Estimating Flash Flood Risk across the Colorado Plateau

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ABSTRACT

Flash flood reports and National Weather Service flash flood warnings across the Colorado Plateau of the southwestern United States are examined during five summer seasons (June-September 2021-2025) to identify watershed characteristics associated with flash flooding. Landform, weather, and recreation-related variables derived from datasets with spatial resolutions ranging from 10 to 1000 m are aggregated within United States Geological Survey Hydrologic Unit Code (HUC) watersheds. Across the region, 6% of over 320,000 stream segments and 25% of nearly 15,000 unpaved road-stream crossings are classified as hazardous.

Since flash floods are known to be underreported, flash flood warnings are used as a proxy for likely hazard occurrence. A random forest model is then used to assess the relative importance of terrain, weather, and human factors influencing the distribution of flash flood warnings at the HUC-10 watershed level. The fractions of hazardous stream segments, high-runoff soils, lightning frequency, and watershed area had the greatest relative importance for explaining the distribution of flash flood warnings within the watershed. These findings may help inform risk communication and warning strategies across the Colorado Plateau.

SIGNIFICANCE STATEMENT

Summer flash floods across the Colorado Plateau are a potential threat to local residents and to the millions of people who visit the region's national parks, monuments, and recreational areas. Rugged terrain, intense summer thunderstorms, and off-highway recreation increase exposure and vulnerability to such rapidly developing hazards. Flash floods occur when intense rainfall exceeds the ability of landscapes to absorb water, generating runoff that is often funneled through narrow channels or across backcountry roads in remote areas. Flash flood reports and National Weather Service flash flood warnings are related to watershed characteristics, including terrain, lightning frequency, and the relative remoteness of recreation areas. Understanding these relationships can improve hazard awareness, warning strategies, and risk communication for emergency managers, responders, and the general public.

1. Introduction

The scenic deserts, mesas, and valleys across the Colorado Plateau in the southwestern United States are sparsely populated with a cumulative total of less than 750,000 residents over an approximate area of 337,000 km^2. However, the region's eighteen protected federal land units (parks, monuments and recreation areas) record over 10 million visits during summer (June–September). Many of the visitors to these sites are unfamiliar with the hazards arising from the rapid onset of summer thunderstorms that may produce intense rainfall, lightning, and flash flooding. These hazards may disrupt travel and pose risks to individuals recreating near streambeds in flood prone areas.

Enhanced flash flood risk across the Colorado Plateau results from terrain, weather, and exposure characteristics, which, in rare instances, leads to people being in the wrong place at the wrong time. Figure 1 highlights the salient features of the Colorado Plateau region defined within the enclosed watersheds. The shaded regions highlight federal parks, monuments, and recreation areas that comprise ~21% of the 189,000 km^2 within this region (a 90% reduction in area of the Grand Staircase and Bears Ears National Monuments on 13 Jul 2026 has now reduced that fraction to ~15%). Destinations such as Glen Canyon National Recreation Area and Zion, Grand Canyon, and Bryce Canyon National Parks report nearly 75% of their annual visitations during summer months .

Roughly 50% of the region's population resides within metropolitan regions near St. George, Washington County, UT, Grand Junction, Mesa County, CO, and Flagstaff, Coconino County, AZ. Private land within this Plateau domain is limited to roughly 15% of the region with the remainder split between federal lands managed by the United States Forest Service and Bureau of Land Management (65%), state trust lands (10%), and tribal sovereign lands (10%).

Figure 1 does not capture the complex landform variability across the region with often steep transitions from high-elevation plateaus and mesas to low-lying deserts (Duniway et al. 2021). Soil types vary from sedimentary bedrock to loose sand. The watershed subbasins shown in Fig. 1 are delineated by the United States Geological Survey (USGS) at the 8-digit Hydrological Unit Code (HUC-8) level. (Flash floods also occur in five of the subbasins in the northwest quadrant of Fig. 1 that drain into the Great Basin.) During summer, it is common for some of the tributaries of the Colorado River labeled in Fig. 1 to have stretches of dry streambeds. However, runoff from thunderstorms can cause increased stream flows by several orders of magnitude in a few hours.

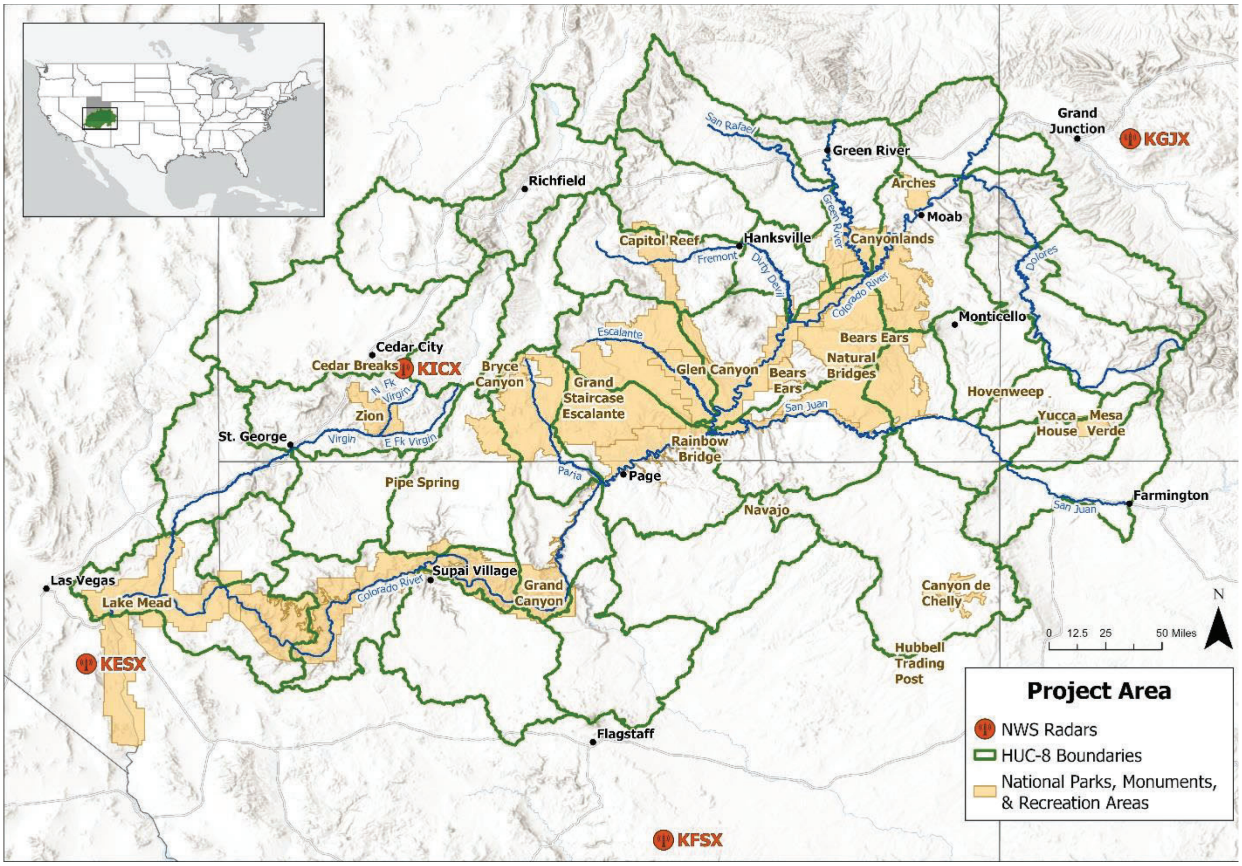

Fig. 1. Colorado Plateau region in the southwestern United States. National Parks, Monuments, and Recreation Areas prior to 13 July 2026 are shaded. Watershed subbasins at the USGS HUC-8 level are outlined. Locations of National Weather Service radars are shown by icons.

Horel and Powell (2024) and Duan et al. (2024) summarize the extensive literature related to the North American Monsoon that leads to the basic ingredients (lift, instability, and moisture) for summer thunderstorms to develop across the Colorado Plateau. Severe weather watches and warnings for protection of life and property across the Colorado Plateau region are provided by staff at National Weather Service (NWS) Forecast Offices in Flagstaff, AZ , Grand Junction, CO, Las Vegas, NV, and Salt Lake City, UT. The Salt Lake City (SLC) Forecast Office developed the Flash Flood Potential Rating (FFPR, SLC 2026) initially for Zion National Park. That rating is now used to benefit the public and government agencies responsible for twelve areas across southern Utah (Seaman et al. 2024). The FFPR estimates the likelihood of flash floods specifically for those areas in four categories from “Not Expected” to “Expected” at lead times from 0-2 days in advance.

Identifying whether flash floods are imminent or underway (the conditions leading to Flash Flood Warnings to be issued by NWS Forecast Offices) is hampered across much of the Colorado Plateau by limited stream gauges and weather observing sites. Forecasters rely heavily on satellite and radar imagery to observe and track severe thunderstorms. However, the operational radars within this domain labeled in Fig. 1 by icons (KESX, Las Vegas, NV; FKSX, Flagstaff, AZ; KGJX, Grand Junction, CO; and KICX, Cedar City, UT) provide incomplete coverage due to their high base elevations and intervening terrain.

The number of flash flood events in any region is difficult to quantify as they are often not reported to the NWS (Marjerison et al. 2016). Local storm reports obtained operationally by NWS Forecast Offices are available in near-real time from the Iowa Environmental Mesonet archive. The operational local storm reports are processed and archived as part of the Storm Events Database maintained by the National Centers for Environmental Information. Events in some cases may have additional information added after their occurrence and are available from the archive typically 90 days after their occurrence. We will use the terms reports and events interchangeably and rely on the Storm Events Database for flash flood reports.

Locations of flash flood reports across the Colorado Plateau during June-September 2021-2025 are shown in Fig. 2. These reports cluster near towns located near canyon exits and within the more developed and frequented areas in the national parks, monuments, and recreation areas, e.g., Zion and Capitol Reef National Parks (two dark-red shaded watersheds). The limited number of flash floods reported also affects validating the accuracy of flash flood forecasts (Erickson et al. 2021).

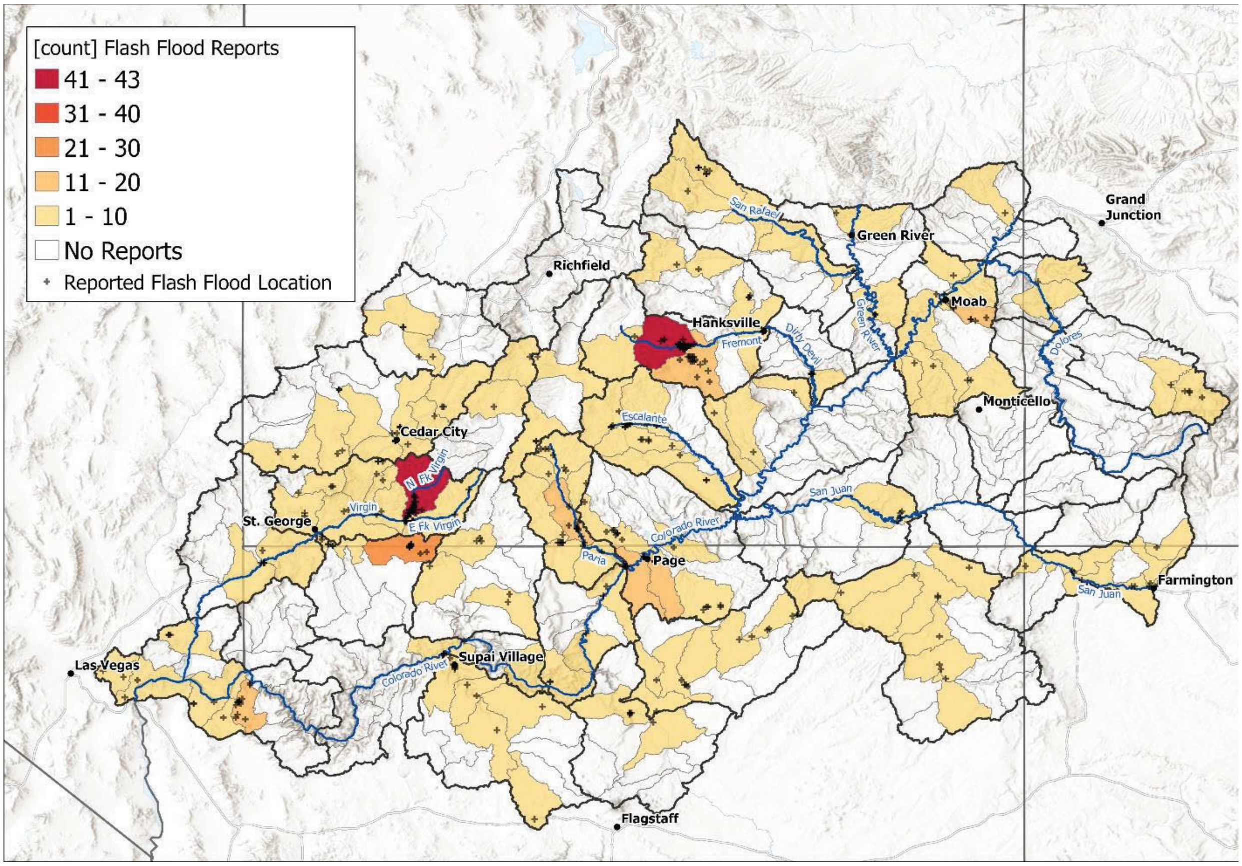

Fig. 2. Locations during June-September 2021-2025 of flash flood events (plus symbols) and total number of flash floods (shaded) in USGS HUC-10 watersheds (thin gray lines). Regional USGS HUC-8 watershed boundaries (heavy black lines) are also outlined.

Smith et al. (2019) provided the most comprehensive analysis of the seasonality and locations of thunderstorms across the Colorado Plateau. Their analysis was motivated by 20 fatalities due to flash floods in Hilldale, UT, and within Zion National Park on 14 September 2015. This pair of flash flooding events illustrates our later categorization of two distinct scenarios of being “in the wrong place at the wrong time”: (1) the potential for local residents as well as visitors to be swept downstream at stream-level crossings of normally dry streambeds and (2) backcountry recreationists caught in slot canyons. The thirteen fatalities in Hilldale resulted from vehicles attempting to cross Short Creek following an initial excessive rain event and subsequently being overtaken by a second pulse that occurred within 20 min of the first. The seven fatalities in Keyhole Canyon, a popular canyoneering destination, happened within 40 min of the second pulse as cells associated with the thunderstorm complex redeveloped 20 km to the northeast. While the Keyhole Canyon watershed is less than 1 km^2, the fatalities there resulted from excessive rainfall over that watershed combined with no opportunities to escape from the canyon. Unfortunately, the third largest number of flash flood fatalities on the Plateau happened recently on 17 July 2026 when 5 family members were swept downstream in a wash within the red highlighted watershed in Fig. 2 near Capitol Reef National Park.

The objective of this study is to quantify, as best as possible, some of the risk factors for individuals to be exposed to flash floods across the Colorado Plateau. Where is the risk greater during summer due to underlying terrain, weather, and human-behavior related factors? A total of 60 fatalities and 160 injuries have been reported in the study area from 1997–2025 (NWS 2026). The relatively low overall fatality number likely results from the tiny fraction of the Colorado Plateau where flash floods are prevalent, limited opportunities to be present when flash floods are underway, and procedures in place by agency staff and recreational guides to follow severe weather warnings issued by the NWS. The second highest loss of life (11 deaths) during this period occurred on 12 Aug 1997 in Antelope Canyon several kilometers south of Page, AZ. In this instance, the guide ignored warnings that the potential for a flash flood was high (NWS 2026). A recent visit to Antelope Canyon by one of the authors confirmed how tour operations changed after that event. Tour providers now inform the hundreds of tourists who visit Antelope Canyon each week that tours will be canceled when conditions indicate the potential for flash flooding. Similarly, feedback from Zion National Park staff on an earlier draft report related to this study included: “Flash flood fatalities can be reduced by providing visitors an accurate assessment of the risk of flash floods through the National Weather Service's FFPR system prior to making a decision on where to recreate in the Park. The rating system is central to staff communication with visitors.”

Figure 3 illustrates connections between the issuance of FFPR guidance by the SLC WFO and visitor behavior at Zion National Park. We obtained from park staff counts per day of visitors arriving by vehicle and summarize those counts as a function of the FFPR. While Fig. 3 indicates that fewer visitors enter the park as the forecasted flash flooding risk increases, park visitors are likely considering other information sources and factors such as excessively high temperatures.

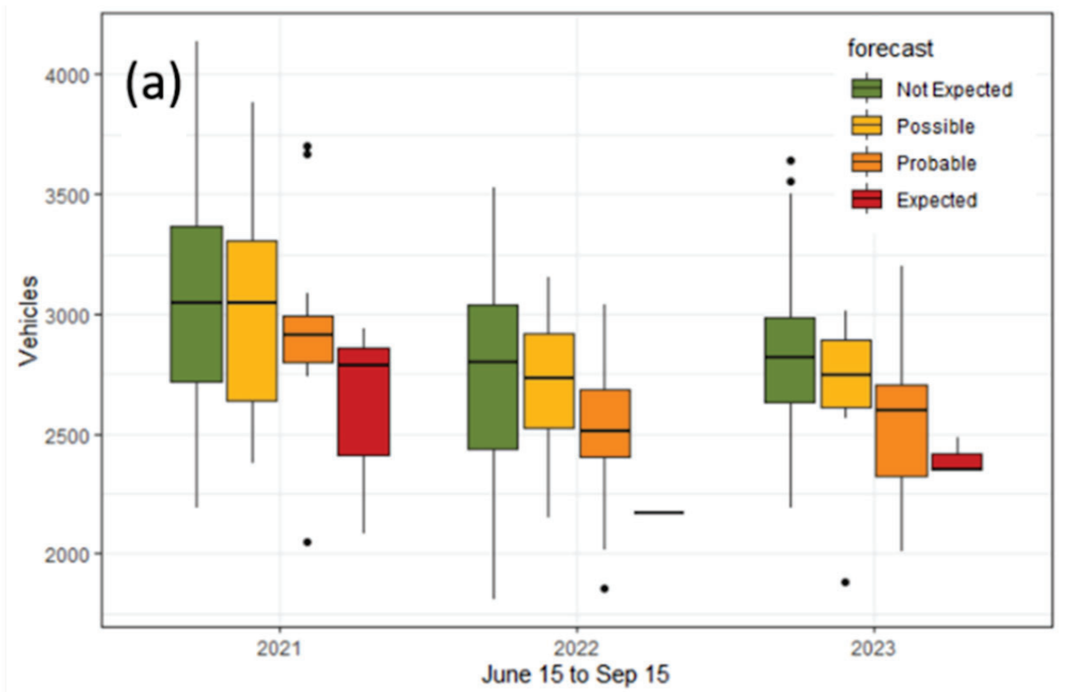

Fig. 3. Daily vehicle counts entering Zion National Park (ZNP) during the 2021-2023 summers categorized by the Flash Flood Potential Rating (FFPR) issued for Zion National Park by the SLC Weather Forecast Office.

The following questions are addressed in this study using data from the 2021-2025 summer months (June-September):

- Where and when have flash floods been reported and NWS flash flood warnings been issued on the Colorado Plateau?
- Which landform, meteorological, and recreation-related factors are associated with the locations and timing of flash floods across the Colorado Plateau? How can knowledge of these factors help reduce flash flood related risk for residents and visitors to the area?
- Using NWS flash flood warnings as a proxy for flash flood occurrence, can a machine learning approach identify the factors most strongly associated with the spatial distribution of flash flood warnings across watersheds?

Data sets used in this study to describe terrain, weather, and vulnerability factors for recreational applications are described in the next section. A random forest model is then used to identify watersheds having a higher likelihood of flash flooding and to assess which factors have greater influence on that potential risk. A summary of our results follows in Section 4. An ArcGIS story map is available to interactively access these figures and accompanying data (Hilton and Horel 2026).

2. Factors Contributing to Flash Flood Risk

As with flash floods elsewhere (Borga et al. 2014), their occurrence across the Colorado Plateau arises from the interaction of diverse static and dynamic factors that control the likelihood and susceptibility for their occurrence. Likewise, an individual's susceptibility to flash flooding is shaped by their exposure, situational awareness, and capacity to respond effectively to available information. Factors that may be relevant for flash flood risk assessment are described here from the standpoint of physiographic, meteorological, and exposure factors.

a. Terrain and Hydrologic Features

Table 1 summarizes the primary data sources used to define geophysical features of the Colorado Plateau. From the USGS digital elevation model, basic terrain characteristics (e.g., elevation and slope) were determined at 10 m horizontal and 1 m vertical resolutions. From the USGS hydrography data, watershed boundaries for 37 HUC-8 watersheds (Fig. 1), 313 HUC-10 watersheds, and 2084 HUC-12 watersheds were obtained. All spatial data analysis was performed with R (version 4.5.3) using sf v1.1-1 (Pebesma and Bivand 2023), terra v1.9-27 (Hijmans et al.2026), and whitebox v2.4.3 (Wu and Brown 2025) packages.

Description	Resolution	Source	Source URL	Last Updated
Digital elevation model	Horizontal: 10 m x 10 m Vertical: 1 m	The National Map – U.S. Geological Survey 3D Elevation Program	https://apps.nationalmap.gov/downloader/	4/17/2026
Boundary polygons and stream flowlines	1/3 arc sec (10 m x 10 m)	The National Map – U.S. Geological Survey National Hydrography Dataset Plus High Resolution) for Hydrological Unit 4	https://apps.nationalmap.gov/downloader/	4/15/2026
Hydrologic runoff properties	1:250,000 scale (~1km)	United States Department of Agriculture STATSGO	https://sdmdataaccess.sc.egov.usda.gov	4/28/2026
Lightning	1 km	Multi-Radar Multi-Sensor	https://registry.opendata.aws/noaa-mrms-pds	5/6/2026
Storm Events	Approximate latitude/longitude	NOAA National Centers for Environmental Information	https://www.ncei.noaa.gov/stormevents/	5/6/2026
Local Storm Reports	Approximate latitude/longitude	Iowa Environmental Mesonet (IEM) archive	https://mesonet.agron.iastate.edu/nws/	5/6/2026
NWS flash flood warnings	Polygons	Iowa Environmental Mesonet (IEM) archive	https://mesonet.agron.iastate.edu/nws/	5/6/2026
Mobile voice coverage	~500 m	FCC Broadband Data Collect	https://broadbandmap.fcc.gov/data-download/nationwide-data?version=jun2025&pubDataVer=jun2025	3/6/2026
Human impact	1km	Mu et al. (2022)	https://doi.org/10.1038/s41597-022-01284-8	5/6/2026
Unpaved Roads		Utah Geospatial Resource Center Bureau of Land Management United States Forest Service	https://opendata.gis.utah.gov/datasets/utah-roads/ https://gbp-blm-egis.hub.arcgis.com/pages/national https://catalog.data.gov/dataset/national-forest-system-roads-feature-layer	9/11/2025 5/13/2026 5/13/2026

Table 1. Data resources used in this study.

The area outlined in Fig. 1, contains 327,368 stream segments, totaling over 285,000 km in length, a distance roughly 10 times the earth's circumference at 40° latitude. On the scales of the HUC-8, -10, and -12 watersheds, the average total stream lengths are approximately 7700 km, 900 km, and 140 km, respectively.

Figure 4 shows three locations of recreational travel risk near Zion National Park, UT, that illustrate the challenges faced by agencies to assist visitors. Location A is the terminus of Orderville Canyon on the North Fork of the Virgin River. Downstream hiking through that wilderness area is by permit only and the areal extent of its upstream watershed is 177 km^2. The blue circle denotes the terminus of Zion's Narrows upstream hike with hundreds of visitors every day wading up the 6-10 m wide streambed wedged between 500-600 m cliffs. Access is closed within the Narrows watershed (area > 700 km^2) when the downstream gauge reports flows in excess of 300 $ft^3\ s^{-1}$ or the SLC WFO issues a flash flood warning. Location B in Fig. 4 is an unpaved road crossing on the East Fork of the Virgin River near Carmel Junction, UT. Under normal summer conditions, that crossing is unassuming and easily traversed by low-clearance vehicles. However, the upstream watershed of this location is over 400 km^2 in area, with high runoff soil covering over 80% of that area. The stream width and depth during storm events may increase to 15 m and over 1 m, respectively. While no fatalities or injuries have occurred at this crossing to date, one of the co-authors has observed several occasions when drivers attempted to cross while dangerous flash floods are underway (e.g., Fig. 5).

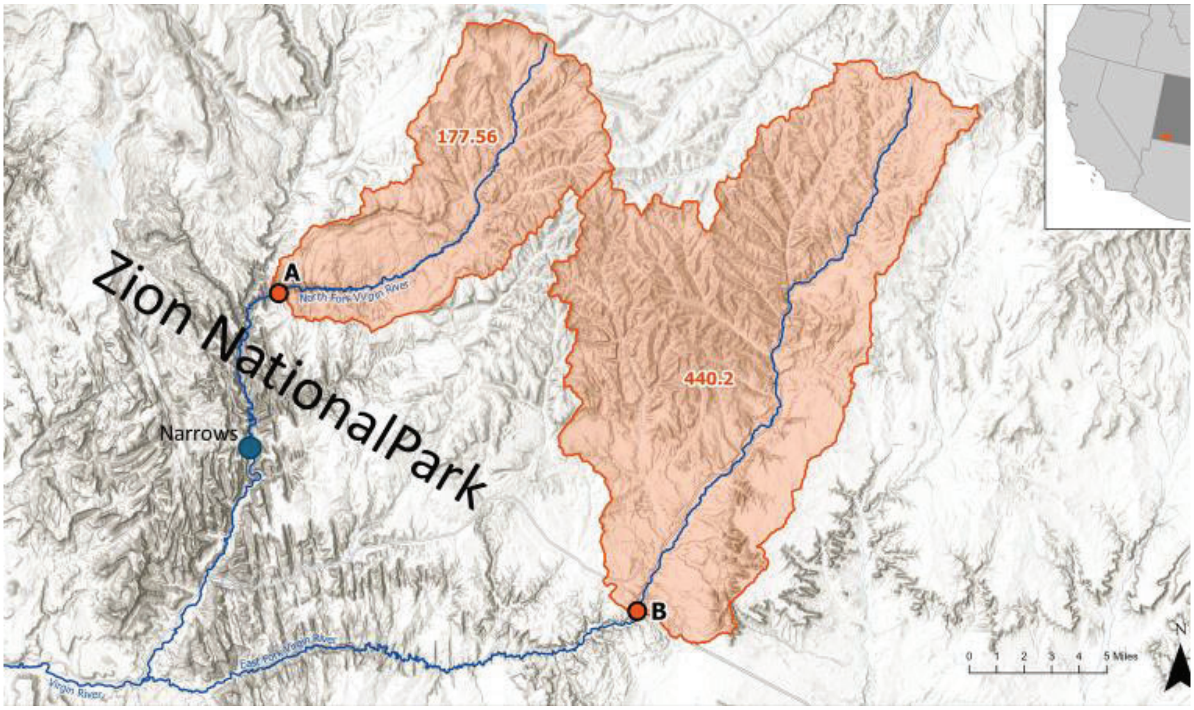

Fig. 4. Orderville Canyon shaded above Point A and beginning of the popular Narrows hike (blue dot) on the North Fork of the Virgin River. Watershed shaded above Point B, an unpaved stream crossing of the East Fork of the Virgin River.

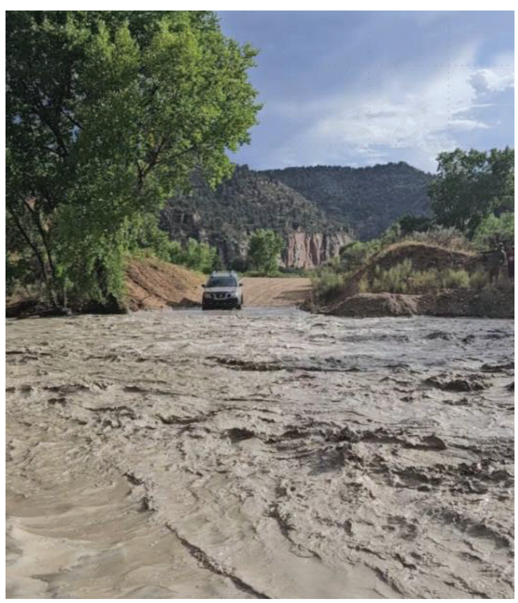

Fig. 5. Off-highway crossing on the East Fork of the Virgin River (point B in Fig. 4) on 17 Aug 2024 during a flash flood event.

Although any of the over 300,000 stream segments in the region could lead to drowning, some have much higher potential to do so. Seaman et al. (2024) identified 277 potentially hazardous recreational routes within 72 of the 313 HUC-10 watersheds within the County Warning Area of the Forecast Office. This identification relied on trail and canyoneering guides, input from agency personnel, and other sources. The locations of these routes relative to our stream segments is provided by Hilton and Horel (2026).

For this study, characteristics common to such recognized hazardous routes were assessed from the perspective of the following questions:

- Would recreational hikers likely be traveling in such streambeds?
- Can hikers escape hazardous stream sections by running short distances downstream of approaching floods?
- Would hikers be able to climb laterally to safety?

To address these factors, stream segments are combined by their USGS coded stream reach number. To be classified as hazardous, a stream reach must be longer than 500 m and have an average slope less than 20°. The length constraint prioritizes stream reaches where there is low likelihood of outrunning a flash flood, whereas the slope constraint emphasizes hazards encountered by recreational hikers as well as the typically short fetches of steep terrain that require canyoneering skills. In addition, hazardous stream segments must have lateral sidewalls estimated by terrain slopes greater than 30° within 20 m on each side of the stream for more than 20% of the stream segment length. The combination of these three constraints is intended to identify those segments where hikers are faced with limited opportunities within a ~100 m stretch to escape downstream or laterally from a flash flood.

Roughly 18,000 stream segments totaling nearly 20,000 km are identified on the basis of these constraints as hazardous. They represent 6% of the total number and 7% of the total length of stream segments in the region. As a crude validation of our approach, 226 of the 277 hazardous routes identified by Seaman et al. (2024) overlap with hazardous stream segments. Many of the "missing" routes have wider lateral extents than our restrictive criterion.

To help contrast relative flash flood risk across the Plateau, Fig. 6 shows the percent drainage density of hazardous streams for each HUC-10. This metric is the ratio of hazardous stream drainage density to total drainage density for each HUC-10 watershed. Large fractions of hazardous streams (> 20%) are evident in 25 of the 313 HUC-10 watersheds including: upper Lake

Powell region; Grand Canyon region; Zion National Park, Capitol Reef (Fremont River), and Escalante River.

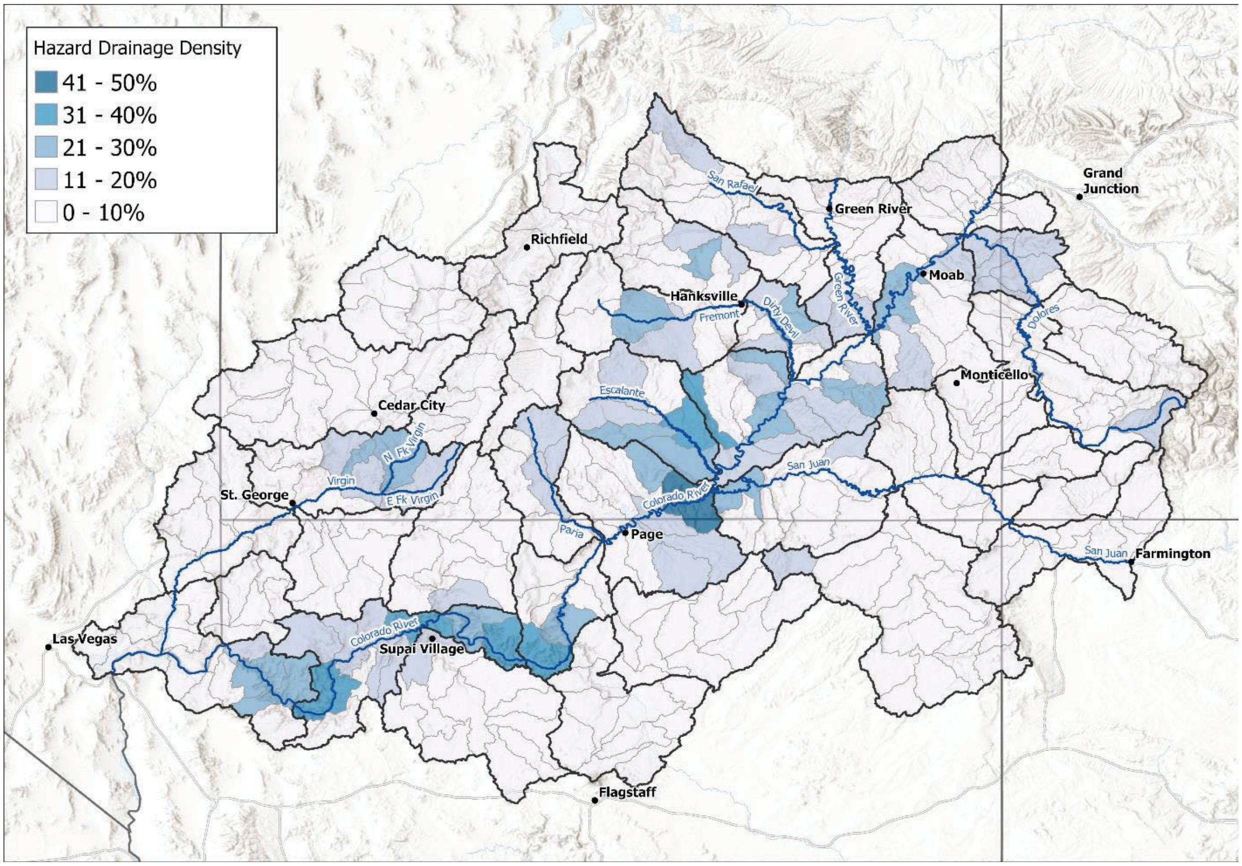

Fig. 6. Hazard drainage density percentage (hazardous length/total length) within HUC-10 watersheds. HUC-8 watersheds outlined.

Soil type within a watershed is another critical factor controlling the rate at which rainfall becomes surface runoff. The United States Department of Agriculture defines four Hydrologic Soil Runoff Groups. Group A soils typically have coarse texture, resulting in low runoff potential. Group B and C soils allow moderate to low infiltration and correspondingly allow low to moderate runoff. Group D soils (clay or functionally impervious sedimentary rocks) have very low infiltration capacities. Consequently, watersheds with a greater proportion of Group D soils are expected to exhibit more rapid runoff during intense rainfall, and increased susceptibility to flash flooding.

In addition to soil type, runoff is influenced by terrain slope. Areas with low impermeable soils and steeper slopes lead to more runoff than areas with high impermeable soils and flat terrain. Figure 7 superimposes for every HUC-10 watershed the relative fractions of Group D soils and median slope. Over half (160) of the HUC-10 watersheds are composed of Group D soils (orange shades) while a quarter (80) have median slopes in excess of 10º (pink tints). The blended darker orange shades highlight the 51 watersheds with both of those conditions (low permeability soils and high median slope). Many watersheds within the Grand Canyon stand out as having impervious soils and high slopes.

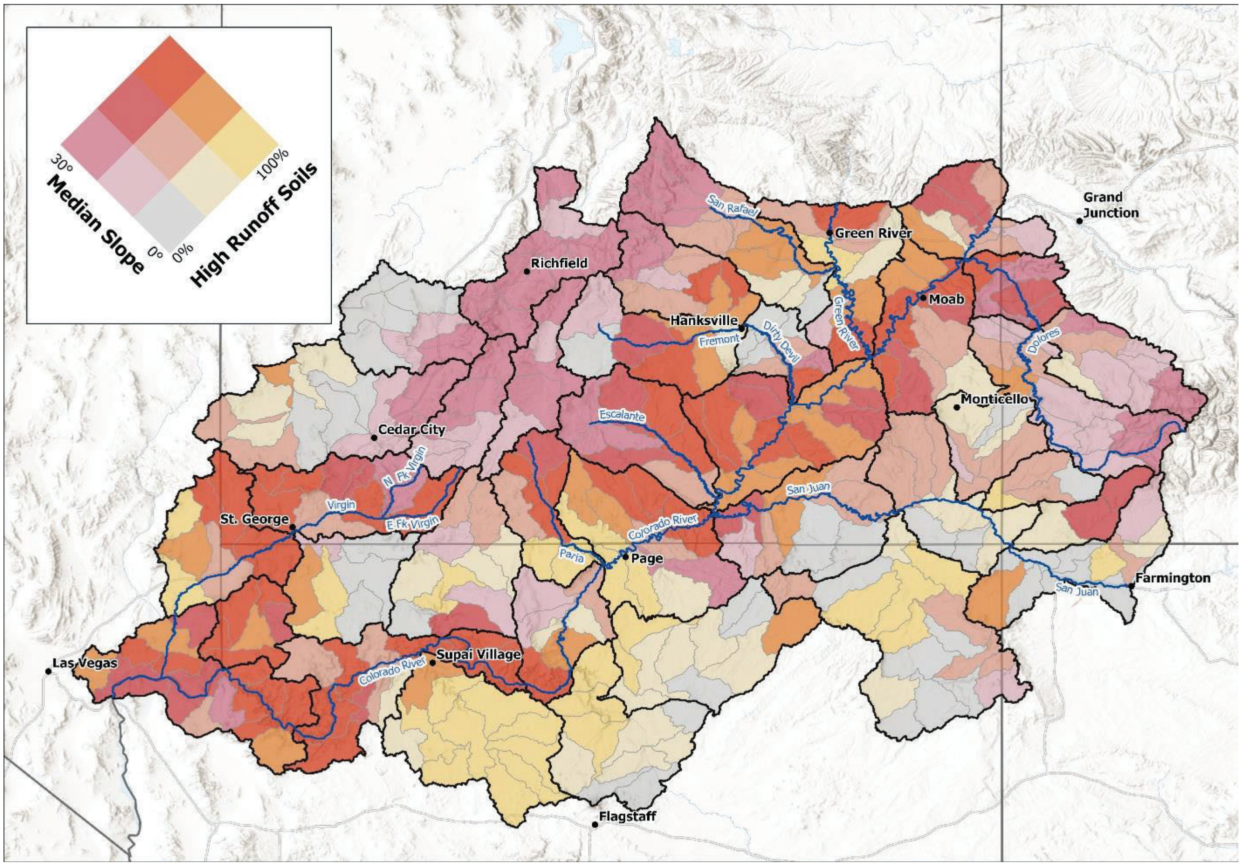

Fig. 7. Median slope (pink shades) and percent of Group D soils (orange shades) for HUC-10 watersheds.

b. Weather

The flash flood guidance from the NWS Colorado Basin River Forecast Center (CBRFC) identifies rainfall rates of 0.5-1.0 in hr^{-1} as increasing the likelihood of flash flooding across much of the Plateau region, particularly where watershed with high runoff soils predominate (CBRFC 2026). Specific areas within Zion and Capitol Reef National Parks, Antelope Canyon and near the Escalante River are identified as being at risk when rain rates exceed 0.25 in hr^{-1}. Horel and Powell (2024) discussed the limited options for obtaining rainfall rates across the

Colorado Plateau. Based on public data accessible via Synoptic Data PBC, there are under 400 stations potentially reporting precipitation in the domain outlined in Fig. 1 (Hilton and Horel 2026). Assuming all stations are reporting, Voronoi tessellation (e.g., Di et al. 2020) highlights their non-uniform distribution with 25% of the stations in data rich regions representing areas of ~100 km^{-2} while the stations in data poor regions represent areas of over 500 km^{-2} (not shown). The operational WSR-88D radars that surround the Plateau leave wide sections of the region without sufficient coverage to estimate rainfall (Fig. 1). Radar-based precipitation estimates such as from the Multi-Radar Multi Sensor (MRMS) system used by Horel and Powell (2024) are inadequate for the watersheds across the entire Plateau.

As a proxy for convective precipitation events, Fig. 8 shows the mean spatial distribution of lightning during the five summers derived from the National Lightning Detection Network (NLDN; Murphy et al. 2021). The average daily number of cloud-to-ground lightning strokes over summer months are summarized by the 1 km x 1 km gridded flash extent density MRMS product accessible from the Iowa Environmental Monitoring archive (Table 1). Figure 8 highlights the frequent lightning that prevailed across the region during these five summers with the most frequent lightning on the elevated terrain on the southwestern flank of the Colorado Plateau and high-elevation plateaus of southern Utah described by Horel and Powell (2024).

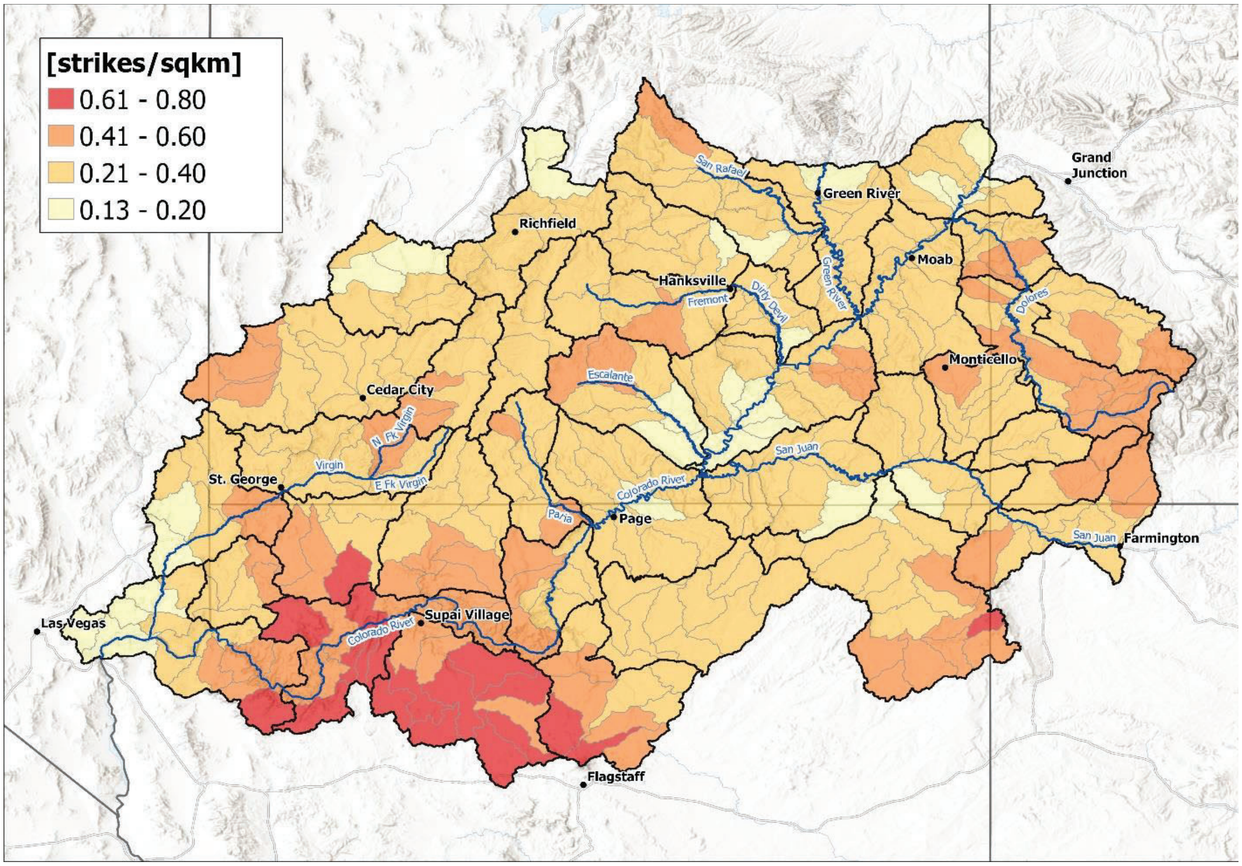

Fig. 8. Mean lightning flash extent density per day (strikes km^{-2} day^{-1}) in HUC-10 watersheds.

Afternoon surface heating of elevated terrain across the Colorado Plateau provides the orographic lift that aids thunderstorm development (Schumacher 2017). Flash flood water volumes in the region's watersheds are less related to basin scale, as is often the case in other regions of the U.S. (Smith et al. 2019). Rather, the flash flood response is tied to the spatial scale of thunderstorms (10-50 km^2) and their proximity to the catchments upstream of channel narrows as estimated by our hazardous stream metric (Fig. 6). The abruptness or "flashiness" (difference between peak discharge relative to baseline flow and then normalized by rise time) of flash floods in the southwestern U.S. is well established (Saharia et al. 2017). For example, James and Schumacher (2024) highlight that short-duration (1-h) Multi-Radar Multi-Sensor (MRMS) (QPEs) align more with flash floods in the southwestern U.S. while 6-h totals are more appropriate to use in many other regions of the country.

Figure 9 addresses the seasonality of summer thunderstorms across the Colorado Plateau. The daily mean lightning density (flashes km^{-2}) across the entire region is shown for each day during the five summer seasons. The core period for thunderstorms in this region during these five summers is from mid-July through August. Thunderstorms during the 2021 and 2022 summers were much more frequent (0.21 and 0.26 strikes km^{-2} day^{-1}, respectively) than the later three years (0.15, 0.19, 0.08 strikes km^{-2} day^{-1}).

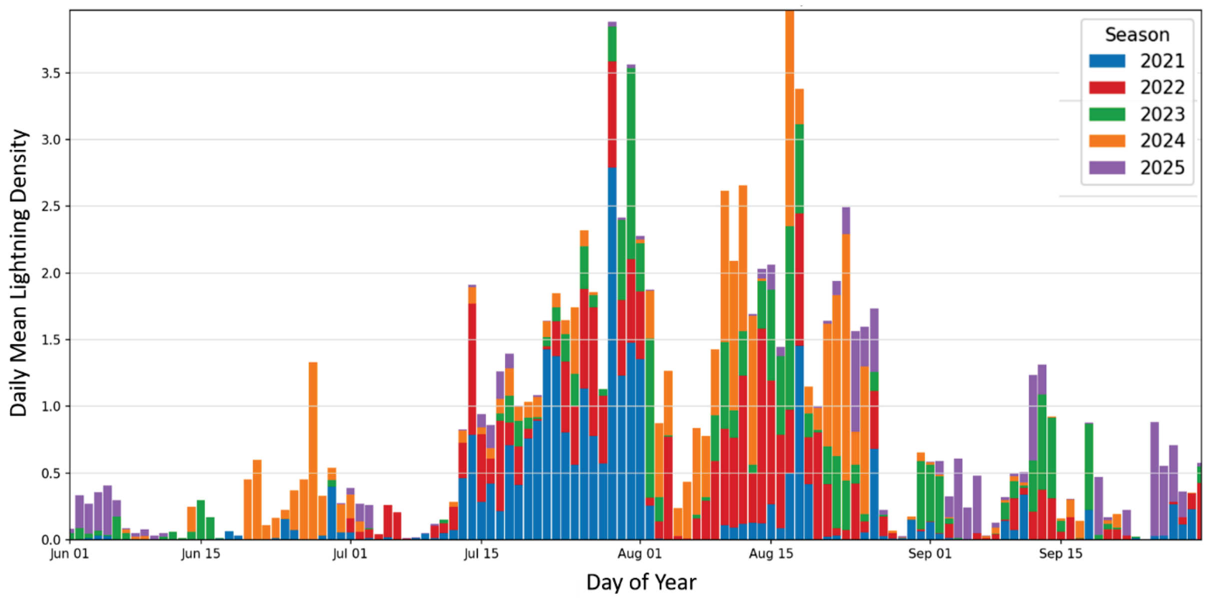

Fig. 9. Daily mean lightning density (strikes km^{-2}) across the Colorado Plateau during the five seasons.

We propose that the most useful metric available to us for identifying where and when hazardous flash flood conditions were present during the past five summers follows from the set of flash flood warning polygons issued by NWS Forecast Offices (Fig. 10). The forecasters issuing the flash flood warnings assess and integrate all the information available to them, including weather information from satellite, radar, station observations, and forecast model guidance. In addition, their knowledge builds on information about underlying landform conditions, such as the terrain factors introduced in Section 2a, as well as current storm reports from park personnel and emergency managers, recent burn scars, and antecedent soil moisture.

Figure 10 shows the number of times each 1 km^2 grid cell is overlapped by flash flood warning polygons. Beginning from the southwest sector of Fig. 10, the warning “hot spots” include: the Hualapai/Grand Canyon region of Mohave County, AZ; Supai, AZ; Hilldale, UT and Zion National Park, UT; Paria River and Buckskin Wash, UT; Antelope Canyon, AZ; Escalante River; and Capitol Reef National Park. Other locales with relatively high numbers of warnings issued are the San Rafael Swell, UT, and near Moab, UT.

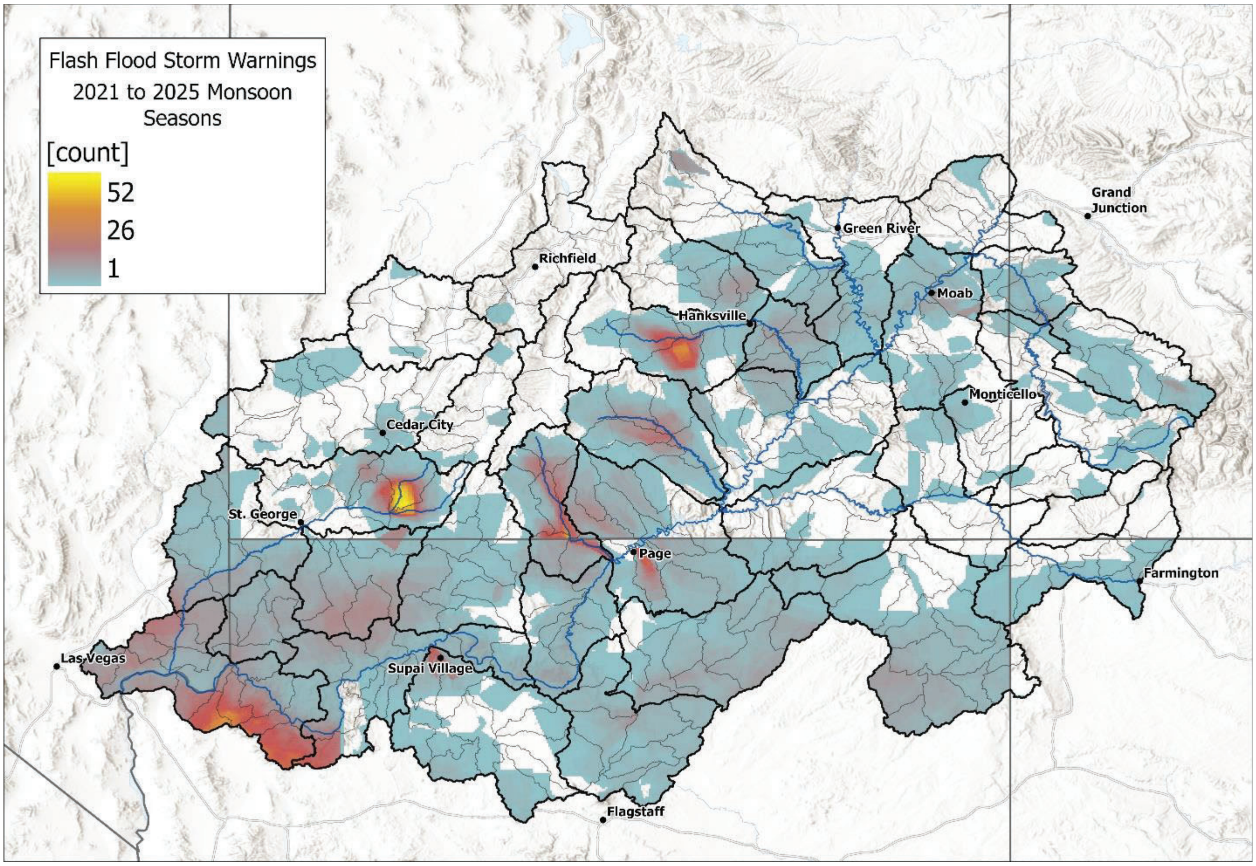

Fig. 10. Number of flash flood warning polygons intersecting each 1 km^2 square.

As shown in Fig. 11 and as expected, the totals of flash flood reports in a year are much lower than the number of flash flood warnings issued. Since flash flood warnings are updated as a storm progresses, unique NWS Event Tracking Numbers were used to identify and count individual warning events. Higher numbers of flash floods were reported across the Plateau during 2021 and 2022 although fewer warnings were issued in 2021 than 2022. The numbers of flash flood warnings overall were roughly comparable during the other three summers with the widest relative spread between reports and warnings during 2025.

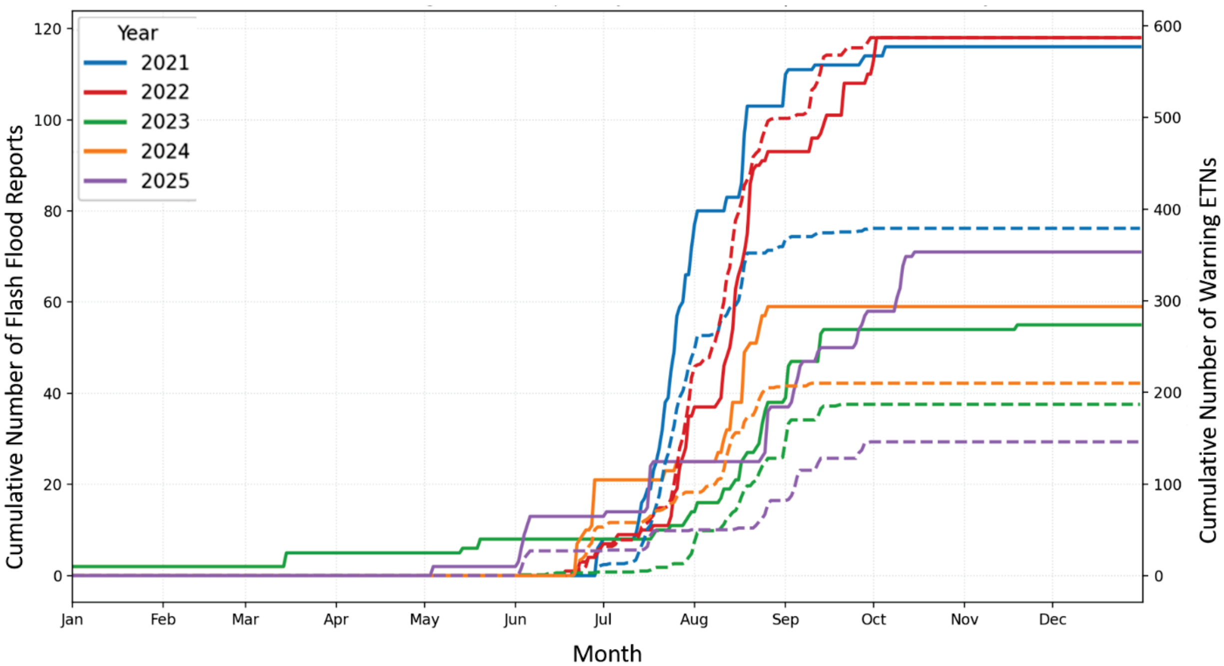

Fig.11. Cumulative numbers across the Colorado Plateau during 2021-2025 of flash flood reports (solid lines) and flash flood warnings with unique Event Tracking Numbers (dashed lines).

c. *Vulnerability*

Duarte et al. (2026) used a large language model to interpret objectively the plain-text remarks within over 22,000 flash flood local storm reports across the United States. We have applied a similar approach to summarize the remarks available from the 1,437 NOAA Storm Events flash-flood events from 1996-2025 within the Colorado Plateau region. The event and episode narrative fields in each report were combined into a single text string and assigned thematic labels using a rule-based keyword approach. After examination of all the reports, eight non-exclusive categories were defined: stream, road, public land, recreation, storm, debris, safety, and infrastructure. The presence of one or more model defined case-insensitive keywords or short phrases were then categorized. A single report could receive multiple labels. As shown in Fig. 12, roughly 60% of the reports were tagged for the stream category as many had clear-cut wording (e.g., "… river gauge recorded a flow rate …"). Similarly, a majority of the reports mentioned direct transportation impacts most often along highways (road closures, washouts, etc.). Other common phrasing that led to placement in the other categories included specific place names (e.g., Natural Bridges

National Monument), terrain indicative of recreational activities (e.g., slot canyons), thunderstorm reports, and specific damage or safety related language.

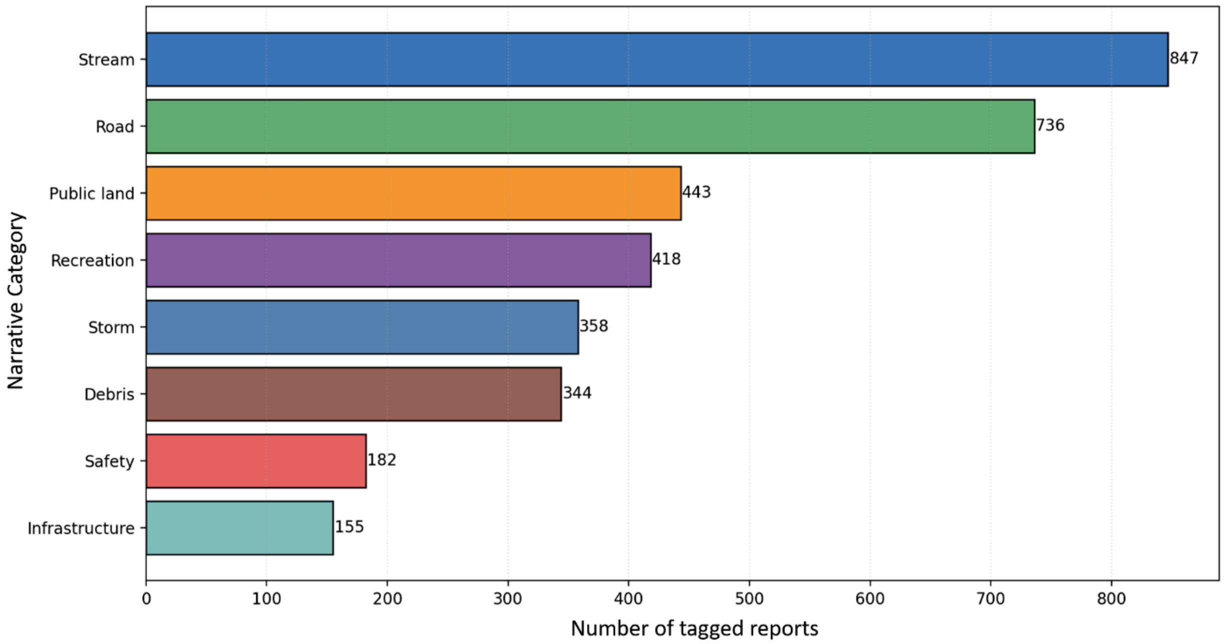

Fig. 12. Large language model categorization of flash flood events across the Colorado Plateau.

As Fig. 12 suggests, residents and visitors to the Colorado Plateau are most likely to be affected by flash floods that impede travel on paved roadways. Fig. 5 illustrated that motorized travel on unpaved roads that cross streams can lead to hazardous situations, particularly when the upstream catchment may be sufficiently large for flooding to occur. Nearly all of these backcountry roads lack culverts or bridges. When such structures are present, they often become clogged during flash flood events. Figure 13 summarizes HUC-10 watersheds by the number of unpaved stream crossings with relatively large catchments (defined as > 40 km^2). The watersheds with the largest

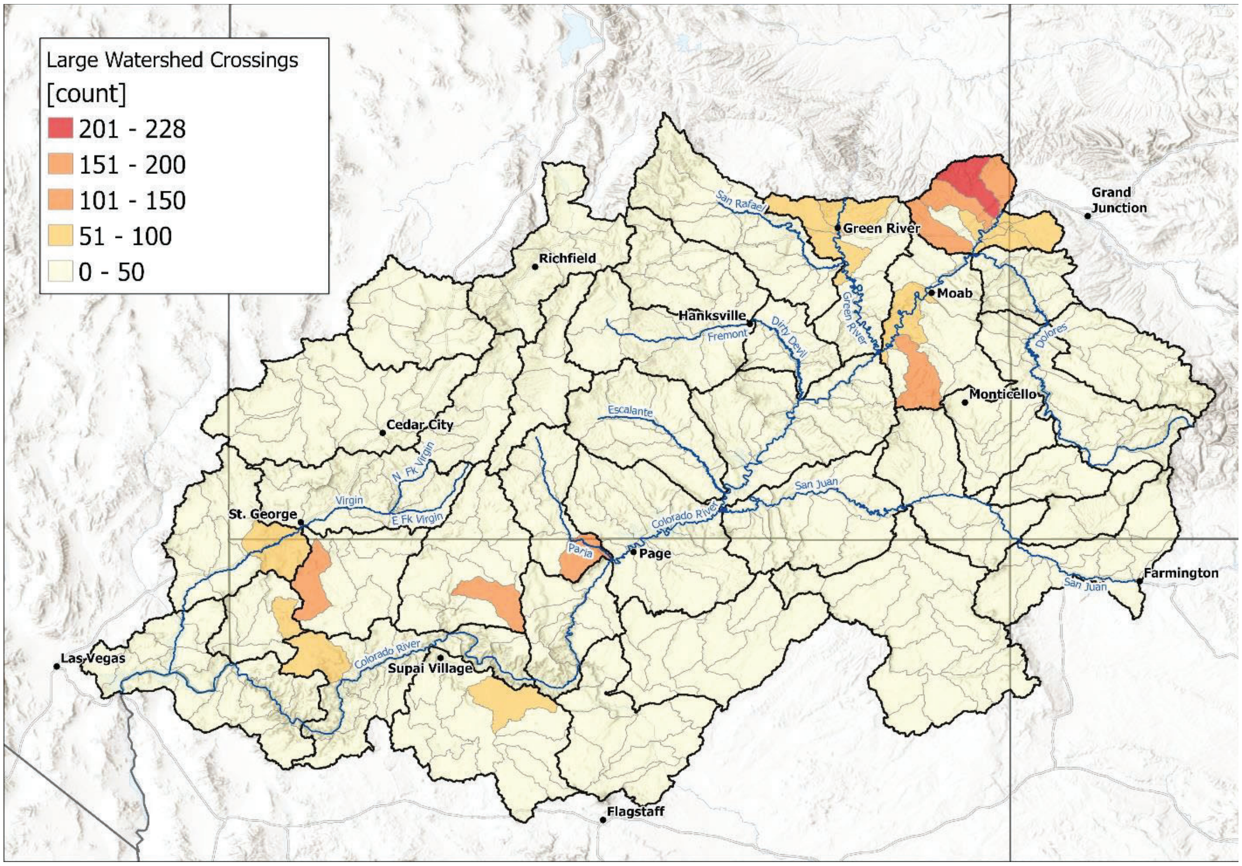

Fig. 13. Number of unpaved road crossings with upstream catchments greater than 40 km^2 within HUC-10 watersheds.

numbers of such crossings tend to be concentrated in regions where relatively dense road networks have been developed for grazing, resource management, and timber and mineral extraction. These areas are often now used for recreational activities.

Morss et al. (2016) and Semmens et al. (2026) illustrate the complexities of public perception of flash flood warnings and how individuals may respond to such guidance. A first step is simply whether individuals can receive such guidance, let alone then act upon it. The ability of commercial cell networks to support text level communication including hazard updates from emergency managers or the NWS is fundamental for public safety. Wireless Emergency Alerts (WEAs) are a critical source available to the general public for flash flood watches and warnings issued by NWS Forecast Offices. The Federal Communications Commission estimates, somewhat optimistically, that only 19% of the HUC-10 watersheds are suggested to have poor cell coverage (less than 33% coverage across those watersheds.

Mu et al. (2022) provide a high resolution (1 km^2) global mapping of the “human footprint” during the period 2000 – 2018 on the basis of eight variables: built environments, population density, nighttime light, croplands, pasture lands, roadways, railways, and navigable waterways. Using the 2018 human footprint map, values in our domain range from below 1 (defined by Mu et al. 2022 as wilderness) to over 50 (high human footprint) (Hilton and Horel 2026). However, mean footprint values for HUC-10 watersheds were above 4 (considered by Mu et al. 2022 to be highly modified) for all but three watersheds in the upper Lake Powell region. Recognizing the limitations of this single metric for our region in comparison to the entire globe, we created a relative wildness value for each HUC-10 watershed as the difference between the highest footprint value (18.5) in the region and the watershed’s footprint value. The upper Lake Powell region has wildness values greater than 15. Surprisingly, the least wild watershed (wildness = 0) is that for the Ojo Amarillo Canyon-San Juan River, NM, watershed with relatively low population but extensive irrigated agriculture. Metropolitan St. George is split among multiple watersheds that leads to higher than expected wildness values for each of them (~4). The human footprint and wildness metric do not reflect the high visitor counts experienced in many of these watersheds. However, they do reflect, in part, the region’s distribution of unpaved roadways and other infrastructure.

Figure 14 merges the indices of limited cell service and wildness for HUC-10 watersheds. The most southeastern HUC-10 watershed (Ojo Amarillo Canyon) is shaded light yellow since it has good cell service and the highest human footprint value while, not surprisingly, many watersheds in the Grand Canyon, shaded green, have limited cell service and high relative wildness.

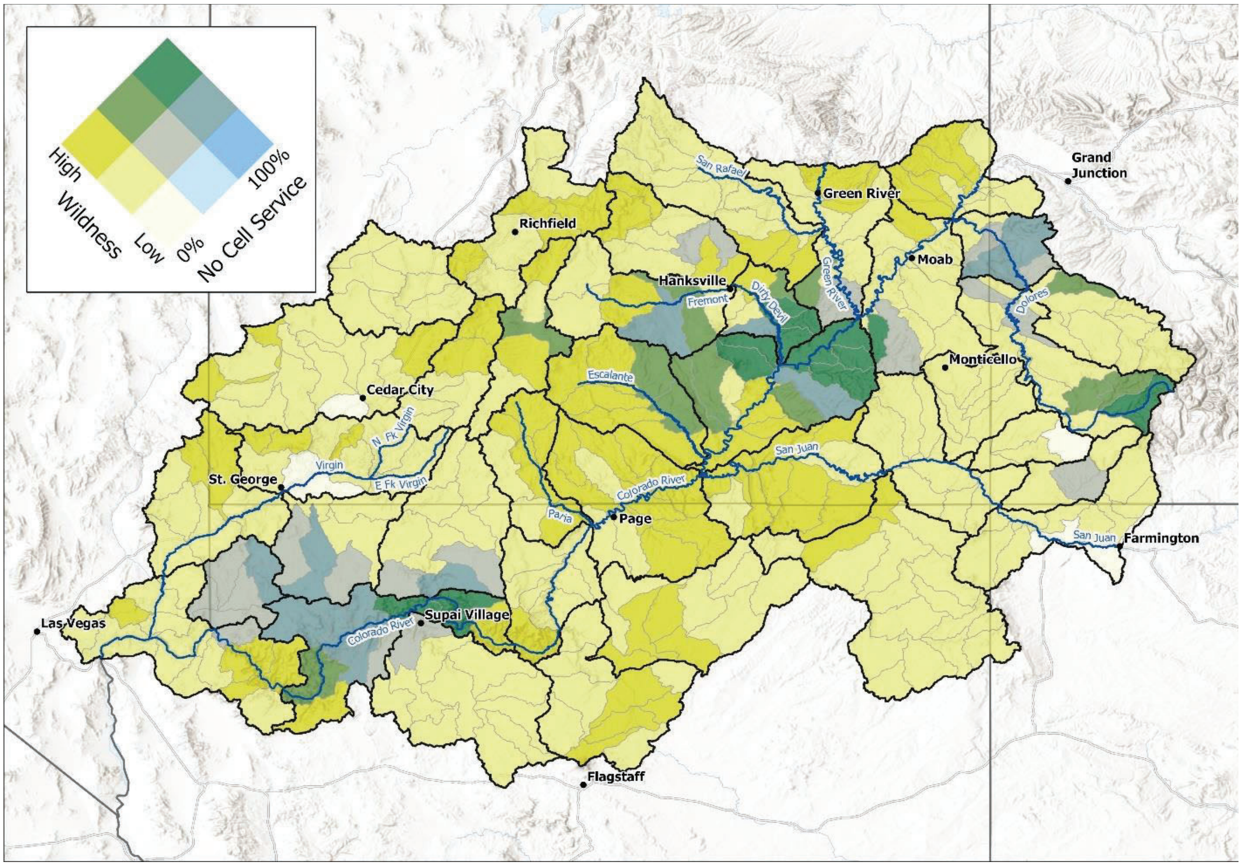

Fig. 14. Percent coverage without cell service (blue shades) and relative wildness (yellow shades) for HUC-10 watersheds. Green shaded watersheds denote limited cell service and higher wildness.

3. Estimating Relative Importance of Factors Leading to Flash Flood Risk

Recognizing the complex interplay among the environmental and human vulnerability factors described in Section 2, we evaluate the extent to which these factors might help explain the spatial distribution of flash-flood warnings across the Colorado Plateau. A key challenge for our study is that it is not practical to compare the small number of flash flood reports directly to these explanatory variables. As discussed in Section 2b, we will assume that NWS flash flood warning polygons issued during the five summer seasons are a practical proxy available for identifying where hazardous flash flood conditions were likely present (Fig. 10). Rather than attempting to validate the accuracy of those warnings, our objective is to assess whether static and climatological environmental and human factors may help explain where flash flood warnings have been issued most frequently and which factors may be most relevant to their issuance.

A random-forest regression model was developed to estimate flashflood warning counts for the 313 HUC-10 watersheds using 11 watershed-scale explanatory variables (Table 2). The model used normalized variables to estimate the actual number of Event Tracking Number warning counts in each watershed. Repeated random holdout resampling was used with 80% of watersheds used for model fitting and 20% withheld for evaluation in each iteration. Model hyperparameters included 500 trees, a minimum of 3 samples per leaf, and random consideration of 3 predictors at each split. Performance for each iteration was summarized for both training and withheld subsets using Spearman rank correlation, root-mean-square error, and the fraction of flood warnings described by the watersheds with the top decile of estimated warnings. Repeated random holdout was used to select the best-performing random forest model using the 11 variables. That selected model configuration was then fit using the full set of HUCs to generate an estimated value for each HUC.

Variable	Relative Contribution	Sign
Hazardous streams	Very strong	Positive
Lightning	Very strong	Positive
Soil D	Strong	Positive
Soil B	Strong	Negative
Upstream area	Strong	Positive
Median slope	Moderate	Positive
No cell service)	Moderate	Negative
Human impact	Moderate	Negative
Soil C	Weak	Negative
Unpaved roads	Weak	Negative
Soil A	Weak	Positive

Table 2. Variables used in the random forest model. The relative contribution and sign of the variable in the model is based on mean absolute and sign of the SHAP values.

Figure 15 compares the NWS flood warning counts in the HUC-10 watersheds with those estimated by the best-performing random forest model. While the overall relationship is quite good (0.89 Spearman correlation), the model underestimated the very high warning numbers at a few HUC-10 watersheds while generally overestimating the many watersheds with small numbers of warnings.

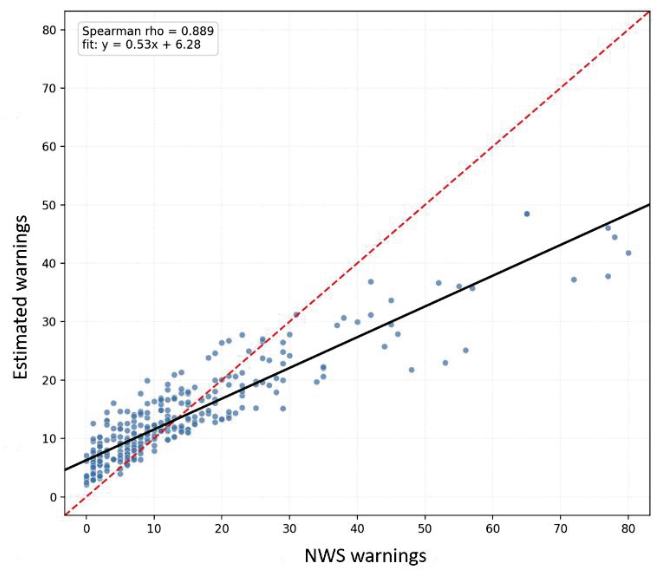

Fig. 15. NWS flash flood warnings vs estimated warnings
at the 313 HUC-10 watersheds across the Colorado Plateau.

Considering the model's bias in estimating the actual number of warnings, Figure 16 relates the level of agreement between the tercile ranges of the actual and estimated warning counts and expresses that in terms of relative risk. The 70% of the watersheds represented along the diagonal reflect agreement between the actual and modeled warning counts, which is loosely interpreted here as agreement on the relative risks of flash flooding in those watersheds. This high level of agreement is not unexpected as we are not able to test the model on an independent sample of watersheds.

NWS \ Estimated	**Low**	**Moderate**	**High**
Low	**81**	21	3
Moderate	24	**59**	21
High	0	24	**80**

Figure 16. Counts of HUC-10 watersheds in each tercile bin for observed and estimated flash flood warning counts that are interpreted here as reflecting low, moderate, and high risk for flash flooding. Cell shading is used to represent these categories in Fig. 17. Diagonal values (bold type) reflect agreement between the actual and model estimates of risk.

The light yellow, grey, and green shaded watersheds in Fig. 17 represent the nearly three quarters of the watersheds for which the actual and estimated number of warnings agree. Most of the model's overestimates of flash flood warnings (blue shades) are near and to the south of the Colorado River upstream of Lake Powell. This clustering suggests that the region may experience greater flash flood risk than is reflected by the limited number of flash flood reports and actual flash flood warnings issued during the 2021-2025 summer period (Figs. 2 and 10). Areas where the model may be underestimating flash flooding (e.g., moderate NWS and low model risk) tend to be remote regions around the fringes of the Colorado Plateau.

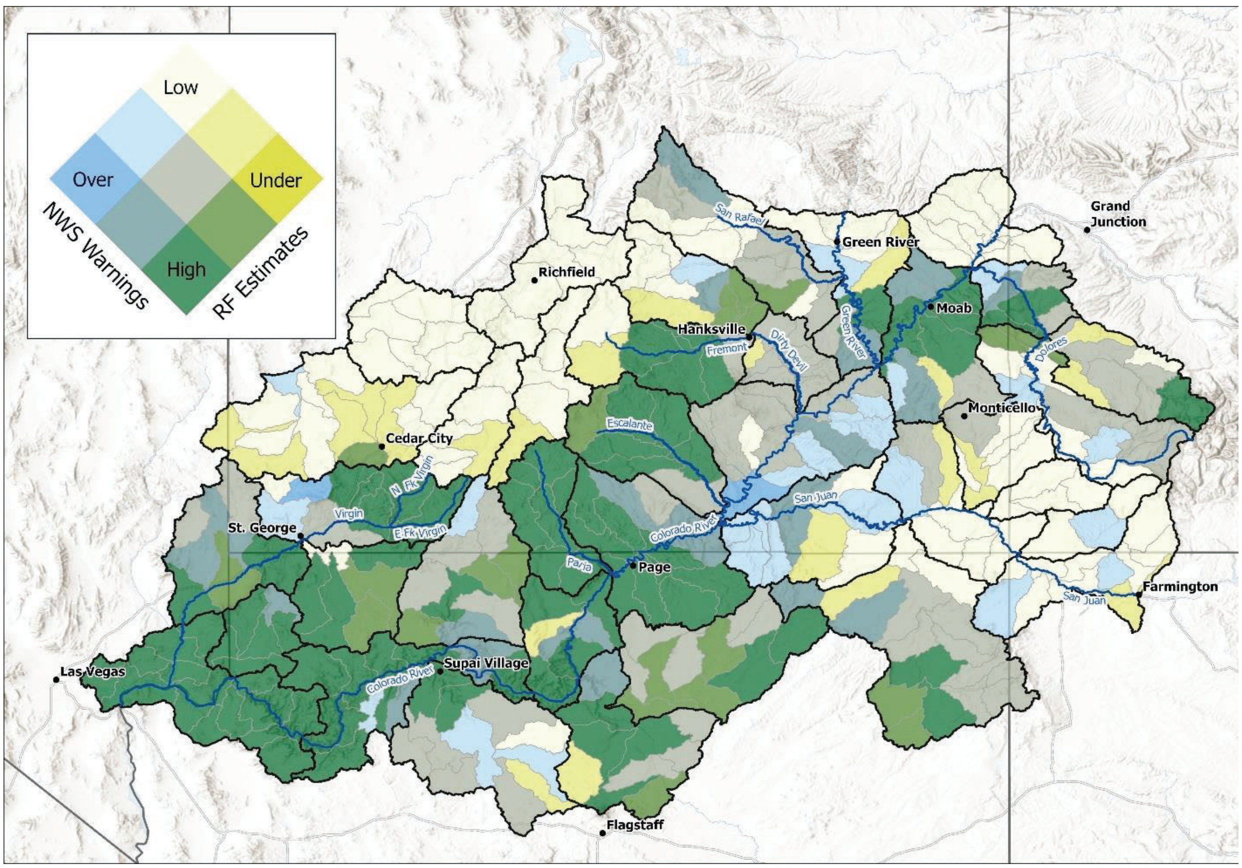

Figure 17. Flash flood risk (shading) derived from the relative amount of agreement between the actual flash flood warnings and those estimated by the random forest model for each HUC-10 watershed. As shown in the legend, good agreement for low (light yellow) to high (green) risk is evident by the shades along the center axis. Overestimated model risk is evident by blue shades. Model risk underestimates are evident by yellow shades.

Figures 15-17 suggest that the model reasonably captures the spatial distribution of flash flood warnings on the basis of the 11 model variables. Scatterplots of each explanatory variable against observed warning counts were used to summarize their bivariate relationships (not shown). To interpret the relative contributions of the 11 variables to the model, we applied SHapley Additive exPlanations (SHAP, Lundberg et al. 2020), which decomposes each individual model prediction into additive contributions from the 11 explanatory variables relative to a baseline prediction. SHAP values across watersheds are used to estimate both the relative importance of each variable, using the mean absolute SHAP value, and its dominant direction of influence, based on whether larger values of a predictor were generally associated with positive or negative contributions to estimated warning counts.

Table 2 summarizes the SHAP-based interpretation for the random-forest model. Mean absolute SHAP values were used to rank predictors by relative strength, and SHAP dependence relationships were used to assess whether higher variable values were generally associated with higher or lower estimated flash-flood warning counts. The variables with the strongest positive contributions to the model were the fraction of hazardous streams, average lightning, and fraction of high runoff soils. The low-moderate runoff soil metric (Soil B) contributes inversely to high flash flood risk, i.e., less Soil B fraction in the watershed is associated with higher risk. The relatively low contributions from the no cell, human impact, and unpaved roads variable were initially somewhat surprising to us. The magnitude of the spatial variability across the Plateau for each of these variables is relatively weak and likely redundant with the leading contributors.

4. Summary

The relatively sparse reporting to the NWS of flash floods across the Colorado Plateau is well recognized. However, there are many “hot spots” for their occurrence in locales for which NWS flash flood reports (Fig. 2) and warnings (Fig. 10) are available. Reports are most likely where stream gauges are available, infrastructure is damaged, or people are likely to be recreating or travelling across public lands (Fig. 12).

Personal observations of debris suspended high above slot canyon floors and anecdotal reports from many others attest to flash floods in locales where official reports have not been received during recent years. Our aim was to objectively identify watersheds where relatively static landform features, weather, and human factors may contribute to increased flash flood risk.

According to the CBRFC, rainfall rates potentially driving small streams to flood within the Colorado Plateau vary from 1.5 in h^{-1} to below 0.5 in h^{-1} (CBRFC 2026). The small number of locales with thresholds below 0.5 in h^{-1} include the North Fork of the Virgin River in Zion National Park, Capitol Reef National Park, and the Antelope Canyon area near Page, AZ. Because of the limited number of rain gauges and radar coverage gaps across the Plateau, we relied on lightning flash extent density as a means to illustrate areas with greater likelihood for summer thunderstorms. Those include areas south of the Grand Canyon and the high plateau regions of southern Utah (Fig. 8). Such storms are most frequent from mid-July through early September (Fig. 9). However, our approach may underestimate intense rainfall resulting from less convective rain bands often associated with decaying tropical storms .

Objective metrics used to classify hazardous stream segments as those with steep terrain over a distance of at least 100 m that might impede non-motorized escape routes. Roughly 6% of the stream segments within the region met these criteria, which is likely an upper bound on high-risk streambeds (Fig. 6). Known locations of hazardous slot canyons helped validate our approach. There are conservatively over 1000 potentially hazardous recreational routes across the entire region of which only a fraction of them are widely known.

Motorized travel along unpaved roads within or across stream beds is quite common in the region. Hundreds of such stream crossings were identified by merging stream segment and road information data. An illustration of this type of risk occurred on 21 June 2024 when two individuals travelling in all-terrain vehicles were swept downstream and died during a flash flood near Moab UT (NWS 2026).

The potential risk to residents and recreationalists from flash flooding across the Colorado Plateau is difficult to assess. Figure 14 attempts to illustrate the relative remoteness of watersheds in the region in terms of a wildness metric developed by Mu et al. (2022) and federal estimates of cell phone coverage. Not surprisingly, the Grand Canyon, AZ region and watersheds above Lake Powell, UT are some of the most remote areas. To help alleviate this issue in the Grand Canyon area, the Grand Canyon River Alert System now provides government-issued emergency alerts accessible to recreationalists in the Grand Canyon using satellite messaging devices (Thomas et al. 2025).

We use flash flood warning polygons issued for the Plateau by the four NWS Forecast Offices as a proxy for where flash floods most likely occurred. Warnings are issued only when a report has been received or flood conditions are expected based on all of the information available to them. We did not attempt to validate specific warnings. Rather, we used the watersheds where warnings were issued during the 5-year period as a means to evaluate the landform, weather, and human exposure factors affecting flash flood risk. A random forest machine learning model was used to estimate the number of flood warnings issued in the 313 HUC-10 watersheds. The relative fractions of hazardous stream segments, lightning, and impermeable soils were the leading contributors to those estimates. The metrics used to estimate "wildness" provided weak contributions to the model.

While overall the model captured the relative risk among watersheds, it underestimated the number of warnings issued for locations such as Zion and Capitol Reef National Parks where warnings are more likely to be verified. The model overestimates warnings in many remote watersheds within and upstream of Glen Canyon National Recreation Area. This model was not expected to be a predictive tool for flash floods. Rather, it helps affirm what is recognized by weather and hydrologic professionals as the general areas where flash flood risk tends to be higher.

Interactive access to the flash flood reports and metrics used in this study are provided by Hilton and Horel (2026). Those displays are intended to be a resource to help examine in more detail where residents and recreationalists may be at higher risk to flash flooding. The web tools also may help to identify where vehicle users must be knowledgeable enough and patient enough to avoid attempting to travel down or across the hundreds of hazardous streambeds and washes when a flash flood is underway.

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Data Availability Statement. The data used in this study are available from multiple sources listed in Table 1. Researchers can retrieve these datasets from their respective repositories according to the terms and conditions specified by each data provider. An ArcGIS StoryMap providing interactive access to the figures and data associated with this study is available (Hilton and Horel 2026).

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