

Article

Snowmelt Volume from Rain-on-Snow Events Under Controlled Temperature and Rainfall: A Laboratory Experimental Study

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Abstract

Rain-on-snow (ROS) events profoundly influence mixed rain–snow flooding and the water resource cycle. However, current research regarding ROS events remains predominantly reliant on existing datasets, lacking detailed controlled experiments under variable conditions. This study employed control variables and an orthogonal experimental design to conduct laboratory-controlled experiments simulating ROS events with different temperatures, rainfall intensities, and rainfall durations. Observations and analyses were performed on the snowmelt volumes during and after events. The results indicate that ROS events significantly accelerate snowmelt rates and increase total snowmelt volume. Under low-intensity ROS, snowmelt volume exhibits greater sensitivity to temperature changes. A temperature threshold exists between 2 °C and 6 °C; beyond this threshold, the melting rate accelerates and ablation volume increases. Under high-intensity ROS, rainwater becomes the dominant factor driving snowpack ablation. When rainfall intensity exceeds 60 mm·h^{−1}, it triggers a sharp increase in snowmelt volume. Concurrently, following an ROS event, snowpacks subjected to low-intensity rainfall exhibit a stronger rainwater retention capacity, an effect that becomes more pronounced at lower temperatures. Additionally, snowmelt volume increases with prolonged rainfall duration, with the increment in snowmelt volume attributable to extended rainfall time being greater under weaker rainfall intensities. These findings provide a scientific reference for better understanding ROS-related disasters mechanisms.

Keywords: rain-on-snow events; temperature; rainfall; snowmelt volume; artificial rainfall simulation experimental



Academic Editor: Fabio Russo

Received: 16 September 2025

Revised: 3 November 2025

Accepted: 13 November 2025

Published: 16 November 2025

Citation: Liu, W.; Hanati, G.; Hu, K.; Danierhan, S.; Jin, L. Snowmelt Volume from Rain-on-Snow Events Under Controlled Temperature and Rainfall: A Laboratory Experimental Study. *Hydrology* **2025**, *12*, 305. <https://doi.org/10.3390/hydrology12110305>

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1. Introduction

Floods, as a common and widespread natural disaster globally, exert significant impacts on human society, ecosystems, economic activities, and more. Mixed rain–snow floods, a specific type of snowmelt flood, are characterized by their sudden onset, high peak discharge, intense flood magnitude, and substantial destructive potential [1,2]. Such floods often develop into disastrous events, causing significant casualties and economic losses. In recent years, with the intensification of global climate change, the frequency of mixed rain–snow floods has been increasing [3,4], leading to escalating associated damages.

In response to this phenomenon, researchers have conducted extensive studies on mixed rain–snow floods, revealing that many of the world’s extreme flood events are associated with rain-on-snow (ROS) events [5], and some researchers even equate ROS events directly with floods [6]. Li et al. [7] found that over 70% of extreme runoff events along the US West Coast and the Appalachian Mountains are linked to ROS events. They further projected that the contribution of ROS to flooding in high-altitude regions will increase under future climate warming. Bean and Watts [8] demonstrated that river surges triggered by ROS events are 3% to 20% larger than those caused by non-ROS events. Similarly, studies by Freudiger et al. [9] and Beniston et al. [10] indicated that the current rise in ROS events will lead to more frequent extreme floods. Consequently, ROS events have gained increasing attention in recent years [11].

Rain-on-snow (ROS), specifically referring to rainfall occurring over a snowpack, is a multivariate hydro-meteorological phenomenon resulting from the interaction of rainfall and existing snow cover. These events involve complex thermal–hydrological processes at the snow surface and within the snowpack. ROS primarily occurs in late autumn and early spring, and occasionally during winter [12,13]. In recent years, with the progressive exacerbation of global climate change, both snow cover and precipitation patterns have been affected across different regions. Snow cover has diminished in low-altitude areas due to warming, leading to a decrease in ROS events there. Conversely, increased precipitation in high-altitude regions under warming conditions has resulted in a greater frequency of ROS events [14–16]. Overall, however, under the influence of climate warming, ROS events are shifting towards areas characterized by higher altitudes, greater snow accumulation, steeper slopes, and a higher propensity for rapid flood formation [17]. This shift is leading to an increasing trend in both the frequency and intensity of ROS events [18,19], establishing them as one of the key drivers affecting the hydrological cycle in high-altitude regions. This is because ROS events not only reduce snow albedo [20], increase snow liquid water content [21], and alter snowpack structure [22], leading to accelerated snowmelt and substantial snowmelt runoff, but also generate compounding effects by combining meltwater with rainfall [23,24]. This predisposes affected areas to secondary disasters such as flash floods, avalanches, and landslides [25,26], posing significant challenges to water resource management, ecosystems, and societal safety.

In response to the increasing frequency of ROS events and mixed rain–snow floods, researchers worldwide have investigated the mechanisms by which ROS affects snowmelt and the formation processes of mixed rain–snow floods. Artificial rainfall simulation experiments represent one of the primary research methodologies [27], employed to elucidate the complex processes of snowpack energy balance, meltwater infiltration, and runoff generation during ROS events. Singh et al. [28], conducting artificial rainfall experiments in the Austrian Alps, demonstrated that rainfall not only accelerates snowmelt but also expedites water movement by enhancing snow deformation and creating preferential flow paths. Utilizing conservative tracers, Lee et al. [29] explored the relationship between solute concentration and discharge within the snowpack through artificial ROS experiments and numerical modeling. In subsequent experiments, Lee and Jung [30] employed isotopic and chemical tracers to study meltwater displacement processes within the snowpack, quantifying the contributions of rainwater, pore water, and meltwater to snowmelt runoff. Similarly, combining artificial rainfall simulations with isotopic tracing, Juras et al. [27] found that under high-intensity rainfall conditions, rainwater accounted for 52.7% of the total runoff, while mature snow layers retained 33.6% of the rainwater, and rainwater significantly affected runoff dynamics through a pushing effect. Eiriksson et al. [31] investigated the hydrological significance of lateral water flow within snow at both hillslope and catchment scales through multiple artificial ROS experiments, revealing its role in water

redistribution and runoff generation during ROS events. Yang et al. [20] conducted field-based experiments simulating ROS events to study their dynamic impacts on snowmelt processes and underlying disaster mechanisms. While these studies have directly or indirectly clarified the causes of mixed rain–snow floods and the processes by which ROS influences snowmelt, research on the snowmelt volume generated by ROS events under varying conditions remains insufficient.

Currently, ROS event research largely relies on field observations or model simulations, leaving a scarcity of fine-grained controlled experiments. These are needed to investigate the dynamic response of snowpacks during ROS events, particularly the interactive mechanisms between rainfall parameters and snowpack layers, as well as to quantify the associated snowmelt volume. Therefore, in contrast to most previous field observations, this study utilizes controlled laboratory experiments. By regulating parameters such as temperature and rainfall, we obtained snowmelt volume data under various conditions to determine the following: (1) the influence of temperature variations on snowmelt volume; (2) the effect of rainfall intensity changes on snowmelt generation; and (3) the impact of rainfall duration variations on snowmelt output.

2. Materials and Methods

2.1. Experimental Setup

The experimental setup of this study comprises an artificial rainfall simulation system, an experimental chamber, a support frame, a measuring bucket, and a temperature control system. The rainfall simulation system (provided by Xi'an Aikesi Intelligence Technology Co., Ltd., Xi'an, China) included a rainfall support frame, a main controller, water supply pipelines, a water pump, nozzles, and a water storage tank. The overall experimental structure was the artificial rainfall simulator system (covered area: 400 cm × 300 cm; height: 400 cm) mounted within the laboratory. A support frame inclined at 5° and the experimental chamber were positioned within the rainfall coverage area. The experimental chamber had tempered glass panels with dimensions of 100 cm × 20 cm on the left and right sides, with 50 cm × 20 cm tempered glass panels on the upstream and downstream ends, and a 100 cm × 50 cm tempered glass panel at the bottom (effective rainfall area). A 5 cm diameter water outlet was left at the bottom, covered with a filter screen to filter impurities, and the water outlet was connected to the measuring bucket on the ground with a water pipe. The bucket had water level markings to quantify snowmelt volume, and it was sealed to prevent rainwater interference (Figure 1). Furthermore, the experimental chamber was carefully sealed, with the exception of the water outlet retained at the bottom. No seepage that could affect the experimental results occurred from any other part of the chamber. Additionally, the main controller, water pump, and water storage tank of the rainfall simulation system were installed externally for operational control. Throughout the experiment, different nozzle combinations were used to maintain rainfall spatial uniformity of 0.85 or higher within the rainfall area; rainfall intensity was adjusted by regulating pressure.

2.2. Experimental Parameters

This study primarily investigates variations in snowmelt volume resulting from ROS events under different conditions by manipulating parameters such as temperature, rainfall intensity, and rainfall duration. Due to the limitations of the experimental conditions, this study is limited to temperature- and rainfall-related factors. Other factors influencing snowpack ablation, such as wind and solar radiation, will be investigated in a subsequent study at the newly established field ROS observation station. The complete experimental parameter matrix is summarized in Table 1. The selected temperature levels were determined based on the following considerations: since rainfall in natural environments

typically occurs above 0 °C, the minimum temperature was set to 2 °C, representing critical melt conditions. The 10 °C level was chosen to simulate extreme warming scenarios, which can occur in high-altitude regions experiencing ROS events. The 6 °C level serves as the intermediate value between 2 °C and 10 °C and approximates a common temperature for snowmelt in snow-covered areas. Consequently, 2 °C, 6 °C, and 10 °C were selected as the experimental temperature levels. Regarding rainfall duration, 20 min represents short-duration rainfall events, avoiding durations too short for adequate water infiltration into the snowpack. A duration of 120 min was used to simulate sustained rainfall events, revealing the cumulative effects of prolonged water infiltration and heat conduction. A 60 min duration was selected as an intermediate interval, firstly, to observe the impact of moderate-duration rainfall on snowmelt, and secondly, to facilitate better comparison with snowmelt volumes from control experiments. Furthermore, to address potential discrepancies in snowmelt volumes arising from variations in the initial state of the experimental subject (snowpack), this study utilized snow samples with similar deposition histories and external environmental conditions. This controlled for the influence of initial snowpack state, thereby minimizing parameter variations other than temperature and rainfall. This control strategy helps ensure the validity of our conclusions regarding the impacts of temperature and rainfall on snowmelt within the context of this study.

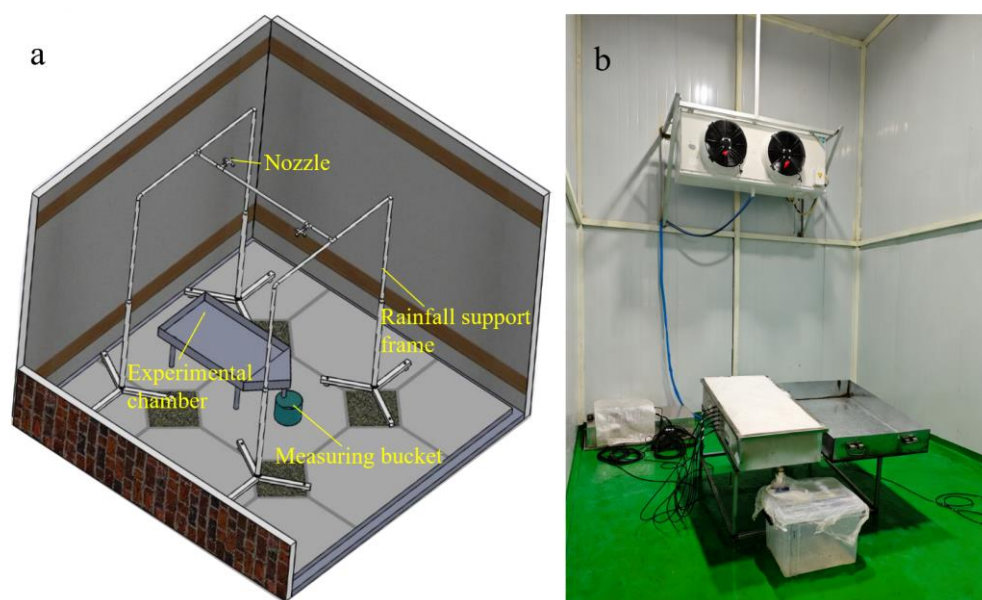


Figure 1. Experimental setup. (a) Schematic diagram. (b) Photograph of the experimental setup.

Table 1. Experimental parameter configuration.

Parameter Name		Value		
Temperature	2 °C	6 °C	10 °C	
Rainfall Intensity	10–30 mm·h ^{−1}	30–60 mm·h ^{−1}	60–120 mm·h ^{−1}	
Rainfall Duration	20 min	60 min	120 min	

2.2.1. Temperature

Temperature is a critical factor influencing snow ablation. When the temperature rises above 0 °C, snowpack begins to melt slowly. If rainfall occurs under these conditions, it will cause an ROS event, accelerating the ablation rate [32]. Therefore, this study utilizes a temperature control system to regulate the laboratory temperature, simulating the snow ablation process under field warming conditions, as well as the characteristics of

snowpack changes and variations in snowmelt volume during ROS events occurring at different temperatures.

2.2.2. Rainfall Intensity

Rainfall intensity, defined as the amount of rainfall per unit time (in this study, 1 h), is commonly used to describe the magnitude or severity of a rainfall event. As ROS events influence snow ablation, rainfall intensity is also a critical factor affecting snowmelt. Existing studies indicate that under high-intensity rainfall, snowmelt runoff rapidly follows the infiltration pathways of rainwater [28]. Conversely, light rain exerts a less pronounced acceleration effect on the ablation of deep snowpacks [31]. Therefore, under otherwise identical conditions, varying rainfall intensities during ROS events also impact the snow ablation rate, resulting in different magnitudes of snowmelt volume. Based on the relative magnitudes of rainfall intensity applied in the experiments, this study defines rainfall intensities of 10–30 mm·h^{−1} as low-intensity rainfall, 30–60 mm·h^{−1} as moderate-intensity rainfall, and 60–120 mm·h^{−1} as high-intensity rainfall.

2.2.3. Rainfall Duration

Rainfall duration in this study refers to the duration of a single rainfall event. Generally, longer rainfall duration corresponds to greater total rainfall volume. For rainfall events occurring over snow cover, a longer duration implies that the snowpack receives a larger amount of rainfall, thereby influencing the runoff generation process and the formation of snowmelt runoff. Consequently, this study also considers rainfall duration to be one of the factors affecting snowmelt volume, investigating snowmelt volume changes under the influence of different rainfall durations.

2.3. Experimental Protocol

To investigate the effects of different snowmelt factors on snow ablation, this study employs a controlled laboratory experiment using the control variable method. This methodology systematically alters one factor while holding others constant to obtain the snowmelt volume generated by the single factor of ROS. Three temperature levels (2 °C, 6 °C, 10 °C), three rainfall intensity levels (10–30 mm·h^{−1}, 30–60 mm·h^{−1}, 60–120 mm·h^{−1}), and three rainfall duration levels (20 min, 60 min, 120 min) were established. To comprehensively account for the interactive effects among these factors, we employed an orthogonal experimental design. To enhance statistical reliability, each combination was replicated three times, and the mean was taken as the experimental result for that group. To explicitly demonstrate the direct impact of rainfall on snow ablation, a control experiment with no rain (subjected only to temperature levels of 2 °C, 6 °C, and 10 °C) was established. The experimental procedure was as follows: The precise start time was recorded. During rainfall experiments, snowmelt volume was measured at 5 min intervals until 40 min after rainfall cessation. For the no-rain control experiment (characterized by comparatively slower ablation rates and less discernible short-term changes than the rainfall experiments), snowmelt volume was recorded hourly until the completion of a 6 h period. The overall research framework is illustrated in Figure 2.

Snow samples were collected using the following method. Before the first snowfall, the experimental chamber was placed in a flat, open area on the northern slope of the Tianshan Mountains (87.604° E, 43.735° N, 982.25 m), a site selected for its minimal anthropogenic disturbance. The chamber was left in place to allow snow to accumulate through multiple snowfall events and undergo natural compaction. Once the snowpack reached the chamber's height of 20 cm, it was used as the experimental subject (Figure 3). This method ensured that all samples experienced similar deposition histories and external conditions,

thereby maximizing consistency in initial snow layer properties such as depth, density, and grain size.

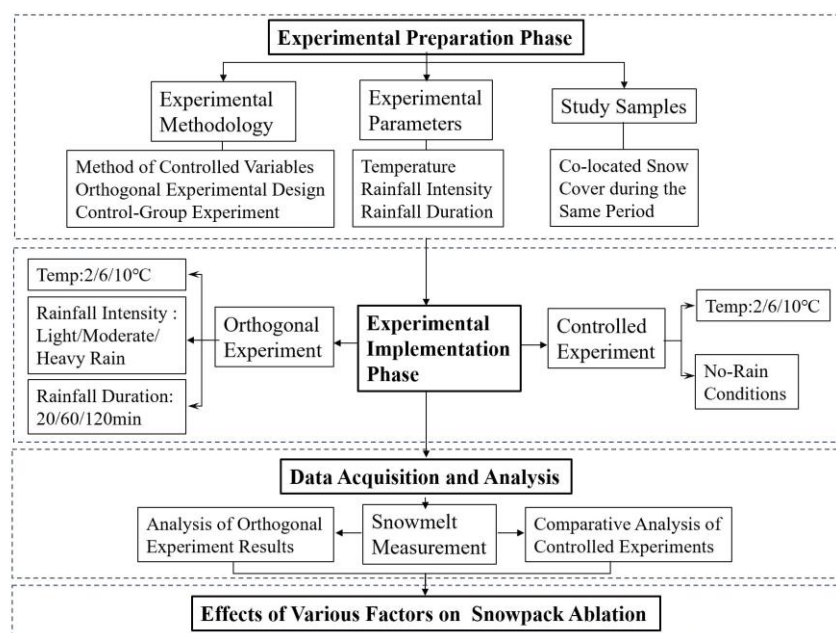


Figure 2. Technical approach. Each dashed box in the figure corresponds to the various stages of the study from top to bottom, and together with the content within, they collectively constitute the technical approach of this study.

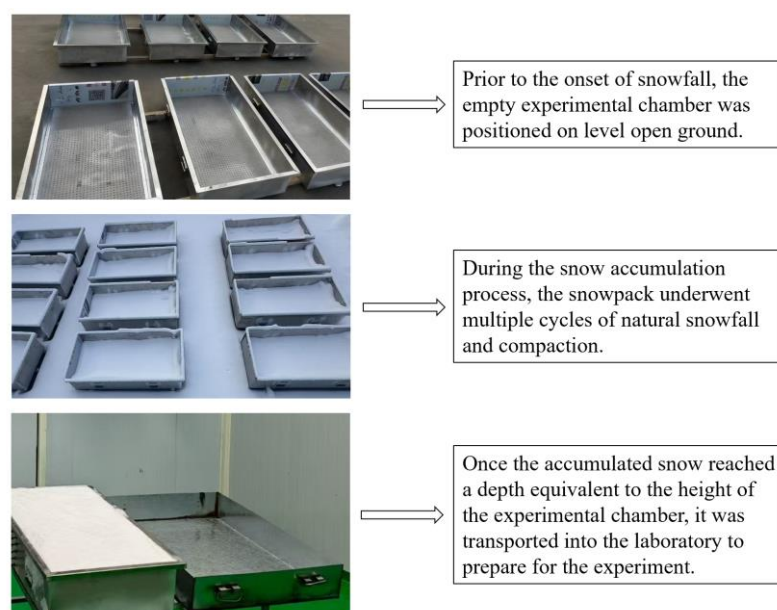


Figure 3. Schematic of snow collection process.

Rainfall intensity was measured using rain gauges, and these measurements were compared with rainfall intensities calculated from the total collected rainfall volume to ensure data reliability. Finally, meltwater volume was quantified using a combination of a measuring bucket and a graduated cylinder.

3. Results

3.1. Temperature Rise Increases Snowmelt Volume During ROS Events

Through experimental comparison, we analyzed the impact of ROS events on snowmelt volume under different temperature conditions (Figure 4). As illustrated, regardless of rainfall intensity, higher temperatures consistently resulted in greater snowmelt volumes. It is important to note that the snowmelt volume data shown in the figure includes both the 20 min ROS event period and a subsequent 40 min post-rainfall seepage period. Additionally, as defined in this study, the term ‘snowmelt volumes’ during the ROS period refers to the total outflow, comprising both meltwater and rainfall. Specifically, the snowmelt volumes were as follows:

- Under a rainfall intensity of $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$, snowmelt volumes were $3.15\text{ kg}\cdot\text{m}^{-2}$ at $2\text{ }^{\circ}\text{C}$, $4.64\text{ kg}\cdot\text{m}^{-2}$ at $6\text{ }^{\circ}\text{C}$, and $5.86\text{ kg}\cdot\text{m}^{-2}$ at $10\text{ }^{\circ}\text{C}$. The volume at $10\text{ }^{\circ}\text{C}$ was approximately 1.86 times that at $2\text{ }^{\circ}\text{C}$.
- Under a rainfall intensity of $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$, snowmelt volumes were $9.08\text{ kg}\cdot\text{m}^{-2}$, $13.07\text{ kg}\cdot\text{m}^{-2}$, and $15.58\text{ kg}\cdot\text{m}^{-2}$ at $2\text{ }^{\circ}\text{C}$, $6\text{ }^{\circ}\text{C}$, and $10\text{ }^{\circ}\text{C}$, respectively. The volume at $10\text{ }^{\circ}\text{C}$ was about 1.72 times that at $2\text{ }^{\circ}\text{C}$.
- Under a rainfall intensity of $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$, the corresponding snowmelt volumes were $60.95\text{ kg}\cdot\text{m}^{-2}$, $62.19\text{ kg}\cdot\text{m}^{-2}$, and $63.83\text{ kg}\cdot\text{m}^{-2}$, respectively, from low to high. The latter snowmelt volume was only about 1.05 times that of the former.

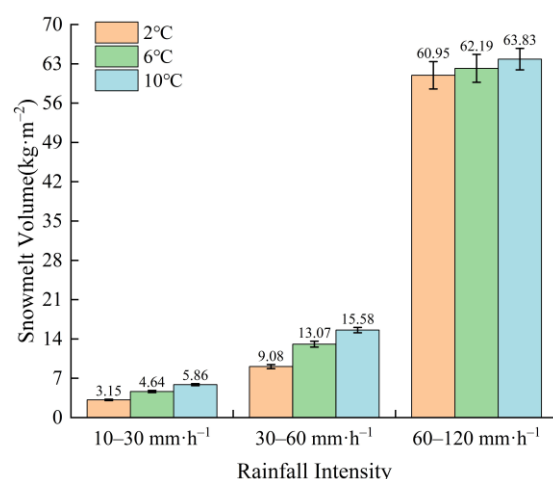


Figure 4. Variation in snowmelt volume under different temperatures. The total snowmelt volume comprises meltwater generated during both the 20 min ROS period and the subsequent 40 min seepage phase. Error bars indicate the uncertainty of the data in the figure.

These results indicate that during ROS events of varying rainfall intensities, snowmelt volume responds differently to temperature increases. Under low-rainfall-intensity conditions, temperature elevation induces a larger amplitude of increase in snowmelt volume, demonstrating a more pronounced effect of temperature. Conversely, under high-rainfall-intensity conditions, the increase in snowmelt volume attributable to warming is relatively limited, indicating a weaker influence of temperature.

Furthermore, we analyzed the temporal variation in snowmelt volume influenced by temperature during, and for a period after, the cessation of ROS events under different rainfall intensities, as shown in Figure 5. The figure demonstrates that during the ROS event, snowmelt volume increased rapidly due to the combined effects of temperature and rainfall. This compound effect also impacted snowmelt volume after the ROS event ceased. Specifically, the post-rainfall snowmelt volumes were as follows:

- Under a rainfall intensity of $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ (Figure 5a), the 40 min post-rainfall snowmelt volumes were $2.02\text{ kg}\cdot\text{m}^{-2}$, $2.63\text{ kg}\cdot\text{m}^{-2}$, and $3.09\text{ kg}\cdot\text{m}^{-2}$ at $2\text{ }^{\circ}\text{C}$, $6\text{ }^{\circ}\text{C}$, and $10\text{ }^{\circ}\text{C}$, respectively. The increase in snowmelt volume attributable to rising temperature was $1.07\text{ kg}\cdot\text{m}^{-2}$.
- Under a rainfall intensity of $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ (Figure 5b), the post-rainfall snowmelt volumes were $3.53\text{ kg}\cdot\text{m}^{-2}$, $3.94\text{ kg}\cdot\text{m}^{-2}$, and $4.14\text{ kg}\cdot\text{m}^{-2}$, respectively, with temperature causing an increase of $0.61\text{ kg}\cdot\text{m}^{-2}$ in snowmelt volume.
- Under a rainfall intensity of $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ (Figure 5c), the post-rainfall snowmelt volumes were $10.83\text{ kg}\cdot\text{m}^{-2}$, $10.89\text{ kg}\cdot\text{m}^{-2}$, and $11.12\text{ kg}\cdot\text{m}^{-2}$, showing a negligible increase of only $0.29\text{ kg}\cdot\text{m}^{-2}$.

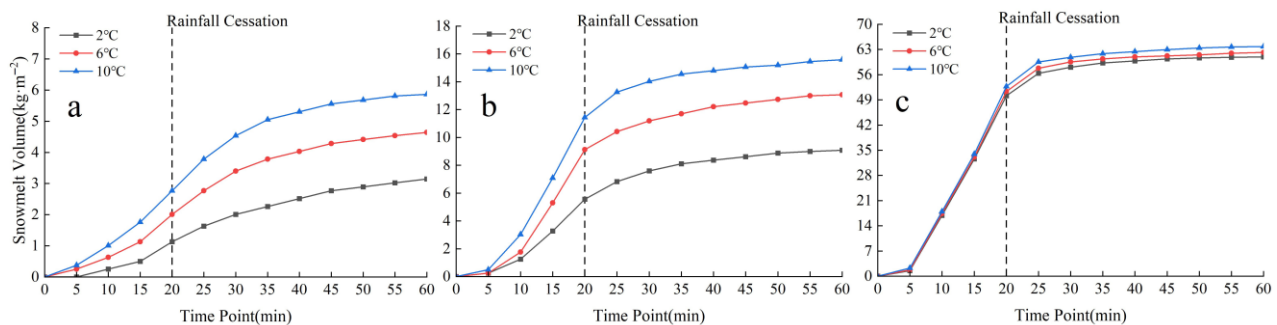


Figure 5. Temporal evolution of snowmelt volume driven by temperature variations across varying rainfall intensities. (a) $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$, (b) $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$, (c) $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$.

These findings further demonstrate that for ROS events under low rainfall intensity, the warming effect is more pronounced, and snowmelt volume exhibits greater dependence on ambient temperature. Additionally, with the exception of snowmelt volume produced under $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ rainfall, the increase in snowmelt volume with temperature was larger between 2 and $6\text{ }^{\circ}\text{C}$ than between 6 and $10\text{ }^{\circ}\text{C}$. For instance, under $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ rainfall, the snowmelt volume difference between 2 and $6\text{ }^{\circ}\text{C}$ was about 1.47-fold, while between 6 and $10\text{ }^{\circ}\text{C}$ it was about 1.26-fold. Under $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ rainfall, the differences were approximately 1.44-fold ($2\text{--}6\text{ }^{\circ}\text{C}$) and 1.19-fold ($6\text{--}10\text{ }^{\circ}\text{C}$). Therefore, this indicates the existence of a temperature threshold within the $2\text{--}6\text{ }^{\circ}\text{C}$ range for the snowpack during ROS events. When temperatures exceed this threshold range, the snowmelt rate likely accelerates, leading to increased snowmelt volume.

3.2. Increased Rainfall Intensity Significantly Enhances Snowmelt Volume During ROS Events

Figure 4 also illustrates the impact of ROS events with different rainfall intensities on snowmelt volume. As shown, high-intensity ROS events consistently induce rapid growth in snowmelt volume across varying temperature backgrounds. Under the same temperature conditions, snowmelt volume exhibits exponential growth with increasing rainfall intensity. Specifically, the snowmelt volumes were as follows:

- At $2\text{ }^{\circ}\text{C}$, the snowmelt volume under $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ rainfall was about 2.88 times that under $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$, while the volume under $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ rainfall was around 6.68 times that under $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$.
- At $6\text{ }^{\circ}\text{C}$, the $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ rainfall snowmelt volume was around 2.82 times the $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ rainfall volume, and the $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ rainfall volume was about 4.76 times the $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ rainfall volume.
- At $10\text{ }^{\circ}\text{C}$, the snowmelt volume under $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ rainfall was approximately 2.66 times that under $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$, and the volume under $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ rainfall was about 4.10 times that under $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$.

This phenomenon primarily arises because rainwater accelerates snow ablation through direct heat transfer and disruption of the snowpack structure, facilitating internal melting. This effect is more pronounced under high-intensity rainfall conditions. When ROS intensity is low, the heat input and disruptive capacity of rainwater are limited; consequently, ambient temperature becomes the dominant factor governing variations in snowmelt volume. However, as ROS intensity increases, the greater heat carried by the rainfall and its enhanced disruptive capacity enlarge pore spaces between snow grains and weaken snow grain bonds. Under these conditions, rainwater emerges as the primary driver of snowpack ablation, significantly influencing snowmelt generation [6,33].

Subsequently, we conducted a more in-depth analysis of the changes in snowmelt volume over time during and after rainfall caused by changes in ROS intensity at different temperatures (Figure 6). As shown, snowmelt volume increased during the 20 min ROS across different temperatures. However, the increase was relatively modest under low rainfall intensity, whereas a surge in snowmelt volume occurred under high intensity. Specifically:

- At 2 °C (Figure 6a), during the 20 min rainfall period, the snowmelt volume under 60–120 mm·h⁻¹ rainfall was approximately 43.35 times and 8.03 times greater than that under 10–30 mm·h⁻¹ and 30–60 mm·h⁻¹ rainfall, respectively.
- At 6 °C (Figure 6b), the snowmelt volume under 60–120 mm·h⁻¹ rainfall was around 24.52 times and 4.62 times greater than that under 10–30 mm·h⁻¹ and 30–60 mm·h⁻¹ rainfall, respectively.
- At 10 °C (Figure 6c), the snowmelt volume under 60–120 mm·h⁻¹ rainfall showed an approximate increase of 18.03 times and 3.61 times relative to that under 10–30 mm·h⁻¹ and 30–60 mm·h⁻¹ rainfall, respectively.

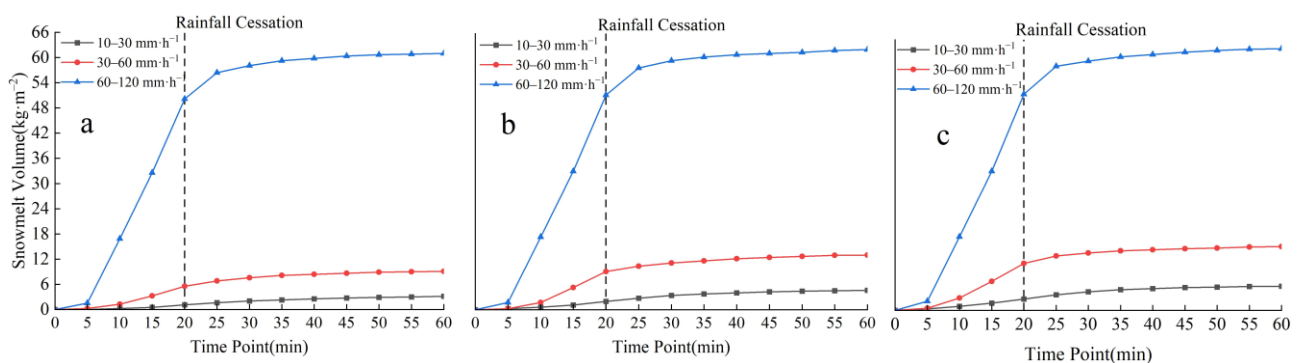


Figure 6. Temporal evolution of snowmelt volume driven by rainfall intensity variations under different temperature regimes. (a) 2 °C, (b) 6 °C, (c) 10 °C.

Consequently, when ROS intensity exceeds 60 mm·h⁻¹, snowmelt volume increases substantially, leading to significantly amplified snowmelt runoff. Furthermore, during the 40 min period after the ROS event ceased, the changes in snowmelt volume were relatively minor overall. Nevertheless, the observed differences also reflect the influence of various factors on snowmelt generation. These changes were as follows:

- At 2 °C (Figure 6a), the cumulative snowmelt volumes over the total 1 h period (rain and post-rain) for rainfall intensities of 10–30, 30–60, and 60–120 mm·h⁻¹ increased by 179%, 64%, and 22%, respectively, compared to the volumes measured at rainfall cessation.
- Similarly, at 6 °C (Figure 6b), the corresponding increases in snowmelt volume were 131%, 43%, and 21%, respectively.
- At 10 °C (Figure 6c), the increases were 112%, 36%, and 21% for the respective rainfall intensities.

These results demonstrate that regardless of temperature background, lower rainfall intensity correlates with stronger water retention capacity of the snowpack, and this effect becomes more pronounced at lower temperatures.

3.3. Snowmelt Volume During ROS Events Increases with Prolonged Rainfall Duration

To investigate the impact of ROS event duration on snowmelt volume, experiments were conducted with a background temperature of 6 °C under varying rainfall intensities. Figure 7 illustrates the differences in snowmelt volume resulting from ROS events with different rainfall durations. These differences encompass snowmelt volumes generated both during the rainfall period and during the subsequent 40 min post-rainfall period. As shown, snowmelt volume increased with longer rainfall duration across all ROS intensities. These changes were as follows:

- Under a rainfall intensity of 10–30 mm·h⁻¹, as rainfall duration increased from 20 min to 60 min to 120 min, snowmelt volumes rose from 4.64 kg·m⁻² to 21.35 kg·m⁻² to 46.41 kg·m⁻², representing an average increase of approximately 0.42 kg·m⁻² per minute, and an increase from 4.64 to 46.41 is 10-fold.
- Under a rainfall intensity of 30–60 mm·h⁻¹, snowmelt volumes increased to 13.07, 52.71, and 102.76 kg·m⁻² with increasing duration, increasing at an average rate of about 0.90 kg·m⁻² per minute, and an increase from 13.07 to 102.76 is 7.86-fold.
- Under a rainfall intensity of 60–120 mm·h⁻¹, the snowmelt volumes corresponding to different rainfall durations were 62.19 kg·m⁻², 172.62 kg·m⁻², and 331.12 kg·m⁻², respectively, showing an average increase rate of approximately 2.69 kg·m⁻² per minute, and an increase from 62.19 to 331.12 is 5.32-fold.

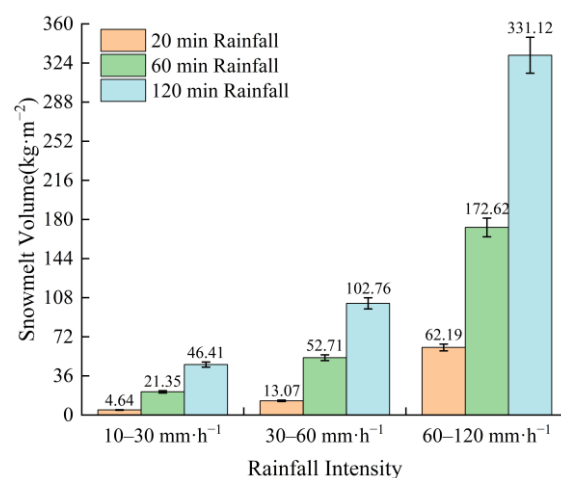


Figure 7. Variation in snowmelt volume under varying rainfall durations. Error bars indicate the uncertainty of the data in the figure.

These results demonstrate that prolonging the duration of ROS events significantly increases snowmelt volume, and the effect of extended duration is more pronounced under weaker rainfall intensities. This indicates that the increase in snowmelt volume attributable to longer rainfall duration is far greater under low-intensity conditions compared to high-intensity conditions. However, overall, higher ROS intensities contribute more substantially to the total increase in snowmelt volume.

Furthermore, by comparatively analyzing the temporal variations in snowmelt volume during the rainfall period and for a period afterward, resulting from ROS events of varying durations under different rainfall intensities, we obtained the impact of different rainfall durations on snowmelt volume across varying intensity backgrounds (Figure 8). The figure reveals that under different rainfall durations, low-intensity ROS events exhibit a

relatively slower initial ablation rate which subsequently accelerates. Conversely, high-intensity rainfall displays the opposite pattern: a rapid initial ablation rate followed by a deceleration. Overall, the snowmelt volume curves for all intensities demonstrate a rapid flattening after rainfall cessation. Specifically, the snowmelt volumes were as follows:

- Under a rainfall intensity of $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ (Figure 8a), the snowmelt volume for a 120 min duration was approximately 20.82 times that for a 20 min duration. Similarly, the snowmelt volume generated during the 40 min post-rainfall period for the 120 min event was about 1.74 times that for the 20 min event.
- Under a rainfall intensity of $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$ (Figure 8b), the snowmelt volume for 120 min was approximately 10.61 times that for 20 min, while the post-rainfall snowmelt volume for 120 min was about 1.49 times that for 20 min.
- Under a rainfall intensity of $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ (Figure 8c), the snowmelt volume for 120 min was approximately 6.21 times that for 20 min, whereas the post-rainfall snowmelt volume for the former was only around 1.14 times that of the latter.

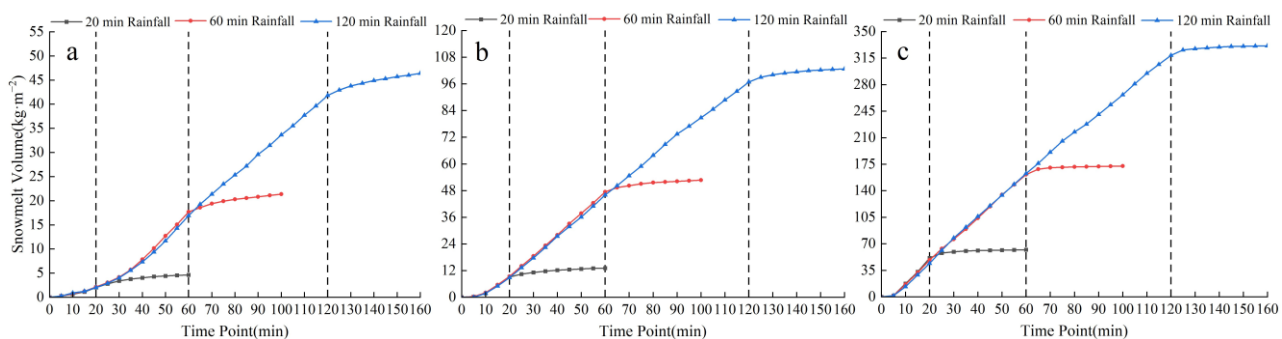


Figure 8. Temporal evolution of snowmelt volume driven by changing rainfall duration under different rainfall intensities. (a) $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$, (b) $30\text{--}60\text{ mm}\cdot\text{h}^{-1}$, (c) $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$. The dashed lines indicate the cessation time of rainfall for varying rainfall durations.

These findings indicate that under low-intensity rainfall conditions, snowmelt volume is more dependent on temporal accumulation effects both during rainfall and in the subsequent period. Rainwater requires longer to infiltrate the snowpack, continuously providing liquid water and latent heat, thereby gradually increasing snowmelt volume. In contrast, high-intensity rainfall achieves substantial snowmelt volume rapidly, demonstrating short-term efficiency. Extending the duration under high intensity yields diminishing relative returns, resulting in a lower growth rate of snowmelt volume compared to low-intensity conditions.

Additionally, prolonged low-intensity rainfall can achieve snowmelt volumes comparable to short-duration high-intensity events. For instance, 120 min of low-intensity rainfall yielded 82% of the snowmelt volume generated by 20 min of high-intensity rainfall. Therefore, the occurrence of prolonged, low-intensity ROS events also warrants heightened vigilance, particularly in mountainous regions.

3.4. The Snowmelt-to-Rainfall Ratio Increases with Both Rainfall Intensity and Duration

To avoid confusion regarding the snowmelt-to-rainfall ratio, the snowmelt volumes in this section refer only to snowmelt generated during the rainfall period, excluding that from the post-rainfall seepage phase. We calculated the snowmelt-to-rainfall ratio for ROS events under a uniform temperature condition of $6\text{ }^{\circ}\text{C}$, as summarized in Table 2. The results indicate that when the ratio is below 100%, the snowmelt volume is less than the rainfall volume. In this scenario, most rainwater reaching the snowpack is absorbed and retained within the snow matrix. Conversely, when the ratio exceeds 100%, the snowmelt volume

surpasses the rainfall volume, with the excess portion representing the net snowmelt contribution (i.e., snowpack ablation excluding the rainfall volume itself). As shown in the table, the snowmelt-to-rainfall ratio increases with both longer duration and higher intensity, although the increase driven by higher rainfall intensity generally results in a larger incremental gain in the ratio. Specifically, the ratios were as follows:

- Under the $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ intensity, extending the rainfall duration from 20 min to 120 min raised the ratio from 26.46% to 91.83%, an increase of 65.37 percentage points.
- In contrast, for a fixed 20 min rainfall duration, increasing the intensity from $10\text{--}30\text{ mm}\cdot\text{h}^{-1}$ to $60\text{--}120\text{ mm}\cdot\text{h}^{-1}$ elevated the ratio from 26.46% to 137.91%, an increase of 111.45 percentage points. This intensity-driven increase far exceeds that attributable to duration extension.

Table 2. The snowmelt-to-rainfall ratio under different conditions.

Rainfall Duration	Rainfall Intensity		
	$10\text{--}30\text{ mm}\cdot\text{h}^{-1}$	$30\text{--}60\text{ mm}\cdot\text{h}^{-1}$	$60\text{--}120\text{ mm}\cdot\text{h}^{-1}$
20 min	26.46%	62.61%	137.91%
60 min	76.43%	98.59%	142.83%
120 min	91.83%	110.28%	145.79%

Furthermore, as rainfall duration increases, the marginal gain in the ratio resulting from a further increase in duration diminishes at higher intensities. Similarly, for longer durations, the marginal gain in the ratio from a further increase in intensity also decreases. Therefore, while the snowmelt-to-rainfall ratio increases with both rainfall intensity and duration, the rate of this increase diminishes as either intensity or duration grows.

3.5. ROS Events Significantly Enhance Total Snowmelt Volume

Based on the no-rain control experiments in this study, Figure 9 presents the variation in snowmelt volume under solely temperature's influence. Over the 6 h experimental period, snowmelt volume at $2\text{ }^{\circ}\text{C}$ was minimal, with no snowmelt occurring between hours 3 and 5. At $6\text{ }^{\circ}\text{C}$, snowmelt volume changed very little in the first 2 h and amounted to only $0.88\text{ kg}\cdot\text{m}^{-2}$; however, after 3 h, snowmelt volume increased significantly and the snow ablation rate accelerated. At $10\text{ }^{\circ}\text{C}$, the overall ablation rate was consistently high. In terms of total volume, the snowmelt generated over 6 h at $2\text{ }^{\circ}\text{C}$, $6\text{ }^{\circ}\text{C}$, and $10\text{ }^{\circ}\text{C}$ was $1.00\text{ kg}\cdot\text{m}^{-2}$, $6.06\text{ kg}\cdot\text{m}^{-2}$, and $9.90\text{ kg}\cdot\text{m}^{-2}$, respectively, while the average snowmelt per hour was only $0.17\text{ kg}\cdot\text{m}^{-2}$, $1.01\text{ kg}\cdot\text{m}^{-2}$, and $1.65\text{ kg}\cdot\text{m}^{-2}$. Notably, the snowmelt volume at $10\text{ }^{\circ}\text{C}$ was approximately 9.90 times that at $2\text{ }^{\circ}\text{C}$, representing a significantly greater increase attributable to temperature than observed under rainfall conditions. However, the absolute snowmelt volumes were markedly lower than those generated during ROS events. Furthermore, similarly to the previously described temperature-influenced ablation under ROS, the same $4\text{ }^{\circ}\text{C}$ total temperature difference (from $2\text{ }^{\circ}\text{C}$ to $6\text{ }^{\circ}\text{C}$ and $6\text{ }^{\circ}\text{C}$ to $10\text{ }^{\circ}\text{C}$) was present, but the proportional differences in snowmelt volume between the intervals were substantial: the volume difference between 2 and $6\text{ }^{\circ}\text{C}$ was 6.06-fold, while between 6 and $10\text{ }^{\circ}\text{C}$ it was only 1.63-fold. Compared to the temperature-induced fold-differences observed under ROS conditions, these differences are significantly larger. This indicates that rainfall reduces the heat deficit from ambient temperature, resulting in greater overall snowmelt production.

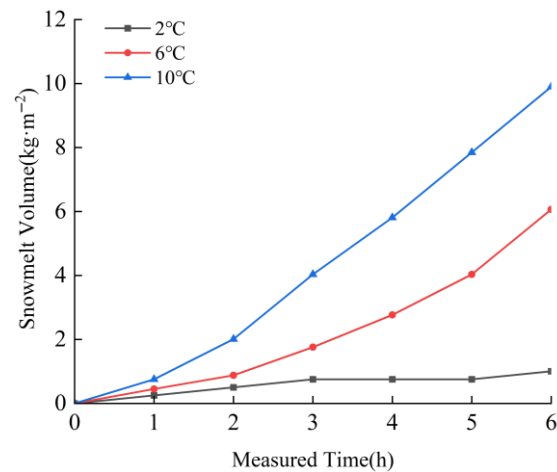


Figure 9. Snowmelt volume variation with temperature in the absence of rainfall.

Subsequently, we compared snowmelt volumes after 1 h and 2 h durations under no-rain conditions versus ROS events of varying intensities at a background temperature of 6 °C (Table 3). Snowmelt volumes for the 20 min no-rain condition were excluded from comparison due to negligible values ($<0.1 \text{ kg}\cdot\text{m}^{-2}$). As shown in the table, under the influence of temperature alone with no rain, the snowmelt volume after 1 h and 2 h was only $0.45 \text{ kg}\cdot\text{m}^{-2}$ and $0.88 \text{ kg}\cdot\text{m}^{-2}$, respectively. The average melt rate over the first two hours was approximately $0.007 \text{ kg}\cdot\text{m}^{-2}$ per minute. However, when rainfall occurred, the snowmelt volume increased rapidly due to the effect of ROS. Under the $10\text{--}30 \text{ mm}\cdot\text{h}^{-1}$ rainfall intensity, the snowmelt volume increased by a factor of 38.27 after 1 h and by a factor of 46.55 after 2 h, compared to conditions with no rain, increasing at an average rate of approximately $0.349 \text{ kg}\cdot\text{m}^{-2}$ per minute. Under the $30\text{--}60 \text{ mm}\cdot\text{h}^{-1}$ condition, the snowmelt volume increased by more than 100 times compared to no-rain conditions, with an average growth rate of $0.807 \text{ kg}\cdot\text{m}^{-2}$ per minute. Under the $60\text{--}120 \text{ mm}\cdot\text{h}^{-1}$ condition, the snowmelt volume increased by over 300 times, with an average growth rate of $2.656 \text{ kg}\cdot\text{m}^{-2}$ per minute. Consequently, compared to no rain, the occurrence of ROS events leads to a significant increase in snowmelt rates, with snowmelt volume increasing rapidly and rising further in response to greater rainfall intensity.

Table 3. Snowmelt volume comparison at 1 h and 2 h intervals across various rainfall conditions.

Rainfall Conditions	No-Rain Conditions	10–30 mm·h ^{−1}	30–60 mm·h ^{−1}	60–120 mm·h ^{−1}
1 h Snowmelt Volume (kg·m ^{−2})	0.45	17.67	47.38	161.28
2 h Snowmelt Volume (kg·m ^{−2})	0.88	41.84	96.89	318.66

4. Discussion

Synthesizing the impacts of temperature, rainfall intensity, and duration on snowmelt volume, rainfall intensity emerges as the primary consideration during ROS events, followed by rainfall duration and ambient temperature. Temperature and rainfall, as important factors governing snow ablation and snowmelt runoff, have been confirmed in numerous studies [34–36]. Our findings regarding temperature-driven ablation align strongly with Scaff et al. [37], confirming that rising temperatures accelerate snowpack degradation. Regarding rainfall intensity, Singh et al. [28] and Eiriksson et al. [31] established that high-intensity rainfall rapidly enhances ablation rates and accelerates meltwater generation. Conversely, low-intensity rainfall exerts minimal ablation influence, consistent with our intensity-dependent snowmelt observations. For rainfall duration, Sanders et al. [38] provide supporting evidence for our conclusion that prolonged low-intensity

rainfall can generate hazardous snowmelt volumes, demonstrating the cross-intensity significance of temporal factors. Concurrently, for the control experiments with no rain, the study by Yang et al. [20] indirectly demonstrated that rainfall substantially increases liquid water content within the snowpack compared to no-rain conditions, triggering rapid melting within short timeframes and generating substantial meltwater output.

Additionally, beyond external factors like temperature and rainfall influencing snowmelt during ROS events, Rücker et al. [39] demonstrated that whether light rain enhances runoff generation depends critically on snowpack characteristics. Consequently, snowmelt volume formation is also governed by the initial state of the snowpack (e.g., snow age, depth). Existing research indicates that under shallow-snow conditions, ROS may induce ice crust formation at the snow surface [40], impeding meltwater outflow. Concurrently, studies confirm that fresh snow layers exhibit greater water retention capacity than older, denser snow [29], enabling more rainwater storage within the snow matrix and reducing outflow.

Based on the above results and the limitations and shortcomings of this study, to better approximate the real-world conditions of snowpack ablation and snowmelt volume generation during natural states, in subsequent experiments, we will further incorporate various factors influencing snowmelt and conduct a more in-depth analysis of how varying snow depths and snowpack ages might affect snowmelt volume during ROS events. Furthermore, the experimental design will be refined by implementing more granular temperature levels and rainfall duration intervals. The additional experimental insights gained will be utilized to enhance the parameterization of hydrological models in future research, thereby improving the accuracy of existing models for assessing whether a specific ROS event is likely to trigger mixed rain–snow floods and determining the necessity of corresponding forecasting and early warning measures.

5. Conclusions

This study employed controlled laboratory experiments with simulated rainfall to investigate the impact of ROS events on snowmelt volume under varying conditions. Concurrently, to better demonstrate the direct impact of rainfall on snow ablation, we established control experiments to track snowmelt variation under no-rain conditions. Through systematic observation and comparative data analysis of snowmelt volumes across temperature levels, rainfall intensities, and rainfall durations, we derive the following key conclusions:

- (1) ROS events significantly accelerate snow ablation rates and promote rapid increases in snowmelt volume compared to temperature-driven melting alone.
- (2) Under high-intensity rainfall, snowmelt volume exhibits weaker temperature dependence. Conversely, low-intensity conditions demonstrate greater sensitivity to temperature variations and stronger reliance on ambient temperature. A distinct temperature threshold exists within the 2–6 °C range for snowpacks under low rainfall intensity, and exceeding this threshold accelerates ablation rates and amplifies melt volume.
- (3) Rainwater constitutes the primary driver of snowpack ablation during high-intensity ROS events, critically influencing snowmelt generation. When rainfall intensity exceeds $60 \text{ mm} \cdot \text{h}^{-1}$, snowmelt volume increases substantially, triggering amplified snowmelt runoff. Additionally, snowpacks exhibit stronger rainwater retention capacity under low-intensity ROS, with this effect becoming more pronounced at lower temperatures.
- (4) Snowmelt volume increases with longer rainfall duration across all intensity regimes. The relative enhancement in snowmelt volume per unit time extension is greater

under low rainfall intensity. Furthermore, snowmelt generation under low-intensity conditions demonstrates stronger dependence on temporal accumulation effects, while high-intensity rainfall achieves substantial snowmelt volumes rapidly with short-term efficiency.

Author Contributions: Conceptualization, W.L., S.D., and K.H.; methodology, W.L., S.D., and K.H.; validation, W.L., K.H., and G.H.; formal analysis, W.L. and K.H.; investigation, W.L., K.H., and L.J.; resources, S.D. and G.H.; data curation, W.L., G.H., and L.J.; writing—original draft preparation, W.L.; writing—review and editing, S.D. and K.H.; visualization, W.L.; supervision, S.D. and G.H.; project administration, S.D. and G.H.; funding acquisition, S.D. and G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Tianshan Elite Leading Talents Project of Xinjiang Uygur Autonomous Region (2022TSYCLJ0012), the Xinjiang Outstanding Young Scientist Fund (2024D01E14), the National Natural Science Foundation of China (42361004), and the Project of Xinjiang Tarim River Basin Authority (TGJYHZX-2025ZXFW0012).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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