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MAXIMUM SNOWMELT RATES: SOME OBSERVATIONS

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ABSTRACT

In response to discussion and debate about how fast snow can melt under extreme conditions, this paper identifies and interprets some reported observations of rapid snowmelt rates. Energy availability suggests that maximum snowmelt under typical conditions in the mountains of North America is about 50 mm per day. Conditions that enhance snowmelt rates include long day-length near the summer solstice, clear skies during daytime combined with cloud cover at night, warm and humid air combined with high wind speeds, particulate matter in the near-surface snow layer, and discontinuous snow cover that is thin enough for sunlight to penetrate to the ground surface. Records of snowmelt rates from four research sites and more than ninety SNOTEL sites provide the observational basis to discuss empirical estimates of maximum melt water generation.

INTRODUCTION

Maximum rates of snowmelt are of concern to hydrologists and flood forecasters but seem to be subject to more folklore than scientific study. Popular-media accounts of big winters occasionally suggest that deep snowpacks could melt almost overnight, and sensationalized stories about global warming raise the threat of dramatic increases in snowmelt. Regardless of exaggerations, river forecasters and design engineers need some estimate of how rapidly a snow cover can produce melt water under extreme conditions. Such information is needed for both clear-weather periods and warm-storm / rain-on-snow events. Estimates of maximum snowmelt are much more constrained than estimates of probable maximum precipitation. Techniques were developed during the Cooperative Snow Investigations to estimate snowmelt inputs for design floods (chapter 10 in U.S. Army Corps of Engineers, 1956). This paper examines theoretical limits on maximum snowmelt and interprets some observations of rapid snowmelt rates in the four decades since publication of Snow Hydrology. Accounts of snowmelt floods, reports about snowmelt studies, and other literature were examined to identify some extremes in reported values from different regions (Table 1).

TABLE 1. Reported high-rates (greater than 50 mm/day) of snowmelt (adjusted to average melt per day)

Melt rate (mm)	Region	Conditions	Source
51	mid-Atlantic states	January 1996	Doesken and Judson, 1997
60	Knob Lk, Canada	spring melt	Price, et al., 1979
60	Blue Canyon	rain-on-snow 1500 m	Kattelmann, 1985
60-65	Wyoming	isolated drift	Bartos and Rechard, 1974
65	Oregon Cascades	rain-on-snow 800 m	Marks, et al., 1997
96	Reynolds Cr, Idaho	deep, isolated drift	Zuzel and Cox, 1979
102	Alaska	chinook wind 10°C	US Forest Service, 1961
121	Wyoming	isolated drift	Tabler, 1985
100-150	Reynolds Cr, Idaho	deep, isolated drift	Cooley, 1996
120-165	western U.S.	SNOTEL sites	Cooley and Palmer, 1997
190-214	Japan	strong advection	Matsuura et al., 1996

Maximum hourly melt rates may be useful for estimating design floods for road drainage structures and erosion control projects. The highest hourly rate of snowmelt found in the literature was 9 mm per hour (Kuzmin, 1961). A six-hour 100-year maximum snowmelt rate of 7 mm per hour +/- 0.6 mm per hour at the 68% confidence level was estimated for the Colorado alpine zone (Payton and Brendecke, 1985). Outflow from snowmelt lysimeters has been observed to occasionally exceed 10 mm per hour when the surface contributing area was larger than the collection area. However, some areas of the soil receive these locally-high rates of snowpack outflow.

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ESTIMATES OF MAXIMUM SNOWMELT

The amount of energy from a variety of sources constrains the melt rate. Upper bounds on daily snowmelt can be estimated from the energy available from potential net radiation and turbulent exchanges. The British Flood Studies Report (Natural Environment Research Council, 1975) uses an estimate of 42 mm per day as probable maximum snowmelt. Church (1988) calculated maximum snowmelt to be less than 43 mm per day at the summer solstice and about 38 to 40 mm per day for most of May, June, and July at latitudes of 30 to 50 °N. Local daily rates of snowmelt tend to be highest when several conditions coincide: solar radiation, air temperature, wind speed, and atmospheric humidity are high; snow albedo and nighttime radiation cooling of the snowpack are low; the snow cover is thin enough to permit radiation penetration to the ground, and there are local sources of longwave radiation. The highest daily amounts of melt often occur during the occasion of clear days and cloudy nights. Snowmelt can be enhanced when rocks or soil become exposed because longwave radiation from the sun-warmed rocks can be more effective at melting snow than direct solar radiation. These high rates of snowmelt are obviously self-limiting because of the disappearance of the snow. In a research basin in the Sierra Nevada, peak snowmelt runoff occurred when 50 to 75 percent of the basin was snow covered (Kattelmann, 1991). Even though local melt rates were quite high, streamflow from this small catchment was limited by declining snow covered area. In larger catchments, peak snowmelt generally occurs at lower elevations a few weeks before that at higher elevations. Snowmelt runoff is also limited by disappearance of snow from south-facing slopes before melt rates peak on north-facing slopes.

Maximum potential melt can be estimated from an energy balance approach (energy for melt = net shortwave + net longwave + sensible heat + latent heat [conduction and precipitation assumed negligible]). Using the highest values we could find in the literature and a variety of assumptions, high values for energy available for snowmelt under non-rain conditions in the western United States should be in the range of 100-200 $W\ m^{-2}$ averaged over 24 hours. These amounts of energy could melt 25-50 mm per day. Extraordinary combinations of extreme conditions could conceivably raise melt up to about 75 mm per day. Another report on estimating energy inputs and calculating maximum melt rates with different snowmelt models is in preparation.

As another indicator of potential maximum melt, we used procedures for estimating snowmelt that use air temperature as an index of the energy available to melt snow. The general form of an air-temperature index snow melt equation for non-rain conditions is $M = M_f (T_i - T_b)$ where: M = melt rate (mm of water / day), M_f = melt factor (mm / [°C • day]), T_i = index air temperature (usually maximum or mean), and T_b = base temperature (usually 0 °C) (e.g., Male and Gray, 1981). The melt factor (M_f) is typically used to relate air temperature to snowmelt for specific environments and varies considerably between locations. Most values in the literature range between 1.5 and 4.5 mm / (°C • day) (Dunne and Leopold, 1978). Another study showed melt factors to range from 1.32 to 3.66 mm / °C for six-hour periods (Anderson, 1973). High daily melt-rates estimated with the degree-day approach and a mean daily temperature of 20 °C are 40 mm if $M_f = 2$ and 80 mm if $M_f = 4$. Mean daily temperatures exceeding 20 °C have been recorded at the end of the snowmelt season at Reynolds Mountain at an elevation of 2072 m in southwest Idaho.

Probable maximum rates of snowmelt during rainfall were estimated using a simplified equation (Dunne and Leopold, 1978) found to perform adequately at two sites in the Sierra Nevada (Kattelmann, 1985):
$M = T_a (1.42 + 0.51\ u_2 + 0.0125\ P) + 2.5$ where M = melt rate (mm / day), T_a = air temperature at 2 m, u_2 = wind speed at 2 m (m / s), and P = rainfall (mm). Various combinations of input values were used with the equation above to determine potential melt rates. For example, a wind speed of 10 m / s (sustained average for 24 hours) and 100 mm of rainfall at 10°C would produce about 80 mm of melt. If the temperature were 15°C for the same wind and rainfall conditions, about 120 mm of melt would be produced. Average wind speeds exceeding 10 m / s have been recorded at exposed sites such as Reynolds Mountain, Idaho.

SNOWMELT RATES AT EXPERIMENTAL SITES

Records of snowmelt at several research stations were examined to find examples of high melt rates. At the Central Sierra Snow Lab, maximum changes in snowpack water equivalence measured with an isotopic profiling snow gage and maximum amounts of snowpack outflow from snowmelt lysimeters have been about 40 mm per day. Apparent depths of snowpack outflow were much greater when the contributing areas of the snowmelt

lysimeters were greater than the area of the collector itself. The same situation has been observed at the study plot at Mammoth Mountain, where snowpack outflow is collected in eight snowmelt lysimeters of 1 m^2 area. At the end of the snowmelt season, when the snow column is isolated within the rim of the snowmelt lysimeters, outflow is probably a better indicator of melt. At such times, maximum daily outflow has been 30-50 mm.

In the Emerald Lake basin of Sequoia National Park (a 1.2 km^2 cirque with northern exposure and elevations between 2800 and 3400 m), snowmelt runoff was at a maximum when high snowmelt rates coincided with a high proportion of snow covered area (Kattelmann, 1991). Streamflow from snowmelt runoff averaged over the catchment area exceeded 15 mm per day on 44 days in one of the years of study. The highest daily equivalent depth on record was about 30 mm. The highest daily amounts of snowmelt averaged over three or four days from ablation-stake data were about 30 mm in June and July.

At the Reynolds Creek Experimental Watershed in southwest Idaho, snowmelt rates from various snowpack conditions were measured with 13 snowmelt collectors located at the Upper Sheep Creek study site. The collectors represent a range of snowpack conditions and aspects at approximately the same elevation. The melt collector data covered an 11-year period from 1984 through 1994. Observed melt rates corresponded to snowpack depth and to aspect since all were at about the same elevation and all were in relatively open sites (low sagebrush, high sagebrush and other shrub species, and aspen groves). The maximum rates at this site were associated with isolated late lying drifts that are subject not only to high radiant energy (both incoming and that reradiated from bare ground and vegetation), but also to considerable amounts of advected heat from adjoining bare ground during windy conditions. In general, maximum snowmelt rates were found to be about 30 to 75 mm per day for shallow snowpacks (114 to 225 mm SWE) on south facing sites, about 50 to 80 mm per day for general snow-covered areas (330 to 850 mm SWE) on a variety of exposures and aspects, and 100 to 180 mm per day for deeper snowpacks on north-facing sites (465-1520 mm SWE), with the highest rates tending to occur at the deepest sites and late in the season (Cooley, 1988 and 1996).

SNOWMELT RATES AT SNOTEL SITES

The United States Department of Agriculture Natural Resources Conservation Service (NRCS) operates a network of automated snow measuring stations in the western United States known as SNOTEL (for SNOw TELemetry). The principal snowpack sensor used at SNOTEL sites is the snow pillow: a metal or synthetic rubber bladder filled with an antifreeze solution, typically 3-4 meters in diameter. The snow pillow hydrostatically weighs the water content of the overlying snowpack; a pressure transducer translates this weight into an equivalent voltage value that can be telemetered to a master receiving station. Cooley and Palmer (1997) analyzed snowmelt characteristics at 94 SNOTEL sites selected from nine different regions in the western United States. Most of these stations had at least 15 years of daily snowmelt record. The analysis of daily melt rates from these 94 stations indicated that the highest daily melt rates occur near the end of the melt season when more energy is available for snowmelt. The greatest daily melt values were generally below 90 mm/day and were almost always below 120 mm/day. Over 50% of the maximum daily melt rates for this area ranged from 20-25 mm/day. For eleven sites in the northern Rocky Mountains, only 0.37 percent of almost 2000 daily values analyzed showed daily melt rates greater than 90 mm per day. Results were similar for other regions.

SUMMARY

Although most reports of high rates of snowmelt were less than 50 mm per day, several observations in excess of that amount have been reported. Some of these extreme values are difficult to explain in terms of energy availability, but appear to occur only during extraordinary combinations of very rare conditions. The highest rates of snowmelt in the absence of rain generally occurred from isolated drifts or snow patches in late spring or summer. Under such conditions, these extreme rates of snowmelt generally do not cause flooding because they occur when snow covered area is minimal. However, when widespread snow cover persists into June, as in the case of 1983 in the western United States, large areas contributing high rates of snowmelt can generate serious flooding. Similarly, this combination of high rates of runoff generation and large contributing area during rain-on-snow events creates devastating floods.

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