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Cover

Flooding of residential areas in Cedar City, Utah, following an intense thunderstorm on July 26th, 2021. Photograph by Shawn Glover, courtesy of St. George News/STGnews.com.

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Snow Drought and Monsoon Floods—Hydrological Extremes in the Cedar Valley Watershed During Water Year 2021, Southwestern Utah

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ABSTRACT

Water year 2021 was a year of extremes in the Cedar Valley watershed of southern Utah, with snow drought resulting in extremely low snowmelt runoff of Coal Creek and intense monsoon rainfall resulting in several floods in different parts of the valley. Winter snow accumulation was depressed throughout southern Utah, perhaps due to La Nina conditions affecting winter storm trajectories. Coal Creek, the principal stream providing surface water to Cedar Valley, typically receives most of its annual flow from snowmelt runoff, but in 2021 had a peak snowmelt discharge 15% to 25% of that recorded in the previous two years and the third lowest snowmelt runoff on record. Following this extremely low snowmelt runoff period, more than 10 floods of Coal Creek occurred following monsoon storms in July and August that exceeded the 2021 snowmelt peak. Additionally, several thunderstorms produced rainfall rates in exceedance of the 100-year event and induced flooding within Cedar City and the town of Enoch. Flood inundation modeling using HEC-RAS and high-resolution topographic data showed good agreement with field and pubic-survey data on the high-water stage during the Enoch flooding, and demonstrated that the flooding was likely exacerbated by the low topography and limited drainage potential in flooded areas. Whereas the monsoon storms improved soil moisture and helped alleviate drought conditions, they also resulted in urban flooding and did little to replenish the regional water supply.

INTRODUCTION

Streamflow and flooding in southern Utah occur through a combination of snowmelt, rainfall, and rain-on-snow (Lund, 1992; Wilkowske and others, 2006; Lund and others, 2010). For perennial or intermittent streams draining higher elevation terrain, groundwater inputs contribute the seasonal baseflow, but floods typically occur from more rapid surface runoff during snowmelt or intense rain storms. From a management perspective, streams and rivers provide a major component of the water supply as both surface runoff and a source of groundwater recharge to downstream basins, but also present a hazard as floods are common throughout the region and often impact developed areas. For larger watersheds with headwaters in higher elevation terrain, snowmelt plays an important role in the regional water supply because most streamflow is derived from direct snowmelt runoff and snowmelt-derived recharge

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of groundwater and stream baseflow (Julander and Clayton, 2018). On the other hand, the largest floods are typically generated by convective thunderstorms in the late summer and early fall or via winter rain events (Wilkowske and others, 2006). For example, the Virgin and Santa Clara Rivers that merge near St. George, Utah, have experienced large floods due to warm Pacific storm systems interacting with terrain to produce sustained rain and rain-on-snow at higher elevations (Bardsley and Julander, 2005; Wilkowske and others, 2006). Flash floods from intense convective thunderstorms also cause flooding across basins of many scales, but often have their greatest impact on smaller watersheds due to the often-isolated nature of storm development (Woolley, 1946; Berwick, 1962; Smith and others 2019); these types of "cloudburst" floods have long been recognized as a frequent cause of flooding throughout Utah (Woolley, 1946).

In this study, we explore the hydrological events during water year 2021 in Cedar Valley, Utah, that both exacerbated drought conditions due to a lack of significant snowmelt, and caused extensive flooding during multiple events within different areas of the valley. We use long-term hydrological records from Coal Creek, the principal stream and primary water source draining into Cedar Valley, to document the long-term watershed hydrology and evaluate water year 2021 relative to nearly 100 years of streamflow measurements. We also use precipitation data to estimate return frequencies for three flood events that occurred due to convective thunderstorms, and hydraulic modeling to evaluate the flood impacts in an urbanized area during one of those events. Cedar City is one of the fastest growing micropolitan areas in Utah, and a limited water supply and potential for flooding in developing areas are prominent concerns. Within Cedar City, numerous flood-control projects have been implemented, such as levees and diversion structures, to alleviate flooding during periods of high streamflow. Additionally, several projects have been implemented so that any excess streamflow can be diverted into basins for aquifer recharge. Water year 2021 provides a perspective on which to view potential challenges in water management for Cedar City and Cedar Valley in terms of both drought and floods.

BACKGROUND

Hydrology of the Cedar Valley Watershed

The Cedar Valley watershed is a closed basin in eastern Iron County, Utah. The watershed extends from the Harmony Hills and Markagunt Plateau in the south, to the Black Mountains in the north (Brooks and Mason, 2005). The valley is a graben bounded by normal faults associated with Basin and Range extensional faulting, and all streamflow drains internally toward Quichapa Lake in the southern part of the basin and Rush Lake in the northern part of the basin (Brooks and Mason, 2005). The primary surface water source to the valley and largest of the contributing watersheds is Coal Creek, which debouches from the Markagunt Plateau at Cedar City (figure 1). The headwaters of Coal Creek occur at the high elevation rim (greater than 10,000 feet) of the plateau in Cedar Breaks National Monument. As a result, significant winter snowfall feeds the perennial flow of Coal Creek and produces the bulk of the streamflow (Julander and Clayton, 2018). Aside from Shirts Creek, which is considerably smaller than Coal Creek, the remaining watersheds emerging from the mountainous areas along the edges of the valley are ephemeral (Brooks and Mason, 2005). Whereas some of these watersheds may experience a minor snowmelt pulse some years, they are most likely to generate significant streamflow and flooding during convective summer thunderstorms. Coal Creek has a long history of flooding; the first recorded flood occurred on September 3, 1853, and caused extensive damage in Cedar City (Lund, 1992). Most of the development in the valley is focused near Cedar City and the nearby town of Enoch, and the focus of this study is on the streamflow hydrology of Coal Creek and the precipitation climatology of flooding during rain events affecting those towns.

For the Coal Creek watershed, the largest volume of water is supplied during the snowmelt period that typically lasts from spring through early summer. Alternatively, the largest magnitude floods occur during intense convective rain events in the late summer and early fall as part of the North American Monsoon. Floods from these storms can cause flooding of Coal Creek or any number of other watersheds and ephemeral streams in the area. For Coal Creek, this imparts a somewhat

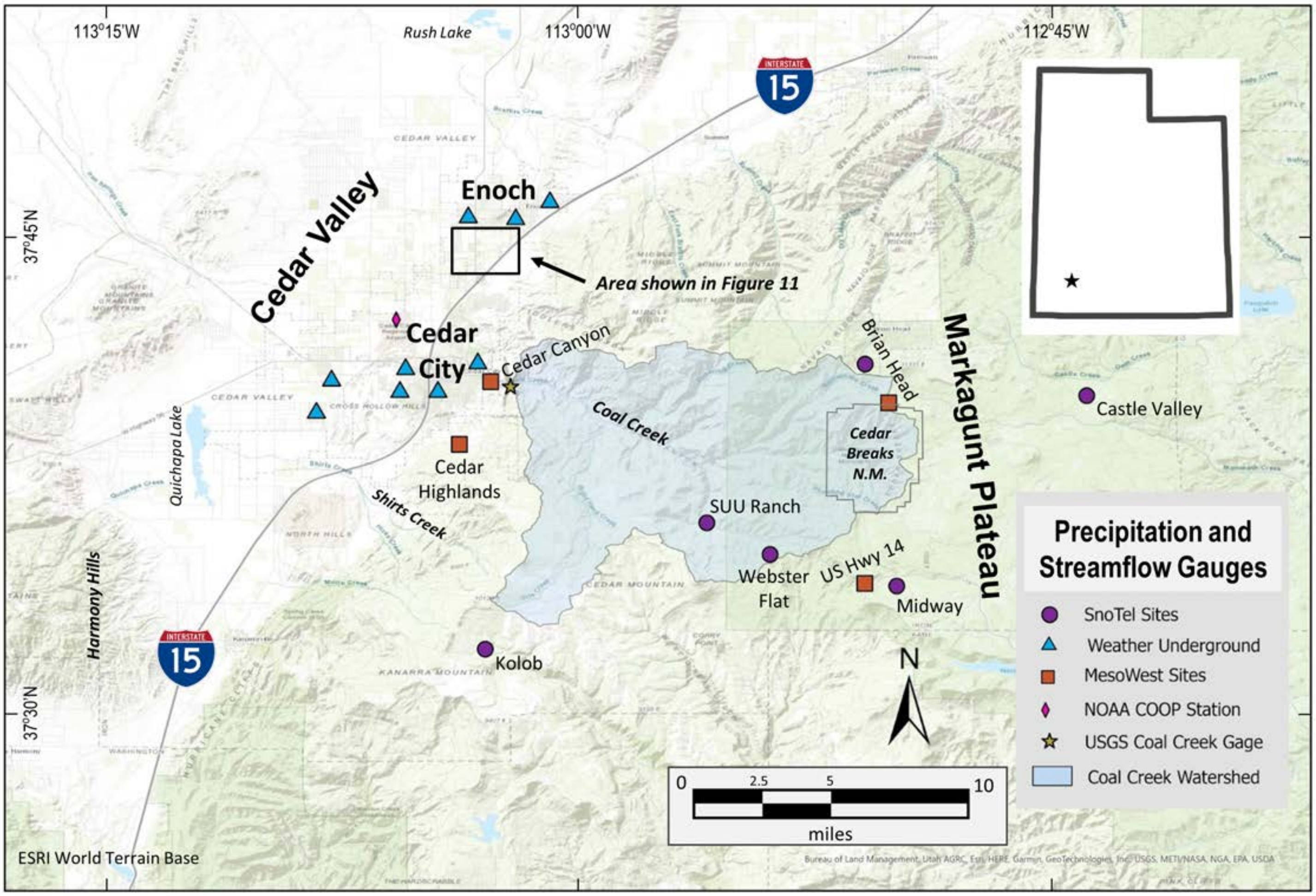

Figure 1. Map of study area showing the locations of the precipitation and streamflow measurement stations used in this study; MesoWest and SNOTEL site names are labeled. The Coal Creek watershed is outlined upstream from the U.S. Geological Survey stream gage just upstream from Cedar City.

unique hydrology with respect to water resources and hazard mitigation: wherein the water supply is dependent on snow during the winter and the resulting snowmelt flood pulse, the primary flood hazards result from short-duration and typically localized intense precipitation during the monsoon season. During the period of record, significant floods of Coal Creek have not occurred during the winter, unlike in the Virgin River system where rain-on-snow events are more common and the mean basin elevation is significantly lower. Coal Creek has streamflow records dating back to 1916, and provides important context to evaluate the unique hydrology of 2021.

Effects of El Nino Southern Oscillation on Winter Precipitation

Previous studies have shown a correlation between the phases of the El Nino southern oscillation (ENSO) and winter precipitation in the western United States (Redmond and Koch, 1991; Cayan and others, 1999; Clark and others, 2001; Jin and others, 2006; Tamaddun and others, 2017). In particular, areas in the southwestern United States tend to experience increased winter precipitation during El Nino years and decreased winter precipitation during La Nina years (Brown and Comrie, 2004). The opposite signal is apparent in the northwestern part of the United States. Importantly, ENSO phases in June through November can be a predictor of the subsequent winter snowpack and spring runoff (Redmond and Koch, 1991; Oubeidillah and others, 2011). Weak La Nina conditions preceded the winter snow accumulation season in water year 2021, and we explore the influence of El Nino/La Nina cycles on snow accumulation and streamflow for the Coal Creek watershed.

North American Monsoon and Summer Precipitation

The North American Monsoon (hereafter, monsoon) is a seasonal change in the predominant windflow direction and atmospheric circulation associated with summer heating of the interior of the North American continent (Adams and Comrie, 1997). Continental heating causes a low-pressure cell to develop over the high elevation interior of the western United States and induces flow of warm and moist air from the Gulf of California and the Gulf of Mexico (Hereford and Webb, 1992). As a result, daily convective storms are common in much of northern Mexico and the southwestern United States due to diurnal heating, and are responsible for numerous flash floods. As Utah is at the periphery of its strongest influence, the year-to-year variability in monsoon intensity can be large. For example, the 2020 monsoon season saw relatively little storm activity and flash flooding in most of southern Utah, whereas the 2021 monsoon season caused widespread flash flooding in much of the southwest (National Oceanic and Atmospheric Administration, 2021). Meteorologically, the monsoon period begins June 15th, but monsoon thunderstorm activity is greatest from July through September, and three floods caused by intense monsoon rains in water year 2021 are evaluated in this study.

METHODS

Streamflow and Snow Hydrology of the Coal Creek Watershed

Coal Creek is the primary surface water source for Cedar Valley (figure 1), and U.S. Geological Survey (USGS) stream gage 10242000 is located just upstream from the mouth of the canyon east of Cedar City. Upstream from the stream gage, the watershed is effectively unregulated, with no major water diversions or reservoirs. As such, the gage provides a useful data source to assess the trends in the long-term natural hydrology of the watershed, with annual flood magnitudes reported back to 1916. For the streamflow, precipitation, and snowpack data described herein, we use English units consistent with those reported by government agencies and commonly used for resource management and hazard assessment. Furthermore, in all cases, we use the water year, which extends from October 1st through September 30th, as the hydrologically relevant time scale over which to assess annual patterns. We consider the March 1st through June 30th period as generally associated with snowmelt, and the July 1st through September 30th period as reflecting monsoon floods overprinted on the baseflow.

Streamflow Volumes

We use the USGS daily data from the Coal Creek gage to evaluate the long-term trends of streamflow volume. We report the total annual runoff volume (per water year), the March 1st through June 30th (snowmelt) runoff volume, and the July 1st through September 30th (monsoon plus baseflow) runoff volume.

Flood Frequency Analysis

A flood frequency analysis using the standard USGS Log-Pearson III approach, with a gage specific skew, was used to estimate return periods for floods of different magnitude (e.g., Kenney and others, 2007). Because the stream is affected by both snowmelt floods and monsoon-induced flash floods, we used multiple approaches to evaluate flood return periods. First, we use the maximum annual flood for each year, regardless of whether it was generated by snowmelt or summer rainfall (Kenney and others, 2007). We then evaluated the gage record to find the maximum snowmelt and maximum monsoon rainfall flood for each year to examine the annual flood frequencies for the different flood-generating mechanisms (e.g., Yu and others, 2022).

For the period since 1988, instantaneous values (every 15 minutes) of discharge are available, and we simply select the highest flows in the snowmelt and monsoon time periods (as defined above) for the different flood types (snow versus rain). For the period prior to 1988, we use the maximum daily discharge during the spring period to estimate the peak snowmelt flood to the beginning of the period of record. For monsoon rainfall floods, the daily discharge will underestimate flood peaks because of the rapid rise and fall of the hydrograph. When the monsoon flood was the peak for the year, we use the (instantaneous) peak flow value reported by the USGS. For other years, we extend the gage record of rain-induced floods by using a relation between daily and instantaneous values for the 1988–2021 period. This provides a conservative estimate of these floods, and allows us to establish a longer record of rain-induced flood frequencies using the standard USGS approach that includes years with smaller monsoon floods.

Snowpack

Because snowmelt is the dominant driver of the streamflow (water supply) of Coal Creek, we evaluate the historical variability in snowpack as a complement to our streamflow analysis. We use data from snow telemetry (SNOTEL) sites operated by the U.S. Department of Agriculture (USDA) Natural Resources and Conservation Service (NRCS) that are within or directly adjacent to the headwaters of the Coal Creek watershed (figure 1). We chose sites with long-term daily records dating back to water year 1981: the Webster Flat, Kolob, Midway, and Castle Valley SNOTEL sites (figure 1). For each site, we found the maximum snow water equivalent (SWE) reported for each site for each year, with the expectation that the maximum SWE value represents the water available for runoff in the subsequent spring and early summer.

Soil Moisture

Soil moisture data at SNOTEL sites were assessed for the period 2019–2021. Soil moisture is known to have an effect on streamflow generation in snowmelt-dominated watersheds of Utah (Clayton, 2016; Harpold and others, 2017). In this case, we used data from the four long-term SNOTEL sites above, and two additional nearby sites installed in the 2010s: Brian Head and Southern Utah University (SUU) Ranch. Soil moisture is reported as volumetric water content at 2-, 8-, and 20-inch depths, and we focus on the 8- and 20-inch data as more representative of the long-term and depth-integrated soil moisture likely to affect streamflow. We report values as the percent of the median from the 2019–2021 period of analysis.

Southern Oscillation Index (SOI)

We use the average of the June through November standardized Southern Oscillation Index (SOI) to assess the impact of ENSO cycles on the snow and streamflow hydrology of Coal Creek (Redmond and Koch, 1991). The SOI is a measure of the difference in sea-level pressure of the equatorial Pacific, and is thus a measure of the relative strength of ENSO. El Nino years occur when the SOI is less than -0.5; whereas, La Nina years occur when the SOI is greater than 0.5. Other years are considered Neutral. Since 1951, about half the years have been Neutral, and the other half were either El Nino or La Nina years. We group maximum SWE values and annual March–June runoff into El Nino, Neutral, or La Nina categories based on the previous year SOI values, and use Student's T-Tests to test for statistical differences based on the ENSO conditions.

Precipitation Hydrology of Monsoon Flood Events in 2021

Precipitation data to evaluate the monsoon flooding in Cedar Valley was derived from a variety of sources. The primary precipitation events evaluated were the July 26th flooding in Cedar City, the August 1st flooding in Enoch, and the August 18th and 19th flooding of Coal Creek (figure 2). National Oceanic and Atmospheric Administration (NOAA) radar reflectivity data available from the National Centers for Environmental Information were used to document the extent and duration of the precipitation events. Additionally, a NOAA National Weather Service station is located near the Cedar City Regional Airport. This weather station recorded significant precipitation on July 26th, but otherwise registered minimal precipitation during the other events. Thus, we gathered data from any publicly available precipitation records for those events, as described below.

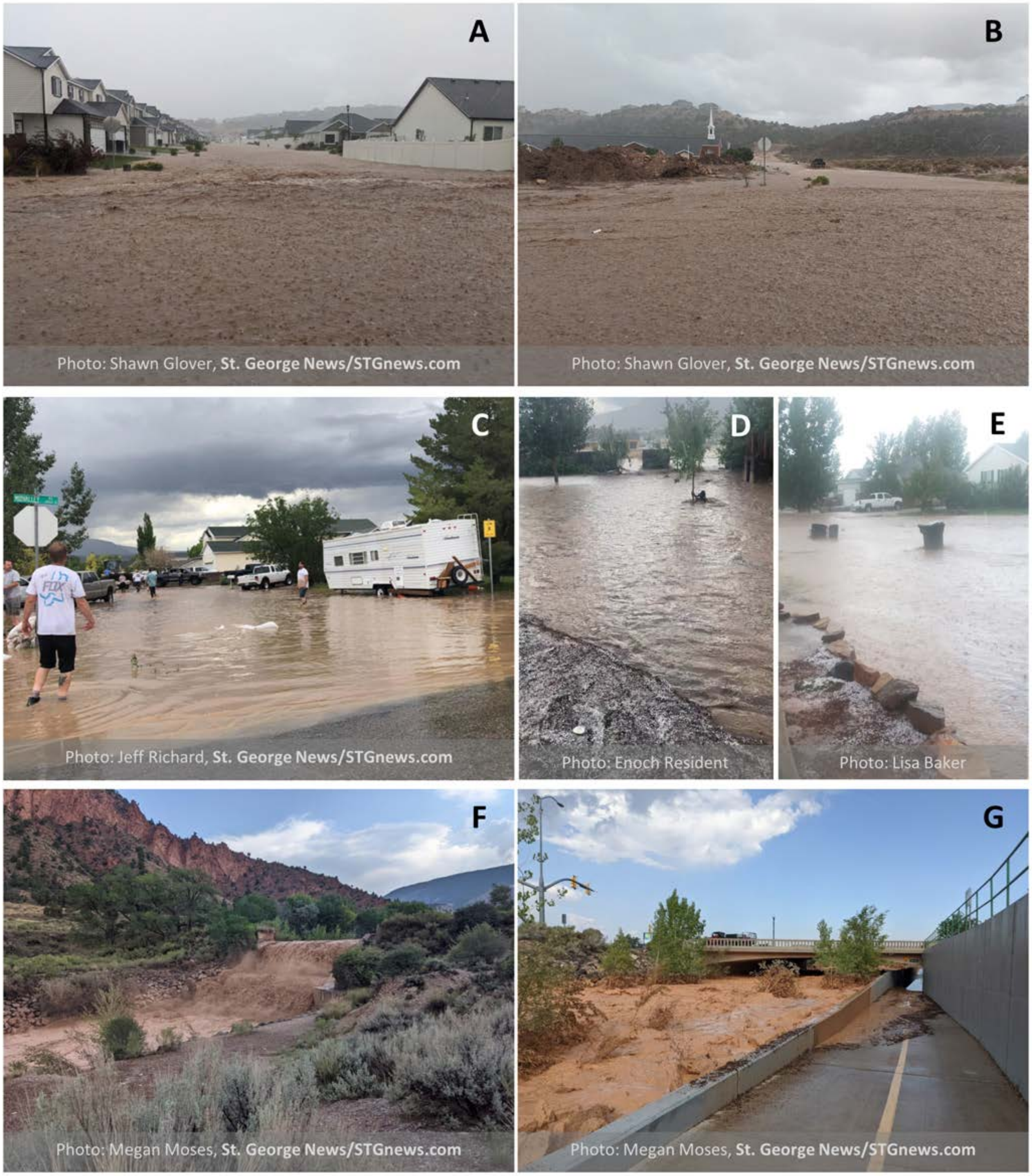

Figure 2. (A) Flooding of residential areas and (B) along Cross Hollow Drive in Cedar City on July 26, 2021 (courtesy of St. George News/STGnews.com). (C) Residents survey flooding along Midvalley Road in Enoch on August 1, 2021 (courtesy of St. George News/STGnews.com). (D) Backyard flooding with a damaged fence in the background in Enoch on August 1, 2021 (courtesy of an Enoch resident). (E) Street flooding in Enoch on August 1, 2021 (courtesy of Lisa Baker). (F) Flooding along Coal Creek east of Cedar City near the USGS stream gage and (G) in Cedar City near Main Street on August 18, 2021 (courtesy of St. George News/STGnews.com). All photographs used with permission.

MesoWest Data

MesoWest is a University of Utah program that collects weather data from a variety of public sources and provides access to the historical data records. Four MesoWest sites were used in this study (figure 1), with two of the sites located near the headwaters of Coal Creek and two sites located near its mouth. These sites were used to evaluate precipitation during the August 18–19 flooding of Coal Creek, with data typically reported at 15-minute intervals. None of the MesoWest sites in the areas of Cedar City or Enoch reported useable data during the July 26th and August 1st floods.

SNOTEL Data

Precipitation data from four SNOTEL sites (SUU Ranch, Brian Head, Webster Flat, and Midway Flat) were combined with the MesoWest data to evaluate rainfall rates during the August 18–19 flooding. SNOTEL data are reported at 1-hour intervals. Precipitation rates at SNOTEL sites compared very favorably to precipitation rates measured at nearby MesoWest sites.

Weather Underground Data

Because of the dearth of precipitation data available from government agencies or MesoWest for the July 26th and August 1st flood events, we utilized publicly available precipitation data from the Weather Underground website. Weather Underground has compiled a network of thousands of Personal Weather Stations (PWS) and provides real-time data access to the network. Further, they provide detailed information on compatible weather stations and station siting to help ensure the accuracy of the data provided. Whereas individual weather stations may not have been professionally installed, information on the weather station manufacturer and precision and accuracy specifications are available for each site. In total, nine PWS stations from the Weather Underground site were used to evaluate precipitation rates. Typically, these data were reported at 5-minute intervals.

Precipitation Probability Data

Measured precipitation rates for the sites above were compared to point estimates of depth-duration-frequency precipitation probability estimates from NOAA (Bonnin and others, 2011). Probability tables were downloaded from the NOAA Atlas 14 point precipitation frequency estimates website based on the latest revision of the Atlas in 2011 (Bonnin and others, 2011). The estimates are based on a partial duration series, meaning that all large events above a threshold are included in the analysis, regardless of the year in which they occurred (as opposed to an annual maximum series). The reported values are then based on the highest *n* number of events for a period of record of *n* years (Bonnin and others, 2011).

Hydraulic Modeling with HEC-RAS

We used the U.S. Army Corps of Engineers Hydraulic Engineering Center–River Analysis System (HEC–RAS) hydraulic model to evaluate the August 1st flooding in Enoch. HEC-RAS solves the two-dimensional (2D), vertically averaged, shallow-water equations to model unsteady flow across channels and floodplains as defined by a digital terrain model that quantifies the topography in the model domain. The Utah Geospatial Resource Center (UGRC) and the Utah Division of Emergency Management acquired lidar over Enoch, Utah from May 2nd through May 25th, 2020. Half-meter bare earth digital elevation models (DEMs) and first return digital surface models (DSMs) were produced and published by UGRC. Aerial photos and lidar aerial surveys with a Real-time kinematic positioning (RTK) enabled airframe and base station, a high-resolution RBG (red-blue-green) sensor, and lidar payload were used to refine the surface model of Enoch in the flooded area using Agisoft Metashape Pro. The bare earth surface model was reviewed to validate point cloud classification results aligned with ground-benchmark data. Remaining data artifacts were then manually removed. Watersheds that flowed into or out of the Enoch study area were delineated using the ESRI (Environmental Systems Research Institute, Inc.) ArcGIS Pro water resource management hydrologic scripting routines. A hydro-flattened DEM was created and mosaiced with existing UGRC DEM data. Manual DEM reconditioning was performed to establish natural surface flow through bridges and culverts, including densely vegetated areas. Stormwater-infrastructure data provided by the Cedar City Engineering Department included culverts, storm drains, weirs, open channels, and riser pumps, but additional data on culvert dimensions were collected in the field using high resolution Global Positioning System (GPS).

Pre-processed shapefiles were imported into HEC-RAS as feature layers and allocated respectively to a geometry type as 2D Flow Areas, Perimeters, Breaklines, and Refinement Regions. Vector data representing structures such as culverts, bridges, weirs, and trapezoidal channels were characterized by their attributes needed to calculate hydraulic flow and dynamically linked to their catchment domain. Unsteady flow was modeled throughout the catchment network in HEC-RAS using a flow hydrograph and rating curve calculated based on peak precipitation rate and expected peak discharge lag time. Field measurements of high water using GPS and online public surveys were used as benchmarks for model calibration. Our voluntary online public survey asked participants to provide a map location, the date and time of when the flooding occurred, and depth of inundation (Ashton and others, 2022). Unsteady flow was computed iteratively to match benchmark calibration parameters. Kairos Group, LLC. gave instruction and advised on flow-model construction, computation, calibration, and verification.

RESULTS AND DISCUSSION

Water Year 2021 and the Long-Term Hydrology of Coal Creek

In a typical year for the Coal Creek watershed, 69% of the runoff volume occurs during the March-June snowmelt period, and 15% of the runoff volume occurs during the July-September monsoon period. The remainder (16%) occurs during the late fall and winter months primarily as baseflow. Furthermore, the bulk of the baseflow that occurs throughout the year likely owes its origin to snowmelt and other cold-season precipitation events (Julander and Clayton, 2018). As such, the total runoff volume for all periods is well predicted by the maximum SWE values at SNOTEL sites surrounding and within the basin; 2021 had the fourth lowest total runoff on record (figure 3). Similarly, the maximum SWE value is also a good predictor of the maximum snowmelt flood each year (figure 3).

The influence of ENSO on winter snowpack and resultant streamflow is also evident. For both the maximum SWE and the March–June streamflow volume, values are greater during El Nino years compared to La Nina years (student's T-test, $p<0.05$) (figure 4). However, La Nina years were not significantly different than Neutral years in terms of snowpack or runoff volume (figure 4). For El Nino years, the maximum SWE was significantly greater than during Neutral years (student's T-test, $p<0.05$), but the March–June streamflow was not. On average, the March–June streamflow volume was about 65% greater than the median value during El Nino years, but only 8% less than the median value during La Nina years. The wettest, and two driest, years were both during Neutral conditions. In 2021, the snowmelt runoff was the lowest ever recorded during a La Nina year. Thus, overall, ENSO has a discernable effect on the watershed hydrology, tending to result in greater streamflow and snowpack during El Nino years. While the opposite is true for La Nina years, La Nina is not as strongly distinguished from Neutral conditions in terms of hydrologic variability.

Figure 5 shows the hydrograph of Coal Creek and corresponding soil moisture conditions for water years 2019 through 2021, contrasting a range of conditions from high (2019) to average (2020) snowmelt with minimal monsoon activity, to that of 2021 with very low snowmelt and frequent monsoon floods. Climatologically, 2019 was characterized by Neutral ENSO conditions, whereas 2020 was a weak El Nino, and 2021 was a weak La Nina. Perhaps the weak La Nina conditions contributed to low snowpack and snowmelt in 2021, but low soil moisture conditions likely also contributed to the reduced snowmelt runoff (Clayton and others, 2021). The exceedance probability for the maximum SWE at the SNOTEL sites ranged from 0.79 to 0.9 in 2021, meaning that there is a 79% to 90% chance of those values being exceeded in a given year. Yet the snowmelt runoff volume had an exceedance probability of 0.95 to 0.97, indicating an exceptionally low snowmelt runoff—the third lowest on record. Figure 5B shows that

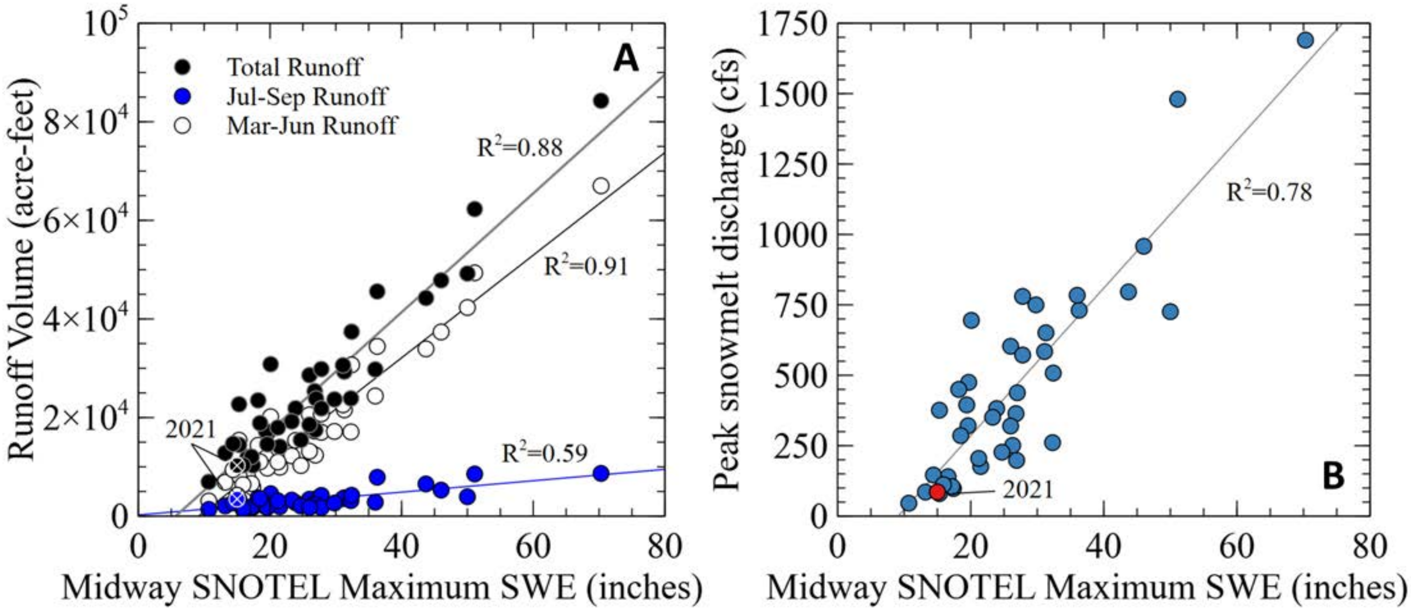

Figure 3. (A) Runoff volume for total annual runoff, snowmelt period runoff, and monsoon period runoff versus the maximum snow water equivalent (SWE) as measured at the Midway SNOTEL site. Values for 2021 are shown with an X through the symbol. (B) Peak snowmelt discharge in cubic feet per second (cfs) of Coal Creek versus the maximum SWE as measured at the Midway SNOTEL site. 2021 shown in red.

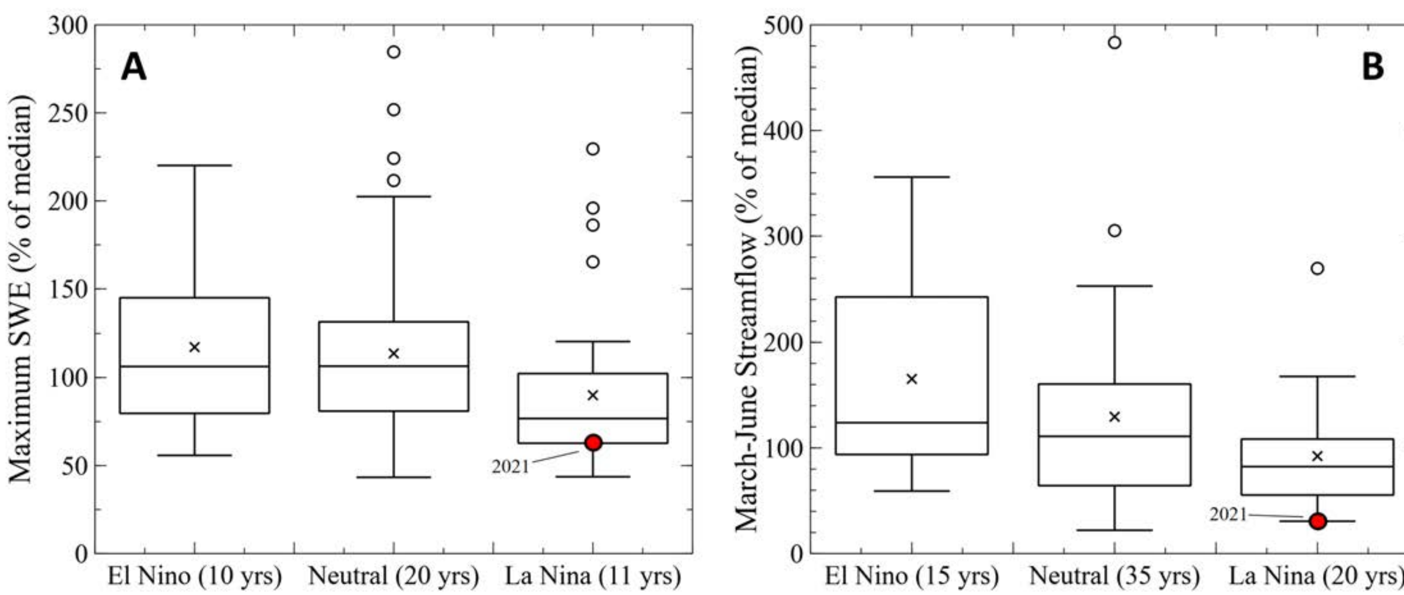

Figure 4. (A) Box plots showing the variation in maximum snow water equivalent (SWE) for four sites bounding the Coal Creek watershed and (B) box plots showing the variation in March through June total stream flow for Coal Creek, differentiated by El Nino, Neutral, and La Nina years. Boxes represent the median and interquartile range (IQR), mean values are indicated by an x, and outliers are shown as open circles (identified as values more than 1.5 times the interquartile range above the 3rd quartile or less than 1.5 times the interquartile range below the 1st quartile).

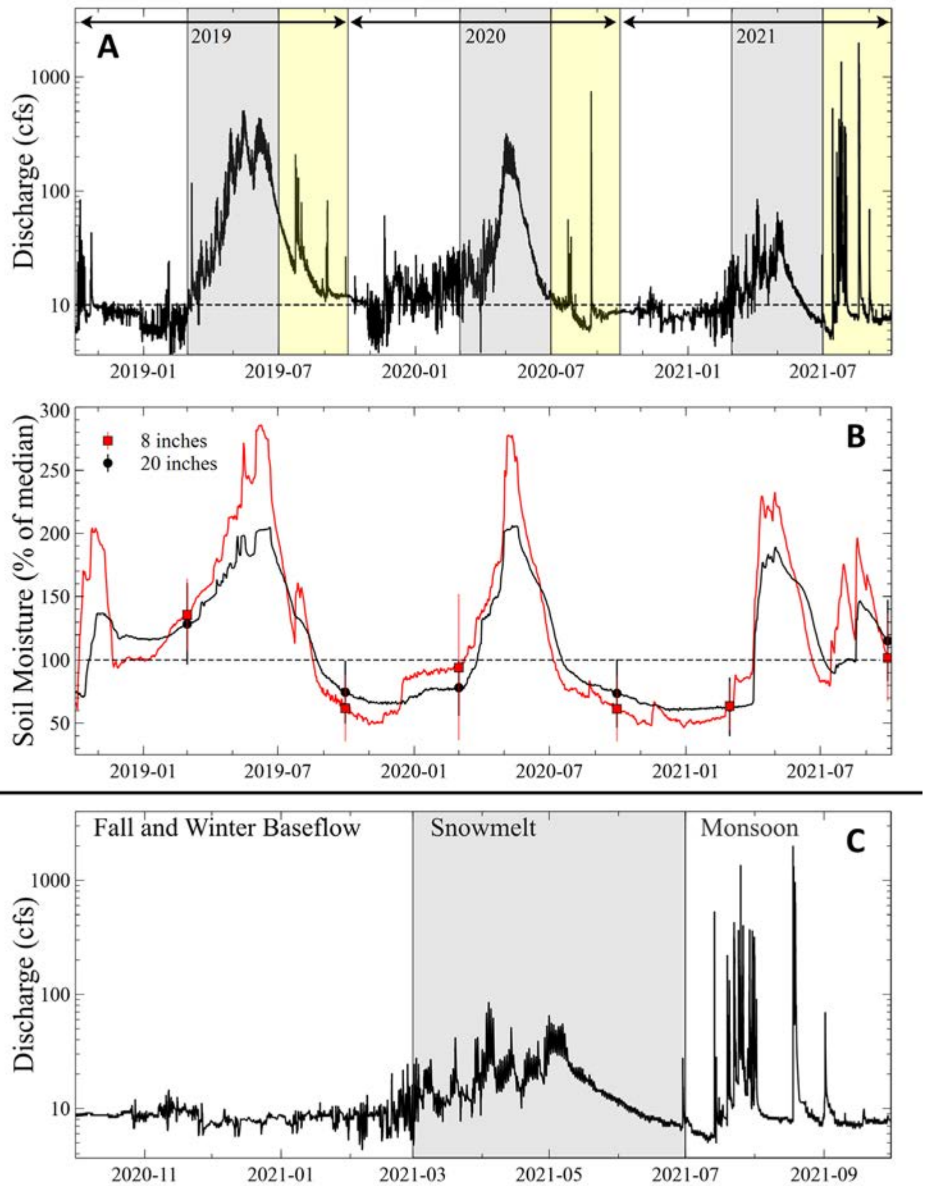

Figure 5. (A) Hydrograph of Coal Creek for water years 2019 through 2021. Gray shading indicates snowmelt period, and yellow shading indicates monsoon period. (B) Soil moisture at 8 and 20 inches depth using the mean value from six SNOTEL sites bounding the Coal Creek watershed. Soil moisture plot shows mean and standard deviation for the six sites on October 1 and March 1 of each year. (C) Hydrograph of Coal Creek for water year 2021.

soil moisture at SNOTEL sites never reached the levels attained in 2019 and 2020, suggesting that the soils at depth were not fully saturated. This would reduce the amount of direct surface runoff from snowmelt as water continued to be stored in soils (Clayton and others, 2021). Figure 5B also shows significant increases in soil moisture following monsoon rain events such that soil moisture at the end of the water year was higher than in 2019 and 2020. More than 10 monsoon floods of Coal Creek exceeded the snowmelt flood during 2021 (figure 5C), and the proportion of annual runoff that occurred during the monsoon period (July 1 through September 30) was the greatest in the observational record and nearly equivalent to that of the snowmelt period (March 1 through June 30) (figure 6). Total annual flow in 2021 was about 10,250 acre-feet, 42% of the long-term average and the fourth lowest recorded.

Annual floods of Coal Creek are caused by either snowmelt, as in 2019, or monsoon rainfall, as in 2020 and 2021 (figure 5A). Figure 7 shows the average day of year (Julian day) for the peak flood of each water year dating back to 1935. For the 86-year record, snowmelt caused the peak flood 35 times (41%), and rainfall caused the peak flood 51 times (59%). The data suggest something of a cyclicity in the dominant mode producing the annual flood, which may reflect longer timescale

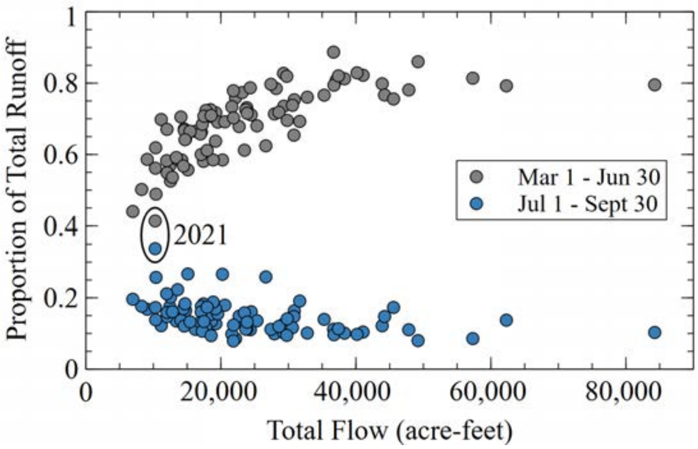

Figure 6. Proportion of total annual runoff derived during the snowmelt (March 1 through June 30) versus monsoon (July 1 through September 30) periods plotted versus the annual flow volume for Coal Creek.

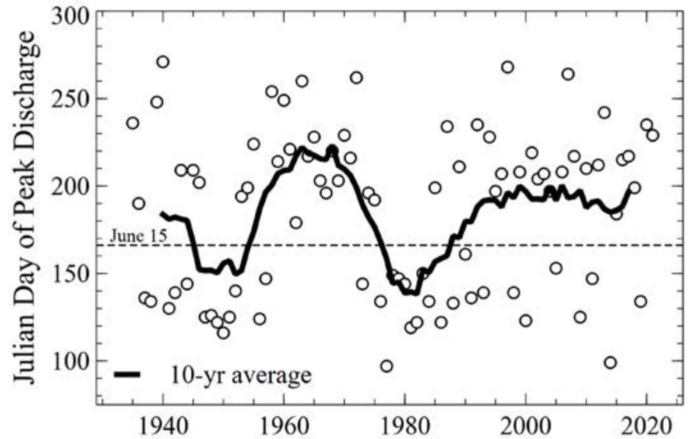

Figure 7. Julian day of annual flood peaks from 1935 to 2021, with the 10-year moving average centered on each point shown as a solid line. Peaks prior to June 15 are considered to be derived from snowmelt, and after June 15 from monsoon rainfall.

climate controls on either winter snow accumulation or monsoon activity (Waite and Thomas, 1955; Hereford and Webb, 1992; Nowak and others, 2012). In the last twenty years, 15 of the largest annual floods were produced during monsoon rainfall (figure 7).

Figure 8 shows the USGS standard Log-Pearson Type III flood-frequency analysis for the annual snowmelt floods, annual rainfall flood, and the annual flood regardless of when it occurred (combined snowmelt and rainfall flood populations). As expected, the peak magnitude of snowmelt floods is roughly half or less than that of rainfall floods for a given return interval. The largest recorded snowmelt flood with an approximate 100-year recurrence was 1820 cubic feet per second (cfs), which would be approximately a 5-year recurrence for rainfall floods. In 2021, the peak flood during the monsoon season was 2000 cfs. While a relatively common flood with a recurrence of 6 to 7 years, the repeated flooding during this event caused considerable localized flooding as discussed in the next section. It is clear that for the combined record the highest discharges with recurrence intervals greater than about 5 years occur primarily due to rainfall (figure 8). On the other hand, smaller floods with recurrence intervals less than 5 years may be caused by either mechanism in the combined record. Treating the flood frequencies separately based on the different flood-generating mechanisms (snowmelt versus rain) demonstrates that published flood probabilities combining flood types may underestimate the magnitude of rare (100-year) monsoon rainfall floods (Yu and others, 2022) (figure 8).

Precipitation Extremes and Monsoon Floods

In the context of the above discussion of watershed hydrology for Coal Creek, water year 2021 can viewed as a year of contrasts – hydrological (snow) drought overprinted by an intense monsoon season that resulted in numerous floods in Cedar Valley. Point precipitation measurements during the three floods analyzed herein all showed locations where precipitation rates exceeded the computed 100-year precipitation rates for durations between 1 and 24 hours. In the following subsections, we describe the precipitation climatology relative to the depth-duration frequencies published by NOAA (Bonnin and others, 2011), and, where available, streamflow hydrology, for the three major monsoon floods that impacted Cedar Valley in 2021.

Cedar City, July 26th, 2021

The storm of July 26th produced intense precipitation over much of Cedar City. Most of this precipitation fell over an urban area with rapid overland flow along roadways, causing significant flooding of residences and roadways in low areas near the intersection of

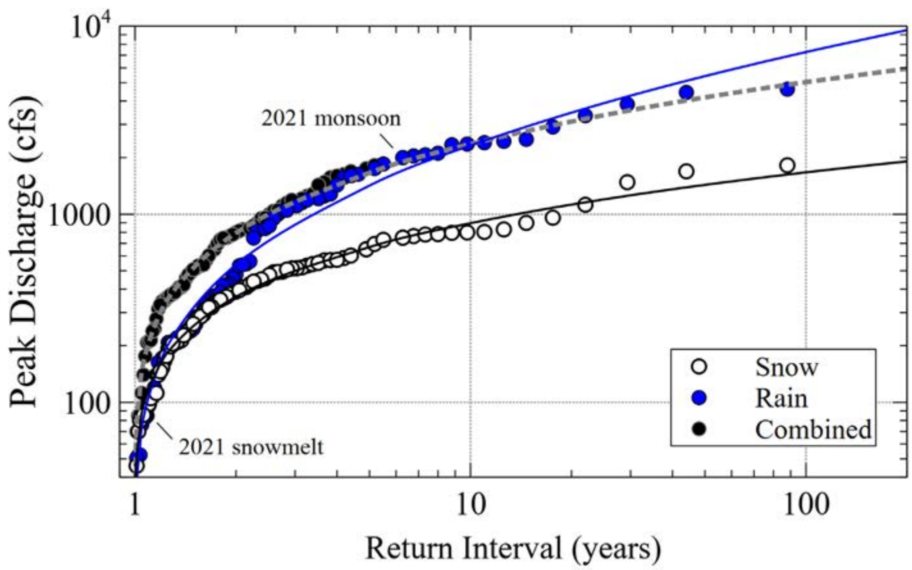

Figure 8. Log-Pearson Type III fits to annual peak flood flows derived from snowmelt, monsoon rain, and the combined snowmelt and rain periods as measured at the Coal Creek USGS stream gage from 1935–2021.

Interstate 15 (I-15) and West 200 North. Precipitation rates exceeded the 200-year event for one of the gauges for durations of 30 minutes to 3 hours (figure 9A). At this gauge, more than 2.5 inches of rain fell in 1 hour. The National Weather Service gauge recorded more than 2 inches of rain in approximately 1 hour, which is greater than a 100-year event. Several other gauges recorded between 1.5 and 2.5 inches of rain in 2 hours (figure 9A). City officials declared a State of Emergency following this event due to the extensive damage caused by flooding of homes in the area.

Enoch, August 1st, 2021

Precipitation rates during the August 1st flooding in Enoch were somewhat less than measured less than a week earlier in Cedar City. One gauge showed precipitation rates that exceeded the 100-year event for durations of 2 and 3 hours, with total accumulations of 2 to 2.5 inches (figure 9B). Yet, no precipitation gauges exist just east of and in the vicinity of I-15, where several small and steep drainages provide direct inflow to low-lying urban areas already experiencing heavy rain. Radar data during the event shows high precipitation rates across these drainages and directly over the southern part of the city for nearly an hour (figure 10). There is also clear evidence of flooding from these drainages in the form of debris, high water marks, and fresh sediment movement. The water from the drainages passed through culverts beneath or overtopped I-15, temporarily closing the roadway. The floodwaters then inundated low-lying areas and neighborhoods of Enoch, causing extensive damage.

HEC-RAS modeling of flood inundation provides a clearer picture of the flood extent on August 1st (figure 11). Using a discharge hydrograph calibrated to measured high-water marks in tributary basins and flooded areas, the modeled inundation shows significant flooding of neighborhoods in low-lying areas of Enoch. The modeled depths and extents are also consistent with feedback from public surveys on flood damage and extent at individual properties (figure 11D). The extent of flooding on August 1st caught many residents of Enoch off guard because there are no major drainages in the area. Because Cedar Valley is a closed basin, floodwaters emanating from steep tributaries along the range front do not necessarily coalesce into a primary channel with a higher conveyance, but instead flood across large areas at relatively shallow depths (figure 11). This highlights the fact that small drainages can produce large floods during convective monsoon storms, and flooding may be exacerbated by rapid runoff from urbanized areas.

Coal Creek, August 18-19, 2021

Precipitation rates during the Coal Creek floods exceeded the 500-year event for one gauge, and the 100-year event for four gauges, but over longer durations of 6 to 48 hours compared to the floods described above

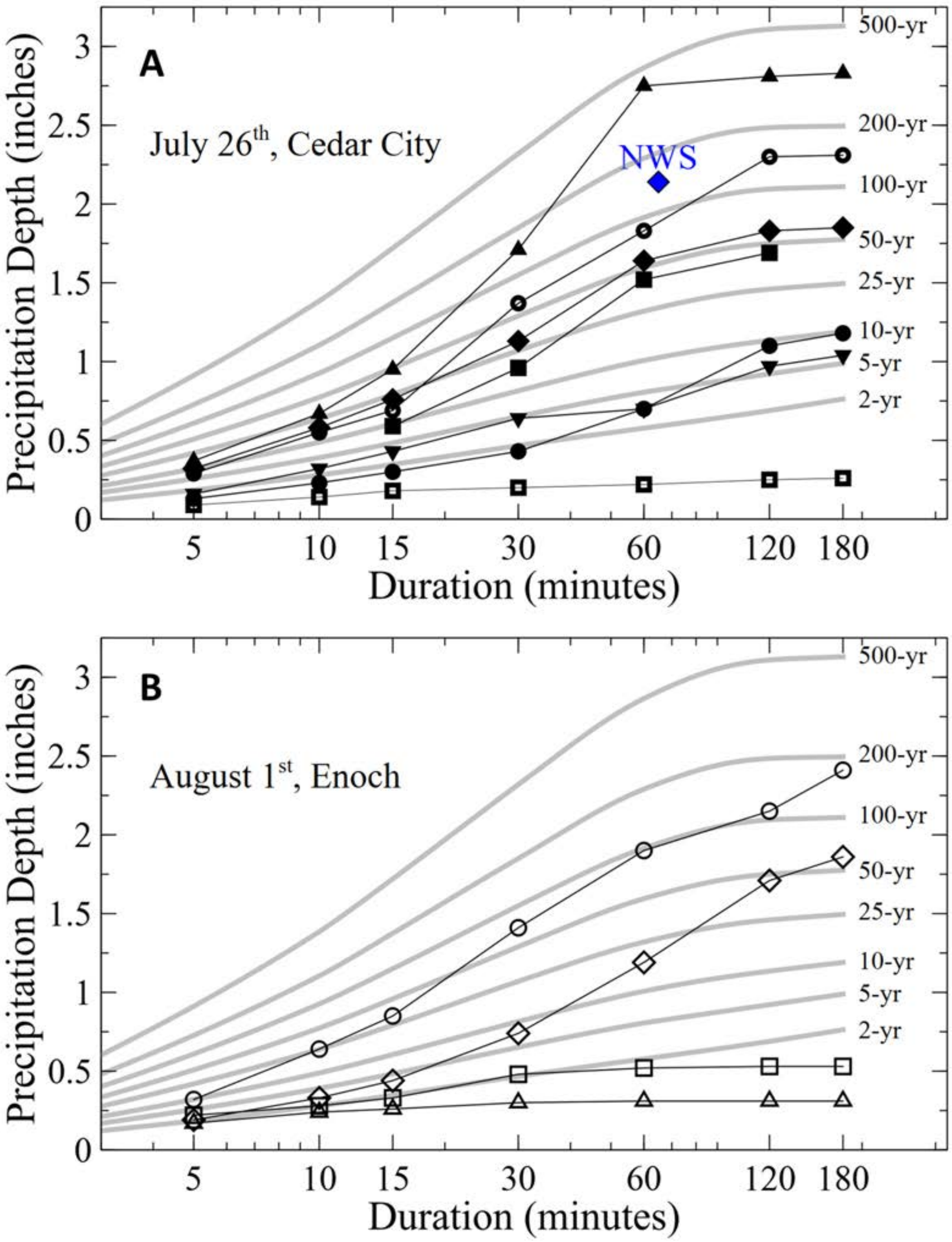

Figure 9. Depth-duration-frequency precipitation plots during (A) the July 26th flooding of Cedar City, Utah, and (B) the August 1st flooding of Enoch, Utah. Symbols represent data from different Weather Underground personal weather stations, except for the Cedar City National Weather Service (NWS) site shown as a diamond on A.

(figure 12). The highest precipitation rates were recorded near the rim of Cedar Breaks at the headwaters of Coal Creek, where 5 to 6 inches of rain fell in 12 hours and storm totals exceeded 6 to 7 inches at two gauges in this study. Cedar Breaks National Monument measured over 6 inches of rain according to media reports. These are among the highest 24-hour rainfall totals ever recorded in Utah – 6.78 inches at the U.S. Highway 14 MesoWest site, and 6.1 inches at the Midway Valley SNOTEL site (figure 12C). According to NOAA's State Climate Extremes Committee, the 24-hour precipitation record in Utah is 5.08 inches; but higher values have been reported in media stories at regional weather stations not likely considered by NOAA.

The initial pulse of intense precipitation began around midnight on August 18th, and caused a rap-

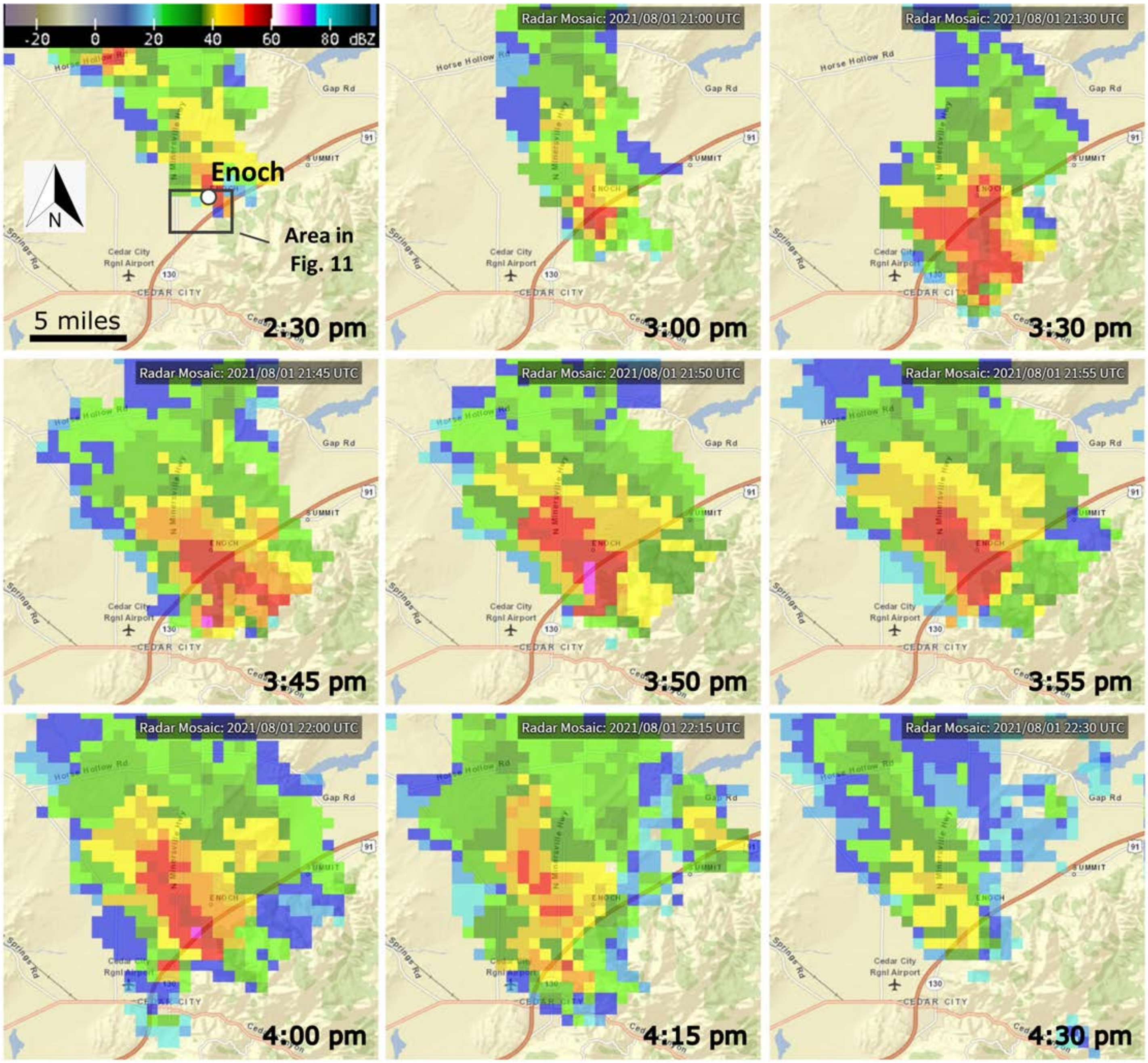

Figure 10. NOAA radar reflectivity mosaic (in decibels, dBZ) showing the August 1, 2021, storm that caused flooding in Enoch, Utah. Top panel shows the 1-hour build up to the peak rainfall rates, middle panel shows 15 minutes during the most intense part of the storm, and lower panel shows the final half hour and initial dissipation of the storm.

id rise in Coal Creek to a peak discharge of 2000 cfs at around 3 a.m. (figure 13). This was the largest flood peak of the water year. This initial flood pulse was followed by a second, smaller pulse of 1310 cfs. After a period of quiescence, a second storm impacted the watershed near midnight on August 19th with as much of 2 inches of additional precipitation focused more in the center of the watershed. This caused a third flood pulse of approximately 1000 cfs (figure 13).

Residents reported all three flood pulses, and significant flooding occurred along a channel of Coal Creek north of the Cedar City airport. Cedar City has

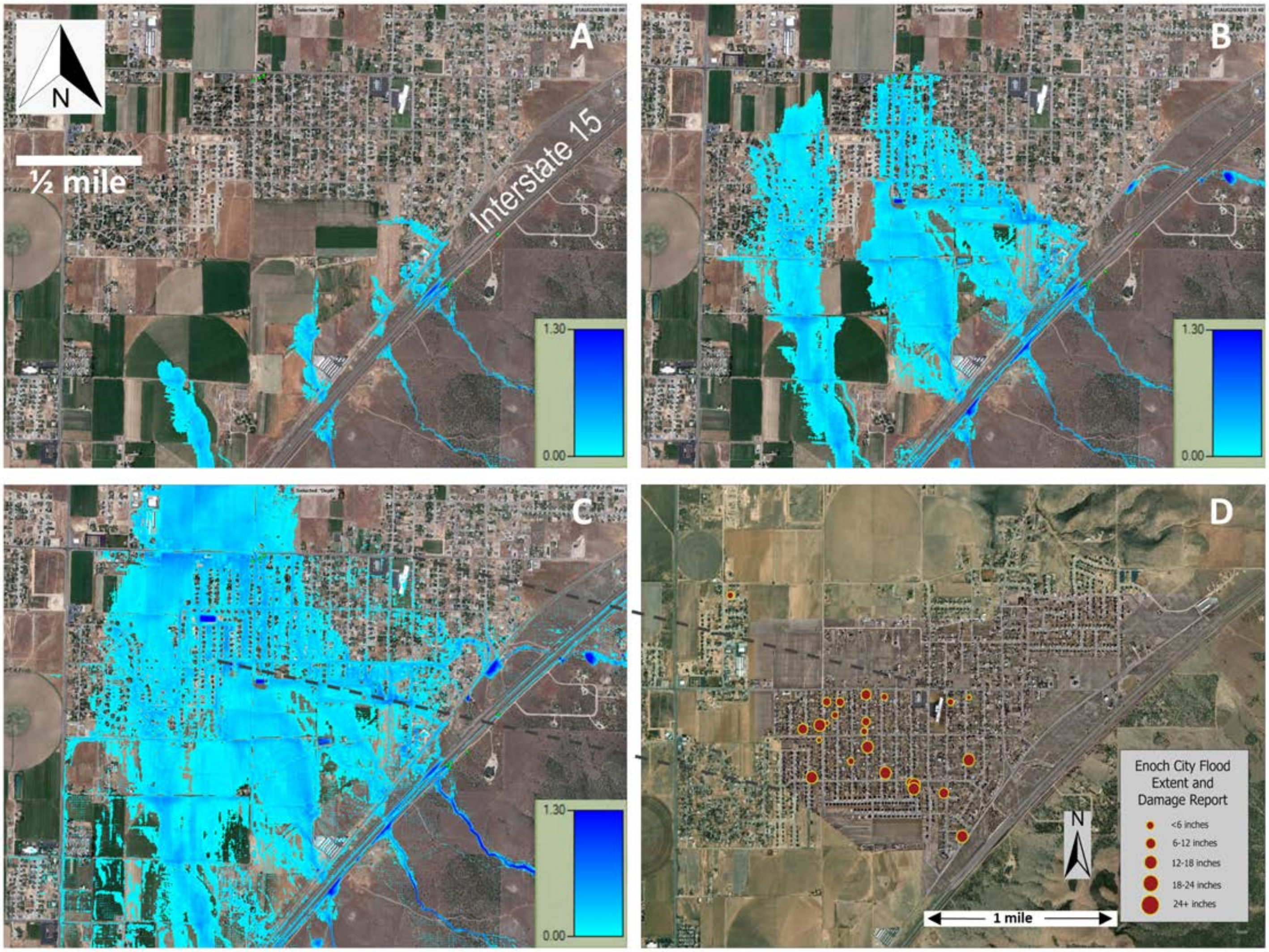

Figure 11. HEC-RAS model results showing inundation depth (in meters) from (A) flood initiation to (B) maximum precipitation to (C) maximum flood extent during the August 1st Enoch, Utah, flooding. (D) Results of public survey showing a subset of impacted homes and estimated inundation depth; note that map in D is not at the same scale as A through C, as indicated by the black lines showing common points in each image.

built flood diversion structures, channels, and levees to protect against flooding of Coal Creek, but some of this infrastructure was overwhelmed by the high debris (wood) and sediment loads of the flood. The intense precipitation during the initial flood event occurred in steep terrain that likely resulted in debris flows and overland flow that picked up woody debris and trees from the forested hillslopes. The debris and sediment clogged diversion structures and channels, resulting in levee overtopping and flooding of some residential areas. Whereas, this was not a particularly large flood (recurrence of 6 to 7 years), it demonstrates the important role of sediment and debris loads in exacerbating flood effects – especially in communities at the mouths of steep mountain watersheds where monsoon floods may occur.

CONCLUSIONS

Water year 2021 in southern Utah was characterized by an extremely muted spring and early summer snowmelt period that worsened existing drought conditions, followed by a strong monsoon season that caused

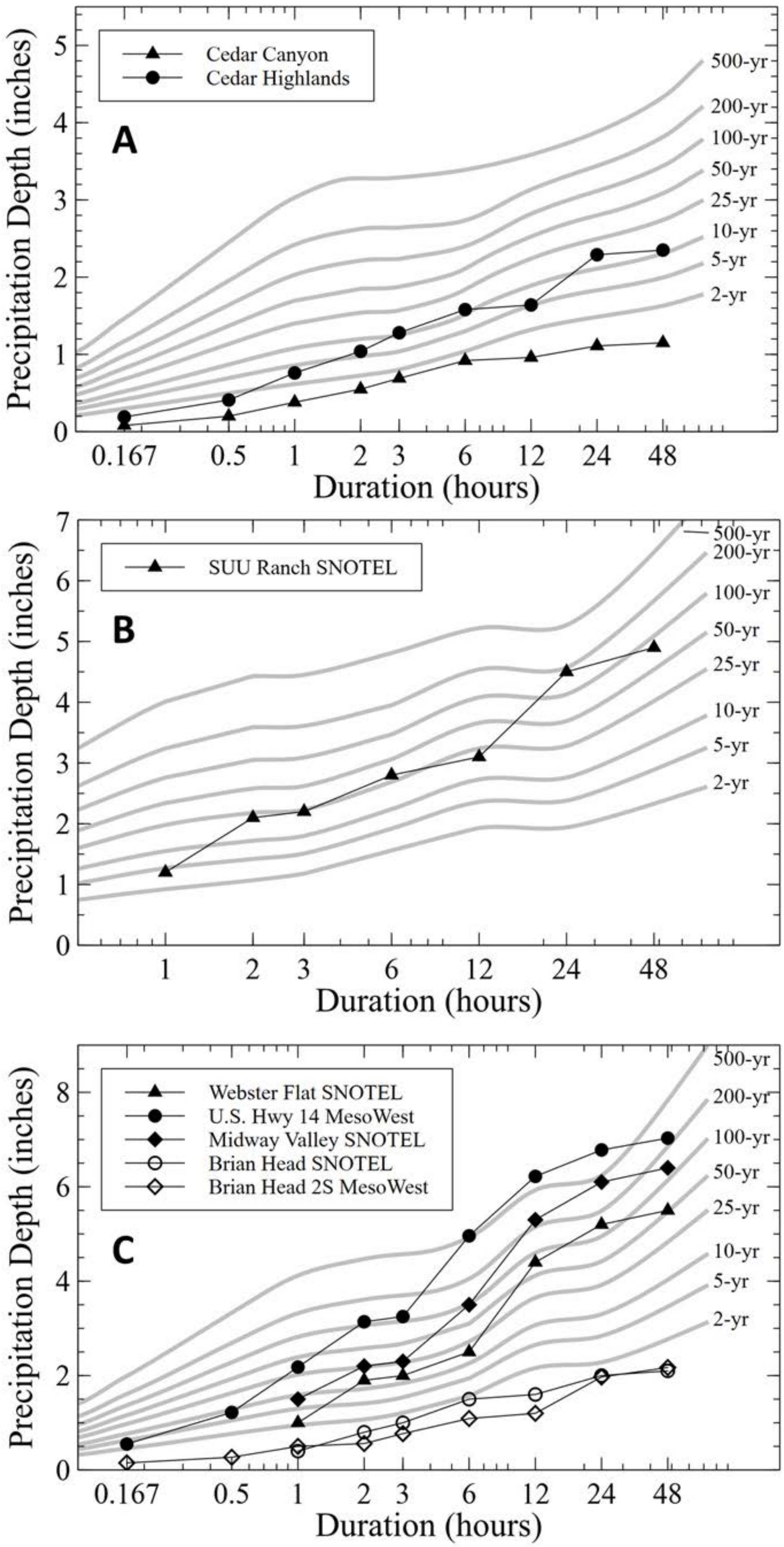

Figure 12. Depth-duration-frequency precipitation plots for the August 18th and 19th flooding of Coal Creek, showing (A) low-elevation sites, (B) a mid-elevation site, and (C) upper-elevation sites.

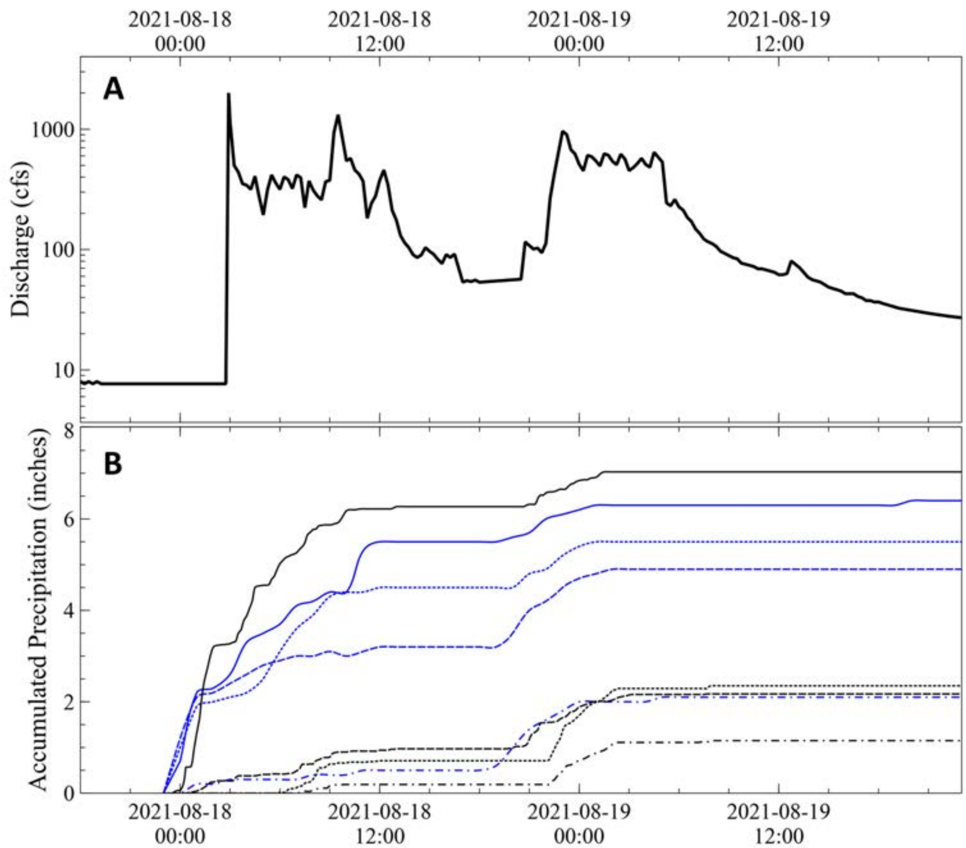

Figure 13. (A) Hydrograph of Coal Creek and (B) accumulated precipitation during the August 18th and 19th flooding of Coal Creek. In B, blue lines indicate SNOTEL sites and black lines indicate MesoWest sites.

numerous floods. The runoff of Coal Creek is vital to the water supply of Cedar City and the groundwater recharge of the Cedar Valley's aquifers. Here we show that the overall streamflow is predictably related to snow accumulation and different phases of ENSO. In 2021, low snowpack and soil moisture during a weak La Nina contributed to extremely low snowmelt runoff. The dry conditions were followed by an unusually intense monsoon season. Measured precipitation rates exceeded the 100-year rainfall rates, and in some cases the 500-year rainfall rates, for multiple storms during the 2021 summer monsoon, resulting in localized flooding throughout Cedar Valley. The floods in Cedar City and Enoch were likely exacerbated due to extreme precipitation over urban areas, and hydraulic modeling shows good agreement with measured inundation and public surveys of the impacted area during the August 1st flooding of Enoch. For Coal Creek, there are no long-term trends in discharge volume or flood frequency in the stream gaging record, and no individual event in the gage record during 2021 broke any records. Yet the hydrology of water year 2021 was unique in the combined effects of an extremely low snowmelt followed by an intense monsoon season that resulted in widespread flooding of residential areas, an unfortunate but instructive combination from the perspective of water resources and hazard analysis.

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REFERENCES

Adams, D.K., and Comrie, A.C., 1997, The North American Monsoon: Bulletin of the American Meteorological Society, v. 78, no. 10, p. 2197–2214.

Ashton, S., Sudweeks, G., Olson, M., and Mueller, E., 2022, Precipitation and streamflow hydrology during the summer 2021 monsoon flooding of the Cedar Valley, Utah: Geological Society of America Abstracts with Programs, v. 54, no. 2, doi: 10.1130/abs/2022CD-373772.

Bardsley, T., and Julander, R., 2005, The documentation of extreme events—two case studies in Utah, water year 2005: Proceedings of the Western Snow Conference, v. 73, p. 33–42.

Berwick, V.K., 1962, Floods in Utah, magnitude and frequency: U.S. Geological Survey Circular 457, 24 p.

Bonnin, G.M., Martin, D., Lin, B., Parzybok, T., Yekta, M., and Riley, D., 2011, Precipitation-frequency atlas of the United States: National Weather Service, Silver Spring, Maryland, NOAA Atlas 14, v. 1, version 5.0, 65 p.

Brooks, L.E., and Mason, J.S., 2005, Hydrology and simulation of ground-water flow in Cedar Valley, Iron County, Utah: U.S. Geological Survey Scientific Investigations Report 2005-5170, 114 p.

Brown, D.P., and Comrie, A.C., 2004, A winter precipitation 'dipole' in the western United States associated with multidecadal ENSO variability: Geophysical Research Letters, v. 31, L09203, 4 p.

Cayan, D.R., Redmond, K.T., and Riddle, L.G., 1999, ENSO and hydrologic extremes in the western United States: Journal of Climate, v. 12, no. 9, p. 2881–2893.

Clark, M.P., Serreze, M.C., and McCabe, G.J., 2001, Historical effects of El Nino and La Nina events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River Basins: Water Resources Research, v. 37, no. 3, p. 741–757.

Clayton, J.A., 2016, Summer soil moisture loss at Utah SNOTEL sites and streamflow recession at nearby gauges—variability in runoff generation and the potential for flow forecasting: Hydrological Processes, v. 30, no. 1, p. 119–134.

Clayton, J., Brosten, T., Sutcliffe, K., Eiriksson, D., Burly, J, and Neff, D., 2021, Utah water supply outlook report (5/1/2021): Salt Lake City, Utah, Natural Resources Conservation Service, 74 p.

Harpold, A.A., Sutcliffe, K., Clayton, J., Goodbody, A., and Vazquez, S., 2017, Does including soil moisture observations improve operational streamflow forecasts in snow-dominated watersheds?: Journal of the American Water Resources Association, v. 53, no. 1, p. 179–196.

Hereford, R., and Webb, R.H., 1992, Historic variation of warm-season rainfall, southern Colorado Plateau, southwestern USA: Climatic Change, v. 22, no. 3, p. 239–256.

Jin, J., Miller, N.L., Sorooshian, S., and Gao, X., 2006, Relationship between atmospheric circulation and snowpack in the western USA: Hydrological Processes, v. 20, no. 4, p. 753–767.

Julander, R.P., and Clayton, J.A., 2018. Determining the proportion of streamflow that is generated by cold season processes versus summer rainfall in Utah, USA: Journal of Hydrology, v. 17, p. 36–46.

Kenney, T.A., Wolkowske, C.D., and Wright, S.J., 2007, Methods for estimating magnitude and frequency of peak flows for natural streams in Utah: U.S. Geological Survey Scientific Investigations Report 2007–5158, 28 p.

Lund, W.R., 1992, Flooding in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 159–164.

Lund, W.R., Knudsen, T.R., and Sharrow, D.L., 2010, Geologic hazards of the Zion National Park geologic-hazard study area, Washington and Kane Counties, Utah: Utah Geological Survey Special Study 133, 97 p.

National Oceanic and Atmospheric Administration, 2021, Review of the 2021 monsoon across the southwest U.S.: compiled by NOAA/NWS Phoenix, Arizona, https://www.weather.gov/psr/2021MonsoonReview.

Nowak, K., Hoerling, M., Rajagopalan, B., and Zagona, E., 2012, Colorado River basin hydroclimatic variability: Journal of Climate, v. 25, no. 12, p. 4389–4403.

Oubeidillah, A.A., Tootle, G.A., Moser, C., Piechota, T., and Lamb, K., 2011, Upper Colorado River and Great Basin streamflow and snowpack forecasting using Pacific oceanic–atmospheric variability: Journal of Hydrology, v. 410, no. 3–4, p. 169–177.

Redmond, K.T., and Koch, R.W., 1991, Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices: Water Resources Research, v. 27, no. 9, p. 2381–2399.

Smith, J.A., Baeck, M.L., Yang, L., Signell, J., Morin, E., and Goodrich, D.C., 2019, The paroxysmal precipitation of the desert—flash floods in the southwestern United States: Water Resources Research, v. 55, no. 12, p. 10218–10247.

Tamaddun, K.A., Kalra, A., Bernardez, M., and Ahmad, S., 2017, Multi-scale correlation between the western US snow water equivalent and ENSO/PDO using wavelet analyses: Water Resources Management, v. 31, no. 9, p. 2745–2759.

Waite, H.A., and Thomas, H.E., 1955, Effect of current drought upon water supplies in Cedar City Valley, Utah: Eos, Transactions American Geophysical Union, v. 36, no. 5, p. 805–812.

Wilkowske, C.D., Kenney, T.A., and McKinney, T.S., 2006, Flooding and streamflow in Utah during water year 2005: U.S. Geological Survey Fact Sheet 2006-3085, 6 p.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850–1938: U.S. Geological Survey Water-Supply Paper 994, 128 p.

Yu, G., Wright, D.B., and Davenport, F.V., 2022, Diverse physical processes drive upper-tail flood quantiles in the US Mountain West: Geophysical Research Letters, v. 49, 11 p., e2022GL098855, https://doi.org/10.1029/2022GL09885.