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Changed Seasonality and Forcings of Peak Annual Flows in Ephemeral Channels at Flagstaff, Northern Arizona, USA

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Abstract: Flood variability associated with urbanization, ecological change, and climatic change is of increasing economic and social concern in and around Flagstaff, Arizona, where flood hydrology is influenced by a biannual precipitation regime and the relatively unique geologic setting at the edge of the San Francisco Volcanic Field on the southern edge of the Colorado Plateau. There has been limited long-term gauging of the ephemeral channels draining the developed lands and dry coniferous forests of the region, resulting in a spaciotemporal gap in observation-based assessments of large-scale flooding patterns. We present new data from over 10 years of flood monitoring using a crest stage gauge network, combined with other channel monitoring records from multiple agency sources, to assess inter-decadal patterns of flood change in the area, with a specific emphasis on examining how various controls and disturbances have altered the character and seasonality of peak annual flows. Methods of analysis included the following: using Fisher's Exact Test to compare the seasonality of flooding between historic data spanning the 1970s and contemporary data obtained since 2010; summarizing GIS-based spatial data and meteorological timeseries to characterize study catchment conditions and changes between flood study periods; and relating spatiotemporal patterns of flood seasonality and occurrences of notably large floods with catchment characteristics and environmental changes. Our results show systematic patterns and changes in Flagstaff-area flood regimes that relate to geologic and topographic controls of the varied catchment systems, and in response to records of climate variations and local catchment disturbances, including urbanization and, especially, high-severity wildfire. For most catchments there has been a shift from predominantly late winter to spring snowmelt floods, or mixed seasonal flood regimes, towards monsoon-dominated flooding, patterns which may relate to observed local warming and precipitation changes. Post-wildfire flooding has produced extreme flood discharges which have likely exceeded historical estimates of flood magnitude over decade-long monitoring periods by one to two orders of magnitude. We advocate for continued monitoring and the expansion of local stream gauge networks to enable seasonal, magnitude-frequency trend analyses, improved climate and environmental change attribution, and to better inform the many planned and ongoing flood mitigation projects being undertaken in the increasingly developed Flagstaff region.

Keywords: peak annual flood; Arizona monsoon; snowmelt; catchment disturbance; climate change; Flagstaff

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1. Introduction

Since the mid-twentieth century, Western North America has experienced an increase in high temperature extremes and drought, with increasing confidence in a human contribution to those observed changes [1]. In conjunction, while there have been strong spatial coherences in increased severe fire weather and decreased snow cover, there has been low confidence and mixed projections associated with broad hydrologic trends, and limited evidence with low agreement for climate change influences on flooding [2], except for earlier snowmelt runoff timing [3,4]. Recently, there has been growing evidence of

increased precipitation and runoff variability and mean intensity in much of the western U.S. [5–7], especially for convective storm-driven floods [4]. Throughout dry conifer forests of the western U.S., multi-decadal climate and land use changes have caused a rapid contemporary increase in wildfire size [6,8] and severity relative to historical reference conditions [9]. Contemporary flooding patterns in the western U.S. are confounded by land use activities [10], the multidimensional behavior of runoff [11,12], and changing seasonal hydroclimatic controls [13,14]. In these and other regional- to continental-scale assessments of flooding trends, there is a large gap in stream gauge coverage within the Colorado Plateau region of northern Arizona. In this high-elevation region of Arizona, large-scale hydrologic modeling by Wobus et al. [15] showed no significant change to a more than doubling of 1-in-100-year flood occurrences for RCP4.5 to RCP8.5 2050 projections. High spatiotemporal variability and uncertainty in flood runoff is recognized as being indicative of strong topographic and geologic local controls in montane environments, exacerbated by more limited and challenged instrumental monitoring.

The city of Flagstaff, situated in north-central Arizona, has experienced diverse flood events during the past three years (2021–2023), including flooding from intense summer rainfall, rapid spring snowmelt, and extreme runoff from post-wildfire impacts occurring during both summer rainfall and spring snowmelt [16]. Flagstaff watersheds exhibit unique patterns of runoff because of the city's geologic/topographic setting, the region's typically biannual precipitation regime, and the influence of varied catchment disturbances [17,18]. Watershed topography and runoff variability are influenced considerably by the city's placement at the interface between a major volcanic field and sedimentary plateau terrain. The ephemeral channels of these watersheds most typically experience flood conditions following heavy rainfall during the summer monsoon season or following rapid spring snowmelt conditions. Environmental change and catchment disturbances during recent decades include urban development, ecological response to contemporary warming, long-term drought, high-severity wildfires, and forest management activities. The purpose of this study is to document environmental conditions and temporal changes within gauged catchments in and around Flagstaff, and to examine associated runoff records to determine inter-decadal flooding pattern change in these high elevation watersheds of north-central Arizona. We relate patterns of flood runoff to geologic controls, urbanization, forest disturbances, and regional climate variations, with a specific emphasis on exploring how these various controls and disturbances may have changed the character and seasonality of peak annual floods.

2. Study Area

In north-central Arizona, Flagstaff (35.18° N, 111.62° W; 2080 m asl.; 76.8 k pop. 2020 census) is situated at the interface of the San Francisco Volcanic Field to the north and the Colorado Plateau to the south (Figure 1). Volcanic features adjacent Flagstaff are predominantly Pleistocene-aged, ranging from basalt flows and cinder cones to the west and northwest, mostly andesite flows of the San Francisco Mountain composite volcano further north, and dacite domes of the Dry Lake Hills and Elden Mountain to the more immediate north to northeast [19]. Sedimentary plateau rock exposed to the south of Flagstaff are primarily Kaibab Formation (Permian) limestone, with some older (Miocene), overlying basalt flows [20]. The main drainage system is the ephemeral Rio de Flag, a headwater stream of the Little Colorado River and greater Colorado River basin.

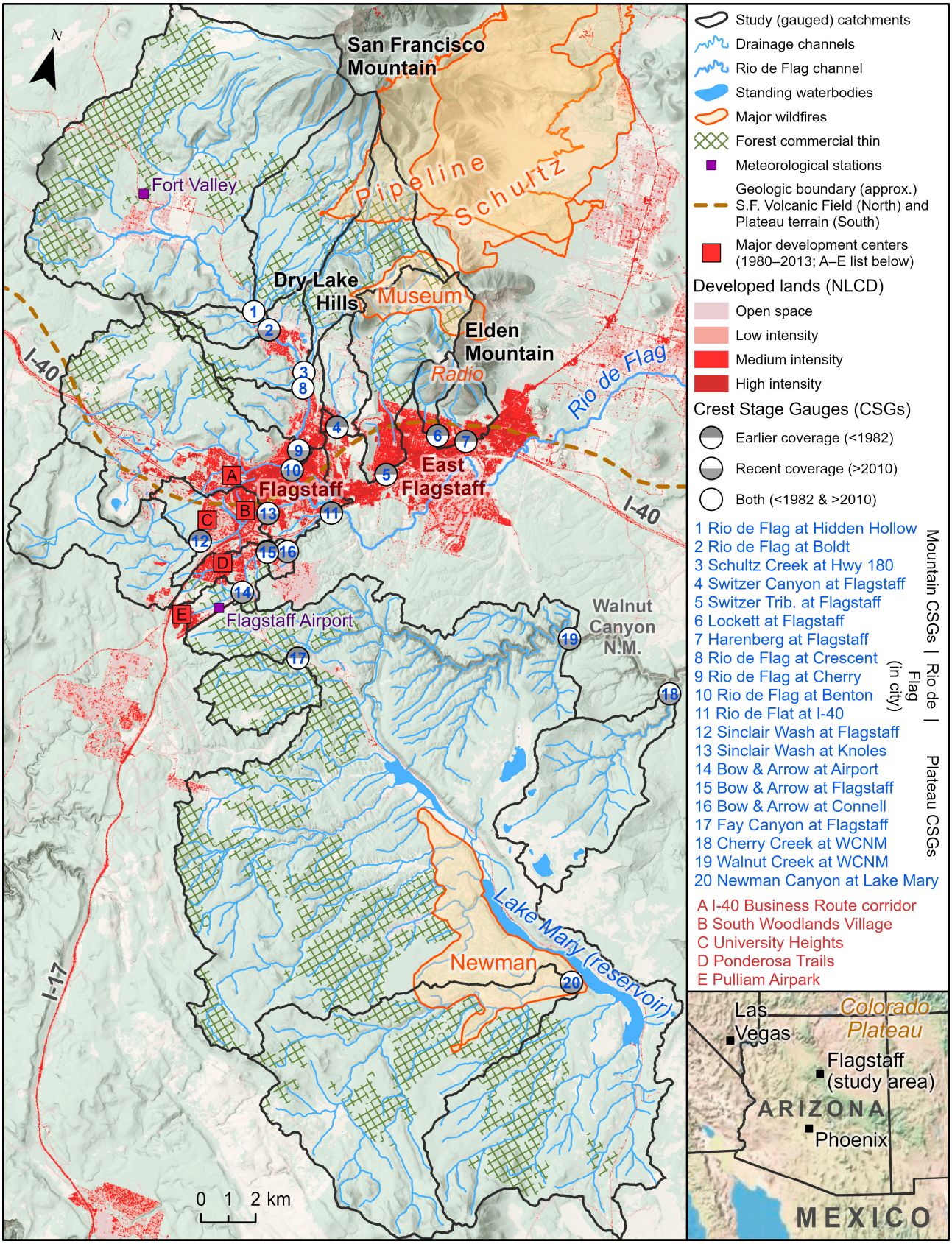

Figure 1. Study area map showing gauge locations, study catchments, topographic features, meteorological stations, developed land cover (USGS National Land Cover Database), major wildfires (multiple sources; see Section 3), and extent of forest thinning within study catchments.

Ponderosa Pine (*Pinus ponderosa*) is the dominant forest type surrounding Flagstaff, interspersed with meadows in low lying depressions or caused by previous forest fires. Higher elevation forests of the San Francisco Mountain include other mixed conifer species, including abundant spruce, fir, and aspen. The dry conifer forests of the region, which were historically adapted to frequent low-intensity fires, experienced increased stand density following land use changes including harvesting, grazing, reforestation, and fire suppression, making them highly susceptible to high severity wildfire [21]. Prescribed fire and mechanical thinning forest treatments have sought to reduce the risk of catastrophic wildfire, as well as provide beneficial hydrologic adjustments [22]. Moderate- to high-intensity urban land use within the city is primarily continuous (Figure 1).

Meteorological station data from Flagstaff Pulliam Airport (Figure 1) provides a long record (>100 years) of climate conditions representative for the city and nearby, plateau-level terrain. Mean monthly temperatures range from 19.3 °C in July to −1.1 °C in December, with mean annual precipitation of 52.1 cm, the majority of which is snow during the winter (1991–2020 climate normal data). The distribution of precipitation is bimodal, with a primary peak in August (7.7 cm) and a secondary peak in February (5.5 cm). Reflective of the montane forest-type gradient, higher elevations are wetter and cooler. Flagstaff-area ephemeral channels contain surface runoff and experience episodic flooding both during rapid snowmelt events, sometimes with a large rain-on-snow component, in the spring, as well as flashier flows during the summer monsoon. The style of flooding impacts varies, with spring events typically causing widespread and longer-duration volumetric flooding, while summer events tend to cause localized damage by high velocity and debris-laden, short-duration floods. More detailed information on study catchment surface conditions, channel characteristics, and local hydrogeology is provided by Schenk et al. [18] and Schenk [16]. Stream gauge data suitable for a Flagstaff-area flood analysis was first systematically collected by the United States Geological Survey (USGS), primarily from the late 1960s to early 1980s [17]. More recent and ongoing gauge data, now of comparable record length to the earlier USGS data, are available, primarily from a Northern Arizona University (NAU) project, with additional records collected by the City of Flagstaff, the USGS, and the U.S. National Park Service (NPS).

3. Methods

3.1. Catchment Environmental Change

For catchment and drainage system base mapping, we used standard USGS topographic, hydrography, land cover, and geologic digital map sources (Figure 1). Watershed boundary delineation was performed using ArcGIS Pro (ver. 3.0) software's Hydrology Toolset functions, with the 10 m USGS National Elevation Database DEM (https://data.usgs.gov/datacatalog/data/USGS:3a81321b-c153-416f-98b7-cc8e5f0e17c3; accessed on 3 November 2023).

We obtained major wildfire perimeters since 1984 that intersected study catchments from the Monitoring Trends in Burn Severity (MTBS; https://www.mtbs.gov; accessed on 7 December 2023) website direct download. One earlier wildfire of potential significance for our study was the ≈1900 ha Radio Fire of 1977 [23], for which we only have an approximate fire boundary from air photo interpretation. The extent of contemporaneous forest thinning was obtained from the USDA Forest Service, Southwestern Region (Title: Activities; Published: 3 January 2024; https://www.fs.usda.gov/r3/gis/gisdata/ActivityPolygon.html; accessed on 24 January 2024). We overlaid aerial photos to identify moderate- to high-intensity urban development growth within the study catchments of west Flagstaff between 1980, near the end of the historic USGS gauge monitoring, and 2013, near the beginning of our recent monitoring. Acquisition of 1980 photos occurred on 1 October, nominal scale 1:58 k (USGS IDs NC1NHAP80027302x; medium-resolution scans), and 2013 imagery was orthorectified 19 June photography from the National Agriculture Imagery Program (NAIP IDs M_3511151_xE_12_1_20130619; 1 m resolution). We georeferenced

earlier photos to align with the NAIP imagery and visually assessed development change at the earlier imagery nominal scale.

We obtained nearly continuous climate station data from Flagstaff Airport (Station Network/ID: GHCND/USW00003103), downloaded from https://www.ncei.noaa.gov/cdo-web (accessed on 17 November 2023) for plotting and analysis. For comparing changes in variable means of temperature and precipitation between the historic stream gauge data and the contemporary data, we used equal-length periods of 1969–1980 and 2012–2023, which overlaps almost all the gauge records of study.

3.2. Stream Gauge Data

The USGS gauge analysis report by Hill et al. [17] compiled peak annual flood records for 11 Flagstaff-area catchments (Figure 1; Table S1), ranging in length from 10 to 18 years (12-year median length), through the operation of a crest-stage gauge network [24]. We used these earlier USGS records, which spanned the 1970s, as 'historic USGS' data for comparison with more recent stream gauging data, noting that the study catchments were already heavily altered by urbanization and/or forest (mis)management. The USGS crest-stage gauges were used to collect annual peak flood stages as a first approximation of flood risk in the area [17].

We used similar crest-stage gauge data collected as part of an ongoing NAU student-led monitoring project, involving eight study catchments (Figure 1; Table S1). Data collection for this gauge network was initiated in 2011 (5 catchments; 13 years of records) and expanded in 2012 (3 catchments; 12 years of records), with three installations matching historic USGS gauging locations. Peak flow measurements were collected monthly, excluding months of site freeze-up or snow burial (typically December–March). It was later determined that some of the NAU gauges were not well suited for defining reliable stage–discharge relations, so most of the gauge records were only used for determining the seasonality of annual floods with no corresponding discharge conversion, or only very approximate discharge estimation (i.e., single significant digit). Depending on gauge site characteristics, multiple methods were used to produce discharge rating tables, including culvert modeling and 1-D streamflow modeling (Appendix D: Stage–Discharge Rating Tables [18]).

Other stream gauge data used in our study include ongoing collection by the City of Flagstaff for Bow and Arrow wash near the airport (pressure transducer; 2010-) [18], USGS gauge 09400815 for Newman Canyon (bubbler; 2015-), and two Walnut Canyon National Monument NPS gauges for Walnut and Cherry creeks (pressure transducers; 2011-). The Newman Canyon gauge is the shortest record (9 years) that we use for quantitatively assessing the seasonal timing of annual floods. Where possible, however, we also used shorter stream gauge records throughout the city and Lake Mary reservoir subcatchments further south, described and tabulated, respectively, by Schenk et al. [18] and Rakowski [25], to confirm the seasonal timing of analyzed floods.

3.3. Peak Annual Flood Analyses

For our assessment of changing seasonality in annual flood occurrences, we grouped flood events into three different, equal-length, hydrologic-regime seasons, including (i) winter–spring snowmelt-dominated (February–May, inclusive); (ii) summer monsoon season, small-scale, convective storm-dominated (June–September), and (iii) autumn-winter, cyclonic/frontal system-dominated (October–January). The National Weather Service defines the 'Arizona Monsoon' as officially running from 15 June to 30 September [26]; however, we chose to include the full month of June to match our monthly data collection interval, and because exact days of flooding were not always reported in earlier data collection.

We used the Fisher's Exact Test to statistically compare seasonality count differences between the historic and contemporary data. A 2×2 Fisher's test was used where records were dominated by two seasonal classes, which was the case for many records with winter–

spring snowmelt and monsoon-season rainstorm types dominating, and a 3 × 2 Fisher's test was used if all three season types were sufficiently mixed, determined to be three or greater occurrences of each event type. These tests were completed using all annual flood events in the flow records, in addition to using only events exceeding the median event magnitude to also assess potential change experienced only with larger flood. The tests were performed for catchments where the historical USGS gauge location was reoccupied for recent monitoring, including the Rio de Flag at Hidden Hollow Road (HHR), Schultz Creek, and Rio de Flag at Crescent, and for a few selected catchment pairs that we deemed similar enough in terms of topography, geology, and disturbance history, as described in the Results.

Reliable estimates of discharge were not consistently available for all gauge sites. We also note that many stage–discharge relations were not sensitive for low flow conditions. We therefore focused on examining changes in event seasonality instead of changing event magnitudes. In comparing event magnitudes, we focus on relatively high flows, including flood discharges exceeding the median or exceeding the third quartile of the annual discharge record, and the peak discharges of record.

4. Results

4.1. Mountain Drainages

Seven study catchments directly incorporate runoff from the mountainous terrain north of Flagstaff (Figure 1). Tributaries for the western-southwestern flanks and the southern flanks of San Francisco Mountain drain to the upper Rio de Flag HHR and Boldt gauges through upland- and plateau-level forests and low-density development in low lying terrain. The Schultz catchment captures a smaller portion of south-facing slopes of San Francisco Mountain in addition to tributaries draining the northwest side of an upland area known as the Dry Lake Hills. The remaining, primarily southeast draining portion of the Dry Lake Hills flows to the Switzer and Switzer Trib gauges.

Steeper west to south flowing drainages of the Elden Mountain lava dome flow to the Switzer Trib, Lockett, and Harenberg gauges, all of which have more exposed rock outcrops and also include relatively high-density urban development in lower catchment areas. The 2022 Pipeline Fire burned some of the east margin of the Boldt catchment and the highest San Francisco Mountain tributaries within the Schultz catchment. The 2019 Museum Fire burned some of the Schultz catchment and a large proportion of the upper Switzer Trib catchment. Large portions of Elden Mountain remain unforested from the 1977 Radio Fire.

Of the seven above-mentioned mountain drainages, historic USGS gauge data are available for all except the Rio de Flag at Boldt. The more western of those catchments, Rio de Flag at HHR and Schultz, which drain portions of San Francisco Mountain, had a greater proportion of winter–spring snowmelt peak annual floods (ratios of 5/8 and 3/4, respectively) (Figure 2A). The intermediately positioned Switzer peak flow record was more mixed in peak flood seasonality, and the only upper drainage with more than one autumn–winter annual peak. The three easternmost historic gauges that capture Elden Mountain runoff were monsoon dominated (ratios of 11/13, 8/9, and 10/12 for Switzer Trib, Lockett, and Harenberg, respectively). Recent peak flow data are only available for the upper Rio de Flag gauges (HHR and Boldt), and the Schultz gauge. Monsoon season events account for the largest proportion of peak flows (ratios of 7/12, 6/10, and 10/13, respectively) followed only by winter–spring snowmelt season flows (no autumn–winter annual peaks) for the more recent period.

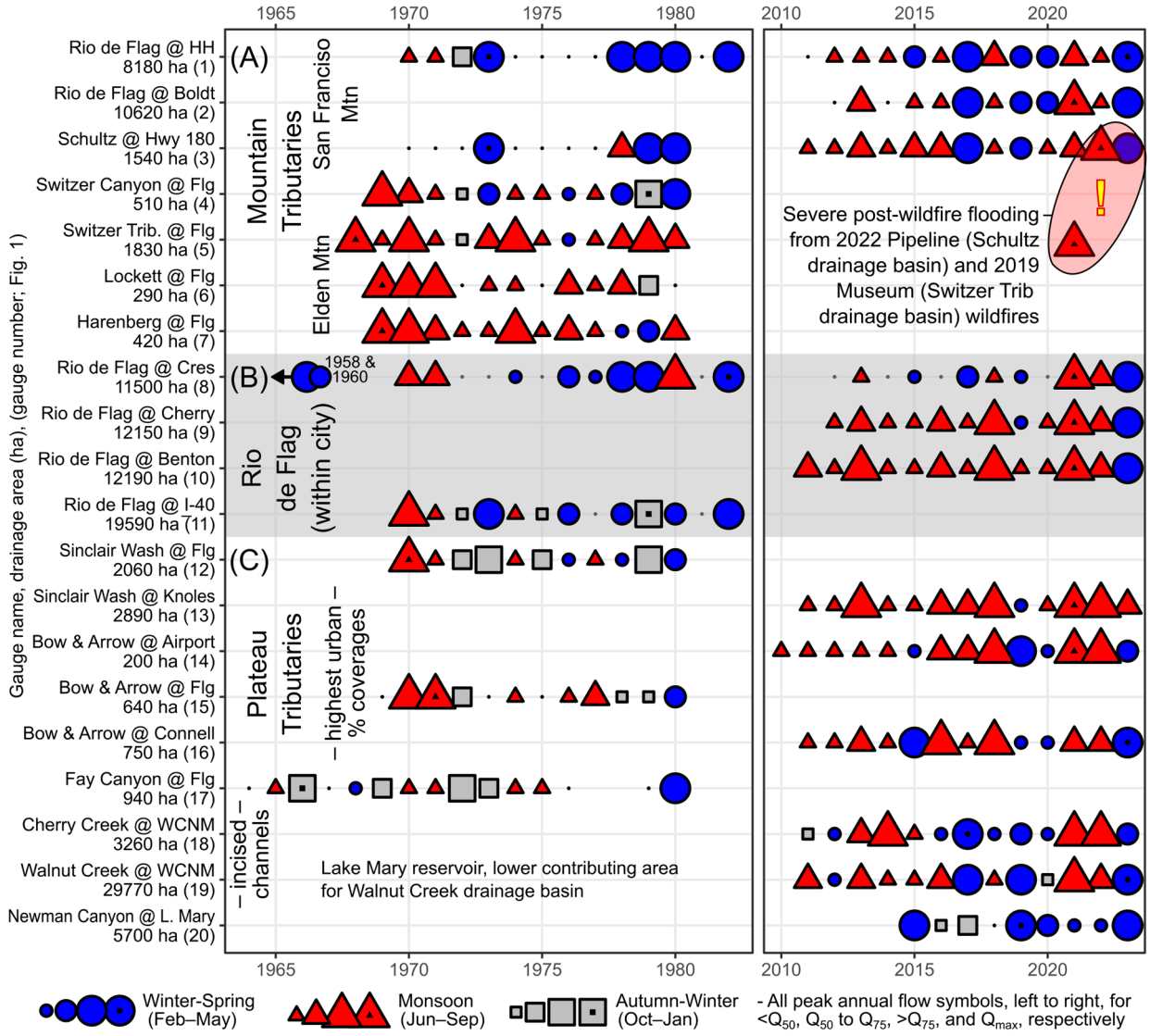

Figure 2. Peak annual flood record for all study catchments (Figure 1) indicating seasonality and relative stage magnitude by group: (A) Mountain tributaries; (B) Rio de Flag (within city); and (C) Plateau tributaries. Three records (Bow and Arrow at Airport, Cherry and Walnut creeks) have additional data prior to what is shown in this figure but were deemed too incomplete for peak annual flood assessment.

The only mountain study catchments that included both historic USGS data and more recent crest stage data for comparing flood season count differences between the two monitoring periods were the Rio de Flag HHR and Schultz gauges. There is relatively low significance of the increased proportion of monsoon peak flows for both catchments from Fisher's Exact Test (Table 1). Of those tests, the most statistically significant result was for Schultz Creek, for all events (odds ratio = 8.5, p-value = 0.10).

Table 1. Fisher's exact test results for seasonal flood count differences between historic (≤1982) USGS data and more recent (≥2011) crest stage annual data for mountain study catchments. Highest event count by period is highlighted (no highlight for ties).

Rio de Flag (HHR)	**All Events** Snowmelt	Monsoon	**Rio de Flag (HHR)**	**Large (>Q50) Events** Snowmelt	Monsoon
historic	5	2	historic	5	0
recent	5	7	recent	2	2
	p value = 0.35			p value = 0.17	
	odds ratio = 3.3			odds ratio = Inf	
Schultz Creek	**All events** Snowmelt	Monsoon	**Schultz Creek**	**Large (>Q50) events** Snowmelt	Monsoon
historic	3	1	historic	3	1
recent	3	10	recent	2	5
	p value = 0.10			p value = 0.24	
	odds ratio = 8.5			odds ratio = 6.1	

For the reoccupied monitoring sites of Rio de Flag HHR and Schultz Cr, discharge estimates of relatively high flows (Q_{75}) were greater, by a factor of about two to three, for the historic, more snowmelt dominated, USGS monitoring period (3 and 0.7 m^3 s^{-1}, respectively) than for our more recent, more monsoon dominated, period (1 and 0.4 m^3 s^{-1}, respectively). For the historic period at Rio de Flag HHR, annual peak discharge exceeded 3 m^3 s^{-1} on four of the recorded winter–spring peak events, of which the peak of the record was estimated to have slightly exceeded 4 m^3 s^{-1} (April 1973 snowmelt). Whereas, for the more recent period of monitoring, annual peak discharge was estimated to have only once reached 3–4 m^3 s^{-1}, during a 2023 April snowmelt flood. Excluding post-wildfire flooding, the Schultz Cr maximum recorded peak discharge was about 1.5 m^3 s^{-1}, also coinciding with 1973 snowmelt.

Post-wildfire peak annual floods on Schultz Cr during the previous two years occurred in July–August 2022 following monsoon rainfall and in March–April 2023 following snowmelt. Immediately downstream of the gauge location, these floods exceed culvert capacity, which was estimated to be about 2 m^3 s^{-1}, with peak estimated flows likely many times greater than that. Upstream of the gauge, the peak-of-record flood for Schultz Cr occurred in early August and may have been in the order of 20 m^3 s^{-1}.

4.2. Rio de Flag in Flagstaff

Four gauges provided peak flow data for the Rio de Flag within the city (Figure 1), two were situated upstream of the Flagstaff downtown core (Crescent and Cherry) and two were downstream (Benton and I-40). Only the most upstream of these gauge records (Crescent) includes the two monitoring periods of study. The two intermediate gauges situated close to, and on opposite sides, of downtown Flagstaff only include more recent flow data. And, only the older USGS data is available for the most downstream Rio de Flag site (I-40).

The historic gauge record for Rio de Flag at Crescent had a greater proportion of winter–spring snowmelt peak floods over monsoon season events (ratio of 8/11), whereas the historic I-40 gauge record was more mixed among winter–spring (5), monsoon (3), and winter–fall (3) season events (Figure 2B). Recent gauge data from the upstream Crescent gauge was evenly mixed between monsoon and winter–spring annual floods (4 each). This gauge site, however, was poorly situated to capture all years of flow, missing lower magnitude floods that were observed, and so this site was excluded from the further statistical analysis due to small sample size. Monsoon season events account for the largest proportion of peak flows for the other recent gauge records (ratios of 12/13 and 10/14 for the Cherry and Benton gauges, respectively) followed only by winter–spring snowmelt flows (no fall–winter peak annual flows).

Fisher's Exact Tests showed moderate significance in the increased proportion of monsoon season over winter–spring event counts between the historic USGS data and more recent crest stage data when comparing Rio de Flag at Crescent with Cherry and Rio de Flag at Benton with I-40 gauge records (Table 2), representing Rio de Flag upstream and downstream of the downtown core, respectively. The most statistically significant result was for the upstream gauge pair, for all events' comparison (odds ratio = 14, *p*-value = 0.005).

Table 2. Fisher's exact test results for seasonal flood count differences between historic (≤1982) USGS data and more recent (≥2011) crest stage annual data for the Rio de Flag within the City of Flagstaff study catchments. Highest event count by period is highlighted (no highlight for ties).

Rio de Flag (Cres-Cherry)	**All Events** Snowmelt	Monsoon	**Rio de Flag (Cres-Cherry)**	**Large (>Q50) Events** Snowmelt	Monsoon
historic	10	3	historic	8	3
recent	2	10	recent	2	5
	p value < 0.01			*p* value = 0.14	
	odds ratio = 14			odds ratio = 5.9	
Rio de Flag (Benton-I40)	**All events** Snowmelt	Monsoon	**Rio de Flag (Benton-I40)**	**Large (>Q50) events** Snowmelt	Monsoon
historic	5	3	historic	5	1
recent	1	12	recent	1	6
	p value = 0.01			*p* value = 0.03	
	odds ratio = 17			odds ratio = 20	

For the only reoccupied monitoring site of Rio de Flag Crescent, discharge estimates of relatively high flows (Q_{75}) were greater, by a factor of about two, for the historic, more snowmelt dominated, USGS monitoring period (2 m^3 s^{-1}) than for our more recent, more mixed flood season, period (1 m^3 s^{-1}). For the historic period at Rio de Flag Crescent, annual peak discharge exceeded 3 m^3 s^{-1} on three of the recorded winter–spring peak events, of which the greatest peak flow was estimated to have reached almost 7 m^3 s^{-1} (March 1982 snowmelt). For the more recent period of monitoring, annual peak discharge was estimated to have only once exceeded 3 m^3 s^{-1}, which was on the peak of the record at about 12 m^3 s^{-1} during August 2023 rainstorm flooding.

4.3. Plateau Drainages

Nine study catchments drain sedimentary plateau terrain (Figure 1). Five of the catchment gauges are within the variably urbanized and forested southern margin of the city of Flagstaff, two for Sinclair Wash and three along Bow and Arrow Wash. The other four gauges (Fay Canyon, Cherry Cr, Walnut Cr, Newman Canyon) are situated further south in well-defined, incised canyons with primarily forested, undeveloped catchments. The largest study catchment in this group is that for Walnut Cr, which includes Fay Canyon and Newman Canyon as upstream sub-catchments, as well as the Lake Mary Reservoir which diverts water for urban consumption. A relatively low severity 2019 fire (Newman Fire) burned portions of the Walnut and Newman catchments, the latter of which has experienced relatively extensive, mid-catchment forest thinning. The Sinclair and Bow and Arrow wash catchments showed the greatest amounts of increased development intensity in our air photo comparison.

Historic USGS gauge records for Sinclair, Bow and Arrow washes, and Fay Canyon, having some of the greatest numbers of autumn-winter annual floods, three or more each, were overall relatively mixed among the three seasonal flood groupings (Figure 2C). For the partially urbanized catchments, monsoon season events account for the largest proportion of recent peak annual flows for the Sinclair gauge and the Bow and Arrow at Airport and Connell gauge records (ratios of 12/13, 10/14, and 9/13, respectively), followed only by winter–spring snowmelt season flows (no autumn–winter peak flows). For the non-urbanized catchments, recent peak flows were most frequently monsoon flows for Walnut

Cr (ratio of 8/13), winter–spring for Newman (ratio of 6/8), and more mixed between those two seasons for Cherry Cr, with all having one or two autumn–winter peak flows.

In comparing flood peak season count differences between the historic USGS data and more recent crest stage data, the Fisher's Exact Tests on 3 × 2 contingency tables were used because of the higher prevalence of autumn–winter events, along with winter–spring and monsoon events (Table 3). For Sinclair and Bow and Arrow washes, the most significant seasonal shift among all peak annual flows was from autumn–winter to monsoon events (p-values = 0.01 and 0.07, respectively), followed by less significant shifts from winter–spring to monsoon for Sinclair (p-value = 0.10) and autumn–winter to winter–spring for Bow and Arrow (p-value = 0.14). Models for larger events (greater than median values) did not differ from the all-event models for those partially urbanized washes. Between Fay Canyon and Cherry Cr, deemed the most morphometrically similar plateau drainages for non-urbanized catchment comparison, the all-events model showed the most significant change from autumn–winter to winter–spring events (p-value = 0.09); whereas the larger events model showed the most significant change from autumn–winter to monsoon events (p-value = 0.03).

Table 3. Fisher's exact test results for seasonal flood count differences between historic (≤1980) USGS data and more recent (≥2010) crest stage annual data for plateau study catchments. Highest event count by period is highlighted (no highlight for ties).

Sinclair Wash	**Fall–Winter**	**All Events** Snowmelt	Monsoon	**Bow and Arrow**	**Fall–Winter**	**All Events** Snowmelt	Monsoon
historic	4	3	4	historic	3	1	5
recent	0	1	12	recent	0	4	10
	full model p-value = 0.01				full model p-value = 0.08		
	group1	group2	p-value		group1	group2	p-value
	Fall–Winter	Snowmelt	1		Fall–Winter	Snowmelt	0.14
	Fall–Winter	Monsoon	0.01		Fall–Winter	Monsoon	0.07
	Snowmelt	Monsoon	0.10		Snowmelt	Monsoon	1
Fay-Cherry Cr		**All events**		**Fay-Cherry Cr**		**Large (>Q50) events**	
	Fall–Winter	Snowmelt	Monsoon		Fall–Winter	Snowmelt	Monsoon
historic	4	2	5	historic	4	1	0
recent	1	7	5	recent	0	3	4
	full model p-value = 0.14				full model p-value = 0.03		
	group1	group2	p-value		group1	group2	p-value
	Fall–Winter	Snowmelt	0.09		Fall–Winter	Snowmelt	0.14
	Fall–Winter	Monsoon	0.58		Fall–Winter	Monsoon	0.03
	Snowmelt	Monsoon	0.35		Snowmelt	Monsoon	1

The most closely situated plateau subregion gauges for discharge comparison between study periods are for Bow and Arrow Wash, using the historic data (Bow and Arrow at Flagstaff) and our more recent monitoring data (Bow and Arrow at Connell). The Connell gauge is 0.38 km downstream of the former USGS gauge, with a 20% larger catchment area. Opposite from the other sub-regions, discharge estimates of relatively high flows (Q_{75}) were greater, by a factor of about three, for the later, more monsoon season-dominated, period (3 m^3 s^{-1}) than for the historic, more mixed flood season, USGS monitoring period (1 m^3 s^{-1}). For the later, generally higher-discharge period, annual peak discharge exceeded 3 m^3 s^{-1} three times, of which the greatest flow was estimated to have reached almost 5 m^3 s^{-1} (February 2015 heavy rain-on-snow). For the historic period of monitoring, annual peak discharge was estimated to have only slightly exceeded 2 m^3 s^{-1} once, which was following a 1971 monsoon season's (August) intense rainfall.

4.4. Climate Variations

In addition to mapping catchment disturbances by wildfire and land use activities, we explored inter-decadal climate variations which may relate to seasonal shifts of Flagstaff-area peak annual flows, especially those for winter–spring snowmelt and monsoon floods. In comparing the two equal-length intervals, one for the historic USGS monitoring (1969–1980) and one for more recent monitoring (2012–2023) (Figure 3), we note the following: (a) an increase in winter–spring mean temperature from 3.84 to 5.39 °C; (b) a decrease in mean highest snow depth in year from 0.61 to 0.46 m; (c) an increase in highest monsoon rainfall from 32.2 to 34.1 mm; and (d) an increase in monsoon number of days with rainfall exceeding 15 mm from 2.92 to 4.17 days. In a preliminary assessment, we observed closely matching climatic shifts in data from another meteorological station (Fort Valley), which is centrally situated within the most upstream Rio de Flag subcatchment (HHR) at a slightly higher elevation (2239 m asl.), but was dropped because of some missing data years. We also explored snow water equivalent as an alternative to snow depth for both climate stations for assessing snowpack change, which showed a similar magnitude of decrease from the historic USGS monitoring and our more recent monitoring period, but again was dropped for having missing records.

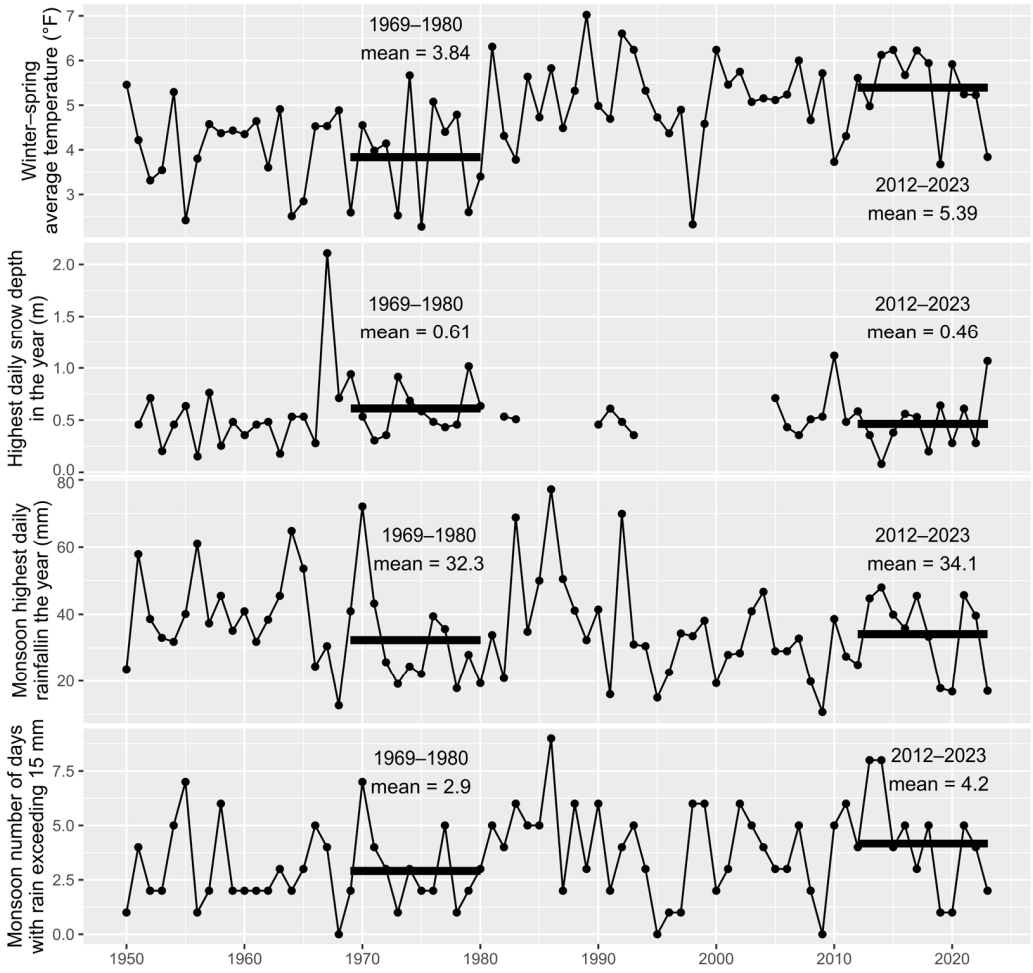

Figure 3. Selected Flagstaff Airport climate station temperature- and precipitation-based variables since 1950, including derived variable means for equal-length intervals (bold horizontal lines) overlapping the historic USGS monitoring (1969–1980) and our recent monitoring periods (2012–2023).

5. Discussion

5.1. Geologic and Topographic Controls

Undisturbed catchments north and south of Flagstaff experience comparatively low surface runoff ratios during rainfall and snowmelt [18]. This low runoff response results primarily from extreme rates of infiltration, which is associated with the local geology of the San Francisco Volcanic Field and upper Colorado Plateau stratigraphy (Figure 1).

The northwestern study areas of the upper Rio de Flag and Schultz Creek catchments are dominated by highly fractured volcanics, primarily andesites of San Francisco Mountain over lower elevation basalts, and coarse-grained surficial materials of volcanic residuum, cinders, and porous recent deposits [19]. The northeastern study catchments, from the Switzer to the Harenberg drainages, are increasingly dominated by the character of Elden Mountain's southern flank, which consists of partly exogenous, dacite dome lobes. These catchments are among the most distinctive in terms of geology and topography with the steepest slopes and most extensive exposed bedrock. Through the winter, relatively little snow accumulates on these steep, dominantly south-facing, and largely unvegetated catchments. In all the historic USGS gauge records, these are the only catchments with peak annual flows dominated by monsoon season rain events, with others being snowmelt dominated or with more mixed flood regimes (Figure 2), which we attribute to those strong geologic/topographic controls. We did not analyze any recent runoff data from these two distinctive catchments. More surface flow monitoring of Elden Mountain drainages has been initiated by the City of Flagstaff, but those records are too short to be included in this study.

High infiltration and generally low runoff for catchments south of Flagstaff also result from the highly fractured character of older basalt flows, as well as the fractured and weathered (karstic) limestone of exposed Kaibab Formation rocks south of the volcanic field [20]. In addition to the gentler, plateau-surface terrain of these catchments, a distinctive feature is the presence of incised canyons that emphasize the main tributary network. In the historic USGS gauge records, these are the catchments with the most mixed-regime peak annual flows, with more frequent autumn–winter events which rarely occurred in the other data (Figure 2). This may be associated with topography, with the lower mean elevation of catchments resulting in more rain-on-snow runoff, plateau-canyon snow and rainfall distribution effects, and/or seasonal changes in runoff routing. These catchments have the highest buffering potential from upland water bodies. An analysis of high elevation, long-term USGS gauges throughout the U.S. Southwest by O'Donnell [27] showed a geologic pattern of less igneous runoff relative to sedimentary terrain, which could suggest seasonal (e.g., winter freeze-up) limiting of infiltration. We also acknowledge a potential for erroneously higher crest stage readings of winter flows from snow and ice buildup effects in canyon settings. The more extensive recent monitoring of annual floods indicates a more monsoon-dominated regime for the partially-urbanized Sinclair and Bow and Arrow washes, and more mixed summer monsoon–spring snowmelt regimes for the non-urbanized catchments of Cherry, Walnut, and Newman.

5.2. Urbanization

In addition to highly porous regional geology, surface flood runoff from undisturbed areas may also be limited by catchment and channel vegetation and detritus buildup. Urbanization can result in greater flood runoff because of increased catchment impervious area and reduced channel infiltration and roughness. The study drainages which experienced the greatest increase in moderate- to high-intensity urban development, between the historic USGS and our more recent gauge monitoring periods, are the Sinclair and Bow and Arrow washes (Figure 1), with relatively dense pockets of urbanization growth around the I-40 business route (old U.S. Route 66) corridor, south Woodlands Village (incl. major shopping centers/parking lots), University Highlands and Ponderosa Trails residential neighborhoods, and Pulliam Airpark commercial expansion. Annual peak flow data show both of these drainages shifting from more mixed seasonal flood regimes to monsoon-

rainfall dominated flood regimes (Figure 2). The Sinclair at Knoles recent flood gauge record was more dominated by monsoon events than any of the other sites. Discharge estimates of relatively high flows for lower Bow and Arrow gauges, opposite to what we observed for other study drainages, were greater for the later, more monsoon dominated monitoring period than for the earlier, more mixed flood season historical period, by a factor of about three. We hypothesize that these flow regime and discharge magnitude changes may be associated with land use development that has occurred since 1980, a pattern that matches large-scale urbanization effects on flood magnitudes through much of the country [10]. This is also consistent with the earlier local estimation by Hill et al. [17] that some urbanized catchments of Flagstaff can have runoff coefficients about four times greater than those of undeveloped basins. We acknowledge, however, that a considerable amount of this land use attributed impact may also be associated with concurrent climate change impacts that can additionally influence surface runoff trends.

5.3. Climate Variations and Forest Treatment

Shifts from predominantly winter–spring and autumn–winter season annual floods towards monsoon-dominated flood regimes for most of the study drainages (Figure 2) may be the result of climatic variations observed in Flagstaff (Figure 3). In comparing summary meteorological data between our recent monitoring and the historic USGS monitoring periods, mean winter snowpacks decreased, resulting in less available snowmelt runoff. At the same time, and consistent with broad patterns of climate change in Western North America [1], increased winter–spring season temperatures may have accelerated melting while also increasing evaporative losses. During the monsoon season, across the same study periods, there has been a corresponding, albeit minor, increase in highest daily rainfall amounts, in addition to an increase in the number of days of relatively heavy rainfall. The latter may relate to effects of antecedent conditions which can be important, especially in the larger catchments [28]. Climate data thus reflects recent conditions being more conducive towards monsoon rainfall flooding over snowmelt flood occurrences. Limited discharge data suggests there may be a corresponding, inter-annual shift in flow variability, from more consistent, moderate magnitude snowmelt flooding to a monsoon season dominated flood regime that is more variable with potential for higher peak annual flood magnitudes. Spring freshet flooding may have been more frequent than other seasonal floods for nearly a century long period prior to the systematic gauging data analyzed herein, based on climate conditions and other historical records. A compilation of notable Flagstaff floods, obtained primarily from newspapers by the U.S. Army Corps of Engineers for the period 1888 to 1973 [29], had seasonal counts of 7 winter–spring, 3 monsoon-season, and 2 autumn–winter floods, although we also note that the largest few events of that compilation were not from snowmelt. A long, alluvium-based chronology from the base of Schultz Cr shows that sediment has been accumulating for approximately 7000 years without strong evidence of major flooding or high-severity wildfire [30].

The Newman forested catchment is the only recent period record that exhibits a winter–spring snowmelt dominated peak annual flood. And the forested catchments of the upper Rio de Flag and Cherry Creek have remained relatively mixed between monsoon- and snowmelt-season annual flood occurrences in comparison to more urbanized catchments and some of the other forested catchments. We note that climate change may have also altered forest conditions which may also influence flood regimes, and forest management of recent decades has included thinning treatments to encourage greater snowpack runoff and soil moisture [31]. Such treatments have been extensive in the Newman gauged catchment [25] and in portions of upper Rio de Flag watersheds (Figure 1). These treatments can have large water budget effects, including on evapotranspiration and sublimation losses, which can be especially considerable in the high elevation, dry climate forests of northern Arizona [22,31]. Forest thinning applications are likely to continue in the region as contemporary climate change, along with legacy impacts of historic forest management, has made high-severity wildfire a major disturbance of recent and ongoing concern [1,21,32].

5.4. Wildfires

The dry conifer forests around Flagstaff had experienced larger and more severe wildfires, as have occurred throughout much of the western U.S. [8,9]. Processes leading to increased runoff and erosion following moderate- and high-severity wildfires have become well documented [33]. Severe post-wildfire flooding occurred on catchments of the east side of the San Francisco Peaks following the 2010 Schultz Fire north of Flagstaff (Figure 1). That flooding has caused long-lasting, costly damage, including loss of life, in the extensive, low-density neighborhood developments northeast of the city, with significant continuing risk and cost accruals for over a decade following the fire [34]. The 2019 Newman Fire south of Flagstaff did not result in major flood impacts, because of its generally lower severity and topographic setting. The 2019 Museum Fire, however, burned steep slope areas of the Dry Lake Hills and Elden Mountain of the Spruce Wash catchment, which drains into large dense neighborhoods of East Flagstaff, and represents a large proportion of the upper Switzer Trib catchment area of the historic USGS peak annual flood study. That fire started mid-monsoon season (July); although, there were no substantial post-fire flood impacts for the remainder of that year and all the following year, coinciding with exceptionally low monsoon precipitation and relatively minimal annual peak snowmelt runoff those back-to-back years (2019–2020; Figures 2 and 3). The 2021 monsoon was then wetter than average, with several high-intensity, July–August rainfall events over the burn scar, triggering highly destructive post-fire flood runoff, catchment erosion, and debris flows [35–37], with downstream neighborhood flooding compounded by high urban runoff from lower subcatchments [38]. During those floods, peak discharge from Spruce Wash, where it enters the urban interface, was estimated to be in the order of 30 m^3 s^{-1} or greater based on hydrologic modeling and empirical evidence [36]. Those floods serve as a potent example of extreme flooding following high-severity wildfire because, in the historic USGS analysis of the Switzer Trib gauge record, that large mountain portion of the catchment which produced extraordinary downstream floods after the Museum Fire was classified as hydrologically 'non-contributing' in the 13 years of study by Hill et al. [17].

Our gauge monitoring of the Schultz Cr catchment captured post-wildfire flooding impacts of the 2022 Pipeline Fire (Figure 1). That fire started in mid-June and was immediately followed by an active monsoon season through July and August, triggering rainstorm-generated floods and debris flows from the fire scar [16,39]. The winter of 2023 had an exceptionally thick snowpack (Figure 3), and flooding resumed in March–April 2023 following episodes of rapid spring snowmelt, resulting in back-to-back peak annual floods of record for each corresponding season of analysis (2022 monsoon, 2023 winter–spring) (Figure 2). Flood flows from Schutz Creek caused extensive urban flooding and flood damage to the downstream neighborhoods of west Flagstaff. In response to these post-fire flooding impacts, novel mitigation structures were constructed [40], including watershed infrastructure upstream of neighborhoods east of San Francisco Mountain, and three detention basins near the edge of the urban interface on Schultz Creek, upstream our recent monitoring gauge. The post-wildfire flooding of Schultz Creek (Pipeline Fire) and Spruce Wash (Museum Fire) resulted in flood discharges likely exceeding historical estimates of peak flood magnitude over decade-long monitoring periods by one to two orders of magnitude.

5.5. Broader Context

Flood variability due to environmental and climate change is a major economic and social concern globally [41]. Floods in the western and southern U.S. may correlate with global climate forcings [13], but with a complex, fragmented pattern of flood change that has clouded meaningful generalization [11]. Where such data exists, small-catchment studies may be key for studying flood change as precipitation events become potentially more extreme in a warming climate [28]. Our newly compiled dataset and analysis of peak annual floods within the Flagstaff region of the Colorado Plateau in northern Arizona provides insight into contemporary flood regime changes at a scale of direct societal

significance, in addition to helping fill a large spatial gap in observation-based, large-scale assessments of flooding trends in the western U.S. Our observations of flood-regime change generally align with contemporary evidence of increased precipitation and runoff variability and mean intensity in much of the western U.S. [5,7], and especially the trend towards increased convective storm flooding [4]. Ephemeral streams in this region should receive greater research attention with the increased realization of their high ecological and societal value [42]. The importance and challenges of relating multifaceted environmental change to small-catchment flood risk and flood intensity trends are expressed in other studied dry forest regions internationally [43–45].

6. Conclusions

Our analyses showed systematic patterns and changes in Flagstaff-area flood regimes that relate to the unique geological setting of the local ephemeral drainages, and in response to local to regional climate variations and catchment disturbances. For many catchments, especially in urban settings, flooding has shifted from snowmelt or mixed seasonal flood regimes towards monsoon-dominated flooding, a trend which corresponds to observed local warming and precipitation changes. Our results indicate moderate to extreme exacerbation of damaging floods by urban development and wildfire disturbances, respectively. We advocate for continued monitoring of Flagstaff-area stream gauges to enable trend analyses for climate and environmental change attribution. Future flood analyses should also be greatly aided by an expanded gauging network implemented by the city. That effort may be enhanced by direct discharge measurements for improved discharge calculation, allowing for improved spatiotemporal flood-frequency and rainfall-runoff relation analyses. Such work will be of high societal and ecological importance for making defensible predictions of flood-regime change for ongoing flood mitigation and for environmental protection in the increasingly developed Flagstaff region of northern Arizona.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology11080115/s1, Table S1: Study gauge details (sources, names, coordinates, catchment areas) and data summary statistics (upper stage and discharge quartiles).

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