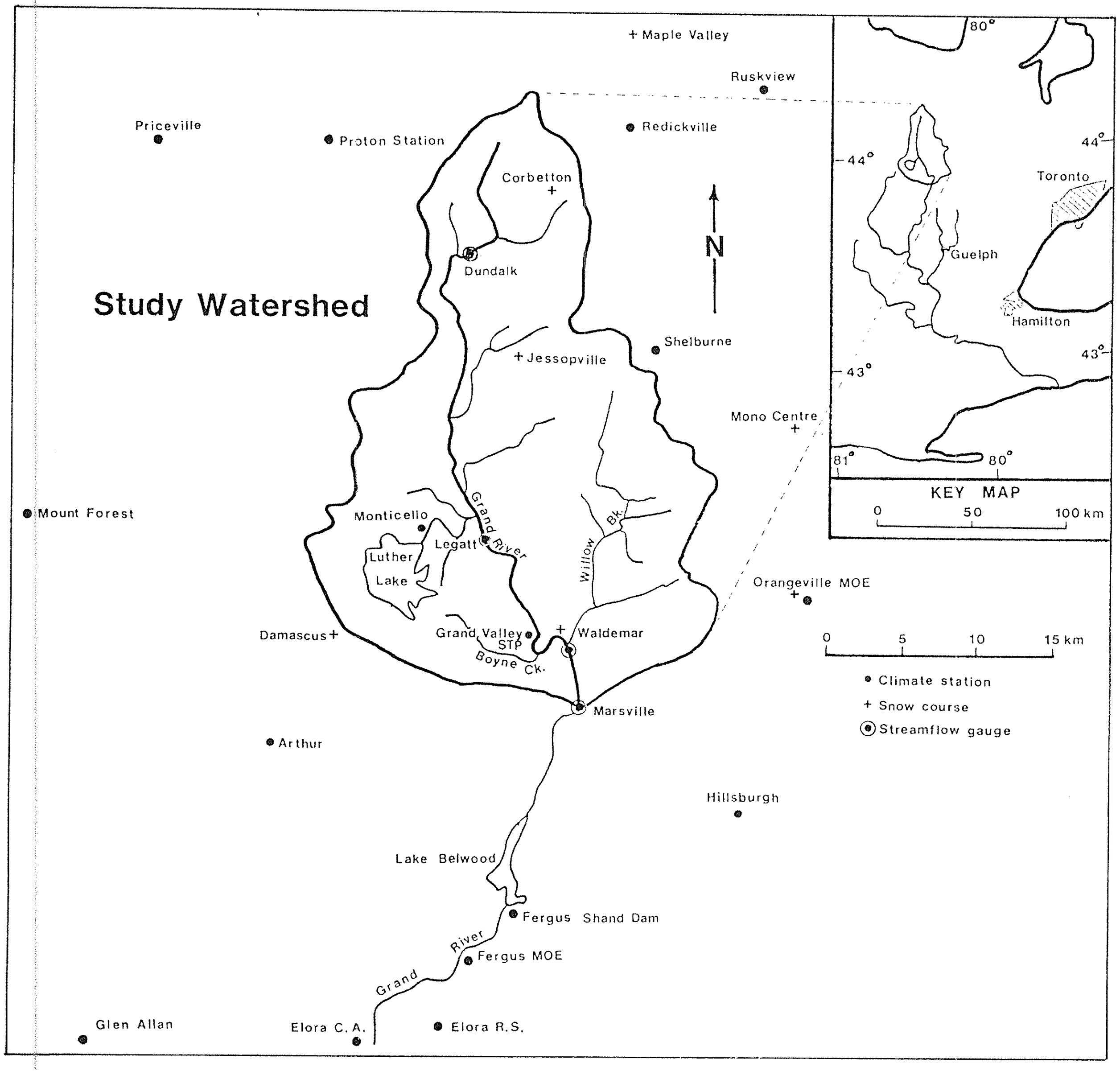

Figure 1. Upper Grand River Valley.

Simulation Results

ASAAM presents information on the areal distribution of snow cover in a watershed at varying levels of aggregation ranging from highly detailed snow depth distribution within a block, through intermediate detail (mean snow conditions for each block), to the most general (mean watershed snow conditions). In the real-time applications presented here, field results were only available for mean block conditions for mean snow depth and equivalent water content for the five block types represented by the snow course survey lines at Corbetton, Jessopville, and Waldemar. Samples of the fully distributive output from ASAAM compared against detailed field measurements have been presented by Schroeter and Whiteley (1990) for the 1985-86 and 1986-87 winters.

Performance of ASAAM measured by Target Achievement Measures (TAM) and Nash-Sutcliffe (1970) model efficiencies, is presented in Table 1. Plots of depth and equivalent water content, upon which the discrete snow survey observations are noted, are illustrated in Fig 2 for the three winters.

ASAAM is used to estimate the initial snowpack conditions that are entered as input to the hydrologic forecast model for a flood event. How good are the ASAAM data? To check we compared the snowpack conditions generated by ASAAM with those 'back calibrated' from the forecast model and hydrograph data. The 'back-calibrated snow conditions are those that give the best overall agreement between the observed and simulated hydrographs at the various streamgauges locations. They are, of course, only available during post-event evaluation. A comparison plot of the snowpack conditions provided by ASAAM and the GRIFFS back-calibrated estimates is presented in Fig. 3 For each winter there are results from each of the three ZUMs in the upper Grand River watershed for one flood event The 20% target level of achievement lines are shown as well. Fig. 4 shows the measured and modelled hydrographs for the Marsville gauge using back-calibrated snowpack conditions. For this comparison the computed the Nash-Sutcliffe model efficiencies were well above 0.9.

Discussion of Results

Upon examination of Table 1 and Fig 2 the agreement between the measured and modelled results are satisfactory, in light of the known uncertainties associated with both model input data, as well as obsrved data used for comparison. The overall Target Achievement Measure (TAM) for snow depth simulation in all five blocks for three winters is 69%, which is very good for real-time work. The corresponding TAM for snow water equivalent estimates is about 44%, which is considered good.

The major discrepanies between the observed and simulated results have been attributed to synchronization difficulties between model output and the field observations, as well as estimating the meteorological inputs for each ZUM (see Schroeter and Whiteley 1987 a,b and 1990) for a detailed discussion). (Recall, that data from only two climate stations, Luther and Shand Dams, are available in real-time for estimating model inputs for three different locations.) It is noteworthy, that ASAAM reproduced the overall trends exhibited by the field measurements, as well as accurately predicting the time when the snowpack disappeared in almost every instance.

The fact that the TAMs are good to very good for the Corbetton and Jessopville blocks (especially for snow depth simulation) suggests that the individual point values in snow course surveys can be used directly to check output from ASAAM in real-time. Here, the the first four point values of the Jessopville snow course survey are used to estimate mean block values for the forest edge block,

Table 1: Summary of ASAAM performance in real-time for the three winters in the Upper Grand River watershed

Snow Course	Block Type	Mean Block Snow Depth			Mean Block Snow WE			Number Sample Dates
		Samples on Target	TAM (%)	ME (r^2)	Samples on Target	TAM (%)	ME (r^2)	
1988-89								
Corbetton	Natural Grass	7	64	0.72	5	45	0.25	11
	Deciduous Forest	8	73	0.81	6	55	0.70	11
Jessopville	Forest Edge	6	55	0.79	3	27	0.03	11
	Coniferous Forest	6	54	0.57	6	54	0.31	11
Waldemar	Coniferous Forest	12	86	0.86	9	64	0.58	14
	1988-89 Average	39	67		29	50		58
1989-90								
Corbetton	Natural Grass	9	90	0.79	7	70	0.86	10
	Deciduous Forest	7	70	0.81	8	80	0.83	10
Jessopville	Forest Edge	8	80	0.90	5	50	0.77	10
	Coniferous Forest	7	70	0.87	4	40	0.70	10
Waldemar	Coniferous Forest	10	91	0.94	4	36	0.59	11
	1989-90 Average	41	80		25	49		51
1990-91								
Corbetton	Natural Grass	7	70	0.70	3	30	0.18	10
	Deciduous Forest	8	80	0.88	6	60	0.76	10
Jessopville	Forest Edge	6	60	0.85	2	20	0.47	10
	Coniferous Forest	7	70	0.68	5	50	0.47	10
Waldemar	Coniferous Forest	7	64	0.79	6	54	0.67	11
	1990-91 Average	35	69		22	43		51
	All 3 winters	115	69		76	48		160

Notes: TAM = Target Achievement Measure
ME = Nash-Sutcliffe (1970) Model Efficiency

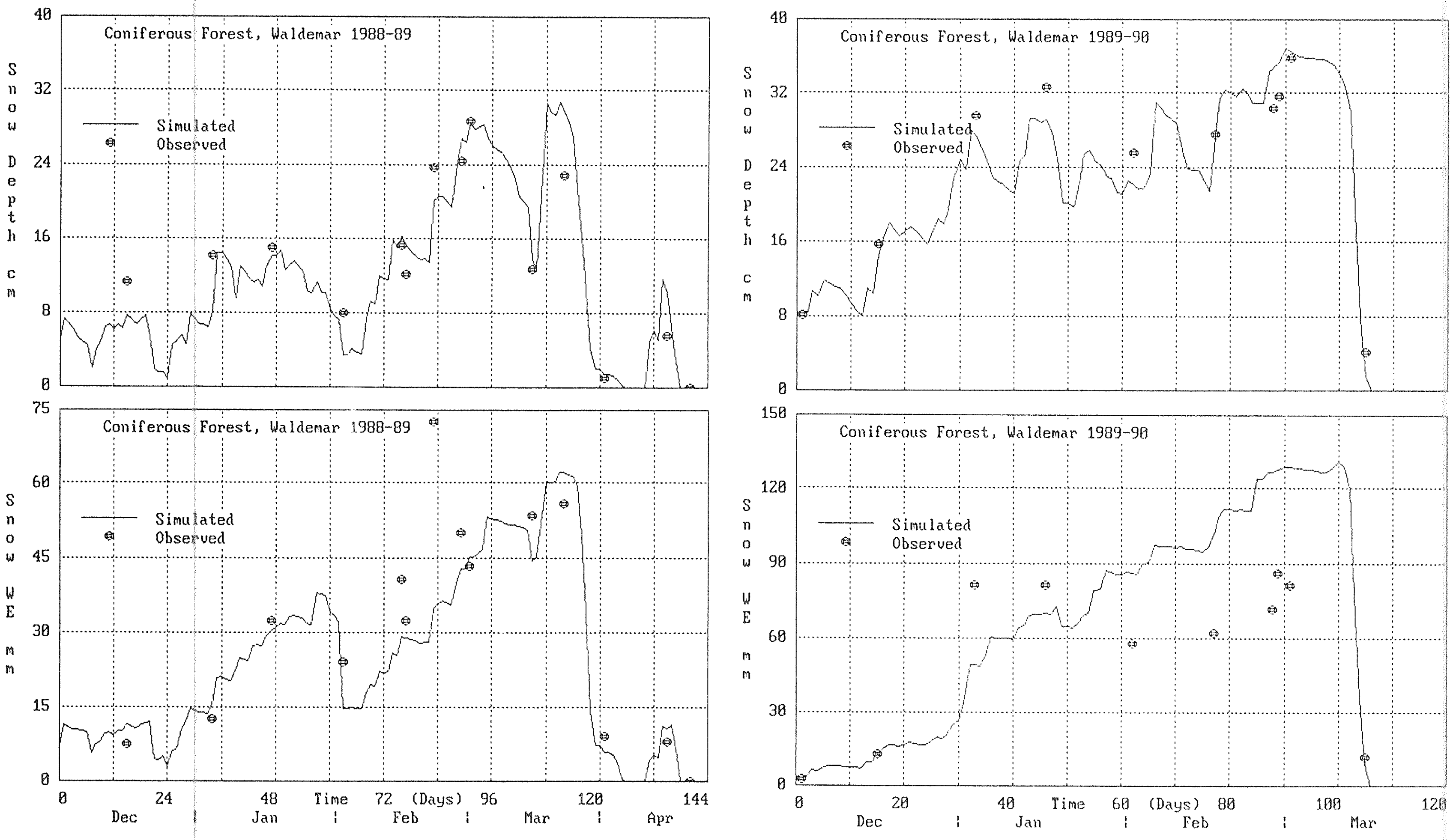

Figure 2. Measured and modelled time-series plots of mean block snow depth and water equivalent for blocks in the Upper Grand River (1990–91).

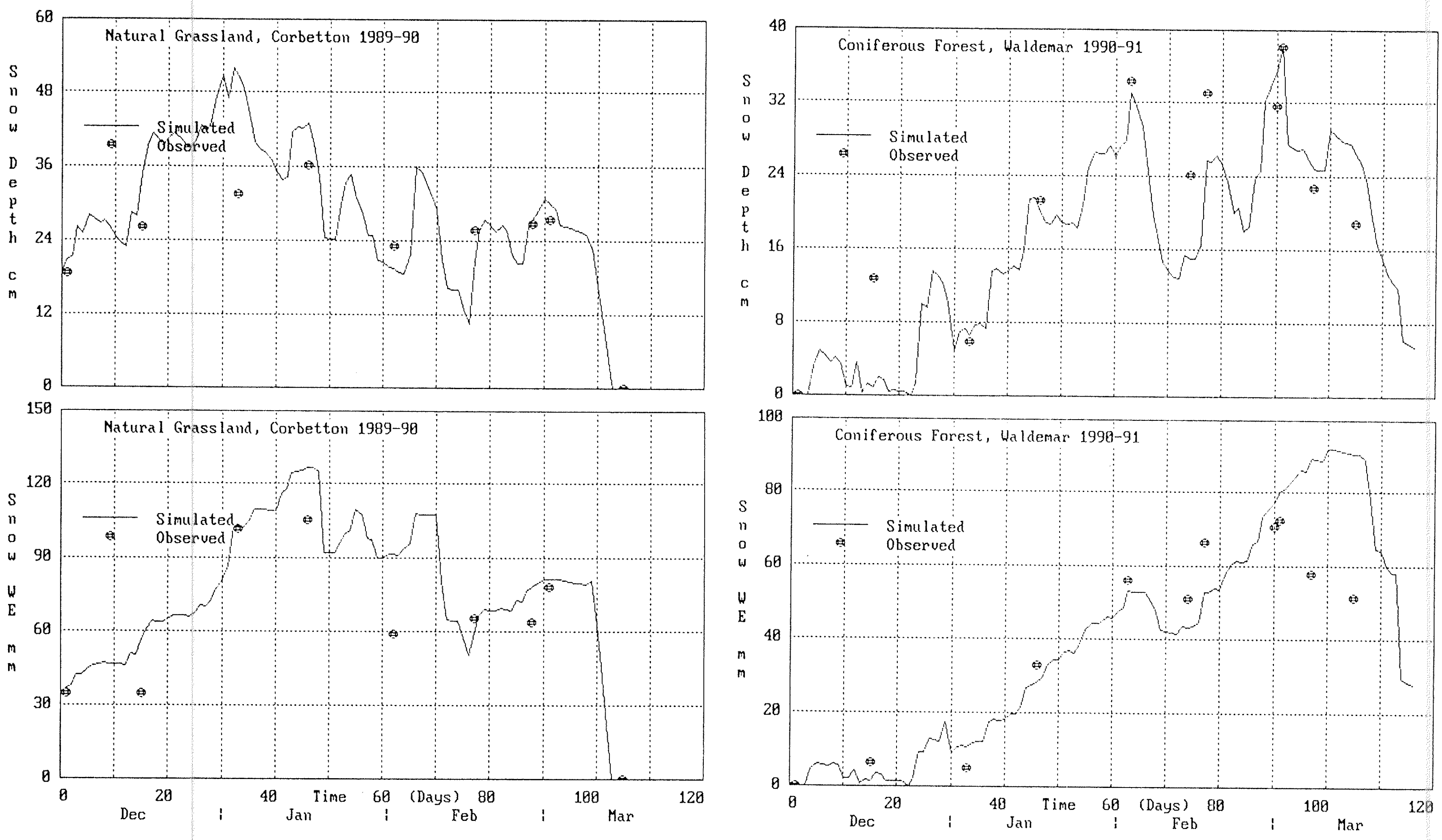

Figure 2 (cont'd). Measured and modelled time-series plots of mean block snow depth and water equivalent for blocks in the Upper Grand River (1990–91).

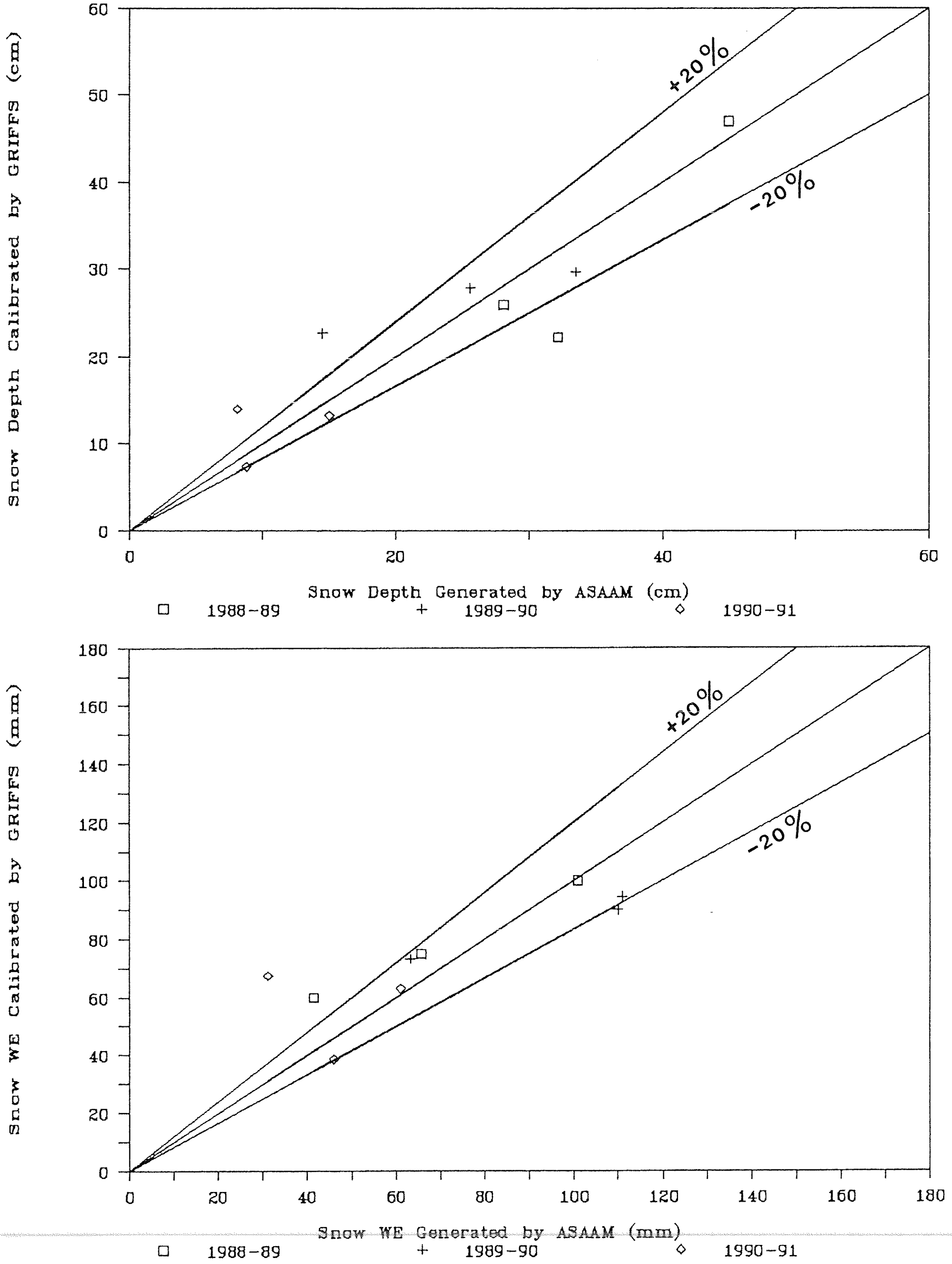

Figure 3. Comparison of snowpack depth and water equivalent given by ASAAM with best-fit values obtained by back-calibration of Griffs Model.

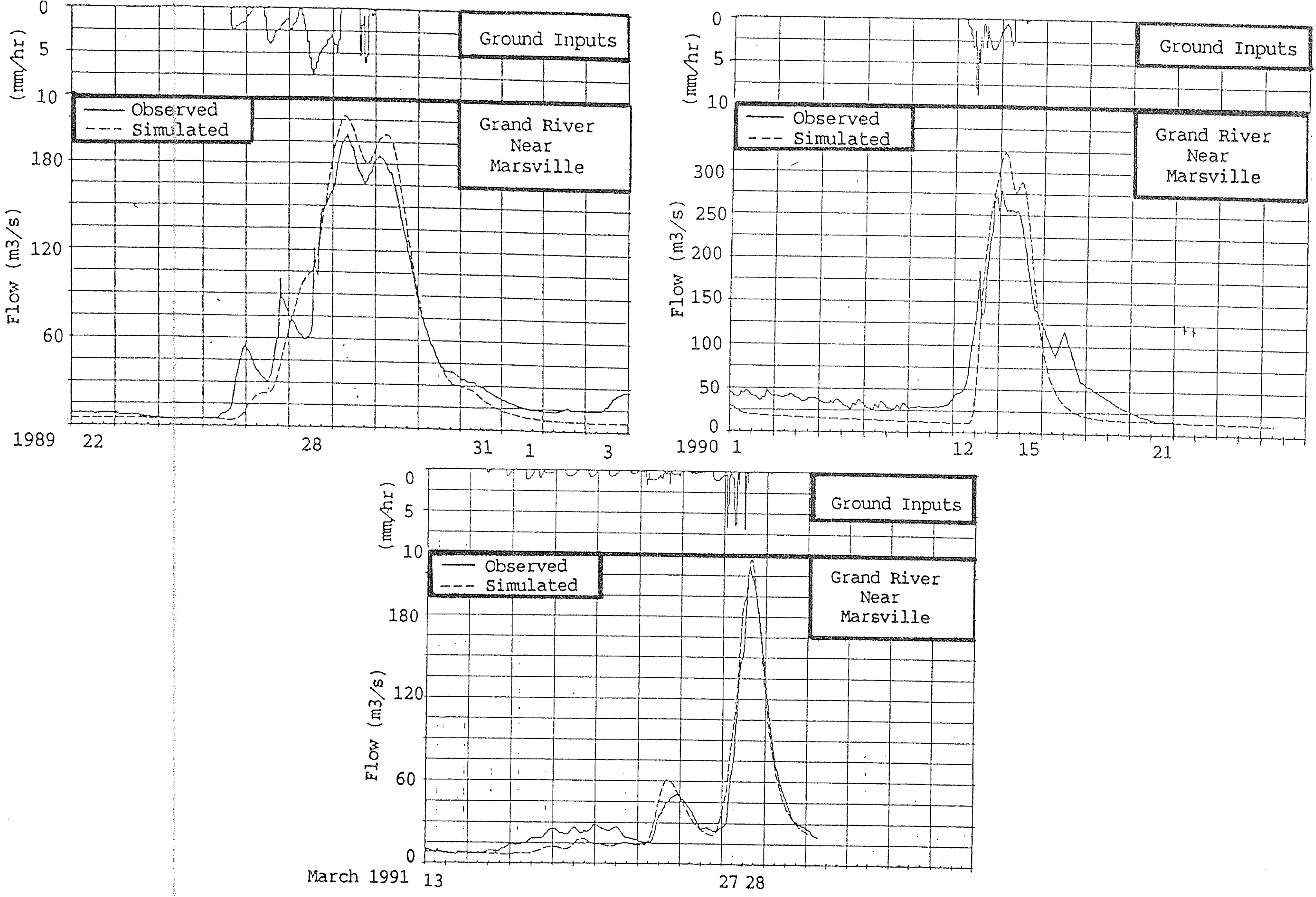

Figure 4. Observed hydrographs compared with Griff simulations using best-fit back-calibrated snow properties.

whereas the last three points in the Corbetton snow course can be combined to estimate the mean snow depth and equivalent water content for the deciduous forest block.

The very good the agreement between the ASAAM generated initial snowpack conditions and the GRIFFS calibrated values (computed TAM for snow depth is 67%, and 78% for SWE) illustrates that ASAAM performs very well in its intended role, that is as a tool for monitoring a watershed's snowpack conditions.

CONCLUSIONS

The utility of ASAAM is summarized by the following.

1. ASAAM simulates the status of a snowpack for the complete winter. It gives estimates of snow cover amounts for dates between snow surveys days and for areas where snow surveys are not carried out. This is significant, because the model provides an estimate of snow cover amounts when the operational water manager needs them for making forecasts of snowmelt runoff. For secondary importance, the model can be used for review of past hydrologic events to establish causes of flow sequences (e.g. floods, or droughts).

2. Real-time testing of ASAAM shows that the individual point values from existing snow course surveys can be used to check and update model output. At last, there is a method of making direct use of snow survey measurements for streamflow forecasting. Moreover, this has implications for snow survey network design, because an effective snow course for checking ASAAM would be one that samples more than one land cover unit.

3. ASAAM tells the water manager how the snowpack is distributed spatially. Decisions regarding operations (e.g. reservoir discharges or field staff allocation) can then be based on how the different parts of the watershed will contribute snowmelt runoff to flow in the river and at what times (e.g. shallow snow cover will contribute first, followed by the deeper packs in forests and edges).

4.ASAAM was designed to be an operational model, and has been tested in actual operational use for the last three winters. It runs on the most widely available meteorological data. Previous research models have not been applied directly because they often require more data than the user has available to run them.

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