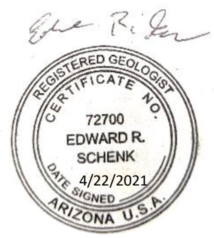
Surface Water Hydrology and Flood Recurrence in the Flagstaff, Arizona Area, 2008-2019

CITY OF FLAGSTAFF ARIZONA ESTABLISHED 1882

FLAGSTAFF WATER SERVICES

Cover photo: Bow and Arrow Wash at the Airport Detention Basin, 2019. Inset right: Sunnyside neighborhood following a monsoon storm in 2013.

April 22, 2021



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Abbreviations:

ALERT	Automated Local Evaluation in Real Time
CFS	Cubic feet per second
COF	City of Flagstaff
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
FEMA	Federal Emergency Management Agency
FIS	Flood insurance study
GPM	Gallons per minute
HEC-RAS	Hydrologic Engineering Center – River Analysis Software
HEC-SSP	Hydrologic Engineering Center – Stream Statistical Package
NAU	Northern Arizona university
NPS	National Park Service
NSS	National Streamflow Statistics
RDF	Rio de Flag
SRP	Salt River Project
USGS	United States Geological Survey

Executive Summary

Flagstaff, Arizona has unique surface water hydrology due to climate, geology, and vegetation. The area experiences extremely low rainfall-runoff in natural undisturbed areas. This "complacent" watershed condition leads to dramatic shifts in flow and flooding when disturbances such as urbanization, wildfire, or even forest thinning are introduced to the landscape. Using 57 stream and rain gauges this report provides preliminary data to inform managers, engineers, and scientists on both the complacent and "violent" watershed characteristics of the Flagstaff area. This is the first regional surface water hydrology report since the 1988 US Geological Survey report on flood frequency in the Flagstaff area. Preliminary results indicate that previous flood frequency analyses provide a much higher predicted flood flow than empirical gauge results have observed. In some sites the over-prediction of regional regressions is over twice observed values. The hope is that this preliminary report will provide a "stepping stone" towards a greater understanding of the hydrologic drivers and stream character of the area. More data, over a longer time period, is required for making defensible predictions of rainfall-runoff, flood frequency, and flood mitigation design in the Flagstaff area.

Introduction

Flagstaff Arizona is at the southern edge of the San Francisco Volcanic Field and near the southern edge of the Colorado Plateau. The area sits at approximately 7000 feet above mean sea level resulting in substantially cooler and wetter climate than the majority of Arizona and the American Southwest. The area has little storm runoff, despite the climate, due to extreme infiltration through volcanic cinders, fractured basalt, and karstic Kaibab Formation sedimentary rocks. This condition is exacerbated by historically dense ponderosa pine (*pinus ponderosa*) forests caused by suppressed wildfire and the cessation of logging in the mid 20th century. The most recent published surface hydrology report is from a USGS 1988 flood frequency report that utilized crest gauge data between the late 1950s and early 1980s (Hill et al. 1988). The purpose of this report is to provide preliminary gauge data between 2008 and 2019 from a variety of different gauge types around the Flagstaff area to provide a foundation for future data and interpretative report releases.

The Rio de Flag is the largest drainage within the study area and is fed by several notable tributaries (Figure 1). The Rio de Flag combines with Walnut Creek east of Flagstaff to become San Francisco Wash, this wash in turn combines with Padre Canyon to become Canyon Diablo and eventually flows to the Little Colorado River near Leupp, AZ. The majority of the stream courses just named are ephemeral with infrequent flow after snow melt or after intense summer monsoon storms.

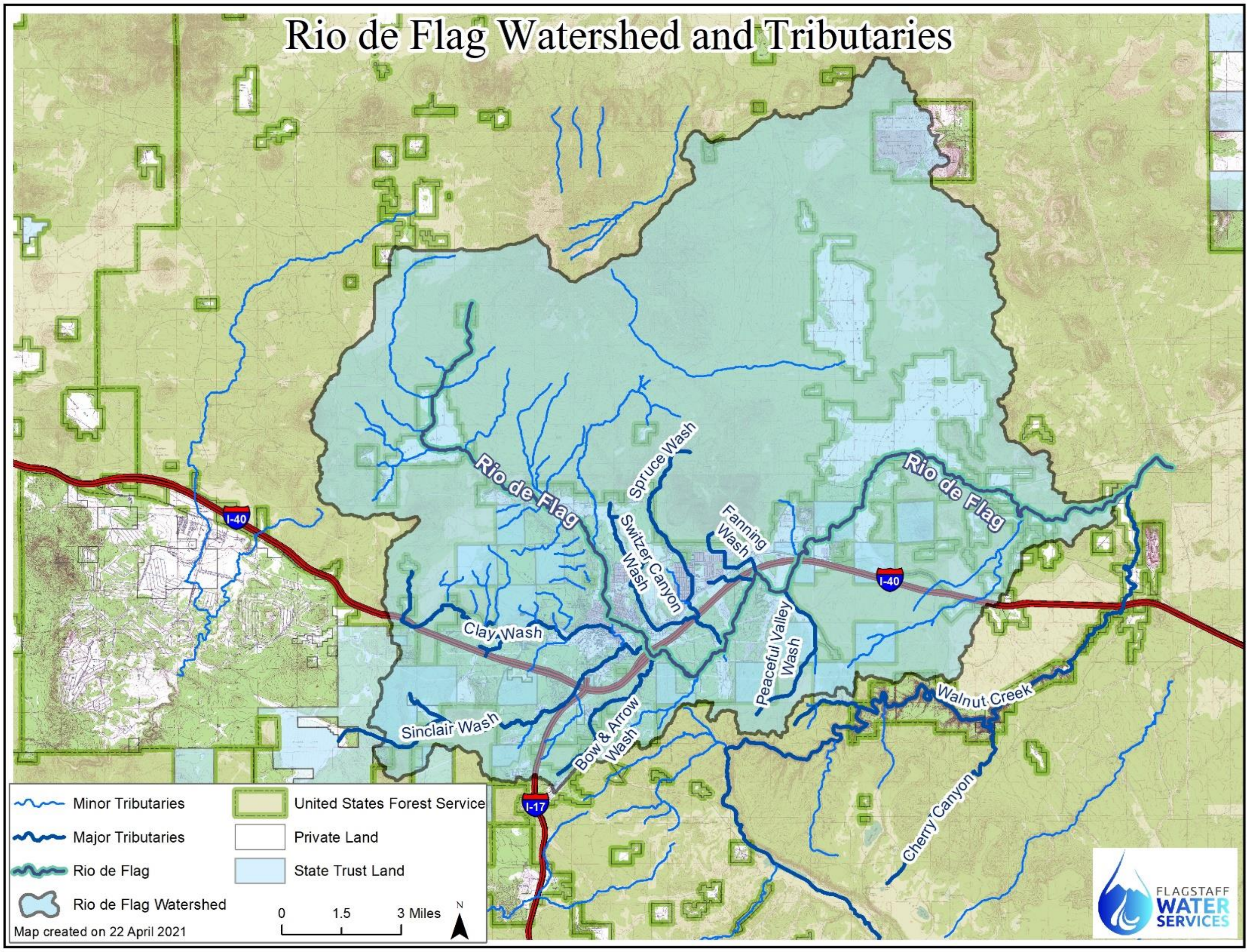

Figure 1. the Rio de Flag in blue and associated streams and washes that combine to drain to San Francisco Wash. The effective watershed is shown in light blue, ineffective drainages around Sunset Crater are not shown since they do not convey surface waters to the Rio de Flag even during extreme events.

The Rio de Flag watershed is dominated by the San Francisco Peaks, Dry Lake Hills, and Mount Elden, a complex of volcanoes that are within the larger San Francisco Volcano Field. The Walnut Creek watershed is dominated by Mormon Mountain, a volcanic basalt/dacite dome and a similar mix of volcanic and karstic Kaibab Formation rocks as the Rio de Flag watershed. Volcanic activity began in the region in the Pleistocene, about 2.6 million year ago. The last eruption was Sunset Crater only 930 years ago (Waring 2018). The volcanic flows make up a considerable portion of the watershed and also create a dramatic elevation gradient from the highest point in Arizona down to 6,170 feet at the confluence with the San Francisco Wash (Holm 2019). The average precipitation in the watershed is 22.4 inches (Leao and Tecle, 2005) but the majority of this rain and snow either evaporates or infiltrates into the cinders or karst limestone. Very little water, less than 5% of precipitation, flows on the natural landscape.

Hydrogeology (Groundwater) of the Flagstaff region

The hydrogeology of the Flagstaff area, and the Rio de Flag, is dominated by the igneous San Francisco Peaks, related cinder fields, and underlying karstic Kaibab Formation. Karst is defined as any rock that can be readily dissolved by weak acids, such as rainwater. The Kaibab Formation is mostly made up of highly fractured and weathered limestone. Both the igneous and karst formations lead to quick water infiltration, one of the reasons that local streams are intermittent at best (Hill et al. 2018). A discontinuous un-named shallow perched aquifer exists under portions of Flagstaff. This aquifer is expressed through shallow residential wells (mostly in the Coconino Estates and Sunnyside neighborhoods) as well as occasional seeps in basements and underground structures. Deeper rock stratigraphy make up the two regional aquifers that underlie the watershed, the “C” aquifer and the “R” aquifer. The C aquifer is made up of the Supai and Coconino formations while the deeper “R” aquifer is the primarily limestone Redwall and Muav formations (Figure 2). Neither the C or R aquifers directly contribute, or impact, surface flows in the Flagstaff region.

Groundwater flow does not necessarily follow the same pathways as the surface flow, this is due to the geologic structure of the rocks including strike, dip, and faults and fractures. The Rio de Flag is part of the Little Colorado River drainage but once the water sinks into the ground it may follow the predominant geologic dip. In the Flagstaff region the groundwater can change course and drain to the Verde River, most likely reaching the surface in Oak Creek Canyon (Figure 3). The groundwater flowpath changes depending on where the water infiltrates within the surface watershed. The flowpaths are generally mapped by groundwater computer models. For the Rio de Flag watershed the most recent water is the revised Northern Arizona Groundwater Model (Pool et al. 2011). Groundwater flow is complicated in the Flagstaff area because of the interplay between the C and R aquifers and the existences of geologic faults, fractures, dissolution chambers, and caves. A recent nearby groundwater tracer study at the Grand Canyon showed that flow paths could change by year, amount of precipitation, or other factors (Jones et al. 2018).

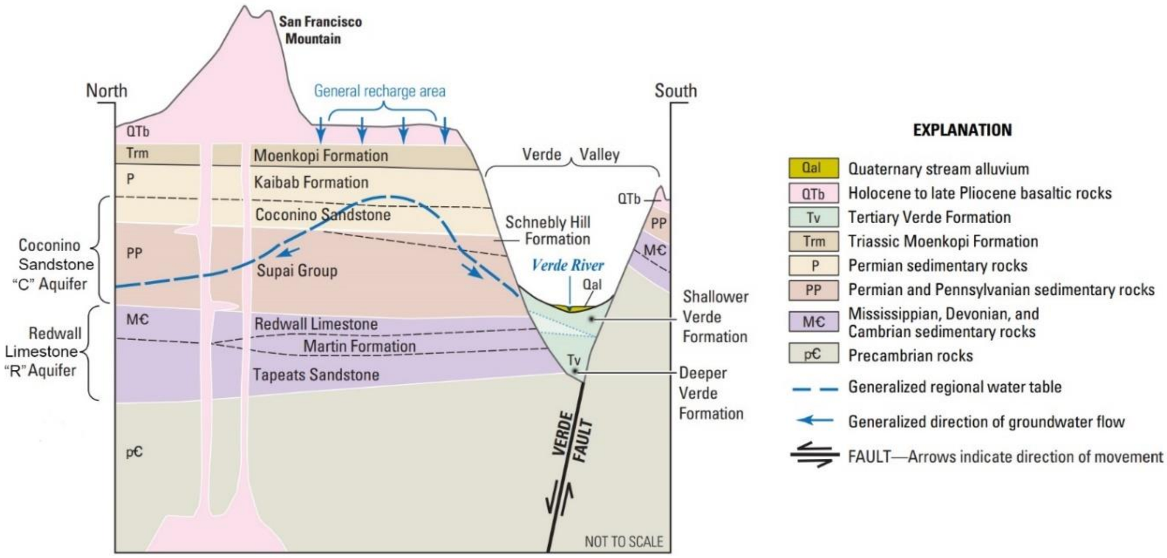

Figure 2. Generalized stratigraphy and groundwater flowpath for the Rio de Flag watershed. Note that the groundwater path leads mostly to the Verde River, different from the surface water pathway. Image from Blasch et al. 2006.

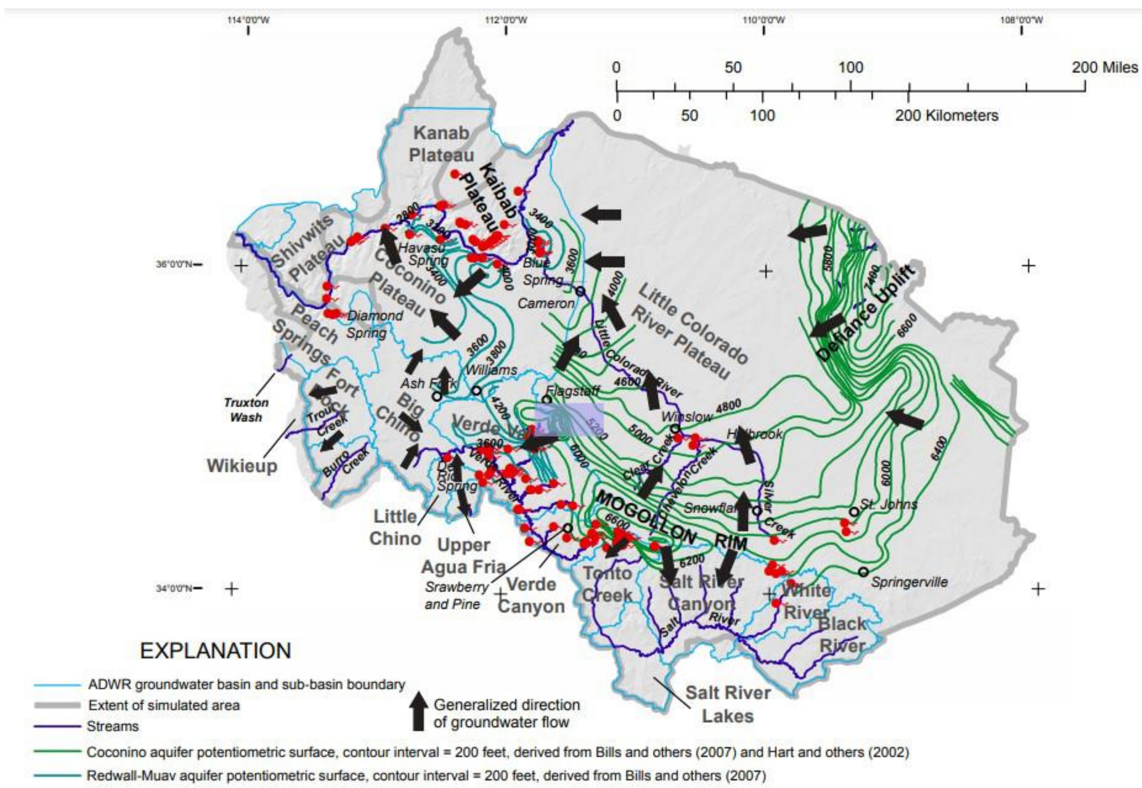

Figure 3. Generalized groundwater flow paths in Northern Arizona, note that the Rio de Flag watershed, marked in a light blue box, mostly drains to the southeast, opposite the surface water pattern (image from Pool et al. 2011).

Soil Infiltration Rates

Infiltration, both in channel and overland, is important for understanding flow losses through the watershed. In humid areas this term is negligible as the soil is often saturated and/or the groundwater level is shallow or at grade with channels. Infiltration is a more important variable in Arizona where soils are often unsaturated, and channels are disconnected with the water table.

Soil infiltration rates were measured in-situ in a study of groundwater recharge commissioned by the City of Flagstaff to Natural Channel Designs LLC and by field measurements of the Rio de Flag during spring snowmelt (April and May) in the Cheshire and Coconino Estates neighborhoods. Both endeavors used empirical techniques (weirs or cutthroat flumes) to measure discharge. The flow at the Rio de Flag at I-40, and in the Cheshire neighborhoods, was at flow equilibrium due to sustained flows. The other flow tests were conducted over a one to two week period and may not be indicative of long term flow regimes. Conversely, infiltration during flash floods may be higher due to unsaturated soil conditions. Post-fire flows were measured using high water marks and a HEC-RAS 1-d model at the Mount Elden gauge and by direct pressure transducer readings at Linda Vista Avenue. The flow attenuated and infiltrated between the two gauges, with a flow of approximately 150 CFS at the upstream gauge and 12 CFS at the lower gauge (Porter et al. 2021). The distance between the two gauges is approximately 2 miles, which translates to an infiltration rate of approximately 70 CFS per mile. The post-fire flow data is not included in Table 1 since the soil was not saturated and an unknown amount of peak flow was lost to attenuation from the event driven flow. The data presented in Table 1 is preliminary and there is a great deal of additional work needed.

Table 1. Soil infiltration rates from field measurements (Cheshire neighborhood) and an aquifer recharge study (Natural Channel Design 2020). The percent loss per 100 linear feet of channel is probably more insightful than gross stream losses.

Location	Flow (gpm)	% loss (per 100 linear ft)	Infiltration (gpm/linear ft)	Infiltration (CFS/mile)
Rio de Flag, Cheshire neighborhood 2019	81	37.0	0.3	3.48
Rio de Flag, Cheshire neighborhood 2020	6.5	0.6	0.0004	0.00
Bow & Arrow Wash at Lonetree Rd.	250	9.5	0.237	2.75
Bow & Arrow Wash at Lonetree Rd.	500	4.6	0.23	2.67
Bow & Arrow Wash at Lonetree Rd.	1000	3.3	0.334	3.88
Switzer Wash at Oak St.	480	1.5	0.071	0.82
Switzer Wash at Oak St.	570	0.6	0.032	0.37
Rio de Flag at I-40	197	2.1	0.041	0.48
Rio de Flag at I-40	416	1.1	0.045	0.52
Sinclair Wash at Lonetree Rd.	550	1.7	0.096	1.12
Sinclair Wash at Lonetree Rd.	770	1.2	0.094	1.09

A more thorough discussion of infiltration by season and by stream can be found in the 2020 aquifer recharge study to the City of Flagstaff prepared by Natural Channel Design (Natural Channel Design 2020).

Surface Water

Surface water resources are limited along the Rio de Flag due to the conditions described earlier. Perennial waters include springs, springs brooks, and reservoirs such as the Frances Short Pond and Rio wetlands. Many perennial waters are supplemented by reclaimed water delivered by the City of Flagstaff. These areas include the Rio de Flag through Picture Canyon (maintained with an agreement with the Arizona Game and Fish Department), the Rio de Flag downstream of the Rio Wastewater Treatment Plant (near I-40), and the Frances Short Pond near downtown Flagstaff. Natural flows occur most spring seasons as snowmelt and spring storms allow the ephemeral and intermittent channels to flow throughout the watershed. Summer monsoonal storms also produce brief runoff events, mostly in developed areas with a larger amount of impervious surface but also in post-fire landscapes such as the Museum Fire burn scar.

Surface water resources are monitored using stream and rain gauges operated by the county, city, National Park Service, USGS, and NAU. These gauges replaced US Geological Survey gauges that were operated between 1969 and 1980 (Hill et al. 1988).

Stream Channel Morphology and Riparian Ecology

While ephemeral streams have historically been ignored by science and society they have recently been found to host high biodiversity and great recreation potential (Goodrich et al. 2018). Perennial, or continuous, reaches of the Rio de Flag, are artificially maintained using reclaimed water from the City of Flagstaff. These reaches include the "Rio Wetlands" near Interstate I-40 and Picture Canyon (Figure 4). The city also maintains Frances Short Pond, near downtown Flagstaff, using reclaimed water.

Figure 4. Rio de Flag channel restoration in Picture Canyon Preserve.

The riparian ecology of the Rio de Flag is based on species that are adapted to ephemeral, or intermittent, water sources. Tree species include box elder, arroyo and coyote willow, aspen, and planted cultivars of cottonwoods, and sycamore. Wetland herbaceous species exist at perennial springs, such as Coyote Spring, as well as perennial reaches of stream channel. Animal species are typically mobile because of the lack of consistent water. Fish are stocked at Frances Short Pond (primarily trout and smallmouth bass) and aquatic macroinvertebrates can be found in perennial springs.

The Rio de Flag, and its tributaries, has moderately to well defined channels depending on the underlying geology. In terms of stream classifications they mostly fall under a Rosgen VIII, a moderately confined valley with fine soils and a distinct floodplain (Natural Channel Design, 2020). Headwater channels tend to be more confined, steeper, and lack floodplains (Type II Rosgen channels; Rosgen 1996). Stream restoration projects in the watershed have used a combination of Rosgen natural channel design stream restoration practices (e.g. Rosgen, 1997) and quasi-traditional channel stabilization methods loosely based on Native American traditions (Zeedyk and Clothier 2014). Examples of both types include the cross-vein weirs and check dams below the Schultz Fire and Museum Fire, "Zuni Bowl" channel stabilization in the Rio de Flag in the Cheshire neighborhood, and one-check dams in the Rio de Flag, Sinclair Wash, and

Bow and Arrow Wash. Many of these restorations have utilized knowledge learned in other areas of Arizona and New Mexico.

There have been few studies of the geomorphology of the Flagstaff area but some recent projects in stream restoration have provided some background information on the topic. Local streams exhibit similar channel morphology to the region, channels that are defined by flashy monsoon storms more so than the longer duration gentle snowmelt periods (Moody et al. 2003). Many of the local streams do not show recent history of violent flooding, except within urban areas, and are defined by gravel beds and grassy slopes (Natural Channel Design, 2020). Stream incision, the act of channels down cutting abandoning their formal riparian area, is relatively uncommon in the Rio de Flag except in areas of extreme disturbance. Stream incision is a major problem throughout the Southwest but the Rio de Flag may have been partly spared by the high infiltration rates of the ponderosa forests and the local geology. While there are flash floods on the Rio it is rarer than true desert environments. The forest detritus, duff, and high elevation soils also help reduce violent flooding. The local channel capacity demonstrates the complacent watershed conditions, many of the channels are undersized for the catchment area (Figure 5).

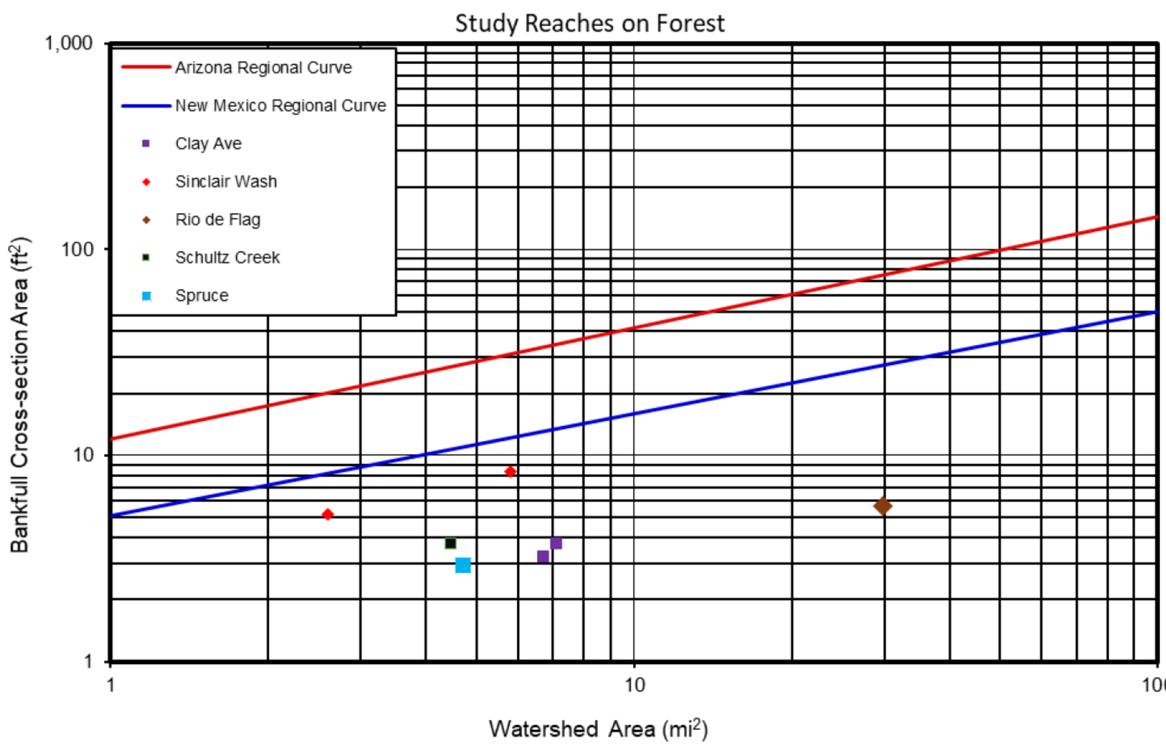

Figure 5. Regional geomorphic curves for the Southwest USA and representative Flagstaff streams (Natural Channel Design 2020). Note that Flagstaff stream channels are much smaller than reference streams.

Soil classification is still poor for most of Arizona, relying on low resolution National Resource Conservation Service (NRCS) soil atlases. Ongoing research in Maricopa County has shown that many areas are mis-classified, leading to errors in flood and hydrologic modeling (Tom Loomis, Maricopa County Flood Control District). The Flagstaff area is no different, with only a gross understanding of the soil types that make up the Rio de Flag watershed (City of Flagstaff, 2009; Natural Channel Design 2020). The soil types that have been mapped are either very poor for infiltrating water (clays created by the weathering of the basalts and cinders) or are extremely good at infiltrating water (cinders, sands, gravels). There is a lack of well-defined loamy soil except in flat outwashes such as Baderville, the Sunnyside neighborhood of Flagstaff, and Freidlein Prairie. Common rainfall-runoff analyses that utilize soil characteristics, like Green and Ampt, are made more difficult in Flagstaff due to low quality soil data.

Climate Responses and Projections

Climate change is already being expressed locally by more prolonged drought, flashier floods, and increased air temperature. Local strategies to respond, or become more resilient, to climate change are just now being implemented. These include the Flagstaff Climate Action and Adaptation Plan (City of Flagstaff 2018), the Flagstaff Watershed Protection Plan (a forest thinning plan) and addressing climate change and forest vulnerability in the Coconino County Flood Control District and Emergency Management Divisions' strategies and planning.

Climate change has always impacted the Rio de Flag watershed, with alternating dry and wet periods and cold and hot cycles through geologic history (Waring 2018; Hereford and Amoroso 2020). Most recently, in the Holocene (about 11,700 years ago), the Southwest heated up stranding cool temperature tree species in "sky islands", high elevation stands surrounded by low elevation deserts. The Rio de Flag watershed is in one of these sky islands, in trees that resemble forests of the southern Rocky Mountains (Betancourt 2004). Recent studies of paleolake levels at Mormon Lake indicate that the area has been in a prolonged drought over the last several decades, possibly due to climate change (Hereford and Amoroso, 2020).

A climate study in 2020 found that 2000 to 2018 is the 2nd worst drought period in the Southwest in 1200 years (Williams et al. 2020). This is leading to massive forest stand die offs and an increase in fire severity. High severity fire, like those of the Rodeo Fire on Mount Elden and the Schultz Fire on the east side of the Peaks, change the forest community to something different. Many of the ponderosa forest stands will be replaced by oak and shrubs following fires in this new climate paradigm (O'Donnell et al. 2018). The impacts on rainfall-runoff are still being quantified.

Forests and Wildfire

The forests of the Rio de Flag are adapted to frequent low intensity fires. Studies have shown that the ponderosa pine forests that surround Flagstaff saw a fire frequency of 2 to 15 years, but mostly low intensity fires (Cocke et al. 2005; Margolis et al. 2011). The forests began changing in the 1900s as sheep herders, cattle ranchers, and Flagstaff area residents began to suppress wildfires. Timber harvest also peaked in the early 20th century leaving large swaths of lands that regenerated without fire. The forest stands became thicker with new ponderosa pine trees, sometimes as much as ten times more dense than pre-European settlement (Cocke et al. 2005; Waring 2018).

More recently the Forest Service, City of Flagstaff, and Coconino County have attempted to restore the forest stand density in an effort to reduce the risk of catastrophic wildfires. The Rodeo Fire, Schultz Fire, and to an extent the Museum Fire, were all high severity fires in or near the watershed that have a profound effect on the forest community. Efforts to return the forest to earlier conditions include prescribed fire and mechanical thinning. Both are being employed by the Forest Service under the Four Forest Restoration Initiative (4FRI) as well as the City of Flagstaff's Flagstaff Watershed Protection Plan (FWPP). The impacts of forest thinning on rainfall-runoff is still being studied but likely provides additional water both as surface and groundwater (Schenk et al. 2020).

Known data and interpretation issues

This report compiles data from a multitude of sources over differing time scales to determine flood frequency and characterize local surface hydrology. Several known, or expected, issues have been identified and are listed below:

Flow year may vary between Federal Water Year (October 1) as reported for USGS gauges and the standard Gregorian calendar (January 1) as reported by data analyses for the other gauges in this report. This likely has little impact on peak flow interpretations.

Flow may be incomplete at ALERT (a trademark of the National Hydrologic Warning Council) gauges due to the on-demand reporting feature. Lost data may occur during radio outages, telemetry outages, or poor reception. There have been no known cases of this happening but QA/QC is difficult due to the lack of continuous fixed-interval reporting.

Flow data is incomplete for Spruce Wash gauges following the 2019 Museum Fire. Debris has truncated the peak flow at both the Mount Elden Road and Linda Vista gauges during events.

Crest gauge reporting may have errors due to tilt in gauge stadia, debris formation on the gauge, or change in gauge vertical position when gauges are maintained or replaced.

Interpretations of trends and flood frequency may be erroneous based on record dry years in 2019 and 2020 and by changing forest conditions caused by forest thinning, forest fire, and continued development.

Precipitation data is intentionally minimized in this report. Tipping bucket rain gauges are precise and accurate for rainfall only events but are not designed for snow, sleet, or ice events.

Please report any concerns or suggestions about data quality or interpretations to Edward.schenk@flagstaffaz.gov, we will attempt to improve later editions of this data series.

Stream gauge locations

This report utilizes 57 local rain and stream gauges instrumented by the City of Flagstaff, Coconino County, National Park Service, Salt River Project, or Northern Arizona University (Figures 6, 7, 8, 9 and 10). Descriptions of the gauge locations and type of gauge is included in the Appendix A due to the number of gauges and locations. A list of gauges and locations is included in Table 2. Stage-discharge rating tables were created for all city, SRP, NAU, and USGS streamgauges. The methods are provided in the rating table appendices but were generally based on culvert modeling software or HEC RAS. Direct stage discharge measurements were not possible due to the ephemeral nature of the Flagstaff streams. More information, especially on stream conditions, can also be provided by the City of Flagstaff Stormwater Section or in various reports (e.g. Natural Channel Design 2018; 2020).

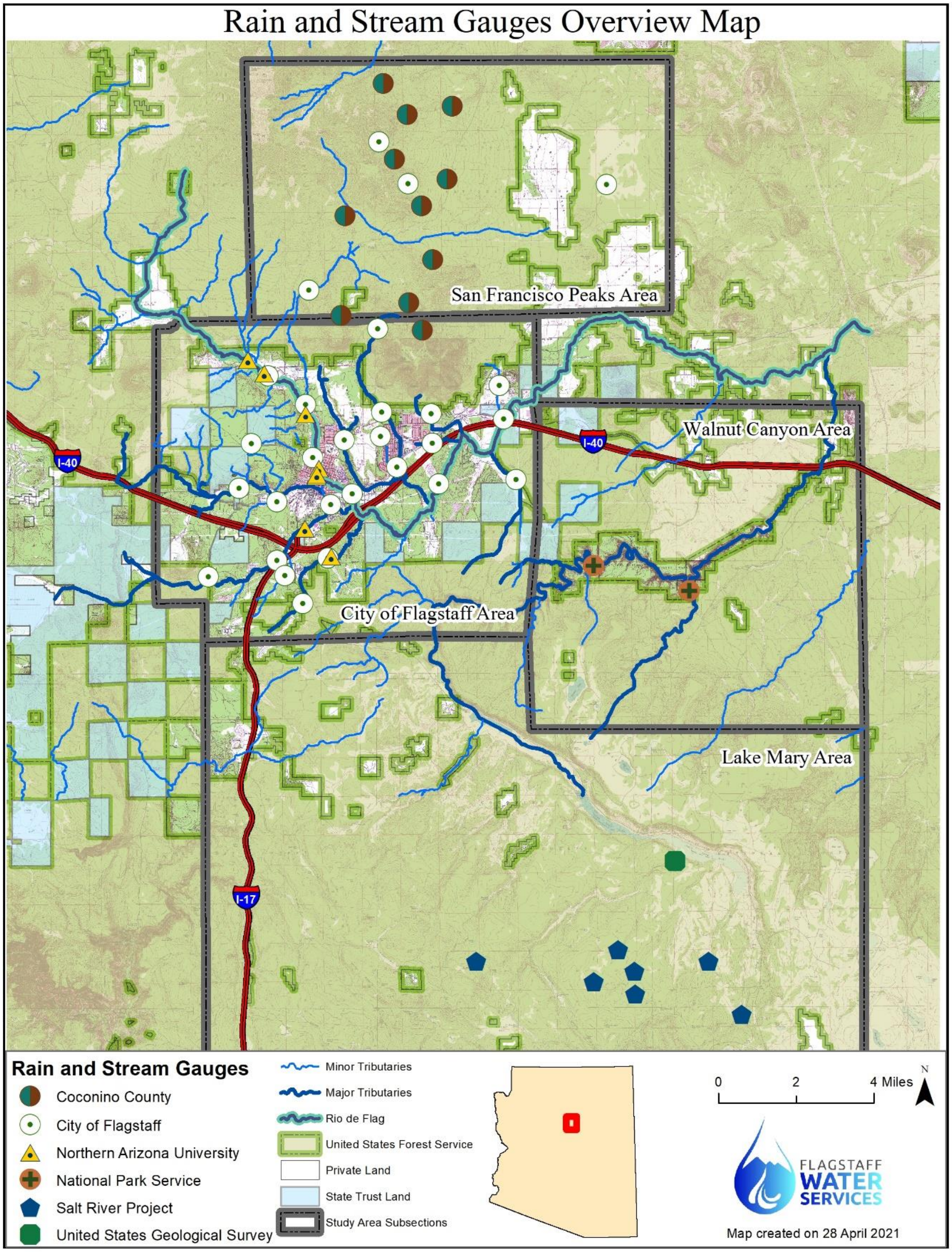

Figure 6. All stream and rain gauges included in this report. Grey boxes indicate detail maps provided elsewhere in this report.

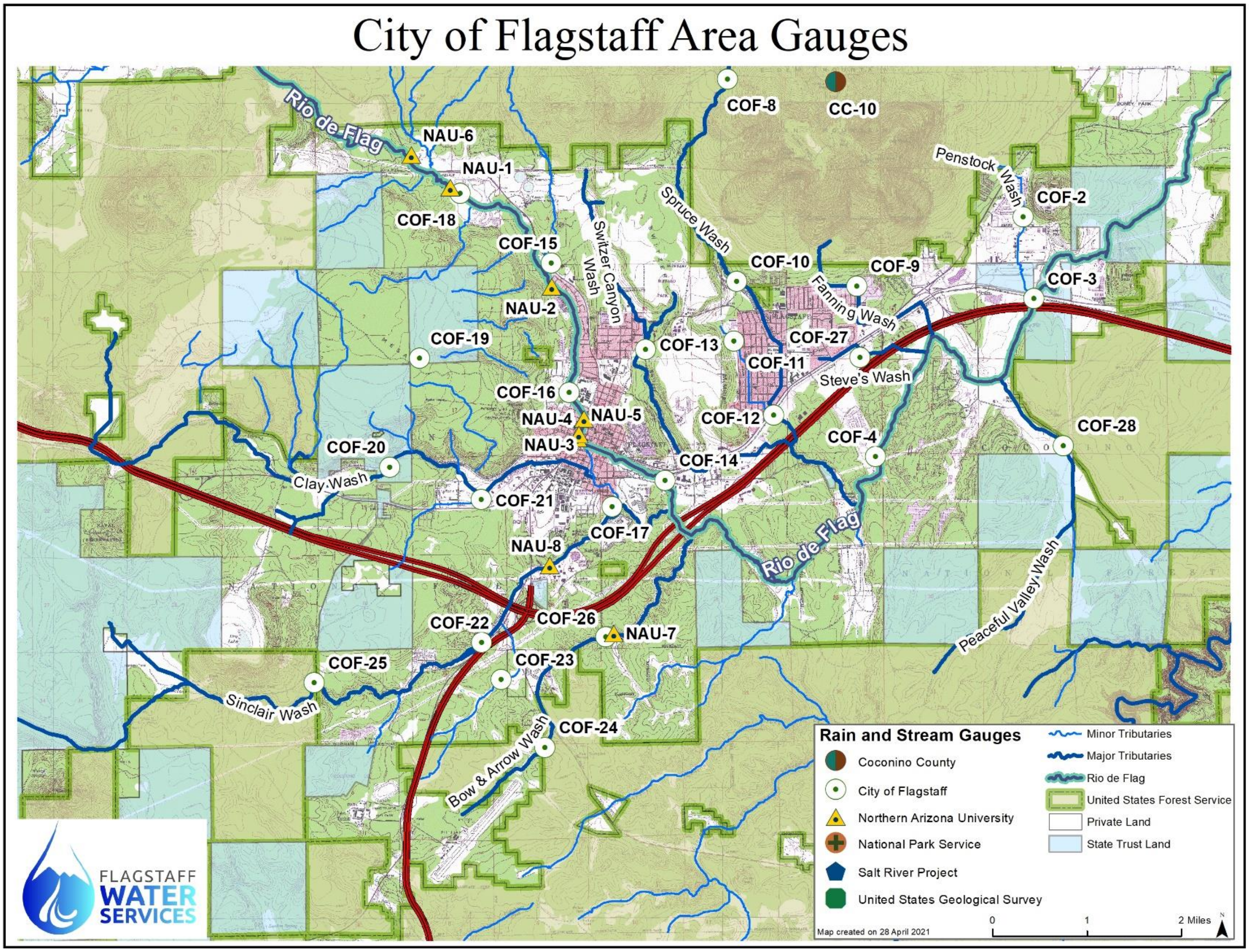

Figure 7. Rain and stream gauges in the City of Flagstaff vicinity.

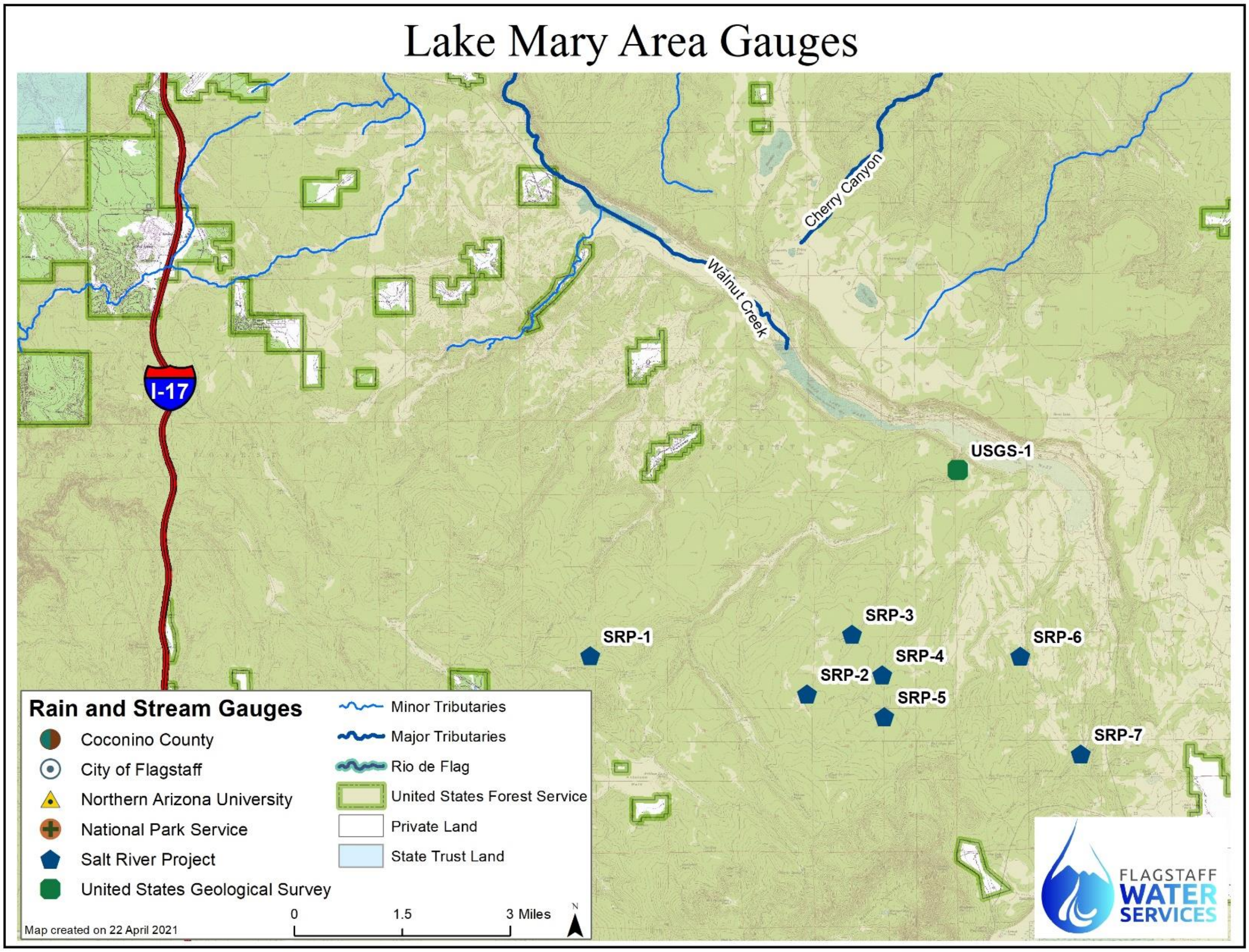

Figure 8. Stream gauges in the southern portion of the study area in the vicinity of Lake Mary (Walnut Creek watershed).

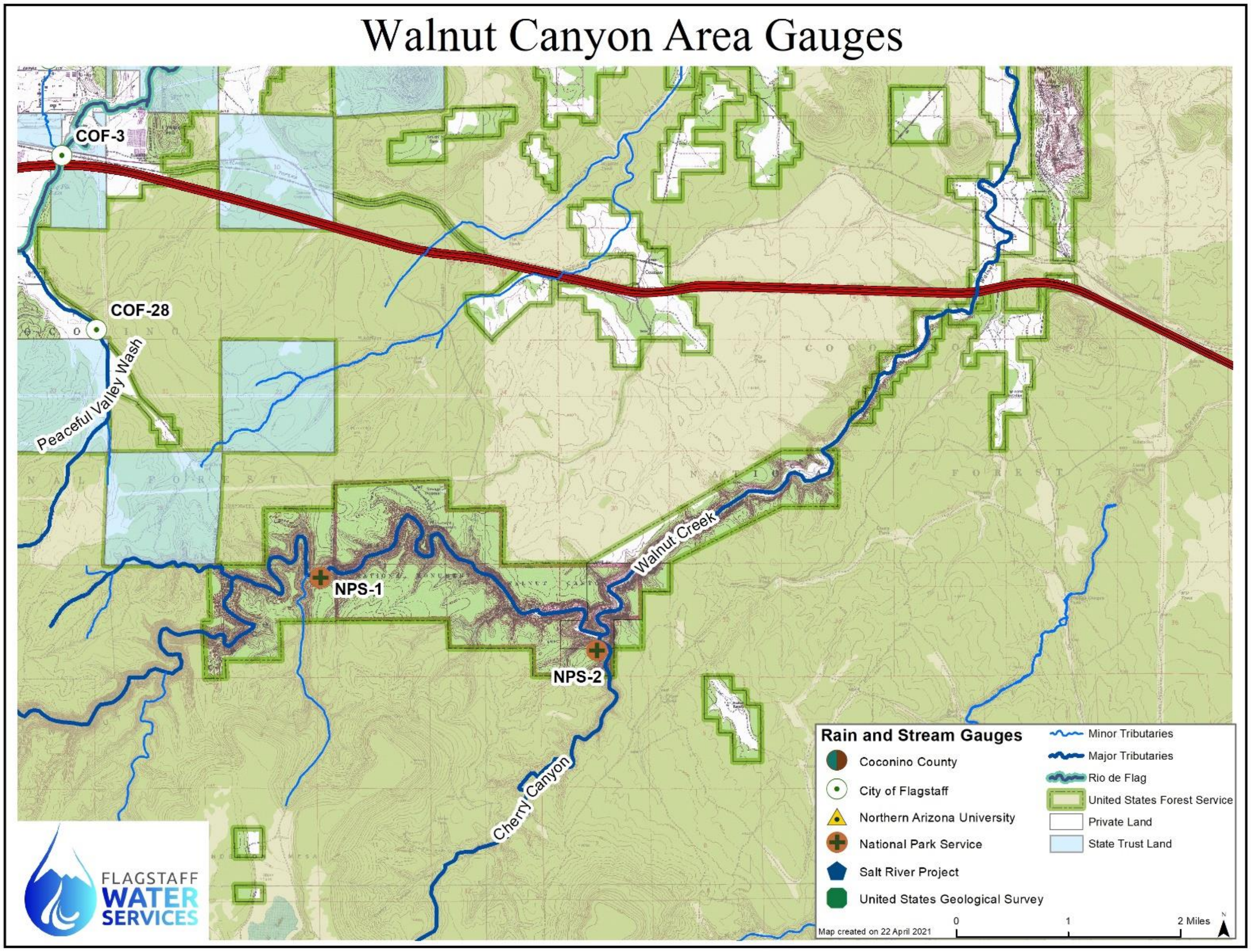

Figure 9. Walnut Canyon area gauges (Walnut Creek watershed southeast of Flagstaff, AZ).

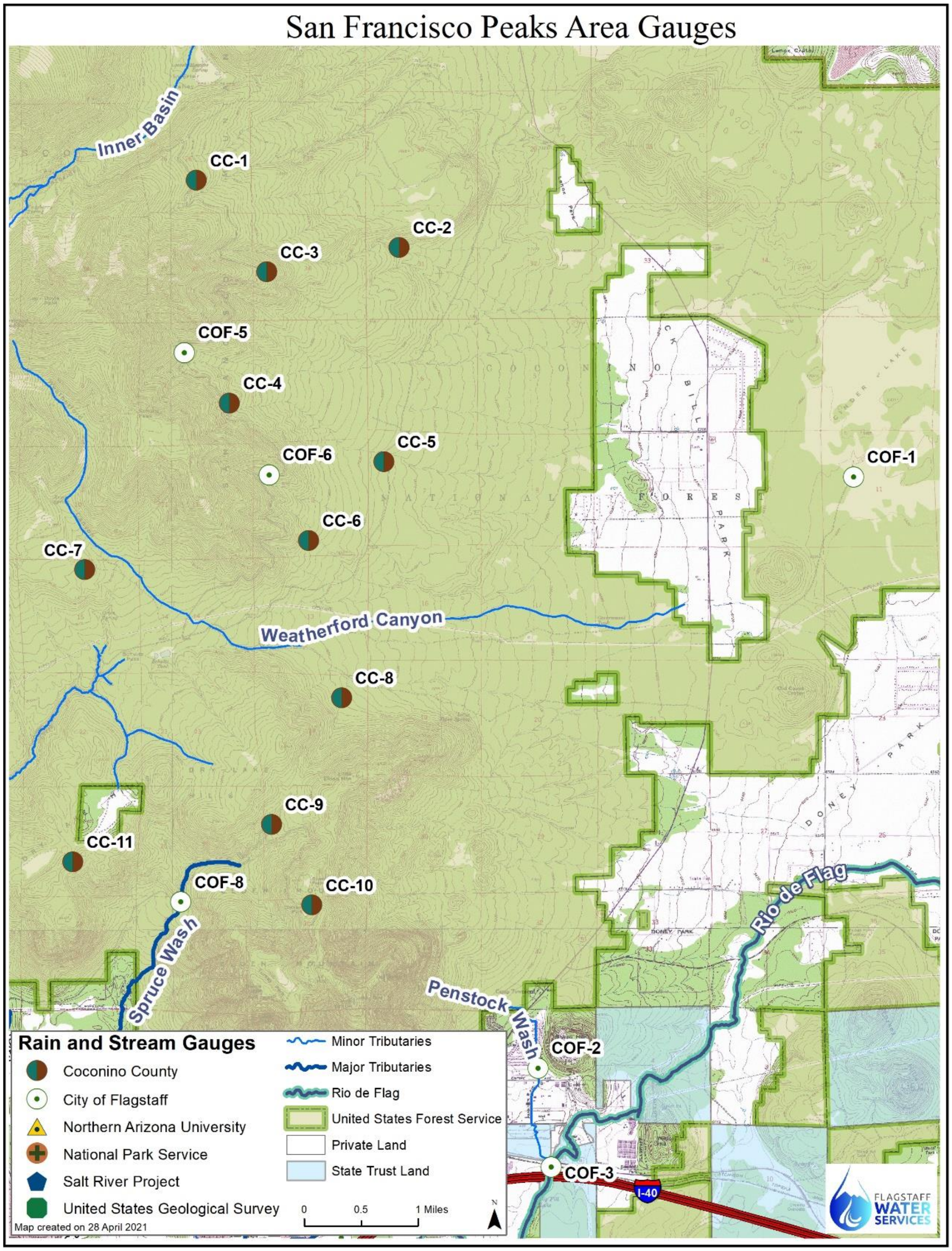

Figure 10. San Francisco Peaks area gauges, north of Flagstaff, AZ. All gauges are in the Rio de Flag watershed though many are in non-contributing areas intended to monitor the 2010 Schultz Fire burn area.

Table 2. List of rain and stream gauges including common name and location.

Heading acronyms:

CC	Coconino County	SRP	Salt River Project
COF	City of Flagstaff	USGS	United States Geological Survey
NAU	NAU Crest	NPS	National Park Service

Coordinate System:NAD_1983_ State Plane Arizona Central

Site	Name	Longitude	Latitude	Flow data Start date	End date	Years
COF-1	Flagstaff Landfill	-111.520	35.307			
COF-2	Penstock Wash	-111.569	35.232	2020	2020	1
COF-3	Rio de Flag at Flagstaff Mall	-111.567	35.220	2020	2020	1
COF-4	Rio de Flag at Foxglenn Park	-111.597	35.196	2011	2020	10
COF-5	Waterline Road #2.5	-111.624	35.323			
COF-6	Waterline Road #3.5 (Siesta)	-111.611	35.308			
COF-7	Schultz Creek Upper Dry Lakes	-111.656	35.268	2018	2020	3
COF-8	Spruce Wash Upper Dry Lakes	-111.624	35.254	2018	2020	3
COF-9	Fanning Wash near Linda Vista	-111.600	35.222	2019	2020	2
COF-10	Spruce Wash near Linda Vista	-111.623	35.222	2017	2020	4
COF-11	West Wash	-111.623	35.213	2020	2020	1
COF-12	Spruce Wash at Route 66	-111.616	35.202	2020	2020	1
COF-13	Switzer Wash	-111.640	35.212	2020	2020	1
COF-14	Rio de Flag at Butler	-111.636	35.192	2020	2020	1
COF-15	Schultz Creek near Highway 180	-111.657	35.225	2017	2020	4
COF-16	Frances Short Pond	-111.654	35.206			
COF-17	Rio de Flag at Sinclair Wash	-111.646	35.188	2020	2020	1
COF-18	Rio de Flag: Peak View Street	-111.674	35.236	2008	2020	13
COF-19	Observatory Mesa	-111.682	35.211			
COF-20	Clay Wash	-111.688	35.194	2016	2020	5
COF-21	South Fork Clay Wash near Kaibab	-111.671	35.189	2019	2020	2
COF-22	Sinclair Wash near University Heights	-111.671	35.167	2019	2020	2
COF-23	Ponderosa Wash	-111.667	35.162	2020	2020	1
COF-24	Bow and Arrow: Airport Detention Basin	-111.659	35.151	2008	2020	13
COF-25	Sinclair Wash: Mt Dell Detention Basin	-111.702	35.161	2020	2020	1
COF-26	Bow and Arrow Wash at Lone Tree	-111.647	35.168	2020	2020	1
COF-27	Steve’s Wash at Industrial	-111.600	35.211	2020	2020	1
COF-28	Peaceful Valley Wash near Old Walnut Canyon	-111.562	35.197	2020	2020	1
CC-1	Waterline Road #1 (Lenox - Wupatki Trails)	-111.622	35.345			
CC-2	Schultz Basin 4 (Thames - Brandis)	-111.590	35.337			
CC-3	Waterline Road #2 (Thames / Peaceful Way)	-111.611	35.334			
CC-4	Waterline Rd #3 (Upper Campbell / Copeland)	-111.617	35.317			
CC-5	Schultz Basin 7 (Upper Campbell)	-111.593	35.309			
CC-6	Schultz Basin 9 (Paintbrush - Siesta)	-111.604	35.299			
CC-7	Waterline Rd #4 (Government Tank)	-111.639	35.296			

Table 2 continued				Flow data		
Site	Name	Longitude	Latitude	Start date	End date	Years
CC-8	Offenhouser	-111.599	35.279			
CC-9	Museum Fire North	-111.610	35.263			
CC-10	Museum Fire East	-111.604	35.253			
CC-11	Museum Fire West	-111.641	35.259			
NAU-1	Rio de Flag at Boldt	-111.676	35.237	2012	2020	9
NAU-2	Rio De Flag at Crescent	-111.657	35.222	2011	2019	9
NAU-3	Rio De Flag at Cherry	-111.651	35.201	2012	2020	9
NAU-4	Schultz Creek at 180	-111.653	35.199	2011	2020	10
NAU-5	Rio De Flag at Benton	-111.652	35.199	2011	2020	10
NAU-6	Rio De Flag at Hidden Hollow	-111.684	35.242	2011	2020	10
NAU-7	Bow And Arrow Wash at Connell	-111.646	35.169	2011	2020	10
NAU-8	Sinclair Wash at Knoles	-111.658	35.179	2011	2020	10
NPS-1	Walnut Creek 0202	-111.527	35.165	2012	2019	8
NPS-2	Cherry Creek 0102	-111.483	35.155	2011	2019	9
SRP-1	LM-2	-111.581	35.017	2015	2020	6
SRP-2	LM-3U	-111.527	35.010	2015	2020	6
SRP-3	LM-3L	-111.516	35.022	2015	2020	6
SRP-4	LM-1	-111.509	35.013	2015	2020	6
SRP-5	LM-2B	-111.508	35.005	2017	2020	4
SRP-6	LM-4	-111.475	35.017	2015	2020	6
SRP-7	LM-5	-111.460	34.997	2015	2020	6
USGS-1	Newman Canyon - Lake Mary Gauge	-111.490	35.055	2014	2019	6

Stream Peak Flows, 2008-2019

The last report of peak flows in the Flagstaff area was the 1988 USGS report on flood hydrology (Hill et al. 1988). The USGS report utilized crest gauge peak flow data collected along the Rio de Flag and major tributaries between the late 1950s and early 1980s, depending on gauge. The purpose of this current technical report is to build on that original study using peak flow data from a variety of Flagstaff area gauges between 2008 and 2019. Many of these gauges are still operating at the time of this writing. It is the hope of the author that continued data collection will lead to improvements in flood frequency understanding in the area and that this current report will serve as a template for refinements in the next decade.

Fifty seven gauges are listed in Table 3, of that list about half are rain only gauges. Of the remaining half many have only been in operation for a short time (Table 3). The following tables show the peak flow for individual gauges grouped by flood ALERT telemetry gauges (pressure transducer gauges with on-demand reporting), NAU crest gauges (monthly measured manually, excluding months of snow and ice effects), SRP-COF Flowtography ™ telemetry gauges, NPS non-telemetry gauges (pressure transducers manually downloaded), and a USGS streamgage (bubbler telemetry gauge).

Flood ALERT gauge data

Data at Spruce Wash for 2019 and 2020 may have errors due to the pressure transducer being buried during post-fire flow events. Flow at Spruce Wash – Upper Dry Lakes was over 200 CFS in 2019 and 2020 (measured by HEC-RAS / high water marks).

Spruce Wash, Upper Dry Lakes		**Stage (Ft)**	**Flow (CFS)**
2018	7/16/2018 18:11	0.18	1.0
2019	3/9/2019 14:33	2.17	12.1
2020	10/25/2020 4:04	1.22	6.8

Rio de Flag at Foxglenn		**Stage (Ft)**	**Flow (CFS)**
2012		0.23	32
2013		11.61	4500
2014		10.65	4000
2015		1.4	194
2018		2.47	342
2019		2.06	285
2020		1.43	198

Data at Spruce Wash for 2019 and 2020 may have errors due to the pressure transducer being buried during post-fire flow events.

Spruce Wash at Linda Vista		**Stage (Ft)**	**Flow (CFS)**
2017	12/19/2017 23:44	0.09	0.8
2018	6/14/2018 17:58	0.9	7.5
2019	3/8/2019 17:44	1.83	15.3
2020	8/13/2020 14:47	1.55	12.9

Fanning Wash at Linda Vista		**Stage (Ft)**	**Flow (CFS)**
2019	8/15/2019	1.24	35.0
2020	4/24/2020	1.52	42.9

South Fork Clay Wash		Stage (Ft)	Flow (CFS)
2019	10/13/2019 23:02	2.14	70.2
2020	8/21/2020 20:10	1.58	51.8

Sinclair Wash at U Heights		Stage (Ft)	Flow (CFS)
2019	11/19/2019 12:10	1.42	43.7
2020	8/13/2020 8:53	0.57	17.5

* Likely erroneous data in 2020			
Schultz Creek at Hwy 180		**Stage (Ft)**	**Flow (CFS)**
2017	-	0	0
2018	-	0	0
2019	12/25/2019 16:26	1.26	48.5
2020	2/21/2020 9:30	3.57	137

Schultz at Upper Dry Lakes		Stage (Ft)	Flow (CFS)
2018	7/13/2018 11:37	0.17	1.4
2019	7/25/2019 15:48	1.5	12.5
2020	3/24/2020 1:28	1.35	11.2

Clay Wash at Detention Basin		Stage (Ft)	Flow (CFS)
2016	-	0	0
2017	-	0	0
2018	8/14/2018 15:54	0.4	NA
2019	2/28/2019 20:30	0.2	NA
2020	-	0	0

Bow and Arrow at Airport		Stage (Ft)	Flow (CFS)
2008	12/29/2008 13:14	0.05	0.4
2009	1/23/2009 20:44	0.63	5.0
2010	8/23/2010 13:11	1.67	13.4
2011	2/9/2011 16:27	3.01	24.1
2012	8/6/2012 13:27	0.11	0.9
2013	7/10/2013 16:11	1.6	12.8
2014	7/4/2014 20:37	0.52	4.2
2015	3/2/2015 10:57	1.15	9.2
2016	8/2/2016 13:32	1.87	15.0
2017	1/7/2017 6:49	9.84	78.7
2018	8/14/2018 16:30	2.3	18.4
2019	3/14/2019 8:25	9.82	78.6
2020	3/13/2020 23:41	1.57	12.6

	Stage adjusted up 0.3 feet for PT location		
Rio de Flag at Peak View		**Stage (ft)**	**Flow (CFS)**
2008	9/17/2008 16:30	0.66	12.7
2009	2/15/2009 13:20	0.57	11.0
2010	4/5/2010 17:25	1.2	23.1
2011	4/8/2011 16:05	0.7	13.5
2012	5/21/2012 15:50	0.6	11.5
2013	9/11/2013 7:02	0.97	18.7
2014	7/22/2014 10:25	0.68	13.1
2015	8/16/2015 10:16	1.02	19.6
2016	6/29/2016 13:45	0.96	18.5
2017	4/21/2017 9:13	0.93	17.9
2018	7/19/2018 13:13	1.3	25.0
2019	3/3/2019 18:52	1.84	35.4
2020	3/21/2020 23:33	0.95	18.3

NAU crest gauge peak flow data

Rio de Flag at Hidden Hollow		**Stage (Ft)**	**Flow (CFS)**
2011		0.0	0.0
2012		0.0	0.4
2013	September	0.4	10.8
2014	September	0.2	4.9
2015	February	0.8	21.0
2016	June	0.2	5.2
2017	Jan-March	1.9	53.2
2018	July	0.9	23.9
2019	February	1.7	46.5
2020	March	0.5	12.9

Rio de Flag at Boldt Dr.		**Stage (Ft)**	**Flow (CFS)**
2012		0.0	0.0
2013	September	0.3	31.4
2014		0.0	0.0
2015	September	0.0	0.7
2016	February	0.1	12.0
2017	March	0.9	102.5
2018	July	0.1	13.1
2019	March	0.7	84.9
2020	March	0.2	19.8

Schultz Creek at 180		Stage (Ft)	Flow (CFS)
2011	July	0.2	6.9
2012	August	0.1	4.9
2013	July	0.3	10.2
2014	September	0.2	7.6
2015	September	0.3	9.9
2016	July	0.3	9.8
2017	March	0.8	29.6
2018	August	0.2	6.7
2019	Jan-March	0.3	11.3
2020		0.0	0.0

Rio de Flag at Crescent		Stage (Ft)	Flow (CFS)
2011		0.0	0.0
2012		0.0	0.0
2013	August	0.2	11.3
2014		0.0	0.0
2015	March	0.1	5.7
2016		0.0	0.0
2017	March	0.8	38.6
2018	August	0.0	1.5
2019	Jan-March	0.4	20.3
2020	No readings taken		

Rio de Flag at Cherry St.		Stage (Ft)	Flow (CFS)
2012	August	1.5	91
2013	July	2.6	163
2014	July	1.5	92
2015	June	1.3	78
2016	August	2.6	161
2017	July	2.1	127
2018	Jan-March	0.8	50
2019	Jan-March	1.3	80
2020	August	1.3	78

Rio de Flag at Benton		Stage (Ft)	Flow (CFS)
2011	August	3.6	62
2012	August	2.4	42
2013	July	4.4	76
2014	July	3.2	55
2015	June	2.3	40
2016	June	3.8	65
2017	August	3.1	54
2018	July	3.9	67
2019	August	2.0	34
2020	August	3.0	51

Sinclair Wash at Knoles Dr.		Stage (Ft)	Flow (CFS)
2011	July	3.1	56
2012	August	3.3	60
2013	September	4.3	77
2014	September	3.1	56
2015	August	3.0	55
2016	July	3.6	65
2017	August	3.5	63
2018	July	4.1	74
2019	Jan-March	3.0	53
2020	July	2.7	49

Bow & Arrow Wash at Connell		Stage (Ft)	Flow (CFS)
2011	August	1.2	17.9
2012	August	0.8	11.7
2013	September	1.5	22.3
2014	July	1.2	16.7
2015	March	2.5	35.9
2016	August	2.3	33.0
2017	August	1.4	20.6
2018	August	2.2	32.2
2019	March	1.0	14.5
2020	No readings taken		

Upper Lake Mary – SRP and City data

Upper Lake Mary peak flow	Current until 9/8/2020

LM1	**Flow (CFS)**
2015	41.95
2016	65.02
2017	31.81
2018	11.95
2019	80.25
2020	42.68

LM3L	**Flow (CFS)**
2015	0
2016	122.56
2017	134.64
2018	19.78
2019	256.09
2020	90

LM2	**Flow (CFS)**
2015	0
2016	23.95
2017	12.34
2018	0
2019	214.39
2020	0

LM3U	**Flow (CFS)**
2015	69.17
2016	46.93
2017	34.98
2018	4.43
2019	107.61
2020	4.64

LM2B	**Flow (CFS)**
2017	0
2018	1.03
2019	52.13
2020	43.88

LM4	**Flow (CFS)**
data missing	

LM5	**Flow (CFS)**
2015	33.5
2016	24.64
2017	51.31
2018	102.24
2019	299.74
2020	0.2

National Park Service gauge data – peak stage data in centimeters

Cherry Creek	
Date	**Stage (cm)**
2011	3
2012	4
2013	77
2014	88
2015	13
2016	39
2017	102
2018	6
2019	80

Walnut Creek 0202	
Date	**Stage (cm)**
2012	3
2013	82
2014	3
2015	3
2016	3
2017	129
2018	3
2019	126

USGS gauge at Newman Canyon (USGS 09400815)

Year	**Date**	**Flow (CFS)**
2014	8/22/2014	24
2015	3/2/2015	643
2016	11/16/2015	255
2017	2/12/2017	589
2018	8/18/2018	0.36
2019	2/14/2019	2,720

Peak flow analysis (flood frequency analysis)

Gauges can be evaluated for flood frequency using the USGS Bulletin 17B method (IACWD 1982). This method requires 10 years of peak flow data to extrapolate design floods. For some gauges old USGS data (Hill et al. 1988) was included in the analysis (Appendix E). Gauges were evaluated using Bulletin 17B using the Hydrologic Engineering Center Stream Statistical Package 2.2 (HEC-SSP). The results were compared to published FEMA flows provided in the 2010 Flood Insurance Study for Coconino County (FEMA 2010), the National Stream Statistics tool provided in the USGS Streamstats web package (https://streamstats.usgs.gov/ss/, version 4.5.1; Paretti et al. 2014), and a regional curve created by the City of Flagstaff using 40 USGS long term stream gages that are similar to the Flagstaff region. The creation of the regional curve is beyond the scope of this preliminary report but it a simple linear regression based on peak flow and catchment area only (Appendix E).

The results of the HEC-SSP analysis can be found in Table 3. The empirical gauge data indicates a much lower 100 year flood than the other techniques, in some cases orders of magnitude lower. This may partially be attributed to the unique geology, forest density, and climate of Flagstaff but may also be skewed by record dry years in 2019 and 2020. Continued data collection will be needed to not only increase the number of sites that can be analyzed but to also provide more precision and confidence to the results presented in Table 3. Additional flood frequency analyses can also be completed to compare the relatively old Bulletin 17B analysis with more updated techniques (England et al. 2019).

Table 3. Flood frequency for select sites using a variety of methods. FEMA flow is from the 2010 FEMA FIS for Coconino County, NSS is the USGS Streamstats (National Stream Statistics) result, the regional curve is derived from 40 USGS sites, and HEC-SSP is the result from a Bulletin 17B analysis of gauge peak flow data. The HEC-SSP result is based on empirical data while the other methods are purely theoretical.

		100 year (1% probability) flow in CFS			
Site	**Area (sq miles)**	**FEMA flow**	**NSS**	**Regional curve**	**HEC-SSP gauge analysis**
Bow and Arrow Wash at the Airport	0.9	146	741	590	184
Rio de Flag at Hidden Hollow Rd.	31.5	680	1370	1685	644
Rio de Flag at Peak View St.	39.6	1200	1570	1975	54
Rio de Flag at Crescent Ave.	50.3	1300	1810	2358	581
Rio de Flag at Benton Ave	53.1	NA	1870	2459	98
Schultz Creek at Hwy 180	6.1	440	209	776	103
Sinclair Wash at Knoles Dr.	9.5	NA	2010	898	102

FEMA flow = 2010 FEMA Flood Insurance Study for the Coconino County, Arizona

NSS = National Streamflow Statistics, also known as USGS Streamstats. Paretti et al. 2014 for Arizona delineations

Regional Curve = 40 select USGS gauges in high country AZ/NM/CO, linear regression of HEC-SSP gauge data to contributing area only

HEC-SSP gauge analysis = empirical site specific gauge data using the B17 method for determining flood recurrence

Gray shading indicates lowest predicted value for a site.

A separate analysis was completed using paired rainfall runoff data at ALERT gauges that included both rain and stream gauging. Precipitation intensity and totals were compared to the regional rainfall intensity table provided in the City of Flagstaff Stormwater Design Manual (City of Flagstaff 2009; Table 4). Rainfall intensities at a site were then compared to peak flow values during the same day at the site. The results are shown in Table 5. Some caution must be used since the rainfall at a rain gauge may not be representative of the entire gauge watershed. The design rainfall frequency provided in Table 4 may also be outdated, the rainfall modeled is from the older NOAA Atlas 2 standard (Miller et al. 1973). Note the much lower observed stream discharges than modeled using the NSS method. FEMA flows were not used due to the lack of high frequency low intensity flows modeled at the particular sites.

Table 4. Rainfall frequency as displayed in the City of Flagstaff Stormwater Design Manual (2009). Data is interpolated from the older NOAA Atlas 2 rainfall map (Miller et al. 1973).

Duration	Frequency, In Years					
	2	5	10	25	50	100
5-min.	3.96	5.04	5.76	6.84	7.68	8.52
10-min.	3.06	3.90	4.50	5.34	6.00	6.66
15-min.	2.48	3.20	3.48	4.40	4.92	5.48
30-min.	1.58	2.06	2.40	2.86	3.22	3.58
1-hour	0.95	1.25	1.46	1.76	1.98	2.21
2-hour	0.56	0.73	0.85	1.02	1.15	1.28
3-hour	0.41	0.53	0.62	0.74	0.83	0.92
6-hour	0.24	0.31	0.36	0.43	0.48	0.53
12-hour	0.14	0.19	0.21	0.26	0.29	0.32
24-hour	0.08	0.11	0.12	0.15	0.17	0.19

Table 5. Rainfall duration as measured at rain gauge, total rain event, rainfall recurrence interval from NOAA Atlas 2, observed stream stage, discharge, and a comparison with predicted flow from the National Stream Statistics (NSS) tool.

* Stage at COF-18 is adjusted up 0.3 ft due to gauge location

Site	Date	Rain Duration (min.)	Rain total (inches)	Recurrence interval (years)	Observed Peak Stage (feet)	Discharge (CFS)	NSS Discharge (CFS)
COF-4	8/16/2012	33	1.06	2	0	0	339
	7/17/2013	25	0.79	2	0.11	15	339
	8/26/2013	106	1.18	2	0.66	91	339
	8/11/2015	5	0.43	5	0	0	716
COF-18	7/24/2012	5	0.44	5	0.52	10	420
	7/29/2012	9	0.55	2	0.51	10	194
	7/30/2012	15	0.75	2	0.53	10	194
	8/7/2012	28	0.86	2	0.57	11	194
	7/20/2013	28	1.77	50	0.92	18	1240
	7/26/2013	58	1.1	2	0.54	10	194
	8/29/2013	27	0.91	2	0.52	10	194
	7/24/2014	51	1.38	5	0.5	10	420
	7/20/2016	57	1.3	2	0.3	6	194
	8/28/2019	28	1.02	2	0.89	17	194
COF-24	7/26/2010	57	2.12	50	1.63	13	545
	7/30/2010	29	1.97	100	1.4	11	741
	8/7/2010	3	0.47	5	0.39	3	134
	8/23/2010	28	0.98	2	1.67	13	50
	7/29/2012	4	0.48	10	0	0	224
	7/2/2013	56	1.29	5	1.24	10	134
	7/10/2013	29	1.03	5	1.6	13	134
	7/25/2013	48	0.95	2	1.6	13	50
	8/17/2013	5	0.39	2	0	0	50
	7/4/2014	14	0.67	2	0	0	50
	7/4/2014	26	0.86	2	0.52	4	50
	7/7/2014	24	0.99	2	0	0	50
	9/27/2014	4	0.36	2	0	0	50

Flow Duration Analysis

Flow duration varies by stream location, forest streams tend to flow only during spring runoff (snowmelt) while urban streams flow mostly during the summer monsoons. No stream reach recharged by storm water is perennial in the Flagstaff area. More information about flow duration can be determined using the continuous data in the appendices as well as a preliminary analysis of ALERT gauges found in Appendix C. Care should be taken with ALERT gauges as they report only event driven changes in stage and have low resolution for sustained flows.

Rain Data, 2008-2019

Rainfall is collected at the majority of the ALERT gauges mentioned in this report as well as at three SRP gauge locations in the Upper Lake Mary watershed. Rain is measured using a standard tipping bucket method, providing precise measurements of rainfall but lacking in clarity during snow events. Data presented here is informational only and has not been analyzed in great depth. Rain data is available in Appendix C.

Rainfall was evaluated at each of the ALERT stations. Stations with similar date ranges were analyzed in groups. Four gauges had data that spanned the 2008 to 2019 range while the majority had 9 years of data and a few only had three or less years of data. Gauges that were installed in 2019 or more recently were ignored. Results are provided in Figures 11 and 12. The only statistically significant differences was between the relatively wet sites at the Rio de Flag at Peak View, Sinclair Wash at Mount Dell Detention Basin, and two of the Waterline Road sites compared to the relatively dry site at the Cinder Hills Landfill on the east side of the peaks. A similar analysis was done by the Water Resources Section of Flagstaff Water Services for the seven stream and three rain gauges operated by SRP in the Upper Lake Mary watershed. No statistically significant difference was found between the three precipitation gauges ($p > 0.1$; ANOVA and paired t-test; Peter Morrow unpublished data).

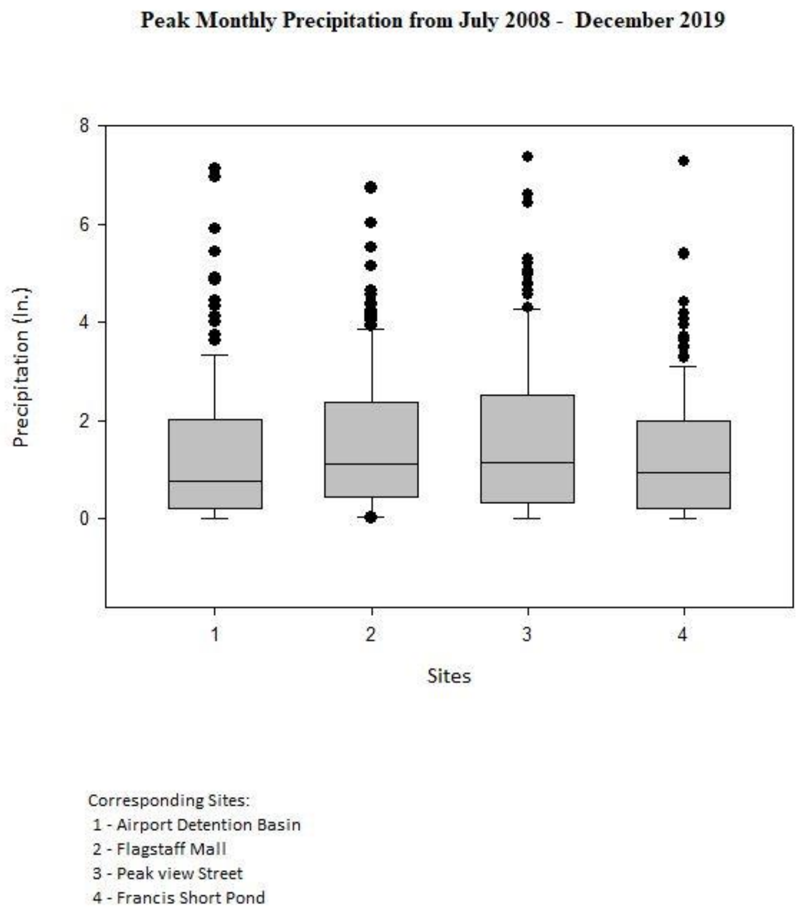

Figure 11. Long term (2008 to 2019) rain datasets. There are no statistically significant differences between the four sites (alpha 0.05; Kruskal Wallace test, Dunn post-hoc test).

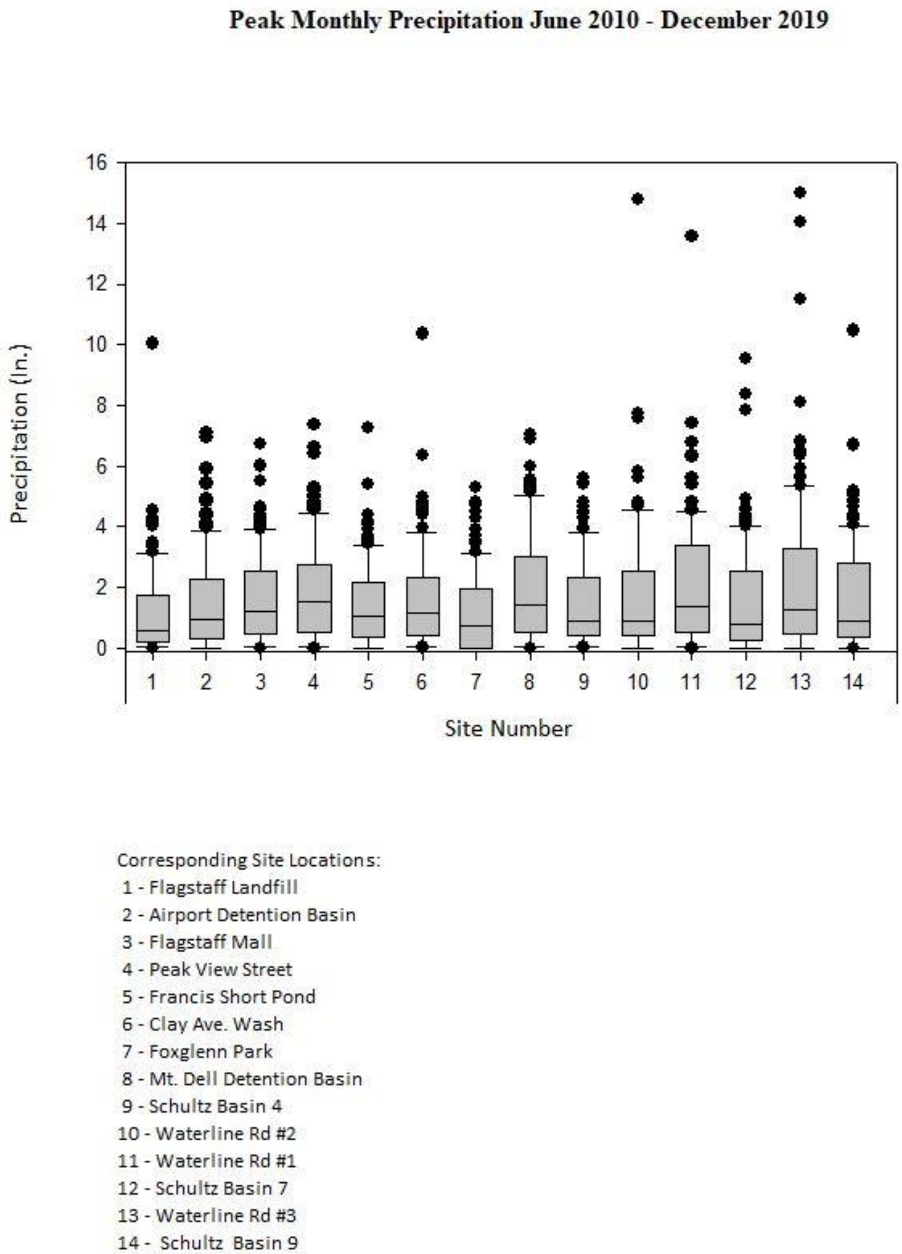

Figure 12. Medium term (9 years data) rain gauge datasets. The only statistically significant relation was between the relatively dry landfill site and the relatively wet Mountain Dell Detention Basin, Waterline Road (#1 & #3) , and Rio de Flag at Peak View ($p < 0.01$; Kruskal Wallace test, Dunn post-hoc test).

Additional Data Needs

This report on preliminary surface water data raises more questions than answers. The following section outlines some of the known data and analysis short comings. Continued peak flow and flood analyses require more years of data, especially on this relatively young gauge network. Continued funding for staffing and maintenance is required to make this gauge network useful not only for real-time flood alerts but for flood design, FEMA floodplain re-maps, and a greater understanding of flood threat, surface water hydrology for ecological needs, and changes in water availability. More data will be needed on forest thinning and climate to provide context for gauge results. An analysis is needed of peak flows and flood risk for the two dominant flood risks: spring rain-on-snow events and summer intense monsoon storms. The two types of storms contribute to different flood regimes with different risk factors. This report provides preliminary data for the Flagstaff area and is not intended to be a long-term reference on the topic. The hope is that future work will help resolve questions on flood risk, flood mitigation, and surface water availability in the Flagstaff region.

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References

Betancourt, J.L., 2004. Advances in arid lands paleobiogeography: the rodent midden record in the Americas. *In* Lomolino, M.V. & L.R. Heaney, eds., Frontiers in biogeography: new directions in the geography of nature. Cambridge University Press.

Blasch, K.W., Hoffmann, J.P., Graser, L.F., Bryson, J.R., and Flint, A.L., 2006. Hydrogeology of the upper and middle Verde River watersheds, central Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5198, 102 p., 3 plates

Bills, D.J., Flynn, M.E., and Monroe, S.A., 2007. Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5222, 101 p., 4 plates.

Bills, D.J., Truini, Margot, Flynn, M.E., Pierce, H.A., Cathings, R.D., and Rymer, M.J., 2000. Hydrogeology of the regional aquifer near Flagstaff, Arizona, 1994–97: U.S. Geological Survey Water-Resources Investigations Report 00-4122, 142 p.

Brown, C.R. and Macy, J.P., 2012. Groundwater, surface-water, and water-chemistry data from the C-aquifer monitoring program, northeastern Arizona, 2005-2011 (ver. 1.1, March 2013): U.S. Geological Survey Open-File Report 2012-1196, 38 p.

City of Flagstaff. 2009. Stormwater Design Manual.

City of Flagstaff 2018. Climate Action and Adaptation Plan.

Cocke, A.E., Fule, P.Z. and Crouse, J.E., 2005. Forest change on a steep mountain gradient after extended fire exclusion: San Francisco Peaks, Arizona, USA. *Journal of Applied Ecology*, *42*(5), pp.814-823.

England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2019. Guidelines for determining flood flow frequency—Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.

Federal Emergency Management Agency (FEMA), 2010. Flood Insurance Study, Coconino County, Arizona and Incorporated Areas, Volume 1 of 2. September 3, 2010.

Fischenich, C. 2001. Stability Thresholds for Stream Restoration Materials. ERDC-TN-EMRRP-SR-29. US Army Engineering Research and Development Center.

Fisher, M.A. and Fulé, P.Z., 2004. Changes in forest vegetation and arbuscular mycorrhizae along a steep elevation gradient in Arizona. *Forest Ecology and Management*, *200*(1-3), pp.293-311.

Goldscheider, N. and Drew, D. eds., 2014. *Methods in Karst hydrogeology: IAH: International Contributions to Hydrogeology*, *26*. Crc Press.

Goodrich, D.C., Kepner, W.G., Levick, L.R. and Wigington Jr, P.J., 2018. Southwestern intermittent and ephemeral stream connectivity. *JAWRA Journal of the American Water Resources Association*, *54*(2), pp.400-422.

Hereford, R. and Amoroso, L., 2020. Historical and prehistorical water levels of Mormon Lake, Arizona as a measure of climate change on the southwest Colorado Plateau, USA. *Quaternary Research*, pp.1-20.

Hill, G.W., Hales, T.A. and Aldridge, B.N., 1988. *Flood hydrology near Flagstaff, Arizona* (Vol. 87, No. 4210). Department of the Interior, US Geological Survey. 20p.

Holm, R.F., 2019. Geology of Flagstaff and Geologic History of Rio de Flag, Northern Arizona with Trail Guides to Geology along Rio de Flag. Arizona Geological Survey Down-To-Earth #23, 70 pages.

IACWD (Interagency Committee on Water Data), 1982. Guidelines for Determining Flood Flow Frequency: Bulletin 17B (Revised and Corrected). Hydrology Subcommittee, Washington, D.C., 28 pp, March.

Jones, C.J., Springer, A.E., Tobin, B.W., Zappitello, S.J. and Jones, N.A., 2018. Characterization and hydraulic behaviour of the complex karst of the Kaibab Plateau and Grand Canyon National Park, USA. *Geological Society, London, Special Publications*, *466*(1), pp.237-260.

Leao, D. and Tecle, A., 2005. A Review of the Hydrology of the Upper Rio de Flag Watershed, Flagstaff, AZ. Arizona-Nevada Academy of Science, April edition. 20p.

Margolis, E.Q., Swetnam, T.W. and Allen, C.D., 2011. Historical stand-replacing fire in upper montane forests of the Madrean Sky Islands and Mogollon Plateau, southwestern USA. *Fire Ecology*, *7*(3), pp.88-107.

Merriam, C.H., 1890. Results of a biological survey of the San Francisco Mountain region and desert of the Little Colorado in Arizona. *North American Fauna*, pp.1-4.

Miller, J.F., Frederick, R.H. and Tracey, R.J., 1973. NOAA Atlas 2: Precipitation-frequency atlas of the western United States. *US Dept. of Commerce, NOAA, National Weather Service, Washington DC, USA.*

Moody, T., Wirtanen, M. and Yard, S.N., 2003. Regional relationships for bankfull stage in natural channels of the arid southwest. *Natural Channel Design Inc., Flagstaff*.

Natural Channel Design, 2018. 2018 Rio de Flag Floodplain Health Assessment. *Natural Channel Design Inc.* technical report to the City of Flagstaff. Flagstaff, AZ. 62 p.

Natural Channel Design, 2020a. Aquifer Recharge Feasibility Study Seepage Evaluation. *Natural Channel Design Inc.* technical report to the City of Flagstaff. Flagstaff, AZ 48 p.

Natural Channel Design, 2020b. Geomorphic Analysis of Flagstaff Streams. *Natural Channel Design Inc.* technical report to the City of Flagstaff. Flagstaff, AZ. 71p.

O'Donnell, F.C., Flatley, W.T., Springer, A.E. and Fulé, P.Z., 2018. Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests. *Ecological Applications*, *28*(6), pp.1459-1472.

Paretti, N.V., Kennedy, J.R., Turney, L.A. and Veilleux, A.G., 2014. *Methods for estimating magnitude and frequency of floods in Arizona, developed with unregulated and rural peak-flow data through water year 2010* (No. 2014-5211). US Geological Survey.

Pool, D.R., Blasch, K.W., Callegary, J.B., Leake, S.A., and Graser, L.F., 2011. Regional groundwater-flow model of the Redwall-Muav, Coconino, and alluvial basin aquifer systems of northern and central Arizona: U.S. Geological Survey Scientific Investigations Report 2010-5180, v. 1.1, 101 p.

Porter, R., Joyal, T., Beers, R., Loverich, J., Laplante, A., Spruell, J., Youberg, A., Schenk, E., Robichaud, P. and Springer, A., 2021. Seismic Monitoring of Post-Wildfire Debris Flows Following the 2019 Museum Fire, Arizona. *Frontiers in Earth Science*, *9,* p.235. doi: 10.3389/feart.2021.649938

Rosgen, D.L. 1996. Applied River Morphology, Second Edition. Wildland Hydrology, Ft. Collins, CO.

Rosgen, D.L., 1997, May. A geomorphological approach to restoration of incised rivers. In *Proceedings of the conference on management of landscapes disturbed by channel incision* (Vol. 1, pp. 12-29). ISBN 0-937099-05-8.

Schenk, E.R.; Jenness, J.S.; and Stevens, L.E. 2018. Springs Distribution, Flow, and Associated Species in the Verde River Basin, Arizona. Springs Stewardship Institute Technical Report to One for the Verde. Museum of Northern Arizona, Flagstaff, AZ. 47p. DOI: 10.13140/RG.2.2.27113.95846

Schenk, E.R., O'Donnell, F., Springer, A.E. and Stevens, L.E., 2020. The impacts of tree stand thinning on groundwater recharge in aridland forests. *Ecological Engineering*, *145*, p.105701.

Vankat, J., 2013. *Vegetation dynamics on the mountains and plateaus of the American Southwest* (Vol. 8). Springer Science & Business Media.

Waring, G.L. 2018. The natural history of the San Francisco Peaks. Self published, Flagstaff, AZ. 210 p.

Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., Baek, S.H., Badger, A.M. and Livneh, B., 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science, 368*(6488), pp.314-318.

Zeedyk, B. and Clothier, V., 2014. *Let the water do the work: induced meandering, an evolving method for restoring*. Chelsea Green Publishing.

Appendix A: Gauge information

The following is a general description of each of the gauge sites.

COF-1, Flagstaff Landfill. This is a rain only gauge installed in 2008 to measure rainfall, wind, and air temperature at the Cinder Hills landfill. The rain data is valuable for monitoring the Doney Park area.

COF-2, Penstock Wash. This is a new flood ALERT gauge installed in 2020 in the urbanized section of Penstock Wash. Penstock Wash starts on the southeast slopes of Mount Elden with a faint channel before becoming channelized within the city. The channel is highly modified and subject to unmitigated urban storm water flows.

COF-3, Rio de Flag at Flagstaff Mall. The site has had a rain gauge for many years but has had flow information added via a pressure transducer in 2020. The gauge is part of the ALERT network. The Rio de Flag is constricted at this site by an under-sized culvert under the BNSF railroad immediately upstream.

COF-4, Rio de Flag at Foxglenn Park. The gauge is located in a channelized section of Rio de Flag near Butler Avenue. The gauge is a pressure transducer connected to the ALERT network. Flows are dominated by unmitigated storm water flows from Spruce and Switzer Washes. The confluence of that combined tributary with the Rio de Flag is approximately a mile upstream of this gauge.

COF-5, Waterline Road #2.5. This rain only gauge is part of the ALERT network for the 2010 Schultz Fire.

COF-6, Waterline Road #3.5. This rain only gauge is part of the ALERT network for the 2010 Schultz Fire.

COF-7, Schultz Creek, Upper Dry Lakes. This pressure transducer ALERT gauge is located near the Schultz Pass road and monitors forest conditions in the Schultz Creek upper watershed.

COF-8, Spruce Wash, Upper Dry Lakes. This pressure transducer ALERT gauge is located near Elden Lookout Road and was originally placed to monitor forest thinning activities. It is currently an important site for monitoring the 2019 Museum Fire burn scar.

COF-9, Fanning Wash near Linda Vista. This new gauge (as of 2019) is meant to mirror the original USGS gauge “Lockett Diversion at Linda Vista”. This gauge is at the upstream end of Linda Vista Drive in the channelized diversion of Fanning Wash.

COF-10, Spruce Wash near Linda Vista. This pressure transducer ALERT gauge is approximately 200 feet upstream of Linda Vista Avenue. The gauge historically monitored a mix of forest and urban conditions in the complacent Spruce Wash. The gauge is now important for monitoring the 2019 Museum Fire burn scar.

COF-11 West Wash. This new (2020) pressure transducer ALERT gauge monitors the small West Wash that drains the east side of McMillan Mesa. The gauge is located approximately 400 feet upstream of Colanthe and Izabel Avenues in a moderately channelized stream reach just upstream of a backwater wetland condition created by sedimentation at the Colanthe Avenue culverts.

COF-12 Spruce Wash at Route 66. This new (2020) pressure transducer ALERT gauge monitors the unmitigated storm water from the Sunnyside neighborhood as well as potential Museum Fire post-fire flows from upstream of the city. The gauge is located at the Flagstaff Urban Trail (FUTs) low water crossing near Route 66.

COF-13 Switzer Wash. This gauge is located near the historical USGS gauge at "Switzer Canyon and Oak St". The gauge is a pressure transducer ALERT gauge monitoring a mix of urban and forest watershed in the relatively small Switzer Canyon upper watershed.

COF-14 Rio de Flag at Butler. This downward looking radar ALERT gauge is placed at the upstream end of the Butler Tunnel along the historic Rio de Flag channel. This channel is currently abandoned but is expected to become the main channel for the Rio de Flag in the next decade as the Rio de Flag Flood Control Project is implemented.

COF-15 Schultz Creek near Highway 180. This pressure transducer ALERT gauge is mirrored by a crest gauge (NAU-4) and also at a historical USGS gauge site. The gauge monitors Schultz Creek including both urban and forest areas.

COF-16 Frances Short Pond. This rain and stage ALERT gauge is used mostly for pond maintenance and operations.

COF-17 Rio de Flag at Sinclair Wash. This new (2020) downward looking gauge is on the Rio de Flag near the confluence with Sinclair Wash. This gauge monitors the existing Rio de Flag but the watershed will change with the Rio de Flag Flood Control Project. After the project the gauge will be monitoring the "Little Rio", a smaller watershed that mostly drains the Southside neighborhood.

COF-18 Rio de Flag at Peak View Street. This pressure transducer ALERT gauge is the oldest ALERT gauge in Flagstaff. Usable data has been collected since 2008 with several years of corrupted data before that date. The gauge is in a channelized section of the Rio de Flag and is expected to be replaced with a downward looking radar unit in the near future.

COF-19 Observatory Mesa. This rain only ALERT gauge is located at a livestock/wildlife tank within the Observatory Mesa Open Space east parcel.

COF-20 Clay Wash. This pressure transducer ALERT gauge is located at the outlet of the Clay Wash Detention Basin, a large Army Corps. dam and flood mitigation reservoir.

COF-21 South Fork Clay Wash near Kaibab Lane. This pressure transducer ALERT gauge is located immediately upstream of Kaibab Lane and monitors a mostly urban tributary of Clay Wash.

COF-22 Sinclair Wash near University Heights. This pressure transducer ALERT gauge was placed in 2019 at the upstream end of the south entrance to University Heights. The gauge monitors a mix of urban and forest environments and is downstream from a recent Coconino County flood control project that channelized and armored a section of Sinclair Wash.

COF-23 Ponderosa Wash. This pressure transducer ALERT gauge monitors the small Ponderosa Wash that starts at the airport and Fort Tuthill County Park. The gauge is at the outlet of the regional detention basin.

COF-24 Bow and Arrow Wash at the Airport Detention Basin. This pressure transducer ALERT gauge is at the most downstream detention basin at the Pulliam Airport. The Bow and Arrow Wash is heavily modified by airport runoff.

COF-25 Sinclair Wash: Mountain Dell Detention Basin. This ALERT gauge was historically a rain only gauge but received a pressure transducer in 2020. The gauge monitors a forested watershed upstream of city and county modifications for flood control.

COF-26 Bow and Arrow Wash at Lone Tree. This pressure transducer ALERT gauge is near a crest gauge (NAU-7) and monitors the heavily modified Bow and Arrow Wash. The watershed has been modified by a large underground stormwater capital improvement in the mid-2010s as well as an older re-alignment of the tributary Ponderosa Wash that removed Ponderosa Wash from this watershed (diverted to Sinclair Wash).

COF-27 Steve’s Wash at Industrial Drive. This pressure transducer is a non-telemetry site maintained by the COF Stormwater team. The wash is a COF administrative floodplain that drains an urban area of east Flagstaff.

COF-28 Peaceful Valley Wash. This pressure transducer is a non-telemetry site maintained by the COF Stormwater team. The wash is primarily forest and meadow with some disturbance from off-road vehicles and hobby farms. The channel is poorly formed and near the backwater effect of “Big Fill Lake”, a backwater impact of an under-sized culvert at BNSF railroad and Rio de Flag.

CC-1 through CC-8. These rain tipping bucket ALERT gauges are maintained by the Coconino County Flood Control District for monitoring the 2010 Schultz Fire burn area for post-fire floods.

CC-9 through CC-11. These rain tipping bucket ALERT gauges are maintained by the Coconino County Flood Control District for monitoring the 2019 Museum Fire burn area for post-fire floods.

NAU-1 Rio de Flag at Boldt Ave. This crest gauge is located near city limits and monitors the mostly forested conditions upstream of the city.

NAU-2 Rio de Flag at Crescent Ave. This crest gauge is located near a historical USGS gauge and monitors the Rio de Flag watershed in both a urban and forest setting.

NAU-3 Rio de Flag at Cherry St. This crest gauge is located in downtown Flagstaff and monitors a mostly urban setting.

NAU-4 Schultz Creek at Highway 180. This crest gauge is located near an ALERT gauge (COF-15) and monitors a mostly undeveloped section of Schultz Creek shortly before the creek meets the Rio de Flag.

NAU-5 Rio de Flag at Benton Ave. This crest gauge is located in downtown Flagstaff and monitors a mostly urban setting.

NAU-6 Rio de Flag at Hidden Hollow. This crest gauge is located near a historical USGS gauge just upstream of city limits. The Rio de Flag watershed is largely forested upstream of this gauge.

NAU-7 Bow and Arrow Wash at Connell Dr. this crest gauge is located immediately downstream of the ALERT gauge (COF-26). The same conditions described for COF-26 apply to this gauge.

NAU-8 Sinclair Wash at Knoles Dr. This crest gauge monitors a largely urbanized environment in the heart of Northern Arizona University.

NPS-1 Walnut Creek 0202. This non-telemetry pressure transducer is maintained by the Southern Colorado Plateau Inventory and Monitoring Network (NPS). The gauge is located near the old 1915 national monument boundary within Walnut Canyon. The upstream watershed is effectively truncated by the Lower Lake Mary Dam.

NPS-2 Cherry Creek 0102. This non-telemetry pressure transducer is maintained by the Southern Colorado Plateau Inventory and Monitoring Network (NPS). The gauge monitors the forested Cherry Creek watershed, one of the larger tributaries to the Walnut Canyon stretch of Walnut Creek.

SRP-1 through SRP-7. These seven Flowtography ™ gauges are funded by the City of Flagstaff but maintained and operated by the Salt River Project. The gauges are installed in sub-watershed of Newman Canyon to monitor runoff to Lake Mary during typical periods as well as after forest thinning.

USGS-1 Newman Canyon gauge. This USGS bubbler system gauge is installed near the mouth of Newman Canyon (confluence with Lake Mary). Funding for the gauge is provided by the City of Flagstaff.

Appendix B: Flow Data

Stream gauge data is included at the CUAHSI HydroShare website:

Schenk, E., E. Schiefer, E. Young, C. Helton (2021). Flagstaff area stream flow and rainfall - 2008-2019. Appendix B, HydroShare, https://doi.org/10.4211/hs.00ff35190ef14046ab9eef41bdef6123

Appendix C: Rain Data

Rain (precipitation) data is provided in a raw format at the CUAHSI HydroShare website:

Schenk, E., E. Schiefer, E. Young, C. Helton (2021). Flagstaff area stream flow and rainfall - 2008-2019. Appendix C, HydroShare, https://doi.org/10.4211/hs.4d2fbd3398fd4dc7858f935106088ae5

Appendix D: Streamflow Rating Tables

Streamflow rating tables and equations are included at the CUAHSI HydroShare website:

Schenk, E. (2021). Flagstaff area stage-discharge rating tables: Appendix D, HydroShare, https://doi.org/10.4211/hs.ca957576f7e947f298f076c21a817385

Appendix E: Peak flow comparisons

Development of a simplified regional curve

A simplified regional flow curve was created using a sub-set of the USGS gauges used for the Arizona-New Mexico regional relationships (Paretti et al. 2014). The USGS sites comparable to the Flagstaff area were selected using a mean elevation greater than 7000 feet and a watershed contributing area no larger than 150 square miles. Period of record was from the gauge start date to end date or 2019 for existing gauges. The simple linear regression is provided below (Figure 11) as is the list of USGS sites selected for this analysis (Table 5).

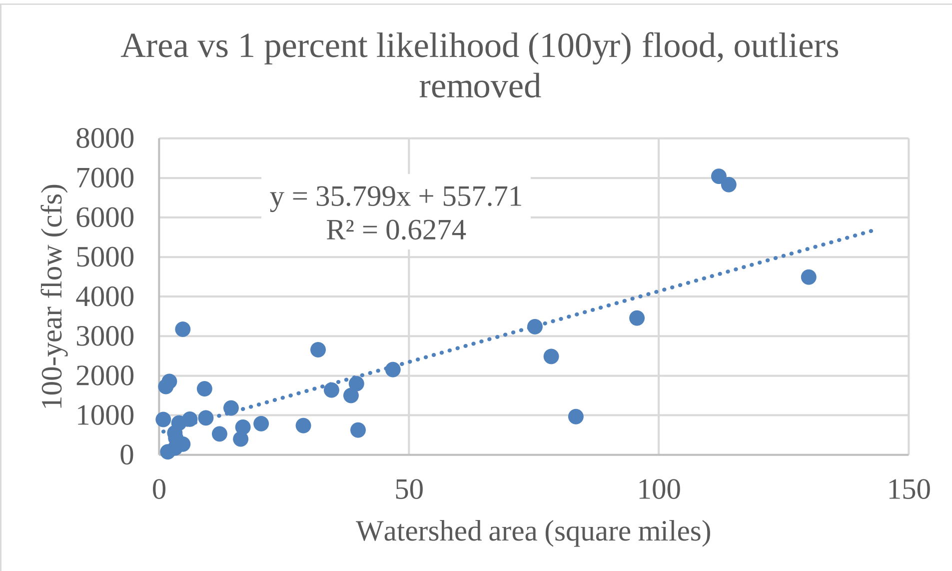


Figure 13. Design flood versus catchment area, three outlier values were removed.

Table 6. USGS gauges selected for the regional curve analysis.

USGS station number	Station name
9356520	Burro Canyon near Lindrith, NM
9365500	La Plata River at Hesperus, CO
9366000	Cherry Creek near Red Mesa, CO
9367840	Yazzie Wash near Mexican Springs, NM
9367860	Chusca Wash near Mexican Springs, NM
9367880	Catron Wash near Mexican Springs, NM
9368500	West Mancos River near Mancos, CO
9369500	Middle Mancos River near Mancos, CO
9383400	Little Colorado River at Greer, AZ
9383500	Nutrioso Creek above Nelson Res near Springerville, AZ
9383600	Fish Creek near Eagar, AZ
9386100	Largo Creek near Quemado, NM
9387050	Galestena Canyon Tributary near Black Rock, NM
9390500	Show Low Creek near Lakeside, AZ
9395400	Milk Ranch Canyon near Ft. Wingate, NM
9400650	Sinclair Wash at Flagstaff, AZ
9400680	Switzer Canyon at Flagstaff, AZ
9400910	Fay Canyon near Flagstaff, AZ
9401210	Slate Mountain Wash near Flagstaff, AZ
9403930	West Cataract Creek near Williams, AZ
9429900	Snow creek near Mogollon, NM
9430300	Copperas Canyon near Pinos Altos, NM
9430600	Mogollon Creek near Cliff, NM
9442630	Mail Hollow near Luna, NM
9442660	Trout Creek at Luna, NM
9442692	Tularosa River above Aragon, NM
9442695	Negro Canyon at Aragon, NM
9442700	Apache Creek near Apache Creek, NM
9489070	North Fork Of East Fork Black River near Alpine, AZ
9489080	Hannagan Creek near Hannagan Meadow, AZ
9489200	Pacheta Creek at Maverick, AZ
9489700	Big Bonito Creek near Fort Apache, AZ
9490800	North Fork White River near Greer, AZ
9491000	North Fork White River near McNary, AZ
9492400	East Fork White River near Fort Apache, AZ

9503800	Volunteer Wash near Bellemont, AZ
9504100	Hull Canyon near Jerome, AZ
9505220	Rocky Gulch near Rimrock, AZ
9505600	Dirty Neck Canyon near Clints Well, AZ
9507700	Webber Creek above West Fork Webber Creek near Pine, AZ

HEC-SSP output results

Bulletin 17B Frequency Analysis

19 Mar 2021   04:09 PM

Analysis Name: Bow and Arrow Wash at Airport Detention Basin

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- End of Input Data ---

<< Low Outlier Test >>

Based on 13 events, 10 percent outlier test deviate K(N) = 2.175

Computed low outlier test value = 0.3603

0 low outlier(s) identified below test value of 0.3603

<< High Outlier Test >>

Based on 13 events, 10 percent outlier test deviate K(N) = 2.175

Computed high outlier test value = 257.7843

0 high outlier(s) identified above test value of 257.7843

--- Final Results ---

<< Plotting Positions >>

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
29 Dec 2008	0.400	1	2017	78.700	5.22
23 Jan 2009	5.000	2	2019	78.600	12.69
23 Aug 2010	13.400	3	2011	24.100	20.15
09 Feb 2011	24.100	4	2018	18.400	27.61
06 Aug 2012	0.900	5	2016	15.000	35.07
10 Jul 2013	12.800	6	2010	13.400	42.54
04 Jul 2014	4.200	7	2013	12.800	50.00
02 Mar 2015	9.200	8	2020	12.600	57.46
02 Aug 2016	15.000	9	2015	9.200	64.93
06 Jan 2017	78.700	10	2009	5.000	72.39
14 Aug 2018	18.400	11	2014	4.200	79.85
14 Mar 2019	78.600	12	2012	0.900	87.31
13 Mar 2020	12.600	13	2009	0.400	94.78

<< Skew Weighting >>

Based on 13 events, mean-square error of station skew = 0.443

Mean-square error of regional skew = -?

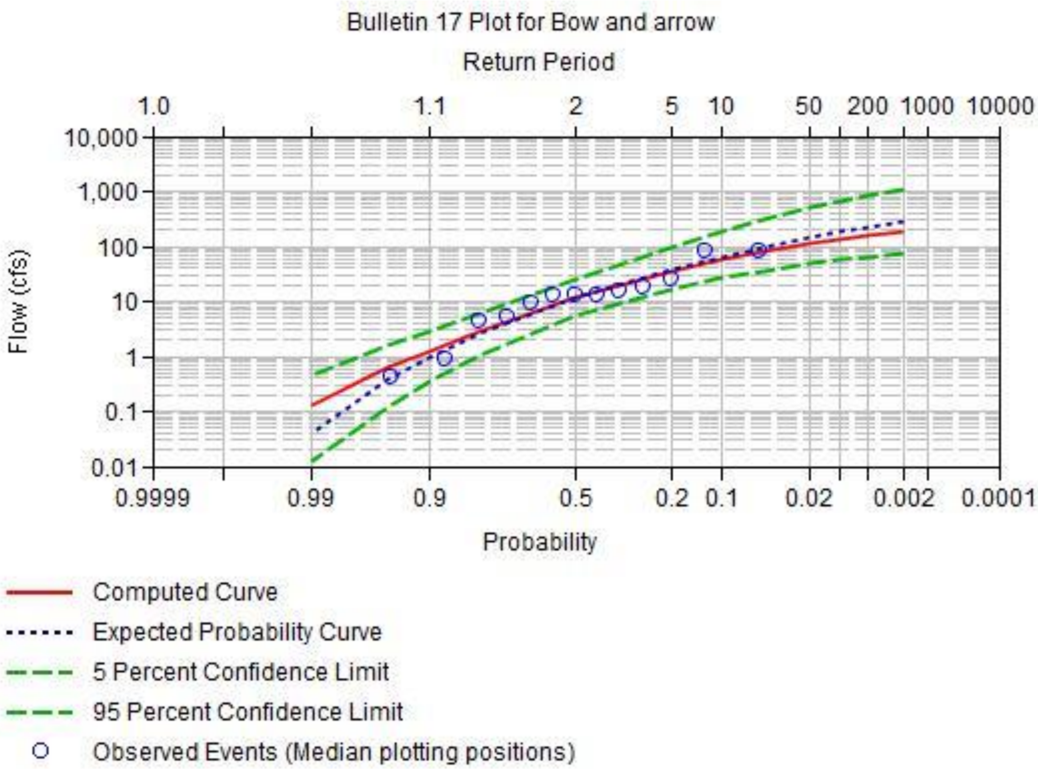
<< Frequency Curve >>

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
194.804	283.451	0.2	1,103.971	73.793
162.746	226.694	0.5	851.775	63.772
137.849	183.998	1.0	671.054	55.675
112.773	143.781	2.0	503.676	47.175
80.149	95.531	5.0	310.572	35.432
56.674	63.904	10.0	191.503	26.309
35.154	37.680	20.0	99.953	17.177
11.655	11.655	50.0	24.909	5.723
2.949	2.613	80.0	5.984	1.075
1.282	0.989	90.0	2.856	0.345
0.606	0.386	95.0	1.529	0.119
0.127	0.040	99.0	0.441	0.012

<< Systematic Statistics >>

Log Transform: FLOW, CFS		Number of Events	
Mean	0.984	Historic Events	0
Standard Dev	0.656	High Outliers	0
Station Skew	-0.762	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.762	Systematic Events	13

--- End of Analytical Frequency Curve ---


Bulletin 17 Plot for Bow and arrow
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
10,000
1,000
100
10
1
0.1
0.01
Flow (cfs)
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Median plotting positions)

Bulletin 17B Frequency Analysis

19 Mar 2021   03:57 PM

Analysis Name: Rio de Flag at Peak View Street

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

----

<< High Outlier Test >>

Based on 13 events, 10 percent outlier test deviate K(N) = 2.175

Computed high outlier test value = 36.1618

0 high outlier(s) identified above test value of 36.1618

<< Low Outlier Test >>

Based on 13 events, 10 percent outlier test deviate K(N) = 2.175

Computed low outlier test value = 8.3235

0 low outlier(s) identified below test value of 8.3235

--- Final Results ---

<< Plotting Positions >>

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
17 Sep 2008	12.700	1	2019	35.400	5.22
15 Feb 2009	11.000	2	2018	25.000	12.69
05 Apr 2010	23.100	3	2010	23.100	20.15
08 Apr 2011	13.500	4	2015	19.600	27.61
21 May 2012	11.500	5	2013	18.700	35.07
11 Sep 2013	18.700	6	2016	18.500	42.54
22 Jul 2014	13.100	7	2020	18.300	50.00
16 Aug 2015	19.600	8	2017	17.900	57.46
29 Jun 2016	18.500	9	2011	13.500	64.93
21 Apr 2017	17.900	10	2014	13.100	72.39
19 Jul 2018	25.000	11	2008	12.700	79.85
03 Mar 2019	35.400	12	2012	11.500	87.31
21 Mar 2020	18.300	13	2009	11.000	94.78

<< Skew Weighting >>

Based on 13 events, mean-square error of station skew = 0.417

Mean-square error of regional skew = -?

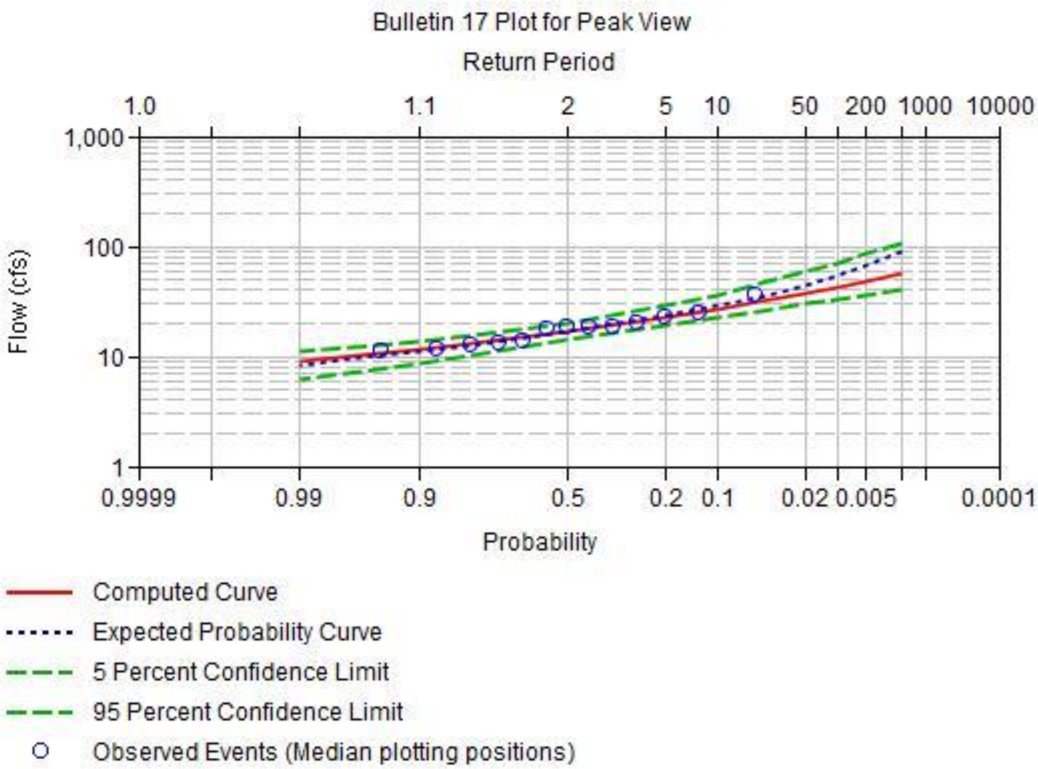
<< Frequency Curve >>

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
56.902	88.294	0.2	106.756	41.015
48.817	66.382	0.5	85.098	36.425
43.219	54.201	1.0	71.122	33.118
38.013	44.575	2.0	58.938	29.925
31.645	34.653	5.0	45.200	25.811
27.134	28.619	10.0	36.341	22.698
22.777	23.364	20.0	28.606	19.435
16.846	16.846	50.0	19.773	14.246
12.991	12.766	80.0	15.246	10.285
11.521	11.162	90.0	13.701	8.731
10.516	10.021	95.0	12.674	7.683
9.022	8.251	99.0	11.170	6.172

<< Systematic Statistics >>

Log Transform: FLOW, CFS		Number of Events	
Mean	1.239	Historic Events	0
Standard Dev	0.147	High Outliers	0
Station Skew	0.525	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	0.525	Systematic Events	13

--- End of Analytical Frequency Curve ---



Bulletin 17 Plot for Peak View
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1,000
100
10
1
Flow (cfs)
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.005
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Median plotting positions)

Bulletin 17B Frequency Analysis

19 Mar 2021 04:34 PM

Analysis Name: Rio de Flag (RDF) at Benton Avenue

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

----

<< Low Outlier Test >>

Based on 10 events, 10 percent outlier test deviate K(N) = 2.036

Computed low outlier test value = 31.5907

0 low outlier(s) identified below test value of 31.5907

<< High Outlier Test >>

Based on 10 events, 10 percent outlier test deviate K(N) = 2.036

Computed high outlier test value = 89.1871

0 high outlier(s) identified above test value of 89.1871

--- Final Results ---

<< Plotting Positions >>

RDF at Benton

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
30 Jun 2011	62.000	1	2013	76.000	6.73
31 Jul 2012	42.000	2	2018	67.000	16.35
30 Jun 2013	76.000	3	2016	65.000	25.96
31 Aug 2014	55.000	4	2011	62.000	35.58
31 Aug 2015	40.000	5	2014	55.000	45.19
30 Jun 2016	65.000	6	2017	54.000	54.81
28 Feb 2017	54.000	7	2020	51.000	64.42
31 Jul 2018	67.000	8	2012	42.000	74.04
31 Dec 2018	34.000	9	2015	40.000	83.65
31 Jan 2020	51.000	10	2019	34.000	93.27

<< Skew Weighting >>

Based on 10 events, mean-square error of station skew = 0.508

Mean-square error of regional skew = -?

<< Frequency Curve >>

RDF at Benton

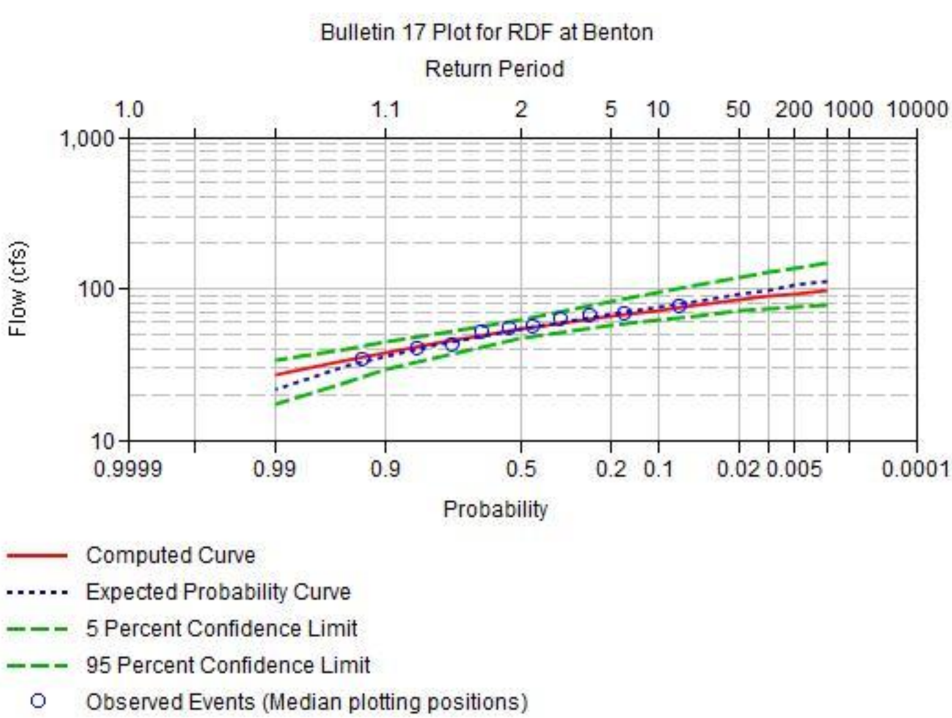
Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
96.573	113.332	0.2	146.177	78.849
92.053	104.294	0.5	135.534	75.966
88.293	97.760	1.0	126.950	73.520
84.168	91.129	2.0	117.823	70.778
77.982	82.173	5.0	104.735	66.527
72.524	75.013	10.0	93.834	62.597
66.017	67.225	20.0	81.727	57.604
54.088	54.088	50.0	62.678	46.986
43.148	42.086	80.0	49.407	35.018
37.920	35.987	90.0	44.093	28.953
33.885	30.975	95.0	40.198	24.369
27.039	21.543	99.0	33.706	17.086

<< Systematic Statistics >>

RDF at Benton

Log Transform: FLOW, CFS		Number of Events	
Mean	1.725	Historic Events	0
Standard Dev	0.111	High Outliers	0
Station Skew	-0.444	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.444	Systematic Events	10

--- End of Analytical Frequency Curve ---



Bulletin 17B Frequency Analysis

22 Mar 2021 10:25 AM

Analysis Name: Rio de Flag at Crescent Ave.

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- Preliminary Results ---

Note: Adopted skew equals station skew and preliminary

frequency statistics are for the conditional frequency curve

because of zero or missing events.

Warning: Number of zero/missing values and low outliers

is greater than 25% of the systematic record.

<< Frequency Curve >>

RDF at Crescent Ave

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,731.272	---	0.2	10,086.824	603.040
1,066.027	---	0.5	5,240.779	406.709
717.595	---	1.0	3,078.257	294.213
467.736	---	2.0	1,736.786	206.659
248.303	---	5.0	750.908	121.529
142.696	---	10.0	365.018	75.459
73.764	---	20.0	158.317	41.764
21.578	---	50.0	37.821	12.251
6.588	---	80.0	11.651	3.056
3.603	---	90.0	6.781	1.424
2.208	---	95.0	4.443	0.754
0.900	---	99.0	2.094	0.230

<< Conditional Statistics >>

RDF at Crescent Ave

Log Transform: FLOW, CFS		Number of Events	
Mean	1.347	Historic Events	0
Standard Dev	0.624	High Outliers	0
Station Skew	0.126	Low Outliers	0
Regional Skew	---	Zero Events	8
Weighted Skew	---	Missing Events	0
Adopted Skew	0.126	Systematic Events	27

<< Frequency Curve >>

RDF at Crescent Ave

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,444.981	---	0.2	---	---
875.752	---	0.5	---	---
580.603	---	1.0	---	---
370.872	---	2.0	---	---
189.614	---	5.0	---	---
104.040	---	10.0	---	---
49.420	---	20.0	---	---
9.824	---	50.0	---	---
---	---	80.0	---	---
---	---	90.0	---	---
---	---	95.0	---	---
---	---	99.0	---	---

--- End of Preliminary Results ---

<< Low Outlier Test >>

Based on 19 events, 10 percent outlier test deviate K(N) = 2.361

Computed low outlier test value = 0.7489

0 low outlier(s) identified below test value of 0.7489

Based on statistics after 8 zero events and 0 missing events were deleted.

<< High Outlier Test >>

Based on 19 events, 10 percent outlier test deviate K(N) = 2.361

Computed high outlier test value = 660.4263

0 high outlier(s) identified above test value of 660.4263

Warning: 29 percent of systematic record was truncated for low outliers, zero, or missing values.

Note: Statistics and frequency curve were modified

using conditional probablity adjustment.

--- Final Results ---

<< Plotting Positions >>

RDF at Crescent Ave

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
30 Jun 1956	0.000	1	1982	240.000	2.55
30 Jun 1957	0.000	2	1973	235.000	6.20
30 Jun 1958	56.000	3	1978	128.000	9.85
30 Jun 1959	0.000	4	1980	104.000	13.50
30 Jun 1960	11.000	5	1979	90.000	17.15
30 Jun 1970	10.000	6	1958	56.000	20.80
30 Jun 1971	10.000	7	2017	38.600	24.45
30 Jun 1972	0.000	8	1976	35.000	28.10
30 Jun 1973	235.000	9	2019	20.300	31.75
30 Jun 1974	3.000	10	1981	14.000	35.40
30 Jun 1975	10.000	11	2013	11.300	39.05
30 Jun 1976	35.000	12	1960	11.000	42.70
30 Jun 1977	8.500	13	1975	10.000	46.35
30 Jun 1978	128.000	14	1971	10.000	50.00
30 Jun 1979	90.000	15	1970	10.000	53.65
30 Jun 1980	104.000	16	1977	8.500	57.30
30 Jun 1981	14.000	17	2015	5.700	60.95
30 Jun 1982	240.000	18	1974	3.000	64.60
30 Jun 2011	0.000	19	2018	1.500	68.25
31 Jul 2012	0.000	20	2016	0.000	71.90
30 Jun 2013	11.300	21	2014	0.000	75.55

31 Aug 2014	0.000	22	2012	0.000	79.20	
31 Aug 2015	5.700	23	2011	0.000	82.85	
30 Jun 2016	0.000	24	1972	0.000	86.50	
28 Feb 2017	38.600	25	1959	0.000	90.15	
31 Jul 2018	1.500	26	1957	0.000	93.80	
31 Dec 2018	20.300	27	1956	0.000	97.45	

<< Skew Weighting >>

Based on 27 events, mean-square error of station skew = 0.203

Mean-square error of regional skew = -?

<< Frequency Curve >>

RDF at Crescent Ave

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,369.820	2,896.603	0.2	7,013.312	463.720
860.203	1,533.619	0.5	3,891.088	313.187
580.601	918.850	1.0	2,369.867	224.369
374.263	531.259	2.0	1,365.494	154.192
190.052	237.930	5.0	587.218	85.829
102.090	117.744	10.0	273.646	49.642
46.928	50.616	20.0	107.499	24.517
9.824	9.824	50.0	18.439	5.276
1.855	1.698	80.0	3.541	0.816

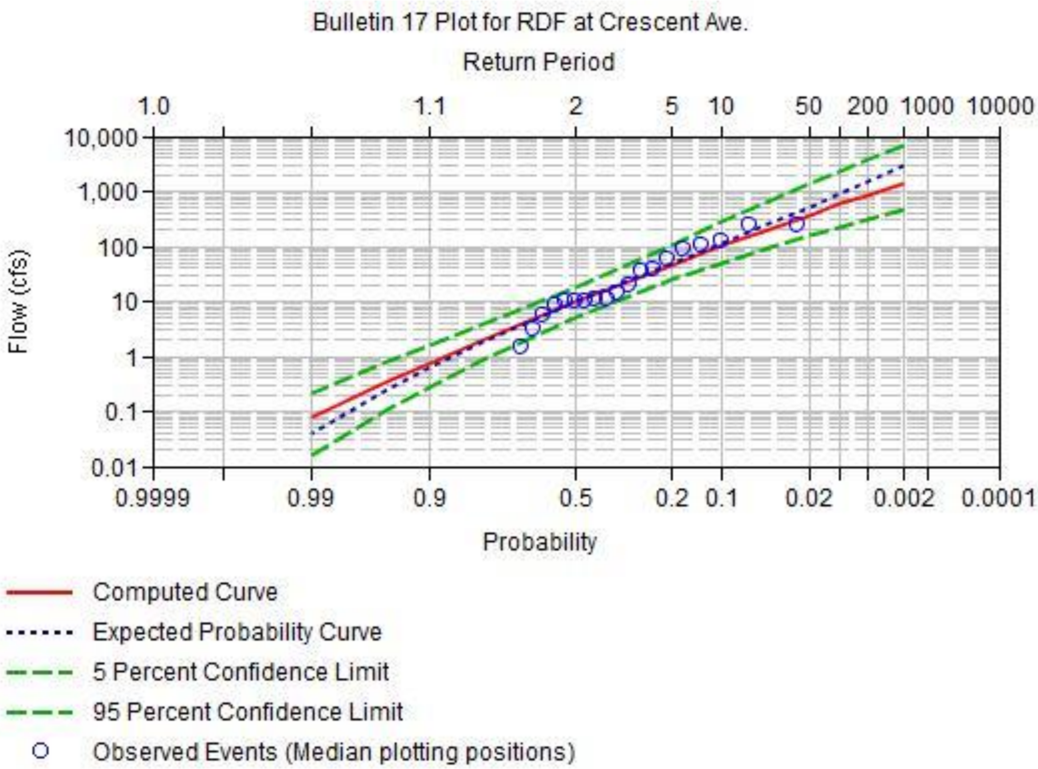
0.745	0.623	90.0	1.547	0.272
0.343	0.256	95.0	0.784	0.104
0.076	0.039	99.0	0.216	0.016

<< Synthetic Statistics >>

RDF at Crescent Ave

Log Transform: FLOW, CFS		Number of Events	
Mean	0.961	Historic Events	0
Standard Dev	0.835	High Outliers	0
Station Skew	-0.227	Low Outliers	0
Regional Skew	---	Zero Events	8
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.227	Systematic Events	27

--- End of Analytical Frequency Curve ---


Bulletin 17 Plot for RDF at Crescent Ave.
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
10,000
1,000
100
10
1
0.1
0.01
Flow (cfs)
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Median plotting positions)

Bulletin 17B Frequency Analysis

22 Mar 2021 09:52 AM

Analysis Name: Rio De Flag at Hidden Hollow

Description: All data, USGS and NAU

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- Preliminary Results ---

Note: Adopted skew equals station skew and preliminary

frequency statistics are for the conditional frequency curve

because of zero or missing events.

<< Frequency Curve >>

RDF at Hidden Hollow

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,260.078	---	0.2	8,806.479	388.797
880.089	---	0.5	5,422.196	289.505
644.380	---	1.0	3,564.612	223.688
450.878	---	2.0	2,210.137	166.055
255.311	---	5.0	1,039.463	102.607
148.856	---	10.0	513.561	64.310
74.092	---	20.0	210.900	34.388
16.950	---	50.0	36.738	8.005
3.199	---	80.0	6.851	1.146
1.236	---	90.0	2.925	0.340
0.540	---	95.0	1.443	0.114
0.103	---	99.0	0.368	0.012

<< Conditional Statistics >>

RDF at Hidden Hollow

Log Transform: FLOW, CFS		Number of Events	
Mean	1.170	Historic Events	0
Standard Dev	0.818	High Outliers	0
Station Skew	-0.433	Low Outliers	0
Regional Skew	---	Zero Events	5
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.433	Systematic Events	23

<< Conditional Probability Adjusted Ordinates >>

<< Frequency Curve >>

RDF at Hidden Hollow

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,148.346	---	0.2	---	---
790.493	---	0.5	---	---
570.137	---	1.0	---	---
391.989	---	2.0	---	---
213.027	---	5.0	---	---
118.353	---	10.0	---	---
54.310	---	20.0	---	---

8.564	---	50.0	---	---
---	---	80.0	---	---
---	---	90.0	---	---
---	---	95.0	---	---
---	---	99.0	---	---

--- End of Preliminary Results ---

<< Low Outlier Test >>

Based on 18 events, 10 percent outlier test deviate K(N) = 2.335

Computed low outlier test value = 0.1825

0 low outlier(s) identified below test value of 0.1825

Based on statistics after 5 zero events and 0 missing events were deleted.

<< High Outlier Test >>

Based on 18 events, 10 percent outlier test deviate K(N) = 2.335

Computed high outlier test value = 1,200.2994

0 high outlier(s) identified above test value of 1,200.2994

Note: Statistics and frequency curve were modified
using conditional probablity adjustment.

--- Final Results ---

<< Plotting Positions >>

RDF at Hidden Hollow

Events Analyzed		Ordered Events			
Day Mon Year	FLOW CFS	Rank	Water Year	FLOW CFS	Median Plot Pos
30 Jun 1970	2.000	1	1973	153.000	2.99
30 Jun 1971	0.000	2	1978	144.000	7.26
30 Jun 1972	11.000	3	1982	133.000	11.54
30 Jun 1973	153.000	4	1980	110.000	15.81
30 Jun 1974	0.000	5	1979	93.000	20.09
30 Jun 1975	0.000	6	2017	53.200	24.36
30 Jun 1976	1.000	7	2019	46.500	28.63
30 Jun 1977	1.000	8	2018	23.900	32.91
30 Jun 1978	144.000	9	2015	21.000	37.18
30 Jun 1979	93.000	10	2020	12.900	41.45
30 Jun 1980	110.000	11	1972	11.000	45.73
30 Jun 1981	0.000	12	2013	10.800	50.00
30 Jun 1982	133.000	13	2016	5.200	54.27
30 Jun 2011	0.000	14	2014	4.900	58.55
31 Jul 2012	0.400	15	1970	2.000	62.82
30 Jun 2013	10.800	16	1977	1.000	67.09
31 Aug 2014	4.900	17	1976	1.000	71.37
31 Aug 2015	21.000	18	2012	0.400	75.64
30 Jun 2016	5.200	19	2011	0.000	79.91
28 Feb 2017	53.200	20	1981	0.000	84.19
31 Jul 2018	23.900	21	1975	0.000	88.46

31 Dec 2018	46.500	22	1974	0.000	92.74
31 Jan 2020	12.900	23	1971	0.000	97.01

<< Skew Weighting >>

Based on 23 events, mean-square error of station skew = 0.275

Mean-square error of regional skew = -?

<< Frequency Curve >>

RDF at Hidden Hollow

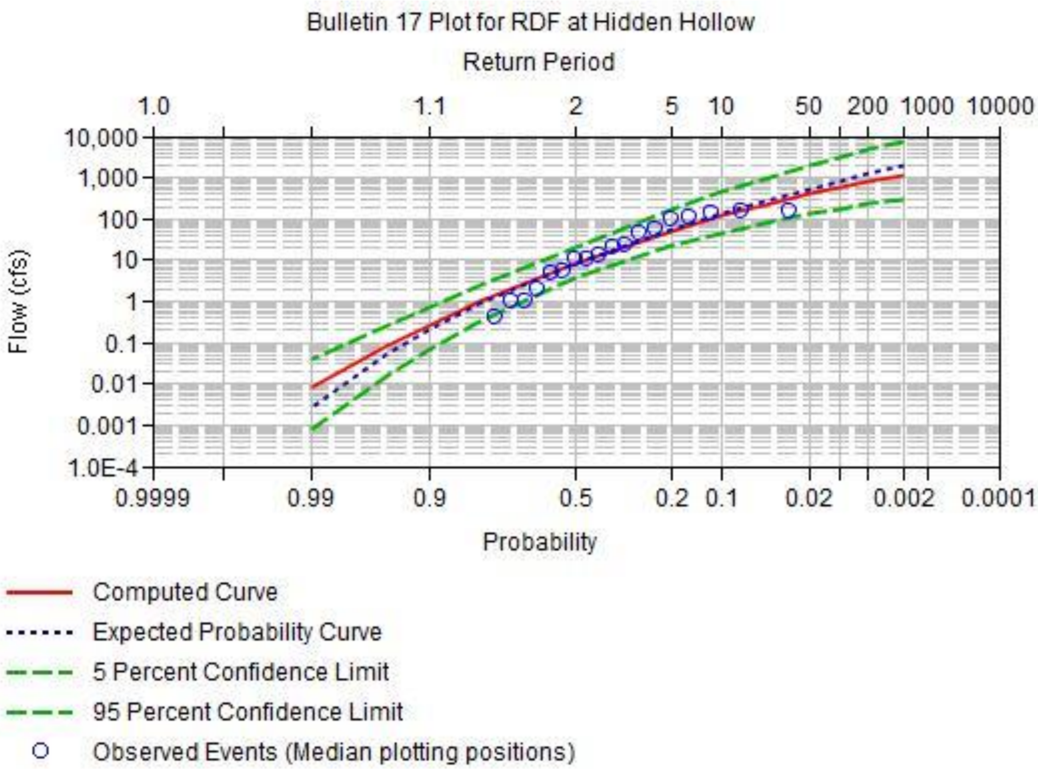
Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
1,105.830	1,890.963	0.2	7,617.883	313.647
780.100	1,229.099	0.5	4,861.917	233.633
570.135	837.429	1.0	3,252.392	179.040
393.706	538.839	2.0	2,027.352	130.479
213.501	265.966	5.0	933.927	76.876
116.778	135.237	10.0	439.091	45.199
51.979	56.498	20.0	162.816	21.720
8.564	8.564	50.0	20.390	3.717
0.988	0.866	80.0	2.339	0.325
0.275	0.209	90.0	0.738	0.068
0.088	0.055	95.0	0.276	0.016
0.009	0.003	99.0	0.039	0.001

<< Synthetic Statistics >>

RDF at Hidden Hollow

Log Transform: FLOW, CFS		Number of Events	
Mean	0.824	Historic Events	0
Standard Dev	1.041	High Outliers	0
Station Skew	-0.632	Low Outliers	0
Regional Skew	---	Zero Events	5
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.632	Systematic Events	23

--- End of Analytical Frequency Curve ---


Bulletin 17 Plot for RDF at Hidden Hollow
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
10,000
1,000
100
10
1
0.1
0.01
0.001
1.0E-4
Flow (cfs)
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.002
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Median plotting positions)

Bulletin 17B Frequency Analysis

22 Mar 2021   10:10 AM

Analysis Name: Schultz Creek at Hwy 180

Description: USGS and NAU datasets

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- Preliminary Results ---

Note: Adopted skew equals station skew and preliminary

frequency statistics are for the conditional frequency curve

because of zero or missing events.

Warning: Number of zero/missing values and low outliers

is greater than 25% of the systematic record.

<< Frequency Curve >>

Schultz Creek at 180

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
183.469	---	0.2	714.209	88.150
133.465	---	0.5	450.648	68.662
103.222	---	1.0	311.240	56.020
78.404	---	2.0	209.932	44.952
52.487	---	5.0	118.919	32.399
37.158	---	10.0	73.591	24.216
24.799	---	20.0	42.735	16.910
11.929	---	50.0	17.553	8.036
6.053	---	80.0	8.892	3.488
4.334	---	90.0	6.607	2.228
3.325	---	95.0	5.272	1.545
2.073	---	99.0	3.575	0.793

<< Conditional Statistics >>

Schultz 180

Log Transform: FLOW, CFS		Number of Events	
Mean	1.093	Historic Events	0
Standard Dev	0.365	High Outliers	0
Station Skew	0.269	Low Outliers	0
Regional Skew	---	Zero Events	7
Weighted Skew	---	Missing Events	0
Adopted Skew	0.269	Systematic Events	21

<< Conditional Probability Adjusted Ordinates >>

<< Frequency Curve >>

Schultz Creek at Hwy 180

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
159.944	---	0.2	---	---
115.133	---	0.5	---	---
88.168	---	1.0	---	---
66.083	---	2.0	---	---
43.180	---	5.0	---	---
29.662	---	10.0	---	---
18.701	---	20.0	---	---

6.903	---	50.0	---	---
---	---	80.0	---	---
---	---	90.0	---	---
---	---	95.0	---	---
---	---	99.0	---	---

--- End of Preliminary Results ---

<< Low Outlier Test >>

Based on 14 events, 10 percent outlier test deviate K(N) = 2.213

Computed low outlier test value = 1.9277

0 low outlier(s) identified below test value of 1.9277

Based on statistics after 7 zero events and 0 missing events were deleted.

<< High Outlier Test >>

Based on 14 events, 10 percent outlier test deviate K(N) = 2.213

Computed high outlier test value = 79.5923

0 high outlier(s) identified above test value of 79.5923

Warning: 33 percent of systematic record was truncated for low outliers, zero, or missing values.

Note: Statistics and frequency curve were modified

using conditional probablity adjustment.

--- Final Results ---

<< Plotting Positions >>

Schultz Creek at Hwy 180

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
30 Jun 1970	0.000	1	1973	48.000	3.27
30 Jun 1971	0.000	2	1979	41.000	7.94
30 Jun 1972	0.000	3	1980	35.000	12.62
30 Jun 1973	48.000	4	2017	29.600	17.29
30 Jun 1974	0.000	5	1978	17.000	21.96
30 Jun 1975	0.000	6	2019	11.300	26.64
30 Jun 1976	0.000	7	2013	10.200	31.31
30 Jun 1977	3.000	8	2015	9.900	35.98
30 Jun 1978	17.000	9	2016	9.800	40.65
30 Jun 1979	41.000	10	2014	7.600	45.33
30 Jun 1980	35.000	11	2011	6.900	50.00
30 Jun 2011	6.900	12	2018	6.700	54.67
31 Jul 2012	4.900	13	2012	4.900	59.35
30 Jun 2013	10.200	14	1977	3.000	64.02
31 Aug 2014	7.600	15	2020	0.000	68.69
31 Aug 2015	9.900	16	1976	0.000	73.36
30 Jun 2016	9.800	17	1975	0.000	78.04
28 Feb 2017	29.600	18	1974	0.000	82.71
31 Jul 2018	6.700	19	1972	0.000	87.38
31 Dec 2018	11.300	20	1971	0.000	92.06
31 Jan 2020	0.000	21	1970	0.000	96.73

|--------------------------|------------------------------------|

<< Skew Weighting >>

Based on 21 events, mean-square error of station skew = 0.248

Mean-square error of regional skew = -?

<< Frequency Curve >>

Schultz Crek at Hwy 180

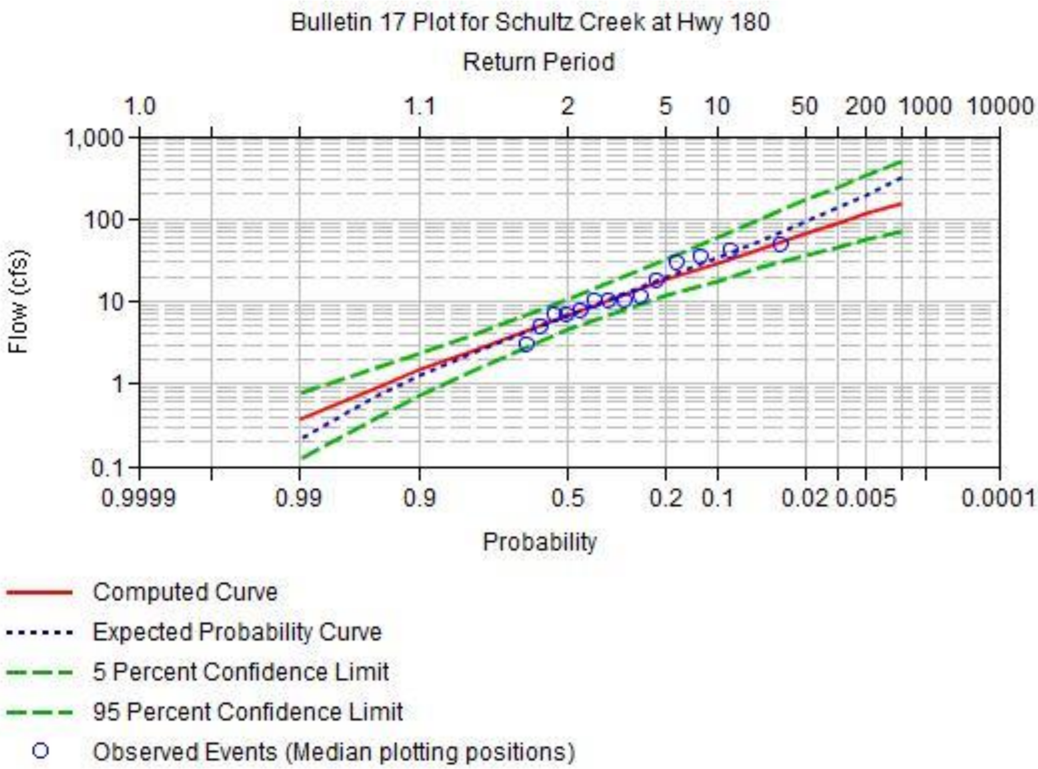
Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
153.437	310.865	0.2	511.554	72.520
113.529	194.050	0.5	343.759	56.555
88.168	134.149	1.0	246.587	45.838
66.591	91.382	2.0	170.847	36.234
43.329	52.860	5.0	97.908	25.151
29.316	33.211	10.0	59.467	17.911
18.060	19.274	20.0	32.536	11.581
6.903	6.903	50.0	10.698	4.475
2.518	2.340	80.0	3.922	1.404
1.459	1.259	90.0	2.400	0.711
0.920	0.722	95.0	1.611	0.394
0.378	0.216	99.0	0.765	0.123

<< Synthetic Statistics >>

Schultz Creek at Hwy 180

Log Transform: FLOW, CFS		Number of Events	
Mean	0.825	Historic Events	0
Standard Dev	0.509	High Outliers	0
Station Skew	-0.169	Low Outliers	0
Regional Skew	---	Zero Events	7
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.169	Systematic Events	21

--- End of Analytical Frequency Curve ---



Bulletin 17 Plot for Schultz Creek at Hwy 180
Return Period
1.0
1.1
2
5
10
50
200
1000
10000
1,000
100
10
1
0.1
Flow (cfs)
0.9999
0.99
0.9
0.5
0.2
0.1
0.02
0.005
0.0001
Probability
Computed Curve
Expected Probability Curve
5 Percent Confidence Limit
95 Percent Confidence Limit
Observed Events (Median plotting positions)

Bulletin 17B Frequency Analysis

19 Mar 2021 04:29 PM

Analysis Name: Sinclair Wash at Knoles Drive

Skew Option: Use Station Skew

Regional Skew: -Infinity

Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05

Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- End of Input Data ---

<< High Outlier Test >>

Based on 10 events, 10 percent outlier test deviate K(N) = 2.036

Computed high outlier test value = 81.1121

0 high outlier(s) identified above test value of 81.1121

<< Low Outlier Test >>

Based on 10 events, 10 percent outlier test deviate K(N) = 2.036

Computed low outlier test value = 44.6542

0 low outlier(s) identified below test value of 44.6542

--- Final Results ---

<< Plotting Positions >>

Events Analyzed		Ordered Events			
	FLOW		Water	FLOW	Median
Day Mon Year	CFS	Rank	Year	CFS	Plot Pos
30 Jun 2011	56.074	1	2013	77.161	6.73
31 Jul 2012	59.638	2	2018	73.715	16.35
30 Jun 2013	77.161	3	2016	65.459	25.96
31 Aug 2014	56.133	4	2017	63.320	35.58
31 Aug 2015	54.529	5	2012	59.638	45.19
30 Jun 2016	65.459	6	2014	56.133	54.81
28 Feb 2017	63.320	7	2011	56.074	64.42
31 Jul 2018	73.715	8	2015	54.529	74.04
31 Dec 2018	53.163	9	2019	53.163	83.65
31 Jan 2020	48.589	10	2020	48.589	93.27

<< Skew Weighting >>

Based on 10 events, mean-square error of station skew = 0.512

Mean-square error of regional skew = -?

<< Frequency Curve >>

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
100.117	130.507	0.2	140.173	85.615
93.827	112.922	0.5	126.325	81.545
89.101	101.930	1.0	116.327	78.411
84.370	92.662	2.0	106.686	75.191
78.025	82.248	5.0	94.391	70.702
73.055	75.326	10.0	85.336	66.981
67.763	68.754	20.0	76.390	62.687
59.473	59.473	50.0	64.478	54.627
53.083	52.543	80.0	57.413	46.949
50.342	49.400	90.0	54.782	43.431
48.339	46.952	95.0	52.944	40.841
45.127	42.691	99.0	50.089	36.720

<< Systematic Statistics >>

Log Transform: FLOW, CFS		Number of Events	
Mean	1.779	Historic Events	0
Standard Dev	0.064	High Outliers	0
Station Skew	0.487	Low Outliers	0

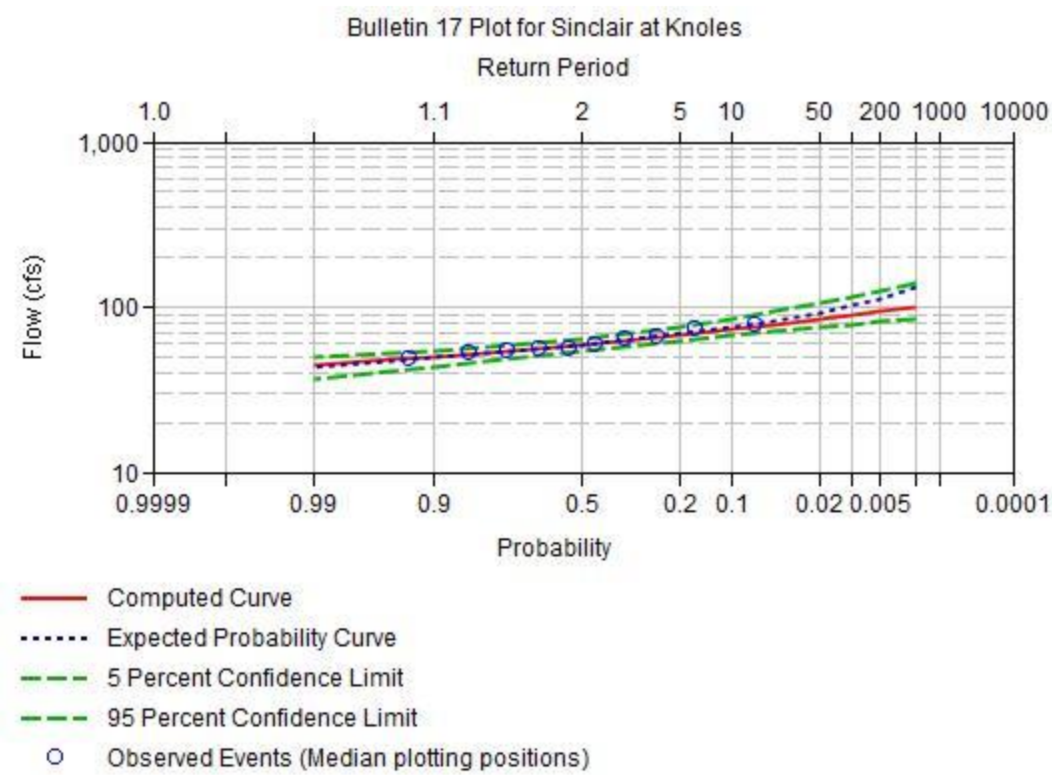
| Regional Skew --- | Zero Events 0 |

| Weighted Skew --- | Missing Events 0 |

| Adopted Skew 0.487 | Systematic Events 10 |

|-----------------------------|------------------------------|

--- End of Analytical Frequency Curve ---



Appendix F: Regional Geomorphic Relationships

The following is lightly edited from Natural Channel Design's report to the City of Flagstaff on area geomorphology (Natural Channel Design 2020).

Area valley types are primarily Rosgen type VIII which are moderately confined, alluvial valleys containing finer soils with well-developed floodplains. Higher up on the San Francisco Peaks, the valley types tend to be Type II which are steeper colluvial valleys. Soils are derived from basaltic lava flows, cinder cone eruptions and volcanic ash. The NRCS has not classified the soils for this area of the forest. The Forest Service classifies the general soils as Eutroboralfs, which are deep or moderately deep to very gravelly volcanic conglomerate materials producing gravelly clay loam or loam. Some soils can be classified as Ustochrepts which contain thick soils that have a shallow horizon in which carbonates have accumulated. This is consistent with the findings from the USGS which classified the soils in the western side of Flagstaff as Soil Group D which overlay cinder substrate, limestone or highly fractured basalt which allow the soils to drain freely (USGS Report 87-4210).

All the channel reaches located on forest lands were within 1.5 miles of the City limits and tended to be small, regardless of watershed size. Due to the highly porous geology and well vegetated watersheds ranging from pine/oak woodland to mixed conifer forest, runoff is slow to accumulate on the watersheds draining from the San Francisco Peaks. This is typical of a complacent – violent runoff watershed where runoff is slow to accumulate until a threshold is reached resulting in a large, sudden discharge of water. This threshold can vary year to year as the watersheds respond to local climatic conditions.

The upper portions of many of the watersheds contain broad swales or drainages lacking clear channel features. Reference reaches for cross section and profile surveys were ultimately located in areas where enough water has accumulated and started to form channels with some identifiable features. Bankfull indicators were not well developed at many of the sites and were difficult to locate. The bankfull indicators were typically a change in substrate size, presence of depositional surfaces or a change in vegetation density or type. Herbaceous vegetation tended to be present in the channel beds, along with scattered pine trees in some of the channels. The presence of such vegetation indicates a lack of sufficient water or scouring flows that would inhibit their growth or remove them from the channel. All channels were fairly straight with sinuosity values of less than 1.2 (Sinuosity is the ratio of stream length to valley length). Meanders were controlled by the valley geography.

None of the channels surveyed on forest had any geomorphic indicators of the 100-year flow having occurred in recent history. The high flow markers located along the channel included debris lines and stains on trees and these flows were within the 2 to 25-year flow events.

The reaches measured are all stable "B" and "C" channels that have an adjacent geomorphic floodplain. "B" channels are stable, moderate gradient, moderately entrenched channels with relatively narrow floodplains while “C” channels are stable, low gradient, meandering channels with broad floodplains. All channels measured were considered a gravel bed stream based on the bed material sampling.

The bankfull cross-sectional area for each reference cross-section on the Forest was then plotted on the Regional curves. With the exception of Sinclair Wash, bankfull indicators result in cross-sectional areas that are consistently below the Regional curves. Further development of a local Flagstaff curve to determine bankfull geometry would be appropriate for streams in the Flagstaff Region and additional data points would need to be gathered to increase the confidence of the curve.

An attempt was made to if the channels in the Flagstaff area have ever experienced the FEMA 100-year flow. For each reach, the FEMA 100-year flow stage was plotted on the reference cross-section to determine the approximate stage, velocity and shear stress produced by the flows. Within this area, crews searched for direct evidence of past flows including flood debris, scars on trees or other indications of scouring flows. There was no evidence seen at any of the reaches. This indicates that the flow either have not occurred, or that they occurred long enough in the past that the evidence has been lost, either due to decomposition, fire or being covered by accumulated debris and vegetation.

The second method used was to look at existing vegetation growing on the floodplains and the presence of grasses and trees. Research has shown that grasses (turf and bunch types) are likely removed when flows exceed 3-4 cfs (Fischenich, 2001). All sites with the exception of Clay Ave. Wash reach 2 have estimated 100-year flow velocities which would disturb or remove this vegetation. Re-establishment of dense bunch grass stands can take several growing seasons and shrubs/trees will require decades. At all sites the floodplains are well vegetated with grasses and/or mature ponderosa pine trees. This even applies to sites that have had their floodplains altered by past mechanical disturbances. In addition woody debris, accumulated needle cast and dead grass have built up on the floodplains. This indicates that there has not been any large flows experienced in the recent past in any of these channels.

Bankfull surveys of the channels around Flagstaff indicate that discharges associated with channel forming flows are much smaller than equivalent return interval flows estimated using the NSS regional equations. Flood frequency discharges based on data collected at local gages provided more consistent results for these low flows, even with the limited data. However, since there were no flows greater than the calculated 10- to 25-year event within the dataset, the local flood frequencies are likely not any more accurate than the NSS data above the 10-year event.

The stream channels with watersheds originating on or near the San Francisco Peaks have a much lower bankfull discharge per watershed area than the other study sites. This was consistent in the bankfull cross-sectional areas surveyed and corresponds closely with the Flagstaff area flood frequency analysis, especially when the gage data collected off the Peaks is separated from the other local gaged sites. This results in two local regions in the Flagstaff area; the San Francisco Peaks flood frequency and a general Flagstaff Area flood frequency.

The San Francisco Peaks frequency was only used to determine flows at the on-forest reaches of the Rio de Flag, Clay Ave. Wash and Schultz Creek. As these channels receive stormwater flows after entering the city limits, the rapid increase in bankfull discharges and higher flows were estimated using the Flagstaff Area flood frequency.

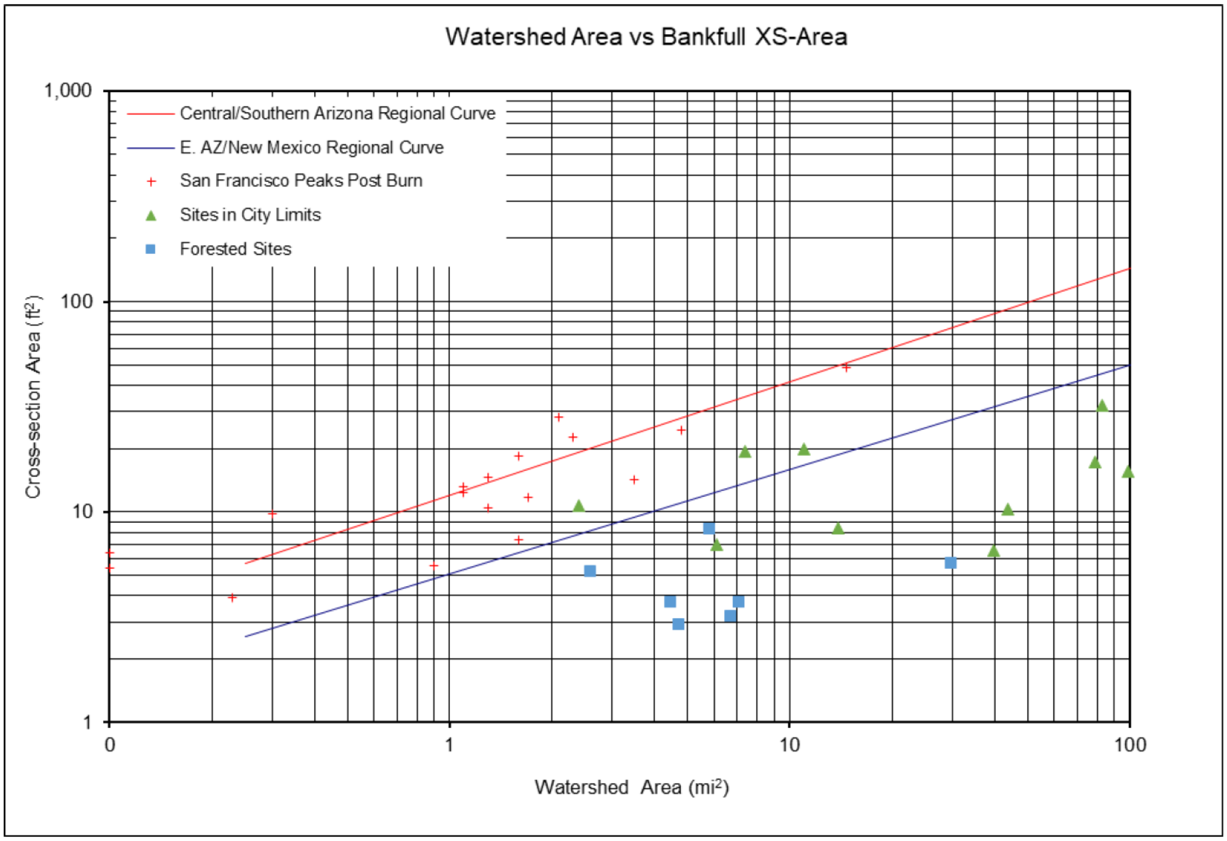


Figure 14. Local channel capacity (y-axis) compared to watershed area (x-axis) for local streams. The 2010 Schultz Fire impacted streams are also shown as red crosses (Figure from Natural Channel Designs 2020).