LEARNING FROM WATCHING SNOWMELT

by

James W. Frazier[1] and Clay A. Brandow[2]

INTRODUCTION

For the practicing forest hydrologist, much can be learned by close observation of the snowmelt process. Directly viewing watershed behavior during hydrologic events can often be more enlightening than remote sensing. Observation and deduction can help the forest hydrologist better understand the processes that sculpt watersheds and influence water quality in order to minimize adverse impacts of forest management activities. Valuable snowmelt observations include stream channel ice flows, bed load movement, oversnow runoff and effects of rain-on-snow events. This paper recounts numerous observations and interpretations made by two forest hydrologists in a subalpine wilderness meadow in the central Sierra Nevada mountains of California.

Environmental Setting

Snowmelt observations were made during one week periods in April 1980, 1981 and 1982 at Cooper Meadow, a 50 ha subalpine site at 2560 m elevation in the Emigrant Wilderness of the Stanislaus National Forest. The 365,000 ha Stanislaus National Forest lies on the western slope of the Sierra Nevada mountains of California. It ranges in elevation from about 500 m in the Sierra foothills to about 3500 m along the Sierra Crest and is located immediately north of Yosemite National Park.

Cooper Meadow lies about 3 km downstream from the headwaters of the South Fork Stanislaus River. Because of its wilderness setting, Cooper Meadow is accessible in winter only on skiis, via a 40 km round trip, and in summer by trail.

Mean annual precipitation at Cooper Meadow is about 140 cm, 90% of which falls as snow falls as snow between November and April. Snowpack averages about 110 cm of water content on April 1. Snow depth on this date usually ranges from about 1.8 to 3.1 meters.

Cooper meadow is composed of sediments eroded from the Sierra Nevada granitic batholith and volcanic mudflows. The South Fork Stanislaus River meanders through the meadow at a gradient of about 3/4 - 1%. The peak of annual streamflow occurs during spring snowmelt, with flows reaching about 3.5 m3/s. Flow recedes rapidly after snowmelt and drops to less than 0.2 m3/s by late summer. Surface flow in late summer of dry years becomes interrupted in the upper meadow as flow percolates intermittently through streambed gravels.

Vegetation in Cooper Meadow consists primarily of sedges (Carex spp.), grasses, forbs and wildflowers, and riparian willows (salix spp.). Forest vegetation surrounding the meadow includes lodgepole pine (Pinus contorta), red fir (Abies magnifica) and western mountain hemlock (Tsuga mertensiana).

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[1]Forest Hydrologist, Stanislaus National Forest, USDA Forest Service, Sonora, California.

[2]Hydrologist, NOAA - National Weather Service - California-Nevada River Forecast Center, Sacramento. Formerly Forest Hydrologist, Sequoia National Forest, Porterville, California.

OBSERVING NATURAL HYDROLOGIC PROCESSES

The Forest Service hydrologist is responsible for prevention of water quality degradation from management activities and restoration of areas adversely effected by historic uses. It is essential to the hydrologist to observe and understand natural physical processes which may affect water quality. "Reading the land" is an observation and deduction technique which can be applied to any hydrologic process including snowpack accumulation, maturation and ablation. Learning from watching the snowpack can provide valuable information for planning forest management activities, restoring degraded areas and understanding why past restoration practices were successes or failures. There is often no substitute for winter field observations (Powell, 1987).

Influences of Snow on Management Activities

Snowpack behavior must be considered when planning forest management activities in the snow zone. Road construction, timber harvest, recreation and watershed restoration practices are of particular concern.

Snowmelt patterns on roads, for example, can significantly influence drainage from the road surface or cut slope. If snowpack characteristics are not properly understood, road washouts and consequent stream sedimentation can occur.

Timber harvest patterns in the snow zone can be arranged in a manner which increases water yeild. Knowledge of snow accumulation and ablation characteristics is vital to insuring water yield improvement through this type of vegetative manipulation.

Recreation developments, such as alpine ski areas, depend on optimizing available snow quantity. The design of ski runs must be carefully planned to capture as much snow as possible and retain it well into the spring. Understanding avalanche characteristics is essential in order to minimize public safety risks.

Watershed restoration practices in the snow zone must consider snowpack behavior since such practices are usually conducted in streams or areas of overland flow during snowmelt. These restoration practices promote recovery of stream channels and banks, raise water tables to help revegetate meadows, improve fish habitat and protect land surfaces from erosion. Structural practices include stream gradient stabilizers, check dams, rip-rap, revetments and in-channel rock and log clusters to improve fish habitat. Non-structural vegetative treatments are used to restore long-term land surface stability. This may include reseeding denuded areas with grasses and planting shrubs and trees such as willows and alders to stabilize streambanks.

SNOWMELT PHENOMENA AFFECTING STREAM FLOW AND MORPHOLOGY

The following phenomena observed in Cooper Meadow are believed to play an important role in streamflow and fluvial morphology in mountain meadows in the snow zone of the Sierra Nevada mountains[1]. Stream channel formation and change are significantly influenced by the occurrence and behavior of the annual snowpack.

Two-Story Streams

Sierran streams flowing at the start of the snow accumulation period usually do not freeze. Even in streams which become covered by the snowpack, some flow is sustained. Melt drip from the snow-ground interface as well as subsurface flow can occur throughout winter (Kattelmann, 1989).

In addition to normal winter streamflow, water can travel above the channel on the surface of the snowpack. This process, called oversnow flow, results from saturated snow or rain-on-snow events. Oversnow flow creates two-story streams; that is, simultaneous streamflow beneath as well as above the snowpack. Oversnow flow can occur during winter months but is more frequent in spring.

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1 - Some observations were made en route to Cooper Meadow, such as Buck Meadow and Whitesides Meadow.

Saturation Oversnow Flow -- Oversnow flow from annual spring snowmelt causes snowpack interstices to become saturated and force water to the surface above stream channels and flow over the top of the pack (Kattelmann, 1987). This type of oversnow runoff can make periodic contact with an open streambed in spring and entrain sediments. Flow can be turbid, staining the snowpack surface dark brown and accelerating the ablation process.

Saturation oversnow flow which entrains fine sediments was observed at a few locations in Cooper Meadow. However, more common was oversnow flow which stayed entirely atop the pack in the stream. In such cases, the second story stream flowed with high clarity, appearing aqua blue above its snow covered bed. This flow was intermittently on the surface; that is, water ran along a reach then infiltrated into the snow and resurfaced and flowed again downstream in another reach.

Rain-on-snow Oversnow Flow -- Rain-on-snow events can cause oversnow flow several times a year. The western slope of the Sierra Nevada mountains is subject to periodic rainfall atop the snowpack (Frazier, 1989). Although this region is dominated by precipitation from northerly storm tracks which bring abundant snowfall, occasional storms have sub-tropical origins. These can occur any time during winter and are often substantial in amount and duration.

Rain-on-snow events occurred at Cooper Meadow several times during the fall, winter and spring of 1981-82 (Table 1). These events were clearly apparent on site in mid-April 1982. Several sediment layers were visible on the face of vertical streambank snow walls, and trails of sediments from the April 10-12 event (four days prior to on-site observations) ran across the snowpack above the main and some tributary stream channels.

Table 1

Rain-On-Snow Events at Cooper Meadow, 1981-82[1]

Date	Rainfall (cm)	Temperature (^{o}C)	Estimated Snow Level (m)
November 13-14	17.3	25	2925
December 19-22	11.9	22	2755
February 14-16	19.4	25	2925
March 10-12	4.3	29	3100
April 10-12	10.6	29	3100

1 - Precipitation and temperature data are from the 1981-82 rainfall year (July 1, 1981 to June 30, 1982), Summit Ranger Station, Pinecrest, 15 km west-southwest of Cooper Meadow. The elevation of Cooper Meadow is 2560 m and the watershed above it rises to about 2925 m. Snow level estimates are based upon theoretical adiabatic lapse rates (Miller, 1966) and field observations of such rates in this area.

The oversnow flow resulting from the April 10-12 event was significantly different from that caused by saturation oversnow flow. Rather than a comparatively slow, gradual rise in the stream hydrograph from snowpack saturation in spring, the rain-on-snow event caused a rapid rise and fall of the hydrograph. It apparently brought relatively high velocity oversnow flow and carried a surprising amount of suspended sediment and bed load.

Oversnow flow caused by rain-on-snow creates a different type of two-story stream than does the saturated type. Water has not upwelled through the melting spring snowpack to create a saturated column from the streambed to the snow surface. During rain-on-snow events, the oversnow flow does not contact its subsurface counterpart (except at infrequent stream openings). True separated two-story flow is achieved over long stream reaches during such events.

The process of rain-on-snow oversnow flow is believed to have five sequential components:

1. Source - Rain falling on the snowpack can deliver a relatively rapid volume of water to the stream channel.

2. Constriction - The sudden increase in streamflow is constrained in cross-sectional area by snowbanks and produces relatively high velocity flow.

3. Streambed Scour - The added streamflow scours the streambed at openings, detaching and transporting bed load materials.

4. Oversnow Flow - Streamflow is forced over snow on closed portions of the channel. Velocity is maintained due to the very low roughness and efficient hydraulic radius of the snow covered second-story streambed. (Oversnow channels were observed to have hydraulically efficient cross-sections; that is, a semi-circle with width twice the depth). Oversnow flow usually but not always runs parallel above its subsurface counterpart. Occasionally it diverts away from the main channel for a short distance.

5. Deposition - Oversnow flow recontacts the streambed wherever the channel is open, depositing transported bed load and entraining more.

Deposition of fine sediments on the beds and banks of the second-story rain-on-snow channels likely plays an important role in the process of streams opening up in spring. Dark silts and sands promote rapid melt of the snow surface if exposed for a sufficient time following a storm.

Ice Flow Processes

The main channel in Cooper Meadow became exposed in the same manner each spring in 1980, 1981 and 1982. Oval depressions began to appear periodically along about 10% of the channel, each about 20 m long by 10 m wide. The depth of the depressions fluctuated diurnally, rising slightly in the late afternoon (likely due to the snowpack bridge over the stream being buoyed-up by the rising water) and dropping by morning. Within a few days the depressions cracked and snow blocks calved off into the emerging stream. Thus, the depressions became openings. A similar process has been observed on a larger, glacial scale (Hughes, 1989).

The snow blocks in the channel became progressively smaller due to solar and liquid melt processes. As they dissipated, they became floatable impediments to increasing streamflow in late afternoon. Forced against the downstream face of the stream openings, they acted as temporary check dams. As a result, water often rose quickly to the surface of the snowpack in the openings. Constriction of cross-sectional area by snowbanks and the sagging of the snowpack bridge over the stream also aided this effect. While other constrictive processes can occur, such as anchor ice (Storer, 1963), the former were observed to be the principal factors.

Most days water rising to the top of a stream opening receded without oversnow flow. Snow blocks often became dislodged from their damming position by rising and circulating water, or the surrounding snow sufficiently absorbed the rising water. However, the water level occasionally rose above the snow surface and produced saturation oversnow flow for a short distance downstream before infiltrating into the snow.

Formation of snow blocks which calve off streambanks in spring is accelerated by the diurnal rise and fall of streamflow beneath the snow. Buoyancy of the snowpack over the streamcourse results in stress fracturing at mid-channel and stream's edge.

Bed Load Movement

Oversnow flow from rain-on-snow events was observed to have a marked effect on the detachment, transport and deposition of channel bed load. Deposition of dark brown fine particles (silts and sands) on the surface of second story streamcouses was widespread. Larger particles (gravels and cobbles, from about 1-10 cm in diameter) were fully transported across the snowpack surface. Virtually no deposition occurred on the snow.

The gravel-cobble component was redeposited at stream openings, which were most likely pools during oversnow flow. Such pools, having a much broader cross-section than the channel feeding it, would have a near-zero flow velocity. The sudden decrease in velocity caused sediment to be deposited in unsorted piles in the openings. The resulting deposition pattern was much different than common point or channel bars. High gravel mounds, or "beehive" bars dotted the streambed. (Mounds up to 1 m tall were observed.) The origin of these depositional features might be difficult to determine if observed when the snowpack is absent.

Influence of Aspect on Streambank Snowmelt

The main channel in Cooper Meadow runs westerly in the upper section then turns abruptly south at mid-meadow where wide meanders begin. Observations were made of melt rates and processes along several streambank aspects.

Northerly aspect streambanks typically calved off. The snowpack fractured cleanly and vertically. This was the principal source of the large snow blocks which caused ice damming leading to diurnal oversnow flow. Insolation was much less than on south facing aspects; this side of the stream was a colder micro-environment. In addition, the sheer snow walls on northerly aspects provided a convenient snow column to observe the seasonal history of the snowpack, including sediment layers from rain-on-snow events.

The vertical snow walls on the north facing streambanks correlated well with vertical streambanks beneath them. A single wall of snow and earth was often seen at stream's edge. The snow wall may provide structural support to the streambank and be a factor influencing the formation of upright streambanks in snow zone meadows.

The melt process on south facing aspects was essentially the opposite of that on the northerly aspects. Snow-covered streambanks were typically well sloped back. More direct solar radiation plus sediment accumulations from oversnow flow caused a much faster melt and produced the lowest angle of streambank repose of any aspect.

West and east aspect streambanks generally sloped uniformly toward mid-channel without exhibiting the extremes of calving or gentle sloping. In the lower meadow, where wide meandering is common, all streambank melt processes were observed over short distances.

DISCUSSION

Three years of observing snowmelt at Cooper Meadow provided a clearer understanding of the natural processes involved and insight on how to apply that knowledge to forest management activities. Repeated field observations are valuable assets in applied hydrology, and are a necessary supplement to remote sensing or measurements. In addition, field observation also complements research activity. Observation, an initial step in scientific methodology, can be used to determine reasearch needs, in applying research findings and to provide feedback for further research programs.

While much was learned at Cooper Meadow, several questions remain for further observation or research. What are the actual velocities and duration of oversnow flow from rain-on-snow events? As streams open in the spring, are the openings in the same location annually and are they formed above one or more morphologic features of the stream channel? How important is streambank aspect to meadow stream morphology in the snow zone?

The knowledge gained from observing snowmelt processes at Cooper Meadow will be useful in planning and observing forest management activities. It will be especially helpful in the design of structural and non-structural treatments to maintain or improve water quality, range forage conditions and fish habitat.

CONCLUSIONS

While further study can help clarify many of the observations made at Cooper Meadow, several interim conclusions were drawn. They will provide helpful information to use in making forest management decisions.

Oversnow flow occurs from at least two sources. The first, from saturated snow during spring snowmelt, was observed at Cooper Meadow. It is an important factor in streamcourse snow ablation. Rain-on-snow events also provide oversnow flow and may dramatically influence channel snow ablation as well as bed load movement. Both types of oversnow flow produce two-story streams and demonstrate that this phenomenon may occur more frequently than previously considered.

Constriction of streamflow during the spring snowmelt process is an important factor in both types of oversnow flow. Snow blocks and reduction in channel cross-section compared with non-snow conditions cause accelerated stream stage elevation.

Streambank aspect and its effect on differential snowmelt processes may play an important role in the stream morphology of some mountain meadows. Formation and erosion of streambanks and the interrelated effect on streambed structure is likely influenced by the snowpack.

Streamflow during winter and spring can be extremely non-uniform diurnally and axially along streamcourses. Stream channel snowmelt and flow in spring is a complex process that produces highly dynamic conditions as the channel emerges from the winter snowpack.

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