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Snowmelt Lysimeters for Real-Time Snowmelt Studies in Turkey

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Abstract

Snowmelt lysimeters collect and measure the meltwater that is released from the snowpack. The data recorded from a snowmelt lysimeter are valuable for the formulation of the physical basis of modules of a snowmelt runoff model. There are few snow studies on the eastern region of Turkey in basins that feed the Euphrates and Tigris Rivers. The design and performance evaluation of the first real-time snowmelt lysimeter in this region is presented in this paper. Detailed information about the snowmelt lysimeter designs in the literature is also summarized. The water released from the monitored snowpack is evaluated on hourly and daily bases and compared with rain and snow-water equivalent values. The snowmelt lysimeter performed well, matching streamflow trends in large basins. Data from rain-on-snow, rainfall-only, and snowmelt-only events could be explained by the lysimeter and other data. The lysimeter rainfall catch (about 5% greater than a rain gauge) was similar to rainfall measurements from a soil-block lysimeter in the USA. This paper contributes to the literature by documenting the first near real-time snow lysimeter research in eastern Turkey. The results are useful for improving the design for other areas in this understudied portion of the world, where snowmelt contributes the major portion of runoff.

Key words: Snowmelt lysimeter, Real-time monitoring, Snowmelt modeling, Turkey

Introduction

In most snowmelt-runoff models, testing and calibration are performed for the entire model based on reproducing only an existing stream flow hydrograph at some downstream point. However, the evaluation of model components leads to a stronger physical base for model improvement, evaluation and use. Data on water released from the base of the snowpack are an ideal variable to use for model evaluation because they serve as the output of the snowmelt-model component and the input to the runoff-production routine. Snowmelt lysimeters have been used to provide this physical measurement for testing models of snowpack energy balance and/or meltwater production (Kattelmann, 2000) and to aid in forecasting water supplies.

Snowpack outflow and snowmelt at or near the snowpack surface are 2 processes that are not well understood. Snowmelt lysimeters collect and measure the liquid water outflow originating from the bottom of the snowpack; thus they are excellent tools for quantifying the snowmelt timing and volume requirements of snowmelt studies, such as water-supply forecasting and hydrologic model-improvement studies.

Turkey connects Asia and Europe, has high mountains in the eastern part of the country, and has plentiful snow storage for water-use requirements around its arid region. However, detailed snow studies in this region using lysimeters have not been conducted. The objective of the present paper is to describe the design and installation of the first operational snowmelt lysimeter in this region, and to present an initial performance evaluation of the lysimeter for model studies.

Snowmelt Lysimeter Design Criteria

Designers of new installations should consult the available literature and experienced users of snowmelt lysimeters for critical details, but they should also experiment with fresh approaches (Kattelmann, 2000). Although design considerations are use- and site- dependent, important criteria are found in the literature, and there are advantages and disadvantages of various lysimeter configurations.

The main components of a snowmelt lysimeter are a collector of meltwater, a flow-measuring device, and a pipe linking them. The collector can be surrounded by either a short raised rim (unenclosed lysimeter) or by a barrier that completely isolates a column of snow (enclosed lysimeter).

Most snow lysimeters are the "unenclosed" kind (Figure 1a). Water within the area of the lysimeter percolating below the top of the rim is captured and measured. Above the top of the rim, water is free to flow laterally into or out of the column of snow directly above the lysimeter.

The "enclosed" ground-based snowmelt lysimeters are used where snowpack outflow volume is the principle quantity of interest (Kattelmann, 1984). Enclosed lysimeters (Figure 1b) trap all of the water percolating through the snow directly above the collection container. Enclosed lysimeters may have an adjustable barrier height to accommodate natural changes in the depth of the snowpack, or they may be of fixed height and artificially filled with snow (Kattelmann, 1984). The variable height barrier eliminates lateral inflow and outflow and enables accurate volume determination for mass-balance studies. However, there is the possibility that the barrier can accelerate the snowmelt by absorption of solar radiation by the walls by conducting heat energy into the snowpack. This is because the natural accumulation of snow is artificially disturbed. Although an enclosed lysimeter is a good configuration for mass-balance studies, the difficulty related to its maintenance makes it difficult for use operationally.

Collector Design

A snowmelt collector, either enclosed or unenclosed, is placed on the ground surface before the formation of the snowpack. Impermeable collectors varying from 1 to 100 m^2 in area are the most common. The water amount received by the measuring device may not be the same as water input at the snow surface. This is due to lateral inflow and/or outflow that may occur within the snowpack that bypasses the collector within the snowpack. The volume of lateral flow is variable within and between the seasons and is unknown. As the area of the collector is increased, the probability of incorporating the lateral inflow and outflow into lysimeter outflow measurements is increased.

The area of the lysimeter collector must be adequate to obtain a representative sample of meltwater flux (Kattelmann, 1984). Larger lysimeters provide a better areal average of the volume and timing of snowpack outflow than smaller lysimeters. Male and Gray (1981) proposed for the dimensions of the snowmelt lysimeters that the area of the lysimeter should be greater than the square of the snowpack depth. Kattelmann (2000) has documented that this criterion was adequate in a number of studies. A minimum rim height varying from 10 to 15 cm around the periphery of the collector for unenclosed lysimeters is essential for accurate monitoring of the flux at the interface between the snowpack and the collector (Kattelmann, 1984). Replicated lysimeters

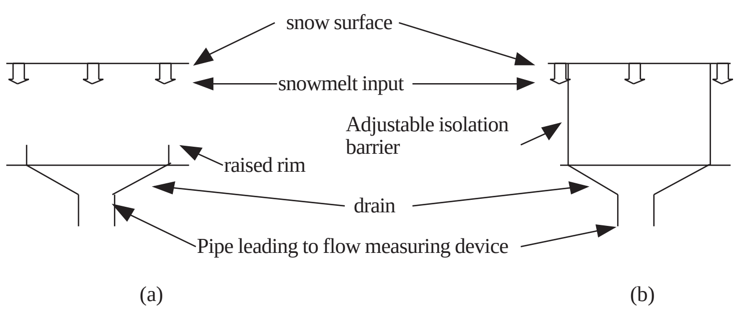

Figure 1. Snowmelt lysimeter configurations a) unenclosed b) enclosed.

at a given site enable the assessment of spatial variability and the repeatability of snowmelt measurements, and the quality and representativeness of the data.

The collector material must be impermeable so that it can withstand moisture, low temperatures, and pressure due to snow loads. The drain of the collector should be at the lowest elevation when loaded with snow. The drain should be screened so that the flow is free of debris that may clog the system. Large diameter pipes and adequate slopes can help avoid the possibility of freezing of the drainage water and the loss of important data.

Based on these recommendations, an unenclosed snowmelt lysimeter was constructed for the snowfall/snowmelt season beginning in October 2002 from a 120 cm x 200 cm galvanized steel sheet of metal 2 mm thick (Figures 2 and 3). The rim along the periphery of the lysimeter is 15 cm high. The resulting lysimeter dimensions are reduced to 90 x 170 cm (area of 1.53 m^2) after accounting for the rims and welding. The square root of the resulting area is 124 cm, which is larger than the maximum snow depth observed at the site (62 cm for the 2002-2003 winter). Although the prototype was designed as an unenclosed lysimeter, it was placed so that the lateral flows intruding into the lysimeter would be minimized. As can be seen from Figure 3, 3 sides of the lysimeter are open, and only the fence exists along the long side of the lysimeter. The lysimeter prototype is placed on smooth, nearly level terrain about 50 cm above the ground surface, in an attempt to minimize lateral in- and outflows (Tekeli, 2002).

Outflow Measurements

Common methods of measuring melt rate and volumes include combinations of collection tanks, water-level recorders, automatic drains and/or siphons. Tipping-bucket recorders, either from precipitation gauges or custom built, have been used successfully with many lysimeters (Kattelmann, 1984). Taking manual measurements, although the simplest way, is not a solution for an operational, unattended snowmelt modeling system. Because there is a wide range of melt flow rates possible, calibration of the measuring equipment is required. Reliability of the measuring system is also an important design factor, because the lysimeter must operate unattended for the entire winter, and may be inaccessible for servicing during this time.

The outflow from the snowmelt lysimeter constructed in the present study is measured with a tipping bucket rain gauge collector placed at the bottom of the lysimeter outlet opening (Figure 4) and screened at mid level of the funnel to minimize debris entering the tipping bucket device. After the meltwater is measured, it flows away from the tipping bucket, preventing the possibility of freezing of the tipping bucket and the measuring system as a whole. The output from the tipping bucket meltwater is measured with a data logger and transmitted via satellite to the main office in Ankara.

Figure 2. View of the Güzelyayla automatic snow pillow and automatic weather station. (Circle indicates the location of the snowmelt lysimeter).

Figure 3. Snowmelt lysimeter and tipping bucket rain gauge at Güzelyayla Station. (Lysimeter 50 cm above the ground surface).

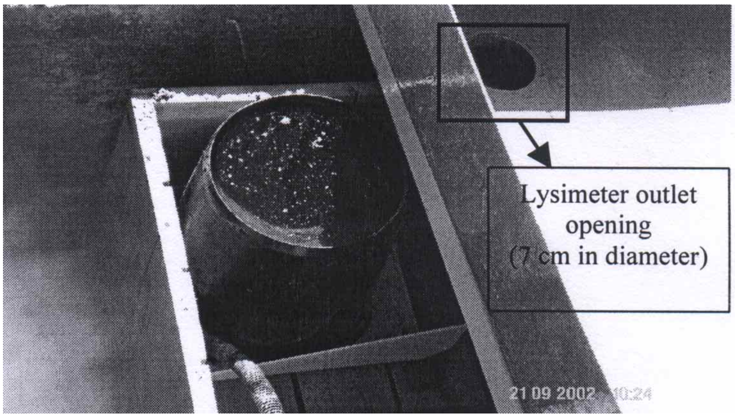

Figure 4. Screened tipping bucket type rain gauge collector to measure snowmelt rate from the prototype snowmelt lysimeter.

The lysimeter was checked for leakage and proper functioning after installation. Photographs were taken during the construction that would be helpful for new lysimeter installations, and for troubleshooting and repairing the equipment when the lysimeter is under snow.

Study Areas

A prototype of the snow lysimeter was installed at the Güzelyayla Automatic Snow Pillow and Weather Station in September 2002 (Figure 2). This station is a part of an ongoing project related to snowmelt in the watershed in which it is located (Şorman *et al.*, 2002). The Güzelyayla station (latitude: 40° 12′ N, longitude: 41° 27′ E, elevation: 2065 m) is located within the Karasu basin, in the eastern part of Turkey (Figure 5). The basin has a drainage area of 10,216 km^2. The study area is rugged and mountainous and elevations range from 1125 to 3478 m within the basin. The land cover of the basin is shrub, grass, pasture and bare land. The Karasu River drains the basin and is a major contributor to the Keban Dam Reservoir on the Euphrates River. The drainage area of the Keban Dam Reservoir is 67,500 km^2. Sixty to seventy percent of the total annual volume of the Karasu River comes during the snowmelt period from the end of March through July (Tekeli, 2000). The Güzelyayla station is also in the 243 km^2 Kırkgöze subbasin of the Karasu Basin, where there is also a streamflow gauging station (Figure 5). The performance of the snow lysimeter (Figures 2 and 3) is compared with streamflow measurements at the Kırkgöze gauging station and inflow into Keban Dam Reservoir.

Procedure for Analysis

The results are discussed under 3 different natural weather conditions during the snow season of 2002-2003.

1) Rainy periods when there is no snow
2) Rainy and non-rainy snowmelt periods
3) Melt rate comparisons between event types

Rainy periods when there is no snow (September and November 2002)

Precipitation is recorded by a tipping bucket rain gauge at the Güzelyayla station (Figure 3), which is also connected to the data logger, logging precipitation depth and intensity. In the absence of snow, the snowmelt lysimeter also acts as a classical tipping bucket rain gauge. During the period from September to November 2002, there is good agreement in the amount and timing of rainfall data measured from both the lysimeter and the rain gauge sensors (Figure 6). The monthly differences between both sensors (Table 1) are negligible, with lysimeter totals +3.6 mm and +2.2 mm greater than corresponding rain gauge totals (deviations of +6% and +5%). This shows that both sensors were working well before the 2003 snowfall period. The slight overbias is attributed to the lower elevation of the lysimeter rim compared with the rain gauge orifice. The lysimeter measurement represents ground-level precipitation better as documented by McGuiness (1966) using Coshocton, OH soil-monolith lysimeters in the USA. He found that average summer precipitation (no snow) was about 5% greater for the lysimeter than for the adjacent rain gauge. The difference was attributed to the disturbance of the wind flow field at the orifice of the rain gauge causing undercatch of rainfall. His results agree closely with the results of this study (Table 1) and show that the snow lysimeter functions well for rainfall, and gives representative ground-level rainfall measurements.

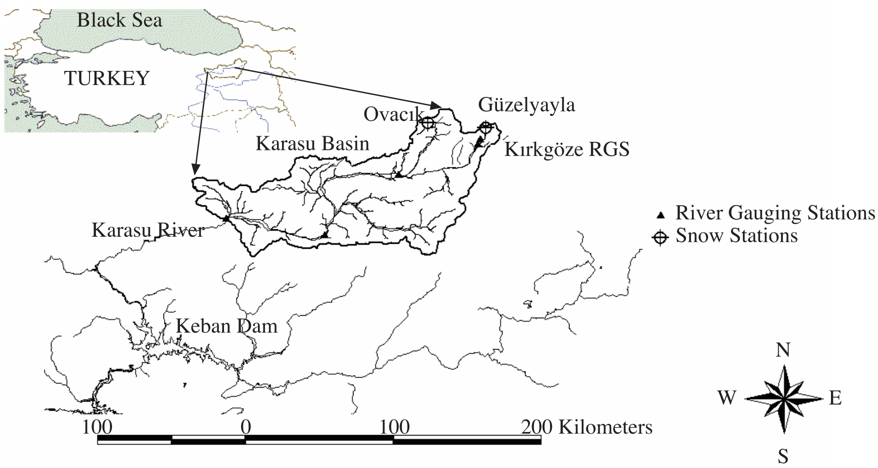

Figure 5. Keban Dam site, river gauging stations and automated snow stations in Upper Euphrates River Basin.

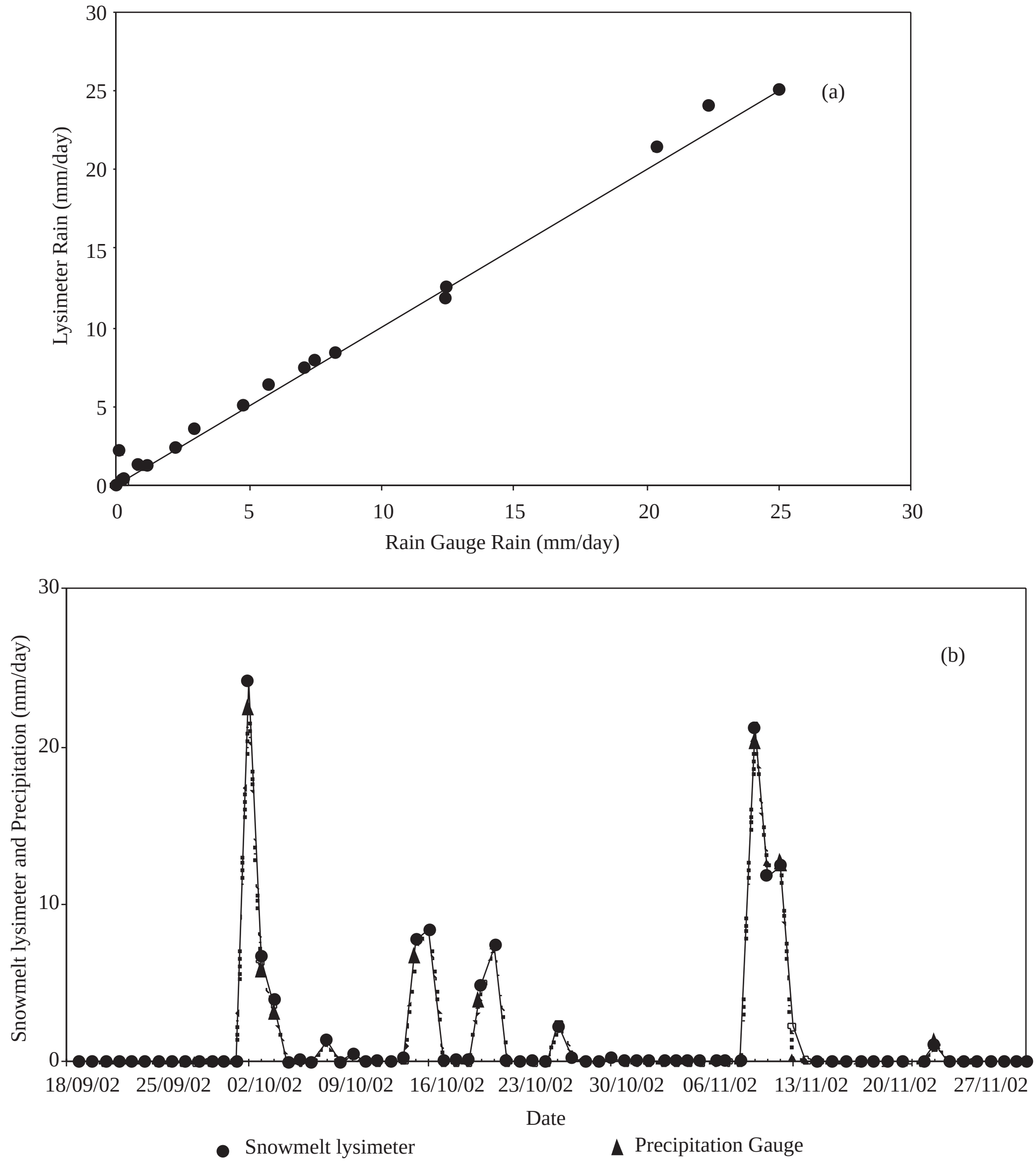

Figure 6. Comparison between daily rainfall data recorded by tipping bucket mechanisms for the snowmelt lysimeter and standard raingauge at Güzelyayla station a) comparison between corresponding daily values b) comparison of timing between rain measuring devices.

Table 1. The monthly total cumulative rain depth by lysimeter and rain gauge.

Beginning Month	Lysimeter (mm)	Rain Gauge (mm)	Difference (mm)	Percent Deviation
Oct-02	66.9	63.3	3.6	+6%
Nov-02	49.0	46.8	2.2	+5%

Rainy and non-rainy snowmelt period (April 2003)

The visual trends of large-area stream discharge at the Kırkgöze gauging station (243 km^2 area) and Keban Dam inflow (67,500 km^2) are remarkably similar to the trend in small-area lysimeter prototype outflows (Figure 7), all starting to increase at nearly the same date. Inflow to Keban Dam and flow at Kırkgöze, which are downstream with respect to the lysimeter at Güzelyayla, starts to increase some time before lysimeter values. In addition, the peak discharges, indicated by Q_{peak} in Figure 7, are in agreement with the lysimeter outflow data. Moreover, as the lysimeter outflow rate decreases, the stream discharges begin to decrease. Snow water equivalent is measured by the snow pillow and an ultrasonic depth sensor at Güzelyayla station measures the snow depth. Both of the values are measured every 30 s and these are averaged and recorded in the data logger every 2 h. Changes in snow water equivalent, snow depth, and cumulative snowmelt lysimeter outflow are given in Figure 8.

In the snowmelt period during April 2003, the volume of snowmelt runoff computed at Kırkgöze runoff gauging station and inflow to Keban Dam Reservoir is 2.17 $\times$ 10^7 m^3 and 7.422 x 10^9 m^3, respectively. During the same period the 177 mm maximum snow-water equivalent (SWE)

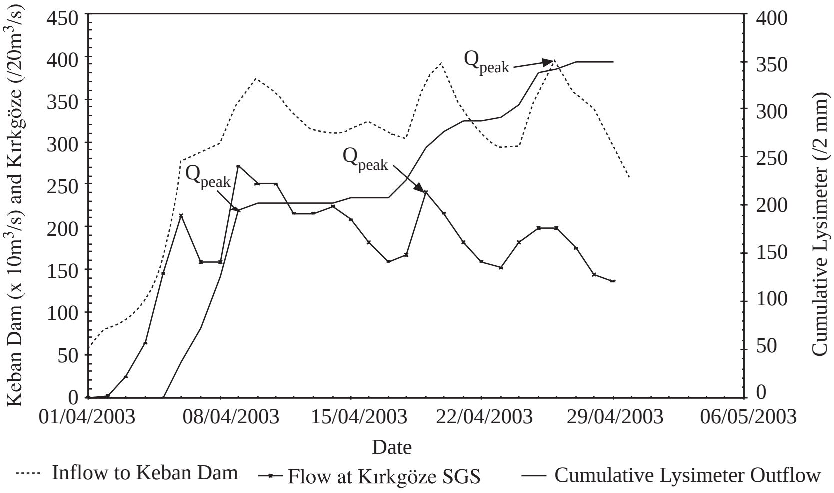

Figure 7. Relationship between discharge measurements, peak values and the lysimeter outflow data.

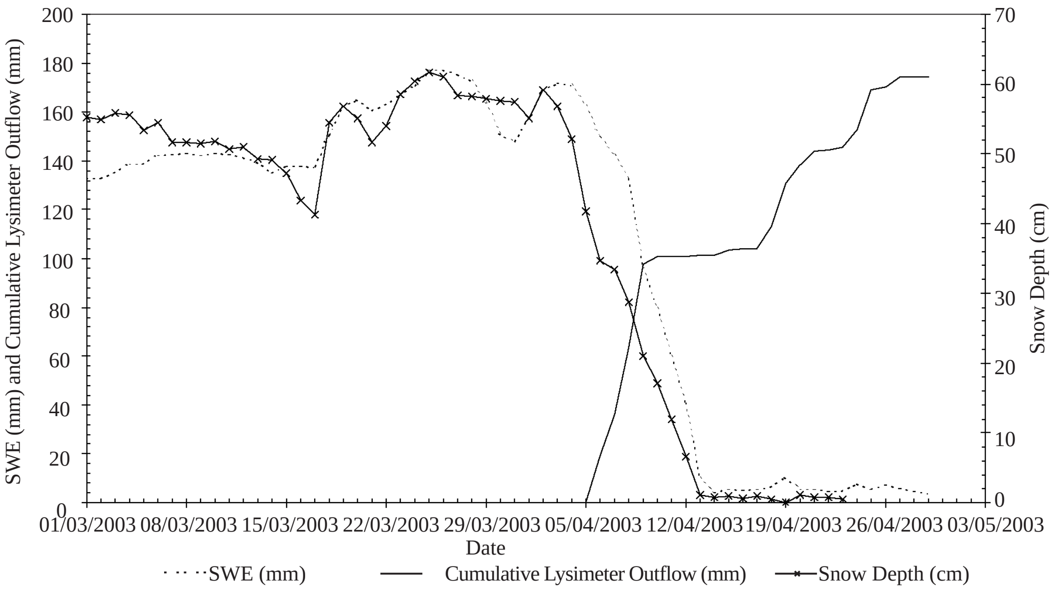

Figure 8. Change of snow water equivalent (SWE), snow depth, and cumulative snowmelt lysimeter outflow data at the Güzelyayla Station.

completely melted at the Güzelyayla automatic weather and snow pillow station where the lysimeter is located (Figure 8).

Based on meteorological observations, April 2003 can be divided into 6 events of 3 major types: rain on snow (ROS), pure snowmelt (SM), and rain (R) (Figure 9). It is easy to see that the last 2 events (14-22 April 2003 and 23-30 April 2003) are purely rain because the change in the lysimeter outflow depth is equal to the rainfall depth, the snow depth is zero, and SWE is nearly zero (Table 2 and Figure 9).

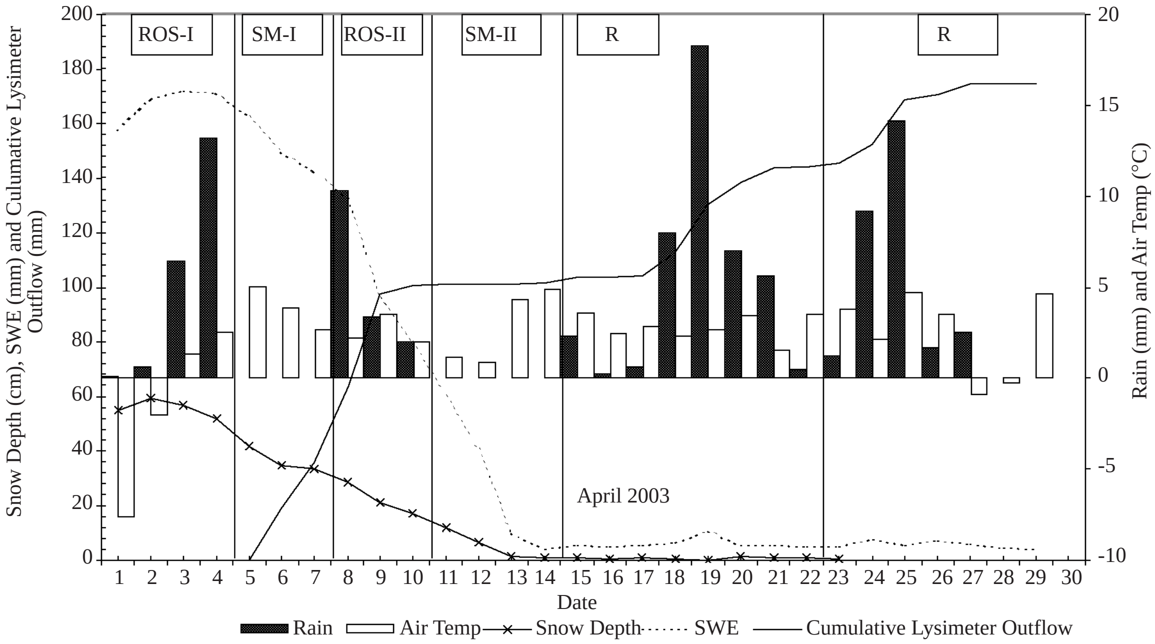

Figure 9. Changes in snow water equivalent (SWE), snow depth, cumulative snowmelt lysimeter outflow, air temperature and rainfall at the Güzelyayla Station for April 2003.
(ROS: Rain on Snow, SM: Snowmelt only, R: Rain only).

Table 2. Comparison of rain-only events measured with a rain gauge and prototype lysimeter.

	Cumulative Lysimeter (mm)	Daily Lysimeter (mm)	Rain (mm)		Change in Lysim (mm)	Total Rain (mm)	Difference (mm)
14/04/03	101.4		0				
15/04/03	103.7	2.3	2.3				
16/04/03	103.8	0.2	0.2				
17/04/03	104.2	0.4	0.6				
18/04/03	112.8	8.6	8.0				
19/04/03	130.4	17.6	18.3	Rain Period 1	**43.0**	**42.5**	**0.5**
20/04/03	138.4	8.0	7.0				
21/04/03	143.8	5.4	5.6				
22/04/03	144.3	0.5	0.5				
23/04/03	145.6	1.3	1.2				
24/04/03	152.5	6.9	9.2				
25/04/03	168.9	16.4	14.1	Rain Period 2	**30.2**	**28.7**	**1.5**
26/04/03	170.6	1.7	1.7				
27/04/03	174.5	3.9	2.5				

Snowmelt (SM) without rain can be seen for the time period in Figure 9 during the time intervals of 5-7 April and 11-14 April, which can be named respectively SM-I and SM-II. During the first period, SM-I, a significant reduction in the snow water equivalent is observed with an increase in lysimeter discharge. However, in the second period, SM-II, the lysimeter does not indicate any corresponding significant yield increase. A number of reasons can be stated for the conflicting case between SM-I and SM-II. The first may be the non-uniformity of the snow depth distribution within the snow station. Thus, the lysimeter might have a snow depth that is less than the depth of snow on the snow pillow. The placement of the lysimeter above the ground might have resulted in an increased wind drift, causing the snow on the lysimeter blown away, leaving a reduced snow depth on the lysimeter. Furthermore, the difference between the areas of the lysimeter (1.53 m^2) and the snow pillow (6.50 m^2) may be another reason for the lysimeter responses between SM-I and SM-II. The material difference between the lysimeter (galvanized steel) and the snow pillow (hypalon) may also cause some problems. The galvanized steel of the lysimeter might have resulted in an increased evaporation rate.

The reason for the lysimeter not giving any yield during 11-14 April 2003 may be the change in temperature values. Figure 10 shows the daily maximum, minimum and average temperatures. The snowpack that melts in the warmer hours of the day causes a reduction in the SWE, while at other times the meltwater is trapped in ice layers within the snowpack and it refreezes in the colder hours. The negative temperatures in Figure 10 (dashed lines with stars) cause stratified ice layers within the snowpack and refreezing of the meltwater. Although this case should have been confirmed by a field study and observations at the site, this could not be accomplished for various reasons (i.e. poor weather, difficult access to the site and the site's great distance from Ankara).

The ROS event is the most complex type of melting in snow-modeling studies. This type of event can best be seen in Figure 9, during April 1-4 and April 8-10 (denoted as ROS-I and ROS-II, respectively). The ROS-I part could not be studied since the lysimeter did not give any response during that time interval. The lack of data might be due to the freezing of the tipping bucket and may indicate a limitation of the system. Figure 8 shows that SWE and depth decreased as melt increased. When 2-hourly

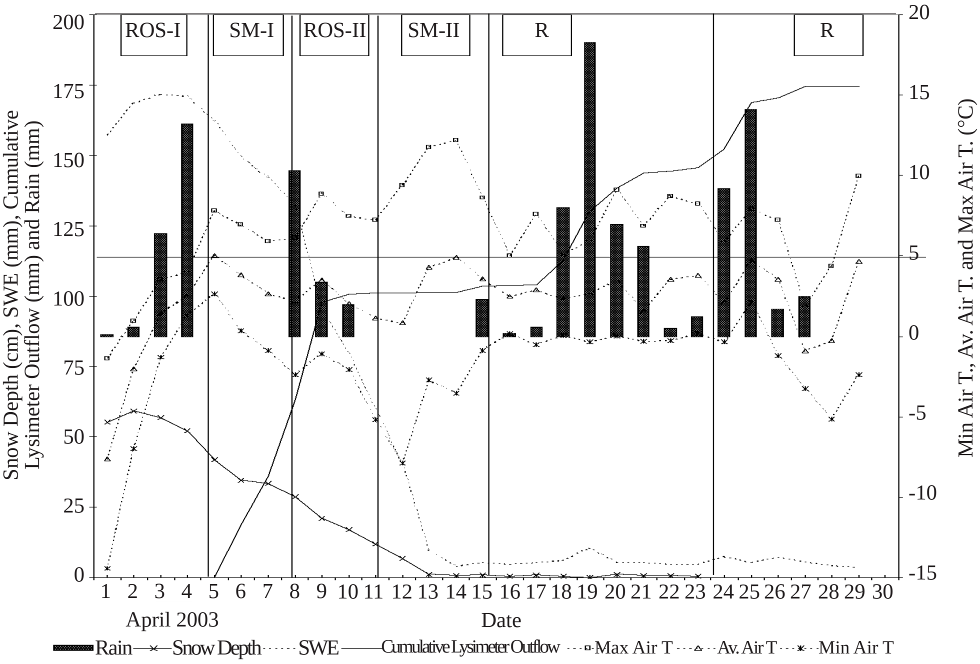

Figure 10. Variations in minimum, average and maximum air temperatures compared with cumulative lysimter outflow, snow-water equivalent (SWE), and snow depth at the Güzelyayla Station.
(ROS: Rain on Snow, SM: Snowmelt only, R: Rain only).

data are examined for ROS-II, the combined rain and snow-melting event is seen (Table 3). Table 3 (top) shows a 24-h period on 8 April 2003 when snow melted during the day, mostly between 1000 and 1600. As precipitation is also occurring, the water outflow recorded by the lysimeter is larger than the amount of incoming water measured by the rain gauge. This excess measured by the lysimeter is due to melting snow. This is a typical ROS process. Similar cases can also be seen for April 9 (0200 – 0600; Table 3 middle) and April 10 (1000-1200; Table 3 bottom). In all 3 cases, SWE and depth of snow either remain the same or decrease.

Melt Rate Comparisons between Event Types

The data of the present study can be compared with those of other studies that quantify the mechanisms of snow water movement with in a snowpack. Comparisons of average daily air temperature, rain and snowmelt lysimeter outflow for April 2003 are illustrated in Figures 11 and 12. A typical event of snowmelt without rain is on 6 April 2003. The lysimeter outflow rate is seen to vary from 0.0 to 3.9 mm/h. The maximum lysimeter outflow rate is recorded as 4.8 mm/h for the ROS event in 9 April 2003 at 1200.

Table 3. Rain on snow event on 8 April 2003.

Day	Time	Lysimeter (mm)	Rain (mm)	Difference Lys-Rain (mm)	Snow Depth (mm)	SWE) (mm)
8/4/03	0200	0.0	0.0	0.0	333	142.5
8/4/03	0400	0.0	0.0	0.0	334	141.8
8/4/03	0600	0.0	0.0	0.0	331	138.6
8/4/03	0800	0.4	0.0	0.4	321	136.2
8/4/03	**1000**	**5.0**	**0.0**	**5.0**	**309**	**139.1**
8/4/03	**1200**	**5.4**	**1.0**	**4.4**	**304**	**137.9**
8/4/03	**1400**	**3.6**	**0.5**	**3.1**	**293**	**135**
8/4/03	**1600**	**1.6**	**0.1**	**1.5**	**299**	**132.4**
8/4/03	1800	1.2	0.1	1.1	299	131
8/4/03	2000	1.5	1.0	0.5	302	130.3
8/4/03	2200	2.9	2.9	0.0	291	130.3
8/4/03	2400	5.8	4.7	1.1	285	132.1

Rain on Snow event on 9 April 2003.

Day	Time	Lysimeter (mm)	Rain (mm)	Difference Lys-Rain (mm)	Snow Depth (mm)	SWE) (mm)
9/4/03	0200	3.3	2.3	1.0	284	131
9/4/03	0400	1.6	1.0	0.6	284	129
9/4/03	0600	0.4	0.1	0.3	284	127.1

Rain on Snow event on 10 April 2003.

Day	Time	Lysimeter (mm)	Rain (mm)	Difference Lys-Rain (mm)	Snow Depth (mm)	SWE) (mm)
10/4/03	1000	2.9	0.5	2.4	180	97.2
10/4/03	1200	0.1	0.0	0.1	169	95.2

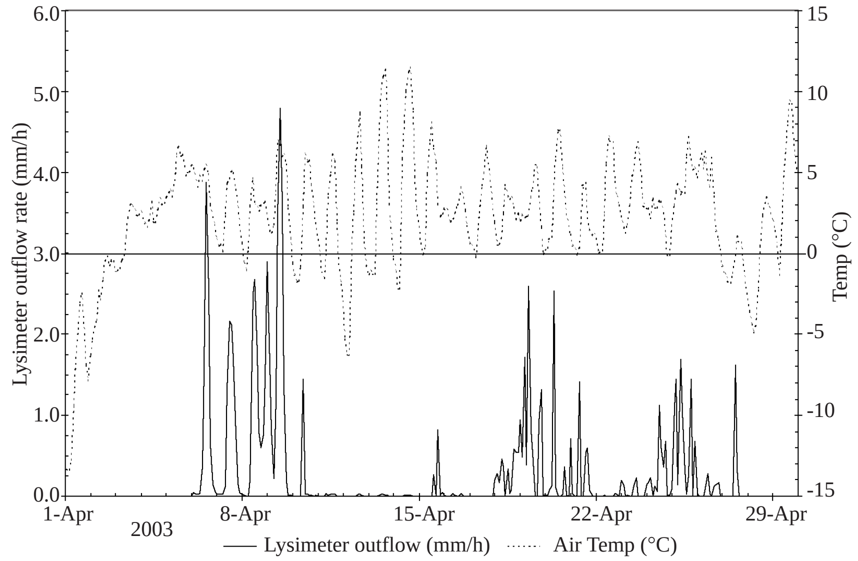

Figure 11. Daily average air temperature and snowmelt lysimeter outflow rate in April 2003 at the Güzelyayla Station.

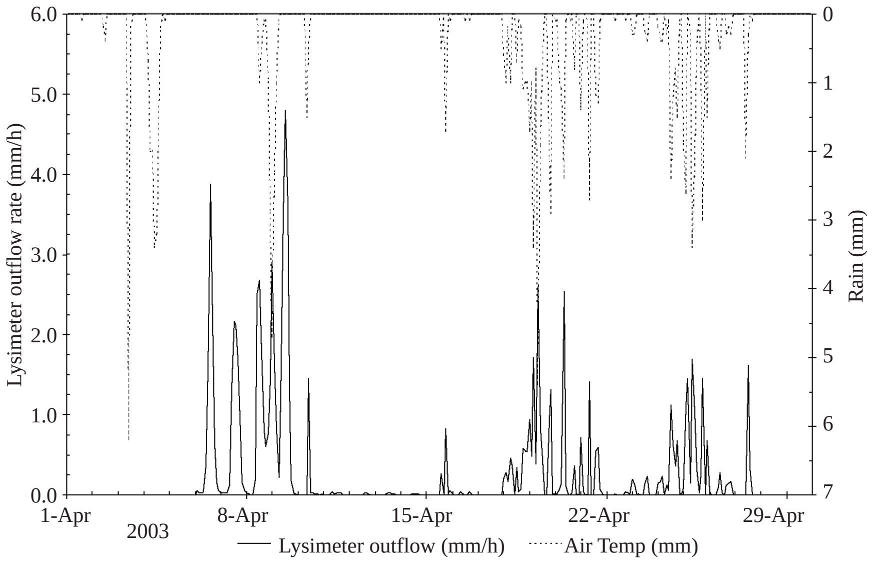

Figure 12. Daily rainfall and snowmelt lysimeter outflow rate in April 2003 at the Güzelyayla Station.

The computed flow rates are in good agreement with the findings of frequency-modulated continuous wave radar given by Albert *et al.* (1999). Their research found that the average number of flow channels within a snowpack varied from 3 to 5 /m^2 of lysimeter area, and the average flow through each flow finger was found to vary from 0.3 to 0.5 mm/channel per hour. Their findings led to the range of reported lysimeter outflow rates from a minimum of 0.9 (mm/h)/m^2 to a maximum of 2.5 (mm/h)/m^2. Because the prototype lysimeter in this study has an area of 1.53 m^2, the expected minimum and maximum outflow rates can be computed as 1.38 mm/h and 3.83 mm/h, respectively. The onsite observed values varied from 0.0 to 4.8 mm/h. The maximum melt rate, 4.8 mm/h, observed on 9 April 2003 is 25% larger than the lysimeter outflow of 3.83 mm/h observed by Albert *et al.* (1999). Albert *et al.* (1999) state, "Clearly, the amount of water that each finger transports is governed both by micro-structure dynamics and by the amount of melt water available for transport, so this value may change in time, and more can be learned from more intensive testing". The high values are less than the range indicated by lysimeter studies performed in Central Sierra Snow Laboratory, where the maximum melt rates of 15 mm/h for clear weather melt and 50 mm/h for ROS conditions were found (Kattelmann, 1984). The higher values reported may be due to the thicker snowpack in the Sierra Mountains.

Conclusions

Snowmelt runoff models are evaluated based on the reproducing capability of an observed hydrograph. The improvements in the snowmelt runoff model's components would lead to a stronger physical base. For this, the water released from the base of the snowpack is an important variable. Snowmelt lysimeters collect and measure the liquid water originating from the bottom of the snowpack.

A prototype snowmelt lysimeter (1.53 m^2 area) was constructed and installed in the field and outflow snowmelt water data were compared with large basin flow rates over the 2002-2003 snow season. The trends in lysimeter snowmelt data were remarkably similar to streamflow rates at large drainage areas of 243 km^2 and 67,500 km^2. The melting trend comparison will be performed in the future when further data are avaliable. The lysimeter performed well as a rain gauge also, and agreed with ground-level rainfall catch experiments with soil-block lysimeters at Coshocton, OH, in the USA. Soil block and snowmelt lysimeters both caught an average of five 5% more rainfall than an adjacent rain gauge due to wind errors at the gauge orifice. ROS, R, and SM events were also gauged well with the prototype and could be explained in terms of snowmelt processes.

With all the above-discussed issues, ROS and pure melting processes can be studied further using the energy mass balance approach and temperature-index methods. The advective heat flux due to rain in addition to net radiation flux (due to temperature and solar radiation) during melting can be solved to determine the positive internal energy within the snowpack that results in snow melting. The outputs of both modeling approaches (temperature-index and energy-mass balance) will give values of runoff yield. Model calibration and its verification can be accomplished using the observed lysimeter records such as the prototype in the present paper. The results of this study provide valuable information regarding the actual rate of melt, its timing and volume. Experience with the prototype discussed in the present paper will lead to future improved lysimeters being installed in Turkey and elsewhere in mountainous regions. The lysimeter design has the potential to be used in a network of such devices as a representative real-time monitoring device for measuring the spatial distribution of snowmelt for flood flows and water-supply forecasting to meet the demands of domestic, industrial and agricultural use.

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