Niveograph interpolation to estimate peak accumulation at two mountain sites

STEVEN R. FASSNACHT & GLENN G. PATTERSON
ESS-Watershed Science, Colorado State University, Fort Collins, CO 80523-1476 USA
steven.fassnacht@colostate.edu

Abstract The typical assumption that 1 April SWE represents the peak annual SWE can be improved by fitting a modelled time series plot of SWE derived from daily SWE measurements, to the monthly data typically available from snow courses. For each year, first of the month SWE values were used to adjust the average daily time series to produce estimates of peak SWE. The average annual from (a) the entire time series and (b) specific years averaged for high, medium and low snow accumulation were implemented. For a station in northern Colorado (Joe Wright, average annual peak SWE of 681 mm) and a station in eastern Arizona (Hannagan Meadow, average annual peak SWE of 334 mm), this method produced good estimates of peak SWE. These estimates were improved when the amount of snow on 1 April or 1 March was considered for Joe Wright and Hannagan Meadow, respectively.
Key words snow, peak SWE, niveographs, SNOTEL

INTRODUCTION AND STUDY SITE

Estimates of seasonal peak snow water equivalent (SWE) are important for predicting annual runoff and for studies of long-term trends in snowpack dynamics (Mote *et al*, 2005; Clow, 2010). Routine measurement of SWE in the western US (Yoakim, 1993) began with monthly manual measurements at snow courses in the early 20th century (Church, 1914). This gave rise to the tradition that 1 April SWE approximates the peak SWE for the season (Cayan, 1996). In the late 1970s the Natural Resources Conservation Service began deployment of a network of automated Snowpack Telemetry (SNOTEL) stations that measure SWE hourly (NRCS, 2009). Thus, a 30-year record of daily SWE is now available for many sites. Evaluation of SNOTEL data has shown that 1 April SWE typically underestimates peak SWE by about 12% (Bohr & Aguado, 2001).

This paper uses annual time series of daily SWE (referred to as niveographs) derived from SNOTEL data to derive a model niveograph, which can then be fitted to monthly SWE data to produce a more accurate estimate of peak SWE. Two sets of annual niveographs were analysed for SNOTEL stations in northern Colorado (Joe Wright, in Fig. 1) and eastern Arizona (Hannagan Meadow, in Fig. 2), as summarized in Table 1.

Both stations are located in areas where snow cover is more prevalent than in surrounding areas (Bales *et al.*, 2008). There is substantially less snow at the Arizona site than the Colorado site (on average the peak SWE is one-half) due to the location, i.e. lower elevation and lower latitude (Table 1). However, the shapes of the niveographs are similar for most years (Figs 1 and 2), as are the SWE time series (Figs 3 and 4). Both sites have been collecting SWE data since the autumn of 1978, which incorporates the water year of 1979, yet continuous data are available from 1980 at Joe Wright station and 1983 at Hannagan Meadow.

Snow depth and SWE are measured monthly at snow course stations, typically at the beginning of the month. Each month, these manual data are used to estimate runoff volumes (Church, 1914). The 1 April SWE value is used by many to represent peak accumulation (e.g. Cayan, 1996). However, the monthly measurements do not represent peak snow accumulation (Figs 3 and 4). For Joe Wright, the 1 April SWE is on average 19.2% less than the actual peak with a range from 1.37 to 55% less (Fig. 3(a)). Peak SWE occurs earlier at Hannagan Meadow, but the 1 March SWE is still on average 14.5% less than the peak with a range from 1.19 to 76.8% less (Fig. 4(a)). Substantial interannual variability also exists with the timing of accumulation, peak SWE and complete melt (Figs 3(b) and 4(b)). Since there can be a large difference between the peak SWE from daily data *versus* the first of the month value, fitting of an average niveograph to individual years will be evaluated for the estimation of peak SWE. Two sets of niveographs will be fitted: (i) the average annual from the entire time series, and (ii) specific niveographs averaged for

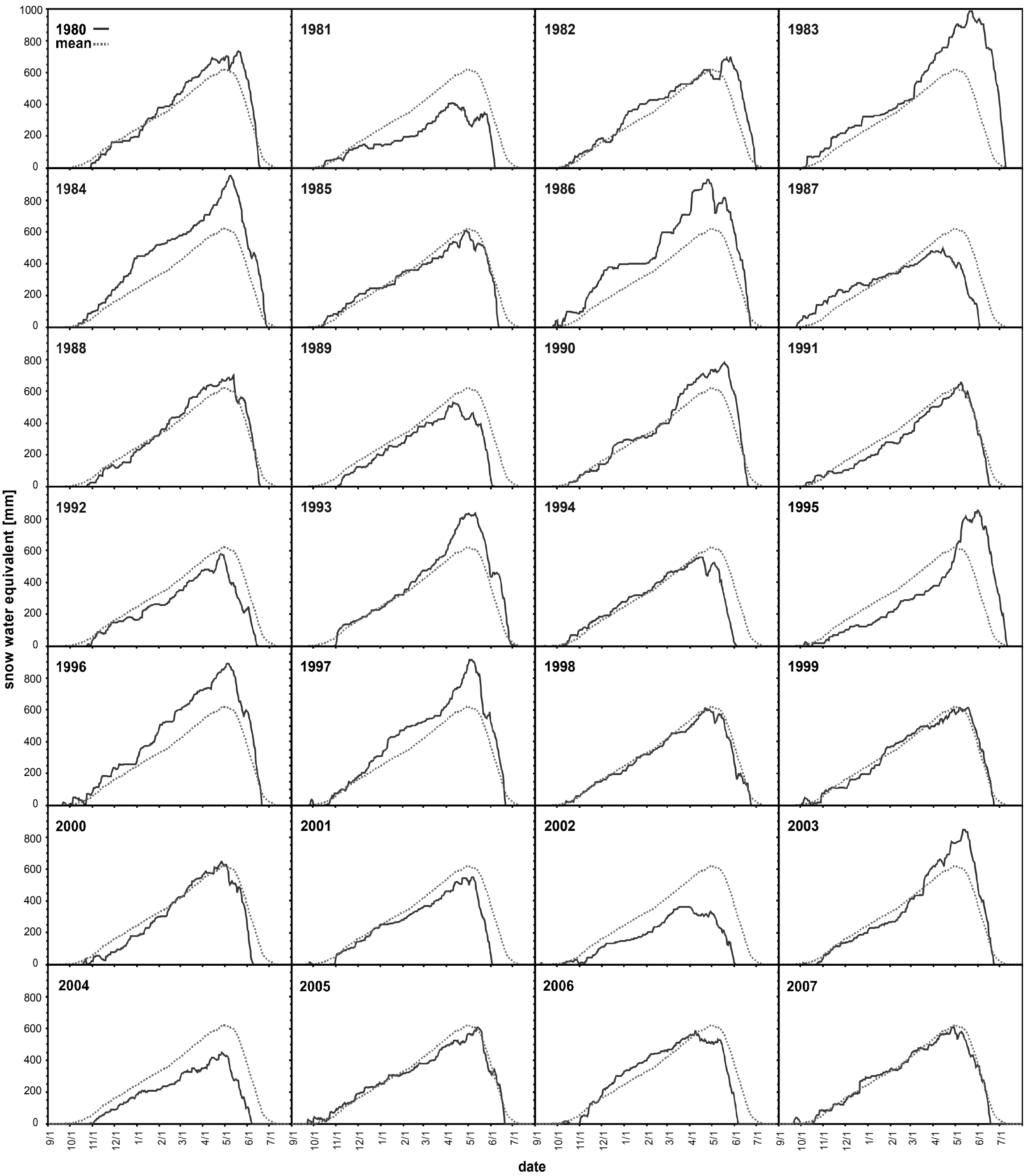

Fig. 1 Twenty-eight years of daily SWE data (1980–2007) for the snow year starting 1 September at the Joe Wright (05J37S) SNOTEL station in north-central Colorado.

Table 1 Station location and average peak SWE and timing of peak.

Name	code	location	Elevation (m)	Latitude (deg N)	Longitude (deg W)	Average peak SWE (mm)	Average date of peak
Joe Wright	05J37S	N. Colorado	3085	40.53	105.89	681	May 2
Hannagan Meadow	09S11S	E. Arizona	2750	33.65	109.31	338	March 12

high, average and low snow years. The type of year will be determined from the April or 1 March SWE value at Joe Wright and Hannagan Meadow, respectively.

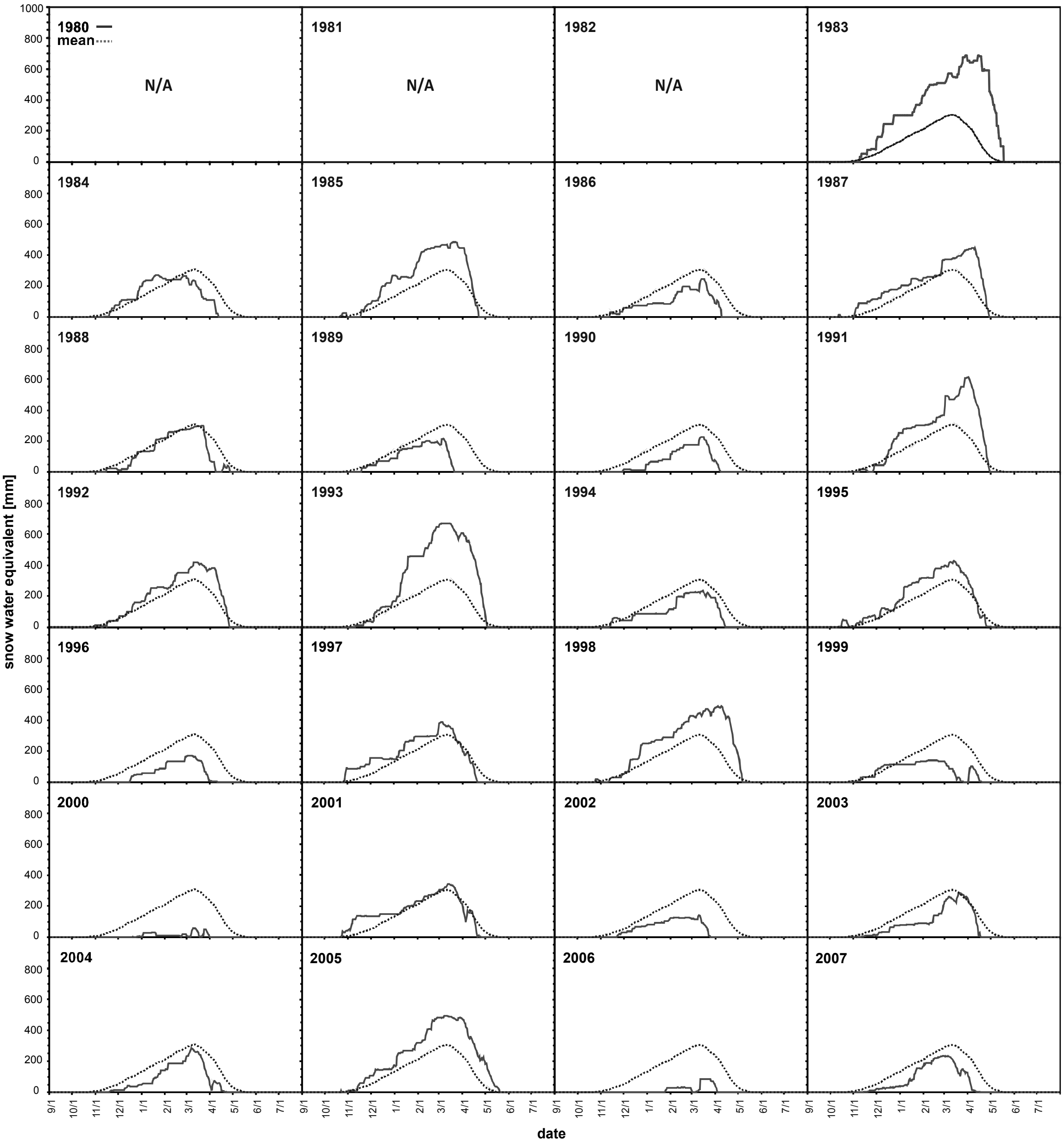

Fig. 2 Twenty-five years years of daily SWE data (1983–2007) for the snow year starting 1 September at the Hannagan Meadow (09S11S) SNOTEL station, eastern Arizona.

METHODOLOGY

For the average annual analysis, the daily average SWE was computed for the time series. This average niveograph $\left(\overline{SWE(t)}\right)$ for each day (t), illustrated as the dotted lines in Figs 1 and 2, was then adjusted annually to yield a modelled daily SWE value ($SWE_{modelled}(t)$), derived as follows:

$$SWE_{\text{modelled}}(t) = M\,(\overline{SWE(t) - A}) + B \quad (1)$$

where M is the stretch of the niveograph (or the slope), A is the horizontal shift (or the x-intercept), and B is the vertical shift (or the y-intercept). The annual values for M, A, and B where computed by minimizing the sum of the square of the difference between the modelled and observed SWE values for the four dates typically used for streamflow forecasting, i.e. January, February, March and 1 April.

The fit of each daily niveograph was determined by computing the Nash-Sutcliffe (N-S) efficiency. This compares the modelled values with using the mean of the annual data, such that a positive N-S value indicates the model is better than using the average, while a negative value indicates that using the average is better. The estimated peak SWE was compared to observed peak SWE.

The second fitting method used specific niveographs averaged for high, average and low snow years. SWE for each year on 1 March and 1 April for Joe Wright and Hannagan Meadow, respectively, were compared to the average to determine the type of snow year. The appropriate average niveograph was chosen and adjusted as previously. Again, the N-S was computed for the daily time series and the estimated peak SWE was compared to observed peak SWE.

RESULTS AND DISCUSSION

While snow accumulation and ablation periods follow a stretched and shifted version of the average niveograph for most average and below-average years, this is not the case for high snow years for Joe Wright (Fig. 1) and Hannagan Meadow (Fig. 2). The horizontal shifting was either limited or offset by the vertical shifting, yielding a similar timing of peak SWE for all modelled niveographs. Specifically, all modelled peak SWE dates were within 3 days of one another. Often the timing of peak SWE is a function of the magnitude of peak SWE (Fassnacht, 2006), as illustrated in Fig. 3(a) and (b). The goal of estimating a peak SWE value was more realistic than determining the timing of peak SWE.

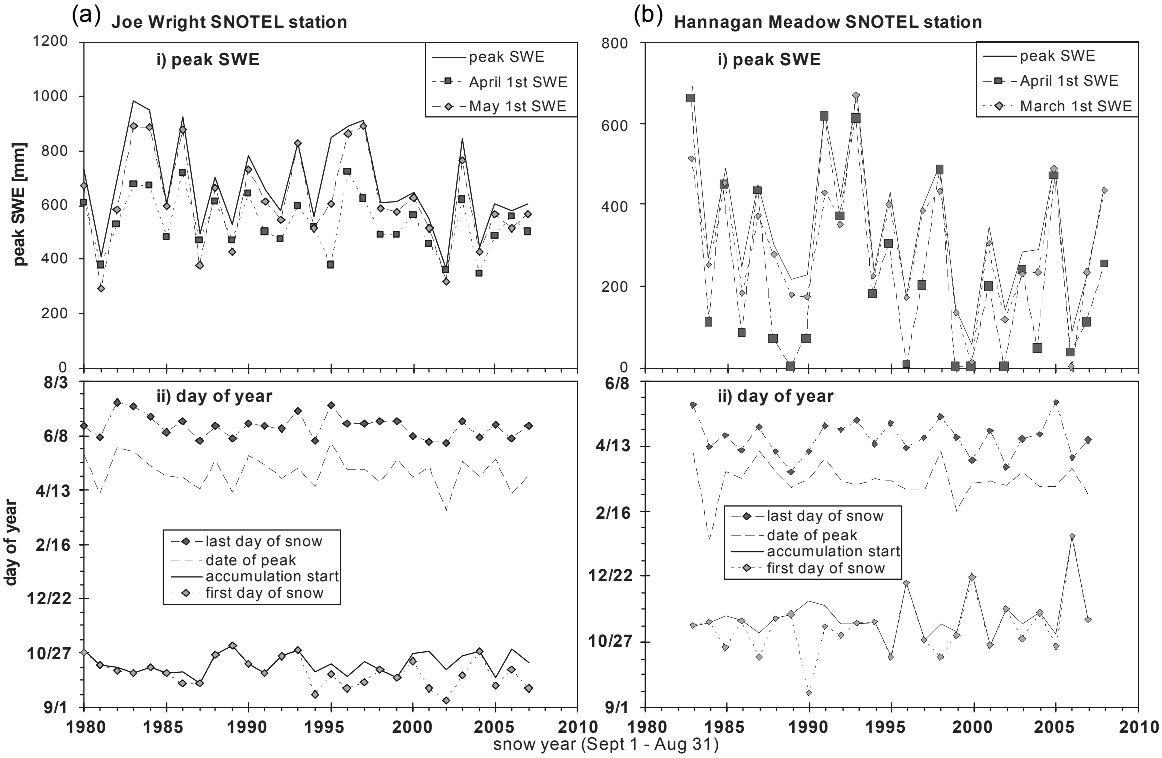

Fig. 3 Time series summary for (a) Joe Wright and (b) Hannagan Meadow SNOTEL of (i) quantity of SWE for peak, 1 April and 1 May (1 March at Hannagan Meadow), and (ii) dates for first snow, start of accumulation (first day with seasonal snowcover), peak accumulation, and last day with snow.

The average annual niveograph was adjusted using the four first of the month (January, February, March, and April) SWE values. This method produced a daily time series that, for most years, was better than using the annual average value (Fig. 4), i.e., the N-S value was greater than zero. This was not case for six years at the Hannagan Meadow station: 1984, 1989, 1999, 2000, 2002 and 2006. The observed niveograph in 1984 was symmetrical, whereas rate of accumulation is typically much slower than ablation (Fig. 2). Little snow persisted in 2000 and 2006, so these years were removed from the analysis. In Arizona, such years could occur more often with warming and thereby likely a decrease in snow accumulation. This requires further investigation. There was no snow remaining on 1 April in 1989, 1999 or 2002. Removing April from the niveograph adjustment actually decreased the N-S value. However, this improved the estimate of peak SWE.

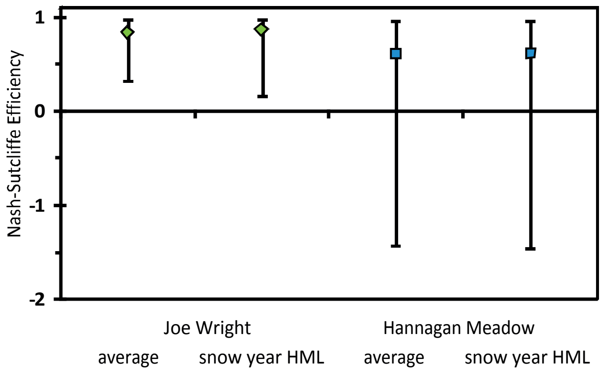

Fig. 4 Maximum, average, and minimum Nash-Sutcliffe efficiency values for the modelled years at Joe Wright and Hannagan Meadow using the average and the different snow year niveographs.

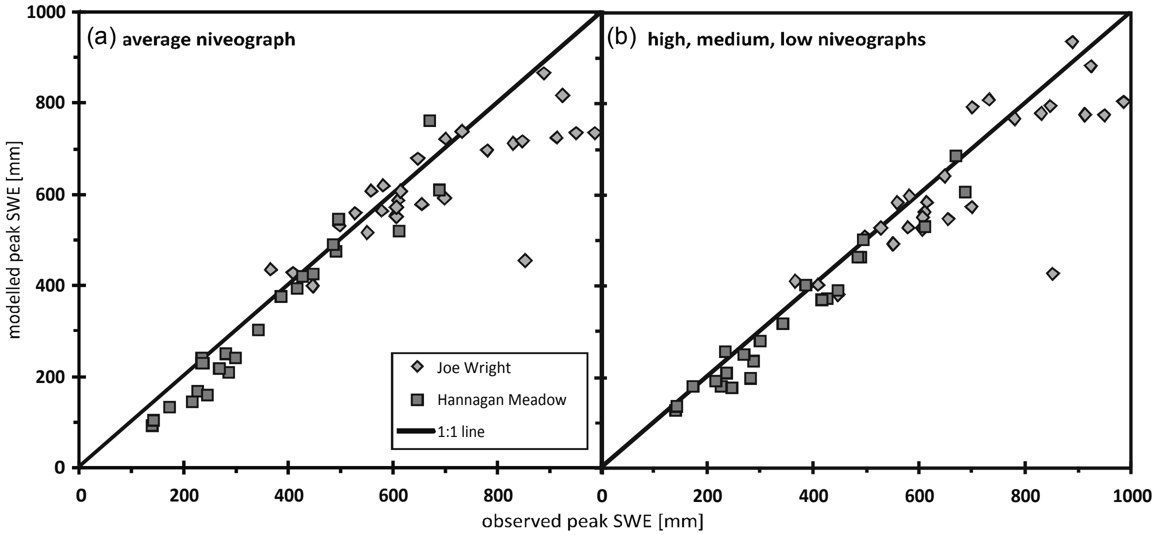

Fig. 5 Comparison of modelled *versus* observed peak SWE using (a) the average niveograph, and (b) division into high, medium, or low niveographs.

For the Arizona station, peak SWE estimates were realistic for all years (Fig. 5(a)), except 2000 and 2006. For lower snow accumulation years at the Colorado station, the modelled peak SWE was quite similar to the observed peak SWE. For snowier years, the modelled peak SWE values were under-estimated. The biggest outlier was 1995 where the modelled value of 455 mm was only 53% of the observed peak of 853 mm. This occurred due to the large snowfalls in April that turned a seemingly dry year into an above average year (Fig. 1).

Using the 1 March or 1 April SWE value (Hannagan Meadow and Joe Wright) to determine the type of snow year (high, medium, or low) for selection of the appropriate niveograph, improved estimation of peak SWE, especially for the above average snow years at Joe Wright (Fig. 5(b)). The outlier was 1995 for the reason stated above. The N-S values for the daily time series did not improve, and in some cases decreased. At Hannagan Meadow, the modelled niveograph for 1984 became better than using the average (N-S of –0.69 became 0.24) but the average became better than modelled for 2003 (N-S of 0.86 became –0.11). For Joe Wright, all N-S values remained greater than zero.

The correlation between the observed 1 March or 1 April SWE and peak SWE is greater than or equal to the correlation between the modelled and observed peak SWE, based on the correlation coefficient. However, the first of the month SWE values are always less than peak SWE (Fig. 3(a) and (b)), so using the simple adjustment of the annual or the snow year type niveograph provided a better estimate of peak SWE. These modelled peak SWE values should be used to estimate runoff volumes, in comparison to using first of the month values. At Joe Wright, March is the snowiest month (Ewing & Fassnacht, 2007) with April being the next snowiest month. At this site, the 1 April SWE value may be sufficient to adjust the average niveograph, i.e. the 1 January, 1 February and 1 March values may not be necessary. Further analysis of the Hannagan Meadow accumulation patterns could determine if a single month is adequate there. Overall, the adjustment of the annual niveograph, especially considering the amount of snow that has accumulated, may be applicable to snowcourses, if accumulation patterns are similar to neighbouring SNOTEL stations with daily data. Investigators should be cautious of the influence of a changing climate, i.e. non-stationarity in the data.

CONCLUSIONS

Depending on the location of the station, the first of the month snow values, especially SWE, do not adequately represent the peak amount. For the station in northern Colorado (Joe Wright), in all but one year, peak SWE occurred after 1 April and as late as after 1 June. For the Arizona station (Hannagan Meadow), the peak usually occurred after 1 March, and even into April in some years.

Using a daily average SWE value from all years of record at a SNOTEL site yielded good estimates of peak SWE. This average niveograph was been adjusted based on the first of the month SWE values, analogous to snowcourse data. The estimates of peak SWE were improved by considering the amount of snow that had fallen on 1 March or 1 April, for Arizona and Colorado stations, respectively. This suggests that daily niveographs from SNOTEL stations can be used to improve estimates of peak annual SWE from snow course sites. Projections using this method require the consideration of non-stationarity, i.e. a changing climate.

REFERENCES

Bales, R. C., Dressler, K. A., Imam, B., Fassnacht, S. R. & Lampkin, D. (2008) Fractional snow cover in the Colorado and Rio Grande basins, 1995–2002. *Water Resour. Res.* 44, W01425. doi:10.1029/2006WR005377.

Cayan, D. R. (1996) Interannual climate variability and snow pack in the western United States. *J. Climate* 9(5), 928–948.

Church, J. E. (1914) Recent studies of snow in the United States. *Quart. J. Roy. Met. Soc.* 40, 43–52.

Clow, D. W. (2010) Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *J. Climate* 23(9), 2293–2306.

Ewing, P. J. & Fassnacht, S. R. (2007) From the tree to the forest: the influence of a sparse canopy on stand scale snow water equivalent. In: *Proceedings of the Eastern Snow Conference* (St. John's NF, June 2007) 64, 149–163.

Fassnacht, S. R. (2006) Upper versus Lower Colorado River sub-basin streamflow: characteristics, runoff estimation and model simulation. *Hydrol. Processes* 20, 2187–2205. doi: 10.1002/hyp.6202.

Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. (2005) Declining mountain snowpack in western North America. *Bull. Am. Meteorol. Soc.* 86(1), 39–49.

NRCS (2009) SNOTEL and Snow Survey and Water Supply Forecasting. *US Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center*, brochure available online. http://www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf, available at http://www.wcc.nrcs.usda.gov (accessed 16 January 2013).

Yoakim, D. (1993) A Thousand Miles. Track 2 on *This Time*, Reprise Records.