CHARACTERISTICS OF SNOWMELT FROM NRCS SNOTEL (SNOwTELemetry) SITES

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ABSTRACT

Snowmelt is affected by a number of factors including elevation, slope, aspect, exposure, snowpack depth, surface reflectance and climatic or meteorologic variables such as solar radiation, temperature, wind speed, vapor pressure, and precipitation. Snowmelt models attempt to account for these factors in various degrees from simple empirical relationships based on air temperature to detailed energy balance procedures. While detailed energy balance models should be superior in estimating snowmelt, there are rarely, if ever, adequate data sets available in practice to use these methods without making simplifying assumptions. Unfortunately, these simplifications usually reduce the models' ability to account for the various meteorologic factors that cause snowmelt to occur. Thus the models can produce estimates of snowmelt based on the input data available and the assumptions required, but these estimates may not relate to actual snowmelt in timing or rate. Since actual snowmelt data is very limited, it is seldom possible to compare model simulated melt rates with actual values. This paper is significant because it presents an analysis of snowmelt data under a variety of conditions encountered at representative SNOTEL sites selected from nearly 600 locations in the western United States. It thus provides a range of snowmelt information including average and maximum daily melt rates, time of onset and cessation of melt, and average day of maximum snowmelt that can be used to compare with snowmelt model simulations and other uses.

INTRODUCTION

In much of western North America, the majority of surface water supplies comes from the melting mountain snowpack in the spring and summer. Spring snowmelt can also produce floods that present a threat to life and property during high snowpack and/or rapid snowmelt years. Daily snowmelt rates are highly correlated to subsequent runoff, however, detailed information on snowmelt is historically lacking. In spite of the importance of snowmelt, little is known about its characteristics over wide areas and different climatic zones. More detailed comprehensive simulation models have potential for improving traditional regression techniques as a means of predicting expected water supplies, and could also be used for flood forecasts. However, information from early snowmelt studies (U. S. Army Corps of Engineers, 1956) is still being used as a reference for comparing model results and calibrating snowmelt models. Up until the installation of the NRCS SNOTEL system in the late 1970's, daily information on snowmelt was not available except in limited research situations. In fact, because of the historic lack of daily snowmelt data, most hydrologic models estimate snowmelt from temperature information. This study analyzes snowmelt parameters such as maximum daily melt rates and timing of snowmelt from 94 SNOTEL sites in a variety of geographic regions in the western United States.

THE SNOTEL SYSTEM

The United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS, formerly the SCS), has the responsibility for monitoring the mountain snowpack in the western United States and making water supply forecasts on snowmelt dominated streams. From the early 1900's until the 1970's snowpack data was collected by manual techniques -- using a snow tube to core the snowpack and weigh its water content; these readings were normally collected on a monthly basis. While this provided adequate information on the total seasonal snowpack used for regression based volume forecasts, it provided very little information on snowmelt. and did not provide information on daily melt rates.

In the late 1970's the NRCS installed a network of automated telemetry stations known as SNOTEL (for SNOw TELemetry). These stations collect snow water equivalent (SWE), cumulative precipitation, and air temperature data on a near real time basis. This information is telemetered to a master receiving station using meteor burst telemetry--a technique that relies on ionized meteor trails in the upper atmosphere, 50 to 75 miles above the earth's surface, as the reflective medium for long range radio transmissions. The information is telemetered on a daily or more frequent basis depending on the needs of the users.

The principle snowpack sensor at SNOTEL sites is the snow pillow: a metal or synthetic rubber bladder filled with an antifreeze solution, typically 3-4 meters (10-12 feet) in diameter. These snow pillows hydrostatically weigh the overlying snowpack. Pressure transducers convert this weight into an equivalent voltage value that can be telemetered from the remote site. The resolution of the SNOTEL system is approximately 3 mm of SWE.

The Agricultural Research Service is the research arm of the U.S. Department of Agriculture. The ARS works closely with the NRCS in conducting research in snow hydrology and other agriculture related areas. It is in the spirit of this partnership between ARS and NRCS that this research project was developed.

SITE SELECTION

The current SNOTEL network consists of about 600 sites located in the western United States. Most sites have at least 15 years of daily record, providing an unparalleled opportunity to analyze the characteristics of daily snowmelt in a mountain environment. For the purpose of this study, 94 SNOTEL sites were selected from nine different regions, including:

Northern Cascades; Southern Cascades; Sierra Nevada; Basin and Range; Arizona Highlands; Idaho Central Mountains; Northern Rockies; Southern Rockies; and Wasatch/Uintas Mountains (Figure 1).

Site selection criteria included good spatial and elevational distribution within the region, long period of record (approximately 15 years of daily data), and good data quality (see Figure 1).
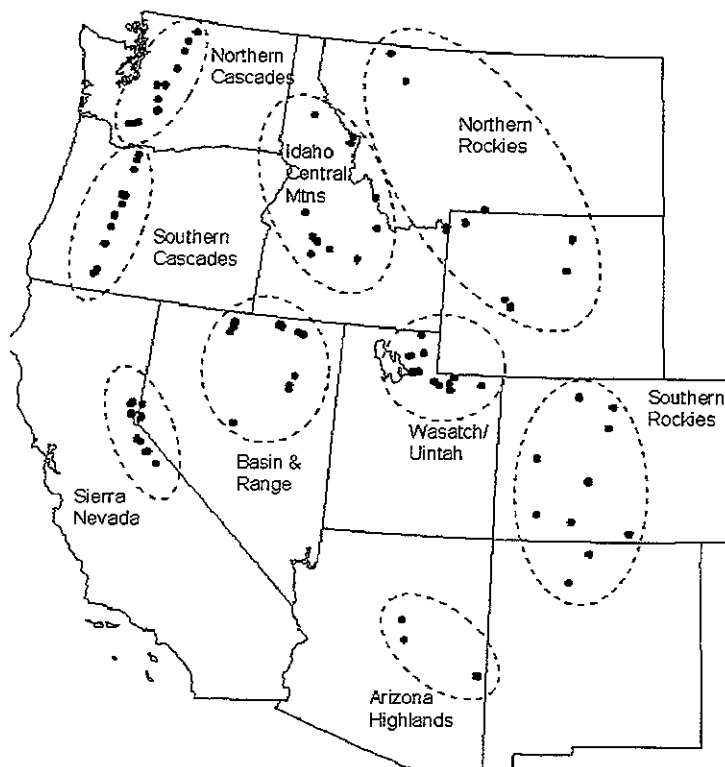

Figure 1   Location of regions and SNOTEL sites used in this study.

DATA ANALYSIS TECHNIQUES

The NRCS and ARS collaborated on a project to develop an automated screening and validation system for hydrometeorological data collected by the NRCS SNOTEL network. The system consists of a series of three computer programs. The first, called MAKEPROF, allows each user to establish evaluation criteria, or profiles, based on historical data from a SNOTEL site or nearby meteorological station. The second, called VALIDATE, uses the evaluation criteria or profiles developed using MAKEPROF to automatically check incoming data each morning, or more often, and flags any values that are suspect. The third program, named SNOTSCREEN provides user friendly methods to plot and edit the flagged or suspect values.
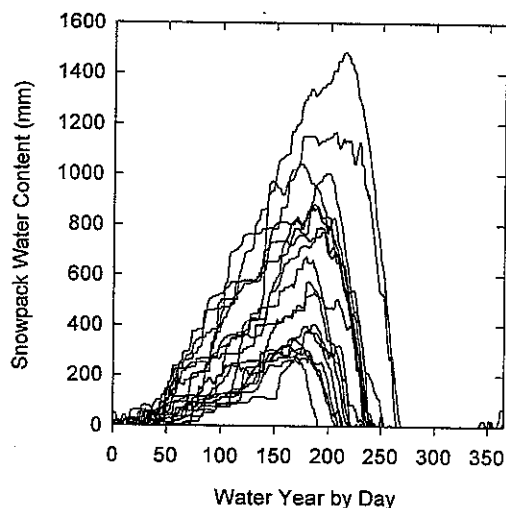

Figure 2 Daily SWE for the 1979-1996 Water Years at the Marlette Lake, Nevada, SNOTEL site.
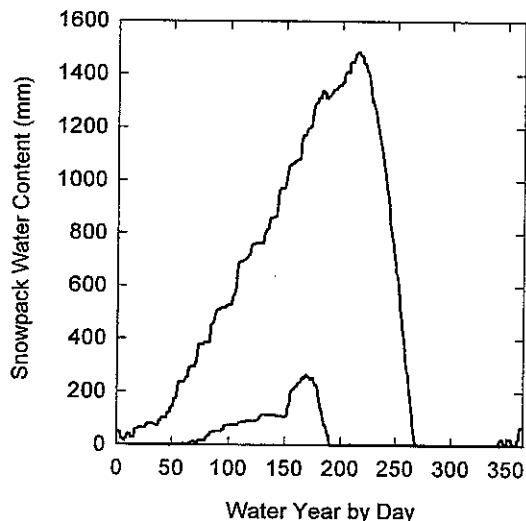
In this study only the MAKEPROF program was used (Cooley, et. al., 1994) to analyze the snow pillow data from the selected SNOTEL sites. Prior to analysis, the MAKEPROF program performs a cursory quality control check on all of the data, eliminating values that are obviously in error. Then MAKEPROF was used to obtain the maximum and minimum amounts of snow accumulation, or SWE, for each day of the year over the period of record. Figure 2 shows the accumulation and melt of the snowpack for each year of the 1980-1996 period at the Marlette Lake, Nevada, SNOTEL site. From this plot the maximum and minimum snow water equivalent (SWE) values for each day of the year for the period of record are assembled in a file. The upper and lower boundaries or limits obtained from this file are shown in Figure 3. For the period of record all daily snow pillow SWE values lie between these two lines, thus these lines are the upper and lower limits of historical values, and in normal practice could be used as the profiles for evaluating incoming data. The data assembled in this file can also be used to determine the maximum accumulation, the time from start of accumulation to peak accumulation, and the time from peak accumulation to melt-out. The same information for average condition values and minimum values can also be obtained from the MAKEPROF files of analyzed data. In the case of Marlette Lake (Figures 2 and 3), there is a rather long accumulation period and a rather rapid melt period, which is quite typical for many of the sites studied. A few sites in the Cascades have a more rounded profile, indicating an accumulation and melt period of more nearly the same length.

Figure 3 Maximum & Minimum Daily SWE for the 1979-1996 Water Years at the Marlette Lake, Nevada, SNOTEL site.

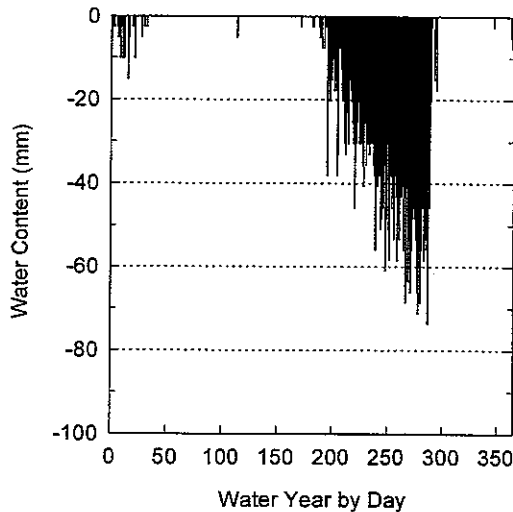In addition to the pattern of accumulation and melt, MAKEPROF provides a plot and file of the maximum daily decline of SWE values (melt) from the snow pillow. Ablation of the snowpack (net volumetric decrease in water from the snow pillow) can be caused by several processes including sublimation, evaporation and melting, or by scour of the snowpack by wind. Sublimation occurs when dry air with a temperature well below freezing comes in contact with the snow surface,
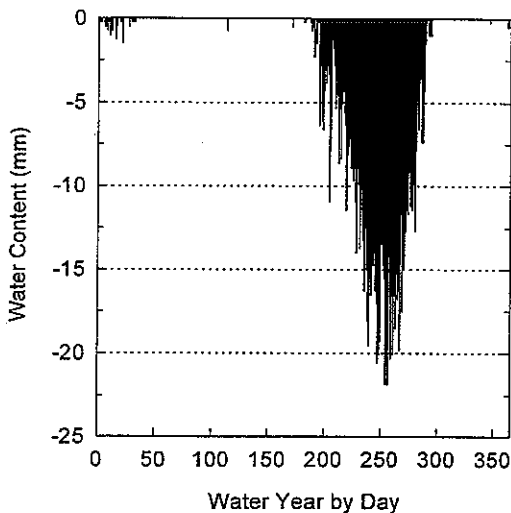
which is not likely to happen for long periods during the melt season (Male and Gray, 1981). Sublimation losses tend to be quite small on a daily basis, usually amounting to no more than a few millimeters per day. Evaporation occurs because of a vapor pressure gradient, and losses of up to 14 mm/day have been observed or modeled, but typical values over monthly or seasonal periods are about 2-3 mm/day (Zuzel and Cox, 1978). In most cases, during the melt season snow melt is by far the largest of the ablation processes and while the maximum values shown in Figure 4 are not entirely due to melt, they can be thought of as snowmelt, since the magnitude of errors associated with the measurement techniques is of about the same range as sublimation and evaporation losses.

The maximum daily decline shown in Figure 4 is obtained from the file of maximum daily declines and represents the largest daily decline for a given day for the period of record. The greatest daily declines tend to occur at or very near the end of the melt season when there is more energy available for melt and the snow pack on the pillows is quite shallow. At the end of the melt season, there is more solar energy and associated air temperatures are typically higher. Also, the advective energy can be quite large as nearby areas become bare, exposing both soils and vegetation that absorb and hold more heat than would a snowpack.

Average daily declines can also be determined for use in estimating daily snow losses. The average daily declines are obtained by summing the observed daily decline values for a given day for each year of the site record and dividing by the number of years of record (Figure 5). Some of the daily values used for determining averages are zero, because there is no snow on the pillow late in the melt season some years. The daily averages are considerably less than the daily maximums as one would expect, and the largest daily average decline values occur nearer the middle of the melt season. The daily maximum, average and minimum increases can also be determined, but the increase or accumulation characteristics were not used in this analysis.

Figure 4   Maximum Daily Decline in SWE for the Water Years 1981-1996 at the Vienna Mine, Idaho, SNOTEL site.

Figure 5   Average Daily Decline in SWE for the Water Years 1981-1996 at the Vienna Mine, Idaho, SNOTEL site.

RESULTS

Using the information obtained from the MAKEPROF analysis for each of the 94 SNOTEL sites in the nine geographic regions, shown in Figure 1, it was found that there were many similarities and some differences in the snowmelt characteristics. For each SNOTEL site, the analysis included the average day of beginning of

accumulation, average day of peak accumulation and average day of melt-out, plus the accumulation and melt windows or periods, for maximum, average and minimum conditions. Also the maximum and average daily declines for each site were noted. The analysis then included grouping the individual sites by region and examining and comparing the range of the above factors for each of the regions. The range in average peak snow water equivalent for the sites in each region are shown in Figure 6. The range of peak snow water equivalents is fairly broad (typically from about 300 mm to over 1100 mm), except for the Arizona Highlands region where only three sites were used. The Basin and Range region also has a smaller range of average peak SWE values (from about 300 mm to 700 mm), but several regions exhibit larger ranges. These ranges in SWE indicate that a variety of sites were selected for the study and that they represented quite different snowpack accumulation conditions overall.
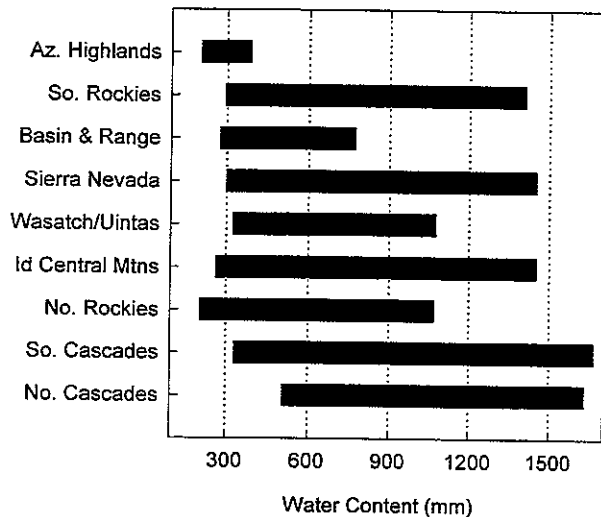

Figure 6　　Range of Average Peak SWE for SNOTEL sites in the Nine Regions of the Western United States.
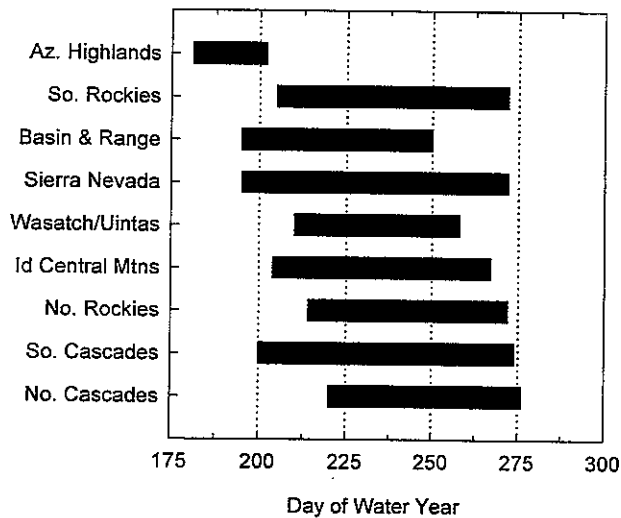

Figure 7　　Range of Average Day of Melt-out for the SNOTEL sites in the Nine Regions of the Western United States.

The ranges of the average day of melt-out, or the day the pillow goes bare on the average, are shown in Figure 7 for the different regions. Again the ranges are fairly broad indicating a wide range of site conditions, except for the Arizona Highlands region. It is interesting to note that all three sites in the Arizona Highlands region are melted-out at about the time that melt-out begins in the other regions. There is considerable overlap in the timing of melt out for all of the regions except the Arizona Highlands. It is also interesting to note that the range in average day of melt out for the sites in all of the regions except the Arizona Highlands covers a period of 60 to 75 days. That is, the first sites melt out two to two and one half months before the snowpacks at the last sites are completely melted. The ranges of average peak accumulated SWE shown in Figures 6 and the ranges of average day of melt out shown in figure 7 both indicate that a broad range of site snowpack conditions exist for the various regions and sites studied. Therefore the analysis should represent snowmelt characteristics within the western United States quite well even though all 600 SNOTEL sites were not used in the analysis.

Elevation vs peak SWE

Plots of elevation versus average peak SWE for the Northern Rockies and the Wasatch & Uintas regions are shown in Figures 8 and 9. Results of this comparison for the Northern Rockies region shown in Figure 8 may
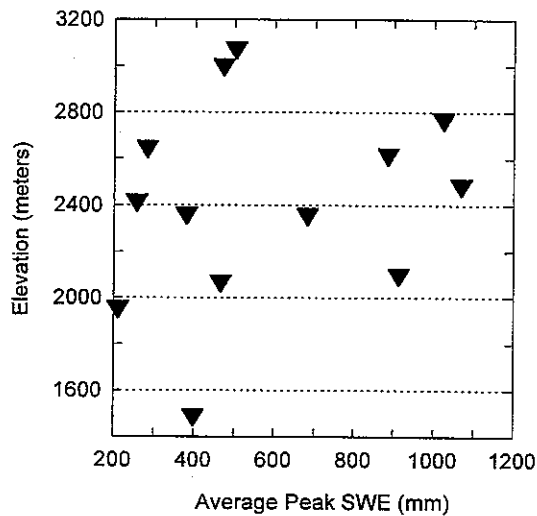
Figure 8 Plot of Elevation versus Average Peak SWE for the SNOTEL sites in the Northern Rockies region.
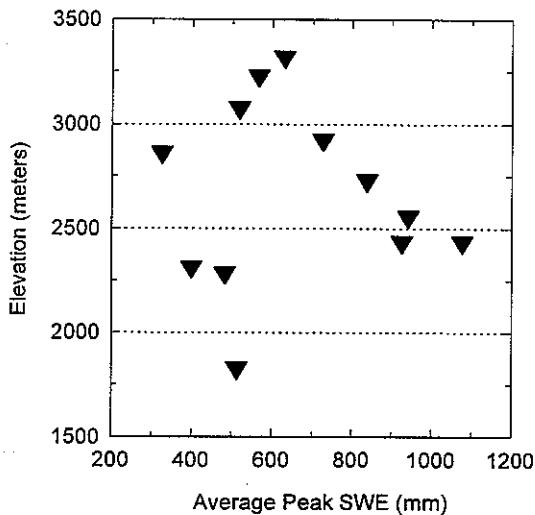

Figure 9 Plot of Elevation versus Average Peak SWE for the SNOTEL sites in the Wasatch & Uintas region.

indicate an increase in precipitation with increasing elevation, particularly if two or three of the outliers were considered to not be representative of general conditions. The results for the Wasatch & Uintas region, on the other hand, exhibits little or no correlation between elevation and snowpack accumulation for the sites studied, in fact it almost appears that there is a decrease in average peak SWE with increasing elevation. Similar plots for the other regions were very much like Figures 8 and 9, with very little if any correlation between elevation and average peak SWE indicated. This is in contrast to the common concept that precipitation generally increases with elevation except possibly right near the crest of mountain ridges (Gray, 1973). As shown in Figures 8 and 9, the selected sites covered a wide range of elevations and peak snow water equivalents or (indirectly) snowpack depths. In both of these regions it is interesting to note that the average peak SWE at the highest and lowest elevations was about the same (400-500 mm for the Northern Rockies and 500-600 mm for the Wasatch & Uintas). The range for the other regions was about the same except for the Arizona Highlands where only three sites were used and the ranges in both elevation and snow water equivalent were much narrower. Actual correlation coefficients were not determined because of the generally poor relationships. After looking at the large difference in accumulated snowpack and the generally poor relation with elevation, it appears that site characteristics play a major role in both accumulation and melt. Snowpack accumulation and snow melt could be more dependant on site conditions such as exposure and aspect, than on elevation or latitude.

Average day of melt out versus average peak SWE

The relationship between average day of melt out and average peak SWE was also developed for each of the regions. As shown in Figure 10, there is a good relationship between average day of melt out and average peak SWE for the Southern Cascades region. In this case the snowpack at sites with large accumulations of SWE persist later into the season or melt out occurs later. However, the same relationship does not exist for the Wasatch & Uintas regions plotted in Figure 11. In this case, while the sites with lower accumulations of SWE tend to melt out early in the season, and the sites with higher accumulations of SWE tend to melt out later in the season, there is
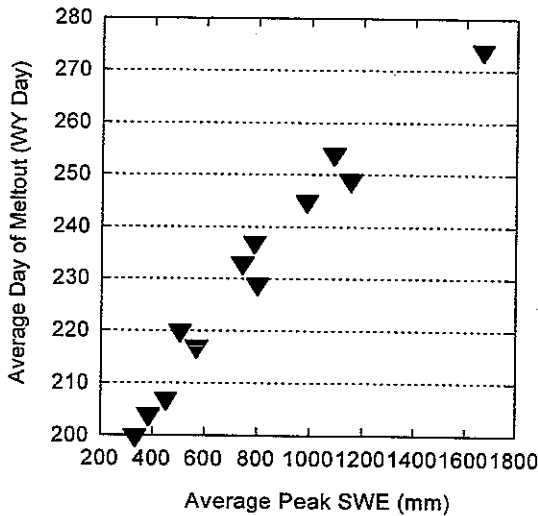
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Figure 10   Plot of Average Day of Melt-out versus Average Peak SWE for the SNOTEL sites in the Southern Cascades region.
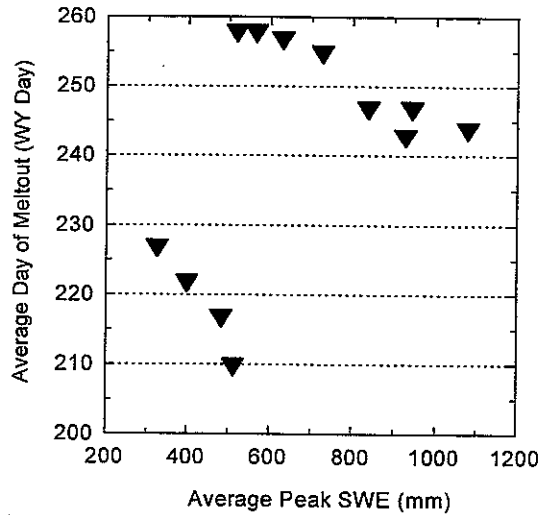
Figure 11   Plot of the Average Day of Melt-out versus Average Peak SWE for the SNOTEL sites in the Wasatch & Uintas region.

definitely not a one-to-one relationship. Two of the sites with nearly the same accumulation of SWE have the earliest and the latest melt out dates. This again points to the importance of site conditions such as exposure and aspect on the melt out characteristics of a site. The relationships for the other regions varied considerably, but none showed the strong trend exhibited in Figure 10 for the Southern Cascade region.

Snow pillow melt characteristics

The maximum daily decline or snowmelt characteristics for the high elevation- medium snowpack (2730 m, 900 mm) Vienna Mine, Idaho site (Figure 4) has a distinct melt free period (December through February) typical of the high Idaho Central Mountains, Wasatch & Uintas, and some of the Basin and Range sites. The lack of snowpack losses in the winter for these medium to high snowpack sites indicates that the pack is deep enough to store most of the surface melt that occurs, there is very little wind scour, and few if any warm storm systems reach this part of the intermountain west. As shown in Figure 4, this site exhibits a skewed melt distribution with greater daily rates later in the season as more energy for snowmelt becomes available due to increased heating from solar radiation and advection from neighboring bare areas. The rather well defined melt period extends from about day 190 to day 290 (Early April to Mid July).
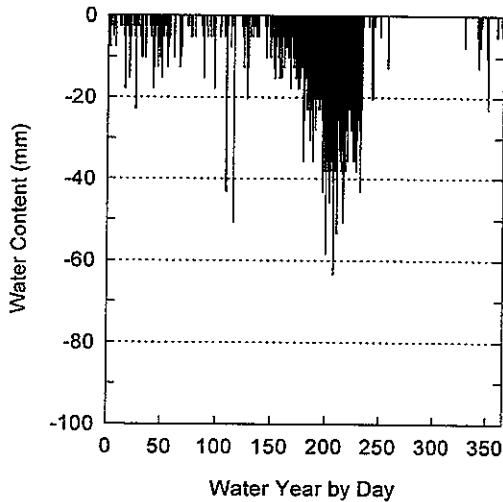
A more common melt distribution is shown in Figure 12 for the lower elevation-medium to low snowpack (1490 m, 400 mm), Many Glaciers, Montana, site. In this case some rather significant losses (up to 40-50 mm/day) occur even during what would normally be the cold winter period, and in fact some losses occur throughout the winter season. The major events may be associated with warm storm systems referred to as

Figure 12   Maximum Daily Decline in SWE for the 1977-1996 Water Years at the Many Glacier, Montana, SNOTEL site.

Chinooks in this area, or to local site conditions. The smaller losses that occur throughout the winter season could be due to evaporation and sublimation losses, or wind scour. The largest daily maximum declines at this site occur near day 205 which is some 40 days before the end of the melt season. The main melt period at this site is from about day 145 to day 230 (Late February to Mid May)
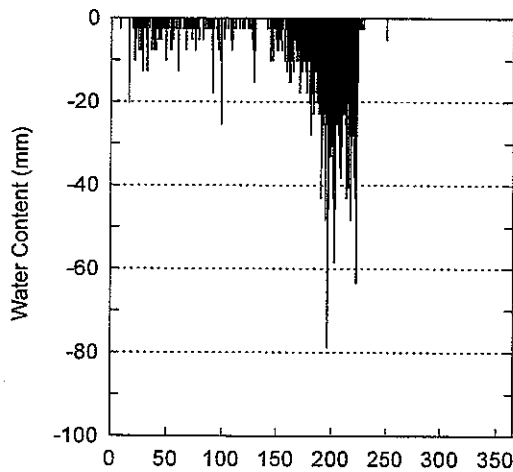

Figure 13 Maximum Daily Decline in SWE for the 1981-1996 Water Years at the Senorita Divide #2, New Mexico, SNOTEL site.
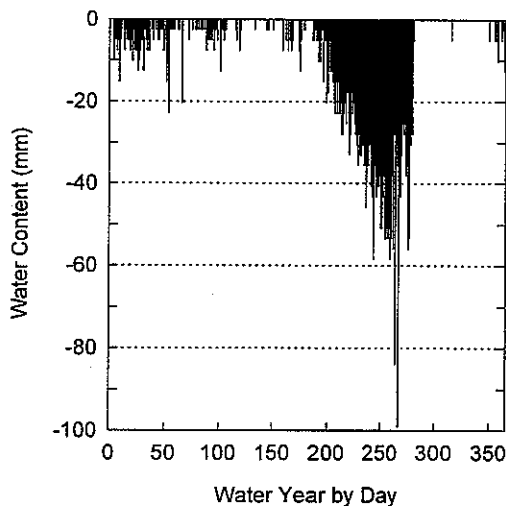
The high elevation-low snowpack (2620 m, 295 mm) Senorita Divide #2, New Mexico, site shows a somewhat similar pattern, however the winter events are less dramatic with maximum daily declines of about 20mm per day, as shown in Figure 13. The winter declines noted at this southern location are probably due to warm periods during which snowmelt occurs at the snow surface and, because of the rather shallow snowpack, melt water drains from the snowpack. While the largest daily maximum decline at this site occurred near day 200, the general trend is for greater daily maximums as the season progresses. The main melt period for this southern site is from about day 150 to day 225 (End of February to Mid May), indicating that this site melts out before some of the deeper, more northern sites begin to melt.

The very high elevation- medium snowpack (3440 m, 602 mm) site at Berthoud Summit, Colorado, also shows some loss during the entire winter period (see Figure 14). A few of the daily losses are about 20 mm/day, which is more than would be expected from normal sublimation or evaporation. This site may experience relatively high inputs of solar radiation on clear days; however, it is unlikely that surface melt, if it occurred, would drain through the rather substantial snowpack normally present. Because of the exposure and wind conditions at this site, the declines in SWE are more likely due to wind scour plus either evaporation or sublimation at this location. The largest daily maximum declines at this site occur about 10 days before the end of the melt season. In this case the main melt period is similar to that at the Vienna Mine site shown in figure 4, starting about day 190 and ending about day 280 (Early April to early July).

Figure 14 Maximum Daily Decline in SWE for the 1979-1996 Water Years at the Berthoud Pass Colorado,. SNOTEL site.

The high elevation-medium snowpack (2440 m, 678 mm) site at Marlette Lake, Nevada, also exhibits a similar pattern of snow pillow maximum daily declines (Figure 15). The winter declines noted in this case may be due to the warm ground and snowpack conditions typically observed in the Sierra Nevada Range, or to warm storm systems associated with moist air moving in to the area from the vicinity of the warm Pacific Ocean.
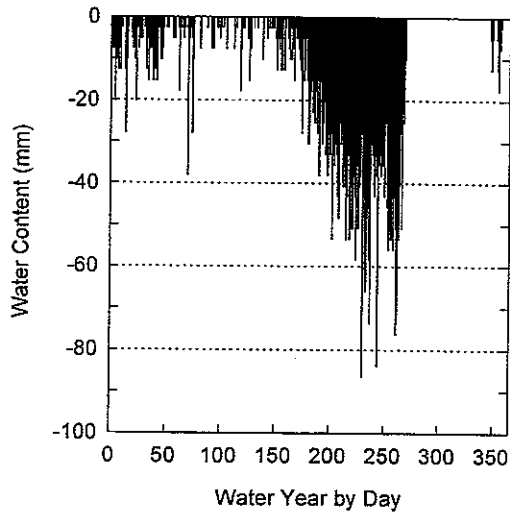
The larger daily maximums of nearly 40 mm/day during the winter are more likely associated with the warm storm systems and rain-on-snow events. The largest maximum daily declines occur between days 240 and 250 at this site, which is 20 to 30 days before the end of the melt season. However, once again the general trend is for the largest maximums to occur at the end of the melt season, but for a couple of exceptions. The main melt at this site starts about day 160 and ends about day 270 (Early March to late June).

Figure 15 Maximum Daily Decline in SWE for the 1979-1996 Water Years at the Marlette Lake, California,. SNOTEL site.

The low elevation-medium snowpack Northern Cascades region site (975 m, 511 mm) at Cougar Mountain, Washington, (Figure 16) exhibits a somewhat different pattern that is due to different climatic conditions. In this case significant losses of as much as 45-60 mm per day occur during the entire winter snow period, although the maximum declines are greater as the season progresses, as is typical at most sites. Early losses at this site are likely due to warm storm systems coming into the area from the Pacific Ocean, which could produce precipitation in the form of rain. These rain on snow events could be significant in size or volume to cause melt or rain water to drain from the medium to shallow snow packs before the end of February. The largest daily maximum declines occur near day 225 at this site, some 20 days before the end of the normal melt season. It is difficult to identify the beginning of a distinct melt season in this case, but the main melt out season appears to begin about day 155 and end about day 240 (Early March to the End of May).

The Cold Springs, Oregon, (Southern Cascades region) site is a higher elevation- medium snowpack (1860 m, 800 mm) site that exhibits a pattern similar to the Cougar Mountain, Washington, site, but with the effects of the early season warm systems dampened out by the higher-colder elevation (Figure 17). The largest maximum daily declines at this site occur within 10 to 15 days prior to the end of the melt season. In this case the main melt season could be defined as starting about day 100 and the melt out occurs about day 265 (Early January to mid June).
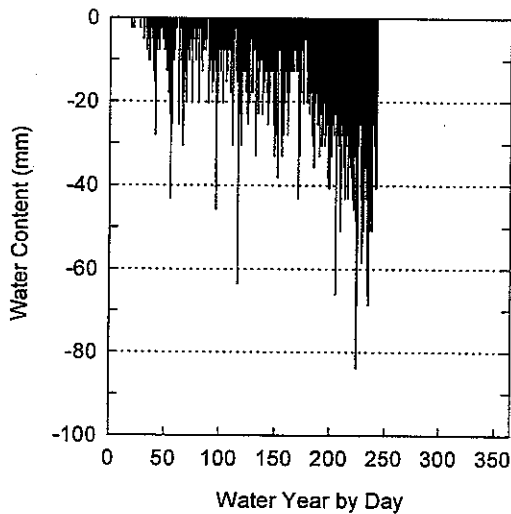

Figure 16 Maximum Daily Decline in SWE for the Water Years 1982-1996 at the Cougar Mountain, Washington, SNOTEL site.
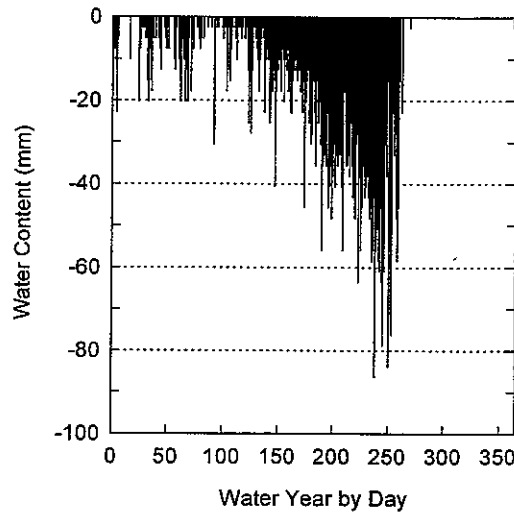

Figure 17 Maximum Daily Decline in SWE for the 1982-1996 Water Years at the Cold Springs Camp, Oregon, SNOTEL site.

The snowmelt discussed above indicates that low to medium snowpack sites at low elevations in the north and high elevations in the central and southern Rockies and Sierra Nevada exhibit similar melt characteristics with some losses occurring even during the cold winter periods. These declines are probably due to exposure to solar inputs, to scour by wind, or to warm chinook type systems. In the central part of the study area (portions of the Idaho

Central Mountains, the Wasatch/Uintas, and the Basin and Range regions) the medium snowpack high elevation sites indicate very little or no loss during the cold winter months indicating a different climatic regime.

Average Daily Decline

As shown previously in Figure 4, and discussed above, the plot of the maximum daily declines from the Vienna Mine, Idaho snow pillow exhibits a skewed distribution, with the higher rates occurring late in the season when more energy is available for snowmelt. This trend is typical for maxim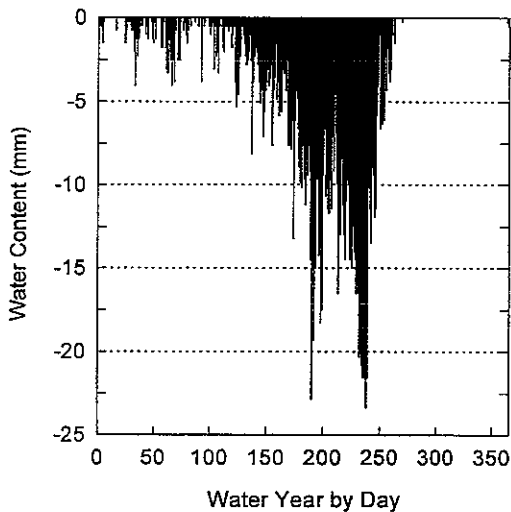um daily declines from almost all of the sites, although many are modified somewhat by the winter melt. The maximum values are between 75 and 80 mm per day, which is typical of most sites in all regions. The average daily rates of decline for the same Vienna Mine, Idaho site, as shown in Figure 5, illustrate a trend common to most sites for average daily declines. In this case the distribution is near normal with maximum daily average rates of between 20 and 25 mm per day. The maximum daily rates are usually associated with the last few days of snow on the pillow, as shown in Figure 4. The later in the year the snow lasts on the snow pillow, the higher these daily maximum rates are. In the case of average daily declines shown in Figure 5, however, values peak about day 260 as opposed to day 290 for the maximum declines. Thus the average day of melt out is nearer day 260 (actual average day of melt out was found to be day 265) and while maximum rates are experienced later in the season, there are also many occurrences of zero snow on the pillow after day 260 leading to the difference in shape of the distributions.

Figure 18 Average Daily Decline in SWE for the 1982-1996 Water Years at the Cold Springs Camp, Oregon, SNOTEL site.

The distribution of average daily declines for the Cold Springs Camp, Oregon, site is shown in Figure 18. In this case, there is a double period of high rates of average daily declines, while the general pattern of the declines over the normal melt season for most sites is approximately symmetrical. The first period of maximum average daily declines occurs near day 190 and the second period of maximum values occurs about day 240. The average daily decline melt season extends from about day 150 to day 265. Again the maximum average daily rates are between 20 and 25 mm per day.
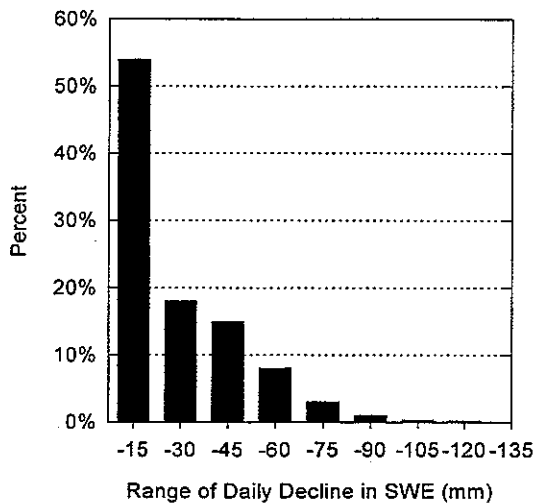

Figure 19 Histogram of Maximum Daily Decline in SWE for the SNOTEL sites in the Northern Rockies region.

General Maximum and Average Decline Relationships

The analysis of maximum and average daily declines from all 94 sites indicated that the maximum average daily rates were in the range of 10 to 30 mm per day. The higher values were associated with the deeper, longer persisting, snowpacks. By far the majority of the maximum average daily declines were found to be in the range of 20-25 mm/day.

The greatest maximum daily declines were generally below 90 mm/day and almost always below 120 mm

per day. A histogram of maximum daily declines for the 11 sites in the Northern Rockies region (Figure 19) shows that the percent of occurrences greater than 90 mm per day is very small.(7 of 1904 values, or .37 percent). The results were similar for the other regions investigated.

Discussion and Conclusions

1. This analysis indicates that there are many similarities in snowmelt characteristics over the entire western United States. Regional patterns and intra-zone differences were also observed.

2. Site characteristics, such as exposure, aspect, slope, etc., appear to have more influence on accumulation and melt than do elevation or latitude. Based on the analysis of the 94 sites used in this study it was found that accumulated peak SWE did not correlate well with elevation, which is contrary to the common perception that precipitation increases with elevation.

3. Snowpacks with greater SWE (deeper snowpacks) tend to have longer windows of accumulation and melt, and higher average daily declines. This is due to the snow persisting later into the season when there is more energy available to produce melt.

4. Future research, using all of the nearly 600 SNOTEL sites and additional information concerning temperature and precipitation at these sites, should be conducted in order to verify the preliminary results reported in this study.

ACKNOWLEDGMENT

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