2022 Storm Water Master Plan Update

Phase 3 - Hydrology & Hydraulics and Floodplain Delineation

Technical Support Data Notebook

Submitted to

City of Sedona

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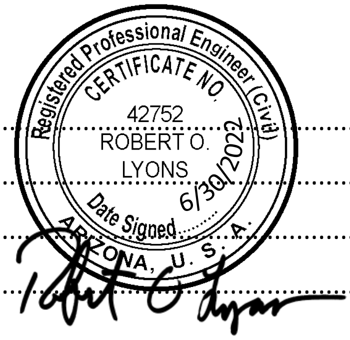

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1.0 Introduction

1.1. Study Purpose

The City of Sedona has retained JE Fuller/Hydrology & Geomorphology (JE Fuller) to update the existing Sedona Storm Water Master Plan (2005) based on the results of new city-wide, two-dimensional hydrologic modeling. The new modeling was conducted in FLO-2D and used new topographic mapping, land use data, and updated precipitation. This Technical Support Data Notebook (TSDN) summarizes the hydrologic and hydraulic modeling conducted and new floodplain delineations used for City regulation.

The results of these hydrologic and hydraulic analyses will be used to:

- Develop new hydrology for use in the design of storm water infrastructure
- Characterize the location and extent of the existing flood hazards in the study area
- Determine if there are practical mitigation solutions that can reduce all or part of the storm water risks

1.2. Study Authority

The Sedona Storm Water Master Plan Update (SWMPU) was prepared for the City of Sedona by JE Fuller. The project manager for JE Fuller is Rob Lyons. JE Fuller performed the study under the direction of the City of Sedona project manager Sandra Phillips. Contact information is provided in **Table 1-1:**

Table 1-1. Project Manager Contact Information

	City of Sedona	JE Fuller/Hydrology & Geomorphology, Inc.
Project Manager:	Sandra Phillips, PE	Rob Lyons, PE, CFM
Address:	102 Road Runner Drive Sedona, AZ 86336	8400 S. Kyrene Road, Suite 201 Tempe, AZ 85284
Phone:	(928) 203-5076	(480) 250-9842

1.3. Study Location

The Sedona SWMPU watershed is approximately 42 square miles in size and encompasses land within the jurisdictions of the City of Sedona, Coconino County, and Yavapai County. A vicinity map is shown in **Figure 1-1.**

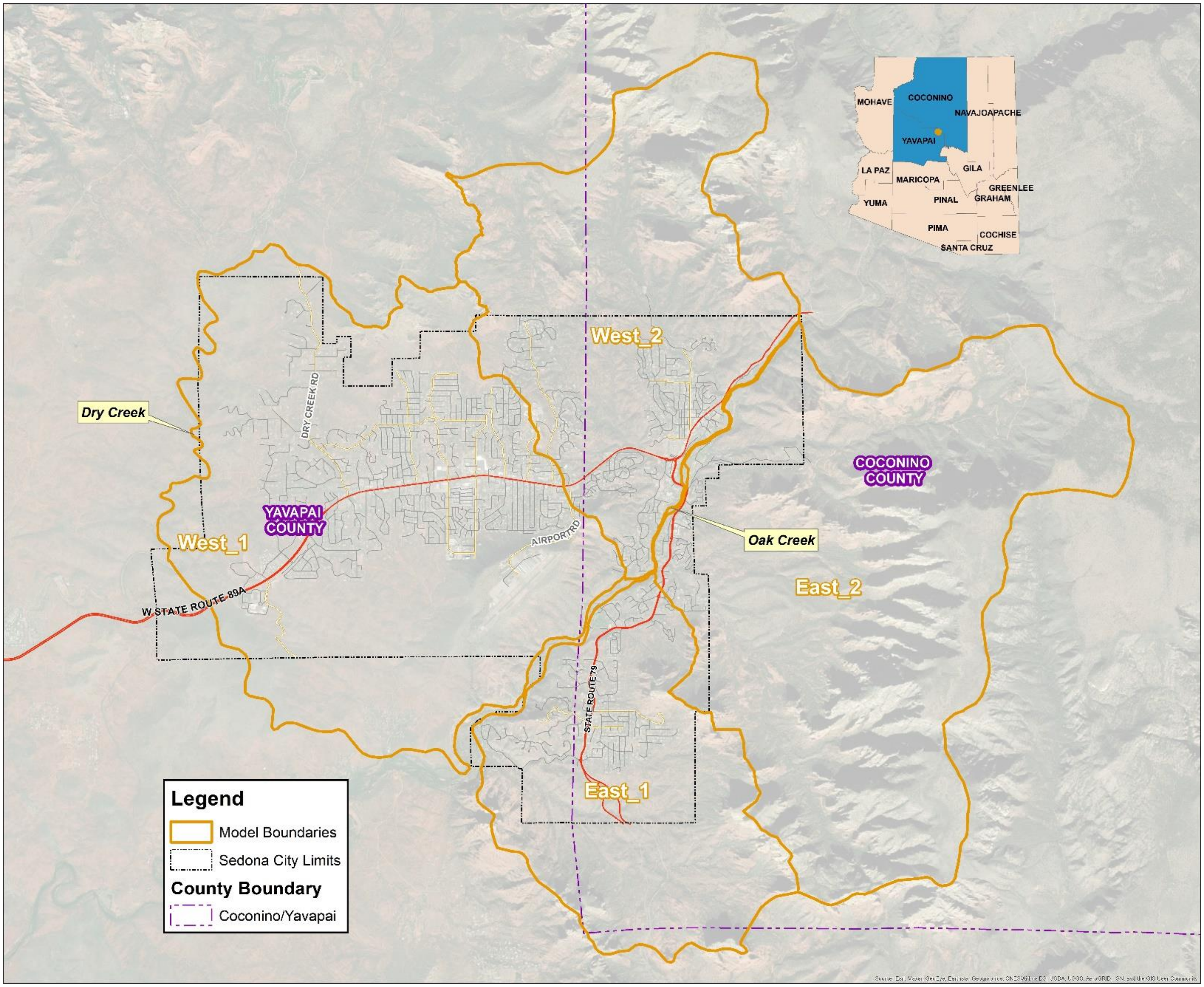

Figure 1-1. Study Area Overview.

1.4. Methodology

Hydrologic and hydraulic (H&H) modeling for this study has been completed using the FLO-2D Pro modeling software (v19.07.21, released 6/10/2020), a volume conserving, quasi-two-dimensional (2-D) flood routing model. The model routes surface flow (rainfall runoff and inflow hydrographs) in 8 directions over a grid comprised of square elements representing the underlying topography. Spatially varied inputs including roughness and infiltration properties can be assigned to each cell. This 2-D modeling approach is highly suited for simulating the shallow, distributary flow prevalent within portions of the watershed as the flow travels from the mountain fronts to the lower elevations through natural channels, existing urban infrastructure, and unintended, distributed overland flow through the urbanized portions of Sedona. The FLO-2D model is capable of simulating hydraulically significant storm drains, culverts, buildings, walls, and channels within the model area. The model developed in this study utilized the existing land use conditions at the time of this study.

2.0 Mapping and Survey Information

2.1. Mapping

The LiDAR mapping used for this study was obtained from a FEMA Cooperative Technical Partner project for Oak Creek and its tributaries. The LiDAR (which covers approximately 75% of the modeled area) was flown in June 2016 by Sanborn Map Co., Inc. (Sanborn, 2016) with a point density sufficient to create 1-ft contours. The raw LiDAR was processed by Sanborn to align with the NAD 1983 horizontal datum and conform to the North American Vertical Datum of 1988 (NAVD88).

The elevation data used for the FLO-2D modeling had to be supplemented with lower-resolution elevation data offered on the USGS website (usgs.gov), for LiDAR data is not currently available for the entire project watershed. The raster downloaded from the USGS website was originally set in the NGVD29 vertical datum. A factor of 2.65748 ft was added to this raster for conversion into the NAVD88 vertical datum. No conversions were done horizontally, for the raster was already set in the NAD 1983 horizontal datum.

The two data sets were then combined into a single global elevation raster. The limits of each source of the raster are shown in **Figure 2-1**. The global elevation raster was in turn used to develop the FLO-2D grid element elevations.

2.2. Digital Projection Information

The surface was developed using ArcGIS with the following projection information:

- Vertical Datum: The North American Vertical Datum of 1988 (NAVD 88)
- Projected Coordinate System: 'NAD_1983_HARN_StatePlane_Arizona_Central_FIPS_0202_Feet_Intl' (FIPS 0202).
- WKID: 2868

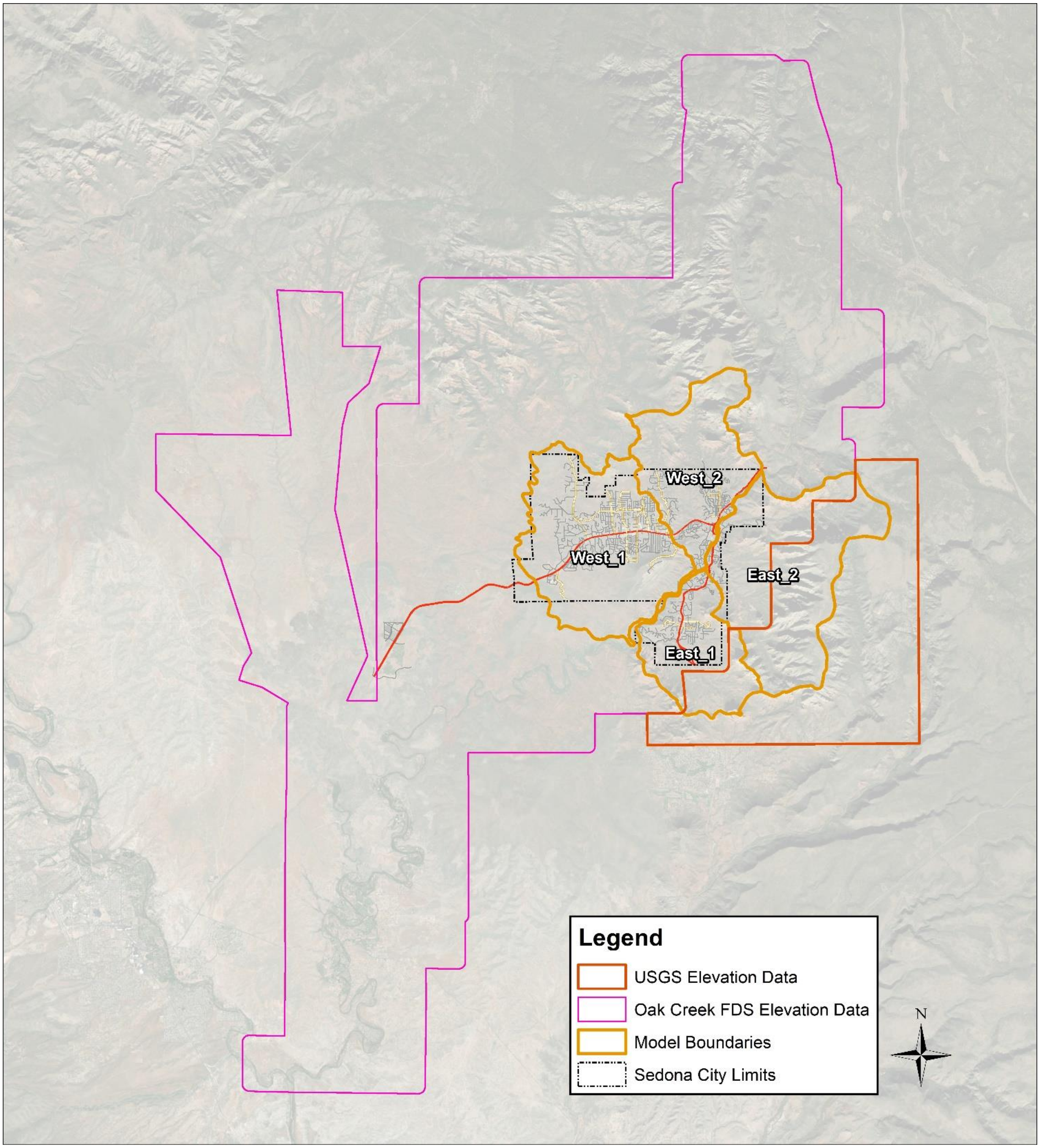

Figure 2-1. Limits of mapping sources in relation to overall FLO-2D model domain

2.3. Additional Information

Using two sources of topographic mapping for terrain-based hydraulic modeling introduces problems at mapping seams, particularly when the mapping is of different mapping accuracy. Since the lower accuracy USGS data is generally in the upper watershed to the east, the USGS dataset was raised by 5 feet to ensure downhill flow to the LiDAR terrain data. A graphic of the combined elevation data has been prepared, and can be seen below (**Figure 2-2**).

There are 7 locations where the detailed Oak Creek LiDAR is upstream of the course USGS dataset. In those instances, large 'virtual' hydraulic structures were modeled to force water that would otherwise erroneously pond at the interface of the two datasets to flow into the USGS terrain portion of the model.

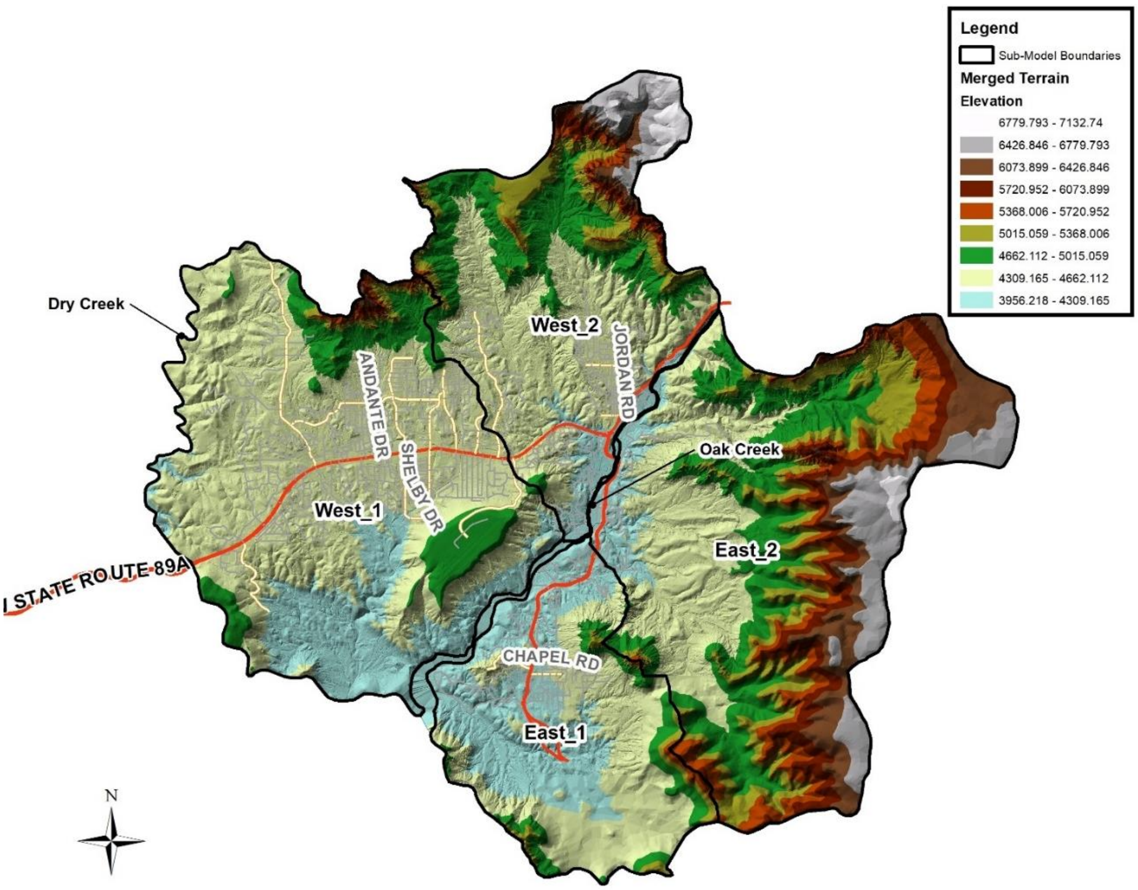

Figure 2-2. Sedona ADMS/S merged elevation dataset

3.0 Model Development

3.1. Method Overview

The analysis was completed using City of Sedona, ADOT, and Yavapai County guidance and recommendations for model parameter estimation and development as well as two-dimensional modeling techniques appropriate for the area. Where applicable, JE Fuller made changes to base input parameters such as Manning's n-values and infiltration parameters (initial abstraction, percent impervious, etc.) in areas where the watershed warranted specific unique values different from the default recommended values from the resources listed above. This is discussed later in this report.

The model was developed and refined over two phases (Phase II and Phase III) of the SWMPU project. Phase II initial model development was conducted in Fiscal Year 2021 and Phase III model refinement was conducted in Fiscal Year 2022.

3.2. Model Domain and Sub-Models

Based on experience from similar studies (Laveen ADMS; Bullhead City ADMS; Sun Valley ADMS), a 15-foot grid was chosen as the desired model resolution to show more accurate flow patterns and generally results in less model debugging. The FLO-2D modeling extent was divided into four sub-models (see **Figure 1-1**) to decrease model runtime and allow for more efficient post-processing. Total sub-model area and grid counts are listed in **Table 3-1.** The sub-model boundaries were delineated such that no cross-flow would occur between sub-models (**Figure 3-1**) and that major storm drain systems and culverts were contained within a single sub-model. The Oak Creek watercourse was not included in the FLO-2D modeling as the upstream hydrology of Oak Creek was not computed or considered in this study. Oak Creek is the primary outflow location for all 4 sub-models.

Table 3-1. FLO-2D sub-model grid elements

Sub-Model Name	Area (mi^2)	Number of Grid Elements
West_1	12.6	1,564,164
West_2	8.1	1,000,991
East_1	6.1	753,009
East_2	13.1	1,623,066

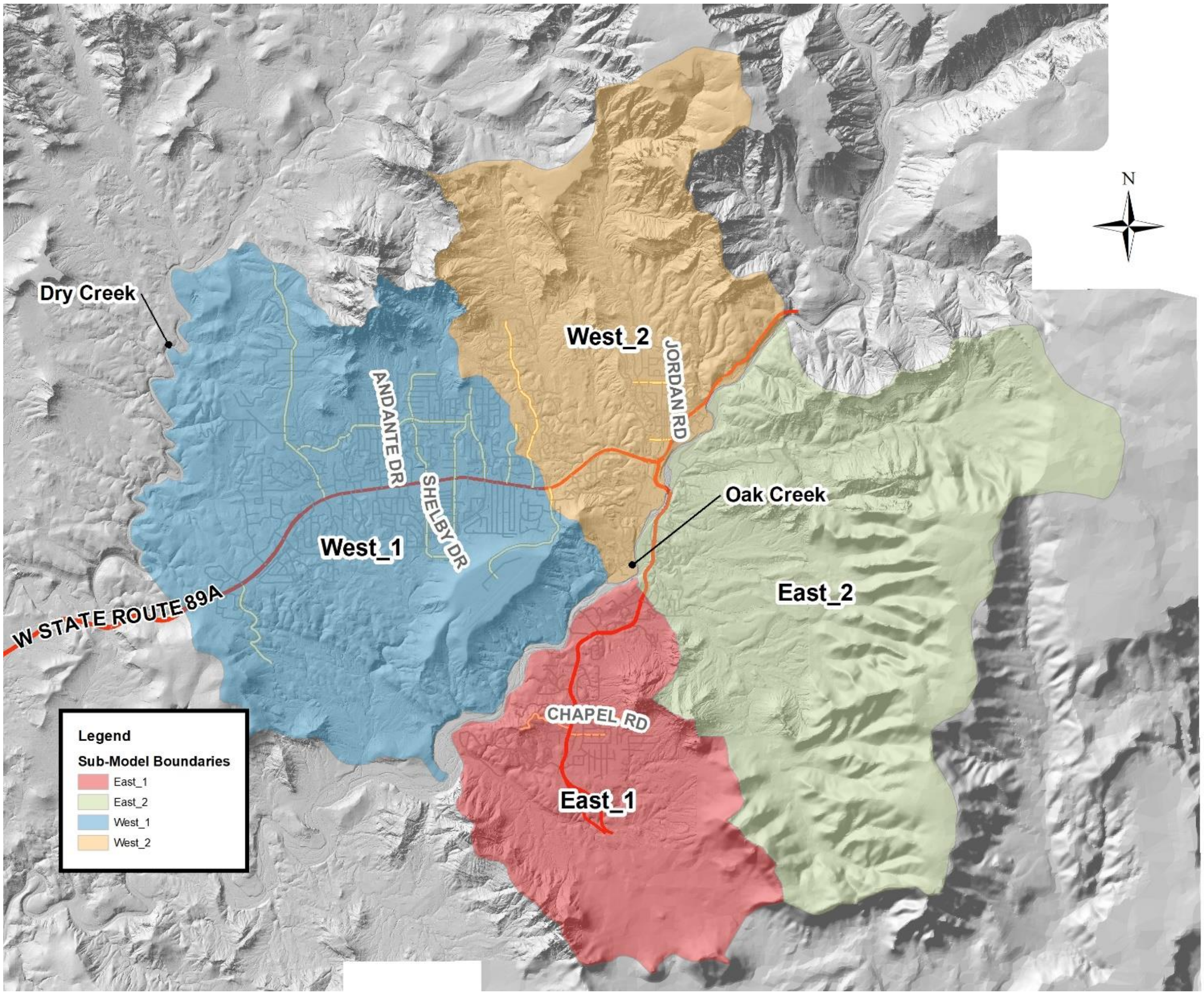

Figure 3-1. Sedona SWMPU FLO-2D sub-model interaction

3.3. Development of Input Files

3.3.1. Overview

Almost all the FLO-2D input data files were required given the large drainage area with multiple culverts, storm drains, and other infrastructure that affects drainage. The input files that are used in this study are shown in

Table 3-2. This table also gives a brief description of the information that is contained in each input file.

Table 3-2. FLO-2D Input Files used in the Sedona SWMPU

File Name	Description
ARF.DAT	area reduction and width reduction factors
CADPTS.DAT	grid number and corresponding x and y coordinate values
*CHAN.DAT**	defines the location of any 1D channels within the model, if this option is used
*CHANBANK.DAT**	defines the location of right/left banks of each cross-section for each 1D channel
CONT.DAT	simulation control file, toggles on/off model switches, such as rain or infiltration
FPLAIN.DAT	file that defines the grid ordering, n-values, and elevations for each grid
FPXSEC.DAT	defines the location of floodplain cross-sections where a hydrograph is automatically calculated
HYSTRUC.DAT	hydraulic structures, such as culverts, small bridges, and simple storm drains
INFIL.DAT	infiltration parameters for each grid
*LEVEE.DAT**	defines the location and characteristics of any linear flow obstructions, such as walls or levees, in the model
OUTFLOW.DAT	defines the floodplain and/or channel outflow elements
MANNINGS_N.DAT	file developed at run time (includes same roughness values specified in FPLAIN.DAT)
NEIGHBORS.DAT	file developed at run time (includes neighboring grids specified in FPLAIN.DAT)
RAIN.DAT	rainfall parameters for the model and reduction factor for each grid
SHALLOWN_SPATIAL.DAT	defines the Shallow n value for each model grid element
*SWMM.ini**	EPA SWMM engine initiation input file
*SWMM.inp**	EPA SWMM engine input file (storm drain geometry)
*SDCLOGGING.DAT**	EPA SWMM model inlet clogging input file
*SWMMFLO.DAT**	EPA SWMM model inlet input file
*SWMMFLORT.DAT**	EPA SWMM model hydraulic rating input file
*SWMMOUTF.DAT**	EPA SWMM model outfall file
TOLER.DAT	numerical controls for the simulation, such as floodplain Courant stability criterion
TOPO.DAT	file developed at run time (includes same elevation values specified in FPLAIN.DAT)
*denotes a file that is not used in all sub-models.	

3.3.2. FPLAIN.DAT and CADPTS.DAT

The FPLAIN.DAT AND CADPTS.DAT input files define the size and layout of the grid on which the FLO-2D calculations are made. The FPLAIN.DAT file contains the grid ordering, the adjacent grid elements, the n-values, and the elevations of each grid, while the CADPTS.DAT contains the coordinates of each grid element.

The elevations of each grid were developed from the comprehensive global elevation raster (shown in **Figure 2-2**). A global 15-foot raster was developed through linear interpolation of the merged elevation raster. From this global 15-foot raster, the elevations were extracted for each grid and applied to the FPLAIN.DAT file for each sub-model.

Land use delineations were established using zoning data provided by the City supplemented with manual delineations by JE Fuller (**Figure 3-2**). Land use categories were discretized based upon land uses shown in the YCFCD Hydrology Manual. City zoning categories were largely limited to residential, commercial, and industrial land uses. Natural land uses were delineated manually, and several natural land uses (i.e., shallow and steep wash) were created to reflect the unique and steep terrain observed in this study area.

Manning's n-values were established for each land use based upon guidance in the YCFCD Hydrology Manual as well as previous FLO-2D experience in similar watersheds (**Table 3-3**). Area weighted averages were used for cells containing more than one land use and n-value.

3.3.3. Shallow n

Spatially-varied shallow n adjustments were made using the SHALLOWN_SPATIAL.DAT file. This parameter allows for depth-integrated n-value adjustments, with a focus on increasing the n-value at shallow depths. SHALLOWN values were assigned to each land use as shown below in **Table 3-3**. These values were determined based upon guidance in the Flood Control District of Maricopa County FLO-2D Verification Report (FCDMC, 2016) as well as previous FLO-2D experience.

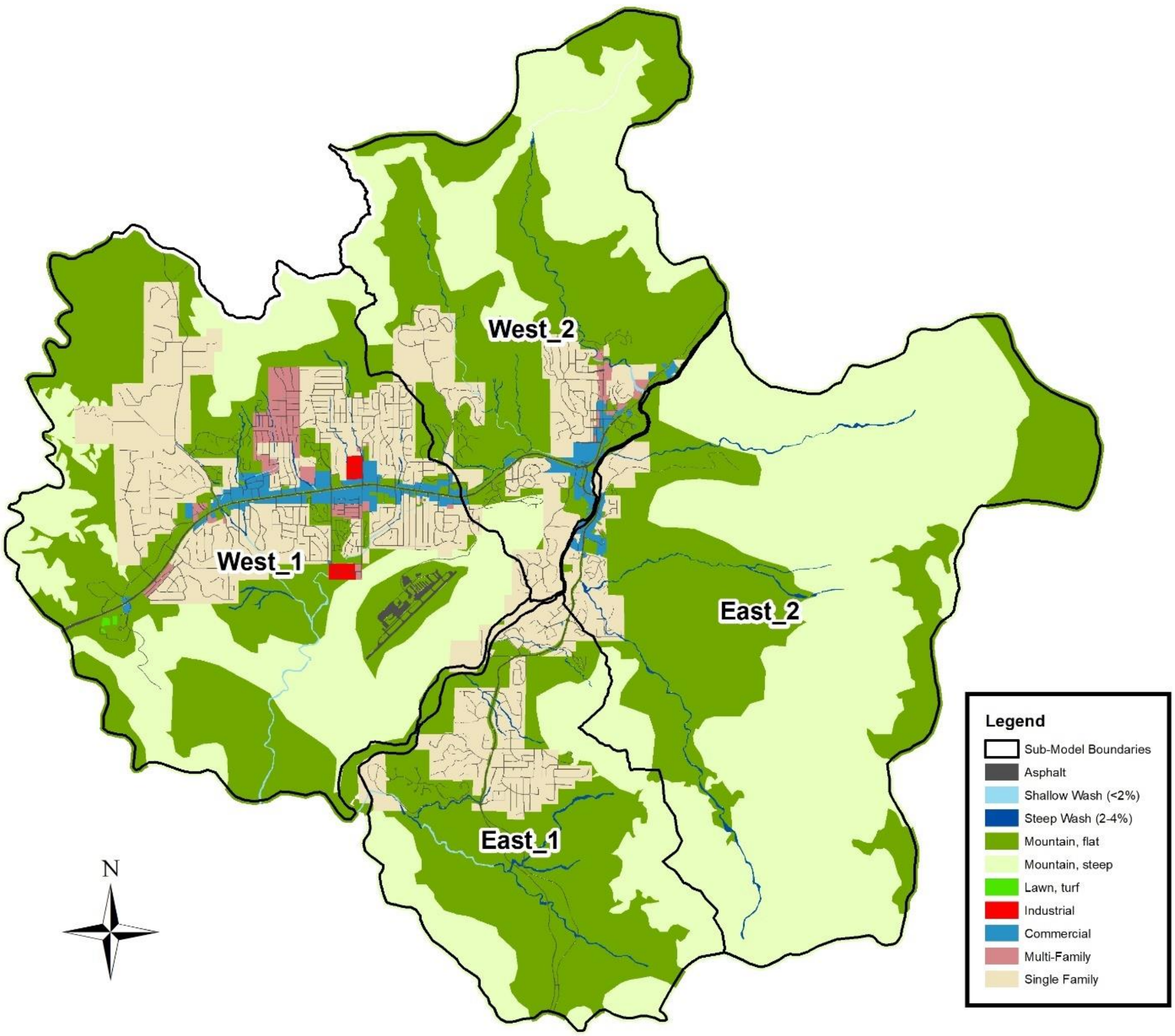

Figure 3-2. Land Use

Table 3-3. Manning's n-values assignments.

Yavapai County Land Uses	Land Use Category-Code	Sedona Zoning Categories	Zoning Category Code	Floodplain n-Value	Shallow n-Value
Natural Grasslands (flat slope)	100			0.045	0.15
Rangeland, flat slope (moderate veg.)	110			0.050	0.20
Rangeland, hill slopes (moderate veg.)	111			0.070	0.20
Mountain, flat slope < 20% (vegetated)	120	OS	560	0.060	0.20
Mountain, steep slope >20% (vegetated)	121			0.090	0.30
Single Family Res. (1/4 acre)	130	RS-6	600	0.040	0.12
Single Family Res. (1/3 acre)	131	RS-10	601	0.040	0.12
Single Family Res. (1/2 acre)	132	RS-18	602	0.040	0.12
Single Family Res. (1 acre)	133	RS-35	603	0.050	0.12
Single Family Res. (>= 2 acres)	134	RS-70	604	0.050	0.12
Multi-Family Residential	140	RM-1	580	0.035	0.12
		RM-2	581		
		RM-3	582		
		RMH	590		
Commercial	150	CO	510	0.040	0.12
		M2	540		
Industrial	160	IN	520	0.050	0.12
Lawn and Turf	170			0.030	0.12
Pavement and Roof Tops	180			0.020	0.10
Steep Wash (2-4%)	190			0.11	0.30
Shallow Wash (<2%)	191			0.075	0.22
Steep Wash (2-4%) HiVel	192			0.2	0.30

3.3.4. RAIN.DAT

The RAIN.DAT input file defines the rainfall temporal and spatial distribution for the model. Five recurrence intervals were assessed in this study including the 10-, 25-, 50-, 100-, and 500-year events. The 24-hour duration was used for all modeling in this study per the YCFCD hydrology manual. The rainfall depths were collected from the NOAA Atlas 14 dataset. The 100-year spatial rainfall distribution is depicted below (**Figure 3-3**). The frequency storm approach was used to develop the hyetograph for this study. A single distribution was computed using NOAA Atlas 14 statistics at the centroid of the study area. The maximum and minimum rainfall depths for the study area are shown in Error! Reference source not found.**Table 3-4**. The 24-hour distribution is shown in **Figure 3-4**. The maximum rainfall value for each sub-model is generally near the highest elevation and the minimum rainfall value is near the lower elevations within the sub-model. The spatial variability in the model was accomplished using the RAINARF routine where the maximum rainfall value is assigned to each sub-model and RAINARFs were calculated as a ratio to the maximum at each grid cell.

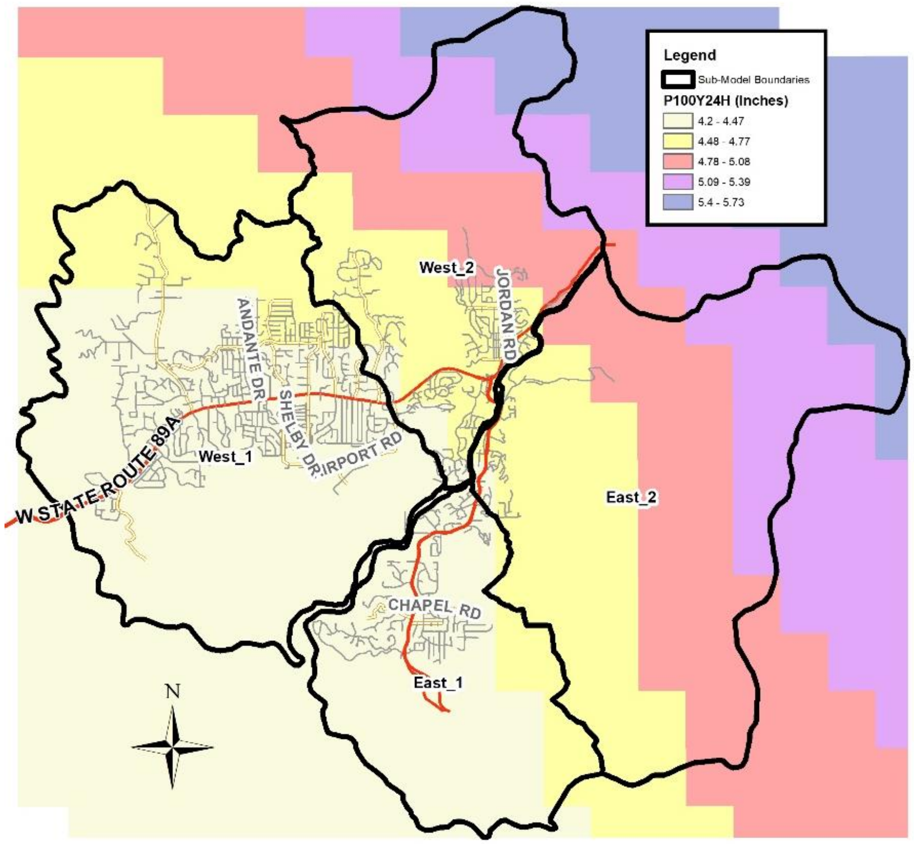

Figure 3-3. NOAA14 100-Year, 24-Hour Spatial Rainfall Distribution

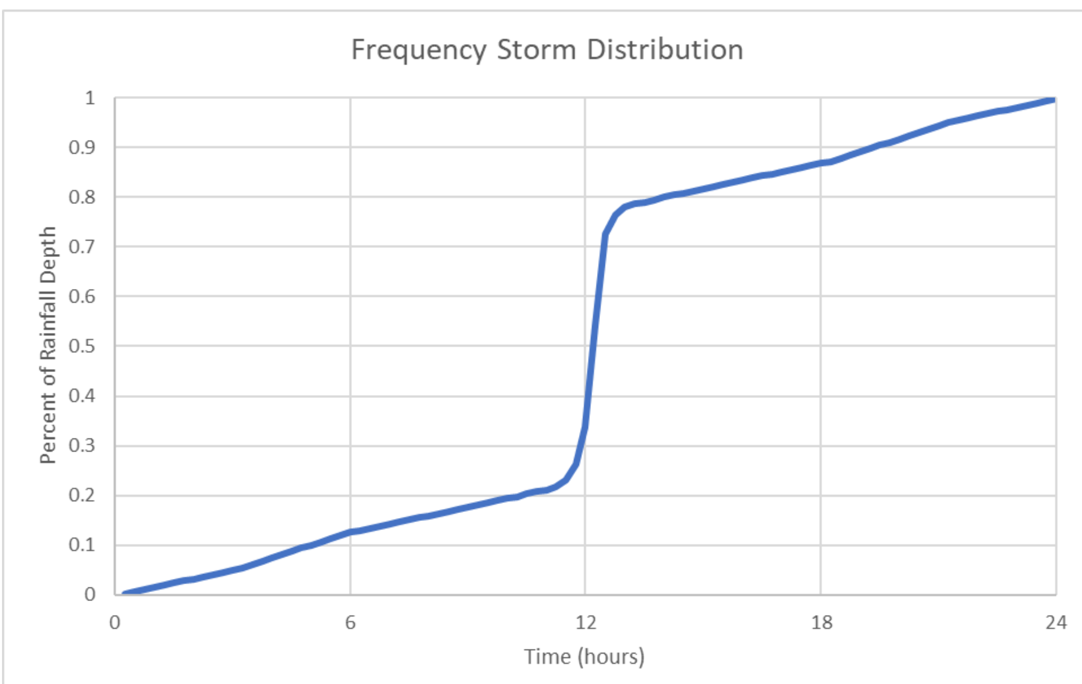

Figure 3-4. 24-hour Frequency Storm Rainfall Distribution

Table 3-4. Maximum and Minimum Rainfall Depths in the Sedona SWMPU

Storm Event	Maximum (inches)	Minimum (inches)
10-year, 24-hour	3.000	2.816
25-year, 24-hour	4.555	3.358
50-year, 24-hour	5.134	3.765
100-year, 24-hour	5.732	4.203
500-year, 24-hour	7.200	5.252

3.3.5. INFLOW.DAT AND OUTFLOW.DAT

No inflow hydrographs were used for any of the four sub-models as all hydrology in this study was computed using FLO-2D. The sub-model boundaries were delineated such that there are no cross-model or offsite flows entering into any of the four sub-models. Outflow nodes (in the OUTFLOW.DAT file) were set at every cell along the perimeter of each sub-model.

3.3.6. INFIL.DAT

The INFIL.DAT file contains the infiltration parameters used in FLO-2D to calculate rainfall losses. The Green and Ampt method was used for this study as recommended by the YCFCD Hydrology Manual. This method requires a number of inputs to be estimated from the land use and soil types within the study area. Infiltration assumptions based on landuse type are organized in **Table 3-7**.

Soil unit delineations and measured soil properties provided in the Terrestrial Ecosystem Survey (2005) were used to establish soil infiltration properties. Soil texture classes and the relative contribution (in percent) of each soil texture class within each soil unit from the Ecosystem Survey were identified for individual map units within the study area. The ADOT Hydrology Manual (2014) lists a generic mapping of soil textures to Green and Ampt infiltration parameters (

Table 3-5), and the parameters were then weighted based upon their relative contribution to determine average parameters for each map unit in the study area. The final soil parameters by map unit are listed below in **Table 3-6** and are also depicted spatially in **Figure 3-5**.

Limiting depth can be an important parameter with regards to results for both peak discharge and runoff volume. Initial modeling for this project included setting the limiting depth at four inches throughout the modeling area. This was increased to 8-inches after initial model results were evaluated, this will be discussed later in this report.

Table 3-5. ADOT Soil Texture Mappings.

Table B-2 Green and Ampt Parameters Based on Texture for Miscellaneous Soils

Texture	Conductivity (in/hr)	Suction (in)	Moisture Content		
			Wilting Point (dry)	Field Capacity (normal)	Saturated
Sand	2.00	0.29	0.021	0.059	0.411
Loamy sand	1.61	0.60	0.030	0.073	0.339
Sandy loam	0.74	2.97	0.058	0.144	0.384
Gravelly sandy loam	0.49	4.71	0.058	0.144	0.384
Loam	0.19	8.19	0.110	0.238	0.390
Gravelly loam	0.13	9.15	0.110	0.238	0.390
Sandy clay loam	0.11	9.49	0.167	0.259	0.393
Silt	0.08	10.03	0.047	0.281	0.369
Extremely gravelly loam	0.08	10.03	0.110	0.238	0.390
Very gravelly loam	0.08	10.03	0.110	0.238	0.390
Silt loam	0.08	10.03	0.124	0.297	0.405
Silty clay Loam	0.04	10.80	0.204	0.370	0.456
Clay loam	0.04	10.80	0.204	0.336	0.429
Gravelly clay	0.01	11.42	0.296	0.423	0.478
Sandy clay	0.01	11.42	0.251	0.360	0.424
Silty clay	0.03	11.00	0.277	0.421	0.504
Clay	0.01	11.42	0.296	0.423	0.478
Rock	0.01	11.42	0.296	0.423	0.478
Unknown texture	0.01	11.42	0.296	0.423	0.478

Table 3-6. Green and Ampt Parameters by Map Unit.

SOIL_ID	XKSAT	PSIF	WILTING	FCAP	SAT	PERC_ROCK
45	1.649	0.569	0.029	0.072	0.346	0
46	1.874	0.558	0.025	0.068	0.408	0
402	0.040	10.800	0.204	0.365	0.452	0
403	0.472	4.932	0.061	0.149	0.384	0
430	0.094	9.868	0.170	0.301	0.415	20
457	0.490	4.710	0.058	0.144	0.384	0
458	0.490	4.710	0.058	0.144	0.384	0
462	0.040	10.800	0.204	0.336	0.429	0
463	0.040	10.800	0.204	0.336	0.429	5
470	0.059	10.474	0.192	0.324	0.424	20
471	0.490	4.710	0.058	0.144	0.384	50

SOIL_ID	XKSAT	PSIF	WILTING	FCAP	SAT	PERC_ROCK
474	0.714	3.888	0.052	0.130	0.375	0
475	0.490	4.710	0.058	0.144	0.384	40
492	0.040	10.800	0.204	0.336	0.429	0
495	0.153	8.843	0.134	0.263	0.400	0
520	0.190	8.190	0.110	0.238	0.390	0
555	0.824	2.791	0.056	0.138	0.386	25
578	0.190	8.190	0.110	0.238	0.390	0
582	0.168	8.582	0.124	0.253	0.396	0
584	0.190	8.190	0.110	0.238	0.390	0

Table 3-7. Land Use Infiltration Parameters in the Sedona SWMPU

Land Use	Land Use Category-Code	Sedona Zoning Categories	Zoning Category Code	IA (inches)	% Impervious (RTIMP)	DTHETA Condition
Natural Grasslands (flat slope)	100			0.50	0	Dry
Rangeland, flat slope (moderate veg.)	110			0.35	0	Dry
Rangeland, hill slopes (moderate veg.)	111			0.15	0	Dry
Mountain, flat slope < 20% (vegetated)	120	OS	560	0.50	0	Dry
Mountain, steep slope >20% (vegetated)	121			0.25	0	Dry
Single Family Res. (1/4 acre)	130	RS-6	600	0.25	40	Normal
Single Family Res. (1/3 acre)	131	RS-10	601	0.25	30	Normal
Single Family Res. (1/2 acre)	132	RS-18	602	0.25	23	Normal
Single Family Res. (1 acre)	133	RS-35	603	0.30	18	Normal
Single Family Res. (>= 2 acres)	134	RS-70	604	0.30	15	Normal
Multi-Family Residential	140	RM-1	580	0.25	50	Normal
		RM-2	581			
		RM-3	582			
		RMH	590			
Commercial	150	CO	510	0.10	75	Normal
		M2	540			
Industrial	160	IN	520	0.20	70	Normal
Lawn and Turf	170			0.20	0	Normal
Pavement and Roof Tops	180			0.05	95	Normal
Steep Wash (2-4%)	190			0.10	0	Dry
Shallow Wash (<2%)	191			0.10	0	Dry
Steep Wash (2-4%) HiVel	192			0.10	0	Dry

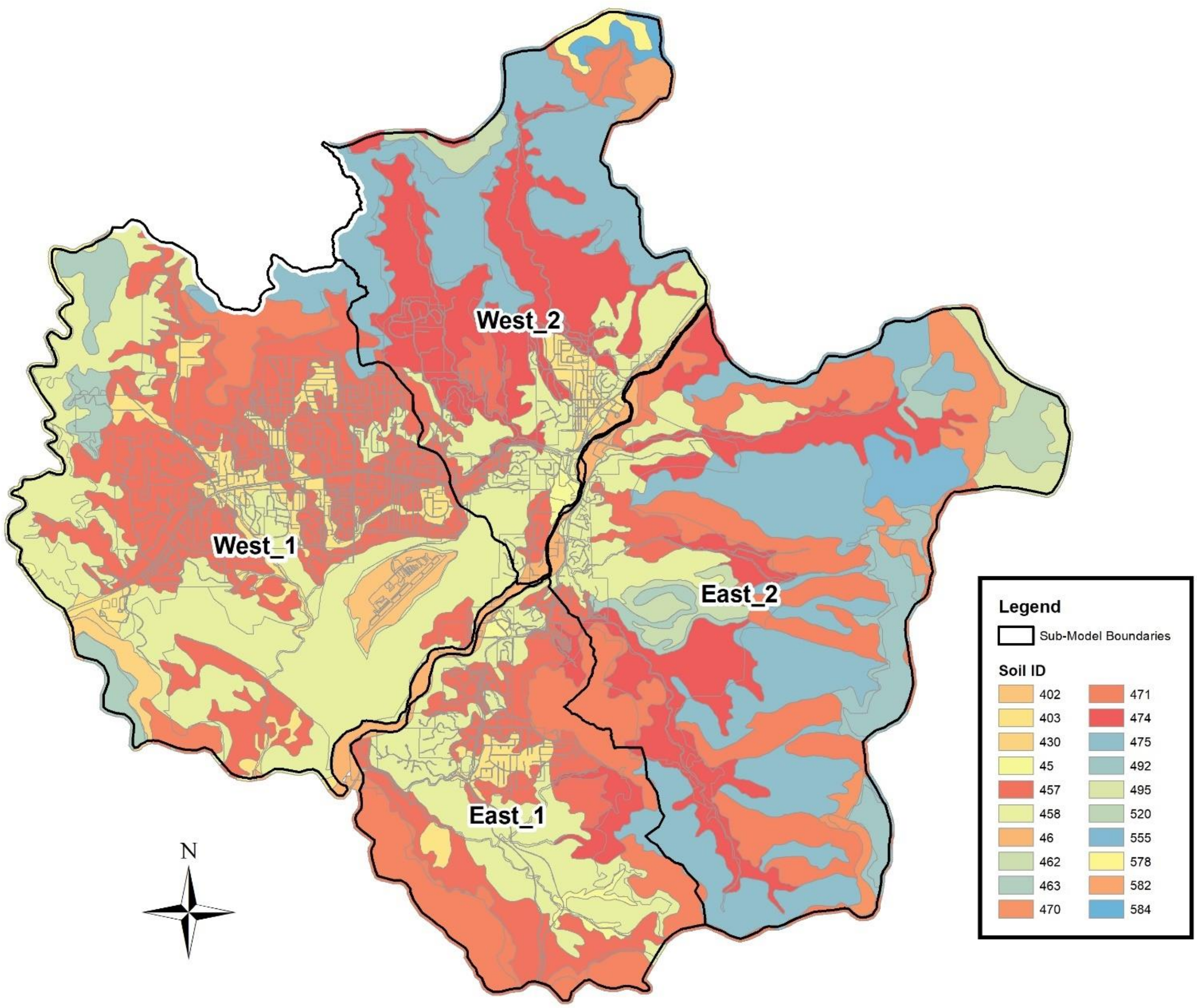

Figure 3-5. Soil Type Distribution

3.3.7. ARF.DAT

Building footprints were obtained from the City of Sedona's GIS department. The buildings were intersected with grid elements to compute the percentage of the obstructed area and assigned to area reduction factors (ARFs) for each cell. The totally blocked cell element routine ("T Line") was not used in order to simplify file development. Totally blocked cells were assigned 1.0 in the partially blocked grid attribute (i.e., the IDG column). Similarly, to ease file development, width reduction factors (WRF) were not used in this study and were assigned a 0 value in the ARF.DAT file.

It should be noted that the IRAINBUILDING value in the RAIN.DAT file was set to 1.0 to simulate rainfall runoff from the roofs of ARFs associated with buildings.

3.3.8. CHAN.DAT and CHANBANK.DAT

The modeling team evaluated preliminary model results for the Soldier Wash improvements from upstream of Brewer Rd to the outfall in the Oak Creek right overbank. The channel improvements were designed and constructed after the 2009 flood in the Tlaquepaque Arts and Shopping Center. The improvements generally consists of a 22-foot wide rectangular channel and bridges although there are slight variations in geometry and construction material. The 15-foot grid element elevation sampling was not adequately representing the channel geometry and it was determined the one-dimensional channel routing module within FLO-2D was necessary.

The channel geometry and invert profile was taken from as-built construction drawings and coded in the CHAN.DAT and CHANBANK.DAT files to simulate the significant capacity of the newly constructed system. **Figure 3-6** shows a picture of a portion of the channel under construction.

One-dimentional channel modeling and input files are only within the West_2 sub-model.

Figure 3-6 Soldier Wash Channel Construction

3.3.9. HYSTRUC.DAT

Hydraulic structures were incorporated into the FLO-2D models using the HYSTRUC.DAT input file. The City of Sedona storm drain GIS database was the primary source for identifying the location, size, type, shape, and culvert configuration of structures within the study area. Additional data were collected by JE Fuller for culverts and structures not included in the City's GIS database. Refer to the Sedona Storm Water Master Plan Update Phase 1 Report (2020) for more detail related to the data collection effort. As-built construction drawings were collected from ADOT for SR 89A and SR 179, from City storm water CIP projects, and significant culverts and storm drains were digitized. Additional information related to significant drainage structures were collected in the field in all three phases of the SWMPU.

Hydraulic structures were modeled using two approaches depending on the structure geometry, inlet type, and number of barrels. The hydraulic capabilities of standard single-barreled structures (structures coded with an 'F' character) are calculated and determined within FLO-2D using the FHWA generalized culvert equations. All other structures (multi-barreled, catch basin inlet, or other uncommon inlet types) were coded with a 'T' structure character. A 'T' character prompts FLO-2D to refer to a specified rating table calculated externally to determine the hydraulic routing. The rating tables for these structures were developed by JE Fuller using FHWA HDS #5: Hydraulic Design of Highway Culverts Third Edition (April 2012), assuming inlet control.

Clogging factors used for the rating tables were derived from the Drainage Design Manual for Yavapai County. The clogging factors applied to the rating tables are:

- Equivalent Diameter <= 48 inches: Reduce available opening area by 50%
- Equivalent Diameter > 48 inches: Reduce available opening area by 20%

Figures depicting the general location of the culverts and stormdrains included in the hydrologic modeling are provided in **Figure 3-7** through **Figure 3-10**.

Lastly, significant storm drain systems were modeled with the storm drain capacity limitation function in the HYSTRUC.DAT file with the exception of the Thunder Mountain/Harmony-Windsong system (see **Section 3.3.10**). Similar to culvert ratings, rating tables were developed based on the pipe inlet or catch basin inlet geometry and the connector pipe. This means that at low depths the curb/grate opening controls the flow, but at higher depths, the connector pipe capacity controls the flow. Finally, the multiple inlet systems were set to outflow to a common outflow node (grid element) and the "D" line functionality that limits the total flow in the storm drain system to a user-specified discharge was used to limit the flow to the trunk line capacity. This capacity was determined by either using the design discharge obtained from the drainage design report for the system provided by the City (when available), or by calculating the normal depth full flow capacity of the trunk line. The limiting pipe capacities that were used in the FLO-2D modeling are shown in **Table 3-8**.

Table 3-8. Storm Drain System Capacity Enforced

Storm Drain System	FLO-2D Sub-Model	Outfall Node	Limiting Discharge (cfs)
Coffee Pot Drive 72-in Dia CMP and SRP	West_1	612,699	490
Stanley Steamer	West_1	908,385	500
Dry Creek Road 60-in CMP	West_1	604,308	313
Farmer Brother's Drive 48-in CMP	West_1	332,557	112
Juniper Hills	West_2	976,369	128
Indian Cliffs Road CMP	East_1	275,194	197
Vista Bonita Drive 60-in SRP	East_1	258,502	325

**Note: not every modeled storm drain is shown*

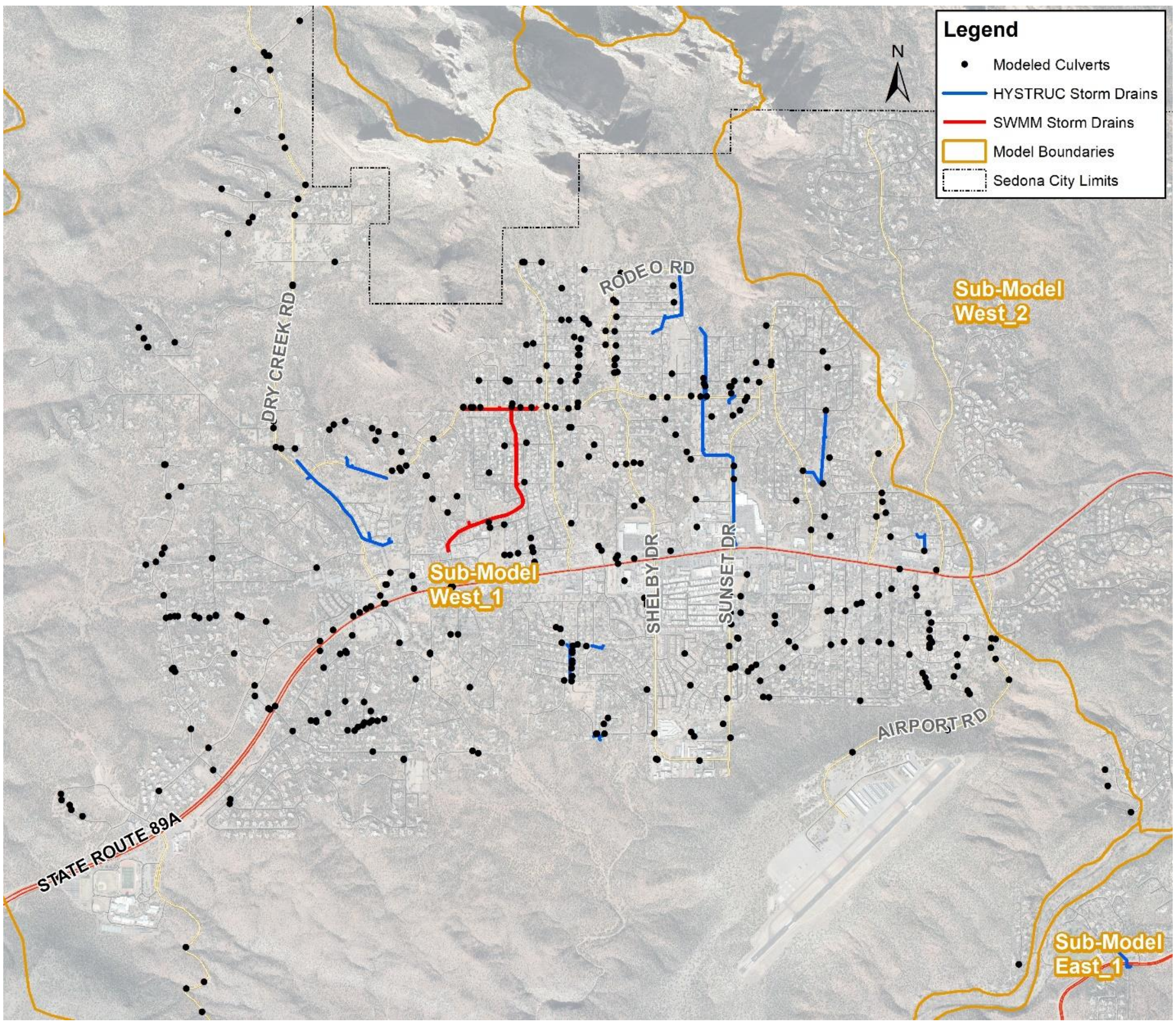

Figure 3-7. Sub-model West_1 modeled culverts and storm drains

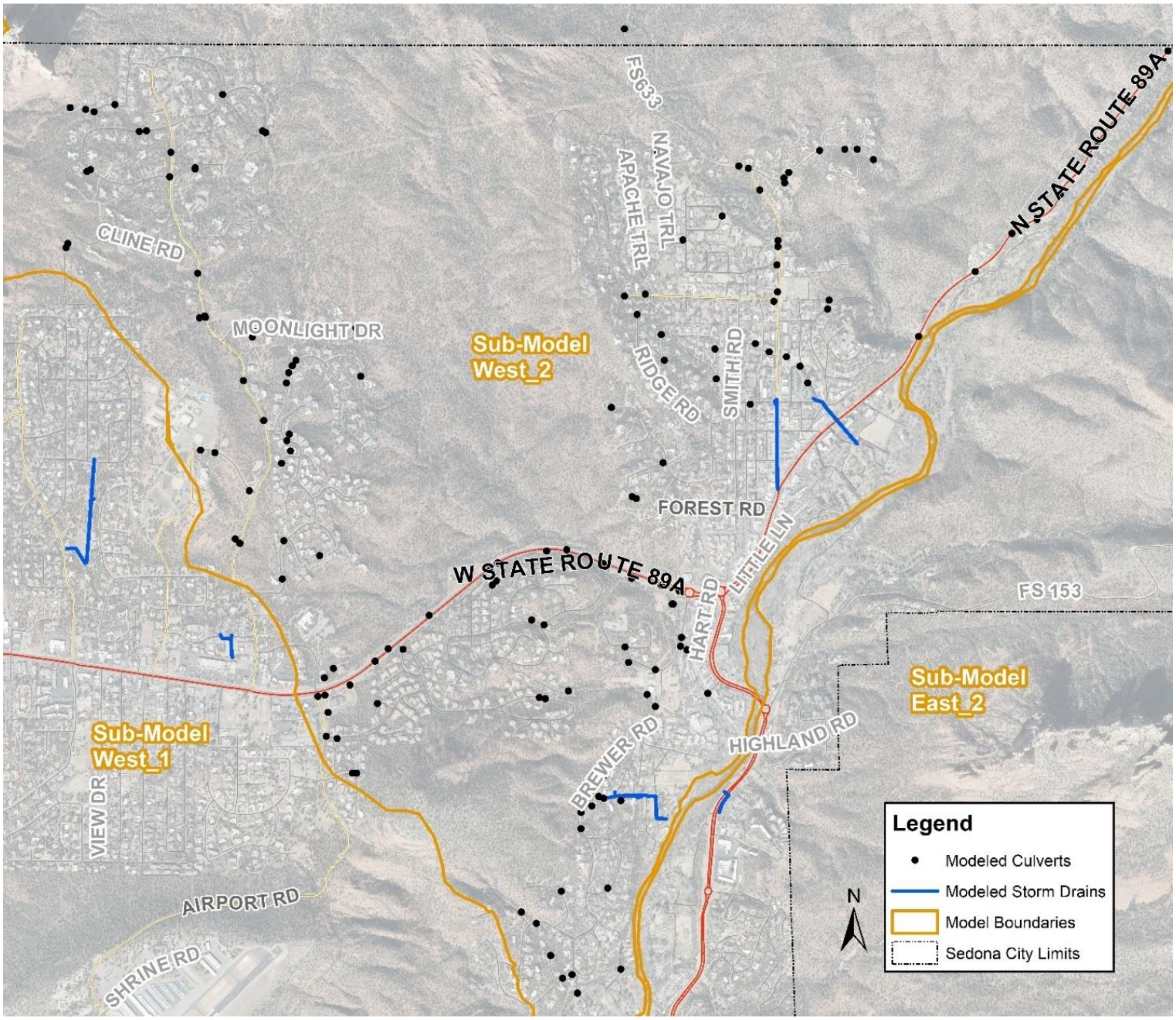

Figure 3-8. Sub-model West_2 modeled culverts and storm drains

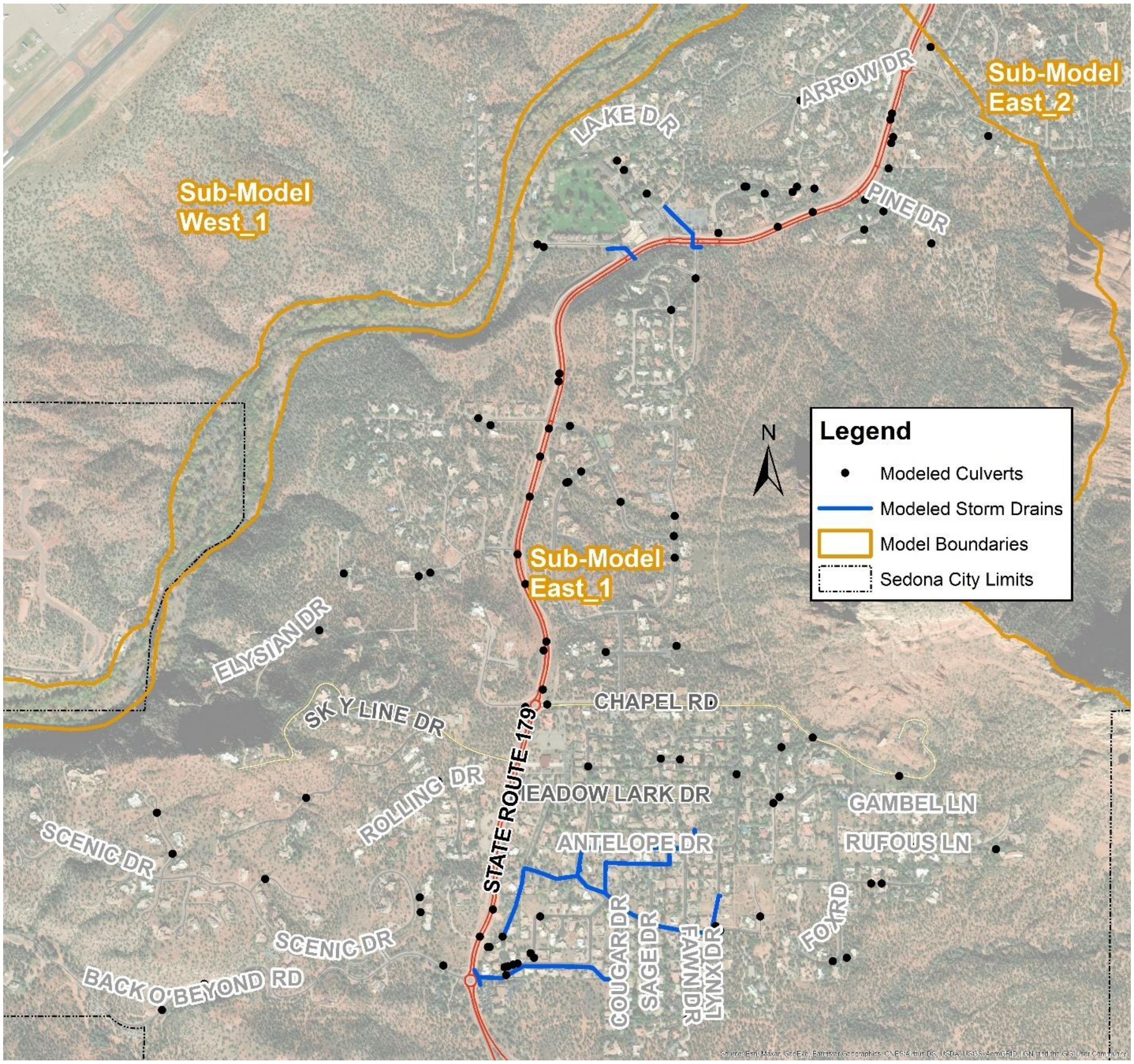

Figure 3-9. Sub-model East_1 modeled culverts and storm drains

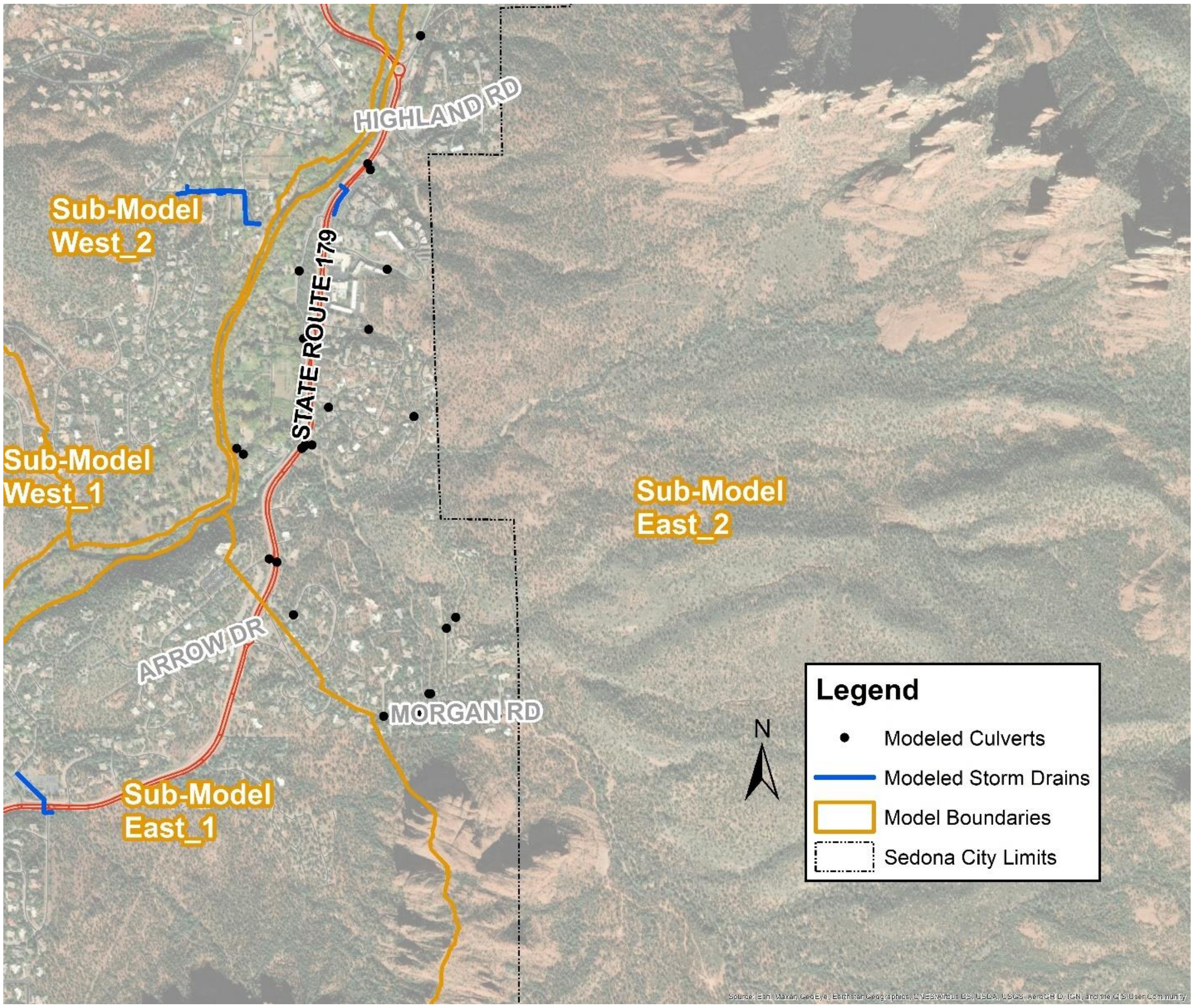

Figure 3-10. Sub-model East_2 modeled culverts and storm drains

3.3.10. EPA SWMM

The modeling team evaluated preliminary model results for the Thunder Mountain/Harmony-Windsong stormdrain system (refer to **Figure 3-7**) initially modeled with the HYSTRUC.DAT with D line total flow limiting functionality. It was determined that the system capacity was not being achieved and it was decided that this system would be more suitable for the EPM SWMM module within FLO-2D. Therefore, a SWMM model was developed for the system and integrated in the FLO-2D model. SWMM input files listed in **Table 3-2** were developed for the system and ran and the results were very reasonable.

SWMM modeling and input files are only within the West_1 sub-model.

3.3.11. LEVEE.DAT

A single linear section of 'levee' was included north of Thunder Mtn. Rd. between Concord Dr. and Andante Dr (blue line, **Figure 3-11**). This levee was added to enforce the section of engineered channel directing flow to one of the main inlets of the Thunder Mtn./Harmony-Windsong drainage systems. The team believes that due to the rasterization of the detailed topography, the initial FLO-2D results were a misrepresentation of what actually occurs during a storm event at this particular location. The team performed a hydraulic analysis of the dual 60" SRP inlet considering the parameters listed in the as-built drawings and concluded that the topography was over-generalizing key features leading up to the inlet, resulting in erroneous overtopping of Thunder Mtn. Rd. The 'levee' was added to better direct flow to the inlet, as the actual engineered channel was intended to do.

The levee modeling and associated input file is only within the West_1 sub-model.

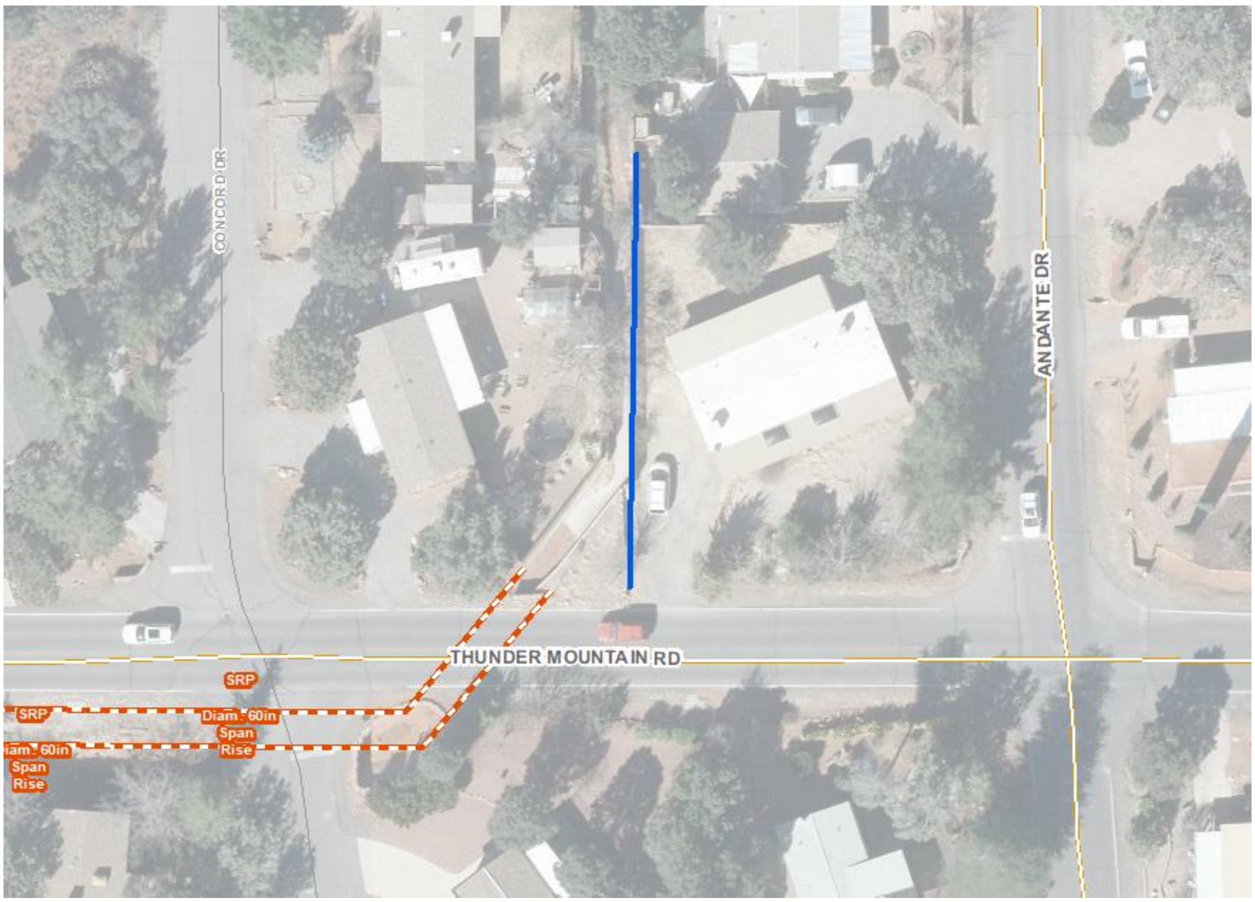

Figure 3-11. Location of only 'levee' (blue line) modeled as a part of the hydrologic analysis.

3.3.12. FPXSEC.DAT

Floodplain cross-sections were developed and included in the FPXSEC.DAT file to query flow hydrographs and peak discharges from the FLO-2D model at key locations within the study area such as:

- Major flow concentration locations
- Upstream/downstream of a hydraulic structure or road crossings
- Areas of interest to the City of Sedona
- Locations of previous study concentration points (HEC-1) for comparison purposes
- Upstream of HEC-RAS Model reaches

3.3.13. CONT.DAT AND TOLER.DAT

CONT.DAT and TOLER.DAT contain numerical stability and simulation controls for the FLO-2D model. The CONT.DAT file controls simulation time, output report time interval, some numerical controls, and model switches such as infiltration and rain. For the 24-hour storm duration, the total simulation time was set to 30 hours. This simulation time was sufficient to ensure the flood wave has traveled through the entire study area.

The numerical controls used in the CONT.DAT file are the shallow flow Manning's n-value (SHALLOWN) and limiting Froude number (FROUDL) values. For this study, the shallow n-value in the CONT.DAT file was set to 0.20, however, spatially-varied shallow n-values were used to override this parameter based upon land use. The appropriate toggles were checked for input data files (e.g. HYSTRUC.DAT, LEVEE.DAT).

The TOLER.DAT file contains the numerical tolerance settings that are specified for the model. These settings are the flow exchange tolerance (TOLGLOBAL), percent allowed change in flow depth (DEPTOL), and Courant-Friedrich-Lewy numerical stability parameter for floodplain grid element flow exchange (COURANTFP). The TOLGLOBAL value was set to 0.004 feet, and this value was subtracted from all initial abstraction values in the INFIL.DAT file. A COURANTFP value of 0.60 was initially used for all runs, however, it was reduced to 0.40 as necessary to improve model stability. These values have been used in other studies by JE Fuller to yield reasonable results.

4.0 Model Results

4.1. Overview

The 25- and 100-year, 24-hour storms were the main focus of the SWMPU existing conditions modeling conducted during Phase II of the SWMPU. The 25-year frequency is the design storm for storm water infrastructure within the City. The 25- and 100-year storms were used to develop and run the initial model input files, fine-tune the input data, model troubleshooting, and model verification. The 10-, 50-, and 500-year storm models were run in the final stage of Phase III after all model updates had been conducted. This will be explained further in the following sections.

4.2. Preliminary Results and Verification

The preliminary FLO-2D model results were compared with USGS Regression Equations, the original 2005 Storm Water Master Plan (Dibble Enginering), and two other studies during Phase II of the SWMPU project. Based on these comparisons, further adjustments were made to model parameters as described in the following sections.

4.2.1. Comparisons with USGS Regression Equation Results

The preliminary 25- and 100-year FLO-2D discharges were compared to estimates using the regional regression equations presented in the 2014 USGS SIR (United States Geological Survey, 2014). These equations were based upon annual peak flow data collected up through water year 2010 with a minimum period of record of 10 years. Separate equations were developed for various frequencies storms for each of the 5 regionalized areas within Arizona. The City of Sedona is within Flood Region 4 (Central Highlands) as shown in **Figure 4-1**. The equations for this region estimate a peak discharge with the input of basin drainage area, mean annual precipitation, and elevation (elevation was used only for the 10-, 20-, and 50-year annual exceedance probabilities).

The 2005 SWMP subbasin boundaries were used to determine the drainage area for the FLO-2D model results since FLO-2D isn't dependent on and doesn't report drainage area given the model methodology. The results comparison is discussed in the next section.

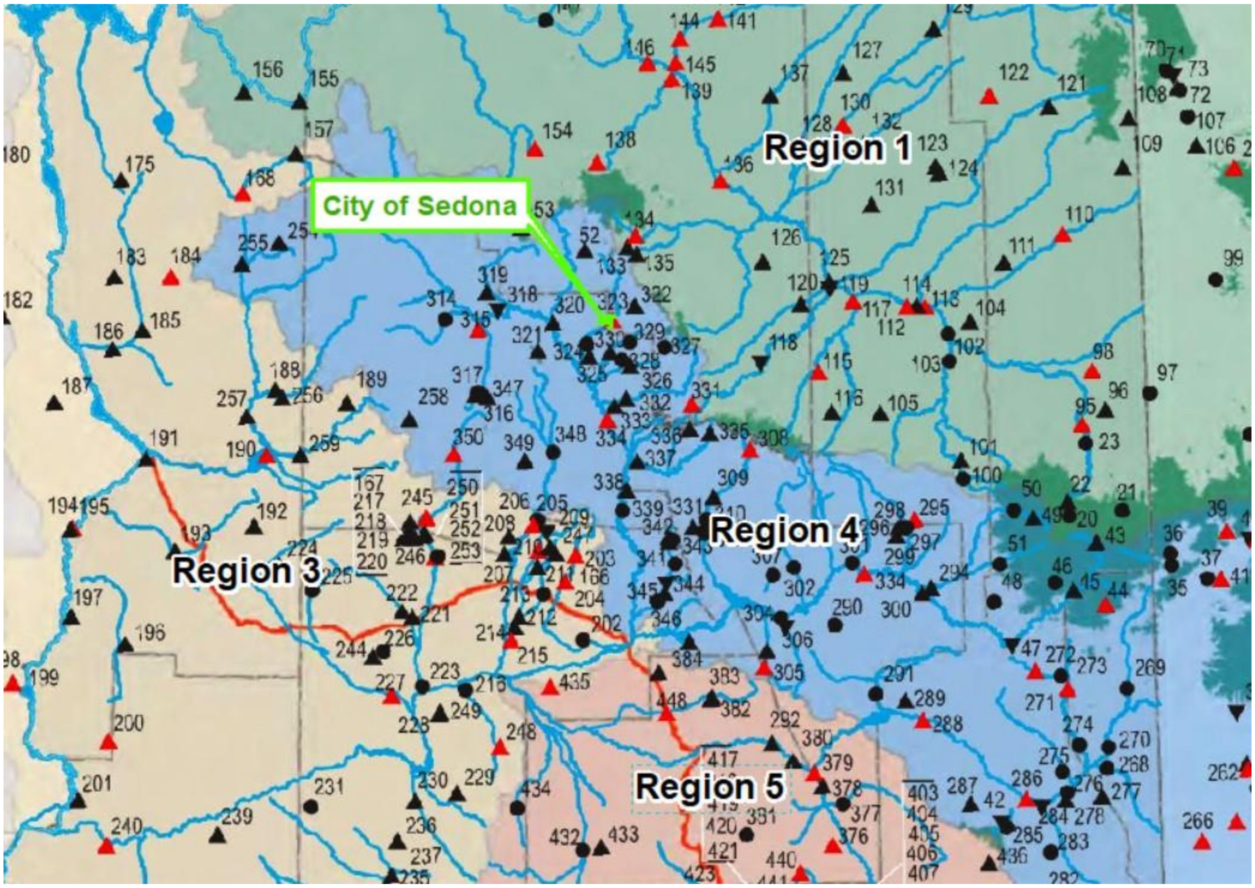

Figure 4-1. USGS Regions with Arizona

4.2.2. Comparisons with Past Studies and Model Verification

The preliminary 25- and 100-year FLO-2D discharges were compared to the 2005 SWMP along with the 2018 Oak Creek FDS (Atkins, 2018), and the Sunset Drive Hydrology Report (JE Fuller, 2020). Locations of comparison within the City of Sedona were strategically selected to coincide with various CIP projects, to compare both small and large watersheds, urbanized, and non-urbanized locations. The locations of comparison are shown in **Figure 4-2**. Based on the comparison, final model refinements were made as discussed in the next section.

Finally, the FLO-2D models were run with two historic storm events using Next Generation Weather Radar (NEX-RAD) and the results were compared to observations made on the ground resulting from the storms.

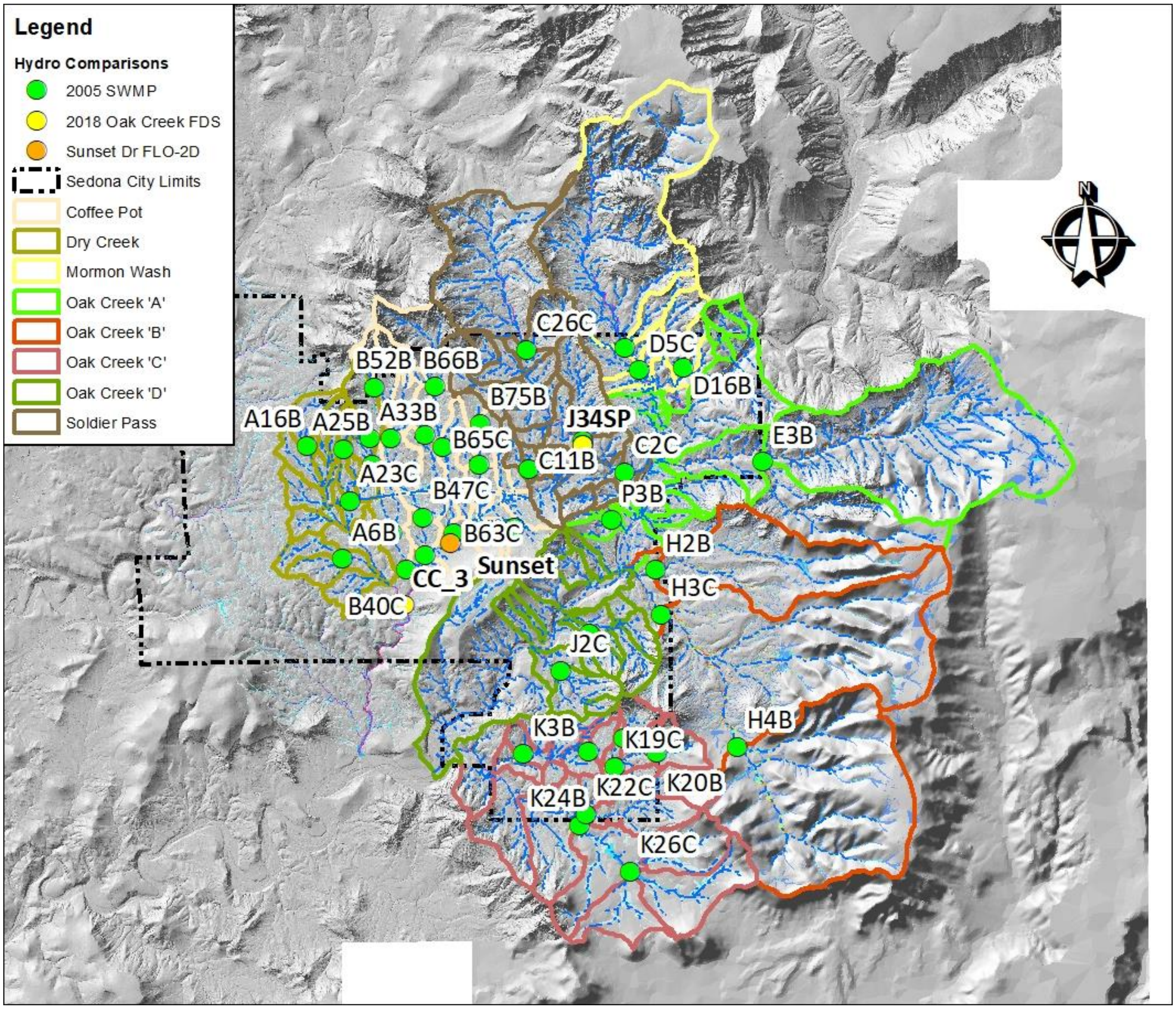

Figure 4-2. Hydrologic Comparison Locations

4.2.3. Model Adjustments

In general, the initial model peak flow results were somewhat higher for the comparison locations when compared to the USGS Regression equation results, the 2005 SWMP, and other studies. This was not a surprise to the study team as FLO-2D has been found to produce higher peak discharges for steep, tributary watercourses when compared to older hydrology models. Lessons learned from past studies with similar steep watershed characteristics were employed to calibrate the results. The following model input parameters were adjusted.

- Limiting Infiltration Depth – The Limiting Infiltration Depth was increased from 4-inches to 8-inches. Four inches is typically used as a starting point for studies or for studies that have limited soil information and is considered conservative.

- Rock Outcrop – The Percent Rock Outcrop was reduced by 50% for soil map units that contain rock. Refer to **Table 3-6**. This adjustment is consistent with the standard of practice of assigning percent rock outcrop reported in soil surveys as 50% effective in HEC-1 or HEC-HMS modeling.

It should be noted that the base Manning's n-values for steep watercourses within the model areas were originally assigned using findings from past studies and didn't require further adjustment. Higher than expected roughness coefficients are recommended for steep watercourses as outlined in a 1985 USGS Paper (Jarrett, 1985).

The final results comparison is summarized in the next section.

4.2.4. Hydrologic Comparison and Verification Results

2005 SWMP Comparison

The first comparison consists of the final 25-year and 100-year FLO-2D results to the 2005 SWMP existing conditions. It should be noted that the Future Conditions models were proposed and adopted for the 2005 SWMP (Dibble, 2005). The primary reason for this comparison is because the 2005 Future Conditions models were not developed or delivered to the City for the Oak Creek Sub-basins (A, B, C, and D) which cover the East_1 and East_2 FLO-2D sub-models. The comparison table is shown in **Table 4-1**. There isn't a consistent trend when comparing the 25- and 100-year Phase II FLO-2D results with the USGS regression equations. However, the 25- and 100-year 2021 (Phase II) FLO-2D results are somewhat lower than the 2005 SWMP results for the urbanized portions of the watershed.

The 100-year peak discharges from the FLO-2D model results and the 2005 SWMP were also plotted against the regression equations, including +/- one standard error from the mean as shown in **Figure 4-3**. The mean regression line was computed using the mean precipitation for the entire watershed. This graph illustrates that the FLO-2D results are generally less than the 2005 SWMP and consistent with the USGS regression equations for smaller watersheds however, somewhat higher than the USGS regression equations for larger watersheds.

Table 4-1. 2021 FLO-2D Model Results Comparison to USGS Regression Equations and 2005 SWMP Existing Conditions Results

								Flood Region 4 Regression Discharges (cfs)				Dibble Flows 24H HEC-1 (cfs)				FLO2D FPXSEC Comparison				Difference (Regression minus FLO2D)				Difference (Dibble minus FLO2D)	Difference (Dibble minus FLO2D)
Sub-Model	Conc. Point KKID	Contributing Sub-basins	Comparison GIS FPXSEC ID	FPXSEC.DAT Sub-Model ID	Contributing Area (sq. mi.)	Mean Elev	Mean Ann Precip (in)	Q2	Q10	Q25	Q100	Q2	Q10	Q25	Q100	Q2	Q10	Q2524H	Q10024H	Q2	Q10	Q25	Q100	Q25	Q100
	A6B	A6B	173	137	0.1171	4428.5	15.3	13	70	120	220	-	-	204	264	-	-	109	224	0	0	11	-4	95	40
	A16B	A16B	818	368	0.1352	4597.7	15.5	14	70	120	230	-	-	201	262	-	-	61	144	0	0	59	86	140	118
	A25B	A25B	687	335	0.0622	4665.9	15.6	9	40	80	150	-	-	85	111	-	-	37	91	0	0	43	59	48	20
	A29C	A29B, A30B, A31B, A32B & A33B	819	369	0.2571	4610.2	15.7	22	110	180	350	-	-	618	796	-	-	50	96	0	0	130	254	568	700
	B45C	See Workmap	704	352	2.5427	4605.6	15.1	102	430	700	1290	-	-	3178	4108	-	-	1455	2749	0	0	-755	-1459	1723	1359
	B50C	B50B, B51B, B52B & B56B	178	142	0.3570	4886.0	15.9	28	120	210	390	-	-	591	762	-	-	251	640	0	0	-41	-250	340	122
	B52B	B52B	558	254	0.0683	5309.5	16.5	9	40	70	140	-	-	136	175	-	-	73	170	0	0	-3	-30	63	5
	B60C	B60B & B61B	214	178	0.1000	4601.1	15.7	12	60	100	200	-	-	196	252	-	-	80	147	0	0	20	53	116	105
	B65C	B65B, B66B & B69B	583	262	0.5099	4928.1	15.9	35	150	250	480	-	-	488	630	-	-	143	276	0	0	107	204	345	354
West_1	B66B	B66B	697	345	0.3548	5081.4	16.4	27	120	200	380	-	-	454	586	-	-	341	749	0	0	-141	-369	113	-163
	B73C	B73B, B74B & B75B	831	372	0.2074	4548.2	14.7	19	90	150	280	-	-	498	638	-	-	245	387	0	0	-95	-107	253	251
	B82B	B82B	808	367	0.1165	4606.1	14.7	13	60	100	190	-	-	324	413	-	-	88	177	0	0	12	13	236	236
	A23C	See regression_subbasin2.xls	882	402	0.1455	4533.2	15.0	15	70	120	240	-	-	745	966	-	-	333	688	0	0	-213	-448	412	279
	A33B	See regression_subbasin2.xls	883	403	0.1474	4672.7	15.6	15	70	130	240	-	-	392	503	-	-	104	260	0	0	26	-20	288	243
	B42C	See regression_subbasin2.xls	839	375	0.1571	4387.6	14.9	16	80	140	260	-	-	375	481	-	-	174	345	0	0	-34	-85	201	136
	B47C	See regression_subbasin2.xls	239	203	0.8460	4646.6	14.8	49	200	340	630	-	-	1059	1371	-	-	451	981	0	0	-111	-351	608	390
	B63C	See regression_subbasin2.xls	235	199	0.6318	4833.3	14.8	40	160	270	500	-	-	2158	2780	-	-	990	1744	0	0	-720	-1244	1169	1036
	B75B	See regression_subbasin2.xls	226	190	0.0585	4606.7	14.9	8	40	70	130	-	-	166	212	-	-	105	178	0	0	-35	-48	61	34
	B40C	See regression_subbasin2.xls	676	324	2.2520	4527.3	15.0	94	400	660	1220	-	-	3306	4275	-	-	1551	2994	0	0	-891	-1774	1755	1281
	C11B	C11B	821	172	0.0654	4515.2	14.5	9	40	70	140	-	-	129	167	-	-	22	71	0	0	48	69	107	96
	C19C	C19B & C20B	822	173	0.1065	4604.7	15.2	12	60	100	200	-	-	202	263	-	-	82	142	0	0	18	58	120	121
	C26C	C26B & C28B	586	125	1.3903	4769.1	16.9	68	310	540	1030	-	-	1183	1544	-	-	817	2035	0	0	-277	-1005	366	-491
	C29B	C29B	310	25	0.3515	4449.8	15.0	27	130	220	410	-	-	339	443	-	-	132	459	0	0	88	-49	207	-16
West_2	D11B	D11B	823	174	2.4362	5476.5	21.9	99	480	880	1780	-	-	1212	1676	-	-	2145	4722	0	0	-1265	-2942	-933	-3046
	D16B	D16B	824	175	0.1921	4707.3	17.0	18	90	170	330	-	-	173	248	-	-	177	438	0	0	-7	-108	-4	-190
	D5C	D10C, D11B, D9B & D5B	731	149	2.7265	5385.2	20.9	106	500	900	1810	-	-	1251	1734	-	-	2135	4856	0	0	-1235	-3046	-884	-3122
	C2C	See regression_subbasin2.xls	810	167	3.2497	4592.2	14.1	120	460	740	1320	-	-	2296	2993	-	-	989	2746	0	0	-249	-1426	1307	247
	P3B	See regression_subbasin2.xls	298	13	0.0343	4470.7	14.3	6	30	50	100	-	-	21	28	-	-	23	54	0	0	27	46	-2	-26
	C12C	See regression_subbasin2.xls	589	128	2.6300	4636.9	15.0	104	430	700	1290	-	-	2022	2638	-	-	940	2589	0	0	-240	-1299	1082	49
	I7B	I7B	770	101	0.0750	4355.7	15.2	10	50	90	170	-	-	117	157	-	-	42	128	0	0	48	42	75	29
	J2C	J2B & J3B	766	97	0.2428	4387.3	15.5	21	110	190	360	-	-	493	647	-	-	101	316	0	0	89	44	392	331
	K3B	K3B	825	108	0.0552	4320.8	15.7	8	50	80	160	-	-	150	192	-	-	91	148	0	0	-11	12	59	44
	K18B	K18B	434	41	0.1036	4677.4	15.9	12	60	100	200	-	-	219	283	-	-	69	189	0	0	32	11	151	94
	K12B	K12B	440	47	0.0673	4348.5	15.8	9	50	90	180	-	-	189	243	-	-	64	127	0	0	26	53	125	116
East_1	K19C	K19B & K20B	596	73	0.2880	4542.2	16.5	24	120	220	420	-	-	507	657	-	-	79	256	0	0	141	164	428	401
	K20B	K20B	826	109	0.1685	4633.6	16.7	17	90	150	300	-	-	349	452	-	-	42	145	0	0	108	155	307	307
	K22C	K22B & K23B	400	7	0.4931	4493.9	17.1	34	180	320	630	-	-	632	822	-	-	94	400	0	0	226	230	538	422
	K24B	K24B, K25B, K26B & K27B	399	6	1.5983	4514.9	17.1	75	380	660	1260	-	-	532	694	-	-	37	382	0	0	623	878	495	312
	K26C	K26B & K27B	426	33	0.7679	4543.1	17.3	46	240	420	820	-	-	942	1227	-	-	46	297	0	0	374	523	896	930
	E3B	E3B	796	111	0.7859	5483.8	21.3	47	230	420	850	-	-	527	706	-	-	738	1558	0	0	-318	-708	-211	-852
East_2	H2B	H2B	827	114	1.3545	4876.5	16.3	67	290	480	920	-	-	1085	1472	-	-	717	1887	0	0	-237	-967	368	-415
	H4B	H4B	828	115	2.6443	5501.0	21.0	104	480	860	1720	-	-	2082	2826	-	-	1347	3790	0	0	-487	-2070	735	-964
	H3C	H3B & H4B	829	116	5.8331	5290.0	20.1	176	810	1410	2770	-	-	3671	4983	-	-	2037	6021	0	0	-627	-3251	1634	-1038

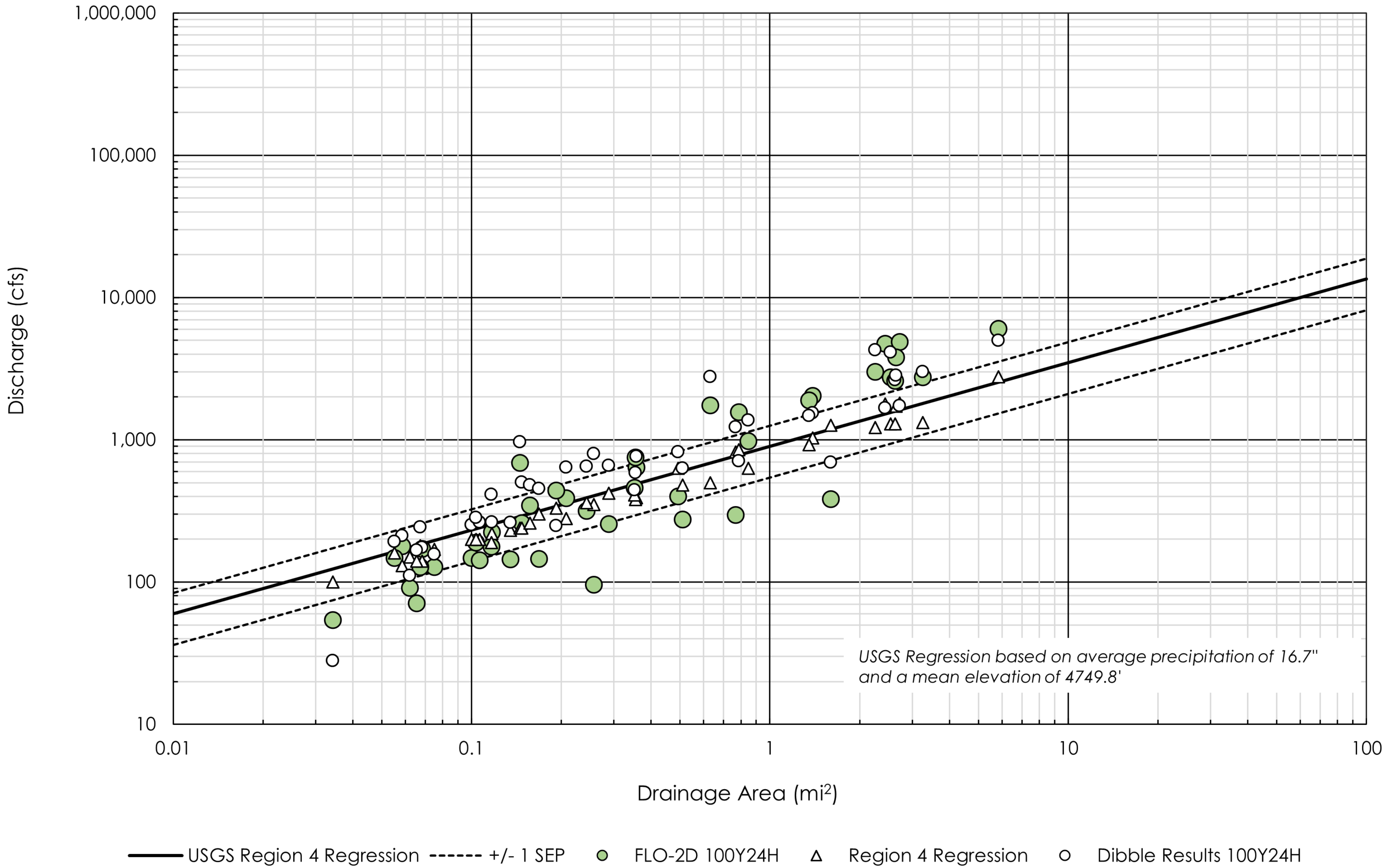

Figure 4-3. 2021 100-Year FLO-2D Model Results Comparison to USGS Regression Equations and 2005 SWMP Existing Conditions Results

The next comparison consists of the final 25-year and 100-year FLO-2D results to the 2005 SWMP future conditions results. The comparison table is shown in **Table 4-2**. The 25-year 2021 FLO-2D results are significantly lower than the 2005 SWMP results, however, the 100-year results comparison is mixed.

The 100-year peak discharges from the FLO-2D model results and the 2005 SWMP were also plotted against the regression equations, including +/- one standard error from the mean as shown in **Figure 4-4**. Similar to the existing conditions comparison, this graph illustrates that the FLO-2D results are generally less than the 2005 SWMP and consistent with the USGS regression equations for smaller watersheds, however, somewhat higher than the USGS regression equations for larger watersheds.

Table 4-2. 2021 FLO-2D Model Results Comparison to USGS Regression Equations and 2005 SWMP Future Conditions Results

								Flood Region 4 Regression Discharges (cfs)				Dibble Flows 24H HEC-1 (cfs)				FLO2D FPXSEC Comparison				Difference (Regression minus FLO2D)				Difference (Dibble minus FLO2D)	Difference (Dibble minus FLO2D)
Sub-Model	Conc. Point KKID	Contributing Sub-basins	Comparison GIS FPXSEC ID	FPXSEC.DAT Sub-Model ID	Contributing Area (sq. mi.)	Mean Elev	Mean Ann Precip (in)	Q2	Q10	Q25	Q100	Q2	Q10	Q25	Q100	Q2	Q10	Q2524H	Q10024H	Q2	Q10	Q25	Q100	Q25	Q100
West_1	A6B	A6B	173	137	0.1171	4428.5	15.3	13	70	120	220	-	-	197	257	-	-	109	224	0	0	11	-4	88	33
	A16B	A16B	818	368	0.1352	4597.7	15.5	14	70	120	230	-	-	180	244	-	-	61	144	0	0	59	86	119	100
	A25B	A25B	687	335	0.0622	4665.9	15.6	9	40	80	150	-	-	81	107	-	-	37	91	0	0	43	59	44	16
	B45C	See Workmap	704	352	2.5427	4605.6	15.1	102	430	700	1290	-	-	3803	5362	-	-	1455	2749	0	0	-755	-1459	2348	2613
	B50C	B50B, B51B, B52B & B56B	178	142	0.3570	4886.0	15.9	28	120	210	390	-	-	628	849	-	-	251	640	0	0	-41	-250	377	209
	B52B	B52B	820	370	0.0683	5309.5	16.5	9	40	70	140	-	-	128	168	-	-	63	131	0	0	7	9	65	37
	B65C	B65B, B66B & B69B	583	262	0.5099	4928.1	15.9	35	150	250	480	-	-	471	664	-	-	439	767	0	0	-189	-287	32	-103
	B66B	B66B	697	345	0.3548	5081.4	16.4	27	120	200	380	-	-	388	523	-	-	341	749	0	0	-141	-369	47	-226
	B73C	B73B, B74B & B75B	831	372	0.2074	4548.2	14.7	19	90	150	280	-	-	508	655	-	-	245	387	0	0	-95	-107	263	268
	B82B	B82B	808	367	0.1165	4606.1	14.7	13	60	100	190	-	-	288	375	-	-	88	177	0	0	12	13	200	198
	A23C	A23B, A25B, A27B, A28B, A28AB, A29B, A30B, A31B, A32B, A33B	-	-	0.2674	4578.5	15.7	23	110	190	360	-	-	834	983	-	-	278	547	0	0	-88	-187	556	436
	A33B	See regression_subbasin2.xls	883	403	0.1474	4672.7	15.6	15	70	130	240	-	-	75	97	-	-	104	260	0	0	26	-20	-29	-163
	B42C	See regression_subbasin2.xls	839	375	0.1571	4387.6	14.9	16	80	140	260	-	-	392	502	-	-	174	345	0	0	-34	-85	218	157
	B47C	See regression_subbasin2.xls	239	203	0.8460	4646.6	14.8	49	200	340	630	-	-	1238	1759	-	-	451	981	0	0	-111	-351	787	778
	B63C	See regression_subbasin2.xls	235	199	0.6318	4833.3	14.8	40	160	270	500	-	-	2378	3275	-	-	990	1744	0	0	-720	-1244	1389	1531
	B75B	See regression_subbasin2.xls	226	190	0.0585	4606.7	14.9	8	40	70	130	-	-	163	210	-	-	105	178	0	0	-35	-48	58	32
	B40C	See regression_subbasin2.xls	676	324	2.2520	4527.3	15.0	94	400	660	1220	-	-	4145	5956	-	-	1551	2994	0	0	-891	-1774	2594	2962
West_2	C11B	C11B	821	172	0.0654	4515.2	14.5	9	40	70	140	-	-	96	127	-	-	22	71	0	0	48	69	74	56
	C19C	C19B & C20B	822	173	0.1065	4604.7	15.2	12	60	100	200	-	-	183	252	-	-	82	142	0	0	18	58	101	110
	C26C	C26B & C28B	586	125	1.3903	4769.1	16.9	68	310	540	1030	-	-	867	1216	-	-	817	2035	0	0	-277	-1005	50	-819
	C29B	C29B	310	25	0.3515	4449.8	15.0	27	130	220	410	-	-	219	318	-	-	132	459	0	0	88	-49	87	-141
	D11B	D11B	823	174	2.4362	5476.5	21.9	99	480	880	1780	-	-	1438	1990	-	-	2145	4722	0	0	-1265	-2942	-707	-2732
	D16B	D16B	824	175	0.1921	4707.3	17.0	18	90	170	330	-	-	191	270	-	-	177	438	0	0	-7	-108	14	-168
	C2C	See regression_subbasin2.xls	810	167	3.2497	4592.2	14.1	120	460	740	1320	-	-	2195	3247	-	-	989	2746	0	0	-249	-1426	1206	501
	P3B	See regression_subbasin2.xls	298	13	0.0343	4470.7	14.3	6	30	50	100	-	-	21	28	-	-	23	54	0	0	27	46	-2	-26
	C12C	See regression_subbasin2.xls	589	128	2.6300	4636.9	15.0	104	430	700	1290	-	-	1717	2495	-	-	940	2589	0	0	-240	-1299	777	-94

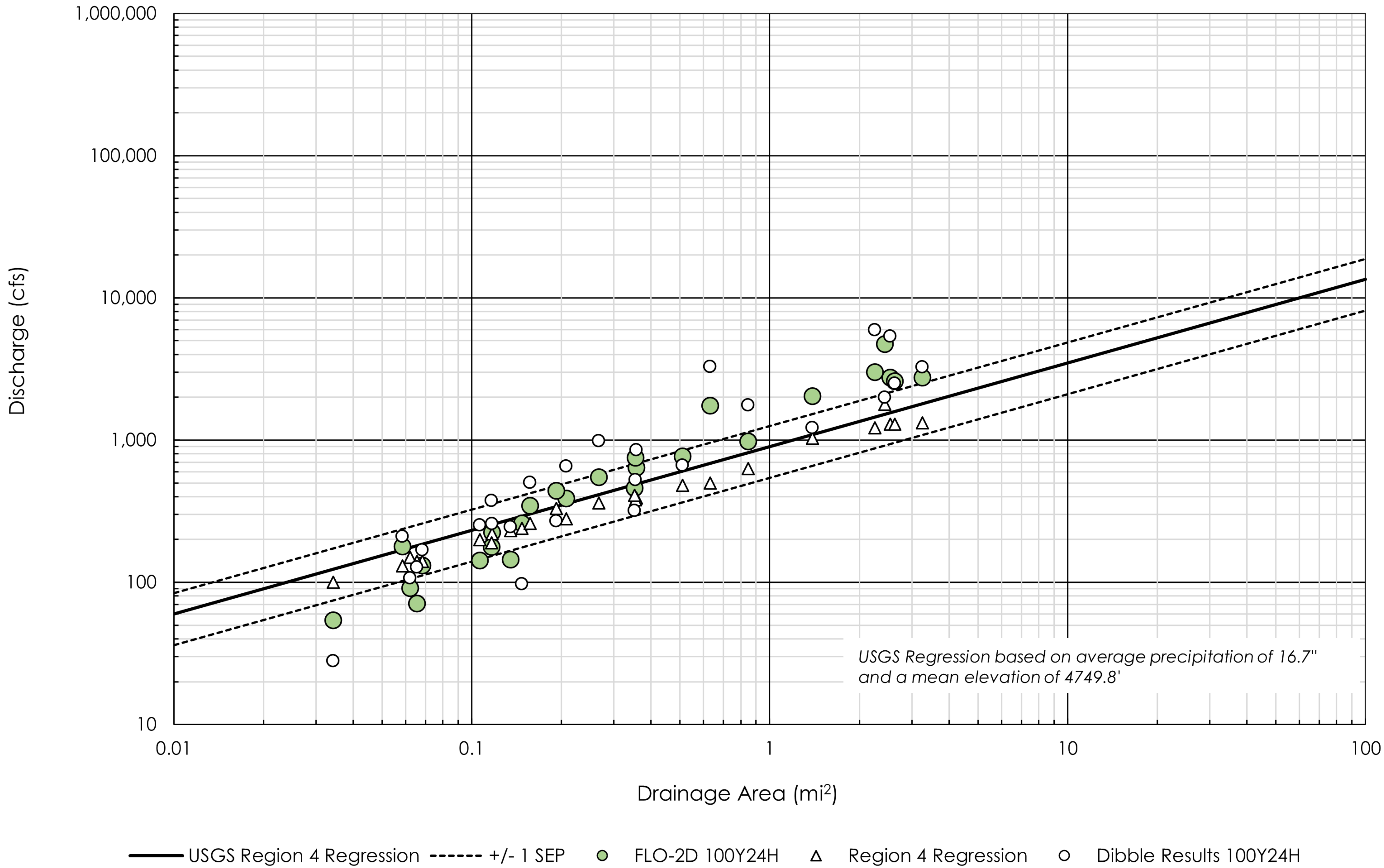

Figure 4-4. 2021 100-Year FLO-2D Model Results Comparison to USGS Regression Equations and 2005 SWMP Future Conditions Results

2018 Oak Creek FDS Comparison

A 100-year hydrograph comparison was made between the 100-year FLO-2D results, the 2005 SWMP, and HEC-HMS model results from the 2018 Oak Creek FDS for Soldier Wash and Carroll Canyon Creek (refer to **Figure 4-2**). The results of both comparisons are shown in **Figure 4-5** and **Figure 4-6**. The FLO-2D peak discharge for Soldier Wash at the comparison location is slightly higher than the prior study results, however, the total runoff volume is significantly less. This location is in the upper Soldier Wash watershed with little or no development. The FLO-2D peak discharge and total runoff volume for Carroll Canyon Creek at the comparison location are significantly lower than the prior study results. This is not unexpected given the significant urbanization within the contributing watershed. Contradictory to past beliefs, urbanization has the effect of attenuating runoff due to intermittent storage and floodwave dampening which has been verified by many past calibrated studies.

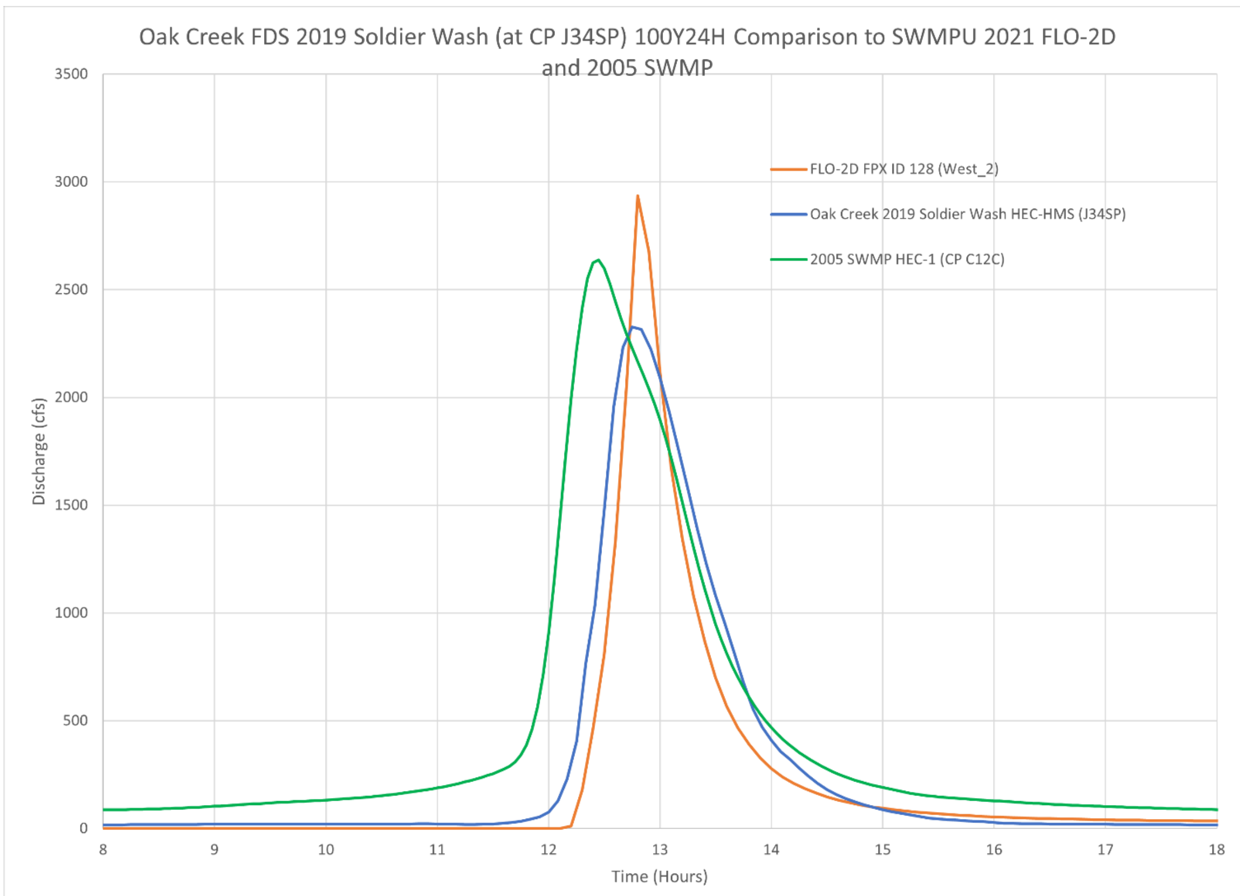

Figure 4-5. Soldier Wash 100-Year, 24-Hour Hydrograph Comparison

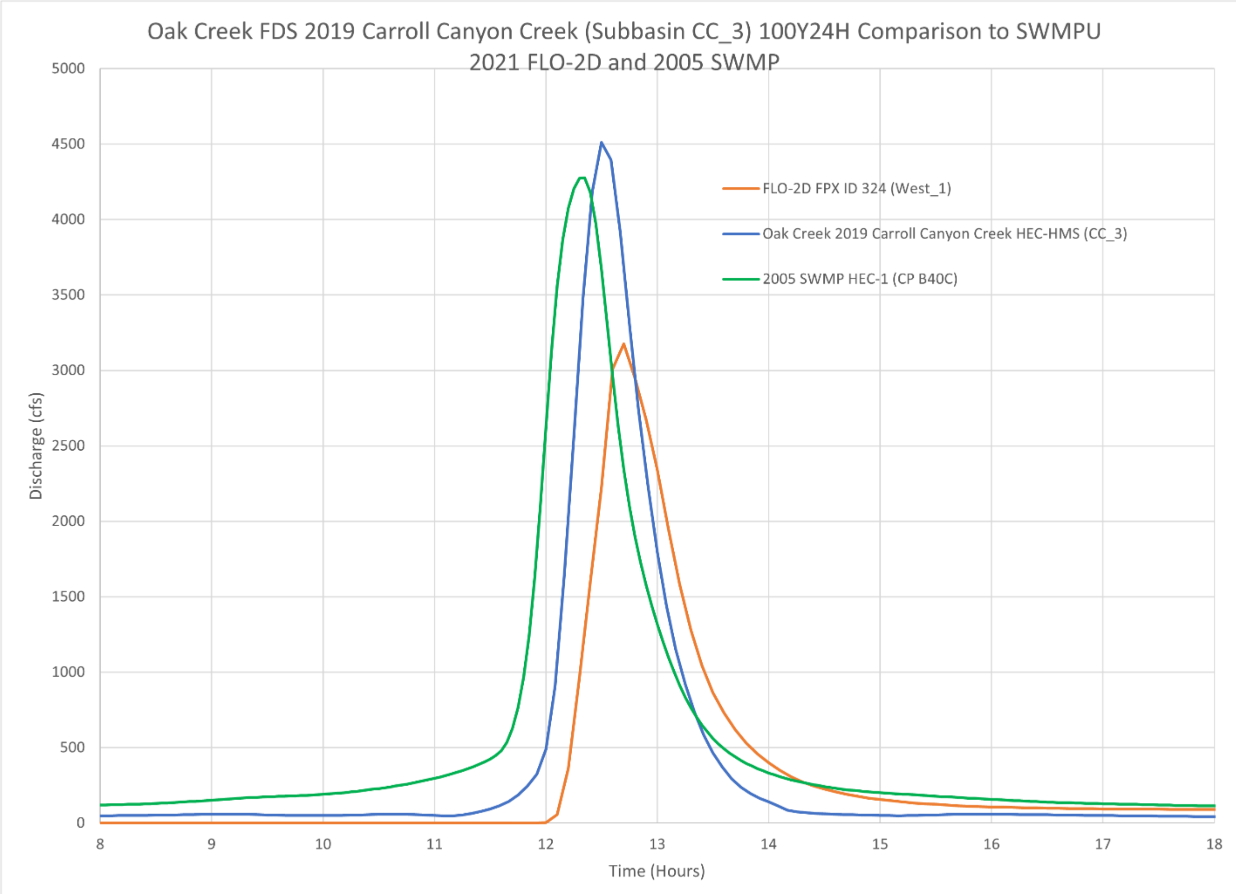

Figure 4-6. Carroll Canyon Creek 100-Year, 24-Hour Hydrograph Comparison

2020 Sunset Drive Hydrology Report Comparison

One final comparison was made between the 2021 (Phase II) FLO-2D model results and the 2020 Sunset Drive Design Hydrology along Carroll Canyon Creek. The estimated 25-year design discharge for the Sunset Drive crossing was 1,145 cfs. The 25-year discharge estimate from the SWMPU project 2021 FLO-2D model is 1,117 cfs. It should be noted that the 2020 Sunset Drive Design Hydrology was also developed using FLO-2D but was a less detailed model that adopted rainfall runoff parameters from the 2005 SWMP.

NEX-RAD Historic Storm Model Verification

JE Fuller initiated an internal verification study using the SWMPU project Phase 2 models as part of an annual Summer Intern program we operate in 2021. The City of Sedona wanted us to review the historic storm of July 25, 2007 that caused significant runoff in Morgan Wash that adversely impacted the a Sewer Lift Station that was under construction at the time. The City provided ground photos of runoff in the wash during the event for verification. JEF also decided to use the September 10, 2009 storm that resulted in several flooding events within the City but is probably best known for the Tlaquepaque Arts and Shopping Center flooding which caused millions of dollars of damage. The models were modified to simulate the conditions on the ground during each event and the historic rainfall obtained from NEX-RAD radar rainfall was used in each model. Both storm models produced results that generally agreed with flood observations on the ground at the time of each storm. A summary document for both storm model verifications are included in the Appendix.

Overall, the 2021 FLO-2D model is yielding reasonable results as compared to the various sources summarized above.

4.2.5. Final Hydrologic and Hydraulic Results

FLO-2D can provide hydrologic and hydraulic results at every location within the model area. Peak flow rates and hydrographics are provided at all predefined floodplain cross sections (FPXSEC.DAT) and hydraulic structure (HYSTRUC.DAT) locations. Large plot Exhibit Maps are included in this report that summarize the model results for each frequency storm. Digital detailed model output and FLO-2D model files are included on a hard drive included in the Appendix.

5.0 Hydraulic Analysis

5.1. Flood Zone Mapping

The purpose of Phase III of the SWMPU project was to update the City of Sedona locally regulated flood zones originally prepared in 1994. The new 100- and 500-year, 24-hour storm SWMPU FLO-2D results were used to define the peak discharges for the hydraulic analysis. The hydraulic modeling performed to provide the basis of the flood hazard zone delineations was a combination of developing new, one-dimensional hydraulic modeling or using the FLO-2D modeling results directly. The following paragraphs discuss in detail the methods used to determine the flood zone delineation limits.

5.1.1. Selection of Studied Watercourses

Watercourses were selected for delineation primarily based on whether the reach has a 100-year discharge (Q100) greater than 50 cfs. No new floodplain was delineated for washes with a Q100 less than 50 cfs, even if there was a pre-existing floodplain, with the exception of drainage channels close to homes that the City has defined as having flooding or erosion problems. Additionally, washes were excluded that were predominantly within US Forest Service land or already defined as regulatory FEMA floodplains. Some exceptions to this criteria were made based on City input and engineering judgement. In some instances, watercourses that didn't meet the 100-year discharge criteria were delineated with a 500-year floodplain that showed high flow depth, inundate a broad area, contains infrastructure, and/or has the potential for future development.

It should be noted that the hydraulic baseline, streamline, or stream centerline for all updated flood zones delineated were given a name with the exception of watercourses that already have a well established name (e.g. Soldier Wash, Carroll Canyon Creek). Names were selected based on nearby placenames, roadnames, or other relevant geographic names obtained from local maps. Furthermore, reach names were provided for flow splits and tributaries in a similar fashion. When a reach name for each segment of the main watercourse was needed for HEC-RAS modeling described below, the name "1" was used. In other words, the reach name of the main watercourse is named 1 (e.g. River = Soldier Wash, Reach = 1).

5.1.2. Floodplain Delineation Methods

Two methods were used to delineate the 100- and 500-year flood zone boundaries of the defined watercourses: HEC-RAS and FLO-2D. The U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) version 6.1.0 was used to create the hydraulic model for the flood zone delineations for washes that have more riverine, one-dimensional flow behavior. 100- and 500-year flow data came from the nearest FLO-2D cross-section. Upstream boundary conditions were set to normal depth and downstream boundary conditions were set to either of the following: the maximum water surface elevation for the 100- and 500-year runs from either the downstream HEC-RAS modeling reach results, the FLO-2D model results, or the FEMA hydraulic model. Additional parameter specifications can be found in Section 5.2.

Watercourses that are 2-Dimensional in their flow nature and/or have a large portion of underground discharge contained in storm drains were delineated using FLO-2D. The hydraulic parameters used for these delineations were computed as part of the hydrology and are documented in Section 3. The general process used for floodplain delineation is to first create a raster surface of the 100-year maximum water surface elevation (WSEL) data from the FLO-2D model output. It is important to note that the FLO-2D models were developed using rain on the grid so every grid has a flow depth and some level of a WSEL above the existing ground. As such, WSEL contours were reviewed and adjusted to smooth out inflection points near the banks and to establish the prevailing water surface elevation across the watercourse from the left floodplain limit to the right. These adjusted WSEL contours are considered the Base Flood Elevations (BFE) for use in floodplain regulation by the City of Sedona. The BFE contours are then overlaid onto the existing ground surface contours. The floodplain limits are then drawn by tracing along the locations where the BFE lines generally intersect or match the existing ground contour data within a specified tolerance. The limits of the 500-year flood zone were determined using the same techniques as the 100-year delineations.

5.1.3. Floodway Determination

Floodways are broadly defined as zones that are preserved to carry the majority of the 100-year flow in a given area. They are typically defined by FEMA as the areas that cannot be encroached within such that the surcharge (increase in 100-year water surface elevation) would exceed 1.0 ft. This is relatively simple in a 1-dimensional HEC-RAS model using the encroachment module, but much more complicated in a 2-dimensional model. Explicitly simulating encroachment for floodway definition within the FLO-2D delineation areas was not warranted for this study. As such, the product of the 100-year depth and velocity rasters was used as an indicator of the floodway zone because it is a good proxy for conveyance potential. A general threshold of 5 to 10 ft^2/s was used to define floodways on washes with less than 150 cfs of flow and greater than 10 ft^2/s for washes with greater than 150 cfs of flow.

5.2. Parameter Estimation and Modeling Considerations

5.2.1. Roughness Coefficients

A unique Manning's n-value (roughness coefficient) was assigned to each reach modeled with HEC-RAS. No distinction was made for channel vs bank. The n-value was computed using the following equation (Jarret, 1985):

$$n = 0.39\, S^{0.38}\, R^{-0.16}$$

Where,

n = manning's roughness coefficient

S = average channel slope

R = average hydraulic radius of the reach

Since Hydraulic Radius is a function of wetted perimeter and cross-sectional area, which increases with increased roughness, an iterative approach was taken to compute the n-values. Firstly, channel and bank values of 0.045 and 0.055, respectively, were input for each reach as these are typical base values given to mountainous streams similar to those seen throughout the City. The models were then run and the resulting average slope and wetted perimeter values were used in the above equation to calculate a new, single n-value for each reach, with no distinction between channel and bank. The models were run again using this n-value and the resulting hydraulic radii were averaged again to recalculate yet another n-value. With this second iteration, the hydraulic radii and n-values converged satisfactorily resulting in the final n-value. The average reach slopes, hydraulic radii, and n-values used for the delienations can be found in **Table 5-1**.

The roughness coefficients used for the FLO-2D delineations were computed as part of the hydrology and are documented in Section 3.

Table 5-13. Roughness Coefficients used in HEC-RAS models

FLO-2D Model	HEC-RAS Model	Reach Name	Avg Reach Slope	Avg Hydraulic Radius	Reach n-value
East_1	BackOBeyondWash	Mystic Hills Creek - 1	0.04	1.52	0.109
		Mystic Hills Creek - SR 179 Trib	0.04	1.70	0.107
		Castle Rock Draw - 1	0.06	1.43	0.129
		Castle Rock Draw - Trib 1	0.07	1.31	0.133
		Back O' Beyond Wash - Rolling Reach	0.06	2.05	0.120
		Back O' Beyond Wash - Sagebrush Reach	0.08	1.34	0.139
		Back O' Beyond Wash - Sagebrush Reach - Trib 1	0.08	1.08	0.148
		Back O' Beyond Wash - 1	0.05	2.94	0.106
		Cathedral Rock Wash - 1	0.15	1.70	0.174
		Cathedral Rock Wash - Scenic Trib	0.01	3.52	0.061
		Back O' Beyond Wash - 2	0.05	1.02	0.127
East_2	OakCreekTribs_E	Artistic Wash - 1	0.06	2.12	0.116
		Gassaway Creek - 1	0.04	2.15	0.105
		Gassaway Creek - Trib 1	0.05	1.13	0.124
		Bear Wallow Creek - 1	0.03	4.68	0.076
West_2	MormanCanyonWash	Morman Canyon Wash - 1	0.03	6.51	0.074
		Morman Canyon Wash - Navajo Reach	0.06	1.09	0.133
		Morman Canyon Wash - Navajo Reach - Trib 1	0.06	1.30	0.125
		Morman Canyon Wash - Park Ridge Trib	0.07	1.39	0.138
		Morman Canyon Wash - Jordan Trib	0.10	1.27	0.156
		Morman Canyon Wash - Munds Mountain Trib	0.06	2.61	0.114
	SoldierWash	Soldier Wash - 1	0.02	3.45	0.070
		Soldier Wash - Rim Shadow Trib	0.07	0.99	0.140
		Soldier Wash - Enchanted Way Reach	0.04	2.86	0.096
		Soldier Wash - Enchanted Way Reach - Trib 1	0.05	0.96	0.124
		Soldier Wash - Enchanted Way Reach - Trib 2	0.06	1.01	0.132
		Soldier Wash - Little Scout Trib	0.07	1.60	0.129
		Soldier Wash - Moonlight Trib	0.08	1.06	0.147
		Soldier Wash - Soldiers Trail Trib	0.08	1.31	0.143
		Soldier Wash - 89A Reach	0.10	1.39	0.157
	OakCreekTribs_W	Palisades Creek -1	0.08	1.47	0.138
		Soldier Wash - SR89A Reach - Trib 1	0.06	1.23	0.126
		Soldier Wash - SR89A Reach	0.04	1.35	0.106
		Soldier Wash - Barcelona Trib	0.08	1.72	0.138
West_1	DryCreek_Tribs	Dry Creek Tributary 1 - 1	0.05	1.73	0.113
		Dry Creek Tributary 1 - Garnet Hill Trib	0.10	1.26	0.158

FLO-2D Model	HEC-RAS Model	Reach Name	Avg Reach Slope	Avg Hydraulic Radius	Reach n-value
		Dry Creek Tributary 1 - Desert Holly Trib	0.07	1.53	0.130
		Dry Creek Tributary 1 - North Slopes Reach	0.07	1.16	0.136
		Dry Creek Tributary 2 - 1	0.06	1.74	0.121
		Dry Creek Tributary 3 - 1	0.08	1.29	0.143
	BristleConesPinesCrk	Girdner Tank Wash - 1	0.04	1.12	0.112
		Grasshopper Flat Tank Wash - Trib 2	0.06	1.23	0.126
		Grasshopper Flat Tank Wash - 1	0.02	1.67	0.088
		Moki Wash - 1	0.04	1.12	0.111
		Bristle Cones Pines Creek - Trib 2	0.04	1.87	0.103
		Bristle Cones Pines Creek - Trib 1	0.04	1.47	0.112
		Bristle Cones Pines Creek - 1	0.03	1.85	0.099
	ChimneyCreek_N	Chimney Creek - 1	0.05	1.39	0.121
	ChimneyCreek_S	Chimney Creek - 1	0.02	3.71	0.068
	ChavezCrossing	Chavez Crossing - Reach 1	0.16	1.29	0.185
		Chavez Crossing - Reach 2	0.12	1.04	0.174
		Chavez Crossing - Reach 3	0.14	0.95	0.188

5.2.2. Bridges and Culverts

Bridge/culvert data input for the HEC-RAS models were obtained from the City's storm water GIS, As-built Construction Drawings, or field reconnaissance conducted as part of this study as discussed in **Section 3.0**. Culverts with a 48" diameter (or equivalent area) or greater were included in the HEC-RAS models. Most bridges were not modeled due to the bottom of the bridge deck being higher than the 100-year maximum depth. Culvert roughness values were based on the pipe material and were assigned as 0.012 and 0.025 for concrete and corrugated metal, respectively.

5.2.3. Expansion and Contraction Coefficients

The expansion and contraction coefficients were set to the default values of 0.1 and 0.3, respectively, except upstream and downstream of culvert locations where 0.3 and 0.5 were used, respectively.

5.2.4. Cross Section Description

HEC-RAS cross-sections were created from the 2016 LiDAR elevation data from the FEMA Cooperative Technical Partner project for Oak Creek described previously.

5.2.5. Levees and Dikes – Not Applicable

5.2.6. Islands and Flow Splits

The FLO-2D model was the basis for delineations where flow splits and distributary flow patterns were found, typically within heavily urbanized portions of the study area. Additionally, many floodplain islands were created during the initial flood zone delineation sampling but most of the islands were very small and removed in the final delineations.

5.2.7. Ineffective Flow Areas

In the HEC-RAS models, ineffective flow areas were specified upstream and downstream of culverts where the flow would not be actively conveyed, upstream or downstream of topographic features, or building obstructions rendering portions of modeled cross-sections ineffective. For the FLO-2D models, ineffective flow area is not applicable.

5.2.8. Supercritical Flow

While the washes run very close to critical due to the high slopes within the study area, the HEC-RAS models were run as subcritical to be consistent with FEMA standards. Additionally, the Jarret (1985) equation for estimating Manning's n was employed as it was developed for predicting roughness coefficients for high gradient natural channels, which better controls supercritical flows and is more consistent with the natural channel flow. Supercritical flow in a natural watercourse is rare and unstable and typically is mitigated by erosion, deposition, and other geomorphic processes.

5.3. Issues Encountered During the Study

Some unique locations that did not fit into the delineation method criteria documented above required engineering judgment and individualized approaches for the delineations. Those locations are described below.

In Bristle Cone Pines Creek, the one-dimensional limitations of HEC-RAS did not properly simulate the right overbank flood extent for cross-sections 4520, 4480, and 4210 (the area just south of Color Cove Rd) due to additional tributary inflow. As such, the flood zones were extended based on the corresponding FLO-2D depth grids. Also on this reach, the right overbank of the 500-year floodplain of Tributary 2 was extended using the FLO-2D depths grids for cross-sections 1256, 1190, 1122, and 1015 (along W Dove Wing Dr) due to the distributary nature of the reach in this area.

In the Enchanted Way Reach of Solider Wash, FLO-2D results were used to delineate the split flow downstream of the private drive toward the downstream-most portion of the reach.

In Mystic Hills Creek – SR179 Tributary, HEC-RAS did not properly capture the flow split on river left at cross-sections 1599 to 1434, therefore, the FLO-2D results were used to extend the floodplain delineations.

A house within Parcel 401-56-027 falls directly on top of the hydraulic baseline of Palisade Creek. Field investigation found that the home was adequately raised above the creek and no further accommodation was made for the delineation.

FLO-2D results indicated that Mormon Canyon Wash overtops SR-89A, therefore these results were used to extend the HEC-RAS delineations from SR-89A to where the wash outfalls to Oak Creek.

A wall intersects Back O’ Beyond Wash – Rolling Reach – Trib 1 behind Parcel 408-15-020. Because this wall could not be observed in person due to accessibility issues and was only observed in aerial photos, it was assumed that it has a sufficient opening to pass flow.

5.4. Work Maps

Work maps displaying the floodplain, floodway boundaries, as well as the BFE contours are included in the digital Appendix. It should be noted that future updates are likely and we encourage local engineering staff and consulting engineers to obtain the final products digitally through the Cit of Sedona or access on the Sedona Web Viewer (www.sedonaaz.gov).

6.0 Erosion, Sediment Transport, and Geomorphic Analysis

No erosion, sediment transport, nor geomorphic analyses were performed as part of this work assignment.

7.0 References

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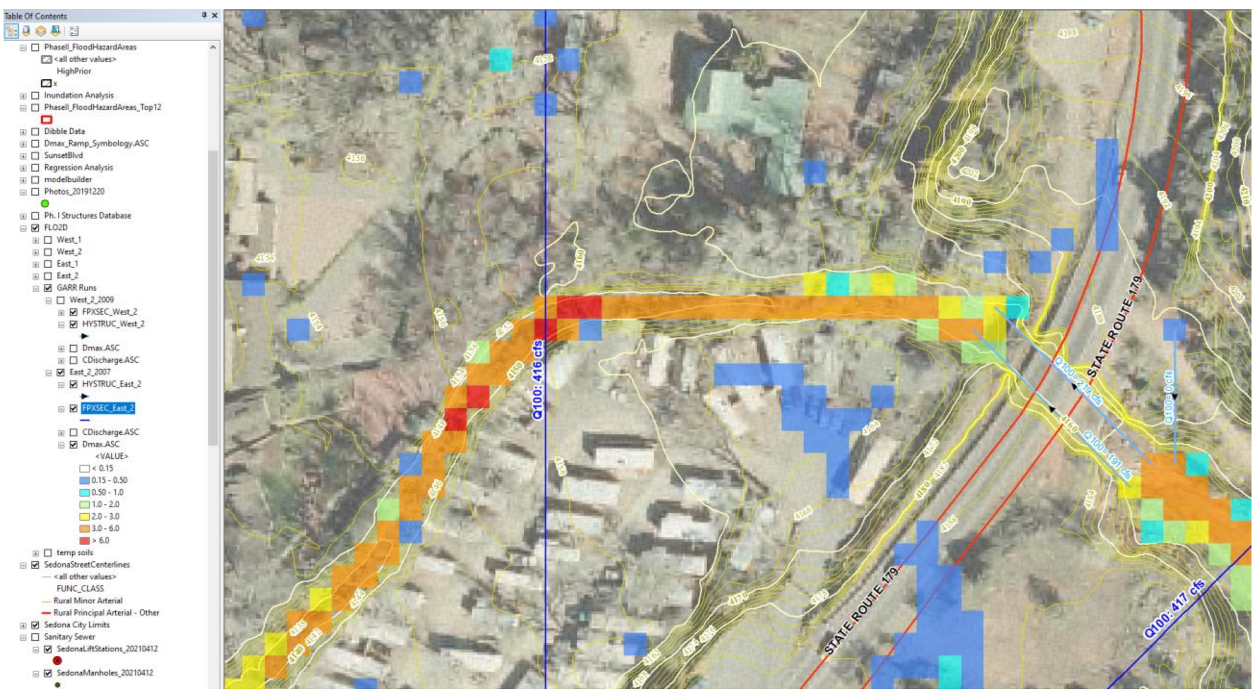
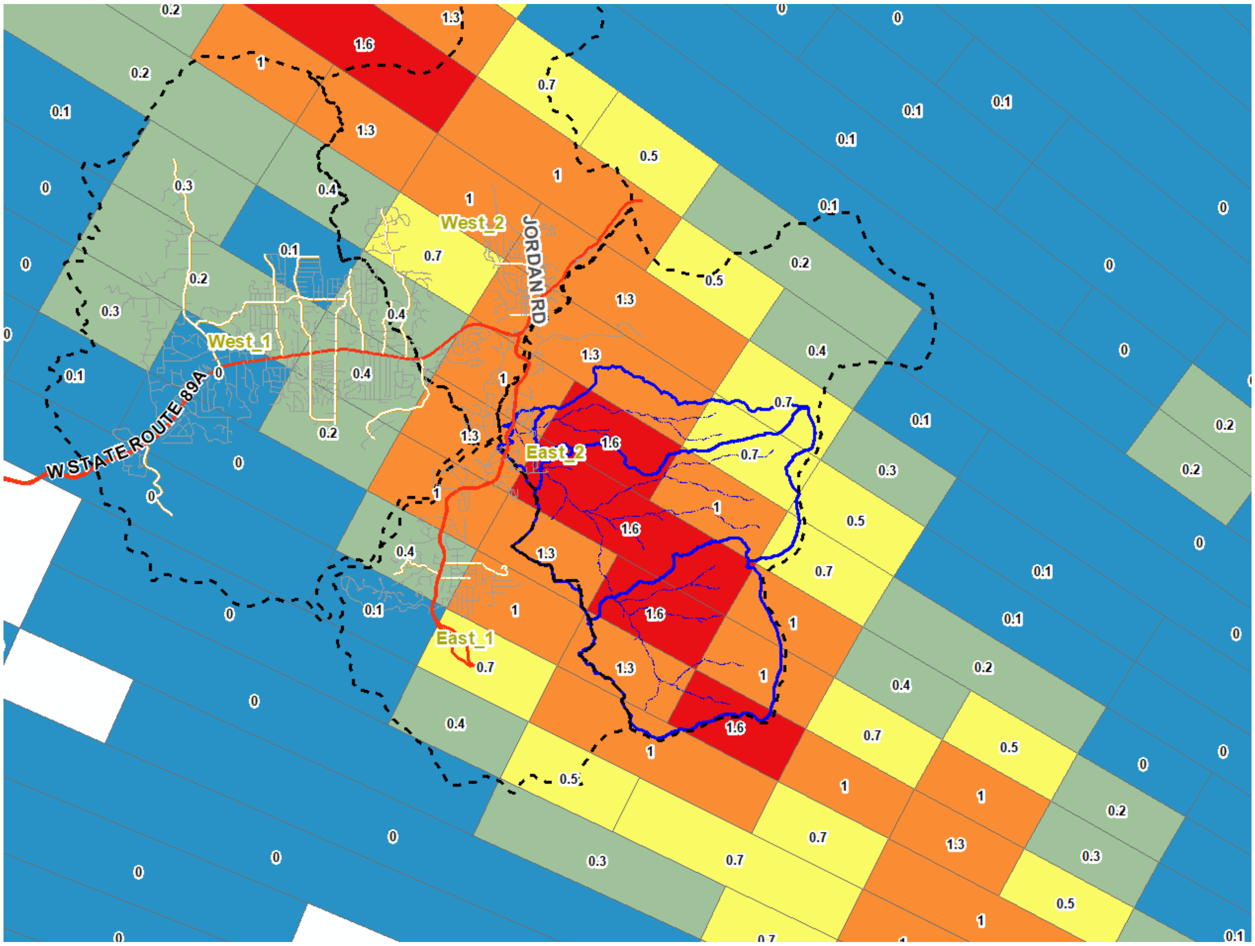
EXHIBITS (Included Digitally)

APPENDIX (Portions included Digitally)

From: Rob Lyons
Sent: Thursday, August 19, 2021 4:42 PM
To: Andy Dickey <adickey@sedonaaz.gov>; Sandy Phillips <sphillips@sedonaaz.gov>
Cc: Chandler Adamaitis <chandleradamaitis@gmail.com>; Rob Lyons <rob@jefuller.com>
Subject: July 25, 2007 Event Radar FLO-2D Model of Morgan Wash Results

Hi Andy and Sandy, we ran the July 25, 2007 event using Radar data for the SWMPU FLO-2D Submodel that includes Morgan Wash and Margs Draw. The area that you had photos for Andy was downstream of the confluence with Margs Draw, so the comparison is on Morgan Wash. The first screen capture below is the results that shows the event was generally contained within the channel and resulted in about 400 cfs according to the model. The photos you sent of the event near the lift station also show that the flow was pretty much contained in the channel, however, it's hard to judge what the flow rate was and if the photos were taken at the peak of the runoff event. I've attached a couple for reference. In general, I think the model is showing similar conditions to those observed on the ground. The second screen capture below shows the storm total Radar for the event. You'll see that much of the watershed (dark blue polygons to the right) received up to 1.6-inches of rain.





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www.JEFuller.com

Ground Photos Taken during the Runoff Event in Morgan Wash (provided by Andy Dickey)

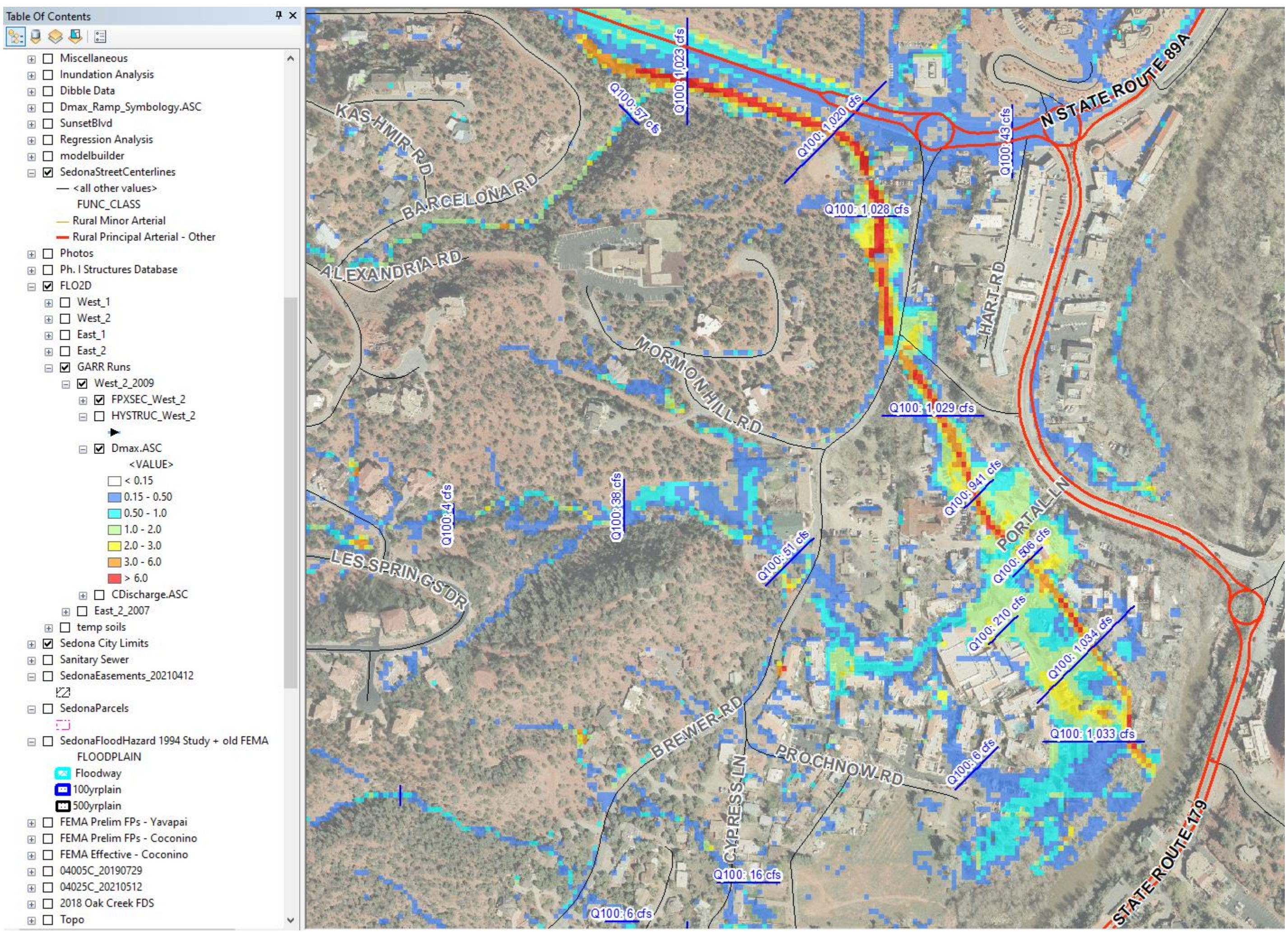

25

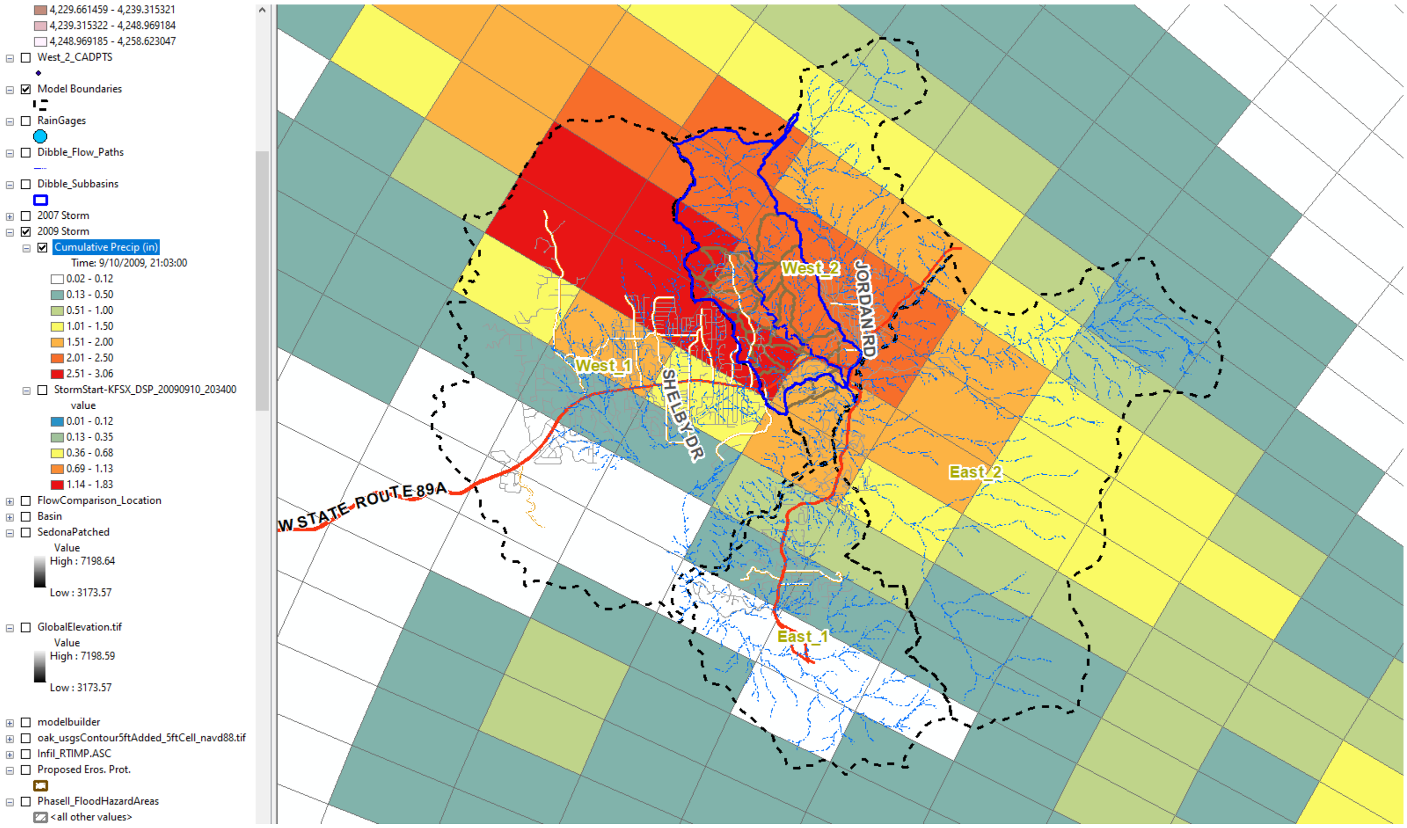
Subject: September 10, 2009 Event Radar FLO-2D Model of Soldier Wash Results

We ran the September 10, 2009 event using Radar data for the SWMPU FLO-2D Submodel that includes Soldier Wash (West_2). This model included revisions to the underlying topography in the FLO-2D model through Soldier Wash downstream of SR 89A through Tlaquepaque to the Oak Creek outfall. The topography used was the Citywide 2-foot contour data from a flight date in 2007. The topographic replacement in the model was so that model results would simulate the terrain at the time of the flood which was prior to the CIP improvements made in several phases to Soldier Wash following the flood of 2009.

The first screen capture below shows the general inundation extents and approximate depths of the even through Tlaquepaque with a resulting peak discharge of approximately 1,000 cfs. David Peck/City of Sedona recalls depths in the parking area on the northeast side of the shopping center and west of SR 179 between 1 and 2-feet. There were several photos taken in this area provided that appear to have high water marks also within this depth range (refer to Oak Creek Brewery sign, below). The event FLO-2D model results also show depths in this area between 1- to 2-ft.

In general, the model is showing similar conditions to those observed on the ground. The second screen capture below shows the storm total Radar for the event. Most of the watershed (dark orange polygons) received over 2.0-inches of rain.





Ground Photos Taken during and after the flood event on Soldier Wash through Tlaquepaque (provided by David Peck)

Flood Hazard Area Workshop Summary for the

STORMWATER MASTER PLAN UPDATE: PHASE 3

Submitted to

City of Sedona
102 Roadrunner Drive
Sedona, AZ 86336

Table of Contents

Submitted by

Beta | Pr

June 30, 2022

1. Public Relations Scope of Work

1.1 Project Information

The City of Sedona (City) and their consultant, JE Fuller, are currently working on the Sedona Stormwater Master Plan Update Project: Phase 3 (SWMPU). The project has consisted of updating the locally regulated Flood Hazard Areas within City limits. The new maps include more accurate models and take into account the extensive changes from new developments, improved stormwater facilities and natural changes to the terrain. Beta Public Relations (BetaPr) was contracted to perform public outreach efforts to notify stakeholders whose floodplain designation has changed, man the Flood Hazard hotline and facilitate a Flood Hazard Area Workshop to discuss new flood zones and hazards with stakeholders.

1.2 Public Involvement Scope of Work

BetaPr was tasked with performing public outreach efforts for the SWMUP Project. BetaPr provided the following Scope of Work to JE Fuller on Friday, June 3, 2022.

Task 1 – Project Notification Production and Distribution

BetaPr produced a Project Notification (Appendix A) that was supplied by the Project Team on Wednesday, June 15, 2022. The flier highlighted project details and served as a community workshop invitation regarding the new flood hazards identified. The fliers were printed, placed in envelopes and mailed directly to 2,788 stakeholders (Appendix B)

Task 2 – Website Maintenance

BetaPr supported the City and JE Fuller with developing the existing project-specific web page.

Task 3 – Project Hotline Maintenance

BetaPr established and maintained a 24-hour project hotline. Hotline calls continue to be answered, with all stormwater-related questions directed immediately to the project team for resolution, if necessary. To date, BetaPr has received 33 hotline calls.

Task 4 – Public Comments Log

A Public Comments Log documenting all project hotline calls is kept. The resolution of each inquiry is recorded to be provided to the project team if requested. There are currently 33 hotline calls recorded in the Public Comments Log, all of which have been resolved.

Task 5 – Flood Hazard Area Workshop Support and Facilitation

On Wednesday, July 29, 2022, BetaPr facilitated a Flood Hazard Area Workshop to allow stakeholders to ask questions about the new flood zones and hazards identified, discuss the need to obtain flood insurance and allow open communication between the Sedona community and the City. Facilitation efforts included the development and production of meeting materials, mediating the workshop queue, assisting with presentations, providing refreshments for attendees, and meeting set-up and take-down.

2. Flood Hazard Area Workshop Summary

2.1 Flood Hazard Area Workshop Date, Time, and Location

The City secured the following venue for the Flood Hazard Area Workshop:

Wednesday, June 29, from 3 p.m. to 6 p.m.
City of Sedona Administration Building
221 Brewer Road, Sedona, Arizona 86336

2.2 Flood Hazard Area Workshop: Attendees

A total of 50 stakeholders signed-in when they arrived (Appendix C) with a few stakeholders choosing not to sign-in. Workshop attendees were residents and stakeholders who received the notification and are impacted by the new flood zones and hazards identified by the SWMPU.

2.3 Flood Hazard Area Workshop: Comment Forms

Five comment forms (Appendix D) were submitted to BetaPr at the conclusion of the meeting. Meeting attendees were also told they could mail the comment form directly to the City Engineer at their convenience.

2.4 Flood Hazard Area Workshop: Displays

Displays were produced by the City and JE Fuller.

APPENDIX A

Project Notification

102 Roadrunner Dr.
Sedona, AZ 86336
(928) 204-7111
sedonaaz.gov
FAX (928) 282-5348

Public Works

June 15, 2022

RE: NOTIFICATION OF FLOOD HAZARD REVISIONS IN SEDONA, AZ

To Whom It May Concern:

The City of Sedona is updating locally regulated Flood Hazard Areas (i.e. floodplains) within the City limits. We have determined there is a change to the floodplain on your property. There are two ways you can review these changes; read on for more details.

A Flood Hazard Area is the area that has been determined to be subject to a 1 percent or greater chance of flooding in any given year (aka 100-year flood) or the area that has been determined to be subject to a 0.2 percent chance of flooding in any given year (aka 500-year flood). These locally regulated Flood Hazard Areas are used to notify residents of potential flood hazards in their area and to help the City of Sedona with floodplain management.

The City of Sedona reviews the Flood Hazard Areas when building improvements or development plans are submitted for permits. The engineering community uses the Flood Hazard Areas and supporting flood data (e.g. flood water elevations) to ensure that proposed building improvements will be safe from flooding and that the improvements will not result in adverse impacts to neighboring properties.

Please go to the website www.sedonaaz.gov/stormwatermasterplan to find your property on the map and view the updated Flood Hazard Areas that affect you. If you have questions related to the updated Flood Hazard Area maps:

1. The City of Sedona will be hosting a Flood Hazard Area workshop from 3:00 PM to 6:00 PM June 29th at 221 Brewer Rd, Sedona, AZ 86336. Staff and engineering contractors will have computers available to review the flood hazard maps with you and answer questions.
2. Please call the Flood Hazard hotline at (928) 852-4164 between 8:00 AM to 5:00 PM Monday through Friday.

Note: the Flood Hazard Areas are not FEMA regulated floodplains and will not result in the requirement to buy flood insurance. However, we encourage our residents to consult with their insurance providers to evaluate the benefits of obtaining flood insurance.

It is our goal to keep our citizens safe from flooding and storm water hazards.

Sincerely,

Sandra Phillips, PE, CFM, ENV SP
City of Sedona Assistant Public Works Director

APPENDIX B

Mailing List

Documentation has been removed that includes names, addresses, and contact information to protect the privacy of Sedona Residents

APPENDIX C

Workshop Sign-In Sheets

Documentation has been removed that includes names, addresses, and contact information to protect the privacy of Sedona Residents

APPENDIX D

Workshop Comment Forms

Documentation has been removed that includes names, addresses, and contact information to protect the privacy of Sedona Residents