Spatiotemporal Shift and Heterogeneity of Rain-on-Snow Events

Serhan Yeşilköy[1,2*], Özlem Baydaroğlu[3]

[1] Istanbul Provincial of Agriculture and Forestry, Turkish Ministry of Agriculture and Forestry, Istanbul, Türkiye

[2] Oak Ridge Institute for Education and Science, Oak Ridge, Tennessee, USA

[3] IIHR-Hydroscience & Engineering, University of Iowa, Iowa City, Iowa, USA

* Corresponding author: S. Yeşilköy (serhan-yesilkoy@uiowa.edu)

Abstract

The rapid snowmelt that typically occurs after snow accumulates at low temperatures and precipitation develops at higher temperatures is a defining characteristic of rain-on-snow (ROS). In ROS events, the significance lies not only in the spatial variability of snow coverage but also in factors like snow depth, variations in rainfall over time and space, rates of snowmelt, topographic conditions, saturation of soil moisture, vegetation, and surface roughness. During ROS events, the swift release of melted snow water can result in flash floods and a substantial surge in runoff, which in turn can lead to the overflow or elevation of rivers and consequently severe inundation and flooding. This study reveals the climatology of ROS events and examines the connections between ROS events and surface runoff quantities, aiming to contribute to flood projections and snow research for Türkiye, specifically focusing on the regions in the north and east of the country that receive substantial snowfall and have previously encountered serious flooding. The findings indicate a decline in ROS events in the Eastern and Southeastern Anatolia regions, particularly throughout the past three decades, while there has been an increase in the Central and Western Black Sea regions. The decline in the quantity of ROS (rainfall over snow) in the Southeastern Anatolia region, which serves as the primary water source for Turkey, is a favorable outcome as it leads to a decrease in the risk of floods, a longer duration of snow cover, and the feeding of water resources. Given the rise in ROS events in the Central and Western Black Sea regions, it is imperative to formulate novel urbanization strategies to mitigate potential flood risks and minimize associated damages that consider the region's topography, urbanization, and precipitation patterns. In addition, the results reveal a startling new trend: ROS events are shifting both spatially and temporally.

Keywords: Rain-on-Snow, Extreme Events, Climate Variability, Runoff, Türkiye

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1. Introduction

Rain-on-snow (ROS) events are multivariate hydrometeorological occurrences when precipitation in the form of rain falls onto a layer of snow, causing the snow to melt. This phenomenon may exacerbate the risk of flooding (Velásquez et al., 2023), snow avalanches (Stimberis and Rubin, 2011), summer drought (Myers et al., 2021), and landslides (Pall et al., 2019). This is because the combination of precipitation and snow leads to a larger volume of water, which can cause rivers and streams to result in an augmented water volume, potentially inducing rivers and streams to overflow (Ohba and Kawase, 2020). The crucial factor that influences the risk of flooding in ROS is antecedent snowfall conditions, which vary substantially with elevation. ROS events are often accompanied by strong snowmelt due to high latent heat flux and incoming long-wave radiation that reduces the radiative cooling of the snowpack. Consequently, significant precipitation might facilitate the occurrence of flooding events (Wever et al., 2014). When the snowpack is deep, like at high elevations, it can cushion rainfall until it melts and achieves saturation, limiting runoff. Shallow snowpacks contribute little to runoff (Marks et al., 1998; Jennings and Jones, 2015). Therefore, a ROS flood requires large precipitation on a substantial snowpack in order to cause melting and discharge. A high number of ROS happenings might have detrimental effects on agriculture (Hoffman et al., 2019), as the sudden thawing can lead to the submergence of agricultural lands, hence adversely affecting crop production. This phenomenon also possesses the capacity to generate detrimental consequences for wildlife habitats (Putkonen et al., 2009) and disrupt the balance of nature (Callaghan and Johansson, 2021).

In recent years, studies have been done to examine the spatiotemporal variations and trends of ROS events, notwithstanding their environmental implications and socio-economic impacts (Beniston and Stoffel, 2016; Mooney and Lee, 2022). ROS events, although rare, have a significant impact when they occur, happening only a few times per year. In the literature, there are ROS studies conducted diverse environments, including across Western North America (McCabe et al., 2007; Musselman et al., 2017), high latitude regions (Pall et al., 2019), snow-dominated watersheds (Sezen et al., 2020) and basins (Myers et al., 2021; Yeşilköy et al., 2023), as well as mountainous environments (Schirmer et al., 2022; López-Moreno et al., 2021) associated with climate extremes such as peak flow (Surfleet and Tullos, 2013), riverine and flash flood (Brunner and Fischer, 2022) events. Some studies also focused on the climate projection of ROS under different climate projections (Mooney and Li, 2021; Schirmer et al., 2022; Myers et al., 2023).

Researchers extensively study the potential impacts of climate change on water resources using global circulation models (GCMs; Turkes et al., 2020) and hydrological models (Dembélé et al., 2022). It is worth noting that Türkiye is situated in the Mediterranean Region, which is particularly vulnerable to climate change (Spinono et al., 2020). A number of hydrometeorological and hydroclimatological extremes like droughts (Yeşilköy and Şaylan, 2021), floods (Haltas et al., 2021; Bağçaci et al., 2021; Baydaroğlu and Demir, 2023), runoff (Yucel et al., 2014), snowmelt (Şensoy et al., 2023), and other atmospheric extremes like temperature extremes (Kelebek et al., 2021), tornados (Kahraman and Markowski, 2014) and thunderstorms (Kahraman et al., 2020) have been increasing in a changing climate across this region. Furthermore, according to EM-DAT (https://public.emdat.be/data), more than 1.8 million residents suffered and 4.3 billion US dollars was calculated as total damage from flood events. Snowmelt is one of the most triggering drivers contributing to the most extreme floods in spring and summer floods in Türkiye between 1960-2014 years (Koç et al., 2020).

There are some efforts in snow-related studies in various basins of Türkiye. Özdoğan (2011) investigated the snow reliability in the Euphrates-Tigris basin in the 21st century. Bozkurt et al. (2021) evaluated the influence of African atmospheric rivers on snowmelt in the

Euphrates-Tigris basin. Şensoy et al. (2023) simulated two hydrological models based on the GCM results to investigate snowmelt in two headwaters of the Euphrates basin. Tekeli et al. (2005) and Sönmez et al. (2014) conducted studies to examine the representativeness of remotely sensed data. They utilized MODIS snow cover data to model snowmelt and analyze the trend of snow cover, respectively. Sorman and Beser (2013) also investigated passive microwave data to model snow water equivalent (SWE). Peker and Sorman (2021) performed the SWAT model to quantify changes in SWE under two climate projections (RCP 4.5 and 8.5). The common feature of all these studies is that researchers focused on certain (i.e., Euphrates and some parts of this watershed) watersheds located in the mountainous areas of Türkiye. Yucel et al. (2015) quantified the impact of climate change on snowmelt based on station data. In addition, Özgür and Koçak (2019) conducted a study on the climatology of snowfall and total precipitation days. Their findings indicated that a majority of the monitoring stations in Türkiye had a decline in snowfall patterns.

In the literature, little is known about the large-scale characteristics of ROS events and their spatiotemporal variations and trends across Türkiye. From this point of view, a better understanding of the variability associated with ROS events is needed so that the effects and number of ROS events on changes in extreme surface runoff will allow for more accurate runoff and flood prediction studies. To fulfill this knowledge gap, the purpose of this study was to analyze the spatial and temporal variability and trends of ROS events and the impacts on extreme surface runoff since the 1964 water year across Türkiye. We additionally determined the spatiotemporal shifts of ROS events as well as the trends and changes in SWE and precipitation.

This paper is structured as follows: Section 2 provides a detailed description of the study area, data used, and calculations performed for the definition of a ROS occurrence. The spatiotemporal variation, trends, and shift of ROS events and densities based on watersheds and their impact on extreme surface runoff can be found in Section 3. We also calculated the spatial variations of SWE and precipitation. Within Section 4, we compare our results to the related studies and emphasize the importance of snow-related studies and their impacts on extreme runoff in a changing climate.

2. Materials and Methods

2.1 Study Area

To investigate climate change impacts on ROS events, we focused on basins where ROS events occur most across Türkiye (Fig. 1). There are important water resources projects (such as the Southeastern Anatolia Project (Güneydoğu Anadolu Projesi (GAP) in Turkish) in these basins, and residents earn their livings with snow and plateau tourism, agriculture, and livestock. Therefore, the number and timing of ROS events are of vital importance for the safety of life and property of locals.

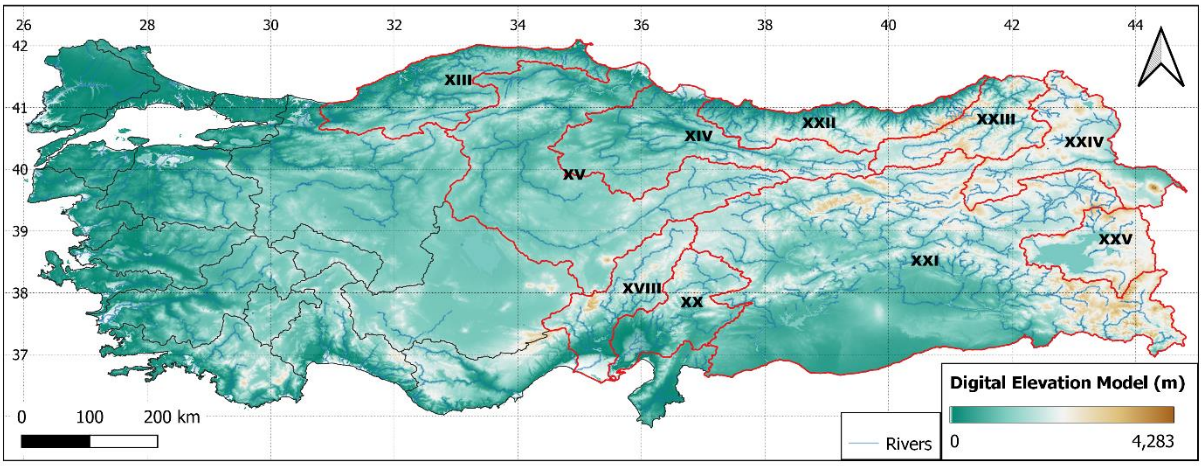


Figure 1. Digital elevation map of Türkiye. Red lines represent borders of 10 watersheds, Aras (XXIV), Western Black Sea (XIII), Ceyhan (XX), Çoruh (XXIII), Tigris Euphrates (XXI), Eastern Black Sea (XXII), Kızılırmak (XV), Van (XXV), Seyhan (XVIII), Yeşilırmak (XXIV), where ROS events occur most.

In this study, we focus on the mountainous part of Türkiye and cover 59.2% of the country. Blue lines represent the rivers and Table 2 shows which watershed the roman numerals represent.

2.2 Data

Hourly snow water equivalent (SWE, mm), rainfall (mm), and surface runoff (mm) were obtained from the European Centre Medium Weather Forecast (ECMWF) ERA5-land reanalysis data (Muñoz Sabater, 2019) with 0.1-degree spatial resolution between the water years 1964 and 2023.

From December to May, spanning the years 1964 to 2023, Figure 2 indicates the spatial distribution of SWE with a maximum value of 650 mm/month.

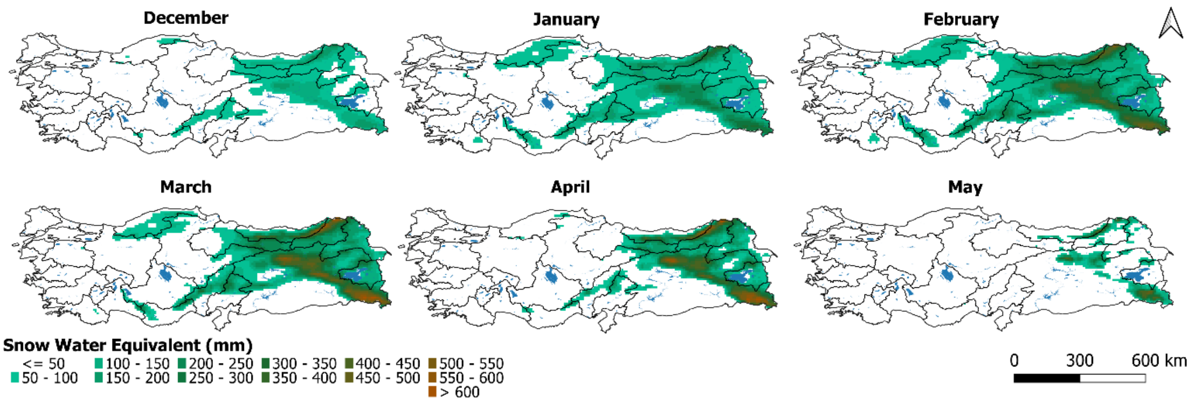


Figure 2. Spatial variability of monthly mean SWE between the years 1964 to 2023.

Based on the data presented in Figure 2, the Eastern Black Sea, Eastern Anatolia, and Southeastern Anatolia regions have significantly higher SWE values throughout the months of February, March, and April. The occurrence of snowfall during the months of March and April is especially remarkable.

2.3 Rain-on-Snow (ROS) Event Definition

There is no scientific consensus on the definition of ROS events. Most of the other ROS studies used less SWE values when compared to the present study, specifically 5 to 20 mm (Pall et al., 2019; Wachowicz et al., 2020). Ohba and Wasabe (2021) chose SWE values as 100 mm over Japan due to high elevation and minimal flat. Some studies also chose the precipitation value as 3, 5 or 10 mm/day (Freudiger et al., 2014; Li et al., 2019). We classified daily ROS with flood potential as heavy rainfall ≥10 mm falling on snowpack with SWE ≥ 50 mm where the sum of snowmelt with SWE decreases ≥ 20% (See Table 1). Finally, we calculated ROS events for each grid cell across Türkiye based on our approach and calculated monthly total by watersheds between the water years 1964 and 2023.

Table 1. Parameters and pivotal values of the parameters employed in the computation of ROS events.

Variable	Amount
Rainfall	≥10 mm
SWE	≥ 50 mm
Snowmelt	≥ 20%

2.4 Statistical Analysis

In order to capture trends in ROS events, the Modified Mann-Kendall (MMK) trend test was applied to monthly data using the significant level of α=0.05. Mann-Kendall (Mann, 1945; Kendall, 1990) is a non-parametric significance test which has been recommended by World Meteorological Organization (Mitchell Jr. et al., 1966) in climate and hydrometeorological trend detection studies (Blahušiaková et al., 2020). The MMK is proposed by Hamed and Rao (1998), adding a correction factor to the variance computation to avoid the effect of the temporal data autocorrelation. The MMK test is more acceptable than the original MK test for capturing trends in hydrometeorological events, and it also shows a low sensitivity to outliers, has no requirements for the sample to have a certain distribution, and it outperforms other widely used models (Daufresne et al., 2009; Hu et al., 2020).

In addition, spatial correlation, and spatial covariance between changes in ROS and surface runoff (90th percentile) were calculated as Eqs (1-2):

$$Cor(t,1) = \frac{\sum_{x\in S(t)} i_1(t,x) i_2(t,x) w(x) - \overline{i_1(t,x)}\ \overline{i_2(t,x)} \sum_{x\in S(t)} w(x)}{\sqrt{\left(\sum_{x\in S(t)} i_1(t,x)^2 w(x) - \overline{i_1(t,x)}^2 \sum_{x\in S(t)} w(x)\right)\left(\sum_{x\in S(t)} i_2(t,x)^2 w(x) - \overline{i_2(t,x)}^2 \sum_{x\in S(t)} w(x)\right)}} \tag{1}$$

$$Cov(t,1) = \left(\sum_{x\in S(t)} w(x)\right)^{-1} \sum_{xES(t)} w(x) \left(i_1(t,x) - \frac{\sum_{x\in S(t)} w(x) i_1(t,x)}{\sum_{x\in S(t)} w(x)}\right)\left(i_2(t,x) - \frac{\sum_{x\in S(t)} w(x) i_2(t,x)}{\sum_{x\in S(t)} w(x)}\right) \tag{2}$$

where $S(t) = \{x, i_1(t,x), i_2(t,x)\}$, $w(x)$ are the area weights obtained by input streams.

3. Results

The study analyzed a 60-year timeframe by separating it into two distinct intervals: the initial 30-year period (first episode) spanning from 1964 to 1993 and the subsequent 30-year period (second episode) from 1994 to 2023 to enhance the visibility of any observed changes. The delta symbol in the figures (Figure 5, 6 and 7) indicates the difference between the second episode and the initial episode.

Figures 3 and 4 display the number of days with rainfall higher than 10 mm and the number of ROS events, respectively, over the period from December to May, covering two episodes.

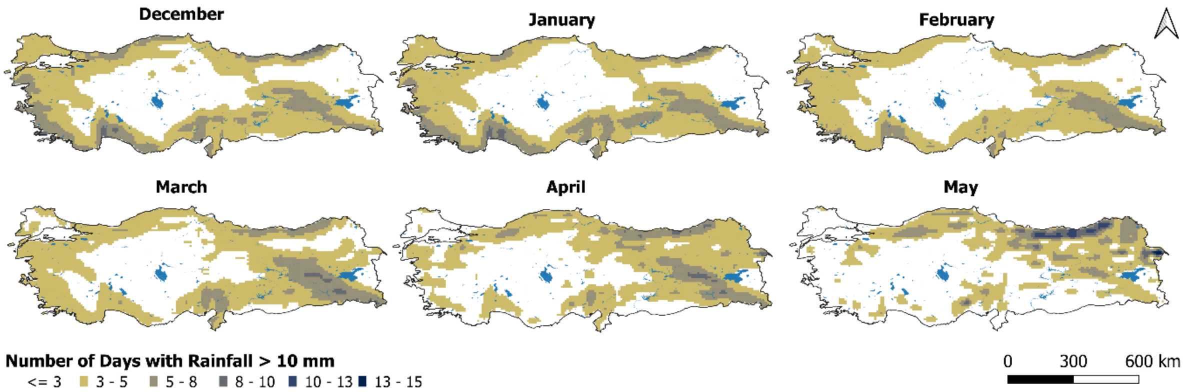


Figure 3. Spatial variability of precipitation over 10 mm, covering the years 1964-2023.

As seen in Figure 3, frontal and orographic rainfalls generally occur in coastal areas and high elevated regions, respectively. Maximum monthly rainfall amount was observed as high as 240 mm. Moreover, the Eastern and Southeastern Anatolia Regions receive rainfall from December to May, with the highest precipitation occurring in March and April. The Eastern Black Sea Region experiences precipitation throughout the year, with particularly high levels in March, April, and May.

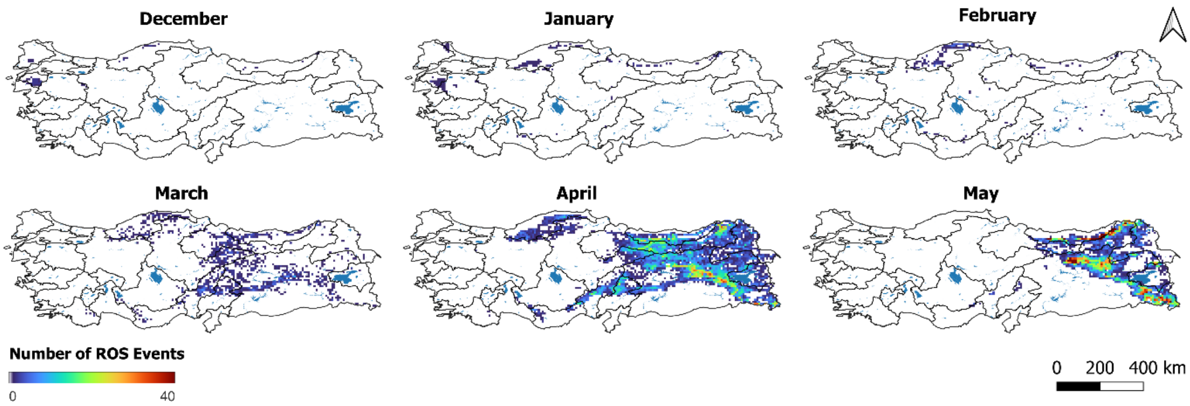


Figure 4. Spatial variability of the number of ROS events, covering the years 1964-2023.

ROS occurrences are observed in all regions depicted in Figure 4, except for the western and southern coastlines of Turkey, specifically the Aegean and Mediterranean Regions. However, the intensities of these events vary throughout the different regions. ROS occurrences are most prevalent during the months of April and May, primarily in the Eastern Black Sea, Eastern Anatolia, and Southeastern Anatolia regions.

Figure 5 illustrates the changes in snow cover between episodes 2 and 1. The decline in snowfall in central and eastern Turkey throughout the winter months is highly obvious as indicated in Figure 5. The most significant decrease is observed in March and April, followed by February and May. Snow is a superior means of replenishing groundwater compared to rainfall. This phenomenon can be linked to the gradual process of melting and the ability of the substance to penetrate the soil, therefore nourishing the groundwater. Hence, the scarcity of water can be attributed significantly to the phenomenon known as snow drought (Yeşilköy et al., 2023).

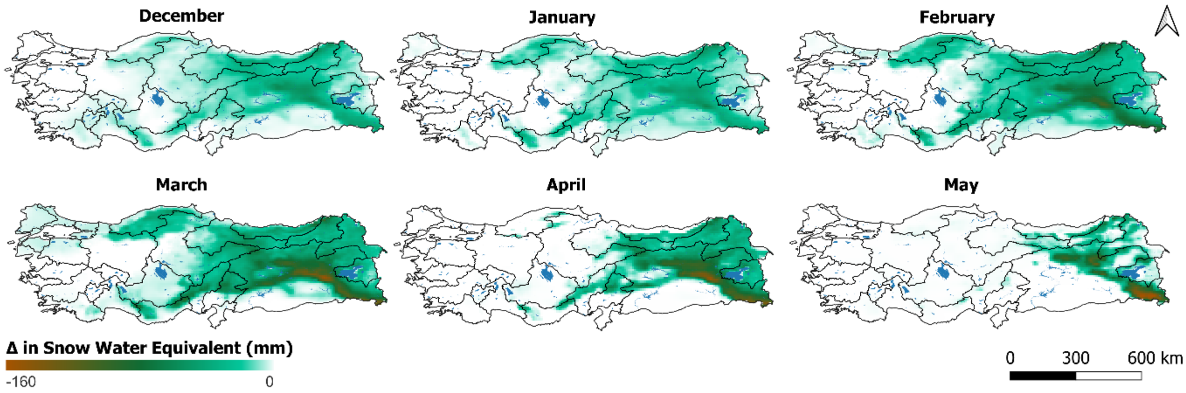


Figure 5. Changes in snow cover between episode 2 and episode 1.

Figure 6 shows SWE values by area in April and May. From this figure, it can be observed that the snow cover area reduced for all SWE levels when comparing the second episode to the first episode.

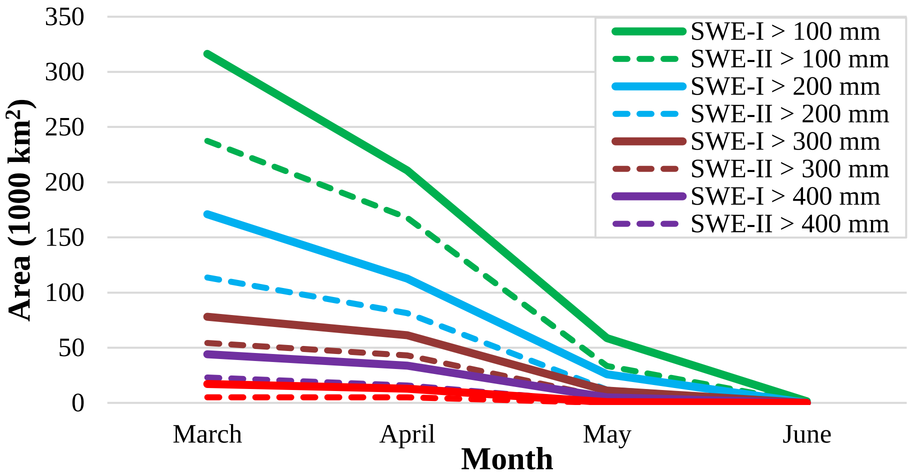
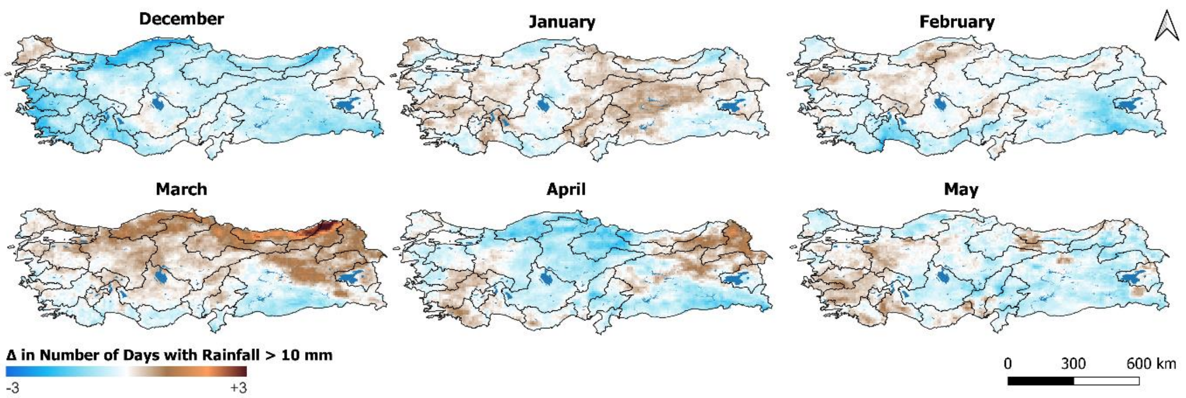


Figure 6. SWE values by area in March, April, and May. Solid lines represent the first episode (I) and dashed lines indicate the second episode (II).

Figure 7 (a) and (b) present the changes in the number of days with precipitation above 10 mm, and the fluctuations in the number of ROS events between episodes 2 and 1.

(a)



(b)

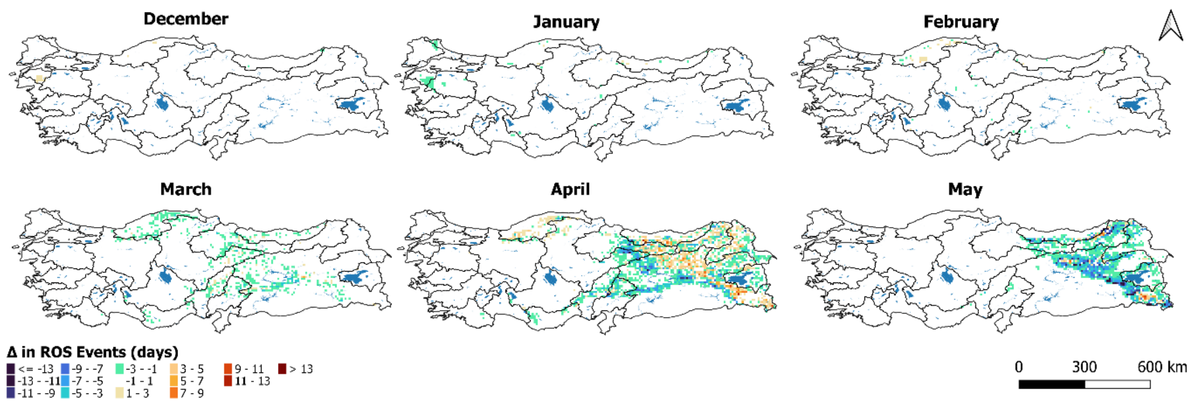


Figure 7. Between episodes 2 and episode 1, changes in (a) number of days with precipitation over 10 mm, and (b) the number of ROS events.

Based on Figure 7 (a), there is a notable decline in the frequency of days with precipitation over 10 mm across the entire country, particularly in the Black Sea and Aegean Regions, during the month of December. April follows December in terms of decrease in precipitation. In January, rainfall decreased in the coastal areas encircling the country on three sides, the Marmara, Central, and Southeastern Anatolia regions, but increased in the latter. Southeastern Anatolia Region precipitation decreases in February, following a similar pattern to January but more significantly. Precipitation decreased throughout May, except in the Aegean, Mediterranean, and Central Anatolia. Except for the Mediterranean coast and Southeastern Anatolia, March rainfall rises countrywide.

Figure 7 (b) illustrates a decline in ROS events in the Black Sea and Eastern Anatolia areas throughout March and May, as well as in the northern Mediterranean and Eastern Anatolia regions in April. However, there is an increase in certain portions of the Eastern Black Sea region. The average number of ROS incidents per year was 450.7 in the first episode, but it was determined to be 369.1 for the second episode.

Based on the episodes, the spatial and temporal variation ROS events in April and May as observed in the watersheds is shown in Figure 8 and Table 2.

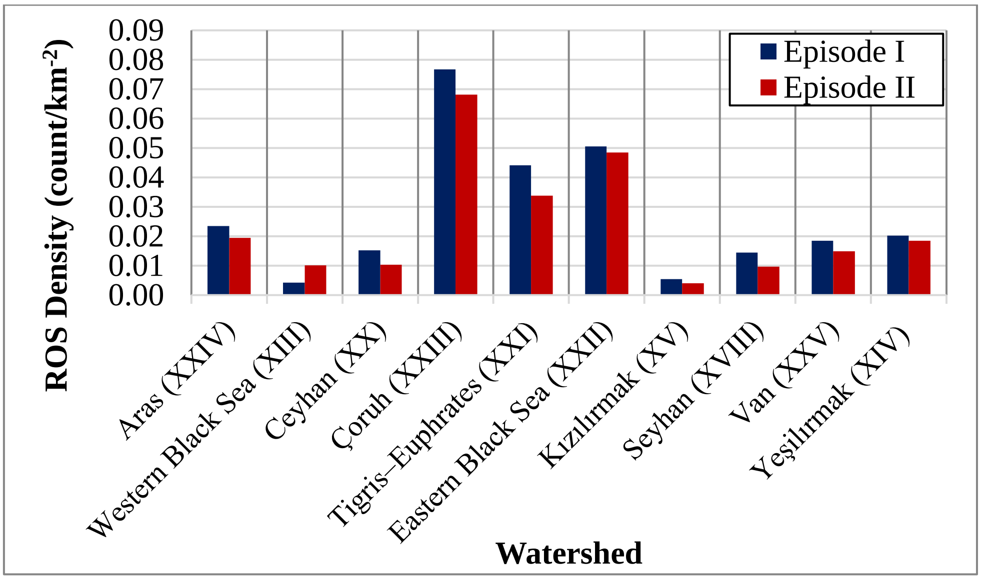


Figure 8. The spatial density of ROS events by watersheds.

Table 2. the temporal distribution of ROS events. According to Modified Mann-Kendall trend analysis ↑, ↓, and ⊙ symbols indicate significant positive, negative and no significant trend detected ($p<0.05$), respectively.

RoS Count/year	1964-1993		1964-2023		Changes (%)	
Watersheds	April	May	April	May	April	May
Aras (XXIV)	**8.5**	**13.5**	**11.9**	**6.3**	**+39.8% ↑**	**-53.0% ↓**
Western Black Sea (XIII)	4.1	0.0	9.7	0.0	+136.6%↓	-
Ceyhan (XX)	10.6	0.3	7.4	0.0	-30.5% ↓	-90.0% ↓
Çoruh (XXIII)	**18.9**	**32.9**	**21.5**	**24.5**	**+14.0% ↑**	**-25.6% ↓**
Tigris–Euphrates (XXI)	**120.4**	**139.5**	**117.4**	**81.8**	**-2.5% ⊙**	**-41.3% ↓**
Eastern Black Sea (XXII)	**15.5**	**22.9**	**19.2**	**17.7**	**+23.8% ↓**	**-23.0% ↓**
Kızılırmak (XV)	14.0	1.0	10.8	0.3	-22.7% ↓	-69.0% ↓
Seyhan (XVIII)	10.4	0.3	7.0	0.2	-32.7% ⊙	-50.0% ⊙
Van (XXV)	5.2	5.9	5.8	3.1	+11.5% ⊙	-46.6% ↓
Yeşilırmak (XIV)	**21.4**	**5.3**	**22.2**	**2.2**	**+3.6% ↓**	**-58.8% ⊙**

Figure 8 clearly illustrates the noticeable rise in ROS events in the Western Black Sea watershed, as well as the substantial decline in the Aras, Ceyhan, Çoruh, Tigris-Euphrates, Seyhan, Van, and Yeşilırmak watersheds. Moreover, there is an increase in ROS events in April in the Aras, Çoruh, Eastern Black Sea, Van, and Yeşilırmak basins, followed by a drop in May. There is a decline in the Ceyhan, Tigris-Euphrates, Kızılırmak, and Seyhan watersheds in both April and May. However, there is a significant rise in April, and there are no occurrences of ROS events in the Western Black Sea watershed in May. Upon evaluating the combined data for April and May, it becomes evident that there is a decrease in ROS occurrences in all watersheds, with the exception of the Western Black Sea watershed. The minimum and maximum values in SWE and precipitation change by watershed are detailed in Table 3.

Table 3. The minimum and maximum values in SWE and precipitation change.

	Range of SWE Change (mm)		Range of Precipitation Change (mm)	
Watersheds	April	May	April	May
Aras (XXIV)	-4.28; 25.72	-19.06; -1.11	-69.29; -0.15	-96.5; -0.07
Western Black Sea (XIII)	-33.24; -10.13	-14.79; 1.41	-34.64; 12.05	-2.18; 0.77
Ceyhan (XX)	-31.41; 1.3	-23.67; 12.47	-70.48; 0.48	-8.84; 0.27
Çoruh (XXIII)	-5.33; 21.23	-22.21; 2.76	-93.96; -15.59	-95.68; -0.34
Tigris–Euphrates (XXI)	-44.96; 16.31	-26.11; 8.29	-162.88; 0.38	-161.08; 0.42
Eastern Black Sea (XXII)	-26.91; 15.79	-19.77; 4.85	-79.32; 8.68	-69.66; -0.01
Kızılırmak (XV)	-30.6; -6.62	-21.51; 2.75	-71.06; 7.54	-30.81; 0.63
Seyhan (XVIII)	-34.08; 4.36	-25.75; 9.24	-57.34; 0.31	-13.38; -0.01
Van (XXV)	-13.22; 7.42	-14.16; 1.93	-78.27; -0.01	-83.97; -0.01
Yeşilırmak (XIV)	-35.39; 2.88	-19.38; -0.25	-55.57; 4.43	-36.17; -0.01

The table clearly indicates that the Tigris-Euphrates watershed exhibits the most significant variations in both SWE and precipitation throughout the months of April and May. Following the Tigris-Euphrates watershed, the Eastern Black Sea basin exhibits the biggest change in SWE during the month of April, whereas the Ceyhan and Seyhan basins experience substantial SWE change in May. The Çoruh watershed experienced the biggest precipitation change following the Tigris-Euphrates watershed in April, whereas the Aras basin had the highest precipitation change in May.

By analyzing the ROS event numbers in Figure 4 and the change in ROS event numbers in Figure 7 (b), while considering that the number of ROS events in April and May represents around 90% of the total ROS events in a year, the surface runoff change for April and May is presented in Figure 9.

As a result of ROS events, water quickly moves towards the surface, increasing surface runoff. This impact becomes particularly pronounced in areas with steep slopes and when the snow cover is saturated. Therefore, surface runoff values were also analyzed for the episodes. Figure 9 illustrates the alterations in surface runoff over the months of April and May, between episodes 1 and 2. These differences may be attributed to ROS events occurring during this period. The rise (in April) and decline (in May) of surface runoff align with the corresponding increase and drop of ROS occurrences throughout these months.

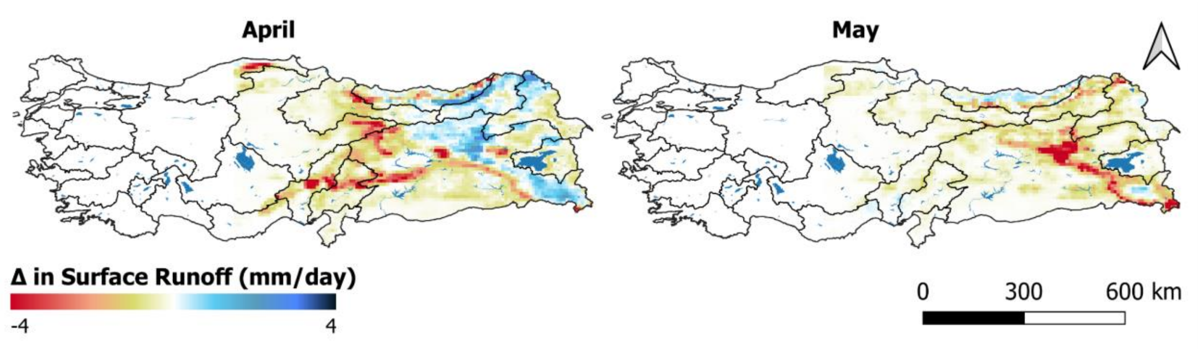


Figure 9. Between episodes 1 and 2, changes in surface runoff.

To assess the impact of increased surface flow caused by ROS events on extreme runoff, we estimated spatial correlation and spatial covariance for the months of April and May, during which the change in ROS was noticeable (refer to Table 4). These data indicate that alterations in ROS events have a substantial influence on extreme runoff, with a more pronounced correlation detected in May as opposed to April.

Table 4. Relationship between changes in ROS events and extreme runoff.

(spatial correlation; spatial covariance)	Change in extreme runoff (April)	Change in extreme runoff (May)
Change in ROS (April)	(0.33; 0.63)	-
Change in ROS (May)	-	(0.42; 0.71)

Table 5 shows the spatial correlation values between April and May for Episodes I and II, considering the shift in ROS events throughout those months. In April, Episodes I and II have a similarity of 76.2%, while in May, the resemblance is 88.3%. Put simply, the difference between the two occurrences is nearly double in April compared to May. The spatial correlation between April of Episode I and May of Episode II is significantly high. The resemblance between May and April, which follows a period of significant change, may be evidence that ROS events show a backward shift in time.

Table 5. Spatial correlation in ROS event counts between the episodes.

	April (E2)	May (E2)
April (E1)	0.76	0.16
May (E1)	0.52	0.88

4. Conclusion

ROS events refer to situations where rain falls onto existing snow cover. This meteorological phenomenon holds significant importance due to its potential impact on various environmental and societal aspects. ROS events can result in accelerated snowmelt, leading to heightened runoff and an elevated risk of flooding. In regions where snowpack plays a crucial role in water resource management, understanding and analyzing ROS events becomes essential for predicting water availability and mitigating potential hazards. Furthermore, the occurrence of rain on snow can influence ecosystems, agriculture, and infrastructure, making it a critical factor to consider in climate studies and risk assessments. Therefore, the analysis of rain-on-snow events contributes valuable insights for both scientific research and practical applications in managing water resources and minimizing the associated risks.

Based on the extensive analysis of the 60-year timeframe divided into two distinct episodes, it is evident that the study provides valuable insights into the changing dynamics of ROS events and their consequences in different regions of the country. In Türkiye, the average number of ROS events each year is 450.7 during the first episode (1964-1993), and 369.1 during the second episode (1994-2023). This is a reduction of 18.1%, attributable to the phenomenon of climate change. The focus on the Eastern and Southeastern Anatolia Regions, critical for the country’s water reservoirs, reveals a noteworthy decrease in SWE levels during the winter months. This decline in snowfall, particularly in March and April, raises concerns about groundwater replenishment, emphasizing the phenomenon known as snow drought.

Furthermore, the study highlights the variations in precipitation patterns, ROS events, and surface runoff across different regions. The Eastern Black Sea Region experiences increased precipitation throughout the year, contributing to higher ROS events. The spatial and temporal variations in ROS events for April and May indicate significant changes in watersheds, with the Western Black Sea watershed experiencing a rise in ROS events, contrasting with a decrease in other regions.

The most significant declines in ROS occurrences are observed in the Ceyhan, Kızılırmak, and Seyhan watersheds, respectively. The western Black Sea watershed has the most significant surge in ROS occurrences during the month of April. The escalation of ROS events is a significant concern that must be acknowledged in the context of flash floods and severe flooding incidents.

Table 3 reveals that the Tigris-Euphrates basin exhibits the most significant alterations in both SWE (Snow Water Equivalent) and precipitation throughout the months of April and May. Regarding SWE, the Eastern Black Sea basin exhibits the most significant variation in April, after the Tigris-Euphrates basin. In May, the basins with the biggest change are Ceyhan and Seyhan. The Çoruh basin experienced the greatest change in precipitation after the Tigris-Euphrates basin in April, while the Aras basin had the highest precipitation change in May.

Figure 7 (b) (April and May) and Table 5 conclusively demonstrate that ROS events undergo both spatial and temporal shifts. The decrease in ROS events in May can be explained by the increase in April in grid cells. In addition, Table 5 shows the spatial correlation between April and May for Episodes I and II, emphasizing a notable similarity between the two months. There is a significant spatiotemporal link between April of Episode I and May of Episode II, indicating a backward shift in ROS events.

The assessment of extreme runoff, influenced by the alterations in ROS events, demonstrates a substantial impact, particularly in May. The spatial correlation and spatial covariance analyses reveal the interconnectedness between ROS events and extreme runoff, emphasizing the importance of considering these factors in understanding the hydrological changes in the country.

In conclusion, the study underscores the critical role of ROS events in shaping hydrological patterns, emphasizing the need for comprehensive water resource management strategies, especially in regions sensitive to changes in snow cover and precipitation. The findings contribute valuable information for policymakers, researchers, and stakeholders involved in mitigating the potential risks associated with changing climate dynamics.

Credit Authorship Contribution Statement

Serhan Yeşilköy: Conceptualization; Methodology; Data Processing; Analysis; Writing – Original Draft.

Özlem Baydaroğlu: Data Processing; Analysis; Writing – Original Draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data used in this study can be publicly available: https://doi.org/10.24381/cds.e2161bac (Last accessed on 17.02.2024)

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