SNOWMELT LYSIMETERS: DESIGN AND USE

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Snowmelt lysimeters collect and measure the liquid water outflow from the bottom of the snowpack or at some level within it. They have been used to develop and evaluate procedures for estimating snowmelt volume and timing, evaporation, water transmission and storage, and the mass balance of snowpacks. Snowmelt lysimeters have been employed in studies of rain-on-snow, snow surface modification, forest harvesting, and snowpack chemistry. They have potential for use in operational streamflow and flood forecasting.

Generally, a snowmelt lysimeter consists of a collector, a flow-measuring device, and a conduit linking the two. The collector is surrounded by either a raised rim (unenclosed lysimeter) or by a barrier that completely isolates a column of snow (enclosed lysimeter). In addition, the collector may be at atmospheric pressure (zero-tension lysimeter) or exert a negative pressure on the overlying snow (tension lysimeter).

Liquid water percolating through a heterogeneous, layered snowpack takes a variety of intricate pathways enroute from the snow surface to the soil (Wankiewicz, 1979). The collector intercepts this spatially variable flow and averages it over some area. The surface areas of most snowmelt lysimeters are of very limited extent and thus they collect only a sample of the highly variable flow within a natural snowpack. Several configurations have been developed to improve the representativeness of the sample.

Most snowmelt lysimeters have been of the unenclosed type (Figure 1a). Water within the area of the lysimeter percolating below the top of the rim will be captured and measured. Above the top of the rim, water is free to flow into or out of the column of snow directly above the lysimeter. Enclosed snowmelt lysimeters (Figure 1b) trap all of the water percolating through the snow directly above the collection container. Such devices may provide accurate long term volume data for mass balance studies, but may alter the timing of melt and water delivery. Enclosed lysimeters may have an adjustable barrier height to accomodate the natural development of the snowpack or may be of fixed height and artificially filled with snow.

This paper describes the various types of snowmelt lysimeters and the factors that affect their design, construction, and installation.

HISTORY

The earliest known attempt to intercept and measure water percolating through snow was made by Hughes and Seligman (1939) in the Alps. That pioneer of snow surveying and forest influences, James Church, was involved with the first known use of ground-based meltwater collectors at the Soda Springs Snow Station, California (Church, 1948). Sharp (1951) obtained some important observations of meltwater flow in the St. Elias Mountains with a series of small funnel collectors. The term "snowmelt lysimeter" was originally used by the Cooperative Snow Investigations of the U.S. Army Corps of Engineers and the Weather Bureau to describe two large meltwater collection systems installed at the Central Sierra Snow Laboratory, Soda Springs, California, in 1949 and 1952.

A sudden resurgence of interest in snowmelt lysimetry occurred in the 1960's with development of several new designs: small cylindrical collectors refilled daily with new snow to measure effects of snow surface modification (Megahan, et al., 1967); a large enclosed lysimeter to monitor meltwater production as a basis for comparing predictive models (Pysklywec, et al., 1968); a snowmelt and rain collector also capable of weighing the snowpack (Cox and Hamon, 1968); and, a series of small enclosed lysimeters to determine the effects of forest cover on water delivery (Haupt, 1969). Since 1970, a profusion of snowmelt lysimeters have been deployed for various purposes, and at least three dozen different designs have been cited in the literature.

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HYDRAULIC CHARACTERISTICS

The placement of an artificial barrier in the path of percolating water has a variety of significant effects on the flow and its measurement. Since 1970, our understanding of water movement in snow has advanced greatly (Colbeck, 1978; Wankiewicz, 1979; and Jordan, 1983). Simply put, water flows through snow primarily in response to the gravitational force. The gravity theory of water percolation through snow (Colbeck, 1972) uses Darcy's law for one-dimensional unsaturated flow:

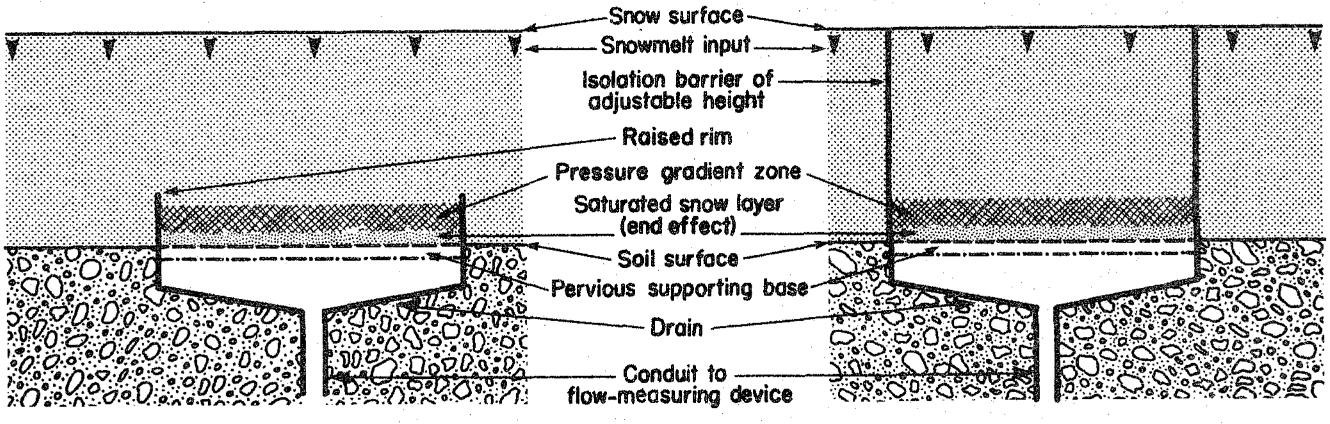
$$V = K\,(d\Psi/dz + 1)$$

where the downward flux V in meters per second is proportional to the sum of the capillary pressure gradient ($d\Psi/dz$) and the gravitational pressure gradient (1 m/m). The constant of proportionality (K) is the unsaturated hydraulic conductivity in meters per second. Colbeck (1974) calculated that gravity drainage predominates during steady or decreasing flow and that the capillary pressure gradient may be ignored, except at very low flux (10^{-8} m/s) or at some interfaces, such as where water accumulates in snow overhanging an airspace. A neglible capillary pressure gradient exists throughout the snowpack as a whole, but significant pressure gradients may occur at major pressure or textural discontinuities (Wankiewicz, 1978b).

A snowmelt lysimeter represents a major discontinuity. The significance of an artificially induced pressure gradient is that percolating water may avoid the area and flow around the lysimeter. Wankiewicz (1978a and 1978b) described in detail the hydraulics of snowmelt lysimeters and pressure gradient flow. The reader is referred to his work for a more complete treatment of these subjects.

The presence of a layer at atmospheric pressure within the snowpack generates an "end effect" (Colbeck, 1974) within the snow above the collector/snow interface (Figure 1). With the addition of liquid water, this end effect results in the formation of a saturated layer some 2 cm (Colbeck, 1974) to 3 cm (Wankiewicz, 1976) thick, where water is held in the intergrain pore spaces by capillary forces. The amount of stored liquid water remains relatively constant (Wankiewicz, 1976), varying diurnally in one example by about 0.2 mm (Colbeck, 1974). Wankiewicz (1978b) calculated the pressure profile above a zero-tension surface or water table and showed that the snow water pressure becomes essentially constant several centimeters above the water table. The area between the discontinuity and the level where the pressure becomes constant is known as the pressure gradient zone (Wankiewicz, 1978a and 1978b). Within this zone, the snow water pressure decreases from atmospheric (0 Newtons/m^2), such as at the collector/snow interface, to -500 to -1000 Newtons/m^2 (5 to 10 cm water) in the snow above. This end effect determines the collection efficiency, dead storage, start-up time, and response of the snowmelt lysimeter.

Where the water pressure begins to change near the collector/snow interface, downward water flow may be affected. Within this pressure gradient zone, water pressure is greater than beyond the perimeter of the interface. This difference in water pressure can induce lateral flow from the higher pressure area (above the collector) to the lower pressure area (outside of the collector), resulting in undermeasurement of the meltwater flux. This lateral flow problem is easily remedied by proper lysimeter design. Because the pressure gradient zone extends over a relatively short vertical distance, it may be contained within a rather low rim around the collector (Figure 1). The vertical extent of



a. Unenclosed snowmelt lysimeter b. Enclosed snowmelt lysimeter

Figure 1. Features of Snowmelt Lysimeters.

the pressure gradient zone is inversely related to the flux. If the rim height is greater than the height of the pressure gradient zone at the lowest flux of interest, the flux measured by the lysimeter should be representative of the average in undisturbed snow at the same level (Wankiewicz, 1978a). A rim height of 12 to 15 cm should contain the pressure gradient zone at all but insignificantly low flows.

Before water can be discharged out of the lysimeter conduit, the capillary storage above the collector/snow interface and the storage of the collection system must be satisfied. The collector storage is best determined empirically for the particular installation. The end effect storage of the snow is equal to the product of the available space (effective porosity) and the amount of water held by capillarity per unit volume of void space integrated over the pressure gradient zone (Wankiewicz, 1978a). As a rule of thumb, 2 to 3 cm of water may be stored above the collector/snow interface.

The start-up time of a snowmelt lysimeter is the time required for the storage to be satisfied at a particular flux after installation. If the interface storage is 2 cm and the flux is 2 mm per day, 10 days of flow at that level will be required before drainage is recorded by the lysimeter. Similarly, if the snow above a collector was dry when rain began at a rate of 1 cm per hour, the lysimeter would show no outflow until 2 hours after the water holding capacity (irreducible water content and cold content) of the overlying snowpack was satisfied. For snowmelt lysimeters located on the ground before snowfall, geothermal melt will often fulfill the storage requirement long before surface melt occurs.

Once the interface storage is satisfied, the snowmelt lysimeter should respond to any input of water percolating through the snowpack. Indeed, it should show the arrival of the wetting front before the water actually arrives at the level of the interface in adjacent undisturbed snow. This phenomenon also results from the end effect (Colbeck, 1974). When the leading edge of a meltwater wave arrives at the top of the pressure gradient zone, a roughly equivalent quantity of water is discharged at the interface, reducing the time required for the water to travel the same distance in unsaturated snow with constant water pressure. Wankiewicz (1976) calculated this "dynamic response time" as a range from about 1 minute for sudden increases to high flow to 15 to 20 minutes for sudden increases to moderate flow. The dynamic response time of zero-tension lysimeters is considered adequate for measuring the time required for a meltwater wetting front to travel from the snow surface to the level of the collector, provided it is at a reasonable depth below the snow surface (Wankiewicz, 1978a).

The tension lysimeter (Wankiewicz, 1976) overcomes many of the problems associated with the end effect in zero-tension lysimeters. In the tension lysimeter, the collector/snow interface is a porous plate or membrane at negative pressure approximating the capillary pressure of the overlying snow. The negative pressure at the interface significantly reduces the storage, start-up time, dynamic response time and height of the pressure gradient zone as compared with a zero-tension lysimeter (Wankiewicz, 1978a). Thus, the tension lysimeter is an important tool for accurately monitoring small scale flow effects. Tension lysimeters must be installed in a preexisting snowpack, are limited to relatively small areal coverage, and may only be used in wet snow.

SNOWMELT LYSIMETER DESIGNS

The most common type of snowmelt lysimeter is the ground based unenclosed configuration (Table 1). The collector is installed on the soil surface before the development of the snowpack. The ground-based unenclosed snowmelt lysimeter, when properly constructed, measures the flux and volume at the base of the snowpack. The low contains the saturated drainage flow within the lysimeter. Most designs use an impermeable collector and the basal snow as the conducting medium to the drain. Collection areas vary from less than 1 m^2 to more than 100 m^2. Three installations use a set of small pans draining to a common recorder in order to sample percolation over a greater ground area while minimizing the collecting area. The quantity of water received at ground level is not necessarily the same as the amount of water input at the snow surface. Considerable lateral inflow and outflow may occur within the column of snow above the collector. Such flow is a natural process and is quite variable within and between seasons. The location of the collector within the flow field is something of a hit or miss proposition. The likelihood of inflow balancing outflow within the snow column above the collector increases with its area.

Table 1. Ground Based Unenclosed Lysimeters

Source	Description	Area	Measurement	Purpose
Church 1948	Drip pans	—	—	Amount and timing of daily snowmelt
Rockwood, et al. 1954 U.S. Army Corps of Engineers 1956	Triangular on natural rock base	120 m^2	Weir tank Water level recorder	Travel and storage of liquid water Amount of daily melt
U.S. Army Corps of Engineers 1956 Hildebrand 1957	Triangular, elevated wood structure	56 m^2	Weir tank Water level recorder	Energy balance
Santeford, et al. 1972	Melt pan with soil substrate	1.5 m^2	Water level recorder	Energy balance Moisture exchange
Sulahria 1972	Square, Polystyrene	1.5 m^2	Manual observation	Water transmission rates
Lemmela 1973	Square	1 m^2	Water level recorder	Mass balance
Anderson 1976	Circular	7.3 m^2	Tipping bucket	Energy and mass balance
Langham 1977	64 square funnels	0.0064 m^2 ea.	Drop counter	Flow variability
Price 1977	Rectangular wood	—	Water level recorder	Energy and mass balance
Herrmann 1978	Square Polyethylene sheet	25 m^2	Water level recorder	Melt measurement Isotope content
Davis and Marks 1980	6 $1m^2$ and 1 $4m^2$ Connected together polystyrene	total 10 m^2	Tipping bucket	Energy and mass balance of alpine snowcover
Helvey and Fowler 1980	10 circular pans connected together	total 4.8 m^2	Tipping bucket	Monitor water input to soil
Beaudry and Golding 1983	—	0.9 m^2	—	Influence of forest harvesting
Beaudry and Golding 1983	Rectangular Reinforced plastic sheet	28 m^2	Tipping bucket	Influence of forest harvesting
Cooley and Robertson 1983	Rectangular 1 metal; 1 soil base	0.9 m^2	Water level recorder	Mass balance of transient snow zone
Harr and Berris 1983	8 triangular pans connected together	total 2 m^2	Tipping bucket	Influence of forest harvesting
Price and Hendrie 1983	Rectangular Polyethylene sheet	25 m^2	—	Runoff generation

Weighing lysimeters are a modification of the ground-based unenclosed design. They may be thought of as pressure pillows that collect and measure snowpack outflow rather than routing water off and away as do standard pressure pillows. The four known devices of this type were designed for specific situations and differ considerably from one another (Table 2). In two of the units, the collection surface is supported by a liquid-filled coil. The other two resemble standard rubber pressure pillows that have been outfitted with drains.

Table 2. Weighing Lysimeters

Source	Description	Area	Measurement	Purpose
Cox and Hamon 1968 Cox 1971	Concrete disc supported by a liquid filled coil of butyl tubing	1.9 m^2	Water level recorder	Snowpack and precipitation monitoring
Molnau 1971	Rectangular metal with rubber cover	3 m^2	—	Assess usefulness in runoff forecasting
Molnau 1971	Square rubber pressure pillow with metal rim	13.4 m^2	Water level recorder	Assess usefulness in runoff forecasting
Waring and Jones 1980	Fiberglass disc supported by liquid filled tube	1.8 m^2	Tipping bucket	Monitor light snowfall, ephemeral snowpack, rain

Another type of unenclosed snowmelt lysimeter is installed within an existing snowpack (Table 3). Commonly, an access pit is first excavated to the desired depth. Then, a lateral tunnel or slot with a flat ceiling is cut for the insertion of the collection pan, which is forced upward into contact with the snow. The tunnel is then backfilled underneath the pan to support it. Some installations have left off one side of the pan and slid the three-sided pan into a slot cut at a slight upward angle in the pit wall. The absence of an uphill rim has an unknown effect (Wankiewicz, 1976) but probably results in less water collected than in a four-sided pan. This type of lysimeter is particularly useful in studies of meltwater movement where it is desirable to measure flux at particular levels in the snowpack.

Table 3. Unenclosed Lysimeters

Source	Description	Area	Measurement	Purpose
Hughes and Seligman 1939	Rectangular metal and wood	—	Manual observation	Monitor melt water in glacial firn
Sharp 1951	Circular funnel	0.023 m^2	Manual observation	Flow patterns in firn
Woo and Slaymaker 1975	Funnels	0.004 m^2 0.013 m^2	Manual observation Water level recorder	Lag times of water precolation
Wankiewicz 1976 Jordan 1983	Rectangular metal Rim on 3 sides	1 m^2	Tipping bucket	Amount and timing of percolation
Wankiewicz 1976	Tension lysimeter Interface of sand	0.11 m^2	Manual observation	Monitor percolation with minimum of distortion
Marsh 1982	Rectangular metal Rim on 3 sides	1 m^2 0.25 m^2	Tipping bucket	Amount and timing of percolation
Marsh 1982	Multicompartment	0.25 m^2	Manual observation	Flow variability

The enclosed ground-based lysimeter (Table 4) is used where snowpack outflow volume is the principal quantity of interest. The barrier of variable height that segregates the measured column of snow from the surrounding snowpack eliminates lateral inflow or outflow and assures accurate volume determination for mass balance studies. However, the barrier disrupts naturally occurring flow processes and can accelerate snowmelt by absorption of solar radiation and subsequent reradiation to the snow. Physical isolation of a part of the snowpack is logistically difficult, and the isolation barrier requires a great deal of routine maintenance.

Table 4. Enclosed Lysimeters

Source	Description	Area	Measurement	Purpose
Pysklywec et al. 1968	Triangular Polyethylene base Styrofoam board barrier	24 m^2	Tipping bucket Water level recorder	Comparison of snowmelt models
Haupt 1969	Rectangular Steel pan and frame Polyethylene sheet barrier	0.25 m^2	Water level recorder	Effect of forest cover on snowpack water release
Schultz 1971, 1973	Rectangular steel pan and frame Polyethylene sheet barrier	0.25 m^2	Water level recorder	Assess lysimeter usefulness for monitoring areal snowmelt
Thompson et al. 1975	2 Rectangular Massive aluminum barrier	6 m^2	Tipping buckets and water level recorder	Snow evaporation and effectiveness of retardants
Gottfried and Ffolliott 1979	Air space around rim cut weekly	0.25 m^2	Water level recorder	Snowmelt model testing
Megahan 1983	Circular	0.9 m^2	Water level recorder	Effects of harvesting and fire on melt

The most complex enclosed snowmelt lysimeter is located at the Central Sierra Snow Laboratory. It was built by the USDI Bureau of Reclamation and University of California at Davis to study snow evaporation and its suppression (Thompson, et al., 1975). This unit consists of two 6 m^2 rectangular melt pans surrounded by a massive aluminum shell located in a deep excavation in bedrock. The shell could be mechanically raised to a height of 4.4 m to isolate each pan. One pan was also vertically movable in order to maintain the same snow surface elevation on both pans. Despite many well designed features and capabilities, this lysimeter has not functioned as originally intended. The shell could not be raised after a snow storm without excessively disturbing the snowpack. Excessive melting around the barrier of each pan resulted in unnaturally high outflow. The operation of the system required nearly 24-hour attention. The melt pans are currently being used without the shell as an unenclosed lysimeter.

Another kind of enclosed snowmelt lysimeter is artificially filled with snow (Table 5). Either a solid container or an impermeable flexible sheet may be used to isolate the snow. The monitored snow may be cut as a single unit or disaggregated and repacked to fill the container. This type of snowmelt lysimeter is used when it is desirable to control as many of the snow properties and processes as possible.

Table 5. Artificially Filled Lysimeters

Source	Description	Area	Measurement	Purpose
Megahan et al. 1967	Cylindrical Plastic filled daily	0.1 m^2	Manual observation	Net radiation as a predictor of snowmelt
DeWalle and Meiman 1971	Placed large volumes of snow on plastic	Variable	—	Energy and mass balance of isolated snow patches
Colbeck and Davidson 1973	Cylindrical tubes filled with repacked disaggregated snow; inserted in glacial firn	0.17 m^2	Recording rain gage	Water transmission through homogeneous snow
Fohn 1973	Cut snow blocks and enclosed in plastic sheet	0.5 m^2	Manual observation	Verify energy balance prediction of snowmelt
Denoth et al. 1979	Cylindrical tubes filled with sieved snow; inserted in snow	—	Water level recorder	Water transmission through homogeneous snow
Colbeck 1981	Tension lysimeter Ceramic plate interface	—	Manual collection	Snow chemistry
Berg and Woo 1983	Cylindrical tube filled with undisturbed column of snow	0.008m^2	Manual observation	Snowpack chemistry

DESIGN CONSIDERATIONS

Each snowmelt lysimeter should be tailored to the specific requirements of the study and the constraints of the site where installed.

Collector area and quantity

The lysimeter collector area must be adequate to obtain a representative sample of meltwater flux. Larger lysimeters provide a better areal average of the volume and timing of snowpack outflow than do smaller lysimeters. At the present, we do not know over what scale the flow field can be considered uniform, that is, the collection area needed to consistently intercept equal volumes of water is unknown. Preliminary results from six snowmelt lysimeters at the Central Sierra Snow Laboratory indicate that flow pathways may vary on the scale of several square meters. Volumes collected from these adjacent 2 m^2 pans differ by orders of magnitude. Herrmann (1978) considered 25 m^2 to be the minimum area representative of snowpack outflow from large (basin-wide) snow covers. Unless small scale flow effects are being studied, the largest collector area that one's site and resources permit should be used. Enclosed lysimeters avoid the problem of lateral flow but should have a large surface area relative to the perimeter in order to minimize the physical disturbance of the snowpack and the influence on outflow.

At least two collection areas should be measured independently at each site. Such duplication allows one to assess the quality and representativeness of the outflow data. A large area (20-50 m^2) partitioned into separately measured collectors would be ideal. This configuration permits the determination of average outflow over a large area, spatial variability within this area, and more detailed information on the timing of the outflow than is possible with a single integrated measurement.

Site selection

Although site selection is closely related to the objectives of the installation, certain site characteristics minimize construction and operational problems. Smooth, nearly level terrain provides the easiest working conditions. On slopes, one must contend with snow creep and glide, surface runoff channels, and highly irregular drainage of the inclined snowpack. However, a slight slope may be desirable for drainage of large collection areas, sufficient gradient of the outflow pipe, and location of the measuring equipment. Drainage around the lysimeter must be adequate. Small forest openings of a few hectares often result in the most uniform snowpack development. Collection pans should be located away from the drip, shading, and reradiation effects of trees, unless these influences are being studied.

Outflow measurement

After the outflow is collected and piped off-site, there are several means of measuring it. The simplest way is to manually observe and record the filling of a container, but this method is not particularly convenient beyond a few hours. A collection tank, continuous water level recorder, and automatic drain valve or siphon are commonly used. A calibrated weir box and stage recorder was used by the Cooperative Snow Investigations for its large-area lysimeters (Hildebrand, 1957). Tipping bucket recorders, either from precipitation gages or custom built, have been used successfully with many lysimeters. Two installations used multiple measuring systems to help ensure data continuity in the event of equipment failure. For example, a tipping bucket mechanism may be mounted ahead of a tank and water level recorder. The enclosed lysimeter at the Central Sierra Snow Laboratory (Thompson, et al., 1975) used two independent measures of meltwater and five separate recording mechanisms.

At times of high flow, some water may not be recorded while the measuring equipment is in midcycle. Water is undermeasured when it pours into a full tipping bucket that has begun to tip and before the empty one is in position. Similarly, water entering a tank in the process of draining is not recorded. To avoid undermeasurement, an automatic valve can shut off the inflow during the drainage cycle (Stein Buer, California Dept. of Water Resources, personal communication, 1984). Calibrating the measuring equipment at different flow rates within the expected range may be necessary. Flow rates corresponding to the range of values expected for the full range of conditions should be run through the measuring apparatus. Lysimeter data from the Central Sierra Snow Laboratory indicate maximum expected values of 15 mm per hour for clear weather melt outflow and 50 mm per hour for transmission of rain. These values may need to be modified for other snow climates. Specific correction factors may be needed for specific flux ranges, depending on the instrumentation. With unenclosed lysimeters, an effective contributing area a few times larger than the collector area is sometimes possible. Such occurrences are relatively rare with proper lysimeter design and installation and are usually obvious when they happen. Calibrations for these unnaturally high flows can be done after the fact if necessary, by estimating the areal depth of snowmelt (e.g., U.S. Army Corps of Engineers, 1956) to approximate the contributing area.

The reliability of the measuring system must be carefully considered. Will the tipping bucket mechanism from a precipitation gage hold up when it receives perhaps 1000 times more water over a season than it was designed for? Will the automatic tank drain valve perform flawlessly over an entire season? The measurement system should be able to handle the highest possible flows, including those from an oversized contributing area. A compromise must often be made between resolution and capacity. Buer (Stein Buer, California Dept. of Water Resources, personal communication, 1984) suggested a simple flow splitting device in which low flows are routed through a small pipe to a small tipping bucket and high flows fill the splitter container to where water overflows into a large capacity tipping bucket.

Construction and installation

Collection pans may be made of almost any impermeable material that is resistant to moisture, cold, and pressure. Plastic sheeting is a low cost base material that has been used successfully in several installations of large area collectors. All parts of the installation, both exposed and buried, must be capable of withstanding the maximum expected snow load. The collection pans must be properly bedded so that the drain is at the lowest point and will remain there under a snow load. The drain should be screened to prevent clogging of the plumbing with debris. During the snow-free season, the installation should be inspected and cleaned.

The thermal regime of the site should be considered in the design of the lysimeter. Soil freezing may be a potential source of damage. Freezing of water within the unit may be minimized by initially charging the system with antifreeze, using large diameter pipes, burying the outflow pipes under several centimeters of soil and at an adequate gradient to minimize ponding, and using heat tape--which can be operated intermittently where possible. Electric aquarium heaters have been used in collection tanks (Robert Davis, University of California at Santa Barbara, Dept. of Geography, personal communication, 1983). A collector/snow interface with some artificial roughness elements several centimeters high (rocks, for instance) may permit flow through a basal ice layer, should one form above the interface.

Testing

Before it is actually used, the lysimeter should be thoroughly checked out. In addition to checks for leaks and proper equipment functioning, the system should be calibrated with controlled applications of water to determine the lysimeter base storage, pipe storage, meltwater travel times, instrument response, and undermeasurement of high flows. The calibration procedure should be carefully documented so that it will be understandable months later when data start coming in. Detailed photographic documentation is helpful for troubleshooting and repair when the lysimeter is buried under snow.

SUMMARY

The need for information on snowpack outflow has led to the development of a few dozen snowmelt lysimeters. While specific objectives must determine the final lysimeter design, some generalities may be observed. The ground-based unenclosed lysimeter fits the widest variety of needs. However, this design permits unobstructed lateral flow of meltwater in the overlying snow column. Thus, the flow it samples near the snowpack base may be quite different from the initial flux at the snow surface. Larger lysimeters eliminate more of the inherent flow variability. A rim 10 to 15 cm high around the collector/snow interface is essential to accurate monitoring of flux at the level of the interface. An initial storage of 2 to 3 cm of water above the interface and some additional detention in the plumbing must be satisfied before a zero-tension lysimeter is at equilibrium and will begin to measure outflow. Enclosed lysimeters and tension lysimeters are useful in precise and carefully controlled studies. Careful design, construction, and installation of snowmelt lysimeters will permit the collection of accurate snowpack outflow data for a variety of purposes.

LITERATURE CITED

Anderson, E.A., 1976. A point energy and mass balance model of a snow cover. National Oceanic and Atmospheric Administration Technical Rep. NWS 19, 150 pp.

Beaudry, P. and D.L. Golding, 1983. Snowmelt during rain on snow in British Columbia. Proceedings of the 51st Western Snow Conference. pp. 55-66.

Berg, N.H. and S. Woo, 1983. Snow meltwater chemistry changes. EOS, Transactions, American Geophysical Union, vol. 64, no. 45, pp. 710 (abstract)

Church, J.E., 1948. The evolution of snowmelt by dyes and drip pans. International Association of Hydrologic Sciences General Assembly of Oslo, Tome 2, pp. 115-117.

Colbeck, S.C., 1972. A theory of water percolation in snow. Journal of Glaciology, vol. 11, no. 63, pp. 369-385.

Colbeck, S.C., 1974. The capillary effects on water percolation in homogeneous snow. Journal of Glaciology, vol. 13, pp. 85-97.

Colbeck, S.C., 1978. The physical aspects of water flow through snow. Advances in Hydroscience, vol. 11, pp. 165-206.

Colbeck, S.C., 1981. A simulation of the enrichment of atmospheric pollutants in snow cover runoff, vol. 17, no. 5, pp. 1383-1388.

Colbeck, S.C. and G. Davidson, 1973. Water percolation through homogeneous snow. in The Role of Snow and Ice in Hydrology: Proceedings of the Banff Symposium, September 1972, UNESCO-WMO-IASH, pp. 242-257.

Cooley, K.R. and D.C. Robertson, 1983. Monitoring a rain-on-snow event. Proceedings of the 51st Western Snow Conference, pp. 19-26.

Cox, L.M., 1971. Field performance of the universal surface precipitation gage. Proceedings of the 39th Western Snow Conference, pp. 84-88.

Cox, L.M. and W.R. Hamon, 1968. A universal surface precipitation gage. Proceedings of the 36th Western Snow Conference, pp. 6-8.

Davis, B. and D. Marks, 1980. Undisturbed measurement of the energy and mass balance of a deep alpine snowcover. Proceedings of the 48th Western Snow Conference, pp. 62-67.

Denoth, A., W. Seidenbusch, M. Blumthaler, P. Kirchlechner, W. Ambach, and S.C. Colbeck, 1979. Study of water drainage from columns of snow. CRREL Report 79-1, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 13 pp.

DeWalle, D.R. and J.R. Meiman, 1971. Energy exchange and late season snowmelt in a small opening in a Colorado subalpine forest. Water Resources Research, vol. 7, no. 1, pp. 184-188.

Fohn, P.M.B., 1973. Short-term snowmelt and ablation derived from heat and mass-balance measurements. Journal of Glaciology, vol. 12, no. 65, pp. 275-289.

Gottfried, G.J. and P.F. Ffolliott, 1979. An evaluation of snowmelt lysimeters in an Arizona mixed conifer stand. Hydrology and Water Resources in Arizona and the Southwest, vol. 9, pp. 221-229.

Harr, R.D. and S.N. Berris, 1983. Snow accumulation and subsequent melt in a forested and clearcut plots in western Oregon. Proceedings of the 51st Western Snow Conference, pp. 38-45.

Haupt, H.F., 1969. A simple snowmelt lysimeter. Water Resources Research, vol. 5, no. 3, pp. 714-718.

Helvey, J.D. and W.B. Fowler, 1980. A new method for sampling snow melt and rainfall in forests. Water Resources Bulletin, vol. 16, no. 5, pp. 938-940.

Herrmann, A., 1978. A recording snow lysimeter. Journal of Glaciology, vol. 20, no. 82, pp. 209-213.

Hildebrand, C.E., 1957. Lysimeter studies of snowmelt. Proceedings of the 25th Western Snow Conference, pp. 94-105.

Hughes, T.P. and G. Seligman, 1939. The temperature, melt water movement, and density increase in the neve of an alpine glacier. Monthly Notices of the Royal Astronomical Society, Geophysical Supplement, vol. 4, no. 8, pp. 616-647

Jordan, P., 1983. Meltwater movement in a deep snowpack: 1. Field observations. Water Resources Research, vol. 19, no. 4, pp. 971-978.

Langham, E.J., 1977. Areal and temporal variation of percolation of water through a snowpack. Journal of Glaciology, vol. 19, no. 81, p. 668.

Lemmela, R., 1973. Measurements of evaporation-condensation and melting from a snow cover. in The Role of Snow and Ice in Hydrology: Proceedings of the Banff Symposium, UNESCO-WMO-IAHS, pp. 670-679.

Marsh, P., 1982. Ripening processes and meltwater movement in arctic snowpacks. Ph.D. dissertation, McMaster University, Hamilton, Ontario, Canada, 179 pp.

Megahan, W.F., J.R. Meiman, and B.C. Goodell, 1967. Net, allwave radiation as an index of natural snowmelt and snowmelt accelerated with albedo reducing materials. International Hydrology Symposium, Fort Collins, Colorado, pp. 149-156.

Megahan, W.F., 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research, vol. 19, no. 3, pp. 811-819.

Molnau, M., 1971. Comparison of runoff from a catchment snow pillow and a small forested watershed. Proceedings of the 39th Western Snow Conference, pp. 39-43.

Price, A.G., 1977. Snowmelt runoff processes in a subarctic area. McGill Sub-Arctic Research Paper 29, McGill University, Montreal, Quebec, Canada, 106 pp.

Price, A.G. and L.K. Hendrie, 1983. Water motion in a deciduous forest during snowmelt. Journal of Hydrology, vol. 64, pp. 339-356.

Pysklywec, D.W., K.S. Davar, and D.I. Bray, 1968. Snowmelt at an index plot. Water Resources Research, vol. 4, no. 5, pp. 937-946.

Rockwood, D.M., P.B. Boyer, and C.E. Hildebrand, 1954. Lysimeter studies of snowmelt. International Association for Scientific Hydrology Publication no. 39, pp. 137-165.

Santeford, H.S., G.R. Alger, and J.G. Meier, 1972. Snowmelt energy exchange in the Lake Superior region, Water Resources Research, vol. 8, no. 2, pp. 390-397

Schultz, R.W., 1971. The use of snowmelt lysimeters for estimating the temporal and spatial distribution of snowmelt at Fraser Experimental Forest, Colorado. Ph.D. dissertation, University of Michigan, 116 pp.

Schultz, R.W. 1973. Snowmelt lysimeters perform well in cold temperatures in central Colorado. Research Note RM-247, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, 8 pp.

Sharp, R.P., 1951. Meltwater behavior in firn on upper Seward glacier, St. Elias Mountains, Canada. International Association for Scientific Hydrology Assembly of Brussels, Tome 1, IASH publication #32, pp. 246-253.

Sulahria, M.B., 1972. Prediction of water retentive capacity of high elevation snowpacks on the east side of the Sierra Nevada. Ph.D. dissertation, University of Nevada, Reno, 115 pp.

Thompson, K., J. DeVries, and J. Amorocho, 1975. Snowmelt lysimeter. Proceedings of the 43rd Western Snow Conference, pp. 35-40.

U.S. Army Corps of Engineers, 1956. Snow Hydrology. 456 pp.

Wankiewicz, A., 1976. Water percolation within a deep snowpack--field investigations at a site on Mt. Seymour, British Columbia. Ph.D. thesis, University of British Columbia, 177 pp.

Wankiewicz, A., 1978a. Hydraulic characteristics of snow lysimeters. Proceedings of the Eastern Snow Conference, pp. 105-116.

Wankiewicz, A., 1978b. Water pressure in ripe snowpacks. Water Resources Research, vol. 14, no. 4, pp. 593-599.

Wankiewicz, A., 1979. A review of water movement in snow. in Proceedings Modelling of Snow Cover Runoff, edited by S.C. Colbeck and M. Ray, U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, pp. 222-252.

Waring, E.A. and J.A.A. Jones, 1980. A snowmelt and water equivalent gauge for British conditions. Hydrological Sciences Bulletin, vol. 25, no. 2, pp. 129-134.

Woo, M.K., and H.O. Slaymaker, 1975. Alpine streamflow response to variable snowpack thickness and extent. Geografiska Annaler, vol. 57A, no. 3-4, pp. 201-212.