Applied Water Science (2024) 14:248
https://doi.org/10.1007/s13201-024-02314-z

ORIGINAL ARTICLE

Separations of meltwater discharge in a snowpack by artificial rain-on-snow experiments

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Received: 5 June 2023 / Accepted: 16 October 2024 / Published online: 7 November 2024
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Abstract

In temperate regions, snow and its meltwater constitute primary freshwater resources and snowmelt isotopes offer valuable insights into understanding the snowmelt processes including the timing and contribution of snowmelt to the soil and watershed in spring. Assessing the storage and movement of liquid water within natural snowpacks, a previously unquantified aspect, holds significance for predicting natural hazards and managing water resources for agricultural purposes and ecosystem health. The escalating occurrence of rain-on-snow (ROS) events, attributed to winter warming, has the potential to trigger natural hazards and surface runoff into major river systems in temperate climate regions. End member mixing calculations (EMMC) based on isotopic and chemical tracers were employed to quantify the proportions of rainwater, meltwater, and pore water within the snowpack discharge. In this study, artificial rain-on-snow experiments involving conservative anions and stable water isotopes were conducted at the surface of snowpack to differentiate each component (rainwater, pore water, and snowmelt) within the discharge collected at the bottom of the snowpack. Pore water content exhibited a shift from $1.1 \pm 1.1\%$ ($\pm 1\sigma$, $N = 23$) after the initial artificial ROS event to $2.8 \pm 1.2\%$ ($\pm 1\sigma$, $N = 19$) following the spray in our experiment. Based on the EMMC, the contributions of rainfall, pore water, and snowmelt to the meltwater discharge were 2,620.2 L (63.3%), 829.0 L (20.0%), and 687.4 L (16.6%), respectively. Notably, contrary to prior studies, our experimental results suggest that rainwater reached the bottom through multiple rapid flow channels before matrix flow occurred. This experimental approach provides additional insights into the dynamics of water percolation in snowpacks during rain-on-snow events.

Keywords Snowmelt · Artificial rain-on-snow · Pore water · Stable water isotopes · End member mixing calculation

Introduction

Approximately a quarter of the global land surface is covered by mountains, serving as natural reservoirs of freshwater in the forms of snow, ice, and glaciers. These mountainous regions play a crucial role as the primary water supply source for many temperate areas (Lee et al. 2008a; Iwata et al. 2012; Cooper et al. 2020; Lone et al. 2021; Jung et al. 2022). The water derived from the melting of snowpacks, ice, and glaciers constitutes a significant portion of the annual river flow, surpassing even the direct runoff from rainfall (Pu et al. 2020; Nyamgerel et al. 2022). Consequently, snowmelt has a profound impact on regional water cycles, significantly influencing downstream watersheds and ecosystems (Brin et al. 2018). Changes in the pattern, timing of melting, or the amount of upstream precipitation can alter the spatial and temporal dynamics of runoff within the watershed. These changes may also modify the relative contributions of snowmelt and groundwater to direct runoff (Wirmvem et al., 2017; Hoeg et al. 2000). Therefore, effectively adapting water resources to the environment, watershed, or ecosystem necessitates a comprehensive understanding of the hydrological function of snow-dominated watersheds. This involves distinguishing the sources of water, elucidating runoff generation processes, and quantifying the proportion of snowmelt in the total stream water flow (Juras et al. 2016, 2017; Kim et al. 2017).

Rain-on-snow (ROS) events, accompanied by snowmelt and snowpack metamorphism, are significant natural processes in temperate climate regions, posing a heightened risk of natural hazards and surface runoff into major river systems (López-Moreno et al. 2021; Singh et al. 1997). The water from ROS events that infiltrates through a snowpack

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can either be stored within the snowpack or move to the soil surface (Rai et al. 2019; Pu et al. 2020). Consequently, the water released from the snowpack eventually makes its way to the stream system through lateral flow within the snowpack or via the soil environment, involving surface runoff or groundwater (Ade et al. 2018). Snowmelt from ROS events has the potential to significantly increase the risk of floods during melting periods (Okamoto et al. 2018). The retention storage capacity of the snowpack can, at least initially, impede the onset of runoff, particularly when the initial snowpack is dry and possesses a high cold content (Garvelmann et al. 2015; Würzer et al., 2016). Moreover, owing to its distinctive chemical composition compared to stream water, rainwater can influence the transport of ions and solutes through the snow, thereby impacting the pH and chemical compositions of nearby streams (Lee and Jung 2022). Indeed, significant fluctuations in solute concentrations and/or pH values have been observed in stream water during ROS events (Bales et al. 1989).

The presence of liquid water in the snowpack introduces additional volume and energy, bringing about changes in the processes of snowpack warming, melting, and metamorphism, as well as affecting structural aspects like snow settling, grain coarsening, and further densification (Kinar and Pomeroy 2015). These alterations in the snowpack lead to increased hydraulic conductivity and snow permeability, resulting in accelerated water flow (Davis et al. 1985). Various factors, including snow temperature, snow stratigraphy, grain size, and snow ripeness, govern the flow and storage of water within the snowpack (Juras et al. 2016). In conjunction with snowmelt, the introduction of rainwater to the snowpack during a rain-on-snow (ROS) event represents a significant additional source of liquid water, contributing to the generation of snowpack runoff (Juras et al. 2017). Previous studies have indicated that fresh snow has the capacity to hold much more water than ripened snow (Lee et al. 2008a). Despite this, there have been relatively few studies specifically addressing the presence of liquid water in the snowpack generated by a particular event.

Understanding the variability in stream flow is a crucial step in assessing, planning, and managing downstream water resources for agricultural activities, ecosystems, and flood control (Goebel et al. 2015; Li et al. 2020; Khmila et al. 2021; Zhu et al. 2021). Water resources derived from snow and/or ice play essential roles in biodiversity, rain-fed and inundated agriculture, and hydropower (Rai et al. 2019). Over the past 40 years, hydrograph separation using isotopic and chemical compositions of stream water, groundwater, precipitation, soil water, etc., has been widely employed to estimate the contributions of various water sources to stream flow (Klaus and McDonnell 2013; Wu et al. 2016). An understanding of water flow processes in the snowpack during a rain-on-snow (ROS) event is crucial for hydrological modeling, forecasting natural hazards, and predicting water quality and chemical compositions of stream water and associated ecosystems (Jeelani et al. 2016). However, there have been limited studies using chemical and isotopic compositions (δD and $\delta^{18}O$) of meltwater to elucidate the hydrological processes in the snowpack. Therefore, the objectives of this study are: (1) to identify the contributions of pore water, snowmelt, and rainwater to the total flow at the bottom of the snowpack by investigating rainwater interaction with the snowpack and the dynamics of rainwater in the outflow, and (2) to discuss the differences between two- and three-component separations by selecting the chemical and isotopic compositions of the end members.

Study site and methods

Field site, artificial rain-on-experiments and analytical method

The study site location and experimental conditions are summarized in Table 1. The experiments and observations were conducted at the Central Sierra Snow Laboratory, situated at 39.32547 N, 122.36737 W, and an altitude of 2100 m. The laboratory is located just west of the crest of the Sierra Nevada near Soda Springs, California, US. Detailed information about the site has been provided in previous works (Feng et al. 2001; Taylor et al. 2001; Unnikrishna et al. 2002; Lee et al. 2008a, 2008b, 2010a, 2010b). The snow laboratory is equipped with two 6 × 3 m2 melt pans, sloping gently to corner drains, and is instrumented to collect meteorological data. For this study, the meltwater discharge from the surface melt pan was measured using a 4-L data logging tipping bucket. During the winter period from November 1, 2002, to June 3, 2003, the total precipitation recorded was 1,450 mm, with 74% of it falling as snow. The maximum snow depth reached 232 cm, representing 92 cm of snow water equivalent (SWE). The initial depth of the snowpack before the experiment was 210 cm, with 92 cm of SWE.

Two artificial rain-on-snow (ROS) events were simulated on April 5 and 8, 2003 (Fig. 1). These artificial rainstorms were generated using two lawn sprinklers positioned 6 m apart and opposite to each other along a line, dividing the length of the snow pan. The irrigated zone was twice the width of the pan to minimize lateral flow effects within the snowpack. Tap water was pumped to the sprinklers from two water supply tanks embedded in the snow and enclosed with plastic sheets. For the first storm, the conservative tracer F^- (as KF) was added to both tanks, while the conservative tracer Br^- (as LiBr) was added for the second storm. In each case, a sample of the tank water was collected to measure the tracer concentrations and isotopic compositions in the artificial rainfall. To quantify the amount of artificial rainfall,

Table 1 The experimental conditions for the artificial rain-on-snow (ROS) events

	Lee et al. (2008a) and (2010b)
Locality	Sierra Nevada near Soda Springs, US (2100 m a.s.l.)
No. of events	2
Input (irrigated water and new snow, mm)	460 (total)
Duration (min)	306–330
Tracer	F^-, Br^-, δD, and $\delta^{18}O$
Flooded area (m^2)	6 × 3
Snowpack depth prior to experiment (cm)	210
Time lag (min) after storm	110–130
Total discharge (mm)	336 (during the experiments)
Infiltration front speed (cm/min)	1.6–1.9
Bulk density (g/cm^3)	0.35 ± 0.14 (before first event) 0.39 ± 0.1 (after first event) 0.43 ± 0.07 (after second event)
Purposes	Solute transport in snow (Lee et al. 2008a) and isotopic evolution of meltwater (Lee et al. 2010b)

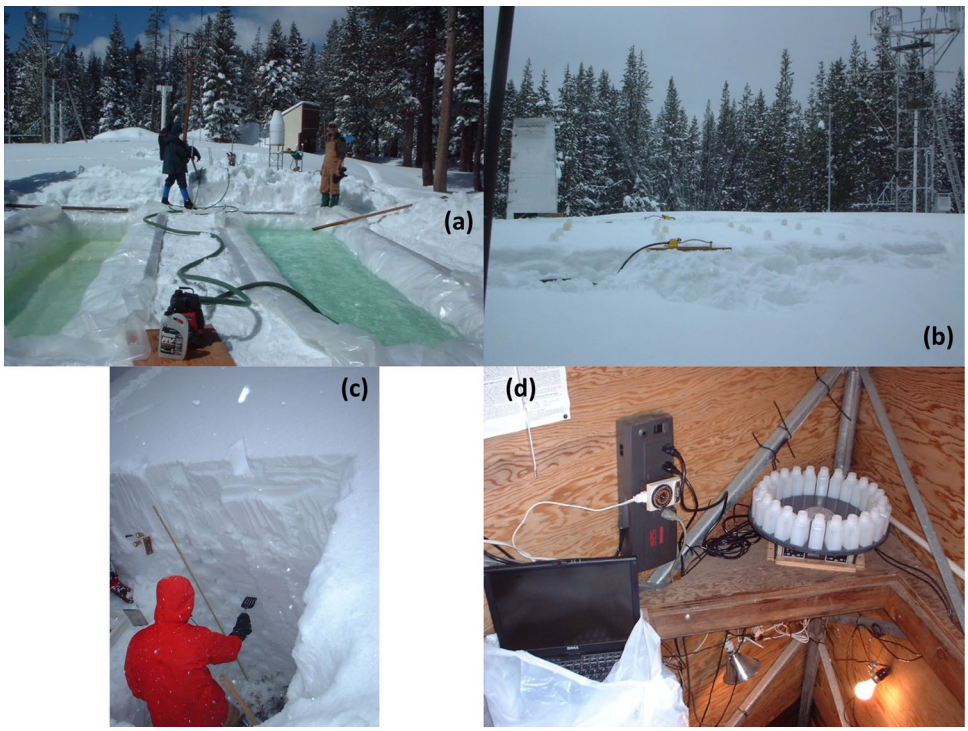


Fig. 1 Description of artificial rain-on-snow experiments. **a** Water tanks for rainstorms. **b** Artificial rain-on-snow by a sprinkler. Meltwater samples were collected in a hut in the left. **c** Sampling for snowpit. **d** Meltwater collecter

twenty plastic cups were strategically positioned over the snow surface to collect rainwater. The first experiment took place in the afternoon of April 5, lasting 5.1 h with a rainfall amount of 157 ± 15 mm (± 1σ, among the 20 cups). The second experiment occurred on the morning of April 8, lasting 5.5 h, resulting in 145 ± 8.5 mm of precipitation. No natural rainfall occurred during the artificial storm periods, but 10 cm of snow fell on April 12 and 13. Following the first storm on April 5, the melt-pan discharge was collected only once, immediately after the artificial ROS event. During and after the second storm on April 8, the melt-pan discharge was initially sampled every 15 min. However, as the outflow rate decreased, the sampling frequency was reduced to once per hour on April 10 and 11, and then once every two hours on and after April 14. Measurements concluded on April 14 at 8:32 am, as the outflow rate almost returned to the initial condition.

To determine the chemical and isotopic compositions of the snowpack as a function of depth before and after the storms, pits were excavated in an adjacent area. Various measurements, including snow density, water content, pore water sampling, and chemical and isotopic analyses of the

snow, were conducted throughout the snowpack. The volumetric liquid water content was assessed using a snow surface dielectric device (Denoth meter) both before and after the experiments. In this process, snow samples were collected at each depth of 10 cm and transferred to pre-cleaned plastic bags. These samples were subsequently melted and transferred to pre-cleaned plastic bottles. Each water sample collected during the field experiment underwent a bifurcated process. One part was utilized for measuring isotopic ratios, while the other was dedicated to measuring anion concentrations, following the procedures outlined by Lee et al. (2010b) and Lee et al. (2008a), respectively. The samples were subjected to analysis for deuterium/hydrogen ratio using an online chromium reduction system (H-device) and for oxygen isotopes ratio using the carbon dioxide equilibrium method with a gas bench. The relative standard deviation (σ) of the anion analysis was within 2%, and the precisions of the δD and $\delta^{18}O$ analyses were 1‰ and 0.1‰, respectively.

Meltwater separations

The end member mixing calculation (EMMC) approach, with the chemical and isotopic tracers suggested by Sklash and Farvolen (1979), was used to partition the meltwater discharge that was collected at the bottom of the snowpack into three components (namely, rainfall, pore water and snowmelt) via the modified mass balance equations given as Eqns. (1)–(3):

$$Q_T = Q_R + Q_P + Q_S \tag{1}$$

$$I_T = I_R \frac{Q_R}{Q_T} + I_P \frac{Q_P}{Q_T} + I_S \frac{Q_S}{Q_T} \tag{2}$$

$$C_T = C_R \frac{Q_R}{Q_T} + C_P \frac{Q_P}{Q_T} + C_S \frac{Q_S}{Q_T} \tag{3}$$

where Q_T, Q_R, Q_P, and Q_S are the respective total, artificial rainwater, pore water, and snowmelt discharges, C_T, C_R, C_P, and C_S are the corresponding concentrations of the tracer (Br^-), and I_T, I_R, I_P, and I_S are the corresponding isotopic compositions (δD or $\delta^{18}O$).

Because solutions for more than three components are difficult to obtain, matrix operation was performed on Eqns. (1)–(3), as shown in Eqns. (4) and (5):

$$A = \begin{pmatrix} 1 & 1 & 1 \\ C_R & C_P & C_S \\ I_R & I_P & I_S \end{pmatrix}, X = \begin{pmatrix} \frac{Q_R}{Q_T} \\ \frac{Q_P}{Q_T} \\ \frac{Q_S}{Q_T} \end{pmatrix}, B = \begin{pmatrix} 1 \\ C_T \\ I_T \end{pmatrix} \tag{4}$$

$$AX = B,\ X = A^{-1}B \tag{5}$$

Thus, a system of linear equations was introduced that enables the three-components hydrograph separation by using both isotopic and chemical compositions. The MATLAB software was used to solve the linear matrix system.

Results

The comprehensive physical, chemical, and isotopic findings of the two artificial rain-on-snow (ROS) events were previously documented by Lee et al. (2008a) and Lee et al. (2010b). In this current paper, we focus on elucidating the variations in the chemical and isotopic compositions of the snowpack and its meltwater, leveraging this information for the hydrograph separation analysis.

Experimental results for the separation

The earlier-discussed mass balance calculations reveal that, according to Lee et al. (2008a), less than 50% of the rainwater and F^- tracer were discharged and recovered at the base of the snowpack before the onset of the second storm. This suggests the potential retention of some storm water from the initial event within the snowpack as pore water or lateral flow into the adjacent dry snow, or a combination of both. By April 12, 100% of the Br^- tracer concentrations were identified in the discharge, and 95% of the water introduced since the commencement of the second storm was recuperated. The complete retrieval of water and tracers from the second storm implies that, once the surrounding snowpack became wet, the water flow primarily adopted a vertical direction, with no further mass loss through lateral flow. Consequently, in this study, we presume that all water within the snowpack consists of rainwater, pore water, and meltwater. The discharge is subsequently segregated into these three components based on the chemical and isotopic data obtained after the initiation of the second storm.

The water fluxes, chemical concentrations, and isotopic ratios from the ROS experiments are presented as a function of time in Fig. 2. Only oxygen isotopic ratio is illustrated because hydrogen isotopic ratio is linearly correlated with that of oxygen. Here, the input water fluxes during the two artificial rainstorms (denoted as Exp. #1 and Exp. #2, respectively) are presented in Fig. 2a, and the corresponding output (discharge) is indicated in Fig. 2b. For each storm, the discharge is seen to respond to the rainfall, rising to the level of the input flux. After the ROS, the water drains gradually from the snowpack. The daily snowmelt (small peaks in Fig. 2a) also causes the outflow flux to increase. The corresponding tracer concentrations and isotopic time series are presented in Figs. 2c and d for Br^- and $\delta^{18}O$, respectively.

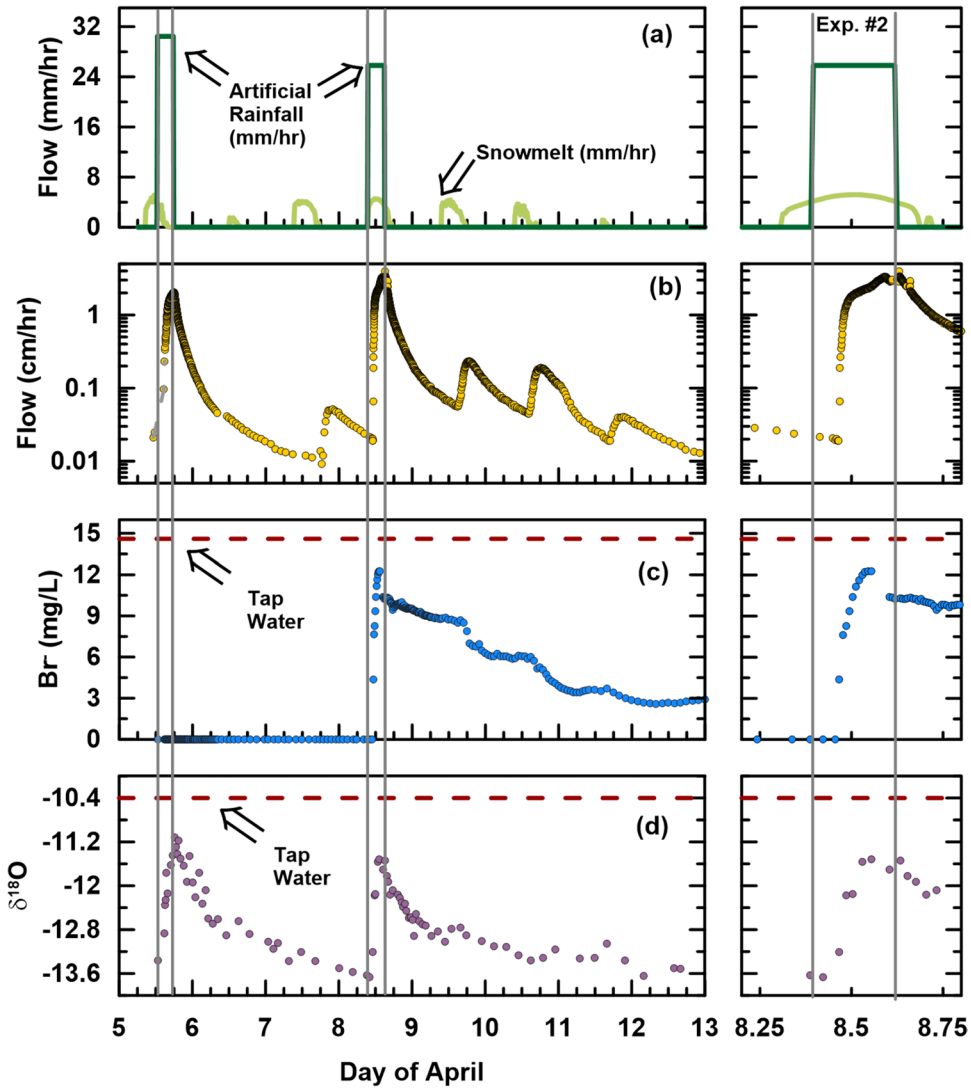


Fig. 2 The experimental observations from the two artificial rain-on-snow (ROS) events (Exp. #1 and Exp. #2), including the entire 8-day time series (left) and the individual timescale of second artificial ROS event (right). The vertical gray lines show the beginning and end of each rainstorm. **a** Water input, including the artificial rainstorms and calculated snowmelt rates. **b** Water output. Here, the dotted and shaded line represents missing flow data resulting from an instrument problem. **c** The concentration of the tracer (Br^-) in the discharge at the base of the snowpack. **d** The oxygen isotopic composition of the discharge. The shaded lines represent the Br^- concentration and $\delta^{18}O$ value of the tap water (0.0 mg/L and –10.4‰, respectively)

The Br^- concentration in the unspiked tap water was 0.0 mg/L, and the average Br^- concentration in the solution sprayed onto the snow was 14.6 mg/L (15.9 mg/L in tank 1 and 13.3 mg/L in tank 2 and both tanks had a same dimension in Fig. 1c). The Br^- concentration clearly responds to the changes in hydrological conditions, such as melting and storm, initially increasing sharply to ~ 12 mg/L at the commencement of the second storm, and then decreasing sharply to 11 mg/L due to the channel flow in the snowpack (Lee et al. 2008a). Meanwhile, the $\delta^{18}O$ value of the unspiked tap water was –10.4‰. At the peak flow, the isotopic composition of the discharge does not approach the rainwater composition as closely as does the concentration of chemical tracer. This is due to isotopic exchange between the liquid water and ice, and/or mixing with the previously-present pore water.

The physical, chemical, and isotopic stratigraphy of the snowpack at the end of the first and second artificial ROS events are shown in Fig. 3. From Fig. 3a, the average density across the entire profile is found to increase from 0.35 ± 0.14 ($\pm 1\sigma$, $N = 23$) immediately after the first event, to 0.43 ± 0.07 ($\pm 1\sigma$, $N = 19$) after the second artificial rainfall event. Changes in density occurred only near the surface within the new snow layer; the depth of this layer also reduced (from 220 m at the end of the first event, to 180 m at the end of the second) by the artificial rainfall. The increase in average snow density, and the decrease in the standard deviation (σ) of the snow density, can be attributed to homogenization via snow metamorphism or increase in water saturation. Meanwhile, from Fig. 3b, the average water content is seen to increase from 1.1 after the first event to 2.8 after the second. In Fig. 3c, the average concentration of Br^- in the snowpack is seen to increase from the background concentration of 0.0 mg/L before the second ROS, to the applied concentration of 14.6 mg/L. Finally, the isotopic composition ($\delta^{18}O$) of the snowpack at a depth of ~ 50 cm

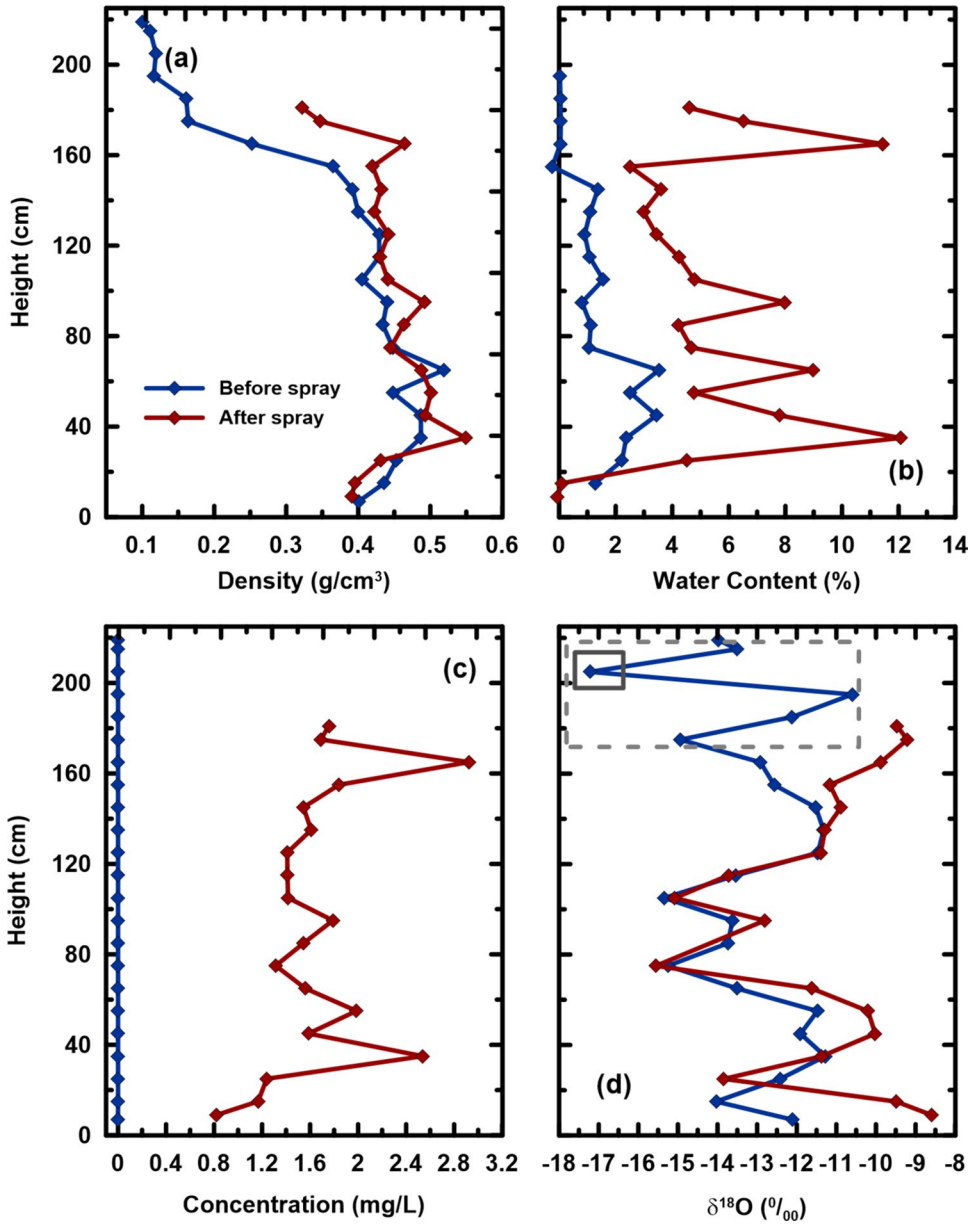


Fig. 3 The measured variations in **a** the density, **b** the water content, **c** the bromide concentration, and **d** the $\delta^{18}O$ value of the snowpack immediately before the first ROS event (5 April 2003; solid shaded line) and immediately after the second ROS event (8 April 2003; solid black solid line)

from the surface is seen to be significantly affected by the artificial rainwater after the second ROS (Fig. 3d).

Three-components mixing calculations

To determine the chemical and isotopic compositions of the end members for the separation, the dual tracer diagram of Br^- concentration and $\delta^{18}O$ shown in Fig. 4 was constructed under the following assumptions: (i) the chemical and isotopic compositions of the rainwater (C_r and I_r) were assumed to be those of the tank water sprayed onto the snowpack (i.e., 14.6 mg/L and –10.4‰, respectively); (ii) the chemical concentrations of the pore water inside the snowpack (C_p) and the snowmelt from the surface of the snowpack (C_s) immediately before the second artificial ROS event was assumed to be zero, because the spray used for the first ROS event contained no Br^- (i.e., $C_p = C_s = 0.0$ mg/L; Fig. 2c); (iii) the oxygen isotopic composition of the meltwater was assumed to be the average of that in the surface layers the snowpack (indicated by the dotted grey box in Fig. 2d), i.e., –12.94‰. The third assumption was made because it is difficult to constrain the isotopic compositions of the pore water (I_p) and snowmelt (I_s). During the first artificial ROS event, the pore water in the flow channels of the snowpack was replaced by the tank water (–10.4‰); hence, the isotopic composition of the meltwater is correlated with the chemical composition (Fig. 4). After the first artificial ROS event, however, the oxygen isotopic composition of the pore water

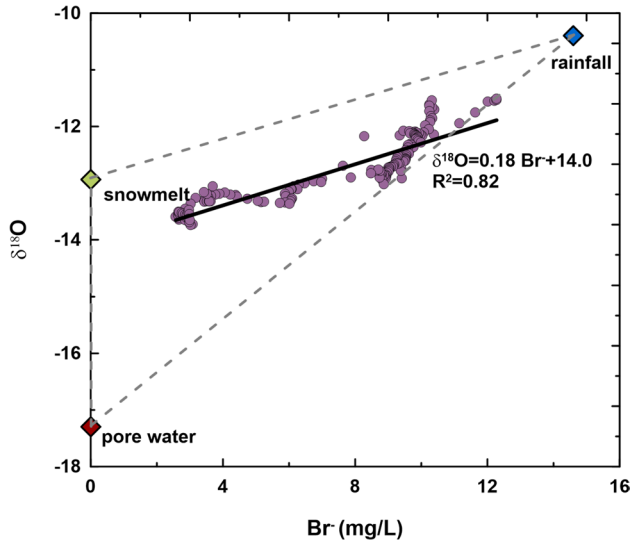


Fig. 4 The dual tracer diagram of $\delta^{18}O$ vs. Br^- concentration showing the measured values (points) from the discharged meltwater lying within the area enclosed by the snowmelt, rainwater, and pore water components

is altered to that of the snowmelt at the surface (–17.3‰; solid grey box, Fig. 3d).

Based on the water flow and chemistry of the second ROS event, and on the above assumptions, the fractional time series of each component (rainwater, snowmelt, and pore water) in the discharged water, were calculated via EMMC, and the results are presented in Fig. 5. Due to the first artificial ROS event, the snowpack was relatively wet before the second ROS event. As stated earlier, the complete mass recovery of water and tracer after the second storm indicates that once the surrounding snowpack became wet, the water flow was vertical, and there was no further mass loss due to lateral flow (Lee et al. 2008a). Thus, after the second ROS event, the maximum contribution of the rainfall (black dashed line, Fig. 5a) is seen to increase sharply to 84%, and then decrease to 71% due to channel (or preferential) flow in the snowpack, as noted in Sect. "Experimental results for the separation". Because the Br^- in the meltwater discharge is entirely derived from the artificial rainfall, a sharp decrease in the Br^- concentration (from 12 to 11 mg/L) is also observed due to channel flow (Fig. 2c). Thus, after the second artificial storm, the rainwater gradually drained from the snowpack. The daily snowmelt also caused the outflow flux to increase, as can be observed from the contribution of snowmelt in Fig. 5a (solid grey line). Compared to the other components, the fraction of pore water remains relatively constant after the storm (dashed grey line, Fig. 5a). The total amount of meltwater that was discharged from the bottom of the snowpack after the second artificial ROS event (as measured from immediately after the event until 14, April, 8:30 am) was 4,136.6 L. The amounts of water discharged as rainwater, pore water, and snowmelt were calculated as 2620.2 (63.34%), 829.0 (20.04%) and 687.4 L (16.62%), respectively.

Discussion

Two-components vs. three-components mixing calculations

In this study, End Member Mixing Calculation (EMMC) was employed to segregate the three components (artificial rainwater, pore water, and meltwater) in the discharge collected from the bottom of the snowpack. Typically, two-component mixing calculations are initially conducted to achieve chemical and isotopic hydrograph separations. This approach has been commonly utilized in watershed

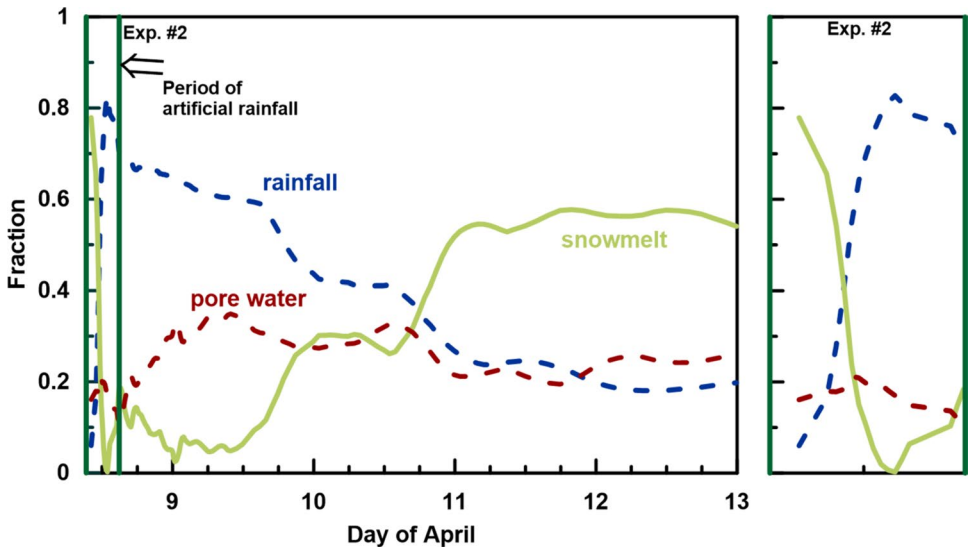


Fig. 5 The time series for **a** the fraction of each end component (rainfall, pore water, and snowmelt), and **b** the outflow rate of the discharged water for each component, as calculated by EMMC

hydrology to comprehend the hydrological processes of the watershed (Kim et al. 2017). In such studies, variations in stream water levels following rainfall are assumed to stem from new water or event water (precipitation) versus old water or pre-event water (groundwater) (Sklash and Farvolen, 1979). The two-component mixing model, a single tracer-based model, is applied to quantify and distinguish two stream flow components, such as direct runoff (or snow/glacier melt) versus groundwater (Kim et al. 2017). However, this model is valid only when the flow of stream water is influenced by only two end-members with significant differences in either their chemical or isotopic compositions. The equations used for the initial two-component mixing calculation in this work closely resemble those detailed in Sect. "Meltwater separations" for the three-component mixing calculations. However, the outcomes of the two-component mixing calculations varied based on the chosen tracer ($\delta^{18}O$ vs. Br^-). When the chemical tracer (Br^-) was selected, successful separation was achieved between the two components of rain-on-snow (ROS) (dirty) versus the combined pore water and meltwater (clean). This success was attributed to the presence of the bromide tracer in ROS, while the pore water and meltwater lacked this tracer. The results of the two-component EMMC indicated a 63% fraction from ROS and a 37% contribution from the combined pore water and meltwater. Notably, despite the non-separation of pore water and snowmelt, this result closely aligns with that obtained using the three-component separation.

When employing the isotopic tracer ($\delta^{18}O$) for the two-component calculation, it became feasible to differentiate the combined contribution of rain-on-snow (ROS) and pore water from that of the meltwater. This separation was achievable due to respective decreases of 10.4‰ and 13.1‰ in the mean isotopic values compared to those of the snowpack. This assumption was made under the premise that the pore water was entirely replaced by the ROS without additional melting. The outcome revealed a 40% contribution from the combined rainwater and pore water, with a 60% contribution from the meltwater in the discharge. In contrast to the three-component calculation, the two-component calculation exhibited an overestimation of the contribution of meltwater to the discharge and an underestimation of those from rainwater and pore water. Consequently, while the assumption of complete replacement of pore water by ROS may hold validity, the results of the two- and three-components separation methodologies are incongruent. It is noteworthy that if there was no significant melting after the second rainstorm, the isotopic compositions of pore water and rainwater should be identical. However, the present three-component calculations suggest complete replacement of pore water by meltwater. The nuances related to the selection of end members and the uncertainties involved will be thoroughly discussed in the subsequent section.

Selection of end members and uncertainty

Several studies employing three-components hydrograph separation based on hydrogeochemical and isotopic approaches with two tracers have been documented (Klaus and McDonnell 2013). These studies highlight that accurate identification is heavily contingent on effectively constraining the chemical and isotopic compositions of the end members, a task made challenging by the temporal and spatial variabilities inherent in these end members. Klaus and McDonnell (2013) emphasized in their review that the selection of end members significantly influences the calculated fractions of event and pre-event water. Therefore, in this study, the dual tracer diagram proposed by Ogunkoya and Jenkins (1993) was employed (Fig. 4) to assess whether the two chosen end members ($\delta^{18}O$ and Br^-) could encapsulate the two-dimensional mixing space of rainfall, pore water, and snowmelt in the collected meltwater samples. However, it is important to note that this separation method has limitations because the isotopic signal of the snow exhibits depth stratification and fractionation during the melting period. Consequently, the isotopic values of the pore water, rainfall, and meltwater collected from the entire snowpack profile differed from those obtained at the bottom of the snowpack. This discrepancy arises because snowmelt was not produced across the entire snowpack but only in the upper layers. As a result, the isotopic composition of the meltwater discharge observed immediately before the second artificial rain-on-snow (ROS) event closely resembled that of the samples taken from the top of the snow profile (Fig. 3).

Furthermore, the outcomes of End Member Mixing Calculation (EMMC) can be influenced by the point of introduction of solutes, specifically whether they were introduced in the rain-on-snow (ROS) water or in the pore water. An illustrative example is the work conducted by Feng et al. (2001), where chemical tracers were introduced by ROS as pore water before the occurrence of rainstorms. Unlike the approach in the present study, in Feng et al.'s work, the rainwater was devoid of tracers, while the snowmelt and pore water exhibited distinct tracer concentrations.

Recently, Bayesian mixing models have been developed to account for uncertainties in end-member concentrations, allowing for the statistical probability of contributions from each source to be estimated (Jung et al. 2023). However, in the present study, the chemical and isotopic compositions of each end-member were determined based on the initial experimental conditions, and the Bayesian approach was not employed.

The importance of pore water in the snowpack

In general, the vertical infiltration of rain and/or meltwater from the snowpack surface can be a major factor influencing

the pore water fluctuations. For a seasonal snowpack, the crucial factors modulating the recharge of groundwater systems and surface runoff include (i) the timing, rate, and magnitude of meltwater infiltration, and (ii) the retention and storage of pore water inside the snow (Jung et al. 2022). Moreover, ROS events can involve an augmented flow risk because the water input from heavy rainfall typically flows through the snowpack more rapidly than does the meltwater in between periods of rainfall. Rapid snow melting due to sudden warming or rainfall on the snowpack can be a major factor in landslide occurrence due to the resulting increase in pore water content or pressure. Thus, the forecasting of snowmelt runoff for an upcoming ROS event demands an understanding of water movement inside the snow. Colbeck (1972) first applied water flow theory to the physics of unsaturated flow during snowmelt percolation and the downward propagation of wetting fronts during diurnal snowmelt cycles. After Colbeck (1972), Colbeck and Davidson (1972) and Hibberd (1984) defined the governing equations for one-dimensional water flow in the snow by mass conservation. Thus, the pore water content is required to model the water flow in the snowpack. The pore water in a snowpack typically occupies about 2–3%, and this was changed from $1.1 \pm 1.1\%$ ($\pm 1\sigma$, $N = 23$) to $2.8 \pm 1.2\%$ ($\pm 1\sigma$, $N = 19$) after the second ROS in the present study, generating up to ~ 30.0% of the total discharged meltwater, due to the previous artificial ROS event.

Modeling water flow in snow poses unique challenges due to the interactions between liquid water and the solid phase (snow or ice). This complexity surpasses that of other porous media, such as groundwater systems (Feng et al. 2001; Lee et al. 2008a, 2008b; Zhou et al. 2008a). While much of the conceptual framework from vadose zone hydrogeology can be applied to explain water flow in unsaturated porous snow, there are two crucial distinctions:

1. The rapid change in snow pore geometry with aging results in alterations to hydrologic properties, including saturated hydraulic conductivity and porosity.
2. Snow mass can transition between liquid, solid and gas phase through processes like melting, condensation, freezing and sublimation (Harrington and Bales 1998; Lee and Jung 2022). Quantifying these transformations during the process is challenging.

Additionally, rain-on-snow (ROS) events may lead to percolation through the snowpack and subsequent freezing, modifying the isotopic compositions of both the snowpack and meltwater (Zhou et al. 2008a, 2008b). This process deposits latent heat into the snowpack and the subsurface soil layer. The present study aimed to segregate the discharge meltwater collected from the bottom of the snowpack into rainwater, snowmelt, and pore water components. The results and ensuing discussion indicate that the proposed approach is valuable when the isotopic composition of each component exhibits significant differences.

Summary

In this study, a three-component hydrograph separation of rainwater, pore water, and meltwater was conducted utilizing chemical and isotopic tracers, field observations at the Central Sierra Snow Laboratory in California, and end member mixing calculation (EMMC). The experimental setup involved introducing artificial rain-on-snow (ROS) to the snowpack, incorporating conservative anions and stable water isotopes to discern each component (rainwater, pore water, and meltwater) in the discharge water collected from the bottom of the snowpack. As a result, the pore water content exhibited a change from $1.1 \pm 1.1\%$ ($\pm 1\sigma$, $N = 23$) immediately after the initial ROS event to $2.8 \pm 1.2\%$ ($\pm 1\sigma$, $N = 19$) following the second event. According to the EMMC results, the quantities and percentage contributions for rainfall, pore water, and snowmelt in the discharged meltwater were 2,620.2 L (63.3%), 829.0 L (20.0%), and 687.4 L (16.6%), respectively. Notably, the results indicated that rainwater reached the bottom through multiple fast flow channels before matrix flow occurred, contrary to findings in previous studies. Therefore, the proposed approach offers valuable insights into understanding the dynamics of water percolation in a snowpack during an ROS event. We anticipate that this method will contribute to a better understanding of water flow in a snowpack based on region or time.

Acknowledgements First, we would like to thank both Dr. Xiahong Feng and Dr. James Kirchner for initiating this experiment. This study was supported by the National Foundation of Korea (NRF) grant funded by both the Korean government (2022R1A2C3007047) and Korea Institute of Marine Science & Technology Promotion (KIMST), and by the Ministry of Oceans and Fisheries (RS-2023-00256677; PM23020). This work is partially supported by the R&D Program for Oceans and Polar Regions of the National Research Foundation (NRF) funded by the ministry of Science and ICT (2020M1A5A1110607). We appreciate two anonymous reviewers, whose comments led to significant improvements.

Author's contribution Data presentation was performed by JUNG. The first draft of the manuscript was written by LEE. All authors read and approved the final manuscript.

Funding The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material Data are available upon request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical standard This article does not contain any studies with human participants or animal performed by any of the authors.

Consent for publication The figures and results presented in this manuscript are from research results and have not been extracted from other resources.

Consent to participation Informed consent was obtained from all individual participants included in this study.

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