Application of the Senorge 1D model to Armenian snow data

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Abstract: The Senorge snow model is used to simulate snow depth and snow water equivalent for five Armenian sites with existing time series of precipitation and temperature. For particular years there are measurements of snow depth which are used for validation. When manipulating the parameters of the model, a reasonable fit to observed values of snow depth is obtained for all observation sites.

Key words: Snow model, snow depth, snow water equivalent, Armenia

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Preface

This work is part of an ongoing cooperation between Armstatehydromet and NVE, financed by the Norwegian Ministry of Foreign Affairs. Snow modelling as a supplement or an alternative to field measurements of snow, might be a very important tool in water management during spring and early summer in Armenia.

Oslo, november 2010

Morten Johnsrud

Director, Hydrology department

Abstract

The Senorge snow model is currently run every day over the whole Norway and provides maps of snow water equivalent (SWE) at a 1 km^2 resolution. The model has precipitation and temperature as input and SWE, Snow depth (SD), liquid water content (LWC) and snow density as output. In order to evaluate the possibility of using the snow model to simulate snow depth and SWE for Armenian snow conditions, we have run a point version of the model (Senorge1D) for 5 Armenian sites with existing time series of precipitation and temperature. For particular years there are measurements of snow depth which are used for validation. When manipulating the parameters of the model, a reasonable fit to observed values of SD is obtained for all observation sites. Due to the known weakness of calculating too high densities, however, the fit to observed values of SWE may not necessarily be as good. The model should be tuned according to the purpose of use (SWE or SD). The Senorge1D model is coded in **R**, which is a freeware and can be downloaded from the net.

1 Introduction

The Senorge snow model (www.senorge.no) is a temperature-index model, which simulates snow melting as a linear function of the air temperature when it is above 0 C. The model is run all over Norway at a 1 km^2 resolution on a daily time scale, and is simple and not particularly data-demanding, since it uses only daily averages of precipitation and temperature. This constitutes a great advantage, given the extension of the domain of simulation and the difficulty to interpolate meteorological observations in such a vast area. However, it has to be taken into account that degree-day factor models only work in “typical” conditions, since they are based on a statistical regression on historical data, assuming that a consistent and definable relationship between temperature and snow cover energy exchanges is present (Garen and Marks, 2005).

The purpose of this work is to test whether a point version of the Senorge snow model (Senorge 1D) can be used to simulate Armenian snow conditions. The Senorge 1D is coded in the **R** language, and is applied at 5 Armenian sites where meteorological measurements and measurements of snow depth were available for validation of the simulations.

2 The Senorge snow model

The Senorge snow model is a precipitation/degree-day type model that simulates snow accumulation, snowmelt (degree-day approach, e.g. Bergström, 1992), as well as production of liquid water and refreezing requiring only precipitation and air temperature as model input data. Internal variables are used for fixed temperature-dependent thresholds for separating rain from snow, and to identify snowmelt and refreezing. Snowmelt intensity is specified by a time-varying variable and refreezing intensity by a constant. The state variables snow water equivalent (SWE) and snow liquid water content (LWC) are updated on a daily basis. Water yield from snowmelt and rain are also simulated. The model was earlier developed, tested and calibrated using point observations of snow water equivalent provided by snow pillows (Engeset et al., 2000, Tveito et al., 2002, Engeset et al., 2004). The degree-day melt factor varies according to the sun elevation between a minimum value at 21 December and a maximum value at 23 June. The minimum value is set to 2.0 mm °C-1 day-1. The maximum value is set to 3.0 mm °C-1 day-1 in forested areas. In non-forested areas, the maximum value varies according to latitude from 3.5 in southern Norway to 4.0 in northern Norway. The threshold temperatures used to separate snow from rain and to identify melting/refreezing are set to 0.5 °C and 0.0 °C respectively. Experience with using the Senorge1D model will show if other values of the parameters are more suitable for Armenian conditions. Figure 1 shows the structure of the degree-day model.

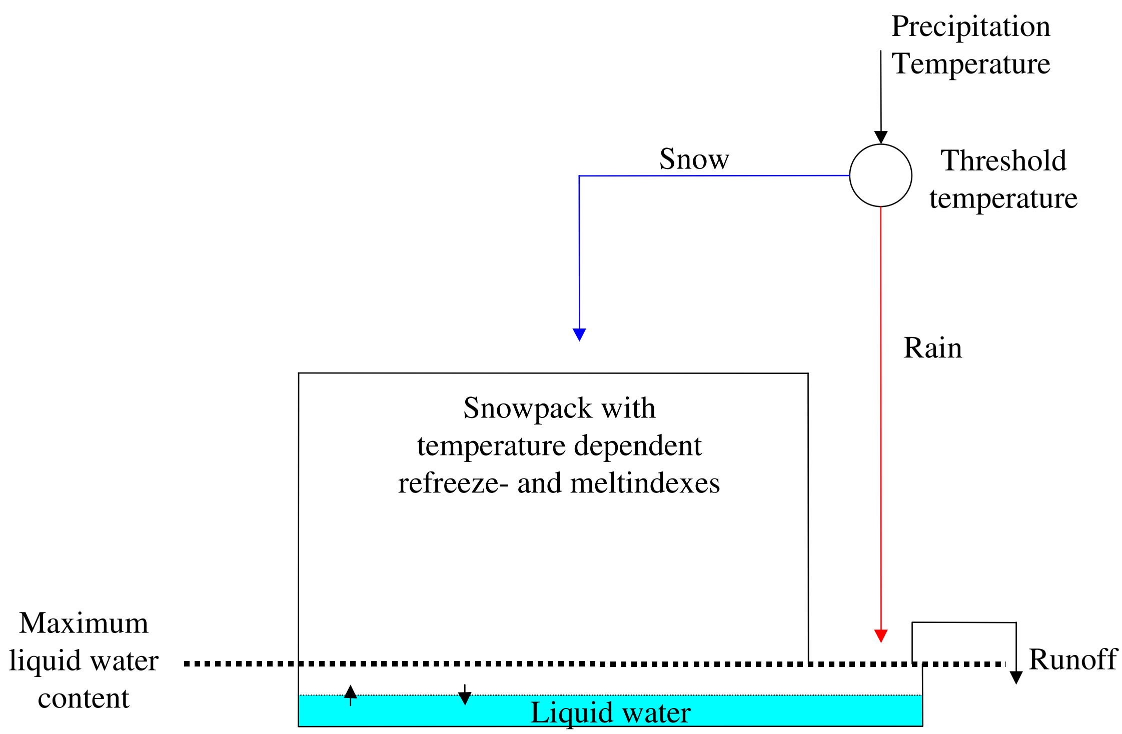


Figure 1. The degree-day module of the Senorge model. The input data is daily averages of precipitation and temperature and state variables are snow water equivalent (SWE) and liquid water content.

The Senorge model has been extended from a pure degree-day model, commonly used in hydrological rainfall-runoff models, to include procedures to simulate snow density and thus snow depth. The calculation of snow depth (SD) in the snow map application follows the VIC approach used in the VIC hydrological model (Liang et al., 1994; Cherkauer and Lettenmaier, 1999) and is divided in three sequential steps:

1. **Snowmelt**: In case of a net reduction of the snow magazine the snow depth is reduced by the snowmelt (mm water equivalent) divided by the snow density (after last time step).

2. **Snowfall**: The snow depth is changed using the equations from the VIC model for density of new snow (temperature dependent) and compaction of the current snow pack due to the weight of the new snow (based on Bras, 1990; see documentation of the VIC approach above). The compaction is limited by a maximum snow density of 0.7 g/cm^3.

3. **Ageing**: Snow densification due to ageing is calculated using the equation from the VIC model (based on SNTHRM89 (Jordan 1991)), see documentation of the VIC approach above). Also here, the densification is limited by a maximum snow density of 0.7 g/cm^3.

This makes it possible to test the model against measurements of snow depth, which are definitely more easily available and with a higher frequency than measurements of snow water equivalent. Figure 2 shows an example of a map of snow depth produced by the Senorge model.

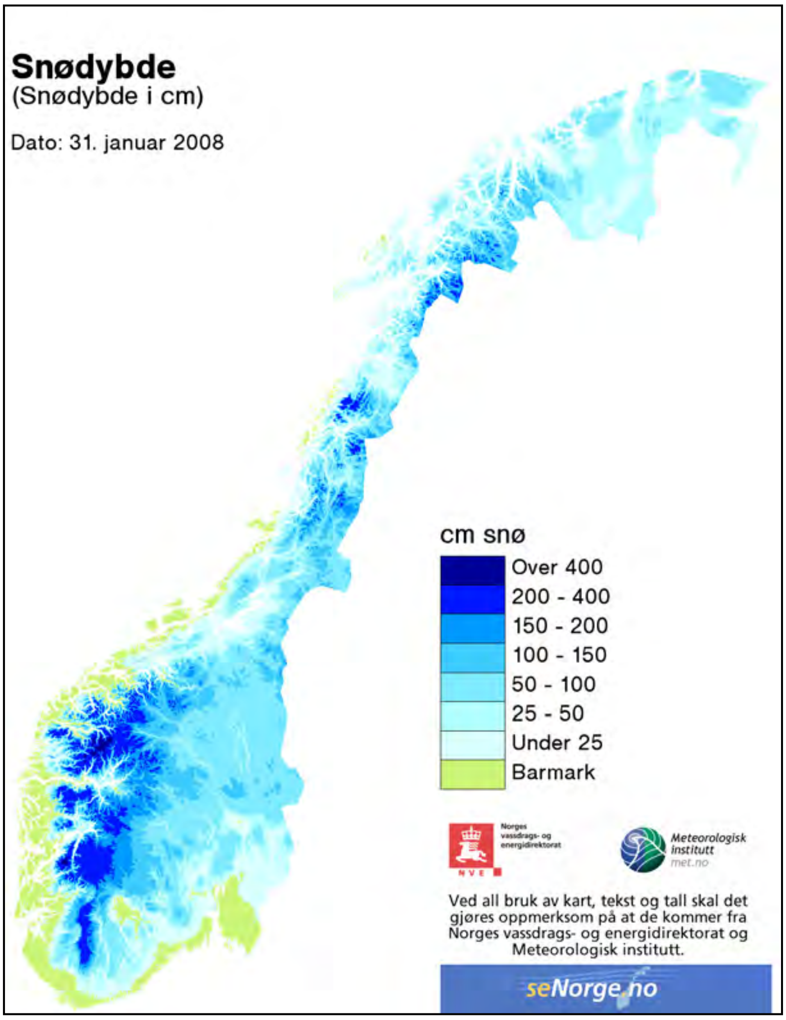


Figure 2. Example of national maps of snow depth produced by the Senorge model.

3 Study sites

The Senorge model has been applied and tested against snow depth measurements at 5 sites in Armenia. Time series of SWE, SD and snow densities have been simulated for the following sites (see Table 1).

Table 1. Name, location and elevation for Armenian sites.

METEOROLOGICAL STATIONS IN ARMENIA				
No.	**Name**	**Elevation**	**Lat.**	**Long.**
		m a.s.l.		
4101.5	Ambert	1890	40° 23′	44° 15′
4101.1	Aparan	1890	40° 36′	44° 21′
4101.4	Aragac	3227	40° 29′	44° 11′
4101.2	Ashtarak	1090	40° 17′	44° 21′
4101.3	Caxkahovit	2099	40° 38′	44° 14′

Daily values of meteorological data, precipitation [mm], temperature [°C] and snow depth [cm] are available for these stations for up to 25 years, starting from 1980 to 2004. The time series suffered from many missing values (see Table 2). *As the Senorge1D only handles complete series*, the missing data had to be substituted. For missing precipitation and temperature data three procedures were followed; if only a few values were missing, these were interpolated linearly with neighbouring days. If an entire month was missing, half the values of the previous month and half the values of the next month was used. If more than a month was missing, a complete period from another year was used. Missing snow depth data were set equal to zero since they do not enter the computation, but are only used for comparison. (At the end of this report, details of the substitutions are listed in a log).

Table 2. Record length and missing data.

No.	**Name**	**Record length**	**Missing periods**
4101.5	Ambert	1.1.1980- 30.11.2004	11.1983, 02.1992
4101.1	Aparan	1.1.1980- 30.11.2004	09-30.11.1991 (only temp), 01-02.1992, 02.1994
4101.4	Aragac	1.1.1980- 30.11.2004	02.1992, 04.1994, 01.11.1996-31.08.1998
4101.2	Ashtarak	1.1.1989- 30.11.2004	02.1992, 1.5.1992 - 31.12.1996
4101.3	Caxkahovit	1.1.1985- 30.11.2004	01.01.1987-31.12.1988, 02.1992, 01.05.1992-31. 12.1996

4 Model results

The length of the time series allows applying the model for a number of years and, therefore, appreciating the inter-annual variability. In the following, the comparison of modelled and measured snow depth will be shown, in particularly selecting the simulations that exhibit the best and the worst agreement with the observations.

4.1 Ambert

At Ambert station the snow cover is continuous from mid December and last until mid April. The approximate maximum snow depth value is normally at 100 cm but can reach as high as 150 cm, and usually occurs around the start of April. The simulations for Ambert were reasonably good when comparing simulated SD against measured. The following parameters (Table 3) were used for producing the plots below for Ambert.

Table 3. Parameter values in the Senorge1D for Ambert

Parameter	Value	Comment
Pro	0.1	Fraction of SWE allowed be liquid water (10 %)
Pkorr	1.05	Correction of the precipitation measurement
Skorr	1.5	Correction of the precipitation (as snow) measurement
TX	-0.5	Threshold temp rain/snow
TS	-1.0	Threshold temp melting/freezing
CFR	0.01	Refreeze degree-day factor of liquid water in snow
CXmin	2.0	Minimum values of degree-day factor
CXmax	4.0	Maximum values of degree-day factor

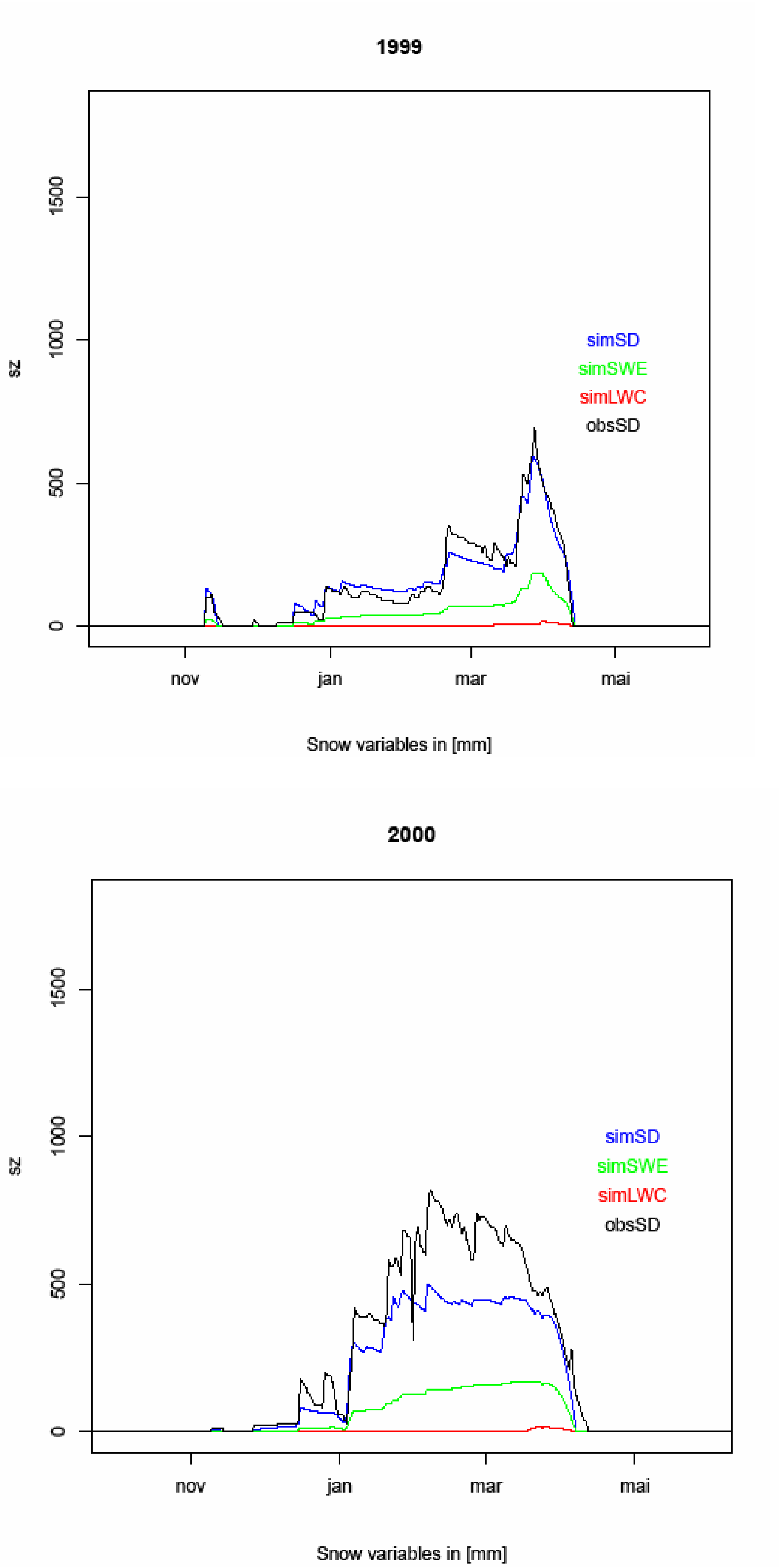


Figure 3. Measured (in black) and modeled (in blue) snow depth, snow water equivalent (in green), and liquid water content (in red) for two snow seasons at the Ambert station. All the measures are in mm and the year is reported on the charts, where 1999 snow season means 1998-1999 snow season. Top panel, a well simulated year. Bottom panel, a typical badly simulated year which has a wrong timing, and underestimates the snow depth.

4.2 Aparan

At Aparan station the snow cover is continuous from mid December and last until mid March - start of April. The approximate maximum snow depth value is seldom above 100 cm and is usually around 50 cm. The maximum snow depth occurs usually around mid March-start of April. The same parameters as used of Ambert, were used for Aparan (see Table 4). As Figure 4 shows, both under and overestimation occurred for this station, indicating that the measured meteorological data could not adequately describe the development of snow depth at this site.

Table 4. Parameter values in the Senorge1D for Aparan

Parameter	Value	Comment
Pro	0.1	Fraction of SWE allowed be liquid water (10 %)
Pkorr	1.05	Correction of the precipitation measurement
Skorr	1.5	Correction of the precipitation (as snow) measurement
TX	-0.5	Threshold temp rain/snow
TS	-1.0	Threshold temp melting/freezing
CFR	0.01	Refreeze degree-day factor of liquid water in snow
CXmin	2.0	Minimum values of degree-day factor
CXmax	4.0	Maximum values of degree-day factor

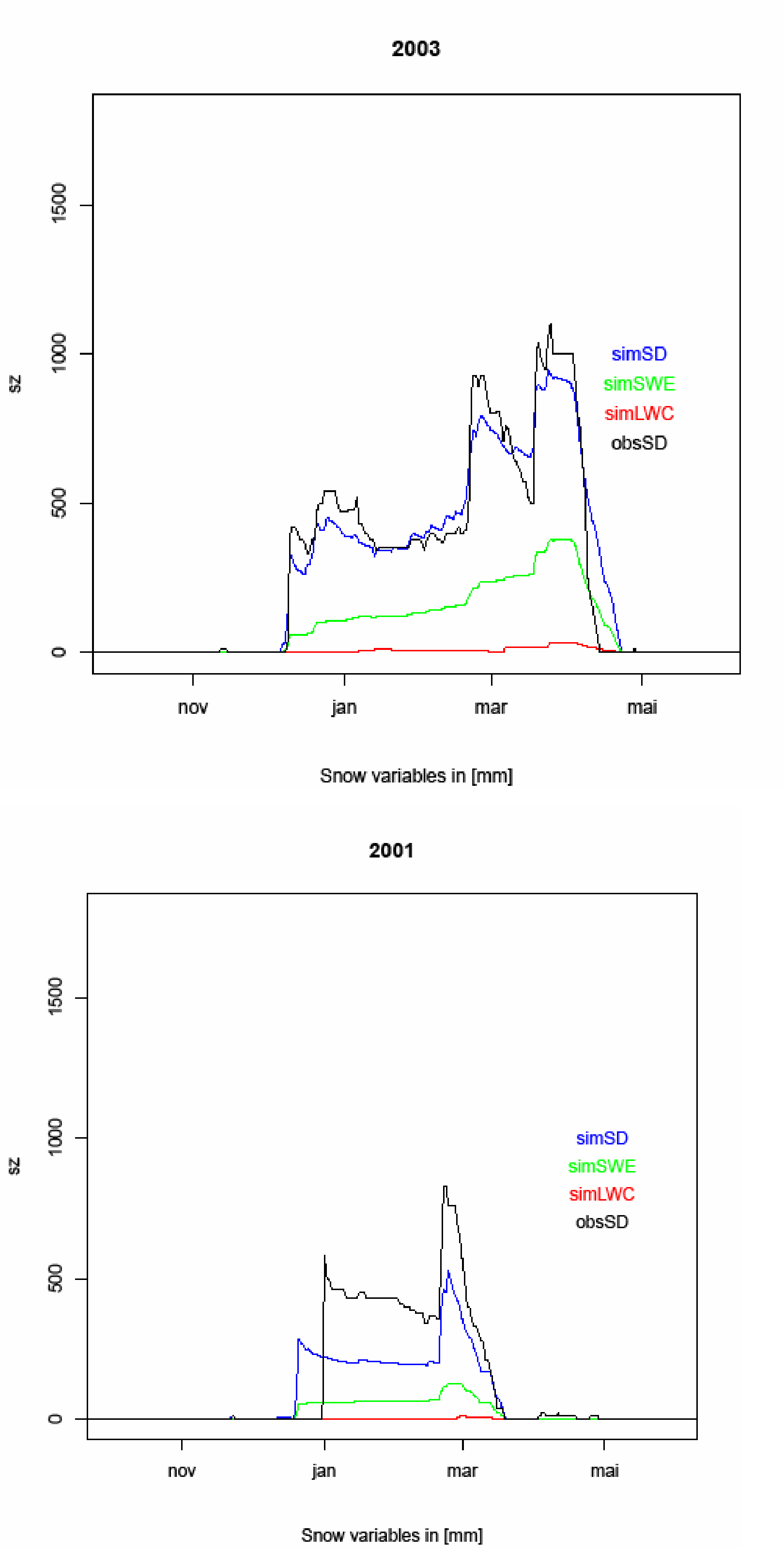


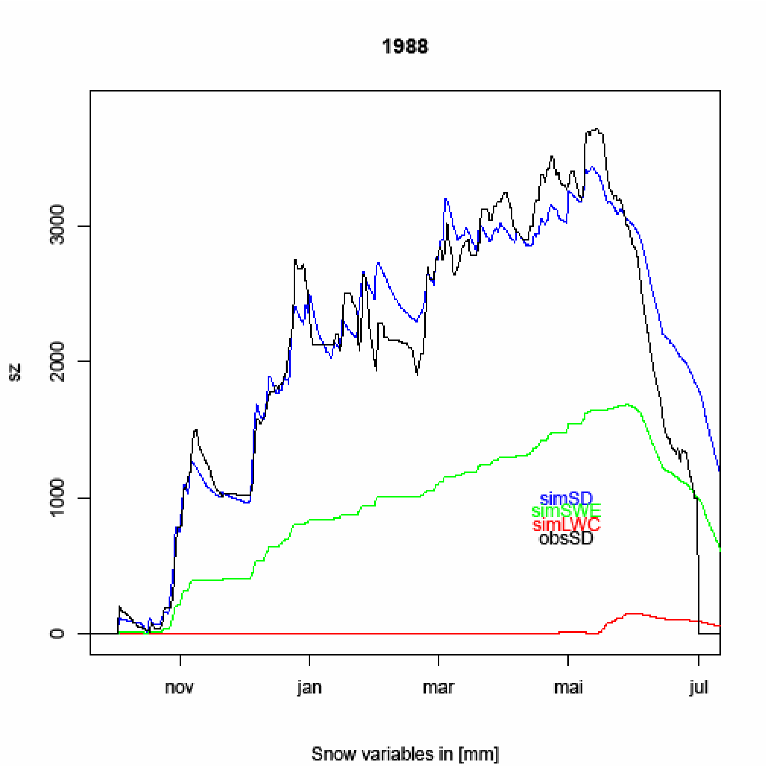
Figure 4. Measured (in black) and modeled (in blue) snow depth, snow water equivalent (in green), and liquid water content (in red) for 2 snow season at the Aparan station. All the measures are in mm and the year is reported on the charts. "2001" indicates the snow season 2000-2001. Top panel, a well simulated year. Bottom panel, a typical badly simulated year, which has a wrong timing, and underestimates the snow depth.

4.3 Aragac

Aragac is the most elevated measurement site (see Table 1) with snow depths above 300 cm. This might occur as late as the start of June. Snow cover might be present from mid October until the end of June. The Senorge1D model did not simulate this site as well as the others. As Figure 5 shows (bottom panel), the snow depth was underestimated, even if we increased the correction factor for snow (Skorr). We also increased the maximum degree-day factor (CXmax) in order to improve the timing of when the area was snow free. The simulation was much better at the start of the period (1980-1989) than towards the end of the period (2000-2004), suggesting, perhaps, incorrect measurements of precipitation towards the end of the period?

Table 5. Parameter values in the Senorge1D for Aragac

Parameter	Value	Comment
Pro	0.1	Fraction of SWE allowed be liquid water (10 %)
Pkorr	1.05	Correction of the precipitation measurement
Skorr	1.7	Correction of the precipitation (as snow) measurement
TX	-0.5	Threshold temp rain/snow
TS	-1.0	Threshold temp melting/freezing
CFR	0.01	Refreeze degree-day factor of liquid water in snow
CXmin	2.0	Minimum values of degree-day factor
CXmax	5.0	Maximum values of degree-day factor



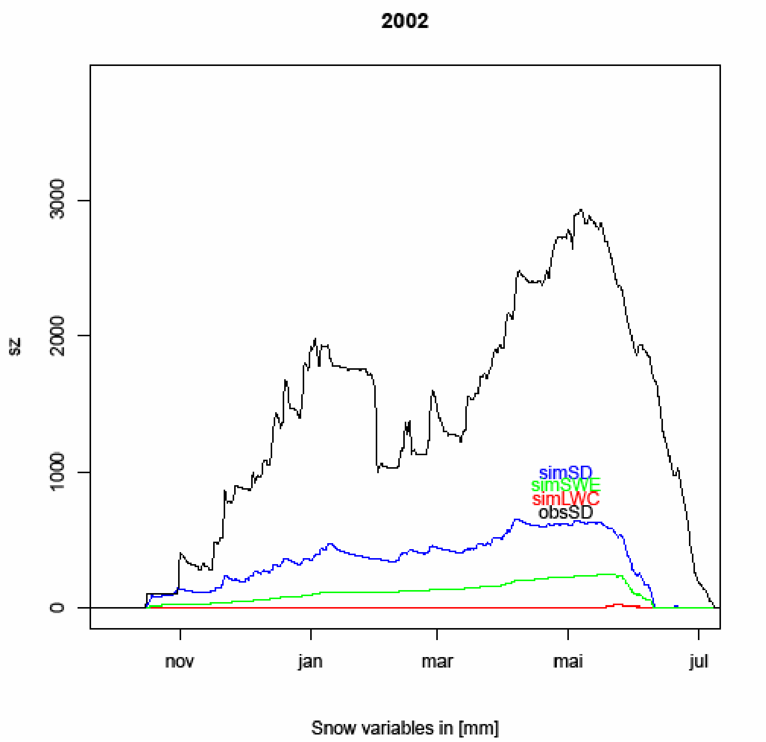


Figure 5: Measured (in black) and modeled (in blue) snow depth, snow water equivalent (in green), and liquid water content (in red) for 2 snow season at the Aragac station. All the measures are in mm and the year is reported on the charts. "1988" indicates the snow season 1987-1988. Top panel, a well simulated year. Bottom panel, a typical badly simulated year with severe underestimation.

4.4 Ashtarak

Ashtarak is the measurements site at the lowest altitude (see Table 1). The snow cover is intermittent, and in some years, there is only snow for some few days during the snow season. The maximum during the years of measurement was about 30 cm, and the snow season may last from mid December until the start of March. The parameters used were the same as for Ambert, and gave reasonable simulations of snow depth.

Table 6. Parameter values in the Senorge1D for Ashtarak

Parameter	Value	Comment
Pro	0.1	Fraction of SWE allowed be liquid water (10 %)
Pkorr	1.05	Correction of the precipitation measurement
Skorr	1.5	Correction of the precipitation (as snow) measurement
TX	-0.5	Threshold temp rain/snow
TS	-1.0	Threshold temp melting/freezing
CFR	0.01	Refreeze degree-day factor of liquid water in snow
CXmin	2.0	Minimum values of degree-day factor
CXmax	4.0	Maximum values of degree-day factor

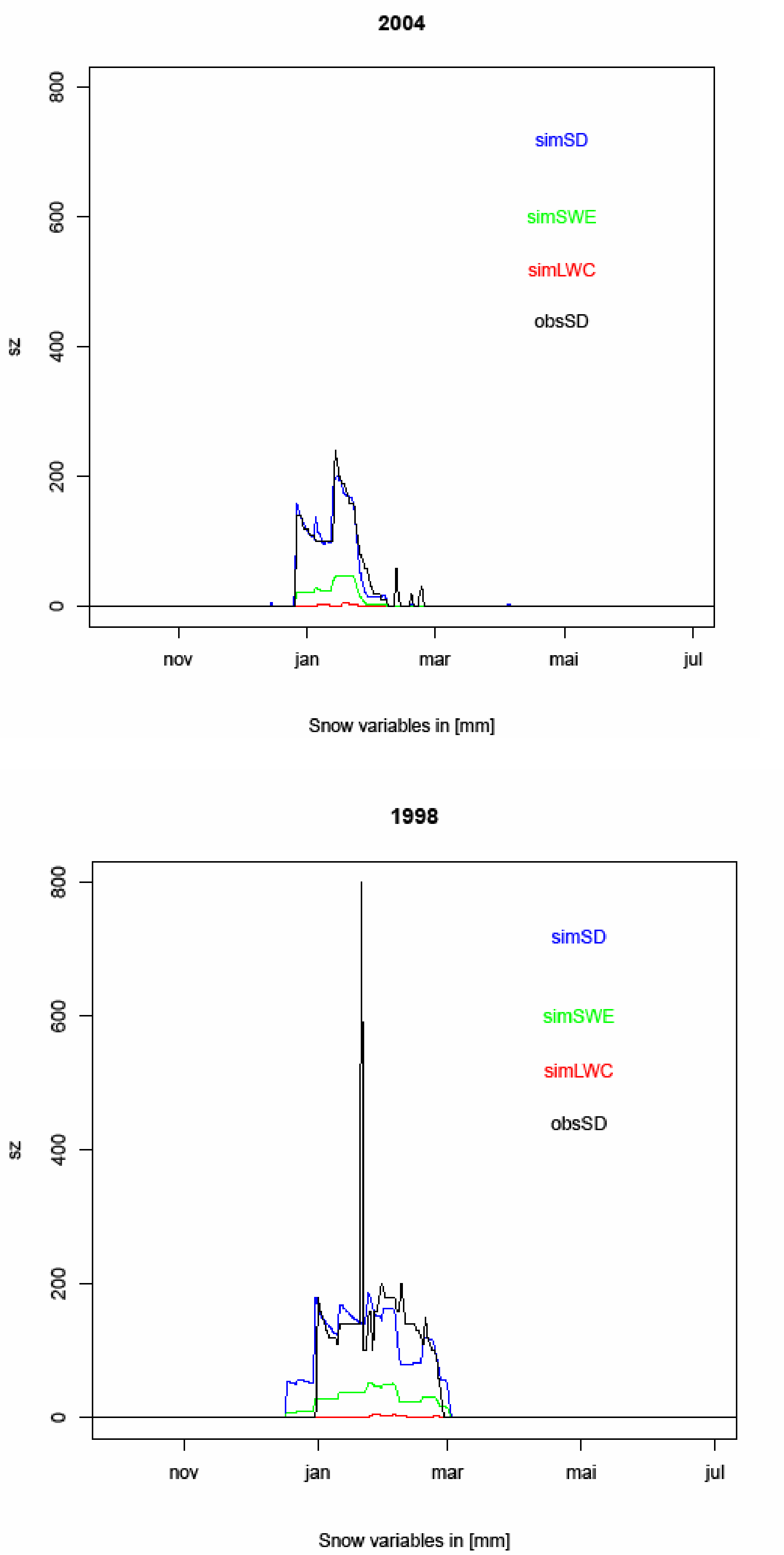


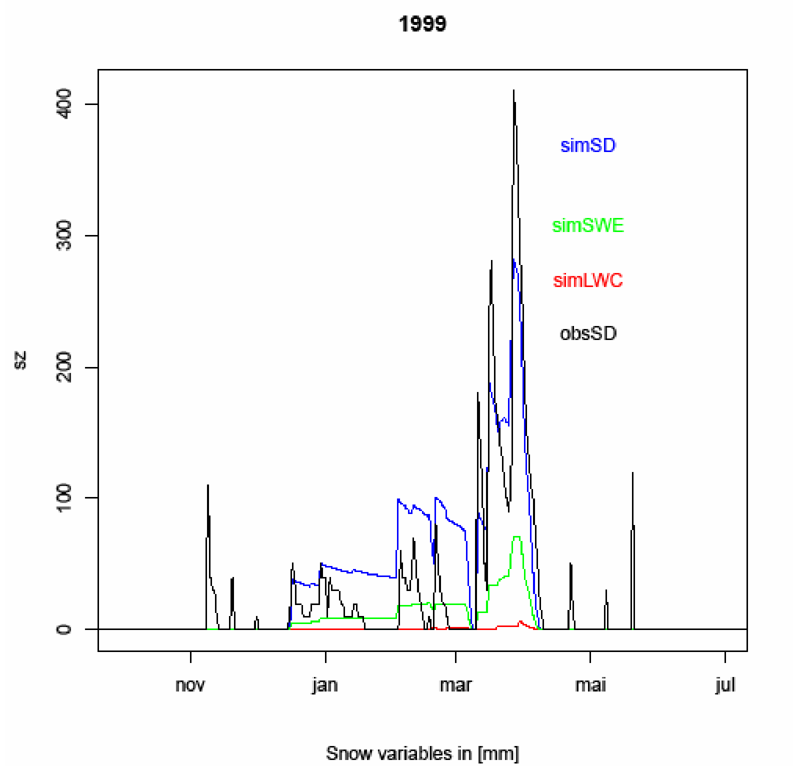
Figure 6. Measured (in black) and modelled (in blue) snow depth, snow water equivalent (in green), and liquid water content (in red) for 2 snow season at the Ashtarak station. All the measures are in mm and the year is reported on the charts. "2004" indicates the snow season 2003-2004. Top panel, a well simulated year. The bottom panel shows some possible erroneous snow depth measurements.

4.5 Caxkahovit

The snowy season at Caxkahovit lasts from start of December until the start of April. The maximum snow depth is about 20 cm and occurs around the start of March. The data shows an intermittent snow pattern during the snowy season, which may also be the result of missing data. The data from Caxkahovit suffers also from suspicious values, and it was difficult to obtain good simulations. Even when adjusting the correction of precipitation as snow (Skorr) down to 1.0, the model tends to overestimate the snow depth.

Table 7. Parameter values in the Senorge1D for Caxkahovit

Parameter	**Value**	**Comment**
Pro	0.1	Fraction of SWE allowed be liquid water (10 %)
Pkorr	1.05	Correction of the precipitation measurement
Skorr	1.0	Correction of the precipitation (as snow) measurement
TX	-0.5	Threshold temp rain/snow
TS	-1.0	Threshold temp melting/freezing
CFR	0.01	Refreeze degree-day factor of liquid water in snow
CXmin	2.0	Minimum values of degree-day factor
CXmax	4.0	Maximum values of degree-day factor



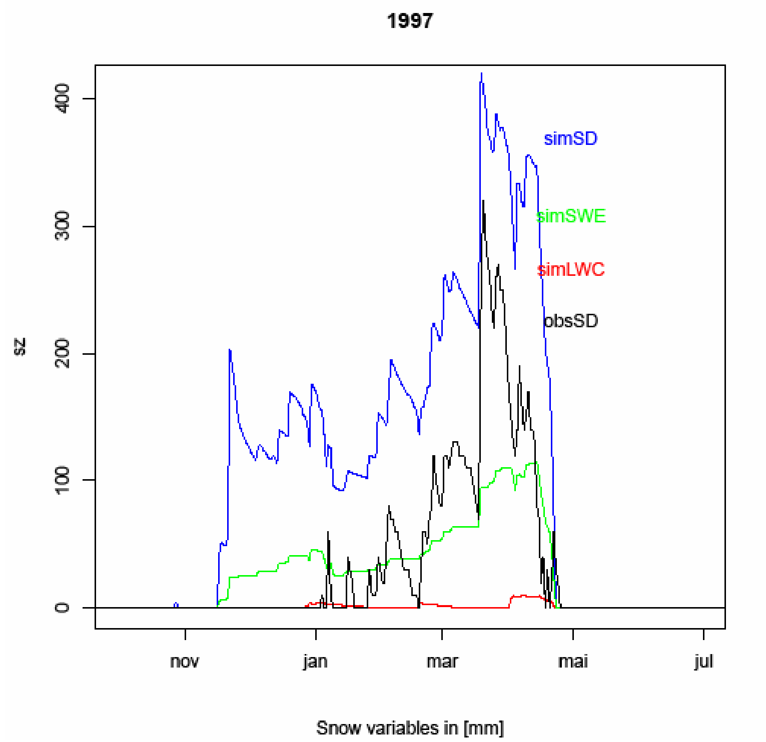


Figure 7. Measured (in black) and modeled (in blue) snow depth, snow water equivalent (in green), and liquid water content (in red) for 2 snow season at the Caxkahovit station. All the measures are in mm and the year is reported on the charts. "1999" indicates the snow season 1998-1999. Top panel, a well simulated year. The bottom panel shows how the model overestimates the snow depth.

5 Discussion

The results reported here suggest that the temporal patterns of the snow depth are, in general, well reproduced. However, the results are affected by uncertainties in the meteorological measurements and measurements of snow depth. Also there are uncertainties in the estimation of precipitation as snow, both in terms of uncertainty of the measurement of the total precipitation and uncertainty in the separation of rain and snow precipitation, given that, in general, only the total precipitation is available. The error in the snow accumulation is kept all through the winter, and may result in a delay or advance of the snow removal date. It may be the case here, that a snowfall is taken as rainfall, and, therefore, a snow accumulation is missed, suggesting that a higher threshold temperature should be used to distinguish rain from snow.

In general, the simulated timing of snow covered/snow free areas appears to be a function of over/underestimation of snow and thus not related to the degree-day melting procedure in the model. When the amount of snow is well simulated, also the timing of snow covered/snow free areas is quite well reproduced.

Dyrrdal (2008) points out that the Senorge model has a tendency to overestimate the compaction of snow. The observed discrepancy between modelled and observed snow depth might well be a combined effect of precipitation catchment loss and over-compaction. In light of this problem, the user of the model has to tune (adjust the parameters) the model to suit the purpose of the simulation. Here, an adjustment of parameters has been made in order for the model to simulate snow depth, which was the observed parameter for which we could validate the model. If the objective is to simulate SWE, a calibration of the model against observed values of SWE has to be carried out.

As far as snow melting is concerned, a particular trend cannot be found towards the underestimation or overestimation of the snowmelt rate. This is consistent with the nature of the degree-day factor approach, which represents a statistically averaged behaviour and is considered quite appropriate for the time resolution of one day (Anderson, 1976).

As stated in the introduction, the great advantage of the degree-day factor approach consists in the characteristics of not being data demanding. However, it is only able to represent typical configuration, and it is unable to provide a detailed description of how the snowpack matures and melts as a consequence of energy input.

The Senorge1D model can be used as a tool for estimating areal values of snow variables. The most straightforward approach may be to interpolate time series of precipitation and temperature at different altitude levels using lapse rates estimated from data or suggested values from the literature. Simulated values of snow variables from such series sites can then be weighted according what fraction the area of the elevation in question is to the total area (derived from an hypsographic curve). Areal estimates of snow variables can then be determined as a weighted average of values from the different elevations.

Note that an optimal parameter estimation was not carried out. This can be carried out by the Armstatehydromet as a suitable exercise for getting acquainted with the model.

6 Conclusion

In this work, a point version of the Senorge snow model (Senorge1D) has been applied at 5 stations in Armenia with the purpose to investigate the capability to simulate the snow conditions against observations. The model was found to be able to follow reasonably well the temporal patterns of the observed snow depths. However, the results are very sensitive to the errors in the estimation of snow precipitation, since they generate errors in the snow accumulation, which cannot be cancelled until snow removal. This problem is more evident for seasonal snow cover, and less for intermittent snow cover, since for the latter case, a reset to snow free terrain occurs a few times during the winter.

The ability of the Senorge1D model to simulate snow covered and snow free areas is quite good, which is of interest for the assessment of Armenian snow conditions. No particular trend to overestimation or underestimation has been found in the predicted snowmelt rate. This is consistent with the typical behaviour of the degree-day factor models, which describe statistically averaged conditions.

Stored on an accompanying CD you will find:
-The Senorge1D model in **R** code (main program + 5 sub routines)
-A short manual for the Senorge1D code.
-Plots for every year for each station of snow depth (simulated and observed), simulated SWE and LWC. Data file with time series of all variables for each site.

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Appendix

Data substitution log

Ambert: two entire months of precipitation and temperature were missing (November, 1983 and February, 1992). These values were replaced with values from the 15-30th (31th) of the previous month and values from the 1-15th of the next month.

Aparan: Precipitation and temperature data from the 9-30th of November 1991 (temperature only, January and February 1992 and February 1994 were missing. These series were completed by substituting in the same manner as for Ambert. For the two consecutive months of missing data in 1992, data copied from 1991 were used. Missing snow depth data were set equal to zero.

Aragac: February 1992 missing, April 1994, 1.11.1996 - 31.08.1998 replaced with 1.11.1994- 31.8.1996.

Ashtarak: Missing February 1992. (normal procedure). Missing values for 1.5.1992 - 31.12.1996. The period 1.5.1997-31.12.2001 was substituted for this period.

Caxkahovit: Data from 1.1.1985- 30.11.2004. Missing from 1.01.1987 – 31 .12.1988 substituted with data from 1.01.1989- 31.12. 1990. Missing data 1.2.1992-29.2.1992. Missing data from 1.05.1992 – 31.12.1996. The period 1.5.1997-31.12.2001 was used as substitute for this period.

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