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Storylines for the 1997 New Year's Flood: The Role of Watershed Antecedent Conditions and Future Warming in Shaping Discharge in the Truckee River Watershed

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1 Introduction

Despite its arid climate, western Nevada is subject to inland-penetrating atmospheric rivers (ARs) and resultant extreme rainfall and flooding (e.g., Albano et al., 2016; Hatchett et al., 2017; Rutz et al., 2014, 2015; Yu, Hatchett, et al., 2023; Yu, Miller, et al., 2023).. The AR-driven New Year's flood event of 1997caused record floods and devastating socioeconomic impacts in numerous watersheds throughout Washington, Oregon, California, and Nevada (Lott et al., 1997; Western Region Headquarters, 1997). Following the catastrophic 1997 New Year's flood, both structural and nonstructural flood mitigation measures have been implemented in Western states such as California and Nevada (CADWR, 2022). With increased awareness of flood risks posed by rain-on-snow events, practitioners, residents, and scientists have wondered, *"if a flood event like 1997 happened in the future, would we be prepared* (e.g., Albano et al., 2016; Ombadi et al., 2023; Rhoades et al., 2024)*."*

Projected changes in precipitation, snowpack, and land surface conditions could alter runoff efficiency, with implications for future flood generation. Recent studies describing climate effects on precipitation in mid-elevation basins like the Truckee River watershed indicate the potential for more intense short-duration, precipitation events and decreasing precipitation snow fractions (Huang et al., 2020; Ombadi et al., 2023; Rhoades et al., 2024; Siirila-Woodburn et al., 2021). In addition, multi-model climate projections (Taylor et al., 2012) and theory (Siler & Roe, 2014) suggest changing storm characteristics, such as precipitation efficiencies, could lead to more spillover onto the leeside of mountain ranges (Huang et al., 2020; Koszuta et al., 2024). These spillover effects could be amplified or offset by how climate change alters land-atmosphere interactions, such as soil moisture and snowpack dynamics that moderate runoff potential. Although snowpacks are expected to diminish with climate change-induced warming (referred to as climate warming henceforth) due to increases in rain-to-snow fractions and earlier snowmelt (Musselman et al., 2021), snowpacks are also likely to have less cold content, which could increase runoff efficiencies of rain-on-snow events (Heggli et al., 2022). Changes in soil moisture during winter have the potential to be more variable in the future due to more precipitation falling as rain and earlier snowmelt onset , which can lead to wetter early and mid-winter soil than historical conditions. Future soil moisture could also be drier due to increases in evaporative demand (McEvoy et al., 2020). Therefore, there is projected to be a net decrease in runoff efficiency across most years, although greater spatial variability in high precipitation years may also be expected across the western United States at the middle to end of the century (Rhoades et al., 2023).

Incorporating information from climate projections into a robust and reliable assessment of future extreme events is a significant challenge. Conventional climate change impact studies aim to estimate the return probabilities of future extreme events using a chain of modeling tools (Gutowski et al., 2020). Typically, these modeling chains include ensembles of global climate model (GCM) simulations that are then downscaled to local scales using regional climate models and/or statistical downscaling approaches (Lafferty & Sriver, 2023) in which estimates are fitted using a generalized extreme value distribution to derive the quantiles for various recurrence intervals (e.g., 100-year flood; Mallakpour & Villarini, 2015; Slater et al., 2021; Yu et al., 2020). However, GCMs are primarily benchmarked by their ability to simulate the average state of long-term weather conditions (i.e., climate) rather than specific events. The probability distribution of future weather events generated using conventional approaches often depends on post-processing techniques, such as bias correction and downscaling (Hartke et al., 2025; Thrasher et al., 2012). These techniques can inadvertently alter the physical processes and spatiotemporal patterns represented in the original GCMs, undermining the confidence and robustness of the simulated results (e.g., Ehret et al., 2012; Vannitsem, 2011; Yu et al., 2020).

Unlike conventional, decadal-to-centennial-length climate change projections, ***storyline approaches*** provide descriptive "stories" of plausible future extreme events (Shepherd, 2019; Shepherd et al., 2018). Rather than directly addressing how climate change will influence the likelihood and severity of events, a storyline approach constructs an event-based climate projection by posing the following questions: (1) What physical causal factors contributed to the historical event? (2) In what ways will climate change affect those causal factors? (3) How will climate change exacerbate the impacts of a similar event in the future? An event-based storyline approach derives a detailed sequential cause-and-effect chain that links climate conditions to hazards and impacts, bridging the gap between global climate projections and their regional and local impacts (e.g., Hazeleger et al., 2015; Hoerling et al., 2013; Lloyd & Shepherd, 2020). Previous studies have applied storylines to investigate the impacts of different global warming levels on droughts (e.g., Chan et al., 2022; Diffenbaugh et al., 2015; Ullrich et al., 2018), crop failures (e.g., Goulart et al., 2023), heatwaves (e.g., Fischer et al., 2023; Wehrli et al., 2020), sediment transport (e.g., Goulart et al., 2024; Rhoades et al., 2023, 2024), and extreme precipitation and the resultant flooding (e.g., Goulart et al., 2024; Rhoades et al., 2023, 2024). Although previous studies have applied storyline approach to investigate rain-on-snow floods, none of these studies investigated the influence of watershed antecedent conditions in shaping floods using ensemble hydrologic simulations (Schaller et al., 2020; Tuel et al., 2022; Wilson et al., 2022).

Rhoades et al. (2023) accurately reproduced the magnitude and phasing of precipitation during the 1997 New Year's event across California and Nevada. Additionally, Rhoades et al. (2024) investigated the changes in 1997 New Year's flood across six warming levels and found that when warming levels exceed +1.7 °C (from 1920), increases in precipitation intensity and decreases in snowpack over the mountainous region and antecedent soil moisture at lower elevations occur. The combined effects of changes in flood drivers led to decreased runoff in the northern Sierra Nevada, with notable increases in southern Sierra Nevada runoff, where antecedent snowpack remains (Rhoades et al., 2024).

Surface and subsurface lateral flows and water movement within the river channels were not optimally simulated in Rhoades et al. (2023) and Rhoades et al. (2024). These hydrologic and hydraulic processes can effectively accelerate water release to streams and reduce the transit time when hydrologic connectivity is high, and therefore they are crucial for flood simulation at catchment scales (Hu et al., 2024). In addition, Rhoades et al. (2024) only explored one realization of the land-surface antecedent conditions using warming levels from specific years and the months that the storyline event occurred (e.g., January 2081).

This study builds on the works of Rhoades et al. (2023) and Rhoades et al. (2024) to examine the influence of interannual climate variability, watershed antecedent conditions, and future warming on the discharge of the 1997 New Year's flood in the Truckee River watershed. By concentrating on a medium-sized watershed (4,100 km^2) located on the leeward side of the Sierra Nevada, we can use a process-based hydrological model at finer-scales (i.e., hourly and 250 m) to explicitly simulate overland and subsurface flow, as well as river routing. With this new process representation in the hydrologic and hydraulic systems, we attempted to answer the following research questions:

1. Under what watershed antecedent conditions can the hydrological model reproduce the 1997 New Year's flood in the context of the current climate?

2. How might the 1997 New Year's flood be affected by the combined effects of watershed antecedent conditions and extreme rainfall resulting from future warming?
3. Are the future changes in peak streamflow for this event dependent on the watershed scales and locations?

These questions focus on the impacts of climate variability on hydrologic extremes and examine how interactions between climate warming and internal variability alter the characteristics of future hydrologic extremes.

2 Study Area and Model Experiments

2.1 Study Area

The Truckee River watershed is located on the eastern slope of the Sierra Nevada, encompassing Lake Tahoe and the Truckee River (Fig. 1). The Truckee River flows 195 km from Tahoe City, California into Nevada and through the cities of Reno and Sparks before ending at Pyramid Lake. The river is the primary source of municipal water for Reno and Sparks, and it is used for irrigation in the Truckee and Carson River watersheds and supplies environmental flows for endangered and threatened fish (Berris et al., 2001). The watershed is home to 500,000 people and contains Interstate 80, a critical east-west transportation corridor. For this study, we delineated the watershed upstream of the US Geological Survey (USGS) gage near Clark City (Gage ID: 10350500), which is located 20 miles east of Sparks (Fig. 1). This portion of the Truckee River watershed has an area of 4,100 km^2, with elevations ranging from 1,290 m to 3,300 m at the Sierra Nevada crest. The watershed receives most of its precipitation during winter months. The leeward location of the watershed leads to a strong geographic gradient in precipitation, with annual average precipitation ranging from 180 mm/year at lower elevations to 1,300 mm/year at higher elevations (Western Regional Climate Center, 2025). Given that much of the upper watershed is at the rain-snow transition zone (elevations near 2,100 m), precipitation phase is highly variable and hard to predict. Atmospheric rivers are the dominant precipitation-generating mechanism and these events have historically driven the largest floods (Albano et al., 2023).

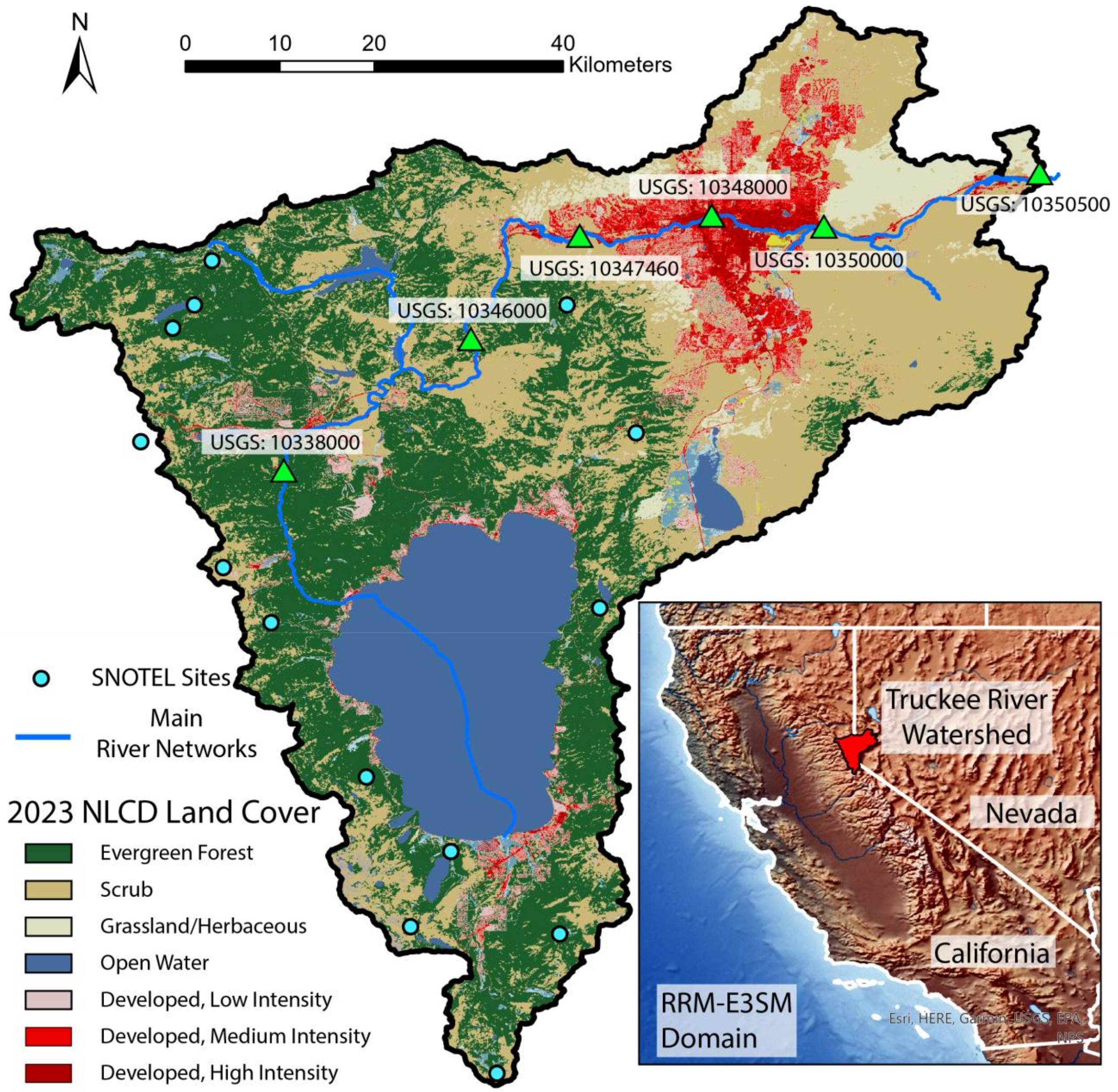

Figure 1. The Truckee River watershed above the USGS streamgage at Clark (gage number 10350500). The main river networks (blue lines), land cover based on the 2023 National Land Cover Dataset (NLCD; Jin et al., 2023), 16 are SNOw TELemetry (SNOTEL) sites, and six USGS gages are shown. The inset map shows the approximate regionally refined mesh Energy Exascale Earth System Model (RRM-E3SM) innermost domain used to simulate

hydrometeorology during the 1997 New Year's flood event. The Truck River watershed, spanning California and Nevada, is highlighted in red.

2.2 Model Experiments

The objective of this study was to explore alternative ways the 1997 New Year's flood event in the Truckee River could have played out under a plausible range of historical and future antecedent conditions and storm magnitudes. Model experiments are summarized as follows (Fig. 2): Section 2.2.1 analyzed the 1997 New Year's flood with respect to the long-term hydroclimatology using both observations and hydrological simulation to identify what watershed antecedent conditions enable a 1997-magnitude event to occur under current climate. Section 2.2.2 incorporated the warming level signatures from the GCM simulations into long-term hydrological simulations that represent potential future watershed antecedent conditions under which future 1997-event based flood simulation plausibly occur. Section 2.2.3 performed ensemble event-based flood simulations for both current and future climate conditions by coupling downscaled hydrometeorological forcings and randomly sampled watershed antecedent conditions from Section 2.2.2 to characterize changes between current and future climate conditions.

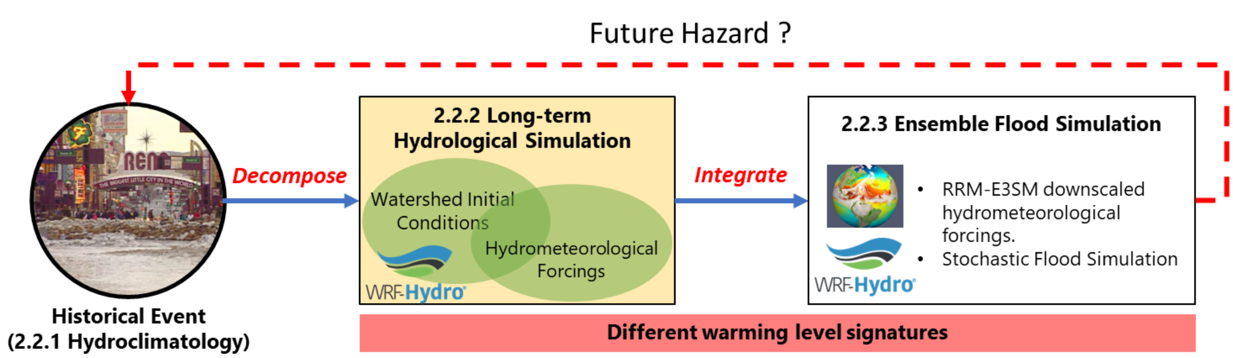

Figure 2. The conceptual workflow used to produce alternative storylines for the 1997 New Year's flood within the Truckee River watershed.

2.2.1 *Hydroclimatology*

It is critical to understand the 1997 New Year's flood with respect to current climate conditions. We compared the streamflow, precipitation, air temperature, snow water equivalent (SWE), and top 2-m layer soil moisture for the 1997 water year against a 40-year (1980-2019) hydroclimatology. The climatology of streamflow was derived using USGS observations from the gauge located at the Truckee River near Reno. The climatology of precipitation and air temperature was derived using basin-averaged values of the North American Land Data Assimilation System version 2 (NLDAS-2; Mitchell, 2004) hourly, 1/8° (roughly 12 km) meteorological forcings for the1980-2019 period.

Furthermore, we derived the climatology of SWE and top 2-m layer soil moisture by running the physics-based distributed Weather Research and Forecasting Hydrological modeling system (WRF-Hydro; Gochis et al., 2018) with NLDAS-2 forcings for the 1980-2019 period (i.e., “Current” scenario in Table 1). The details about the WRF-Hydro model calibration and validation are provided in Supporting Information and Fig. S1.

2.2.2 *Long-term Hydrological Simulation for Future Climates*

The warming level signatures used for the study area were the same signatures used in the Rhoades et al. (2024) and were derived from the ensemble mean Community Earth System Model version 1 Large Ensemble (CESM-LE) monthly temperature, specific humidity, precipitation, and longwave radiation (Kay et al., 2015). Relative to 1920, the CESM-LE ensemble mean projects global mean temperature increases of 1° C, 2° C, 3° C, and 4° C by the years 2019, 2044, 2063, and 2081, respectively. Because the +1° C of warming for the 1980-2019 period represents "current" atmospheric and oceanic conditions, we developed three future climate scenarios: "Delta 2" for the 2005-2044 period (representing an average of +2° C of warming over that period), "Delta 3" for the 2024-2063 period (representing +3° C of average warming), and "Delta 4" for the 2042-2081 period (representing +4° C of average warming; Table 1; Fig. S2).

The warming level signatures are expressed as additive deltas for temperature and specific humidity, and as multiplicative ratios for precipitation and longwave radiation for the 40-year periods of the Delta 2 to 4 scenarios (Fig. S2). We used the calibrated and validated WRF-Hydro to run long-term continuous simulations for four 40-year periods, including 1980-2019 (current), 2005-2044 (Delta 2), 2024-2063 (Delta 3), and 2042-2081 (Delta 4). For the Delta 2 to 4 runs, we perturbed NLDAS-2 forcings by adding monthly deltas for temperature and specific humidity, and multiplying the monthly ratios for longwave radiation and precipitation (Table 1; Fig. S2). Simulated watershed states (e.g., soil moisture, streamflow, snowpack, and ponded water depth) from long-term continuous simulations were saved at daily time steps, which will provide the antecedent conditions for subsequent event-based simulations.

2.2.3 Event-based Ensemble Flood Simulation

Event-based ensemble flood simulation requires ensemble watershed antecedent conditions (Section 2.2.2) and hydrometeorological forcings of the 1997 New Year's event under the future climate conditions. The hydrometeorological forcings of 1997 event were recreated using the U.S. Department of Energy-funded Energy Exascale Earth System Model version 2 (E3SMv2; Golaz et al., 2022; Harrop et al., 2023; Tang et al., 2023) and downscaled using Regionally Refined Meshes (referred to as RRM-E3SM). We encourage readers to refer to the Supporting Information for a summary of the fidelity of the RRM-E3SM simulations for the 1997 event, and to Rhoades et al. (2023) for a thorough description on model setup and validation.

The hydrometeorological response of 1997 New Year's flood to warming level that was simulated by RRM-E3SM is described in greater detail in Rhoades et al. (2024). Notably, for this study, warming systematically increased storm total precipitation across the California side of the Sierra Nevada and magnified precipitation extremes at hourly-to-sub-hourly timescales, particularly in the rain-snow transition of Sierra Nevada. Eight of the RRM-E3SM simulated meteorological forcings were used in this study to drive WRF-Hydro: precipitation, specific humidity, temperature, surface pressure, shortwave and longwave radiation, and zonal and meridional wind speeds.

Our objective for the event-based simulations was to recreate the 1997 New Year's flood across current and future climate conditions. Under the current climate conditions, we ran WRF-Hydro for the 1997 event using both the NLDAS-2 observed forcings and the RRM-E3SM simulated forcings, which are referred to herein as the "current scenario" and "control scenario", respectively (Table 1). For future climate conditions, we ran WRF-Hydro using only the RRM-E3SM simulated meteorological forcings (Table 1). For all the scenarios, we randomly selected 100 sets of watershed antecedent conditions (e.g., snowpack, soil moisture, and streamflow) from the corresponding long-term (40-year) hydrological simulation to yield 100 ensemble floods (Table 1). To achieve seasonally consistent watershed antecedent conditions, we only sample watershed conditions between November 15th to January 15th.

Subsequently, we determined that the watershed conditions associated with daily streamflow ≥ 75th percentiles consistently reproduce the 1997 New Year's flood (see Section 3.1 and Fig. 4). This finding has served as an additional criterion to refine the sampled watershed antecedent conditions. For ensemble flood simulations for the Delta 2-4 climate conditions, we also randomly sampled 100 watershed antecedent conditions from the 40-year WRF-Hydro simulations when daily streamflow exceeds the 75th percentile for the corresponding period.

Table 1. Summary of simulation scenarios.

Scenario Name	Forcings for the Long-term Hydrological Simulation	Forcings for the 1997 Flood Simulation
Current	NLDAS-2 forcings	NLDAS-2 forcings
Control	NLDAS-2 forcings	RRM-E3SM simulated forcings with observed atmospheric and land conditions in 1997
Delta 2	NLDAS-2 forcings perturbed by an average of +2° C of warming level	RRM-E3SM simulated forcings with CESM-LE simulated atmospheric and land conditions with an average of +2° C warming level
Delta 3	NLDAS-2 forcings perturbed by an average of +3° C of warming level	RRM-E3SM simulated forcings with CESM-LE simulated atmospheric and land conditions with an average of +3° C warming level
Delta 4	NLDAS-2 forcings perturbed by an average of +4° C of warming level	RRM-E3SM simulated forcings with CESM-LE simulated atmospheric and land conditions with an average of +4° C warming level

3 Results

3.1 The Historical Hydroclimatological Context of the 1997 New Year's Flood

The streamflow at the Truckee River near Reno remained above the 75th percentile for two months following the start of the 1997 water year while exceeding the 95th percentile 15-days prior to the flood event (Fig. 3a). The basin-averaged accumulated NLDAS-2 precipitation substantially increased from 23 mm (< 25th percentile) in mid-November 1996 to 325 mm (>75th percentile) by December 29, 1996, marking the onset of the storm event (Fig. 3b). The accumulated NLDAS-2 precipitation further increased to 590 mm (95th percentile) in February 1997 and remained relatively stable for the rest of that water year, with its percentiles declining from the 95th percentile to below the 75th percentile (Fig. 3b).

Although basin-averaged air temperatures show a large variability throughout the 1997 water year, it was exceptionally warm during the 1997 New Year's flood event, reaching 6 °C (> 95th percentile) on January 1 and 2, 1997 (Fig. 3c). A SNOTEL station situated at an elevation of 2,100 m in the leeward of Sierra Nevada recorded a maximum temperature of 7°C on January 1, 1997 (Heggli et al., 2022). Such a high air temperature also caused a basin-averaged snowmelt of 31 mm within 3 days during the flood event (Fig. 3d). However, the basin-averaged SWE remained within the normal range throughout the 1997 water year (Fig. 3d). The accumulated precipitation from mid-November to mid-December elevated soil moisture levels from dry (< 25th percentile) to wet (>75th percentile) conditions (Fig. 3e). During the flood event, substantial rainfall and snowmelt further saturated the soil, causing the basin-averaged soil moisture to exceed the 95th percentile on January 3rd (Fig. 3e). Therefore, the 1997 New Year's flood was driven by a complex combination of saturated antecedent soil moisture, substantial precipitation, high air temperature and rapid snowmelt (Rhoades et al., 2023).

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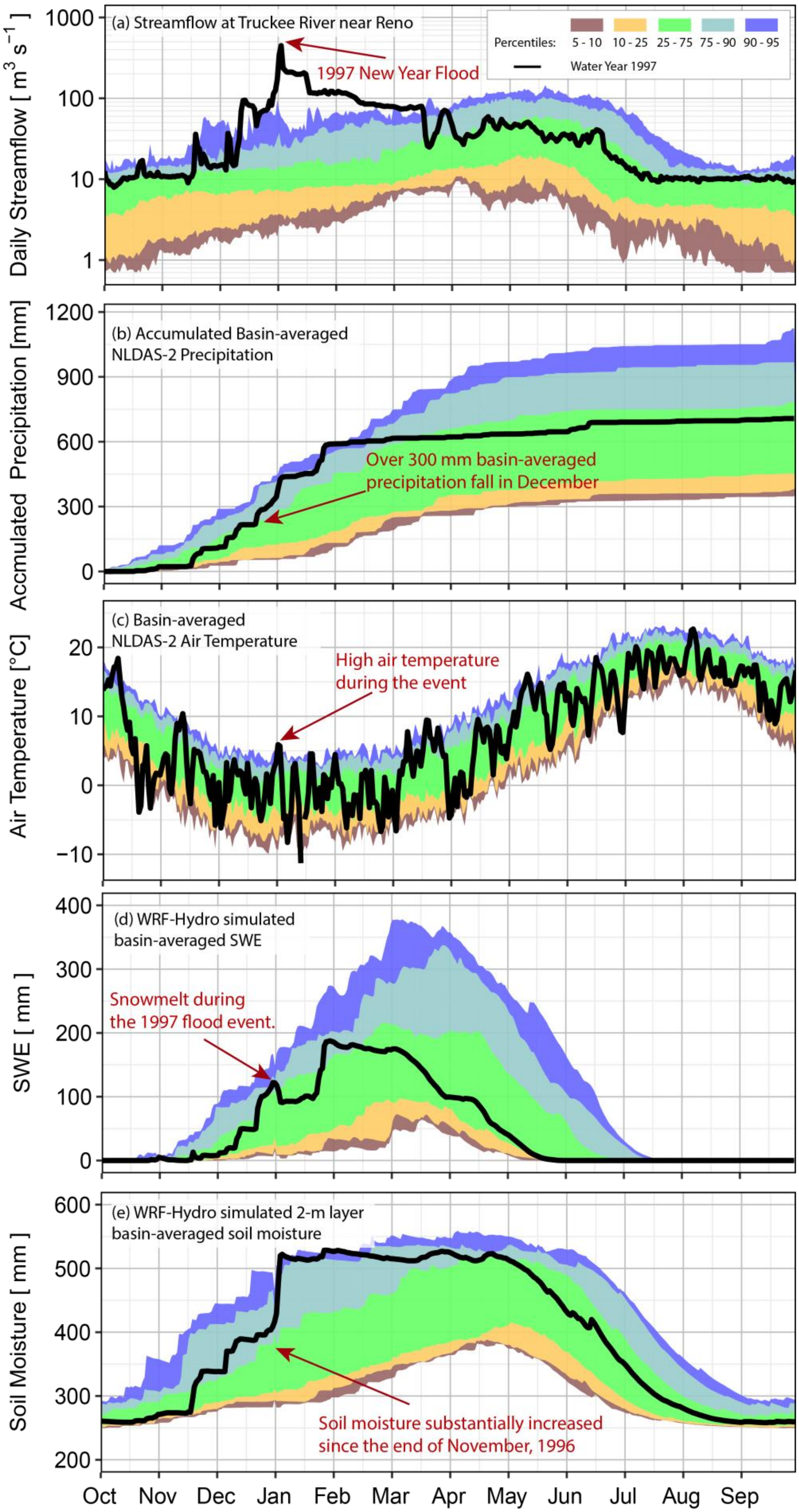

(a) Streamflow at Truckee River near Reno
Percentiles: 5 - 10 10 - 25 25 - 75 75 - 90 90 - 95
Water Year 1997
1997 New Year Flood
Daily Streamflow [m^3 s^-1]
(b) Accumulated Basin-averaged NLDAS-2 Precipitation
Over 300 mm basin-averaged precipitation fall in December
Accmulated Precipitation [mm]
(c) Basin-averaged NLDAS-2 Air Temperature
High air temperature during the event
Air Temperature [°C]
(d) WRF-Hydro simulated basin-averaged SWE
Snowmelt during the 1997 flood event.
SWE [mm]
(e) WRF-Hydro simulated 2-m layer basin-averaged soil moisture
Soil moisture substantially increased since the end of November, 1996
Soil Moisture [mm]
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep

Figure 3. The (a) streamflow at the Truckee River stream gage near Reno, (b) accumulated basin-averaged precipitation, (c) basin-averaged air temperature, (4) basin-averaged SWE, and (d) basin-averaged soil moisture for the top 2m layer for the 1997 water year (black lines) overlaid on the long-term hydroclimatology. The hydroclimatology is based on the 1980-2019 period. The streamflow, precipitation, and air temperature are based on observations, whereas SWE and soil moisture are based on WRF-Hydro simulations.

To better understand the impacts of watershed antecedent conditions on the 1997 New Year's flood, we conducted ensemble flood simulations (*n*=100) across four distinct groups based on the percentiles of the daily streamflow. We used the daily streamflow as a proxy to represent the watershed's antecedent conditions for two reasons: 1) the in-channel streamflow is a crucial antecedent factor in flood generation (Fig. 3a); and 2) daily streamflows show a strong correlation with basin-averaged soil moisture and SWE, with Spearman's $\rho=0.61$ (p-$value \ll 0.001$) and $\rho=0.28$ (p-$value \ll 0.001$), respectively. The watershed conditions corresponding to daily streamflow > 75th percentile, 50th to 75th percentile, 25th to 50th percentile, and ≤ 25th percentile conceptually represent wet (Fig. 4a), above normal (Fig. 4b), below normal (Fig. 4c), and dry (Fig. 4d) conditions, respectively. These watershed conditions were derived from the continuous 40-year (1980-2019) WRF-Hydro simulation, driven by the NLDAS-2 forcings.

For the current scenario (Table 1), the simulated ensemble mean flood peaks appear to align closely to the observations under the wet antecedent condition (Fig. 4a) but are approximately half the observed peaks for the other three scenarios (Fig. 4b-d). Even when the 1997 New Year's precipitation event was paired with the 50th to 75th percentile watershed antecedent conditions, reconstructing the 1997 New Year's flood remains unlikely (Fig. 4b). This suggests that while it would be a rare event, the 1997 New Year's flood could happen with antecedent conditions that are close to or slightly above normal. Furthermore, the diverse watershed antecedent conditions resulting from the interannual climate variability led to ensemble streamflow mean peakflows ranging from 212 m^3 s^{-1} (Fig. 4d) to 532 m^3 s^{-1} (Fig. 4a). This highlights that anomalous (75th to

100th percentile) antecedent conditions played a significant role in shaping Truckee River streamflow during the 1997 New Year's flood.

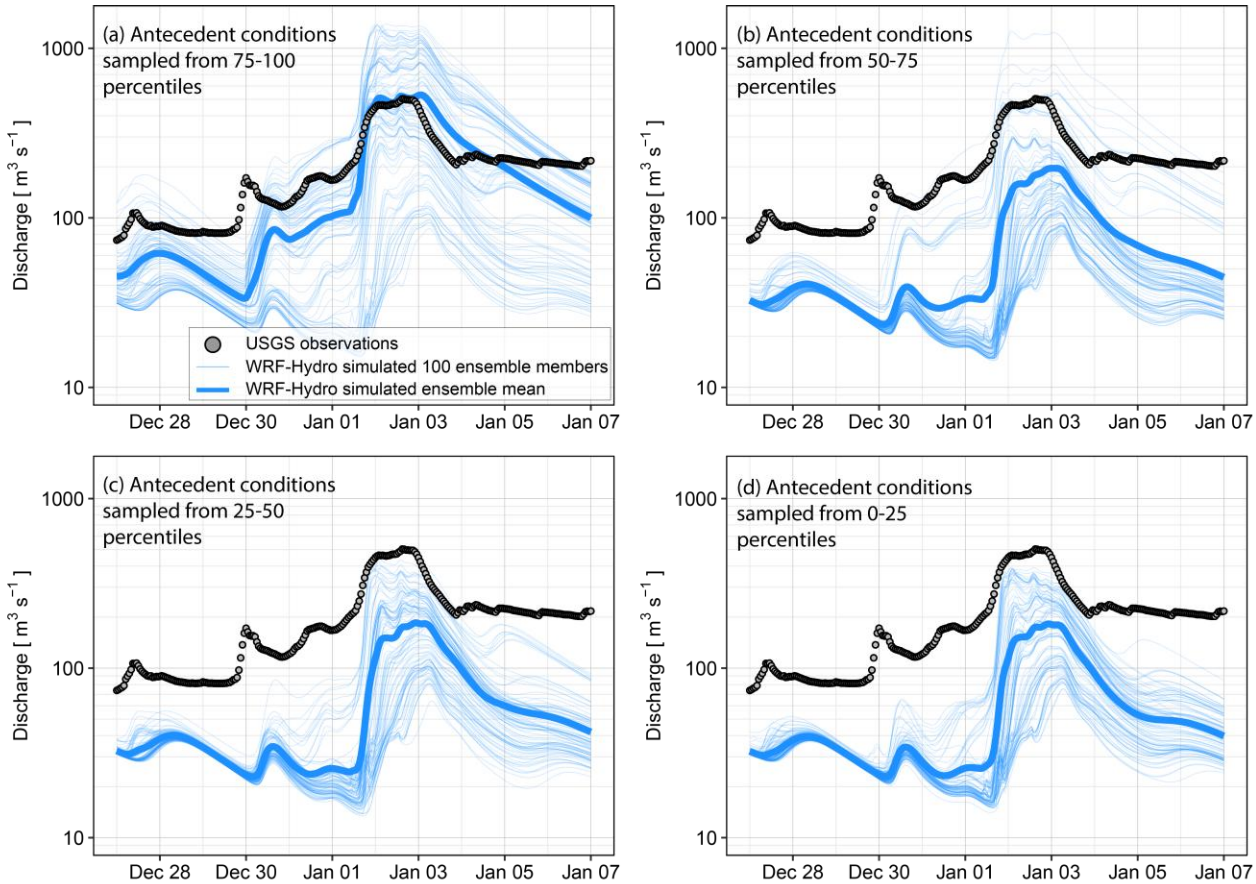

Figure 4. The ensemble flood simulations for the current scenario. The USGS observed streamflow for Truckee River near Reno (black dots), and the WRF-Hydro simulated 100 ensemble streamflow members (blue lines) for the 1997 New Year's flood under four distinct watershed antecedent conditions. These antecedent conditions were constructed by randomly sampling 100 watershed antecedent conditions from November 15 to January 15 during the 1980-2019 period when the corresponding streamflow fell between (a) 75th to 100th, (b) 50th to 75th, (c) 25th to 50th, and (d) 0 to 25th percentiles.

For the control scenario (Table 1), the simulated ensemble floods exhibit a pattern comparable to the current scenario pattern, specifically the ensemble mean flood peaks only surpass the observed peak from the 1997 New Year's flood under the wet antecedent conditions (Fig. S3). However, flood simulations using the control scenario show higher values compared to those using the current scenario, regardless of watershed antecedent conditions (Fig. 4 and Fig. S3). This discrepancy is mainly because the basin-averaged total precipitation between December 31, 1996, and January 3, 1997, are 216 mm in the RRM-E3SM simulation, which is higher than the 128mm in the NLDAS-2 observation. However, it is important to note that the Truckee River WRF-Hydro model was calibrated and validated using 40 years of NLDAS-2 forcings. The uncertainties associated with meteorological forcings, model parameters, and structures, and how their interactions affect model performance are outside the scope of this study. Further exploration of this topic can be found in Beusekom et al. (2022), Evin et al., (2024), Zhu et al. (2018), and Zoccatelli et al. (2024). Our study focused on the relative changes in ensemble flood peaks between the control scenario and three future climate scenarios (i.e., Delta 2-4).

3.2 Projected Changes to the Antecedent Conditions of the 1997 New Year's Flood Under Warmer Climates

It is important to understand how long-term watershed conditions will change in a warmer future climate because antecedent land-surface conditions (e.g., snowpack and soil moisture) played a dominant role in driving the hazards brought about by the 1997 New Year's flood (Section 3.2; Fig. 3-4). Therefore, we assessed the daily median values of basin-averaged SWE, basin-averaged soil moisture, and streamflow throughout the water year derived from four distinct 40-year periods (Fig. 5). Although the total precipitation slightly increases in the future (Fig. S1d), the volumes and peaks of basin-averaged SWE considerably decrease from the current to the Delta 4 period (Fig. 5a). The starting time of snow ablation also shifts from mid-March in the current period to the end of February in the Delta 4 period, accompanied by a reduction in the duration of snow coverage (Fig. 5a).

Since precipitation is more likely to fall as rain than snow in the future, the basin-averaged soil moisture between December and May increases markedly from the current period to Delta 4 period (Fig. 5b). However, there is negligible change in basin-averaged soil moisture in the dry season (i.e., June-October) because the soil moisture is close to its wilting point even under the current climate condition (Fig. 5b). The interplay between changes in basin-averaged SWE and soil moisture results in a bimodal shift in daily streamflow from current to Delta 4 climate conditions, as shown by the slight increase in streamflow from January to March and a marked decrease in streamflow from May to July (Fig. 5c). The increase in streamflow in spring is due to enhanced soil moisture, whereas the decrease in streamflow in summer stems from reduced SWE and earlier snowmelt.

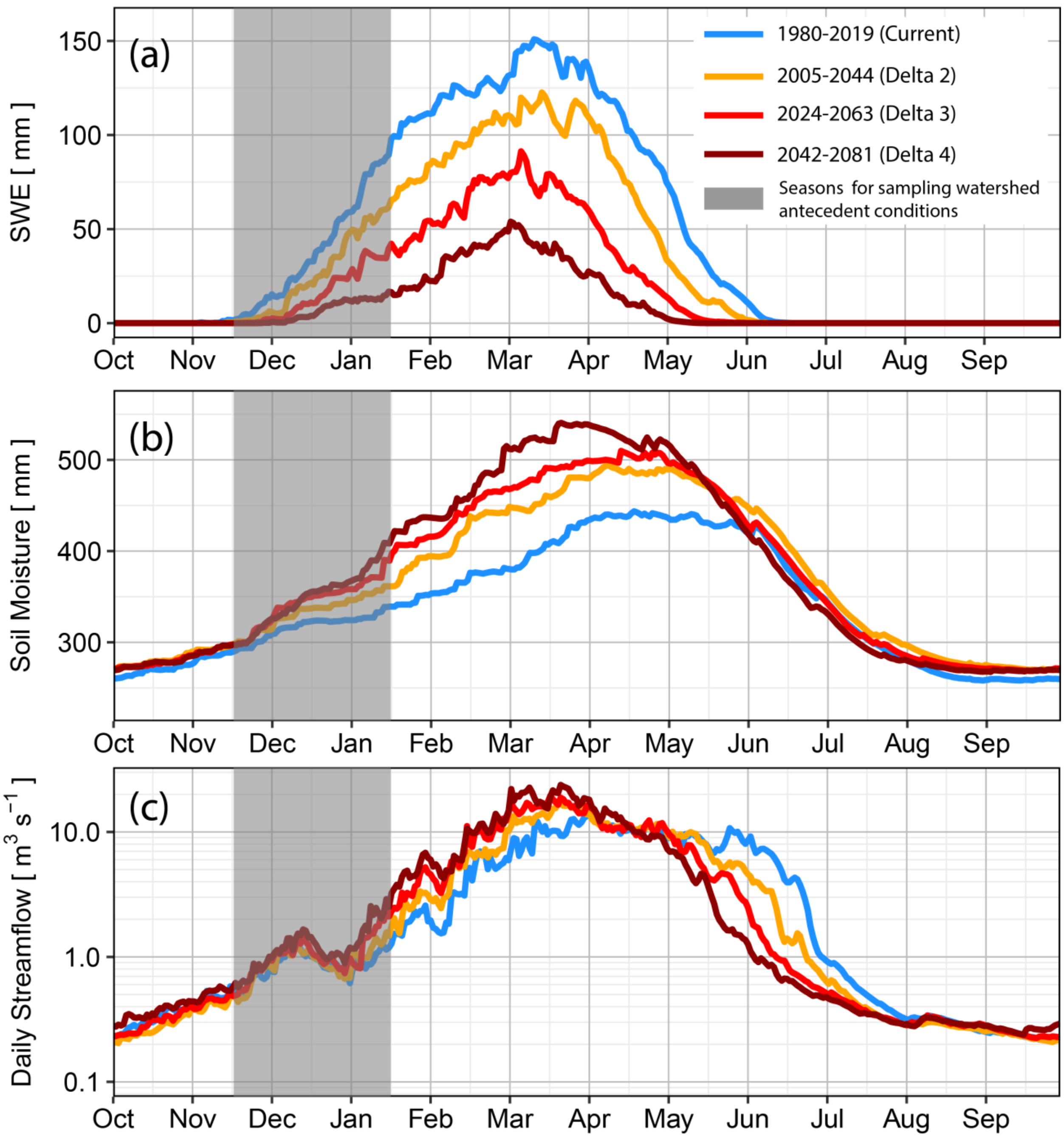

Figure 5. The climatological median values for (a) basin-averaged SWE, (b) basin-averaged soil moisture, and (c) daily streamflow across the four 40-year periods representing a current (blue), +2° C (orange), +3° C (light red), and +4° C (dark red) climates.

3.3 Projected Changes to the Streamflow Response of the 1997 New Year's Flood Under Warmer Climates

Under the Delta 2 condition, there is a slight increase in the ensemble mean peak flows in the high-elevation headwaters along the Sierra Nevada crest and a slight decrease (or no changes) over other regions within the watershed relative to the control scenario (Fig. 6a). The increases in peakflows in the headwater basins upstream of the Truckee River are counterbalanced by decreases in peakflows in the tributaries near the California-Nevada border, leading to negligible changes in the peakflows in the main stem across the Reno-Sparks area (Fig. 6a). The changes in the ensemble mean peak flows under the Delta 3 and Delta 4 conditions are comparable (Fig 6b and 6c). All warming scenarios show significant increases (>100%) in peakflows in the headwater basins, but there are slight decreases (or no changes) in the tributaries in the eastern portion of the watershed (Fig 6b and 6c). The combined effects of the changes in peakflows over the tributaries results in increased peakflows in the main stem of the Truckee River, especially over the Reno-Sparks area (Fig 6b and 6c). For example, the ensemble mean peakflow for the river channel near the USGS gage in Reno increased by 18% and 14% under the Delta 3 and Delta 4 conditions, respectively.

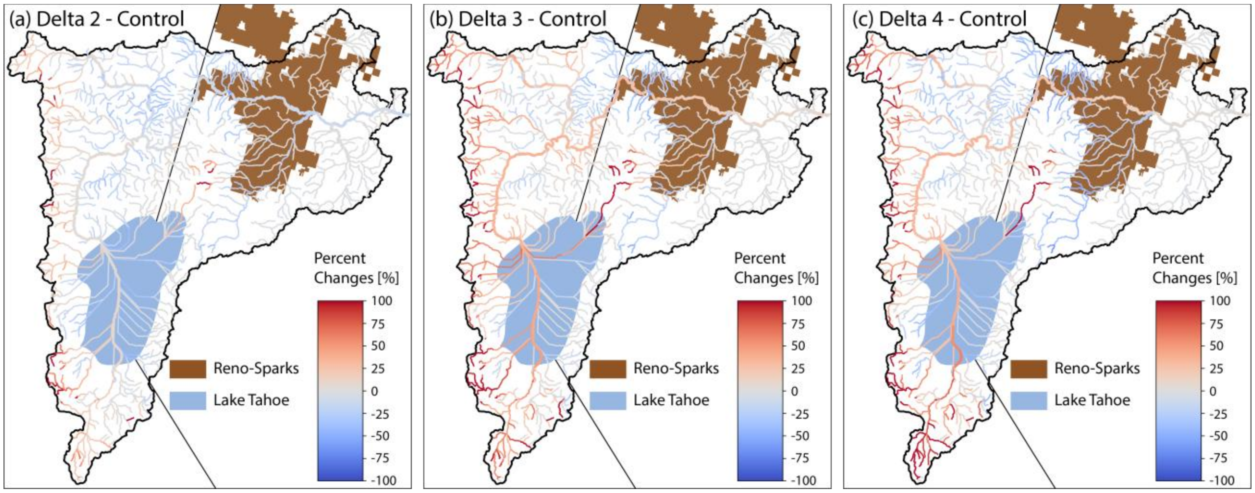

Figure 6. The percentage changes in the ensemble mean peak flows across all the river networks within the Truckee River watershed under (a) Delta 2, (b) Delta 3, and (4) Delta 4 climate scenarios compared to the control scenario. Each ensemble consists of 100 members that are driven by the same precipitation but different watershed antecedent conditions.

We also analyzed the projected changes in ensemble mean peakflow conditions categorized by the watershed size (Fig. 7a) and mean elevation (Fig. 7b) across the Delta 2 to 4 climate conditions. For small watersheds ($A \leq 10\ km^2$), peakflow can be 2 to 5 times higher under all the Delta 2 to 4 climate conditions compared to their values in the control scenario. For a medium-size watersheds ($10\ km^2 < A \leq 100\ km^2$), the projected peakflows for the future conditions are generally less than twice those of the control scenario. The projected peakflows for large watersheds under the Delta 3 and 4 conditions will be approximately 1.3 to 1.5 times greater than their values under the control scenario.

The increases in peakflow under the Delta 2 to 4 conditions are more pronounced in high-elevation watersheds compared to low-elevation watersheds (Fig. 7b). There are negligible changes in peakflows for watersheds below 1,500 m (Fig. 7b). However, the projected peakflows across the Delta 2 to 4 conditions can be 2 to 5 times higher than their values under the current climate for watersheds higher than 1,500 m (Fig. 7b). The projected peakflows are greater for most watersheds above 2,500 m and such increases in peakflow are more pronounced for the Delta 3 and 4 climate conditions (Fig. 7b).

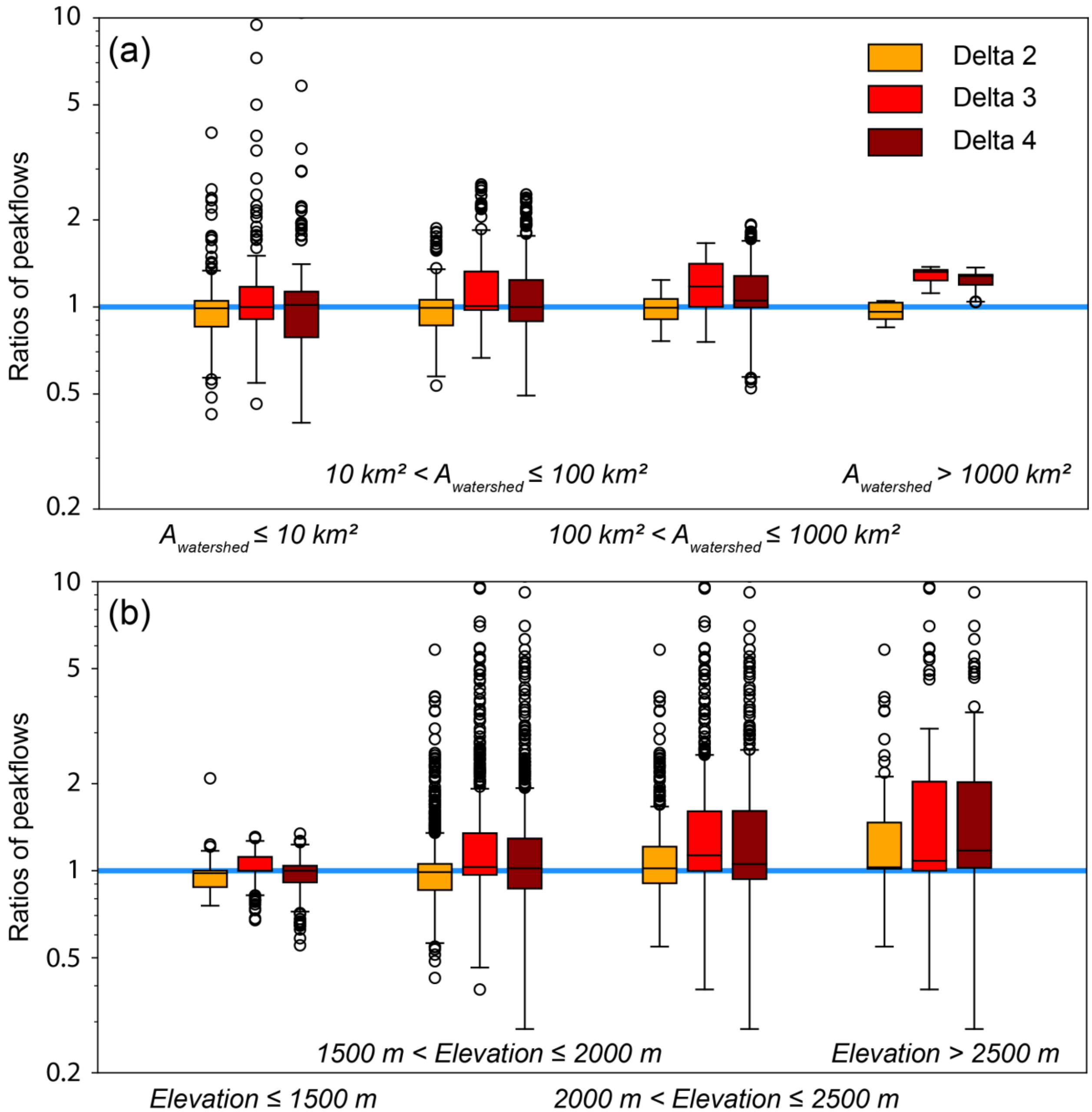

Figure 7. (a) Projected changes in peakflow across Delta 2 to 4 climate conditions compared to the control scenario categorized by watershed size: less than 10 km^2, 10 to 100 km^2, 100 to 1,000 km^2, and greater than 1,000 km^2. (b) Projected changes in peakflow across Delta 2 to 4 climate conditions compared to the control scenario within watershed elevation bands: below 1,500 m, 1,500 to 2,000 m, 2,000 to 2,500 m, and above 2,500 m.

3.4 Projected Changes in the Hydrometeorology of the 1997 New Year's Flood Under Warmer Climates

We used two members from the ensemble of 1997 flood simulations that produced the median peak flows under control and Delta 4 scenarios, respectively, to project hydrometeorology changes under warmer climates (Fig. 8). The basin-averaged total precipitation and hourly precipitation rate are comparable between control and Delta 4 scenarios (Fig. 8). This similarity in total precipitation comes from the increased precipitation over the Sierra Nevada crest under the Delta 4 scenario, which balances out the decreased precipitation observed over North Lake Tahoe (Fig. S4). It is important to note that the storm total precipitation and hourly-to-subhourly maximum precipitation rates have systematically increased on the windward side of Sierra Nevada between the control and Delta 4 scenarios (Rhoades et al., 2024). This highlights the important differences in how precipitation could respond to warming in windward versus leeward portions of mountains with notable implications for localized flooding and debris flows.

The total snowmelt and the mean hourly snowmelt rate are higher under the Delta 4 scenario (Fig. 8a). The more intense snowmelt under the Delta 4 scenario is attributed to more sensible heat absorbed by the Earth's surface (Fig. 8b) and warmer basin-averaged ground temperatures (Fig. 8c). Although the basin-averaged SWE under the Delta 4 scenario is significantly lower throughout the event compared to the control run, the accumulated basin-averaged snowmelt between December 31st and January 4th (96 hours) is 28 mm for the control run and 52 mm for the Delta 4 run (Fig. 8d). Between December 31 and January 4, there was an increase of 75 to 100 mm in snowmelt in the headwaters along the Sierra Nevada crest and North Lake Tahoe under the Delta 4 scenario compared to the control (Fig. S5). Therefore, future warming can increase the risk of hazardous rain-on-snow flood events, even with a decrease in basin-averaged SWE.

The enhanced snowmelt under the Delta 4 scenario resulted in increases in basin-averaged soil moisture in both the top-layer (0-10 cm) and deep-layer (100-200 cm; Fig. 8e). The increases in maximum top-layer soil moisture during the flood event under the Delta 4 scenario are most notable in the headwaters along the Sierra Nevada crest (Fig. S6), whereas the increases in maximum deep-layer moisture are concentrated around the mountainous region in North Lake Tahoe (Fig. S7). Enhanced snowmelt and the resultant saturated soil moisture under the Delta 4 scenario lead to higher maximum ponding depth, indicating more overland flows (Fig. S8). The combined effects of these changes in the key flood drivers resulted in increases in streamflow for the main stem of the Truckee River (Fig. 8). Such warming-induced enhancements in snowmelt and flooding could occur in hydrologically similar catchments in the Western US in the future, particularly in mountainous regions that rely on atmospheric rivers and seasonal snowmelt (Bertola et al., 2023; Collins et al., 2022). Thus, the modeling framework developed in this study could be extensible to investigate larger regional flood response behavior in the Western US.

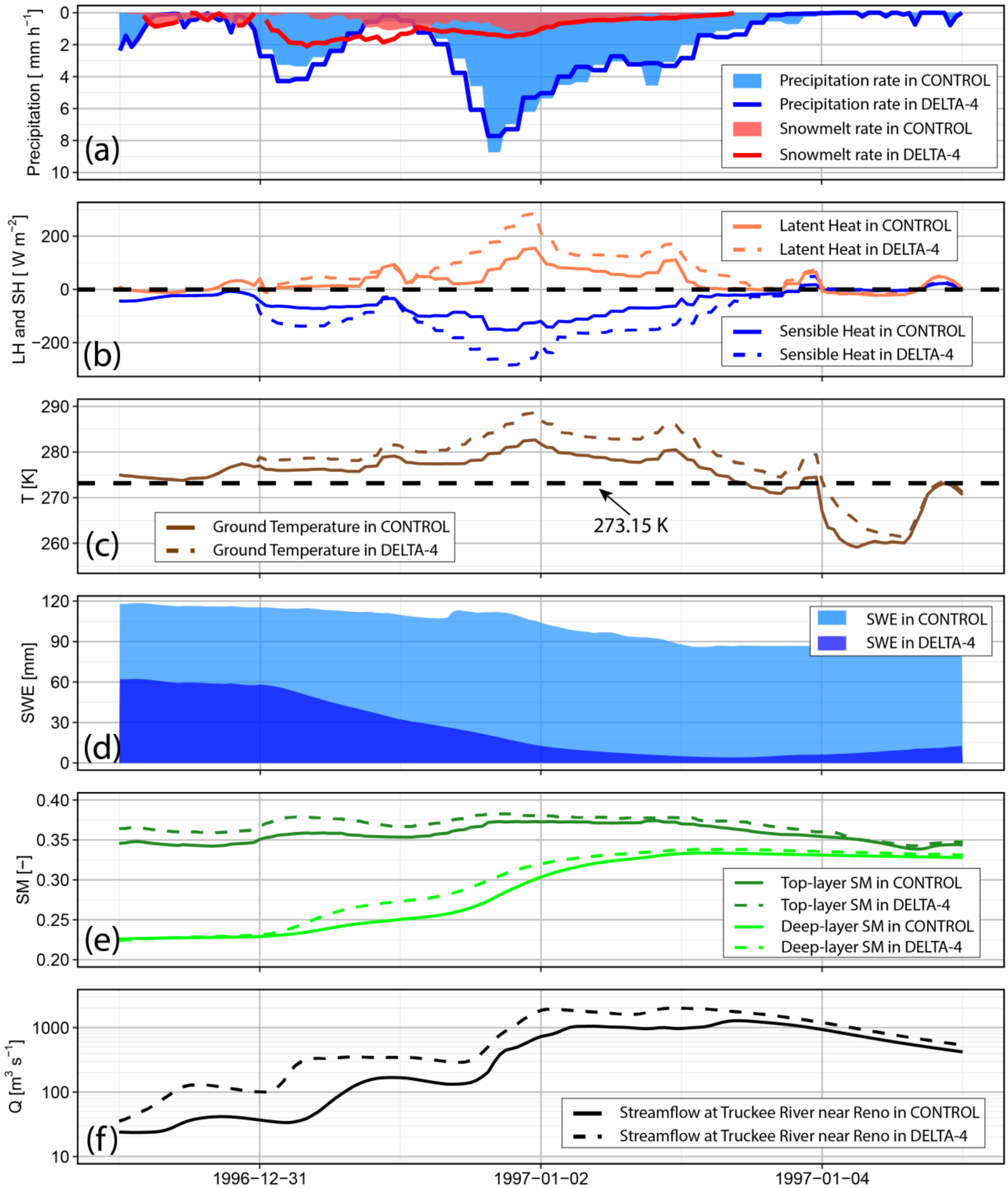

Figure 8. Comparison of Truckee River basin averaged (a) precipitation and snowmelt rate, (b) latent heat (LH) and sensible heat (SH), (c) ground temperature, (d) SWE, (e) top- layer and deep-layer soil moisture (SM), and (f) streamflow in the Truckee River near Reno between the control and Delta 4 scenarios.

4 Discussions

4.1 Elevation and scale dependent changes in flood responses

The changes in future peakflows are scale and elevation dependent, exhibiting a pronounced spatial variability (Fig. 6). The most significant increases in simulated peakflows under the future conditions are clustered in high-elevation mountainous regions (Fig. 6). This is primarily attributed to increased snowmelt in mountainous regions, as the 1997 New Year's event could occur at even warmer air temperatures than the event of the current climate (Fig. 8). In addition, randomly sampled watershed antecedent conditions indicate that the SWE in mountainous regions remains sufficiently high to "fuel" the 1997 event, despite projected decreases in future climate (Fig. 8d). This supports the idea that rain-snow transition zones, such as the Sierra Nevada are approaching a period of "peak rain-on-snow conditions (Heggli et al., 2022)", driven by a combination of more precipitation falling as rain and enhanced snowmelt.

Over the low-elevation regions (i.e., below the snowline), peakflows for the future 1997 events show negligible changes or slight decrease (Fig. 6), the latter of which is due to the decreased precipitation total over the lower elevations (Fig. S4). These regions are located at the relatively middle and downstream of the Truckee River watershed, thus attenuating the increases in peakflows at the upstream headwater basins. Thus, the percentage increases in peakflows decreases as the watershed size increases (Fig. 7a). Despite the attenuating effects of the downstream portion of the watershed, the peakflows at the main stem near the City of Reno still indicate 14% - 18% increases under future climate conditions.

4.2 Implications for Water Resource Management

First, this study highlights the importance of watershed antecedent conditions in driving the flood responses, noting that the ensemble mean peak flows can differ by a factor of three between dry and wet conditions. (Fig. 4 and S3). Thus, it is critical to monitor the watershed conditions—such as SWE, soil moisture, and reservoir depth—in real time. Second, the projected reduction in SWE does not necessarily lead to decreases in flood responses driven by snowmelt and rain-on-snow (Fig. 8). If there is sufficient snowpack available for melting, as demonstrated by the simulated 1997 events under future conditions (with a basin-averaged SWE of 80 mm before the event), the snowmelt is primarily governed by the net energy. As a result, the risk of increased snowmelt and rain-on-snow flooding will remain in warmer temperatures until snow conditions are depleted. Third, flood risks in high-elevation headwater basins of the Sierra Nevada mountains, where most reservoirs were built, are projected to increase most. This highlights the urgent need to update water management practices (e.g., reservoir operational rule curves) and invest in infrastructure resilience.

5 Summary and Conclusions

In this study, we used a storyline approach to investigate the 1997 New Year's flood under current climate conditions and three different future warming levels for the Truckee River watershed, utilizing meteorological forcings simulated by a regionally refined mesh enabled GCM (Rhoades et al., 2023, 2024) and long-term (40-year) and event-based hydrological simulations. Instead of estimating the impacts of climate change on flood frequency (e.g., the 100-year flood), the storyline approach focuses on a historical extreme event and provides quantitative estimates of such an event under future climate conditions. This study demonstrates the potential of using storyline approaches to analyze the complex causal chains between flood drivers and peakflows across all river networks (main stem and tributaries) within a watershed. Our analyses resulted in four key findings that address the research questions outlined in the Introduction:

1) We contextualized the 1997 New Year's flood event hydrometeorology using long-term hydroclimatological perspective (40 years), emphasizing that its rarity stemmed from an unusual combination of multiple flood drivers rather than a single extreme (Fig. 3). The watershed antecedent conditions (e.g., snowpack, soil moisture, and in-channel streamflow) play a dominant role in driving the flood. Our ensemble flood simulations show that the 1997 New Year's flood can be reproduced or exceeded only when the antecedent streamflow is >50 percentile (Fig. 4).
2) We conducted one current climate and three future 40-year continuous hydrological simulations, covering climate warming levels that range from 2 to 4 degrees (i.e., Delta 2 to 4) higher than pre-industrial levels. From the control to Delta 4 periods, the basin-averaged SWE decreases considerably, whereas the basin-averaged soil moisture increases between December and May, indicating a change in precipitation phase in the winter (Fig. 5a and 5b). The combined effects of decreased SWE and wetter soil moisture cause increased streamflow in the spring and decreased streamflow in the summer (Fig. 5c).
3) The ensemble mean peakflow for the Truckee River near Reno shows negligible changes under Delta 2 but shows 18% and 14% increases under the Delta 3 and Delta 4 conditions, respectively (Fig. 6). The increases in peakflows under Delta 4 can be attributed to wetter antecedent watershed conditions (Fig. 5b) and enhanced snowmelt, resulting from increased absorbed sensible heat and higher ground temperatures during the event (Fig. 8).

4) The future changes in the 1997 New Year's flood are scale and elevation-dependent, with the largest increases in peakflows occurring at small (e.g., $\leq$ 10 km^2) headwater basins in the high (>2,000 m) elevations (Fig. 6-7).

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Open Research

Data Availability Statement

The RRM-E3SM simulation used in this study can be found via a publicly accessible repository (Science Gateway) through the National Energy Research Scientific Computing Center (https://portal.nersc.gov/archive/home/a/arhoades/Shared/www/California_New_Years_Flood_1997). NLDAS-2 forcings are available at Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov/datasets?keywords=NLDAS).

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