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Memorandum

DATE: January 23, 2017

TO: **Lucinda Andreani; Coconino County**

FROM: Joe Loverich, PE, CFM, Mike Kellogg, PG, CFM, GISP; JE Fuller, Inc.

RE: **Coconino County Post-Wildfire Flood and Debris-Flow Risk Assessment:**
Task 3 and Task 6 – Pre- and Post-Wildfire Hydrologic and Hydraulic Modeling

Registered Professional Engineer (Civil) CERTIFICATE NO. 45648 JOSEPH BERNARD LOVERICH Date Signed 1/23/17 ARIZONA U.S.A. Expires 12/31/2018

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Executive Summary

Tasks 1 and 2 of the Coconino County Post-Wildfire Flood and Debris-Flow Assessment identified two pilot study areas for detailed hydrologic, hydraulic, and debris flow modeling: (1) Fort Valley, and (2) Williams. These pilot study areas were selected due to their potential for significantly increased post-wildfire flooding in the residential and commercial areas located downstream of forested mountain watersheds. Flood impacts and hazards in the pilot watersheds were determined using a two-dimensional computer model (FLO-2D PRO) to model the 2-, 10-, and 100-year events with watershed conditions simulating pre- and post-fire conditions. One aspect of this study is to understand and quantify the impact of increased forest health due to forest treatments (thinning, control burns, etc.) on the downstream flood impacts. To accomplish this, each pilot area was modeled with several watershed condition scenarios as described below.

Fort Valley

- Pre-Fire (unburnt, existing condition)
- Post-Fire, No Treatment
- Post-Fire, Treatment up to 8,200 Feet (No treatment in wilderness areas)
- Post-Fire, Treatment (all areas)

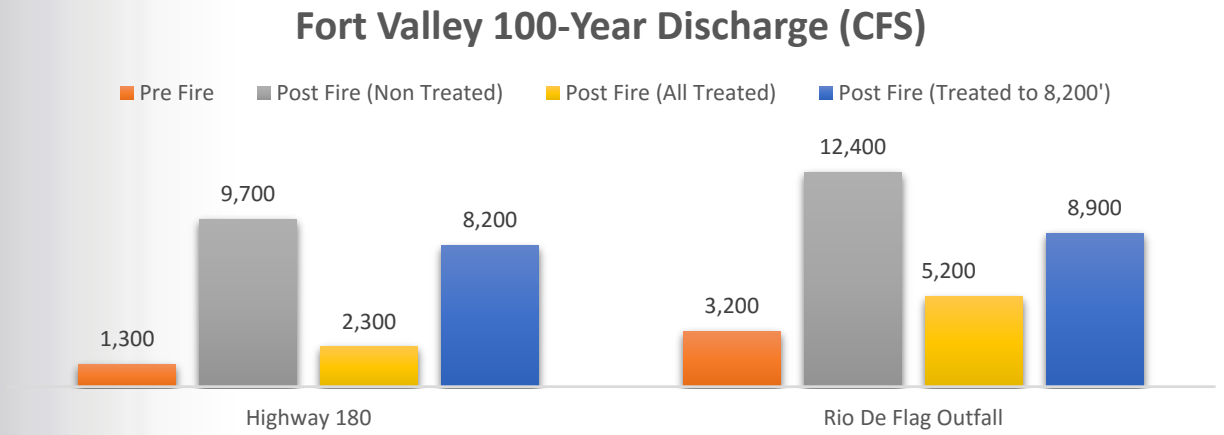
Williams

- Pre-Fire (unburnt, existing condition)
- Post-Fire, No Treatment
- Post-Fire, Treatment (all areas)

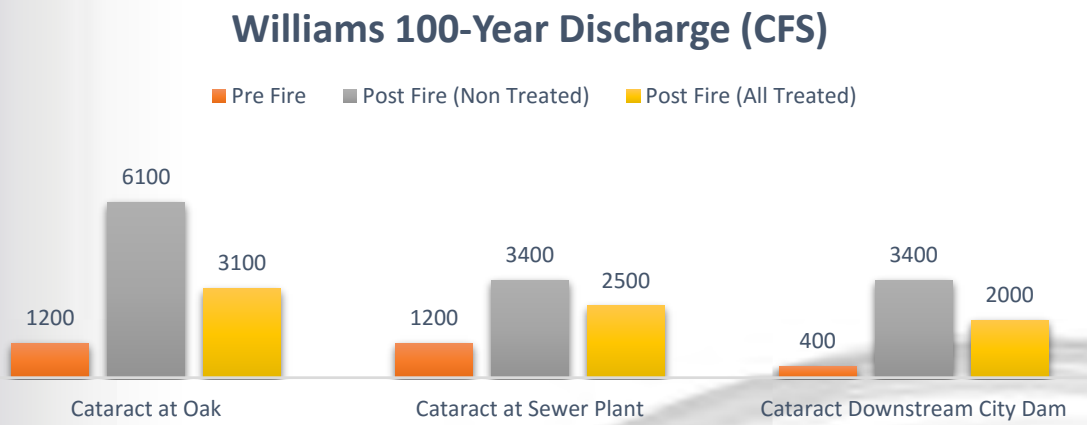
The Fort Valley watershed extends to the top of Agassiz Peak, and includes a large portion of Wilderness Area which has use restrictions that may prohibit certain types of forest treatment. As such, a post-fire scenario was included, modeling a fully treated watershed except for the area within the wilderness area. Treatment within each watershed has the effect of reducing the potential burn severity as described in the Fort Valley Fire Modeling and Assignment of Post-Wildfire Curve Numbers, Technical Memorandum (JE Fuller, 2016).

The 100-year modeling results for the **Fort Valley Pilot Area** indicate post-fire (no treatment) flows in the Rio de Flag downstream of Fort Valley are up to *4 times* higher than pre-fire discharges. Treating the watershed has the effect of reducing the post-fire discharges by 58% if the entire watershed including the wilderness

area is treated, and 28% if the wilderness area is untreated. Discharges originating from Agassiz Peak are of interest due to the fact that a large portion of the contributing watershed is wilderness. Post-fire (no treatment) discharges that cross Highway 180, originating from Agassiz Peak, are up to 8 *times* higher than pre-fire discharges. If the same watershed is fully treated, post fire discharges may be reduced by 77%. However, the wilderness area is a large portion of the Agassiz Peak contributing watershed and if the area is excluded from treatments (Post-fire, Treatment up to 8,200 feet), post-fire discharges may still be 6 *times* higher than pre-fire conditions, as shown in the graph below.



The 100-year modeling results for the **Williams Pilot Area** indicate post-fire (no treatment) flows in Cataract Creek at the south end of Williams (Oak Street) increase by up to *5 times* the pre-fire discharges. Treating the watershed has the effect of reducing the post-fire discharges by 49%. Cataract Creek Discharges near the sewer treatment plant are up to *3 times* higher than pre-fire discharges. Treating the watershed has the effect of reducing the post-fire discharges by 27%. Some of the upper watersheds on Bill Williams Mountain that have the potential to burn the most severely experience significant increases in flows. Directly downstream of the City Dam, post-fire (no treatment) flows are up to 8 times higher than pre-fire discharges. Treating the watershed has the effect of reducing the post-fire discharges by 40%, as shown in the graph below.



FLO-2D was used to assess the flood hazards associated runoff from each watershed condition scenario. The hazard assessment is a function of water flood intensity which is a combination of maximum depth and the product of maximum depth times the flow velocity. Hazards are classified into Low, Medium and High zones, as the risk they pose to people or structures. The Fort Valley and Williams flood hazard assessment results summarized below demonstrate that watershed treatment has the potential of significantly reducing the number of properties that would be threatened by post-wildfire flooding.

FORT VALLEY FLOOD RISK RESULTS (number of impacted buildings)				
Hazard Level	**Pre-Fire**	**Post-fire No Treatment**	**Post-fire Treatment up to 8200'**	**Post-fire All Treated**
Low	86	225	211	135
Medium	36	122	80	50
High	2	11	7	3

WILLIAMS FLOOD RISK RESULTS (number of impacted buildings)			
Hazard Level	**Pre-Fire**	**Post-fire No Treatment**	**Post-fire All Treated**
Low	228	540	399
Medium	39	268	127
High	11	44	20

The modeling results suggest that in a burned condition, the Fort Valley and Williams Pilot Areas produce significantly higher flood discharges compared to pre-fire conditions. Treatment of the impacted watersheds significantly reducing post-fire discharges and is critical to reducing the hazards. Based on these results, it is recommended that Coconino County continue to work closely with the Forest Service in managing and treating the forests that contribute runoff to developed areas. The results also suggest that it would benefit the County to include forest treatment in future capital improvement project plans.

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Appendix A – LiDAR Survey Reports

Appendix B – Flood Depth Maps

Appendix C – Flood Hazard maps

1. Study Areas

The Fort Valley study area includes the upper Rio de Flag watershed which drains a portion of the southwest side of the San Francisco Peaks and extends south to A1 Mountain (Figure 1). The Williams study area includes a portion of the upper Cataract Creek watershed which drains the northeast side of Bill Williams Mountain (Figure 2).

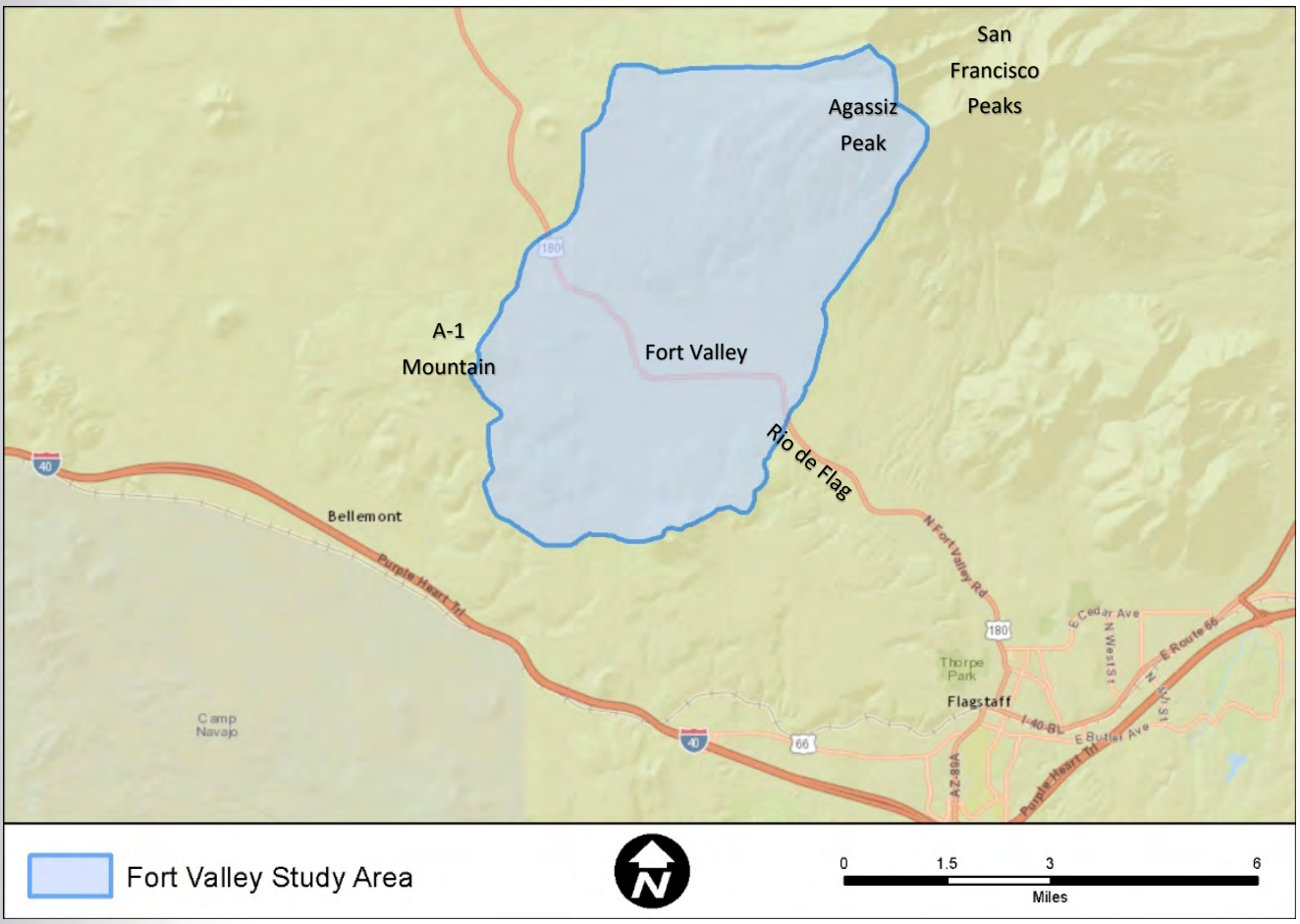

Figure 1 – Fort Valley Study Area

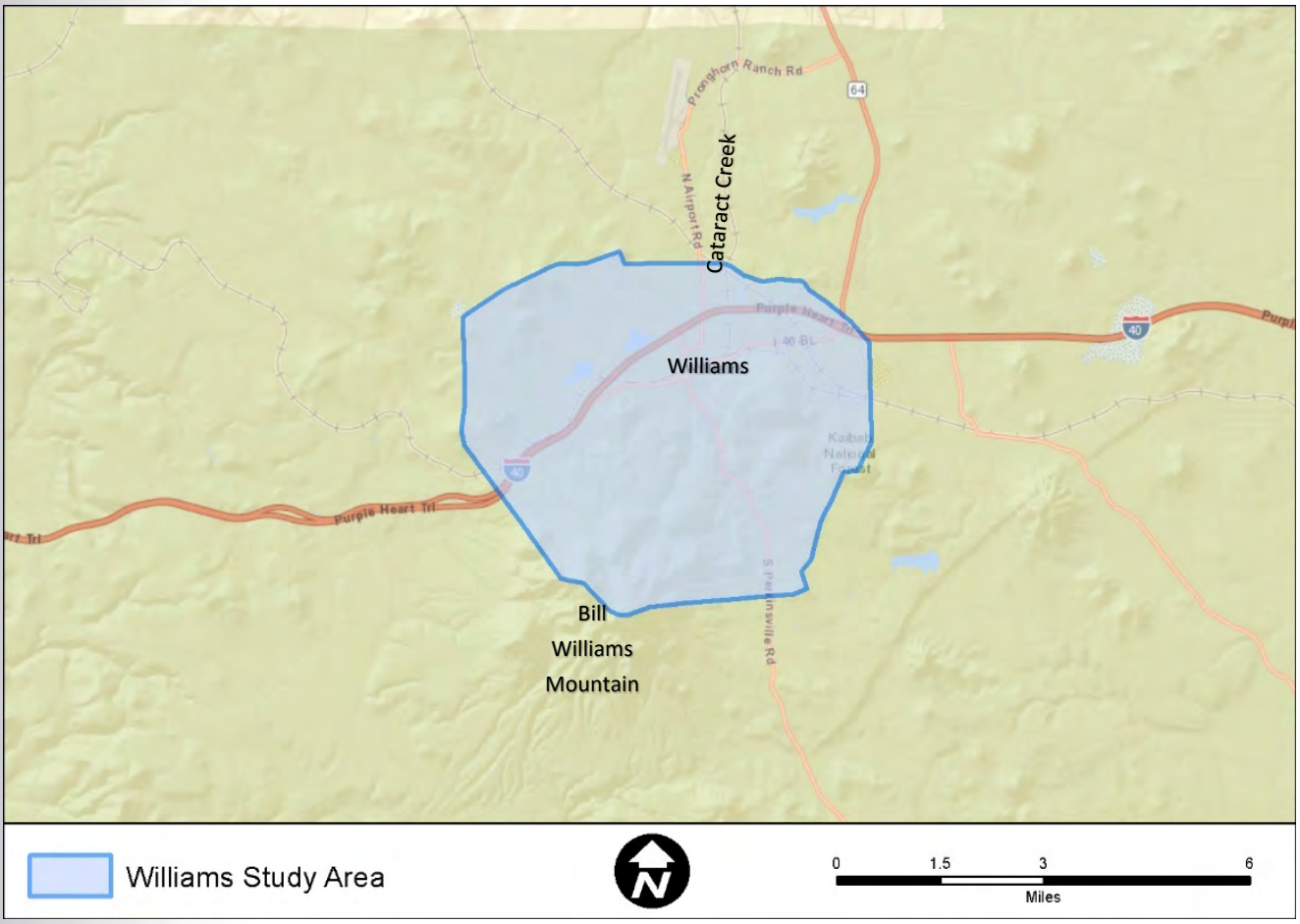

Figure 2 – Williams Study Area

2. Mapping

The mapping for this study came primarily from the LiDAR data that was developed by Quantum Spatial, Inc. (2016). The limits of the LiDAR mapping for Fort Valley are shown in Figure 3. For the Williams study area, the LiDAR data did not cover the extreme northern fringe of the watershed. For this small fringe area, supplemental topography was taken from the United States Geological Survey (USGS) 10-meter digital elevation model (DEM) data. The limits of the LiDAR mapping and USGS DEM area are shown in Figure 4.

A Terrain Data Set (TDS) surface was developed using ArcGIS for each area to incorporate the mapping data as described above. The TDS was built with the following projection information:

- Vertical Datum: The North American Vertical Datum of 1988 (NAVD 88)
- Projected Coordinate System: 'NAD_1983_StatePlane_Arizona_Central_FIPS_0202_Ft_Intl.

This TDS provided the basis for the grid elevations in the FLO-2D models.

Mapping Information is included in Appendix A.

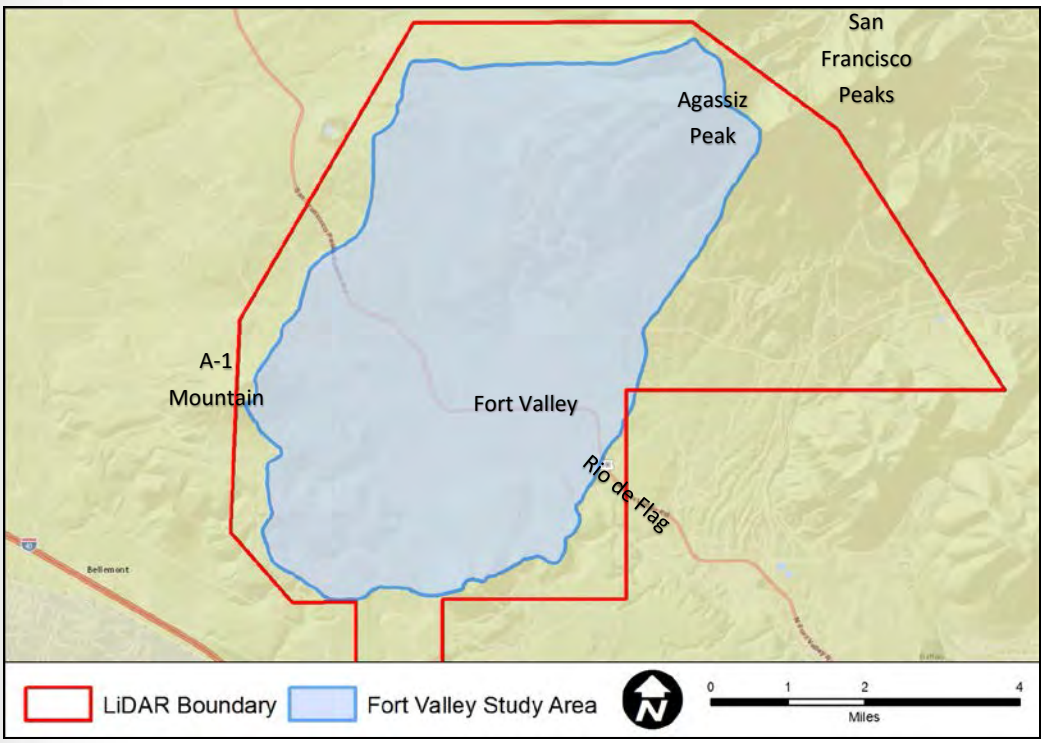

Figure 3. Mapping Sources for the Fort Valley Study Area

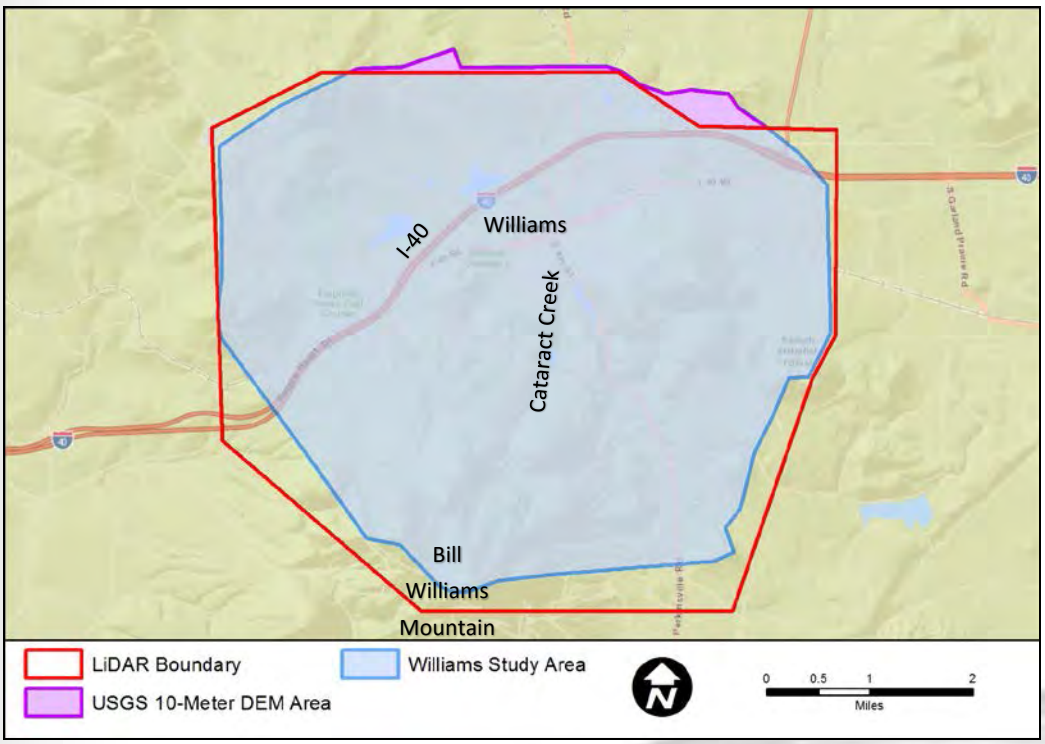

Figure 4. Mapping Sources for the Williams Study Area

3. Fort Valley Hydrologic and Hydraulic Modeling

A. Fort Valley Model Description

FLO-2D PRO was chosen as the combined hydrologic and hydraulic model for both the pre- and post-fire conditions analysis. FLO-2D is a 2-dimensional, flood routing model that simulates unconfined overland flow over complex topography. This modeling platform was chosen because of the distributary and unconfined sheet flooding conditions in the Fort Valley area. The flood simulation includes components such as rainfall, infiltration, and hydraulic structures. An emphasis of this study is to understand and quantify the impact of increased forest health due to forest treatments (thinning, control burns, ect.) on the downstream flood impacts. To accomplish this, the Fort Valley area was modeled with several watershed condition scenarios as described below.

Fort Valley

- Pre-Fire (unburnt)
- Post-Fire, No Treatment
- Post-Fire, Treatment up to 8,200 Feet (Excluding the Kachina Peaks Wilderness Area)
- Post-Fire, Treatment (all areas)

B. Fort Valley Grid Development and Inflow/Outflow Nodes

The Fort Valley pilot area watershed is 29.3 square miles. The grid size used for the FLO-2D model was 20 feet by 20 feet resulting in 2.13 million grids. Recurrence interval rainfall of 2-, 10-, and 100-year was modeled for each burn scenario (discussed later in the Fort Valley Rainfall and Loss Parameters Section). In order to better manage and facilitate the 36 models for the Fort Valley area, and to reduce computing time, the watershed was split into the following three model domains:

1. San Francisco Peaks
2. Wing Mountain
3. Fort Valley

Each of these domains were connected to each other by inflow or outflow nodes at adjoining boundaries. The San Francisco Peaks model's entire boundary was outflow nodes and the nodes that border the Wing Mountain and Fort Valley areas were assigned as inflow nodes for the respective adjoining model domains. The Wing Mountain model outflows also become inflow nodes for the Fort Valley model at the adjoining boundary. Outflow from the Fort Valley model was set along the eastern boundary. Figure 5 shows the relative locations and spatial limits of these domains.

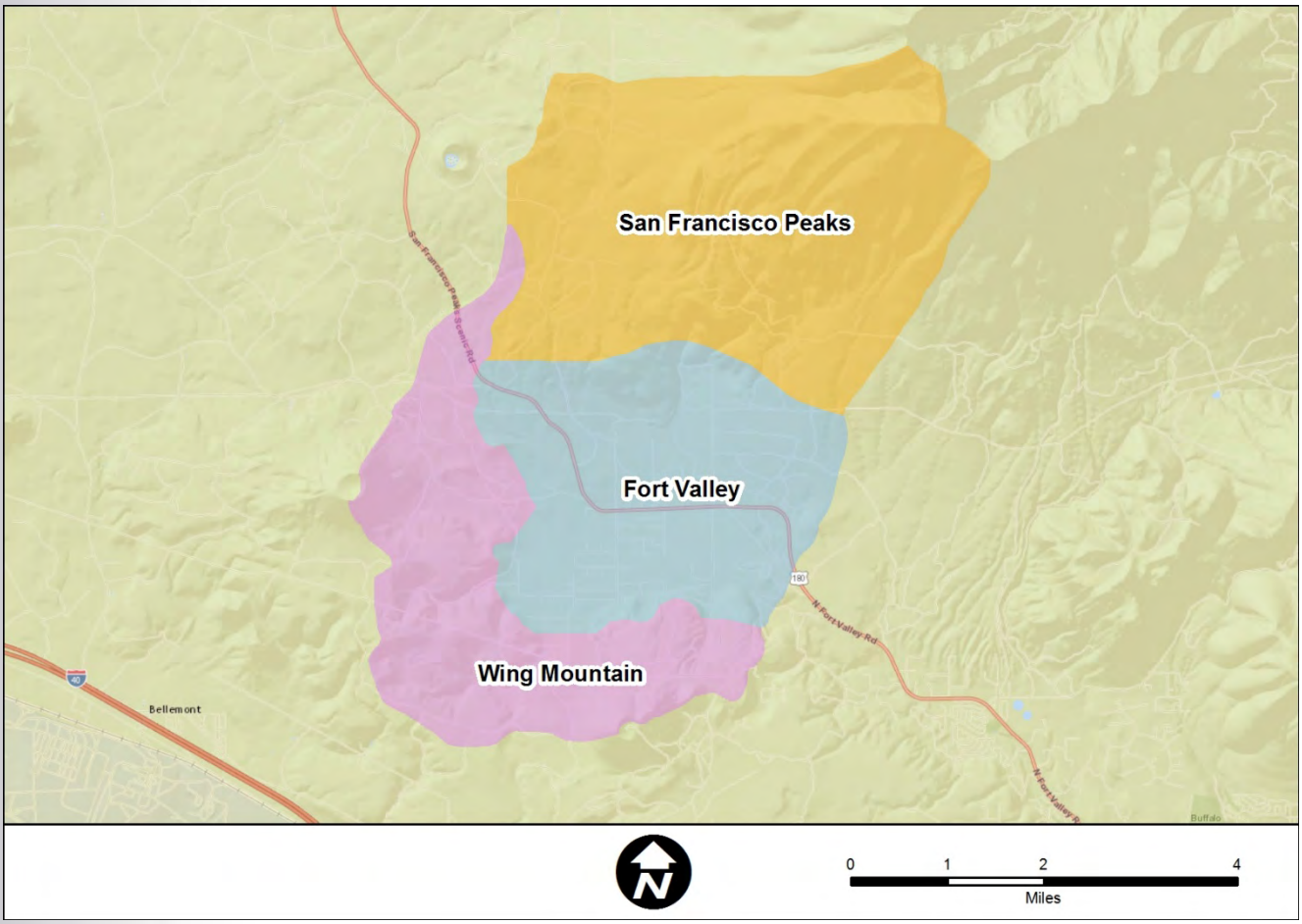

Figure 5. Fort Valley FLO-2D Model Domains

C. Fort Valley Grid Elevations, Roughness, and Area/Width Reductions

The elevation of each 20-foot grid element in the FLO-2D model was calculated based on the average elevation within the 400 square feet that the grid element covers. Grid elevations were determined from the 2016 Coconino County LiDAR data generated for this project.

Grid element roughness was approximated using Manning's 'n' values and are referenced from the Fort Valley Initial Engineering Assessment (JE Fuller, Civiltec, 2015). Roughness coefficients assigned to the FLO-2D grid elements ranged from 0.035 to 0.080. Table 1 summarizes the categories used to assign the roughness coefficients. Figure 6 shows the spatial distribution of the roughness coefficients assigned to the model throughout the watershed. Roughness values were consistent between the pre-fire model and all of the post-fire models.

Table 1. Fort Valley Roughness Coefficients

Description	Roughness Coefficient
Cinders	0.035
Residential (2-acres)	0.045
Range Grasses	0.050
Pine Forest	0.065
Mountain Top	0.080

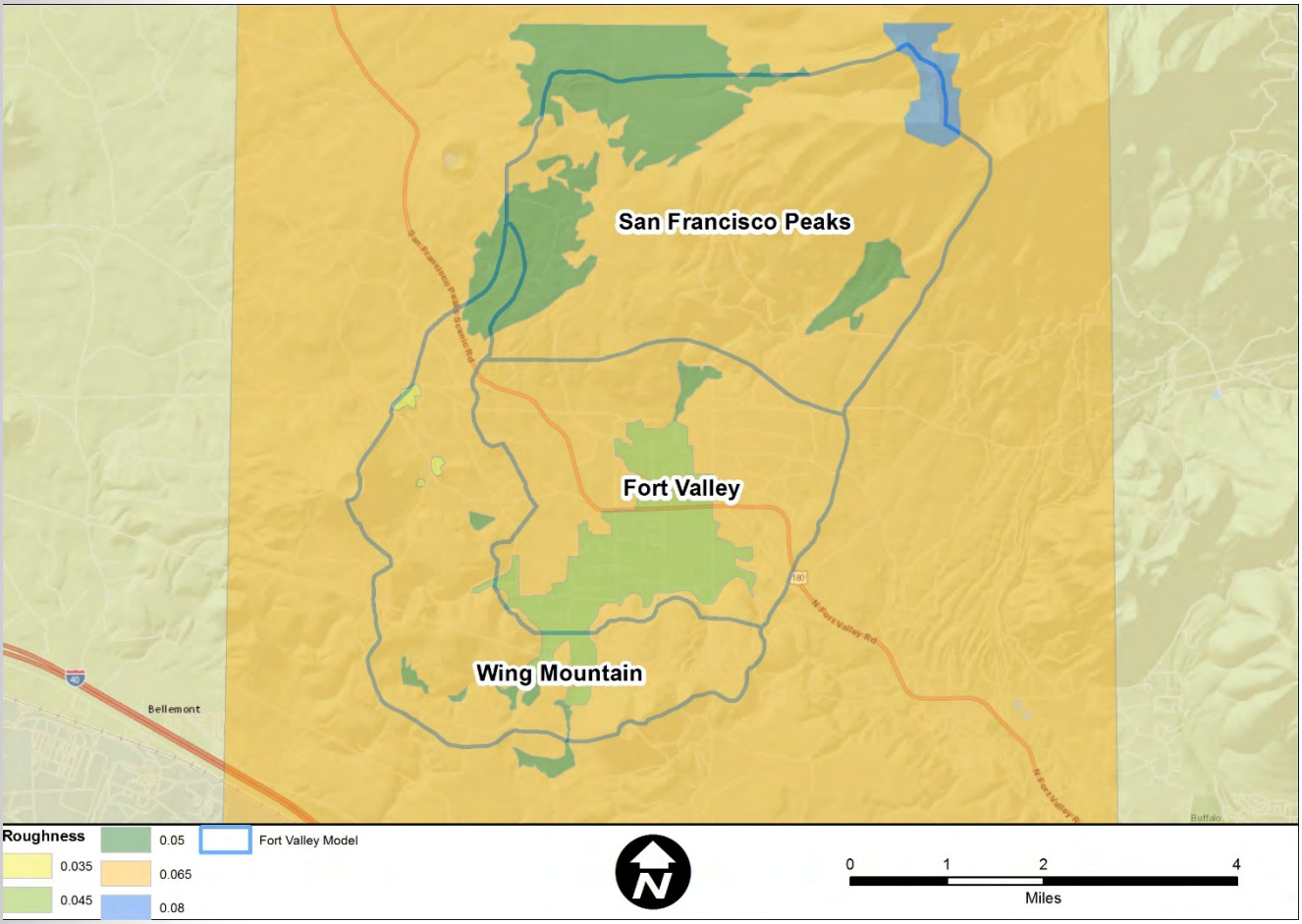

Figure 6. Fort Valley Spatial Distribution of Grid Element Roughness

D. Fort Valley Rainfall and Loss Parameters

Rainfall data tiles at a 30-second resolution (about 0.5 mile x 0.5 mile) for the entire modeling domain were obtained from NOAA Atlas 14 datasets and were entered as spatially varied point depths unique to each FLO-2D grid cell. For reference, the maximum point rainfall depth for the watershed and the rainfall depth at the watershed centroid are shown in Table 2.

Table 2. Fort Valley NOAA 14 Point Rainfall Depths

Description	24-hr* Maximum Depth in Watershed (inches)		
	SF Peaks Domain	Wing Mountain Domain	Fort Valley Domain
2-year	2.54	2.22	2.25
10-Year	3.69	3.22	3.27
100-year	5.55	4.82	4.90

*The 24-hour storm was chosen due to the large watershed size and ADOT modeling procedures.

Rainfall losses were simulated using SCS Curve Number methodology to be consistent with standard hydrologic modeling practices in Coconino County. Curve Numbers were assigned to grid elements based on four scenarios:

1. Pre-Fire
2. Post-Fire – No Treatment
3. Post-Fire – Treatment up to 8200' (Excluding the Kachina Peaks Wilderness Area)
4. Post-Fire – All Treated

Pre-fire Curve Numbers were selected using NRCS guidance, which incorporates soil type to define hydrologic soil group (HSG), vegetative cover and watershed condition (as identified in the 2011 Fort Valley Drainage Study Report). Post-fire curve numbers were assigned as described in the *Coconino County Post-Wildfire Flood and Debris-Flow Risk Assessment: Fort Valley Fire Modeling and Assignment of Post-Wildfire Curve Numbers Technical Memorandum (JE Fuller, 2016).*

Soil Map Unit boundaries were provided by the Coconino National Forest. The Soil Map units were delineated as part of the *Coconino National Forest Terrestrial Ecosystem Survey*. Table 3 shows each map unit and respective HSG.

Table 3. Fort Valley Specific Soil Types and HSG

Map Unit	HSG	Map Unit	HSG	Map Unit	HSG	Map Unit	HSG
770	A	654	B	585	C	557	C
850	A	653	C	582	C	562	A
790	B	611	B	584	C	570	C
785	B	613	B	595	C	055	C
740	B	551	B	560	A	565	C
715	B	640	B	586	C		

Table 4 shows a summary of the pre-fire Curve Numbers assigned to the FLO-2D grid elements based on land use and HSG. Figure 7 shows the spatial variation of the pre-fire Curve Numbers used for modeling.

Table 4. Fort Valley Pre-Fire Curve Number Data

Land Use	CN (HSG A)	CN (HSG B)	CN (HSG C)	CN (HSG D)
Pine Forest	30	55	70	77
Range Grasses	39	61	74	80
2 Acre Residential	46	65	77	82
Mountain Top	68	79	86	89
Cinders	30	30	30	30

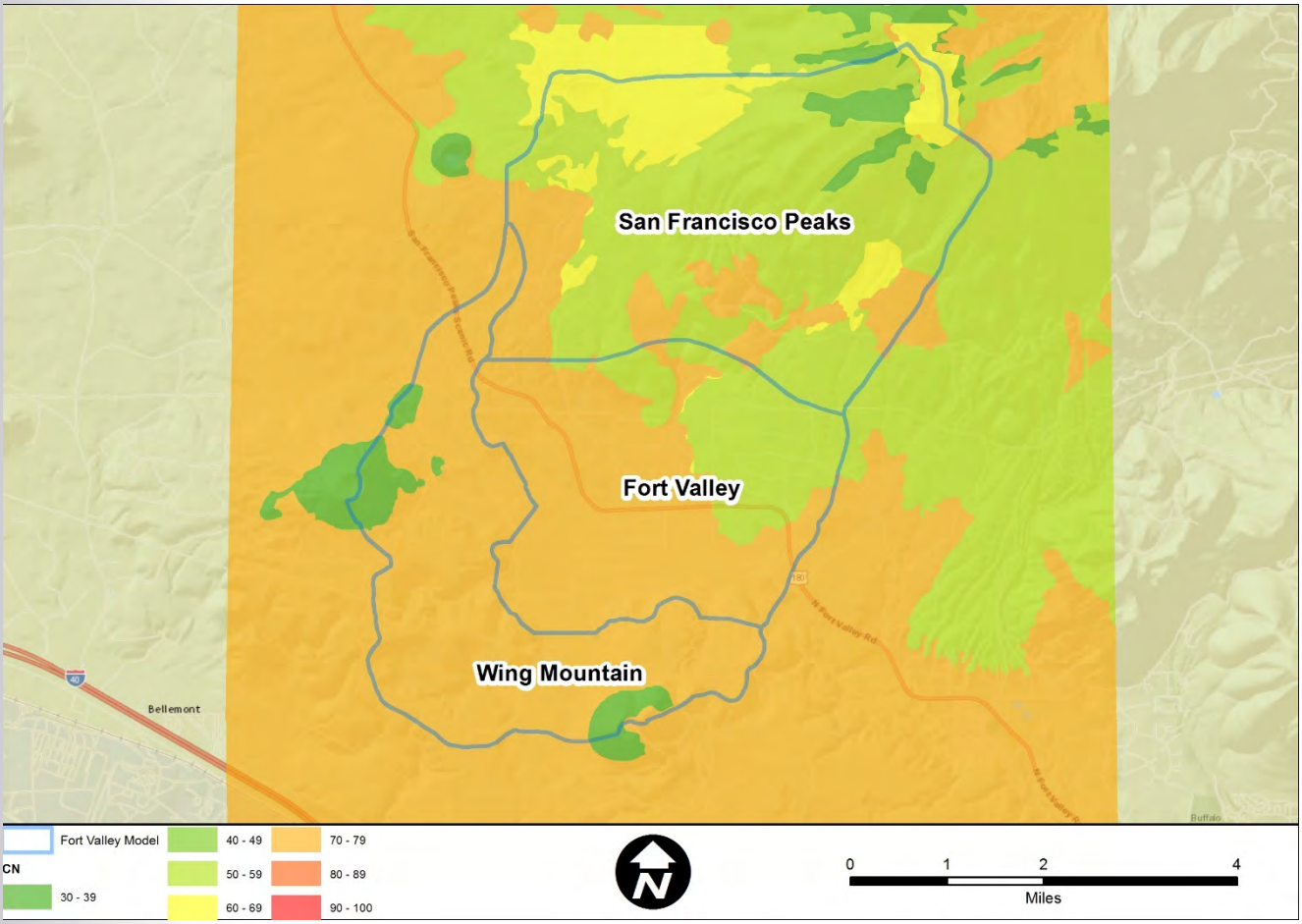

Figure 7. Fort Valley Pre-Fire FLO-2D Curve Numbers

E. Fort Valley Hydraulic Structures

Seventeen (17) hydraulic structures were included in the Ft. Valley FLO-2D model. Each of these hydraulic structures are located at existing road crossings. The locations of the modeled hydraulic structures are shown in Figure 8. Brief descriptions for each of the modeled hydraulic structures are included in Table 5. Many of hydraulic structures noted in the table had decreased efficiency resulting from sediment loads and the model roughly approximates this reduction in efficiency.

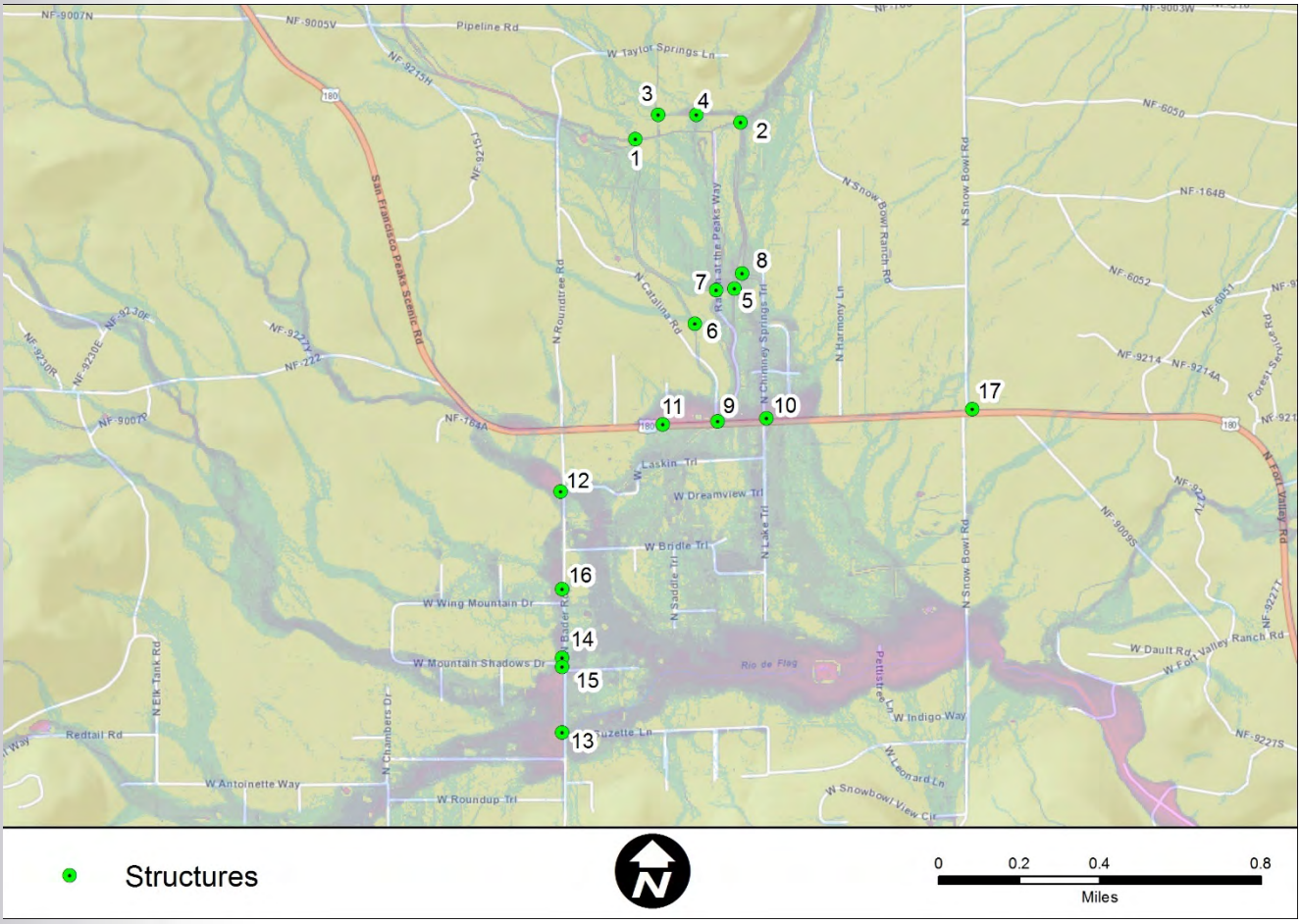

Figure 8. Fort Valley FLO-2D Hydraulic Structure Locations

Table 5. Fort Valley FLO-2D Hydraulic Structure Description

Map ID	Road Crossing	Description
1	Vista Peak Way	1 - 3 ft. X 8 ft. RCBC
2	Ranch At The Peaks Way	1 - 3 ft. X 8 ft. RCBC
3	Ranch At The Peaks Way	3 - 18 in. CMP[1]
4	Ranch At The Peaks Way	1 - 18 in. CMP
5	Ranch At The Peaks Way	2 - 18 in. CMP
6	Vista Peak Way	3 - 18 in. CMP
7	Ranch At The Peaks Way	2 - 3 ft. X 8 ft. RCBC
8	N. Chimney Springs Trail	2 - 18 in. CMP
9	US Highway 180	1 - 4 ft. X 8 ft. RCBC[2]
10	US Highway 180	Inlet: 1 - 3 ft. X 6 ft. RCBC Outlet: 2 - 36 in. CMP
11	US Highway 180	1 - 24 in. CMP[1]
12	N. Bader Road	2 - 18 in. CMP[1]
13	N. Bader Road	2 - 30 in. CMP[1]
14	N. Bader Road	1 - 24 in. CMP[1]
15	W. Mountain Shadows Dr.	1 - 24 in. CMP[1]
16	N. Bader Road	1 - 24 in. CMP[1]
17	US Highway 180	2 - 24 in. CMP[1]

Hydraulic structures for private properties and driveway crossings were not modeled. Additionally, the hydraulic structure at the major crossing along N. Snowbowl Road was also not included in the model as it was essentially fully clogged with sediment as shown in Figure 9.

[1] Decreased hydraulic efficiency due to sedimentation at the inlet.
[2] Decreased hydraulic efficiency due to outlet grade.

Figure 9. Hydraulic Structure at Snowbowl Rd. (left photo: outlet, right photo: inlet)

There are no stormdrains within the modeling domain and the main channels were adequately represented in the topo. Therefore, no channel or storm drain elements were added to the existing condition model. The grids appear to adequately represent the major topographic features and as such no adjustments were made to grid elevations.

F. Fort Valley Numerical Controls and Tolerances

FLO-2D controls and numerical stability are user controlled by modifying the CONT.DAT and TOLER.DAT input files. Table 6 outlines values for some of the key inputs used for the existing condition models by domain area.

Table 6. Fort Valley Numerical Controls and Tolerances

Description	Values Used for Each Model Domain		
	SF Peaks Domain	Wing Mountain Domain	Fort Valley Domain
Model Simulation Time (hrs.)	40	40	40
Output Time Interval (hrs.)	0.1	0.1	0.1
Modeled Hydraulic Structures	No	No	Yes
Froude Limit	0.95	0.95	0.95
Shallow “n”	0.20	0.20	0.15
Floodplain Courant Number	0.2	0.2	0.2
Minimum flow depth for flood routing (ft.)	0.001	0.001	0.001

More detail on the selection of these modeling parameters is provided in the FLO-2D User’s Manual.

G. Fort Valley Peak Flow Rate Summary

The results of the FLO-2D modeling are divided into separate tables for each storm event so that comparisons can be made between the fire scenarios. The locations of the output cross sections are shown in Figure 10.

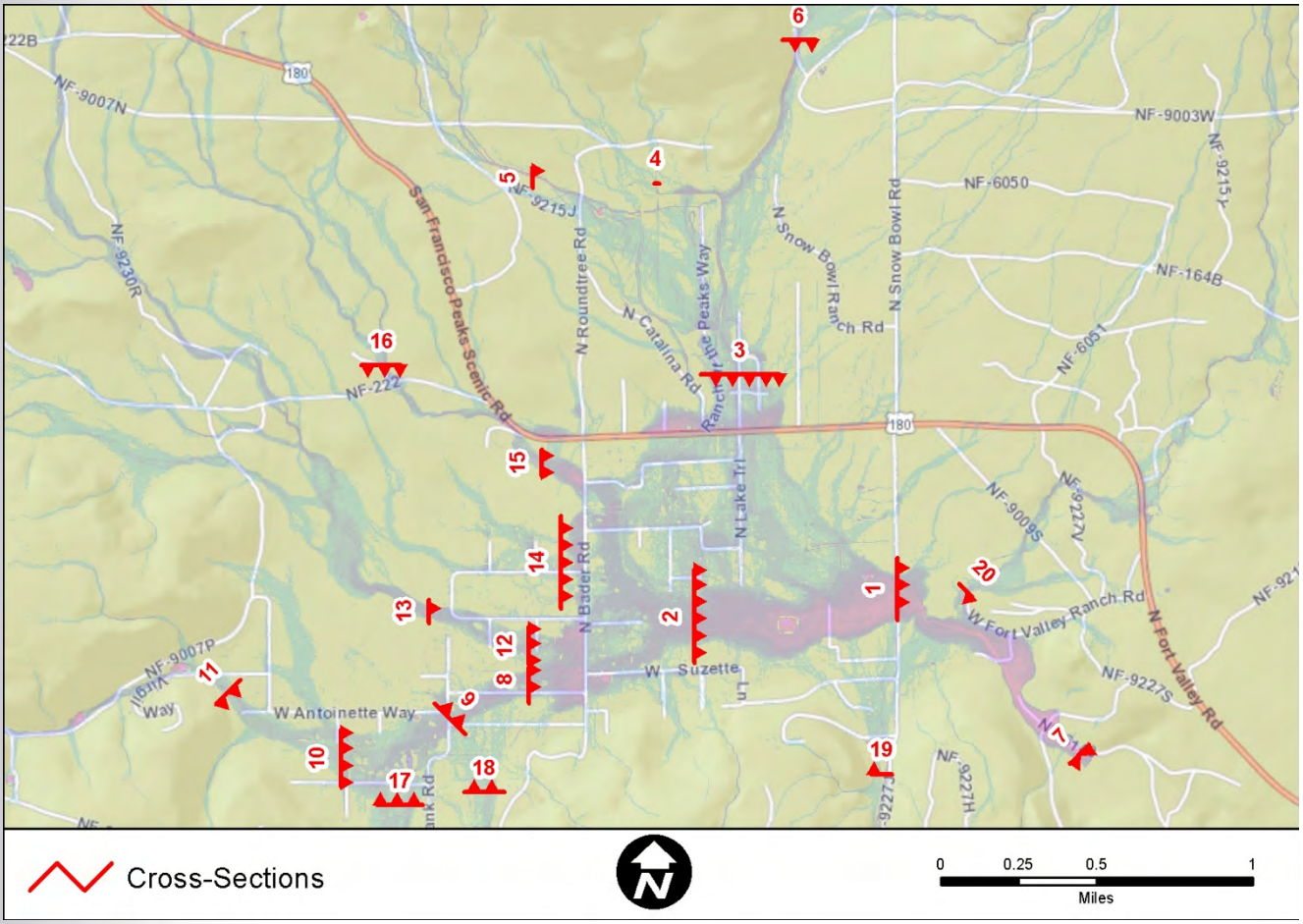

Figure 10. Fort Valley Cross Section Locations

Table 7. Fort Valley 2-Year Peak Flow Rate Summary

Cross Section ID	Pre-Fire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire Treatment up to 8200' (CFS)	Post-Wildfire All Treated (CFS)
1	70	1,444	782	225
2	65	831	395	142
3	48	1,840	1,314	115
4	3	55	6	6
5	23	573	499	66
6	19	1,548	1,286	54
7	72	1,568	865	244
8	27	198	57	56
9	25	183	50	49
10	14	158	29	29
11	5	112	13	13
12	32	260	66	60
13	33	272	73	65
14	5	32	9	9
15	25	147	50	45
16	18	114	40	34
17	3	68	12	12
18	7	46	16	16
19	16	66	33	31
20	6	321	230	49

Table 8. Fort Valley 10-Year Peak Flow Rate Summary

Cross Section ID	Pre-Wildfire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire Treatment up to 8200' (CFS)	Post-Wildfire All Treated (CFS)
1	537	4,635	2,365	1,140
2	404	2,465	1,247	822
3	229	4,288	3,543	512
4	14	83	23	23
5	99	1,132	1,076	265
6	111	3,559	3,337	256
7	586	4,649	2,604	1,244
8	131	730	256	255
9	111	649	230	229
10	70	581	152	151
11	48	428	107	106
12	142	662	267	239
13	149	682	279	249
14	23	95	39	39
15	101	359	177	166
16	80	323	148	137
17	51	353	111	111
18	33	142	68	68
19	75	215	137	135
20	54	763	586	176

Table 9. Fort Valley 100-Year Peak Flow Rate Summary

Cross Section ID	Pre-Wildfire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire Treatment up to 8200' (CFS)	Post-Wildfire All Treated (CFS)
1	2,998	11,659	8,373	4,863
2	2,418	7,110	4,588	3,684
3	1,271	9,736	8,196	2,285
4	50	126	68	68
5	520	1,998	1,905	961
6	686	7,591	7,327	1,352
7	3,187	12,446	8,903	5,203
8	889	2,859	1,479	1,473
9	788	2,445	1,308	1,305
10	518	1,532	850	848
11	381	1,155	642	640
12	603	1,620	917	881
13	622	1,791	955	914
14	98	240	140	140
15	372	679	505	494
16	348	870	546	524
17	407	1,182	653	653
18	183	489	312	309
19	341	657	510	509
20	288	1,572	1,330	670

Figure 11 through Figure 22 illustrate the maximum flood depth for the 2-, 10-, and 100-year, 24-hour storm events for the Fort Valley study area and include all burn scenarios in the following order:

1. Pre-Wildfire scenario
2. Post-Wildfire, no Treatment scenario
3. Post-Wildfire, Treatment up to 8200' scenario
4. Post-Wildfire, Treatment (all areas) scenario

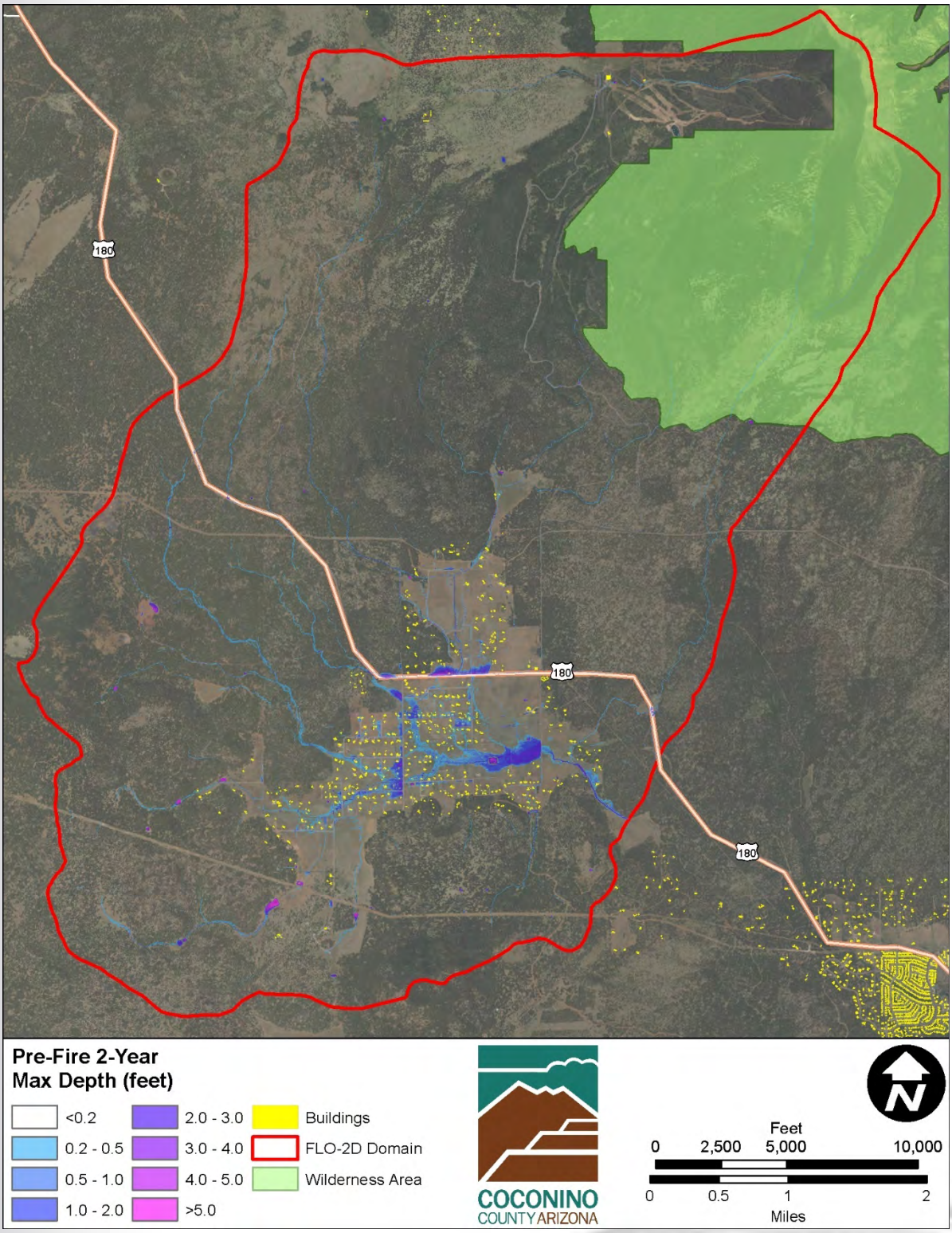

Figure 11. Fort Valley 2-Year Pre-Wildfire Max Flow Depth

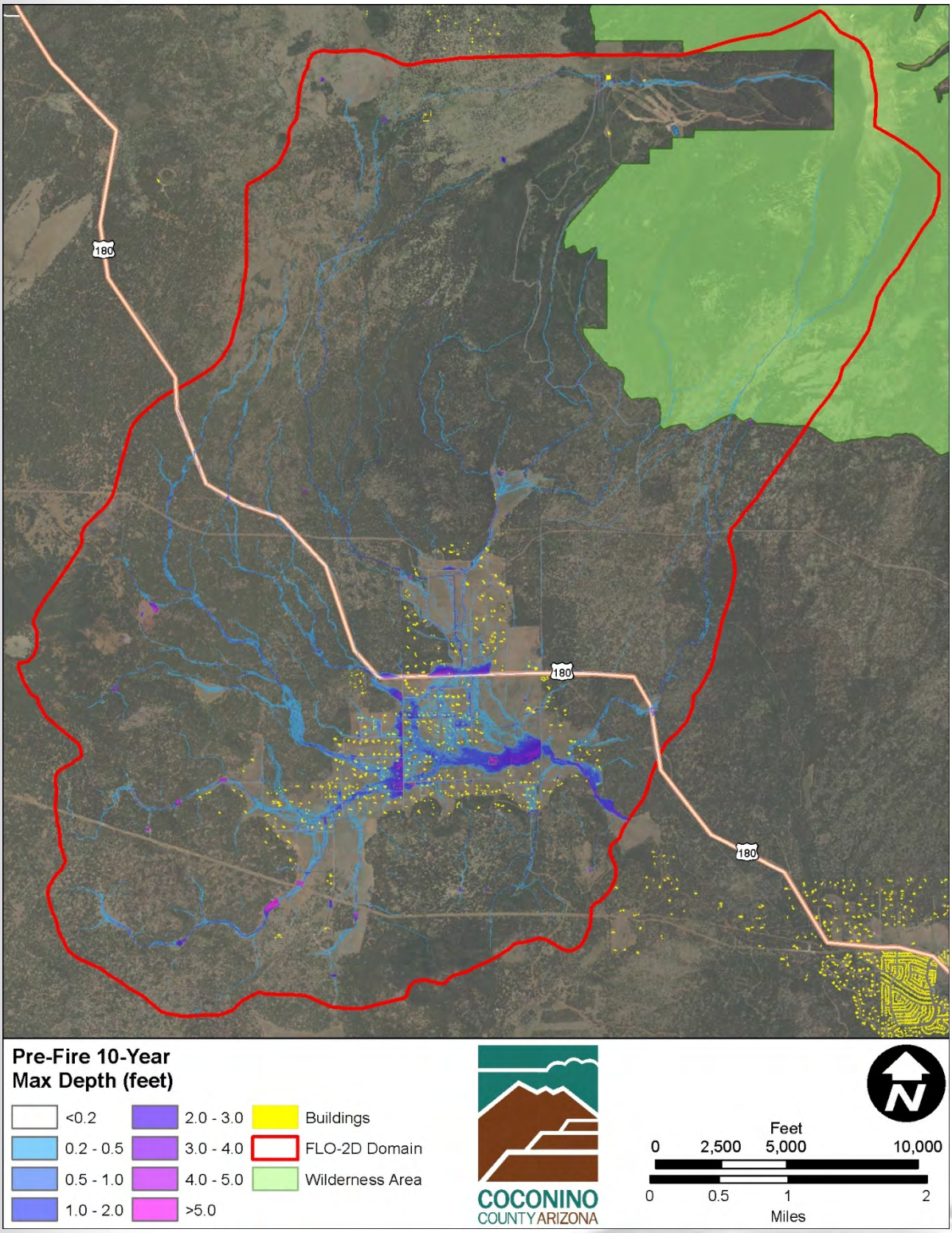

Figure 12. Fort Valley 10-Year Pre-Wildfire Max Flow Depth

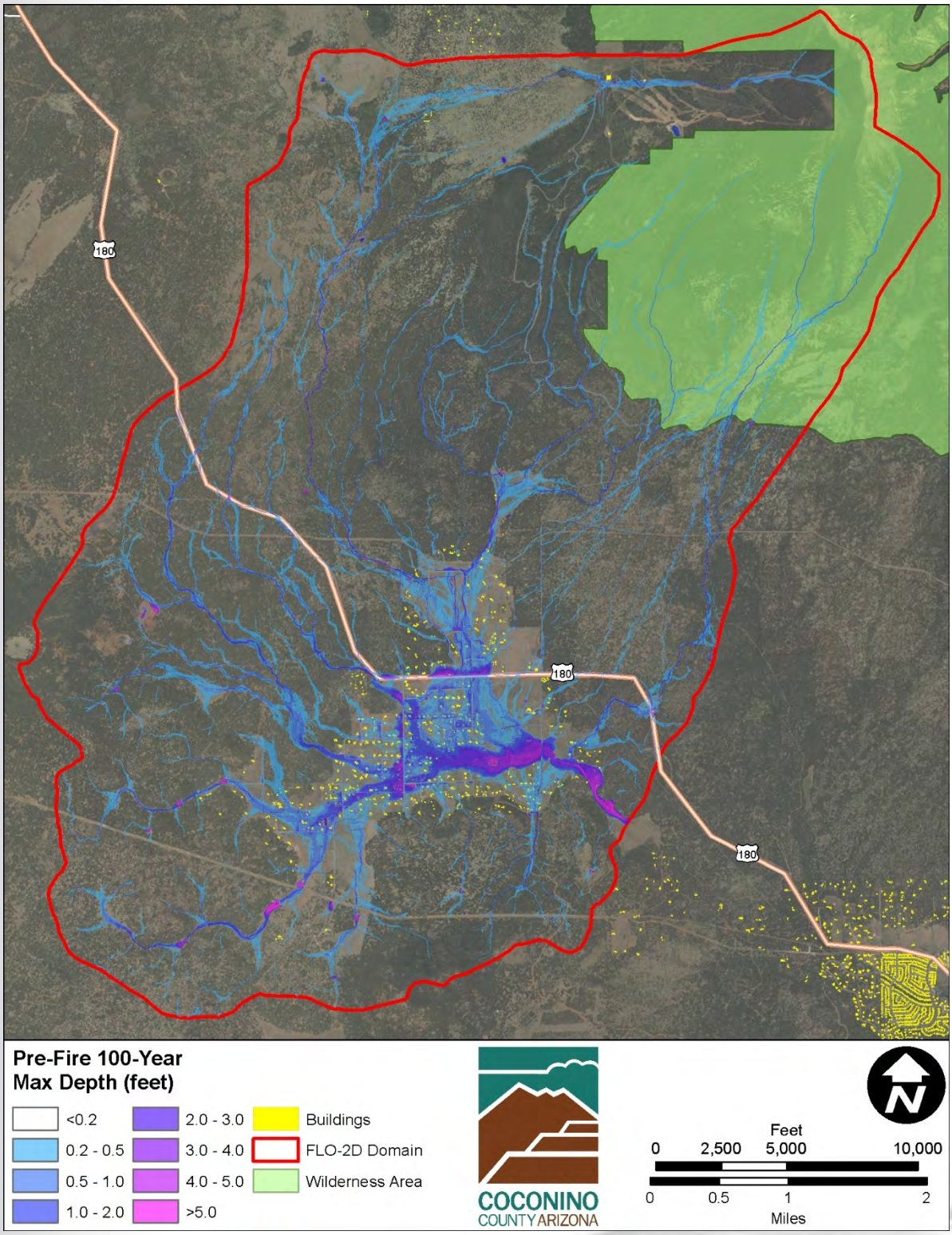

Figure 13. Fort Valley 100-Year Pre-Wildfire Max Flow Depth

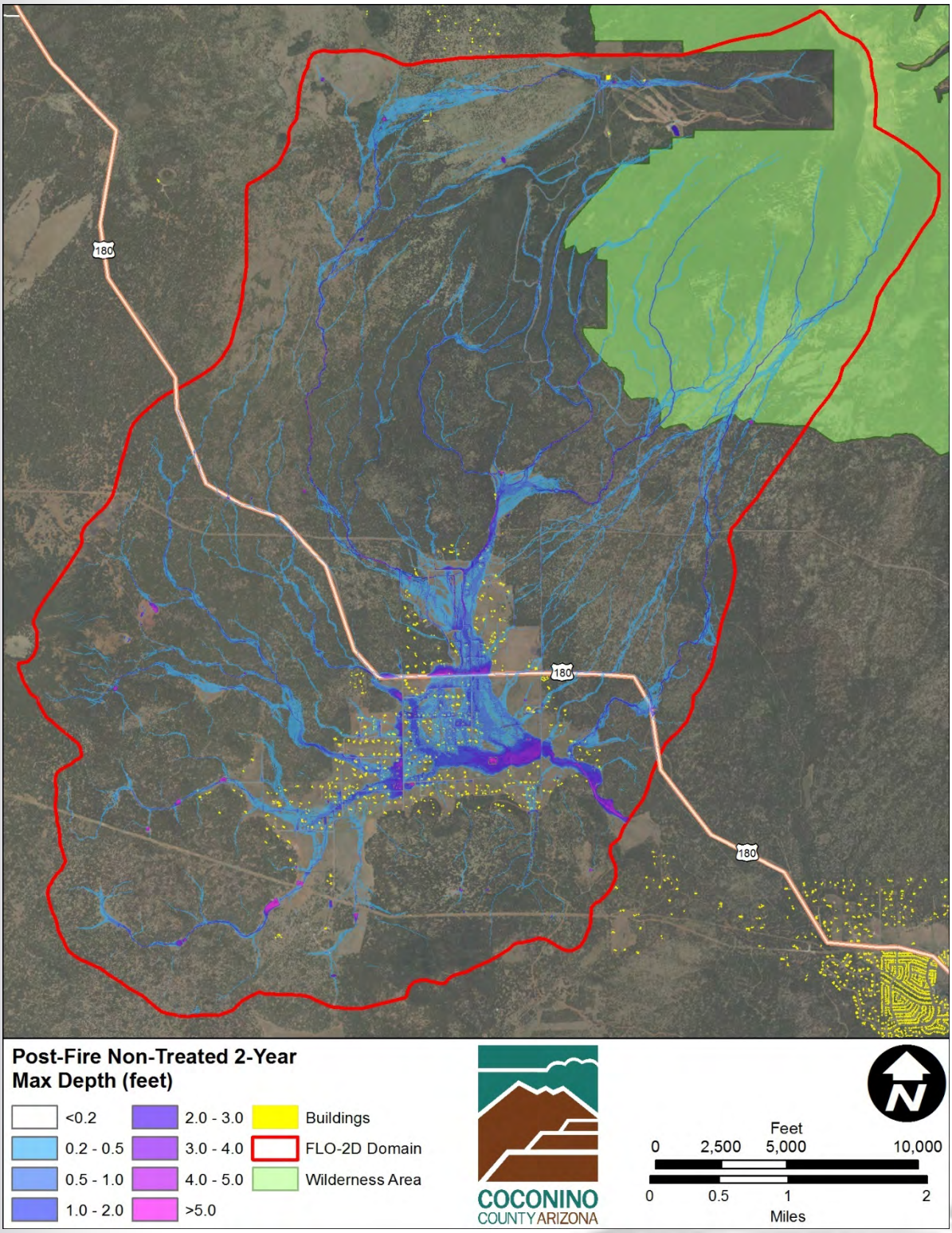

Figure 14. Fort Valley 2-Year Post-Wildfire Non-Treated Max Flow Depth

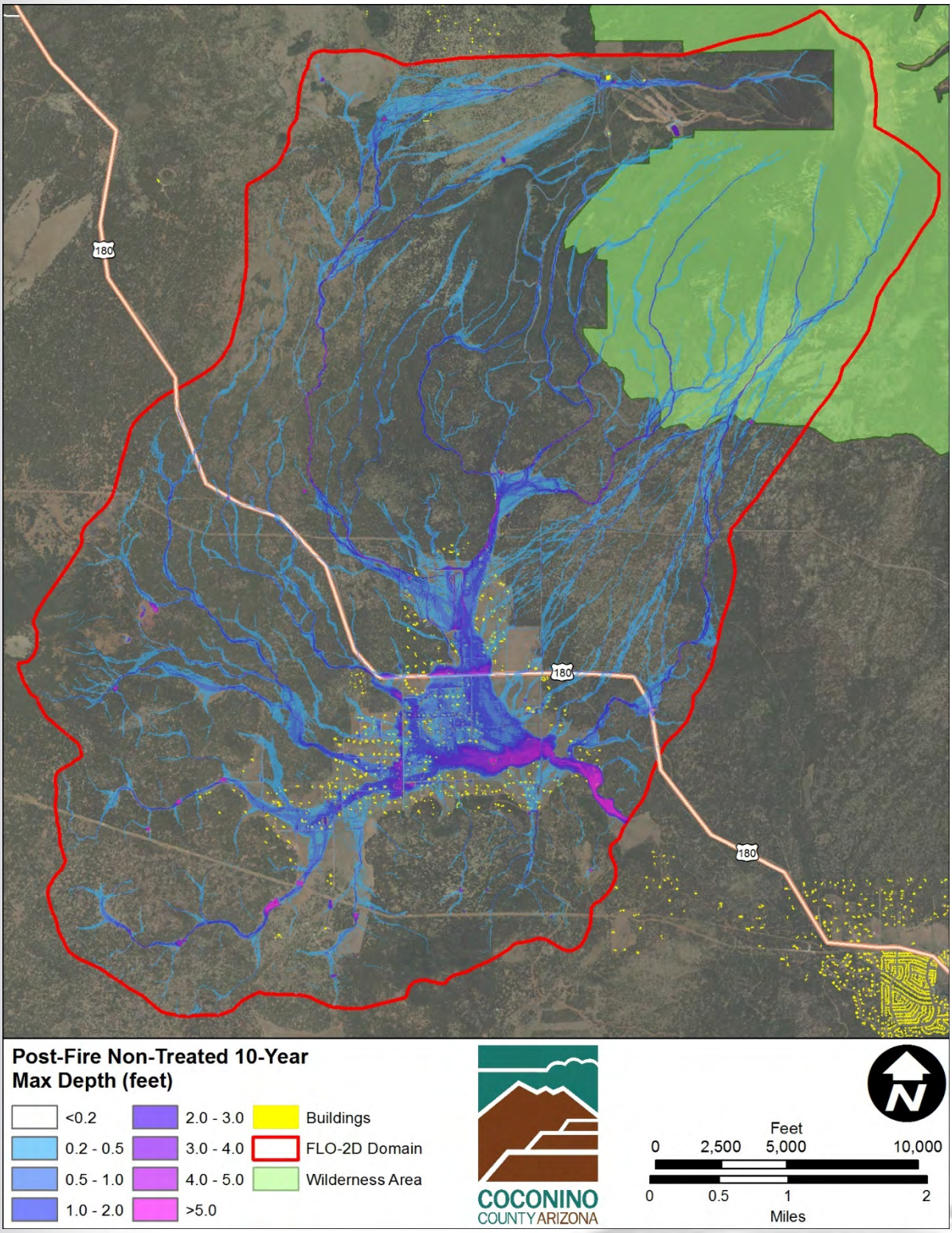

Figure 15. Fort Valley 10-Year Post-Wildfire Non-Treated Max Flow Depth

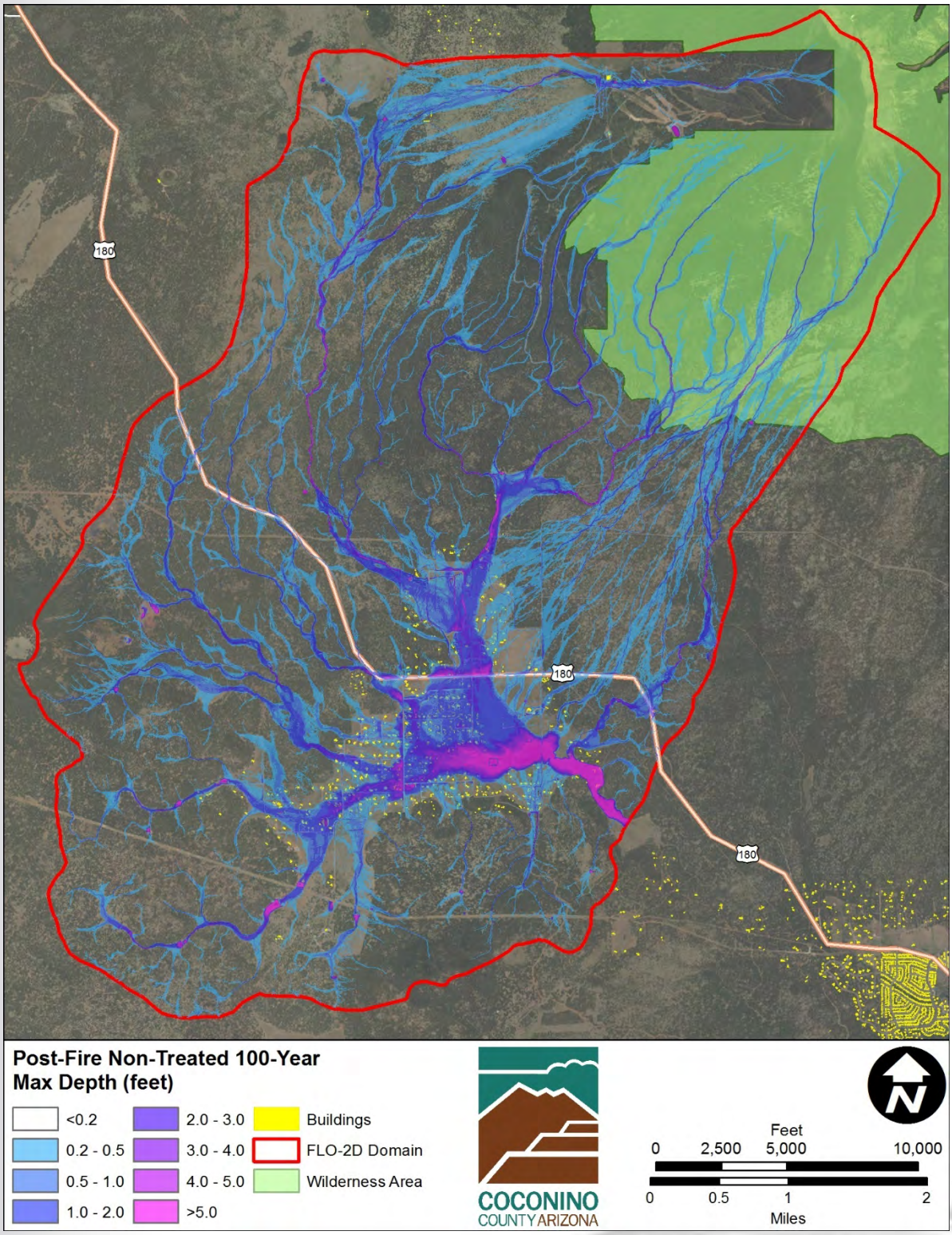

Figure 16. Fort Valley 100-Year Post-Wildfire Non-Treated Max Flow Depth

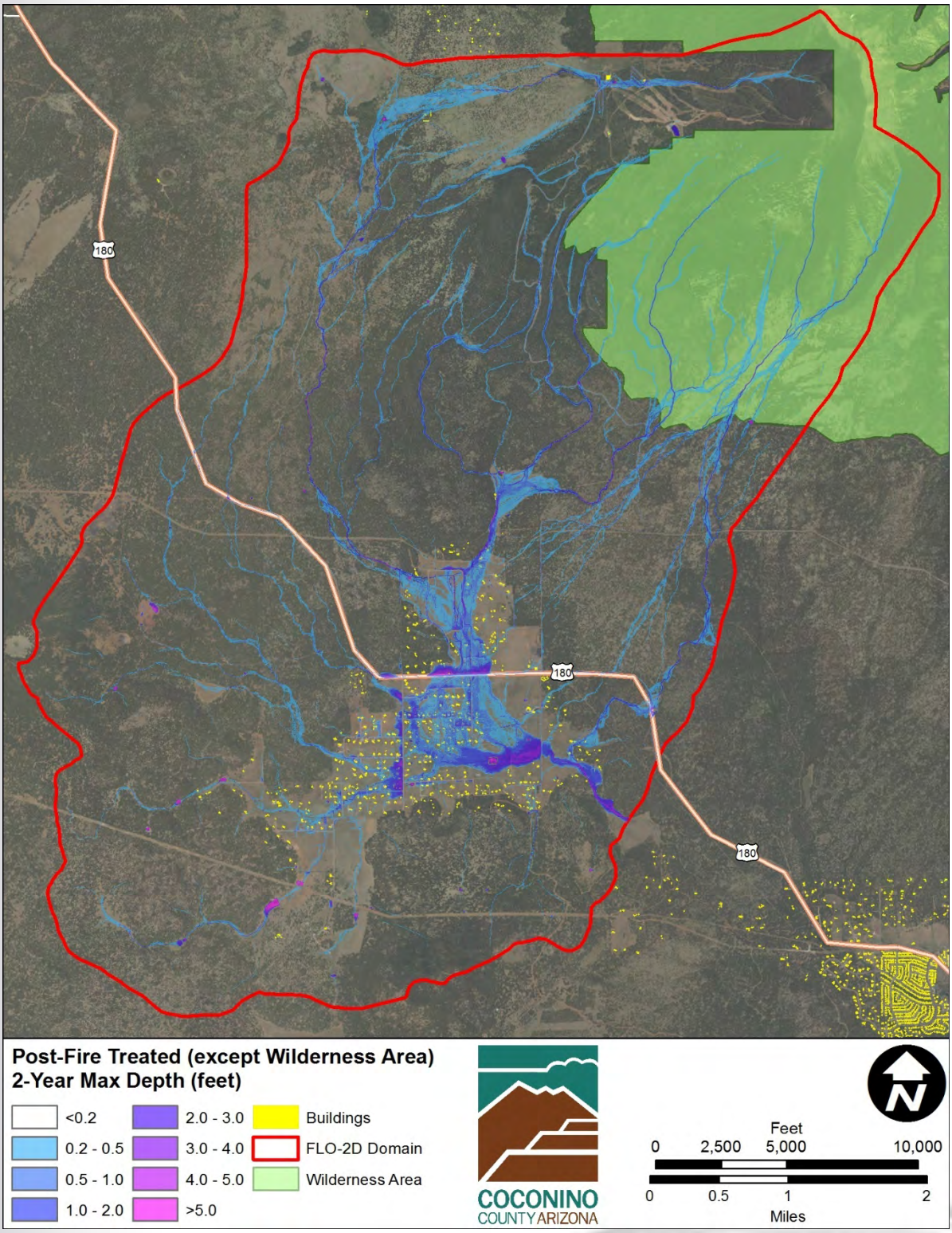

Figure 17. Fort Valley 2-Year Post-Wildfire Treated up to 8200' Max Flow Depth

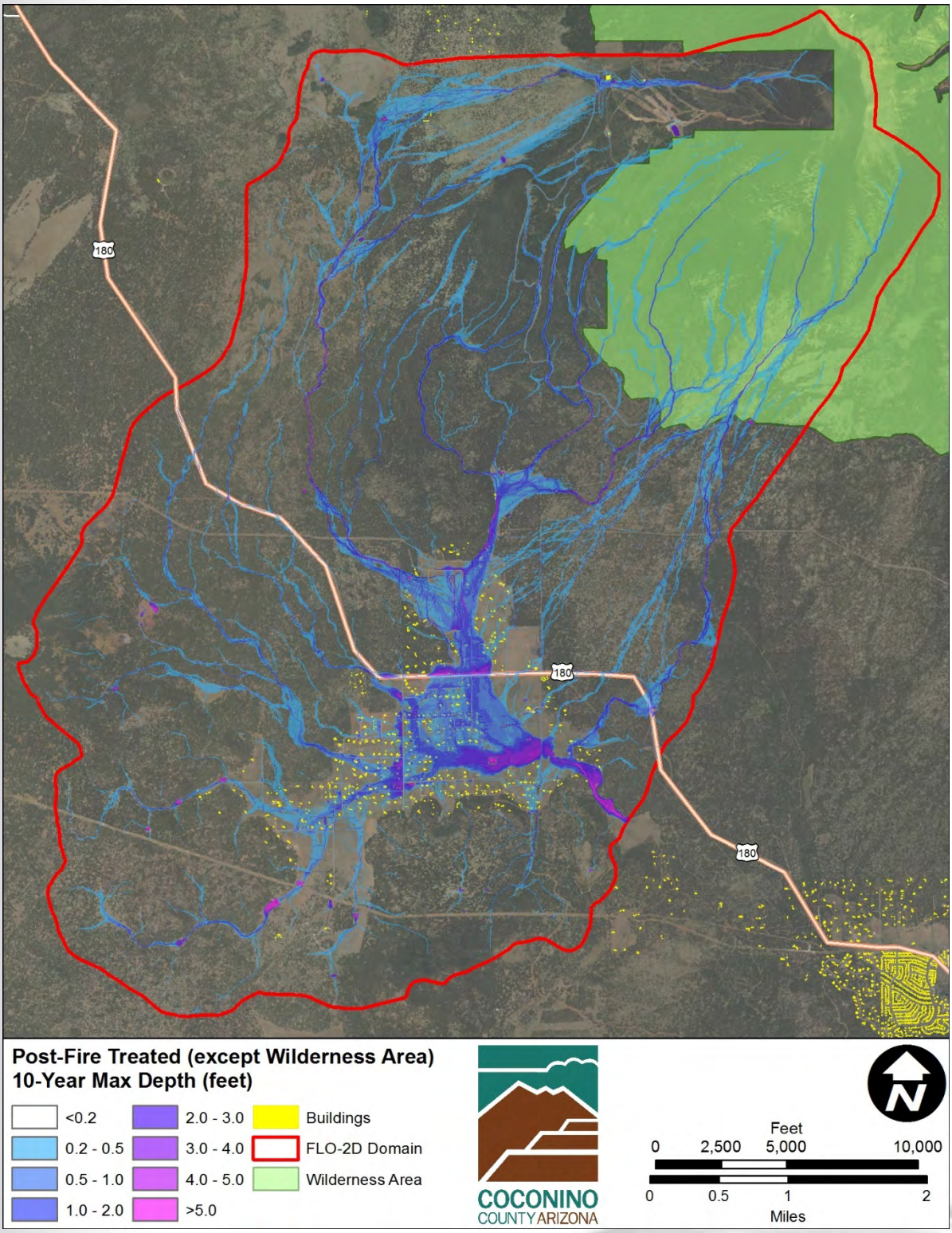

Figure 18. Fort Valley 10-Year Post-Wildfire Treated up to 8200' Max Flow Depth

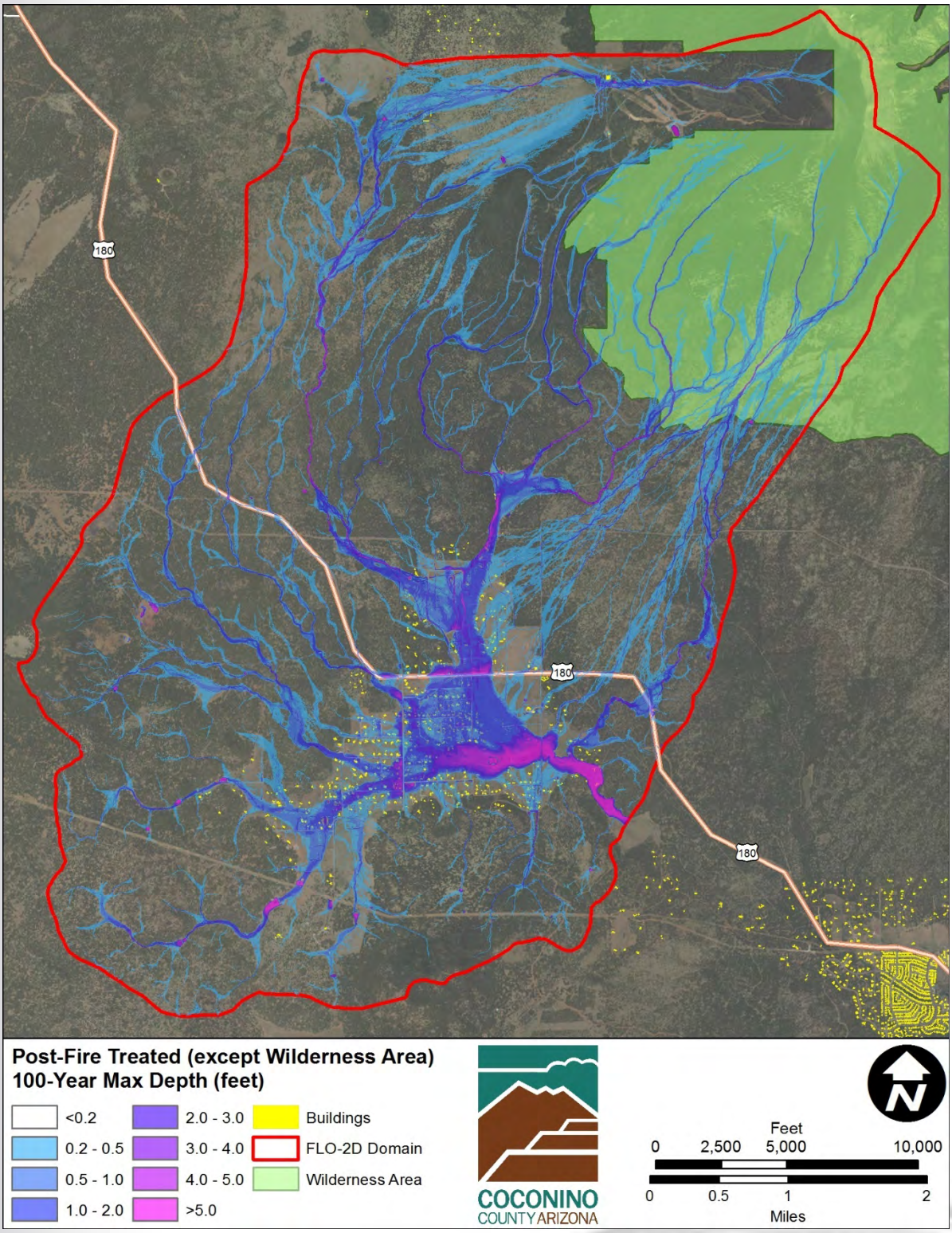

Figure 19. Fort Valley 100-Year Post-Wildfire Treated up to 8200' Max Flow Depth

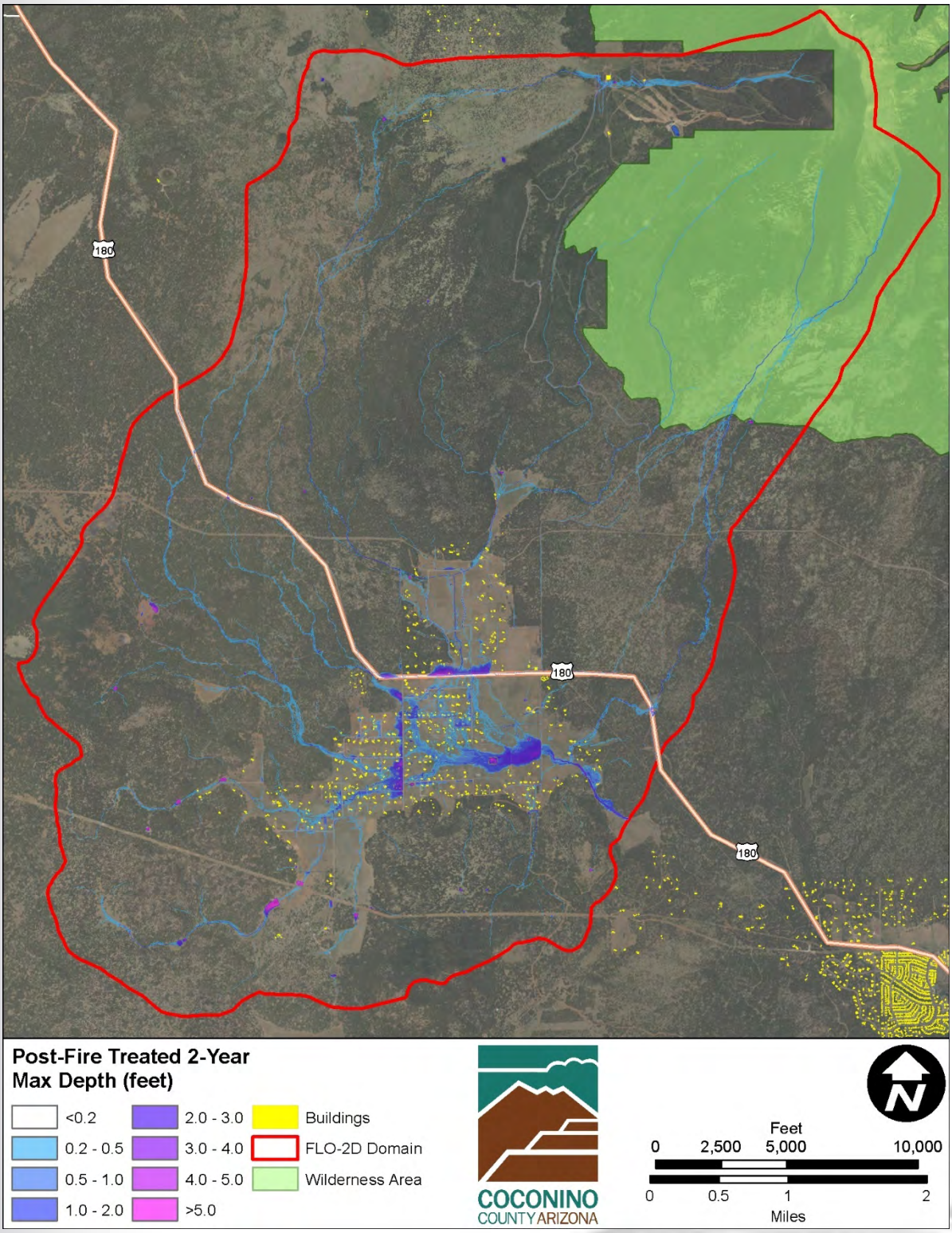

Figure 20. Fort Valley 2-Year Post-Wildfire Treated (all areas) Max Flow Depth

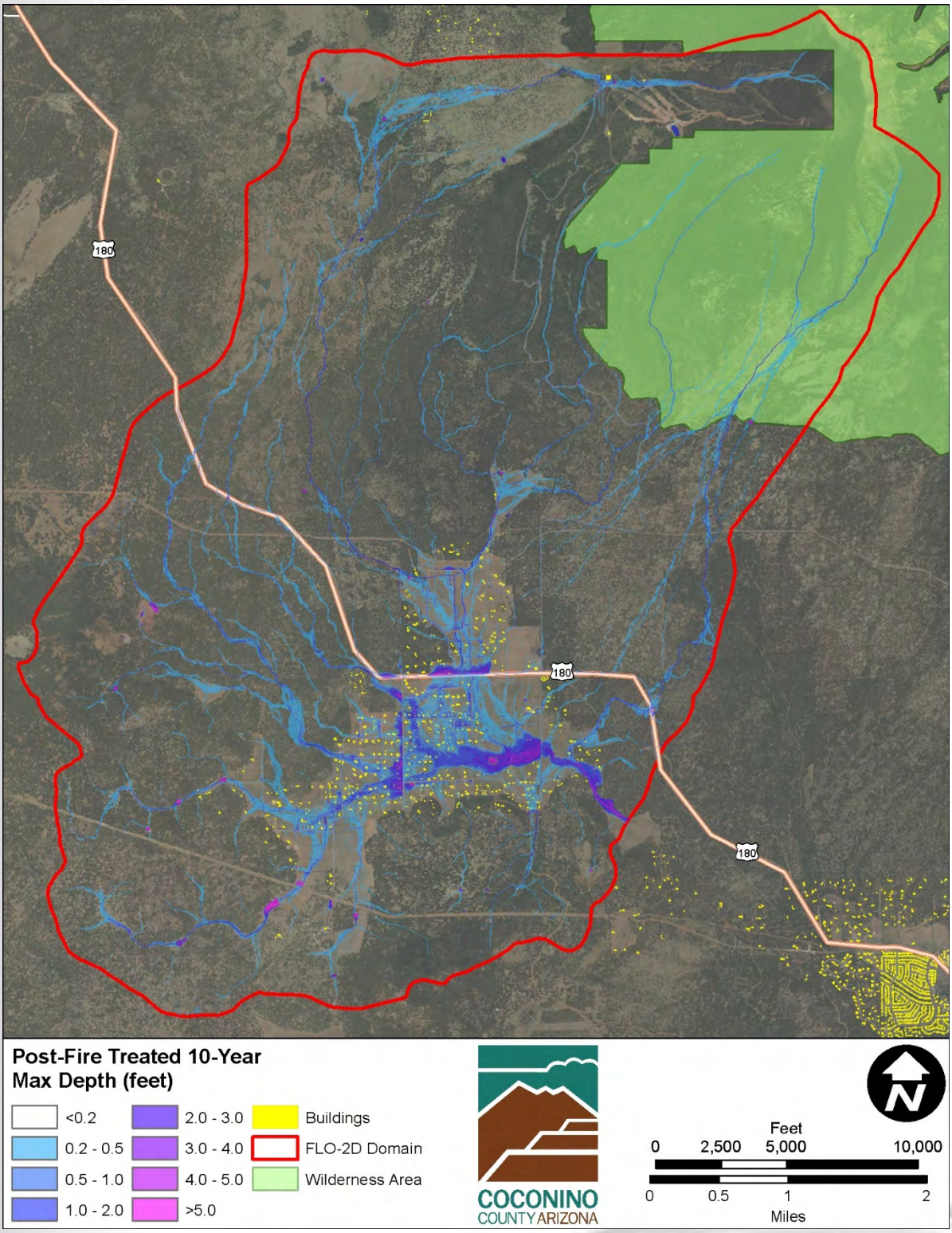

Figure 21. Fort Valley 10-Year Post-Wildfire Treated (all areas) Max Flow Depth

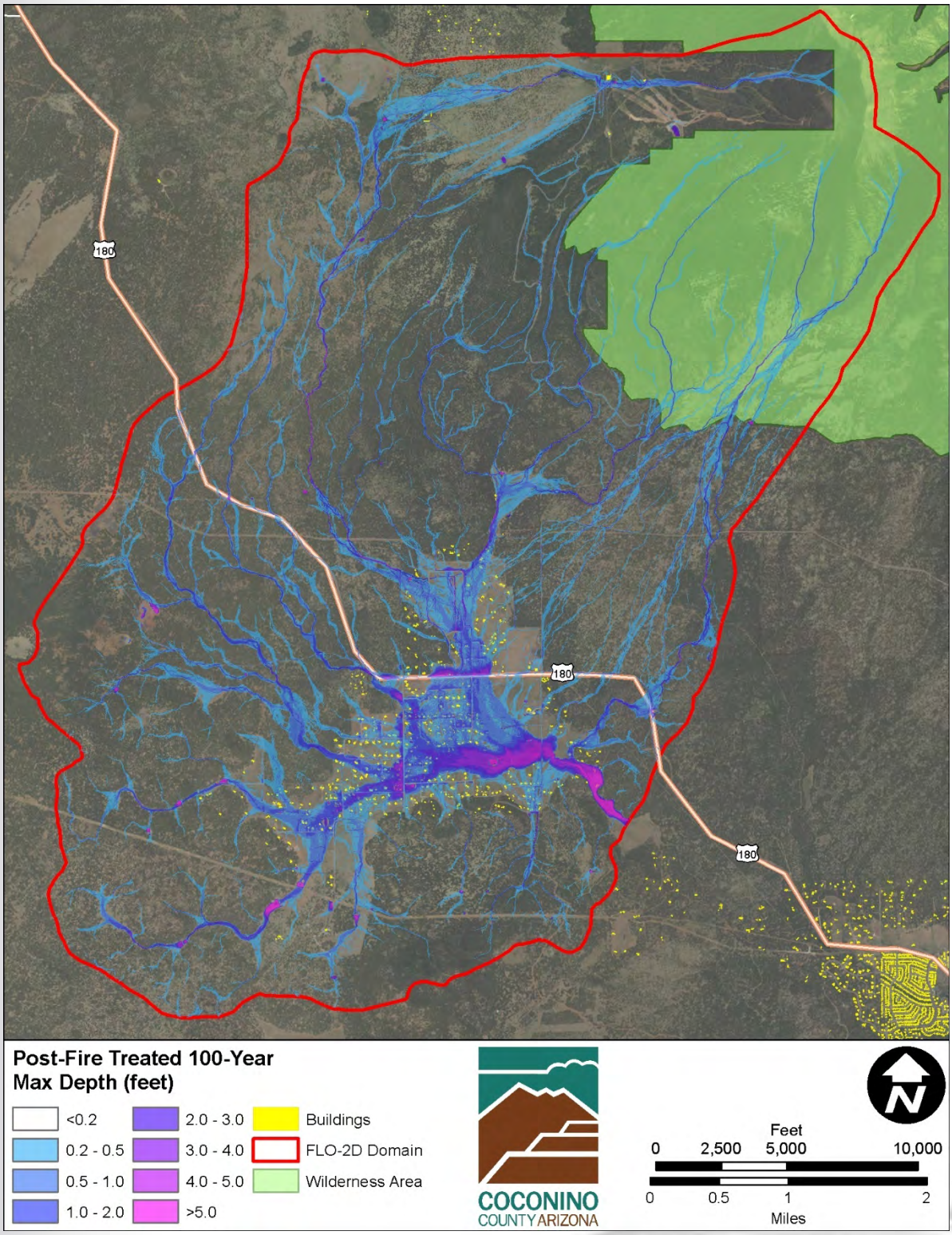

Figure 22. Fort Valley 100-Year Post-Wildfire Treated (all areas) Max Flow Depth

4. Williams Hydrologic and Hydraulic Modeling

A. Williams Model Description

FLO-2D PRO was also used for the Williams study area, using the same modeling procedures as Fort Valley. The Williams area was modeled with several watershed condition scenarios as described below.

Williams

- Pre-Wildfire (unburnt)
- Post-Wildfire, No Treatment
- Post-Wildfire, Treatment (all areas)

B. Williams Grid Development

The Williams pilot study area is 24.2 square miles. The grid size used for the FLO-2D model was 20 feet by 20 feet resulting in a total of 1.69 million grids. The Williams model was conducted using a single model domain. Figure 23 shows the location and spatial limits of the model domain.

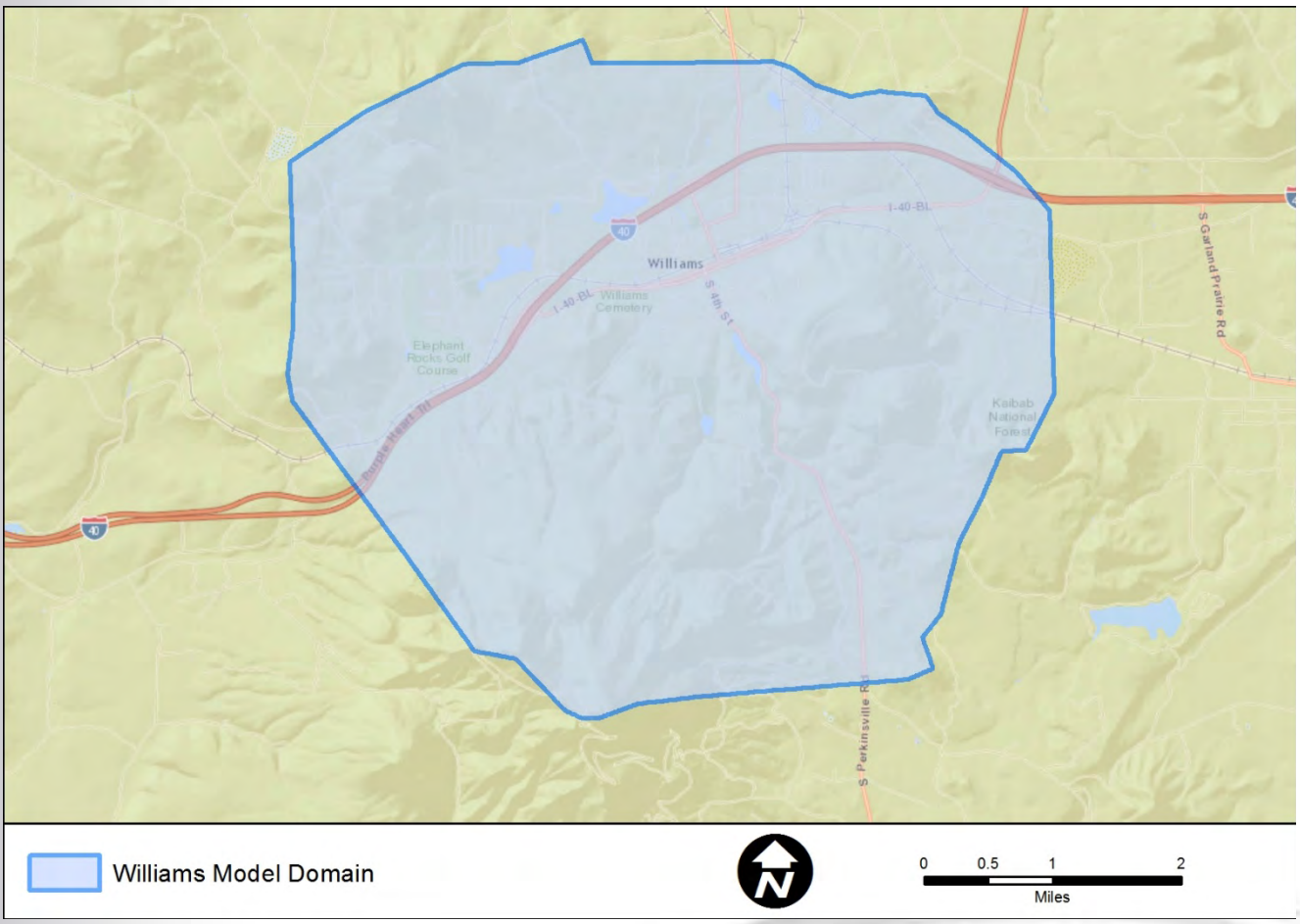

Figure 23. Williams FLO-2D Model Domain

C. Williams Grid Elevations, Roughness, and Area/Width Reductions

The elevation of each 20-foot grid element in the FLO-2D model is calculated based on the average elevation within the 400 square feet grid element. Grid elevations were determined from the 2016 Coconino County LiDAR data generated for this project.

Grid element roughness is approximated using Manning's 'n' values. Roughness coefficients assigned to the FLO-2D grid elements ranged from 0.022 to 0.065. Table 1 summarizes the categories used to assign the roughness coefficients. Figure 6 shows the spatial distribution of the roughness coefficients assigned to the model throughout the watershed. Roughness values were consistent between the pre-wildfire model and all of the post-wildfire models.

Table 10. Williams Roughness Coefficients

Description	Roughness Coefficient
Deciduous/Evergreen Forest	0.065
Deciduous shrubland/Grassland	0.05
Developed	0.045
Non-vegetated	0.02
Water	0.022

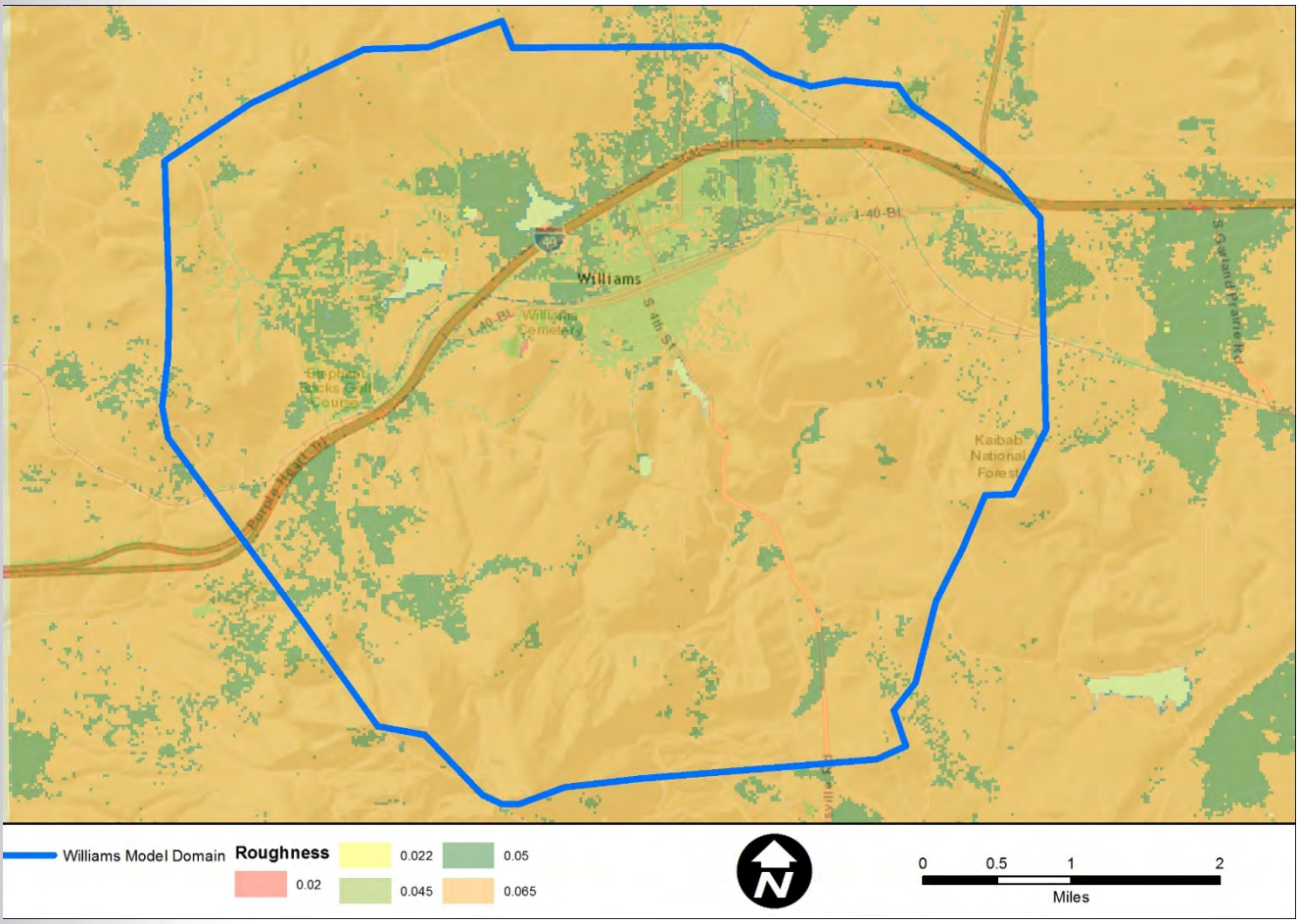

Figure 24. Williams Spatial Distribution of Grid Element Roughness

D. Williams Rainfall and Loss Parameters

Table 11. Williams NOAA 14 Point Rainfall Depths

Description	24-hr* Maximum Depth in Watershed (inches)
2-year	2.6
10-Year	3.79
100-year	5.69

*The 24-hour storm was chosen due to the large watershed size and ADOT modeling procedures.

Rainfall losses were simulated using SCS Curve Number methodology to be consistent with standard hydrologic modeling practices in Coconino County. Curve Numbers were assigned to grid elements based on four scenarios:

1. Pre-Wildfire
2. Post-Wildfire – No Treatment
3. Post-Wildfire – All Treated

Pre-wildfire Curve Numbers were selected using NRCS guidance, which incorporates soil type to define the hydrologic soil group (HSG), vegetative cover and watershed condition. Post Wildfire Curve numbers were assigned as described in the *Coconino County Post-Wildfire Flood and Debris-Flow Risk Assessment: Fort Valley Fire Modeling and Assignment of Post-Wildfire Curve Numbers Technical Memorandum (JE Fuller, 2016).*

The Arizona General Soils map was used to determine the HSG since detailed soil survey information was not available on the NRCS Web Soil Survey. Generally, there are Type C and D soils in the Williams area and curve numbers were calculated for Williams with a slightly different methodology than for Fort Valley. Land uses for the study area was assigned based on the existing vegetation type and existing vegetation coverage generated from Landfire.gov. Landfire.gov contains nationwide datasets that are compiled in central location and administered by the US Department of Agriculture and the US Department of the Interior. is a This was then translated into curve numbers utilizing Table 9-1 and Table 9-2 in the NRCS National Engineering Handbook. Resulting curve numbers for the study area are listed in Table 12. Figure 25 shows the spatial variation of the pre-wildfire Curve Numbers used for modeling.

Table 12. Williams Pre-Wildfire Curve Number Data

Landuse	Cover Type	Hydrologic Condition	C	D
Annual Graminoid/Forb (Close Grown Crop)	Close Seeded (C-Good)	-	78	83
Non-Vegetated (Water)	Lakes	-	98	98
Non-Vegetated (Barren)	Mixed Barren Land	-	91	94
Evergreen Shrub	Rangeland (Desert Shrub)	Poor	85	88
		Fair	81	86
		Good	79	84
Herbaceous Grassland	Rangeland (Herbaceous)	Poor	87	93
		Fair	81	89
		Good	74	85
Evergreen Tree Canopy (except Pinyon/Juniper)	Rangeland (Oak - Aspen)	Poor	74	79
		Fair	57	63
		Good	41	48
Evergreen Tree Canopy (Pinyon/Juniper)	Rangeland (Pinyon - Juniper)	Poor	85	89
		Fair	73	80
		Good	61	71
Evergreen Dwarf Shrubland (sagebrush)	Rangeland (Sage - Grass)	Poor	80	85
		Fair	63	70
		Good	47	55
Residential (30%)	Residential (30%)	-	81	86
Roads	Roads (Paved with ditch)	-	92	93
Quarries	Strip mines, Quarries	-	91	94
Developed - Medium Intensity	Urban (72%)	-	91	93
Developed - High Intensity	Urban (85%)	-	94	95

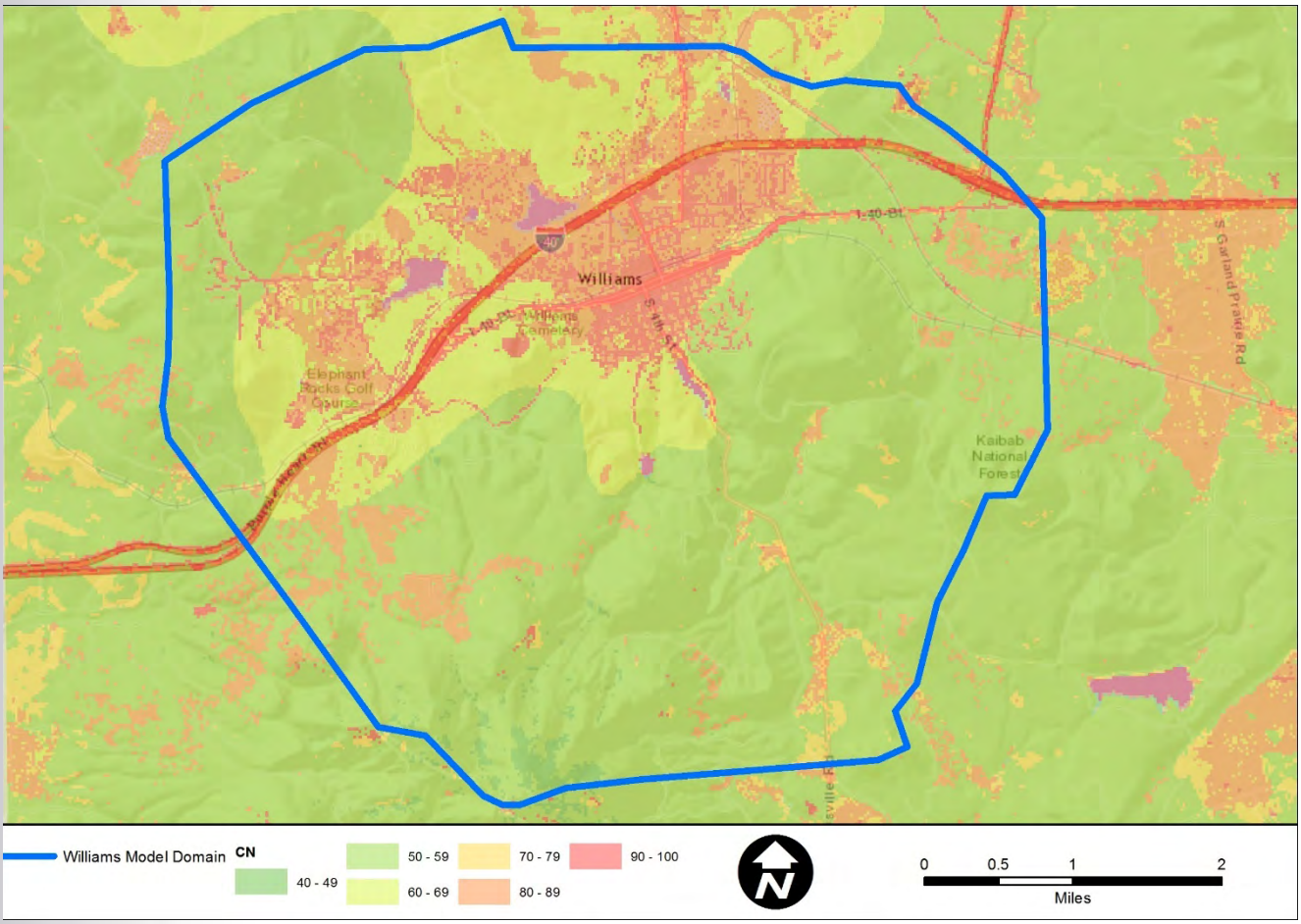

Figure 25. Williams Pre-Wildfire FLO-2D Curve Numbers

E. Williams Hydraulic Structures

Sixty-seven hydraulic structures were included in the Williams FLO-2D model domain. Each of these hydraulic structures are located at existing road or railroad crossings, as shown in Figure 26 and Figure 27. Brief descriptions for each of the modeled hydraulic structures are included in Table 13. The major structures included in the model were necessary to preserve the major flow paths and patterns. Smaller structures that do not affect the overall flow paths were not modeled for this study.

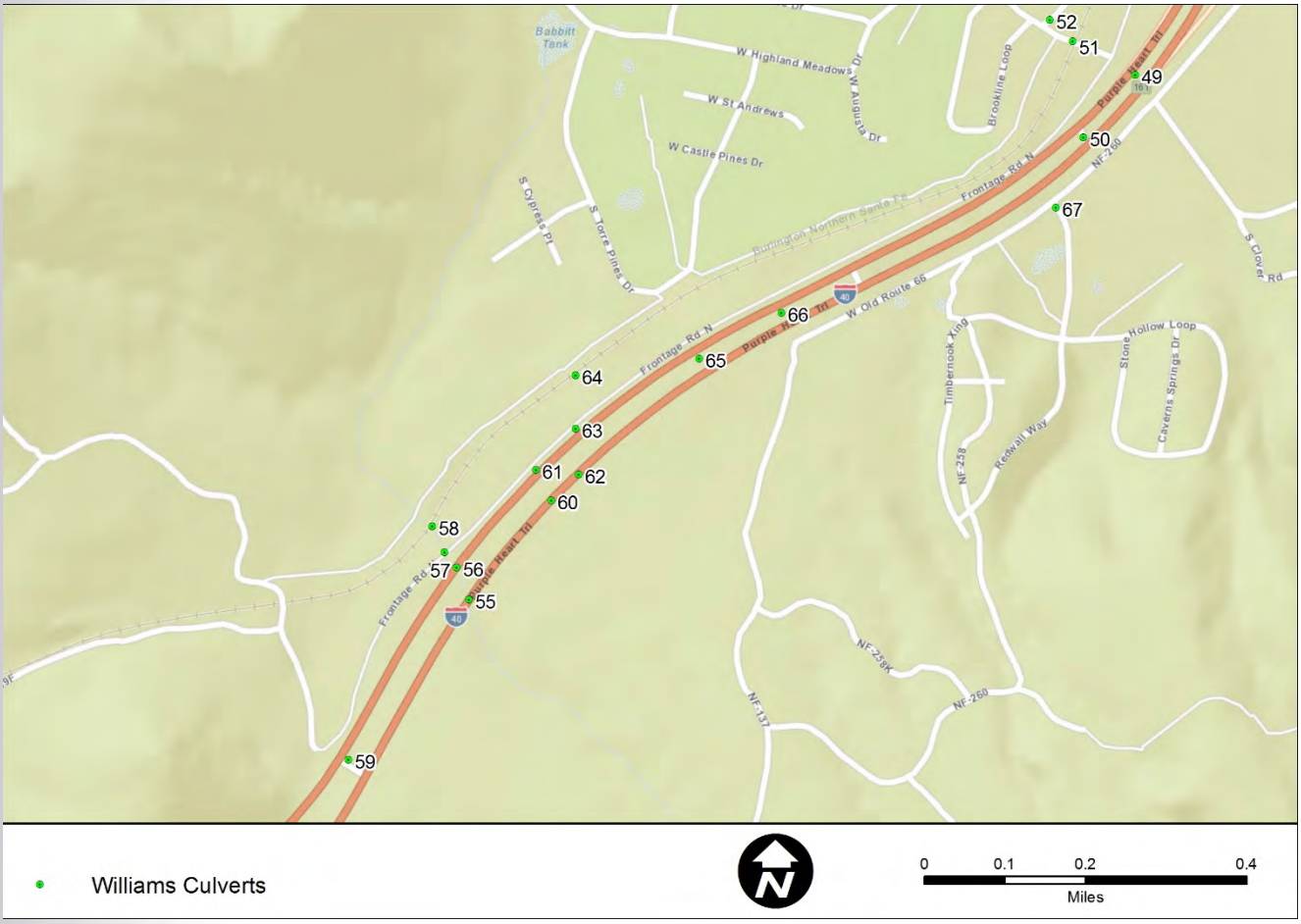

Figure 26. Williams West Hydraulic Structure Locations

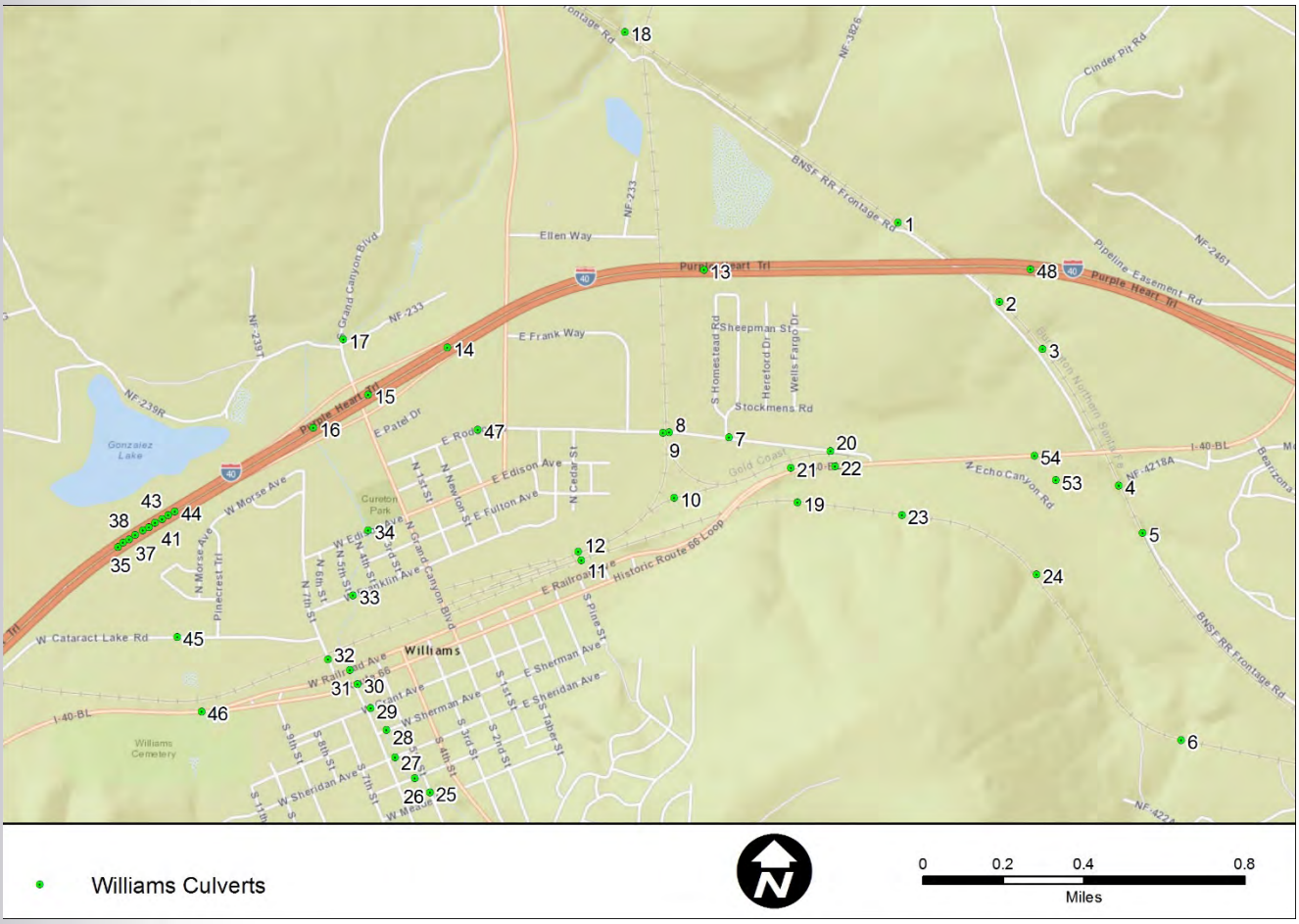

Figure 27. Williams East Hydraulic Structure Locations

Table 13. Williams FLO-2D Hydraulic Structure Description

Map ID	Road Crossing	Description
1	BNSF	1 -72" CMP
2	BNSF	1-66" CMP
3	BNSF	1-66" CMP
4	BNSF	1-66" CMP
5	BNSF	1-78" CMP
6	Old BNSF	2-78" CMP
7	Quarter Horse Rd.	1- 6'x8' RCBC
8	E. Rodeo Rd.	1-42" CMP
9	E. Rodeo Rd.	2-42" CMP

Map ID	Road Crossing	Description
10	Old BNSF	1 -48" CMP
11	Old BNSF	1-10'X12' RCBC
12	GCRW	3-3'X8' RCBC
13	I-40	3 - 6'X8' RCBC
14	I-40	3 -48" CMP
15	I-40	3 -48" CMP
16	I-40	5-6'X8' RCBC
17	Grand Canyon Blvd.	3-6'X8' RCBC
18	BNSF	3-16'X14' RCBC
19	Old BNSF	1-60" CMP
20	E. Rodeo Rd.	1-48" CMP
21	Route 66	1-60"CMP
22	Route 66	1-48" CMP
23	Old BNSF	1-48" CMP
24	Old BNSF	1-60" CMP
25	S. 5th St.	3-4'X10' RCBC
26	W. Hancock Ave.	3-4'X10' RCBC
27	W. Sheridan Ave.	3-4'X10' RCBC
28	W. Sherman Ave	3-4'X10' RCBC
29	W. Grant Ave.	3-4'X10' RCBC
30	W. Route 66	3-4'X10' RCBC
31	W. Railroad Ave.	3-4'X10' RCBC
32	N. 7th St.	5-36" CMP
33	Franklin Ave.	3-5'X10' RCBC
34	Edison Ave.	4-4'X10' RCBC
35	I-40	1-36"X48" CMPA
36	I-40	1-36"X48" CMPA
37	I-40	2-36"X48" CMPA
38	I-40	2-36"X48" CMPA
39	I-40	3-36"X48" CMPA
40	I-40	3-36"X48" CMPA
41	I-40	2-36"X48" CMPA
42	I-40	2-36"X48" CMPA
43	I-40	1-36"X48" CMPA
44	I-40	1-36"X48" CMPA
45	Cataract Lake Rd.	4-36"X48" CMPA

Map ID	Road Crossing	Description
46	W. Route 66	1-7'X8' RCBC
47	E. Rodeo Rd.	3-30" CMP
48	I-40	1-42-CMP
49	I-40	1-3'X8' RCBC
50	I-40	1-3'X8' RCBC
51	Old BNSF	1-13'X15' RCBC
52	Cataract Lake Rd.	4-30" CMP
53	Old RR Grade	1-7'X12' RCBC
54	Route 66	2-6'X10' RCBC
55	I-40	1-6'X10' RCBC
56	I-40	1-6'X10' RCBC
57	Frontage Rd.	1-6'X10' RCBC
58	Old BNSF	1-6'X10' RCBC
59	I-40	1-6'X10' RCBC
60	I-40	1-6'X10' RCBC
61	I-40	1-6'X10' RCBC
62	I-40	1-6'X10' RCBC
63	I-40	1-6'X10' RCBC
64	Old BNSF	1-6'X10' RCBC
65	I-40	1-6'X10' RCBC
66	I-40	1-6'X10' RCBC
67	Redwall Way	1-6'X10' RCBC

Although there may be minor stormdrains within the modeling domain, storm drain elements were not added to the existing condition model for simplicity. The topo appears to adequately represent major topographic features and as such, no adjustments were made to grid elevations.

There are several dams and lakes within the modeling domain. The existing elevations used in the FLO-2D model reflect the water surface elevations of those lakes at the date of the LiDAR survey. No adjustments were made to the grid elevations to reflect the existing ground under the water. The attenuation shown in the cross sections at various locations upstream and downstream of the dams is due to the flood storage behind the dams, which will fluctuate throughout the year. Spillway configurations and elevations were determined by the LiDAR Survey and no additional structures were added to the model to more accurately reflect the actual spillway configurations.

F. Williams Numerical Controls and Tolerances

FLO-2D controls and numerical stability are user controlled by modifying the CONT.DAT and TOLER.DAT input files. Table 14 outlines values for some of the key inputs used for the existing condition models by domain area.

Table 14. Williams Numerical Controls and Tolerances

Description	Values
Model Simulation Time (hrs.)	40
Output Time Interval (hrs.)	0.1
Modeled Hydraulic Structures	Yes
Froude Limit	0.95
Shallow “n”	0.20
Floodplain Courant Number	0.6
Minimum flow depth for flood routing (ft.)	0.001

G. Williams Peak Flow Rate Summary

The results of the FLO-2D modeling are divided into separate tables for each storm event so that comparisons can be made between the fire scenarios. The locations of the cross sections used for comparison are shown in Figure 28.

Figure 28. Williams Cross Section Locations

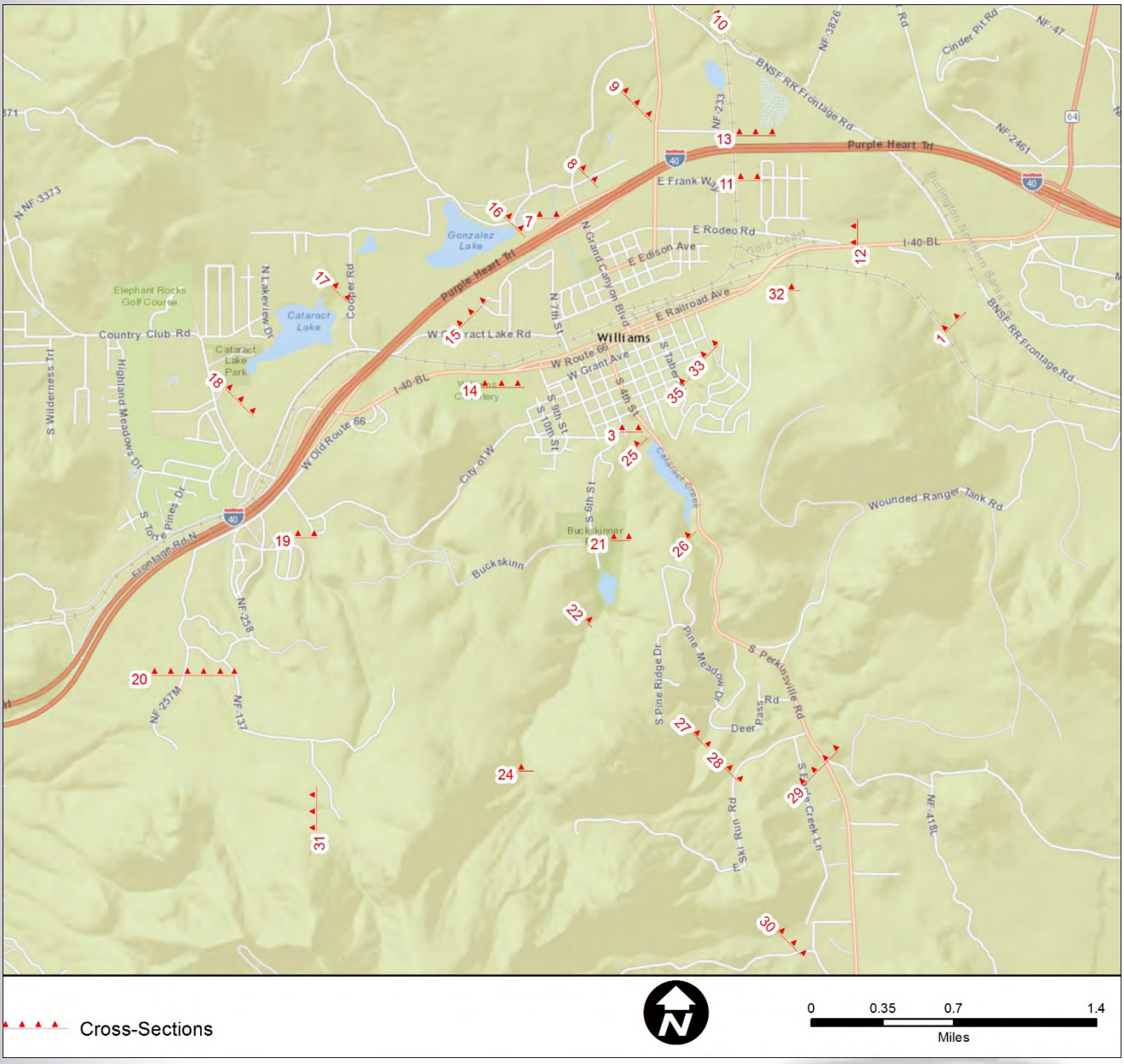

Table 15. Williams 2-Year Peak Flow Rate Summary

Cross Section ID	Description	Pre-Wildfire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire All Treated (CFS)
1	ECHO CANYON*	3	3	3
3	CATARACT AT OAK	24	1274	370
7	CATARACT N OF 40	68	877	402
8	CATARACT DS GC BLVD	81	1107	475
9	CATARACT AT SEWER PLANT	104	1108	449
10	CATARACT DS BNSF	154	1115	509
11	AIRWAY TO HOMESTEAD	5	5	5
12	EAST 66*	5	5	5
13	TRAIN YARD	18	18	18
14	NORRIS INN	8	396	138
15	PONDEROSA LOOP	14	277	71
16	DS GONZALES LAKE	6	6	6
17	DS CATARACT LAKE	3	3	3
18	US CATARACT LAKE	34	590	299
19	FS OFFICE	9	332	127
20	WEST CATARACT	18	728	575
21	CATARACT DS CITY DAM	8	939	287
22	CATARACT US CITY DAM	9	1133	501
24	CATARACT NEAR SKI	8	892	445
25	BELOW SANTA FE	16	719	237
26	ABOVE SANTA FE	16	755	262
27	DEER PASS ROAD	1	89	48
28	SKI RUN ROAD	5	526	181
29	PERKINSVILLE RD	9	511	179
30	BENHAM	4	491	290
31	WEST SLOPE	4	532	518
32	SUPER 8*	0	0	0
33	UPPER HANCOCK*	5	5	5
35	UPPER TABER ST*	4	4	4

*Flows from an unburnt watershed

Table 16. Williams 10-Year Peak Flow Rate Summary

Cross Section ID	Description	Pre-Wildfire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire All Treated (CFS)
1	ECHO CANYON*	25	25	25
3	CATARACT AT OAK	186	2774	1062
7	CATARACT N OF 40	233	1146	845
8	CATARACT DS GC BLVD	243	1958	1043
9	CATARACT AT SEWER PLANT	294	2144	1063
10	CATARACT DS BNSF	385	2256	1201
11	AIRWAY TO HOMESTEAD	37	37	37
12	EAST 66*	39	39	39
13	TRAIN YARD	54	54	54
14	NORRIS INN	44	781	278
15	PONDEROSA LOOP	45	420	143
16	DS GONZALES LAKE	14	14	14
17	DS CATARACT LAKE	8	154	56
18	US CATARACT LAKE	145	1191	594
19	FS OFFICE	47	645	293
20	WEST CATARACT	75	1324	1129
21	CATARACT DS CITY DAM	62	1815	781
22	CATARACT US CITY DAM	80	2007	1057
24	CATARACT NEAR SKI	59	1559	919
25	BELOW SANTA FE	128	1582	709
26	ABOVE SANTA FE	124	1615	760
27	DEER PASS ROAD	6	172	100
28	SKI RUN ROAD	40	981	449
29	PERKINSVILLE RD	62	972	521
30	BENHAM	38	883	604
31	WEST SLOPE	42	913	895
32	SUPER 8*	2	2	2
33	UPPER HANCOCK*	16	16	16
35	UPPER TABER ST*	12	11	11

*Flows from an unburnt watershed

Table 17. Williams 100-Year Peak Flow Rate Summary

Cross Section ID	Description	Pre-Wildfire (CFS)	Post-Wildfire No Treatment (CFS)	Post-Wildfire All Treated (CFS)
1	ECHO CANYON*	147	147	147
3	CATARACT AT OAK	1157	6061	3076
7	CATARACT N OF 40	877	1624	1227
8	CATARACT DS GC BLVD	1151	2861	2174
9	CATARACT AT SEWER PLANT	1179	3405	2485
10	CATARACT DS BNSF	1430	3707	2742
11	AIRWAY TO HOMESTEAD	171	261	200
12	EAST 66*	219	219	219
13	TRAIN YARD	267	341	293
14	NORRIS INN	229	1570	586
15	PONDEROSA LOOP	205	611	398
16	DS GONZALES LAKE	35	391	157
17	DS CATARACT LAKE	195	871	459
18	US CATARACT LAKE	591	2237	1456
19	FS OFFICE	246	1252	740
20	WEST CATARACT	425	2350	2115
21	CATARACT DS CITY DAM	412	3373	2024
22	CATARACT US CITY DAM	562	3600	2343
24	CATARACT NEAR SKI	426	2711	1923
25	BELOW SANTA FE	882	3314	2120
26	ABOVE SANTA FE	881	3381	2145
27	DEER PASS ROAD	43	331	223
28	SKI RUN ROAD	263	1777	1073
29	PERKINSVILLE RD	467	1884	1263
30	BENHAM	248	1563	1202
31	WEST SLOPE	266	1545	1523
32	SUPER 8*	17	17	17
33	UPPER HANCOCK*	55	55	55
35	UPPER TABER ST*	31	30	30

*Flows from an unburnt watershed

Figure 29 through Figure 37 illustrate the maximum flood depth for the 2-, 10-, and 100-year, 24-hour storm events for Williams study area and include all burn scenarios in the following order:

1. Pre-Wildfire scenario
2. Post-Wildfire, No Treatment scenario
3. Post-Wildfire, with Treatment scenario

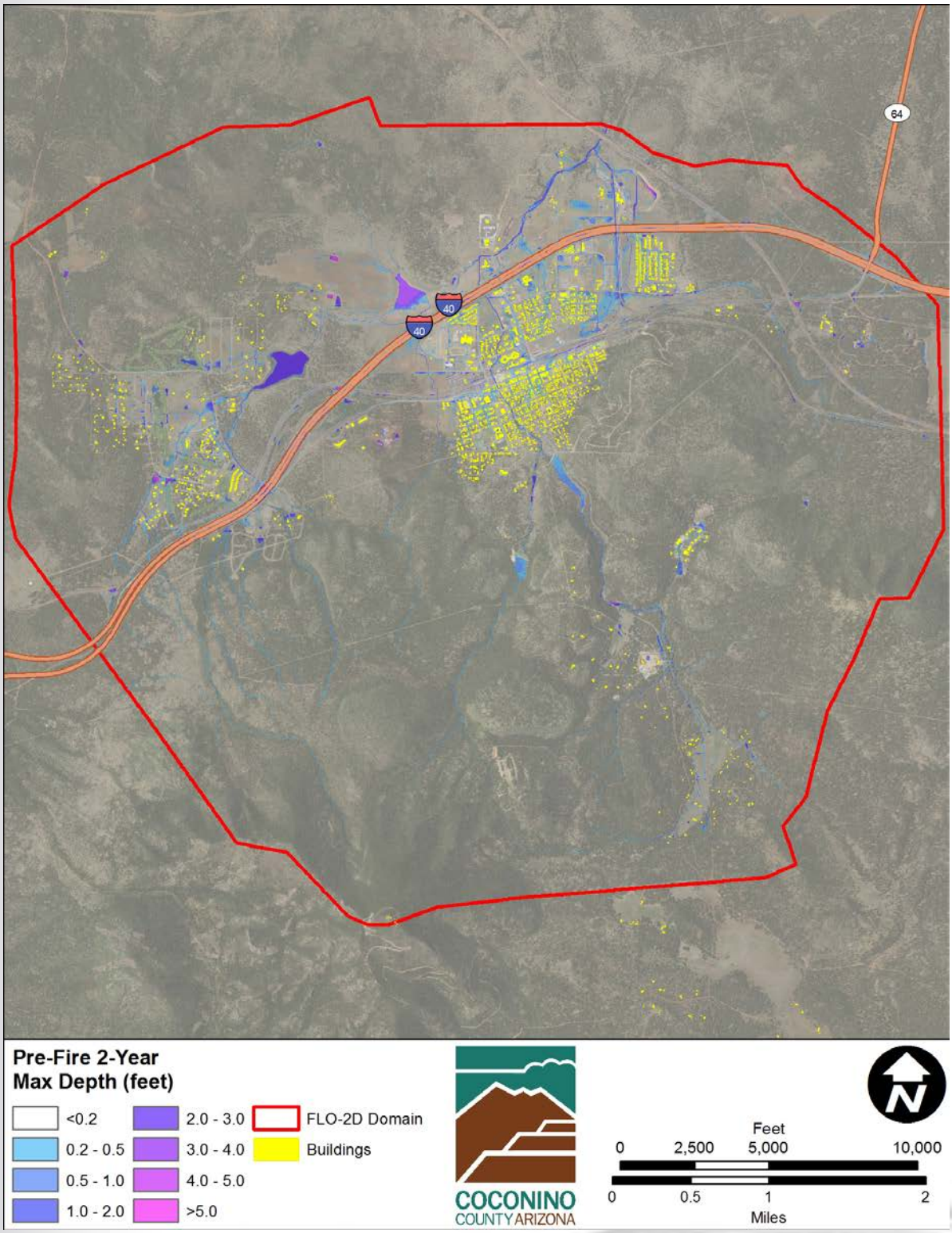

Figure 29. Williams 2-Year Pre-Wildfire Max Flow Depth

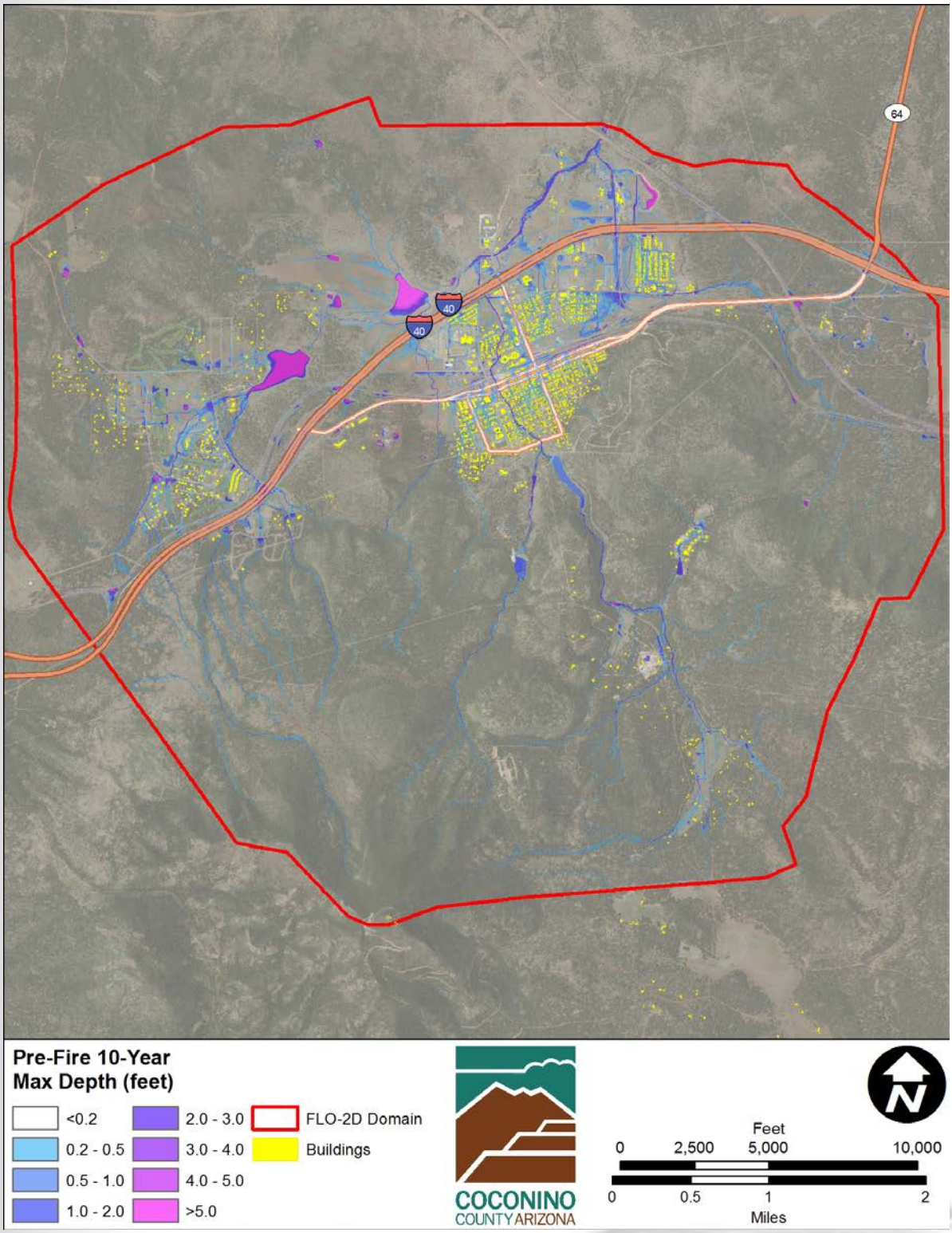

Figure 30. Williams 10-Year Pre-Wildfire Max Flow Depth

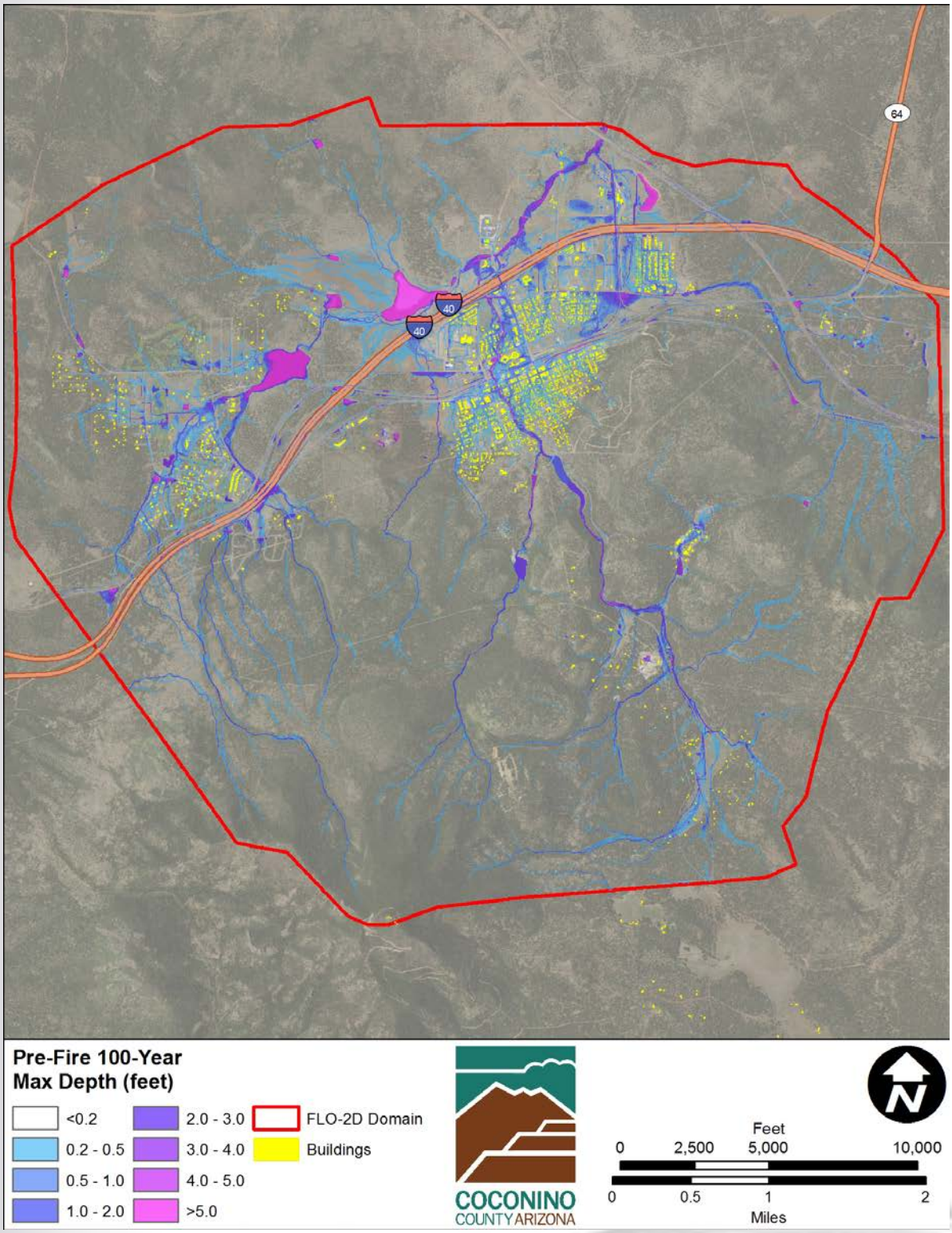

Figure 31. Williams 100-Year Pre-Wildfire Max Flow Depth

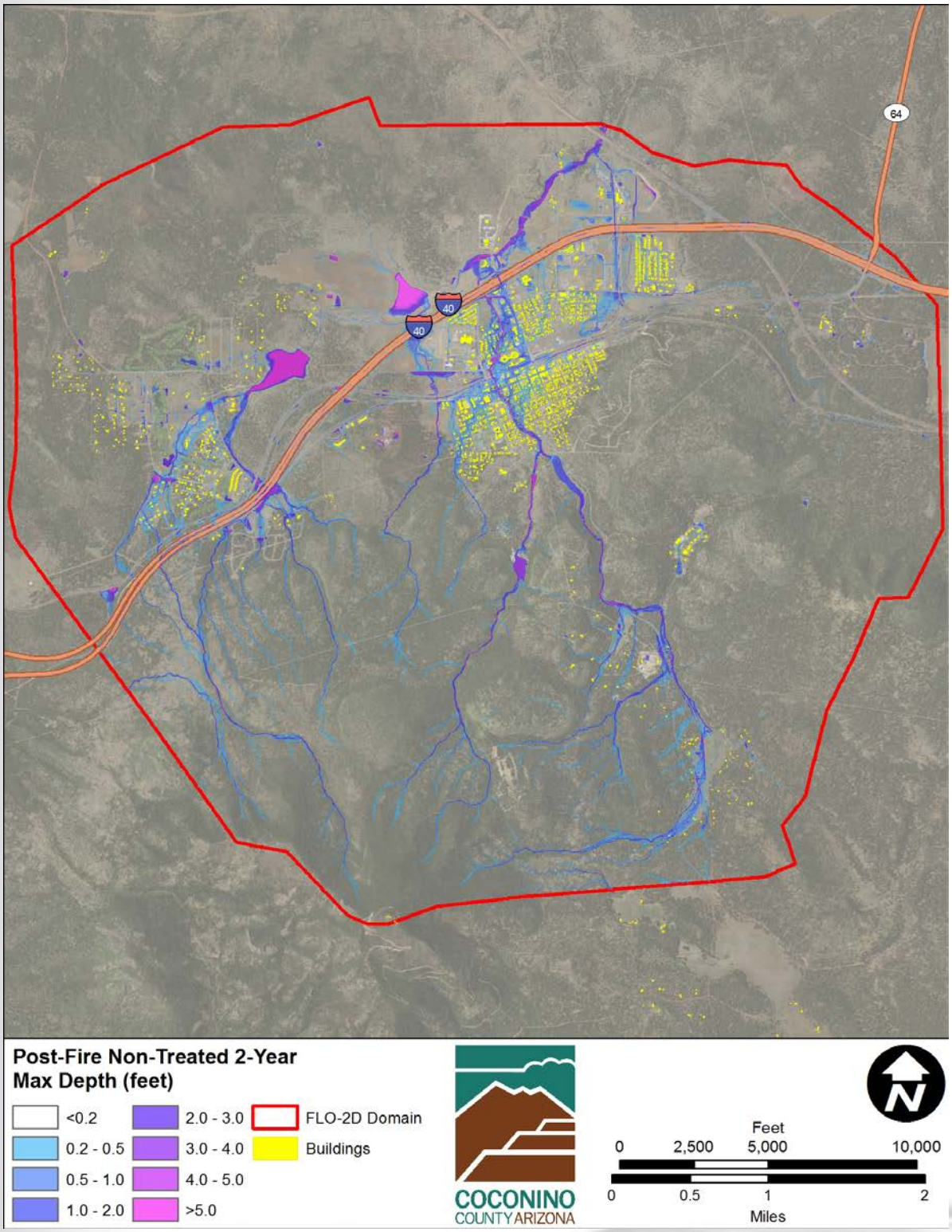

Figure 32. Williams 2-Year Post-Wildfire Non-Treated Max Flow Depth

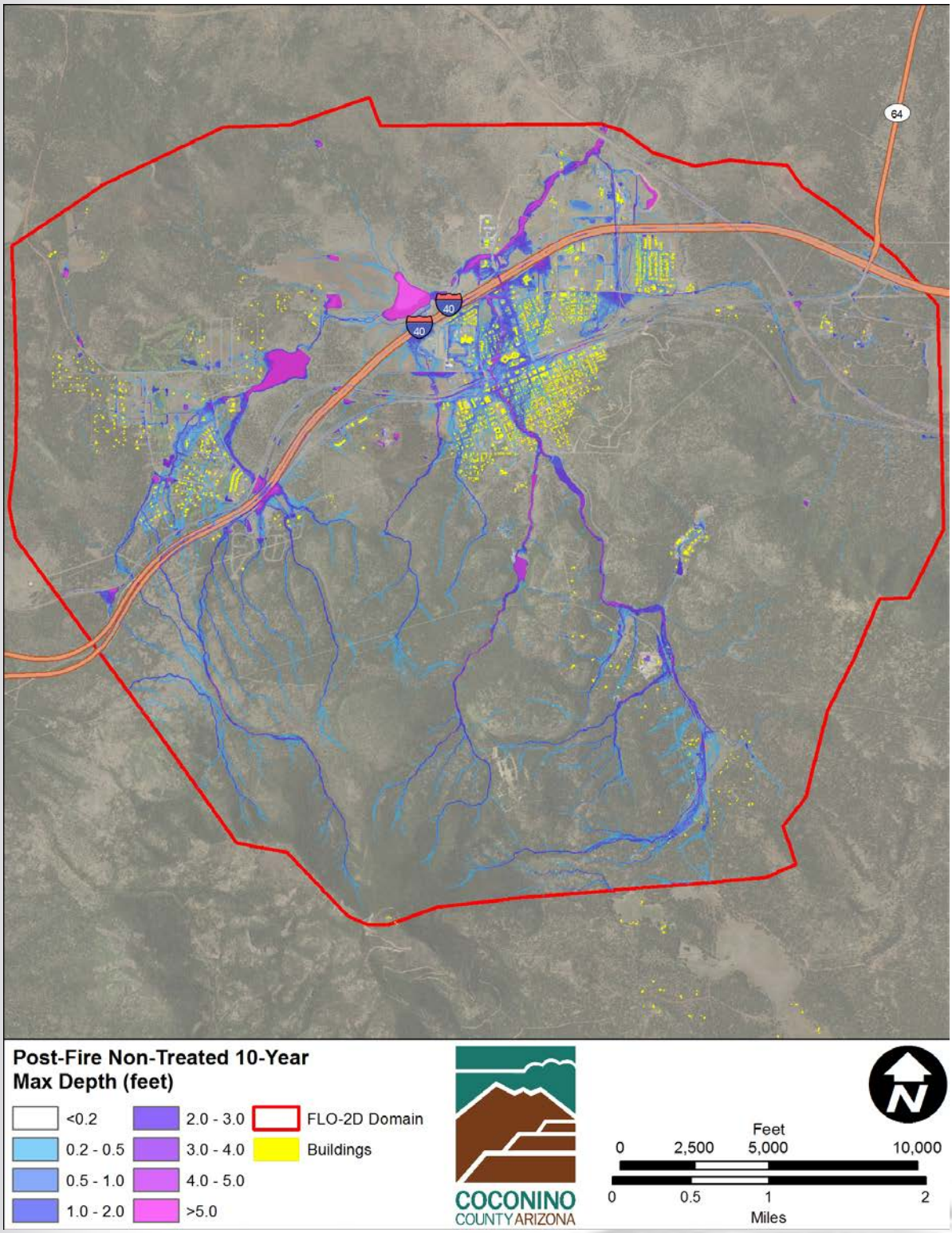

Figure 33. Williams 10-Year Post-Wildfire Non-Treated Max Flow Depth

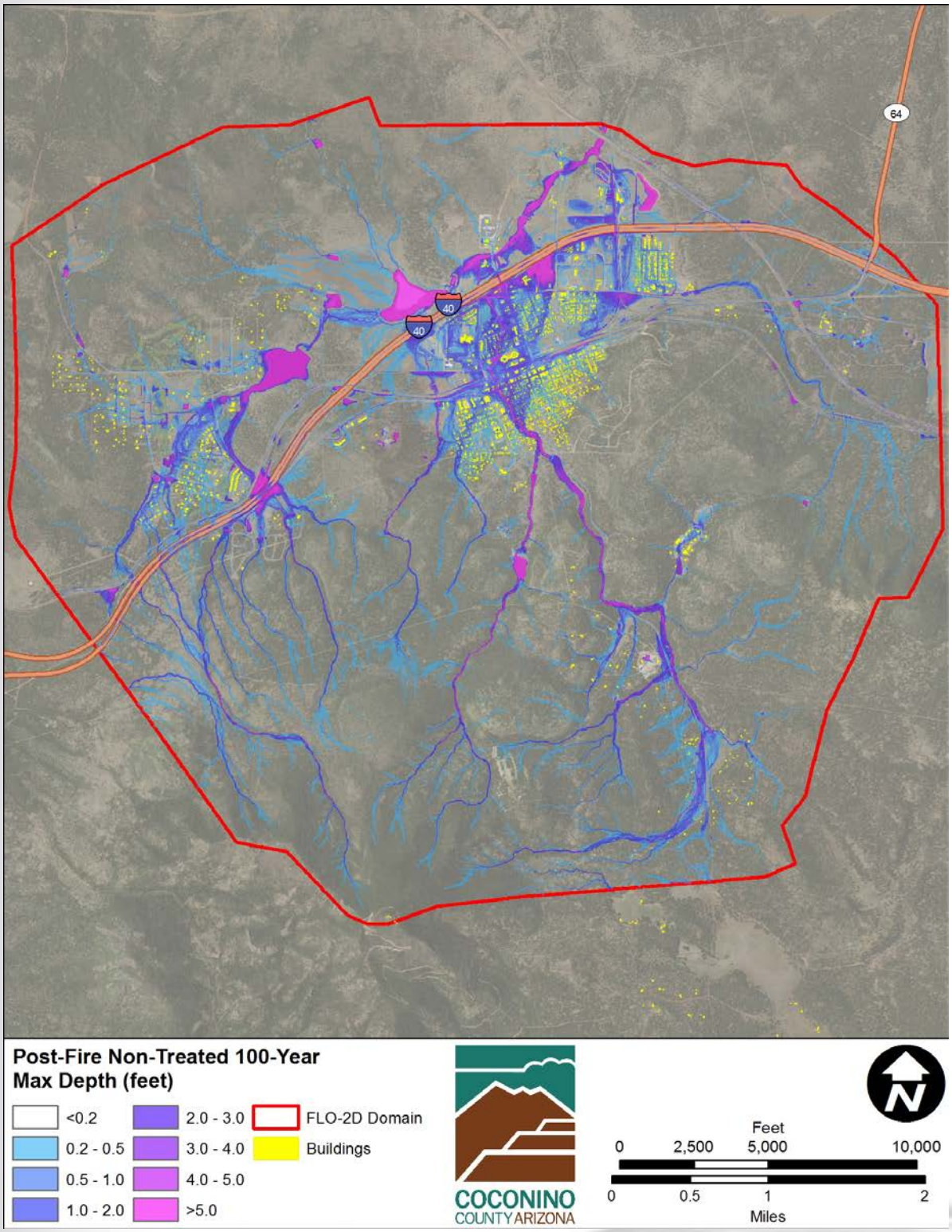

Figure 34. Williams 100-Year Post-Wildfire Non-Treated Max Flow Depth

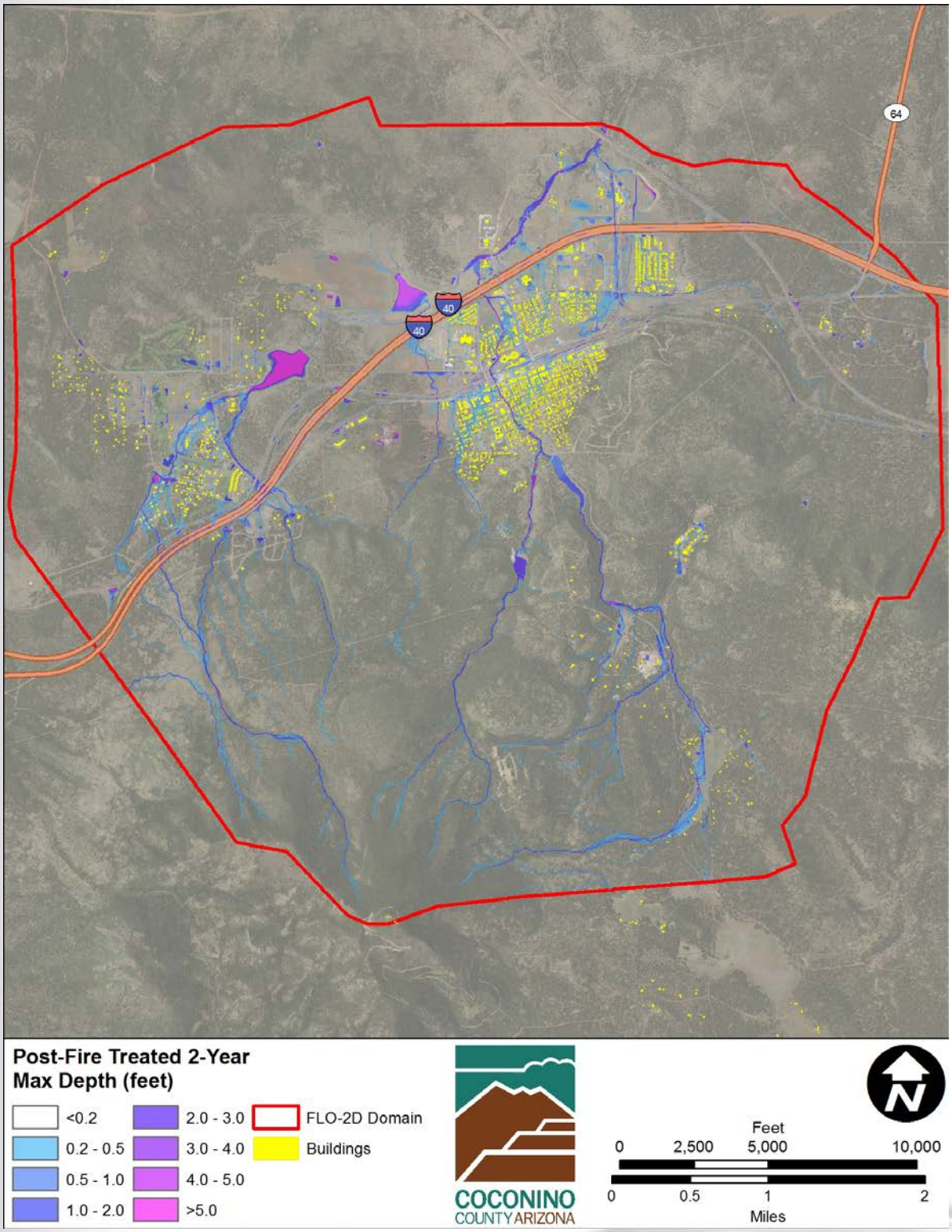

Figure 35. Williams 2-Year Post-Wildfire Treated Max Flow Depth

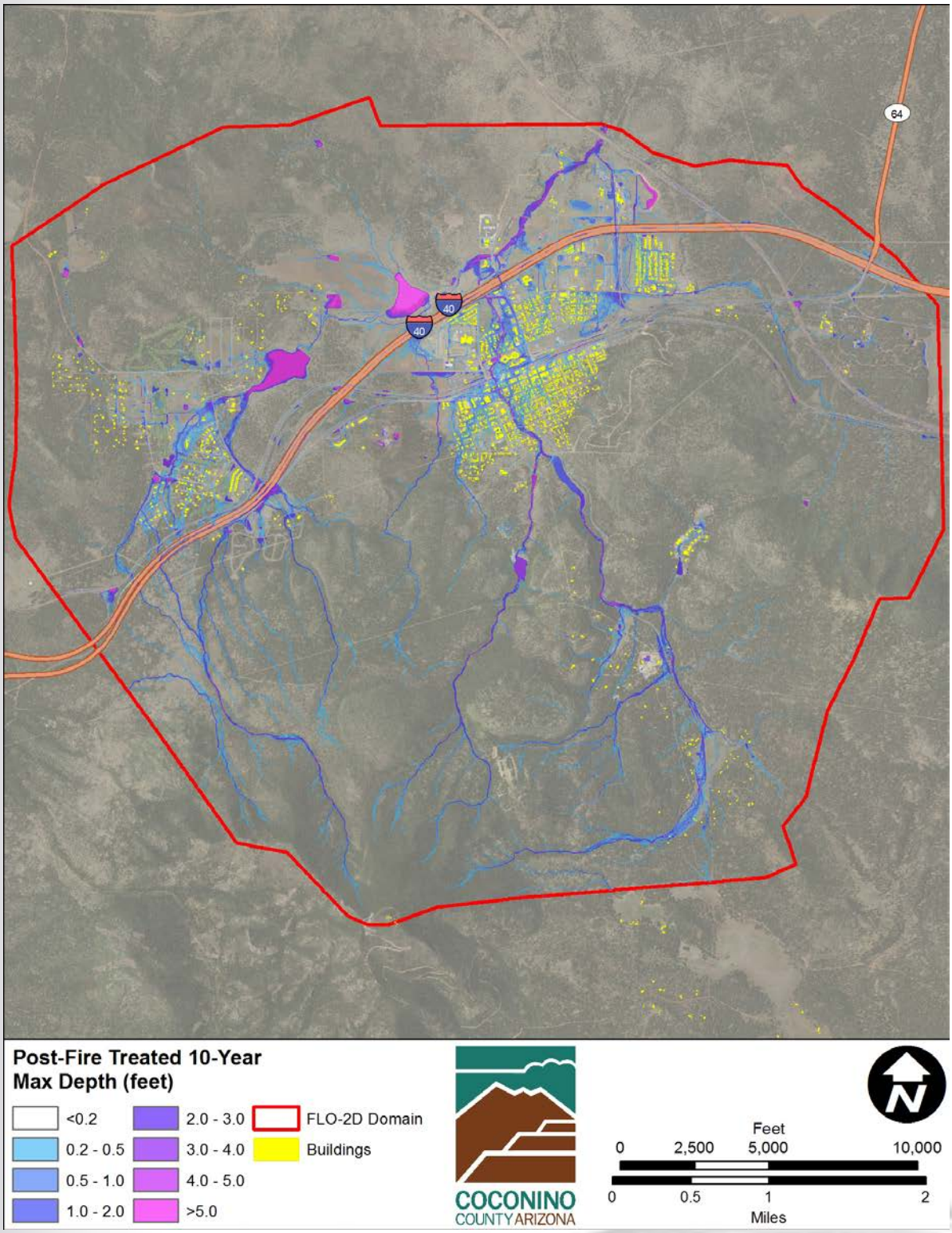

Figure 36. Williams 10-Year Post-Wildfire Treated Max Flow Depth

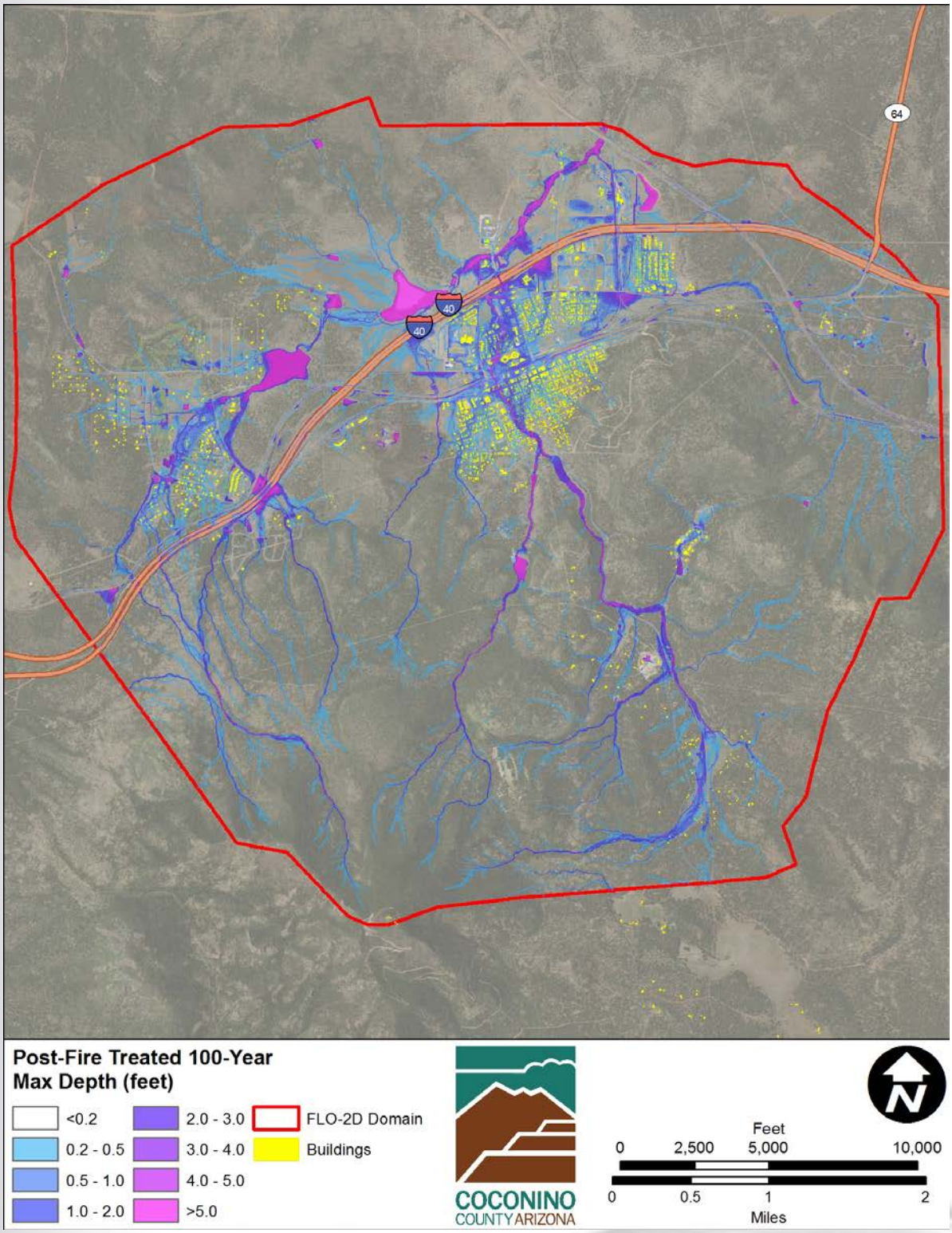

Figure 37. Williams 100-Year Post-Wildfire Treated Max Flow Depth

H. Flood Depth Summary

Table 18 and Table 19 compare the total number of buildings impacted by flow depths greater 0.2' (2.4") for all the burn scenarios for both Fort Valley and Williams. 0.2' was chosen for the purposes of this memo to match criteria set forth in the Coconino County Initial Engineering Assessment Guidelines (2015).

Table 18. Fort Valley Impacted Buildings for Flow Depth > 0.2'

Recurrence Interval	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire Treatment up to 8200'	Post-Wildfire All Treated
2-Year	129	302	239	185
10-Year	236	414	355	302
100-Year	399	511	472	444

Table 19. Williams Impacted Buildings for Flow Depth > 0.2'

Recurrence Interval	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire Treated
2-Year	711	936	807
10-Year	1,041	1,297	1,171
100-Year	1,451	1,618	1,571

5. Flood Hazard Assessment

FLO-2D was used to assess the flood hazards associated with the 2-, 10-, and 100-year, 24-hour storm events. The hazard assessments were analyzed as a function of water flood intensity which is a combination of maximum depth and the product of maximum depth times the flow velocity. Table 20 shows the definition of the water flood intensity used in the FLO-2D modeling.

Table 20. Definition of Water Flood Intensity

Flood Intensity	Maximum Depth (h) (ft)		Velocity (v) * Maximum Depth (h) (ft^2/s)
High	$h \geq 4.9$	or	$vh > 16.1$
Medium	$1.6 < h < 4.9$	or	$5.4 < vh < 16.1$
Low	$0.3 < h < 1.6$	and	$1.1 < vh < 5.4$

The hazard level was determined based on the water flood intensity for the aforementioned storm events. This is illustrated in Table 21, where red represents a high hazard level, orange represents a medium hazard level, and yellow represents a low hazard level.

Table 21. Hazard Level Definitions

Hazard Level	Map Color	Description
High	Red	Persons are in danger both inside and outside of their houses. Structures are in danger of being destroyed.
Medium	Orange	Persons are in danger outside of their houses. Buildings may suffer damage and possible destruction depending on construction characteristics.
Low	Yellow	Danger to persons is low or non-existent. Buildings may suffer little damages, but flooding or sediment may affect structure interiors.

Figure 38 through Figure 58 are the Hazard Maps for the 2-, 10-, and 100-year, 24-hour storm events for both the Fort Valley and Williams study areas and include all burn scenarios in the following order. Large-format Hazard Maps (24”x36”) are provided in Appendix C.

Fort Valley

- Pre-Wildfire (unburnt)
- Post-Wildfire, No Treatment
- Post-Wildfire, Treatment up to 8,200 Feet (Excluding the Kachina Peaks Wilderness Area)
- Post-Wildfire, Treatment (all areas)

Williams

- Pre-Wildfire (unburnt)
- Post-Wildfire, No Treatment
- Post-Wildfire, Treatment (all areas)

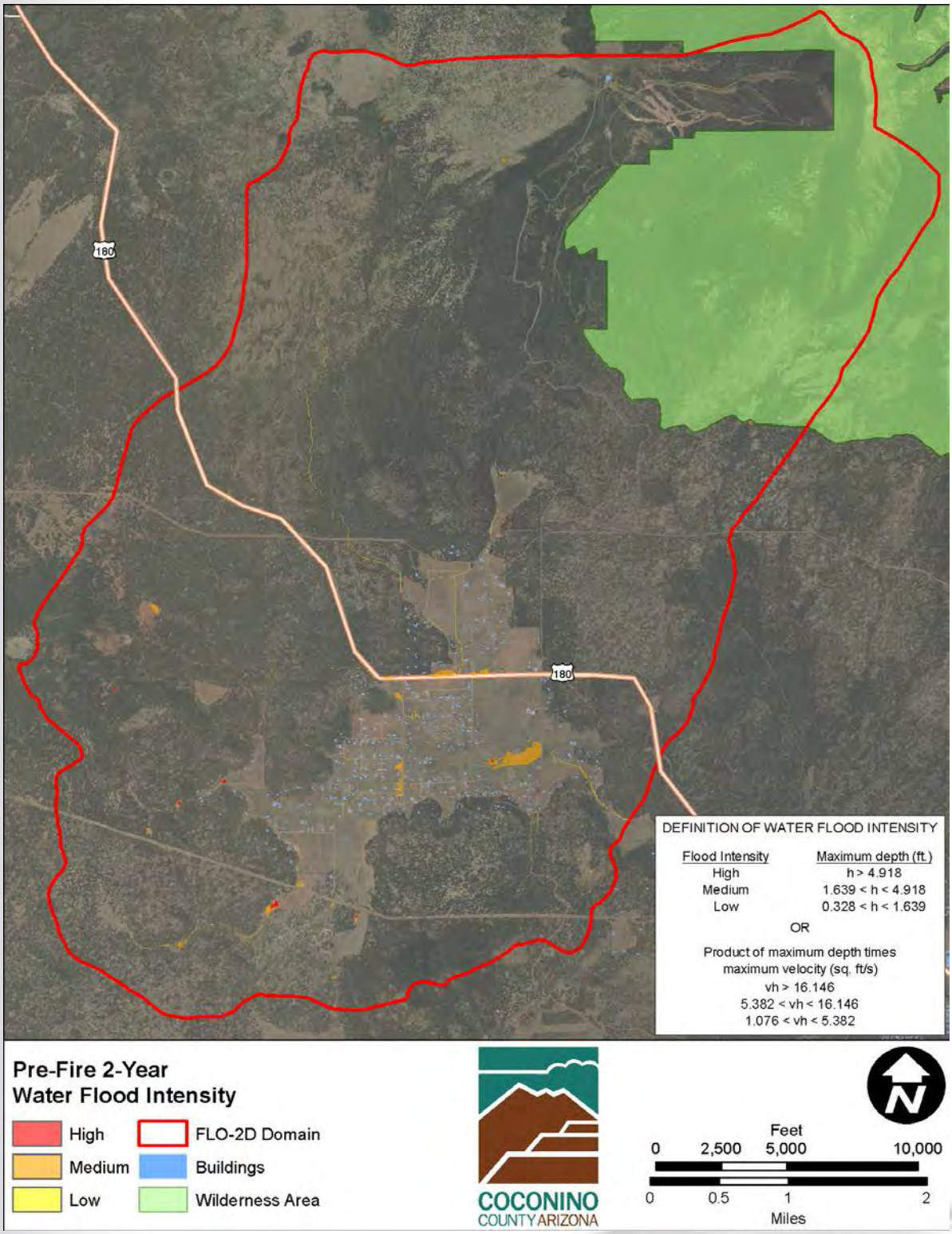

Figure 38. Fort Valley 2-Year Pre-Wildfire Hazard Map

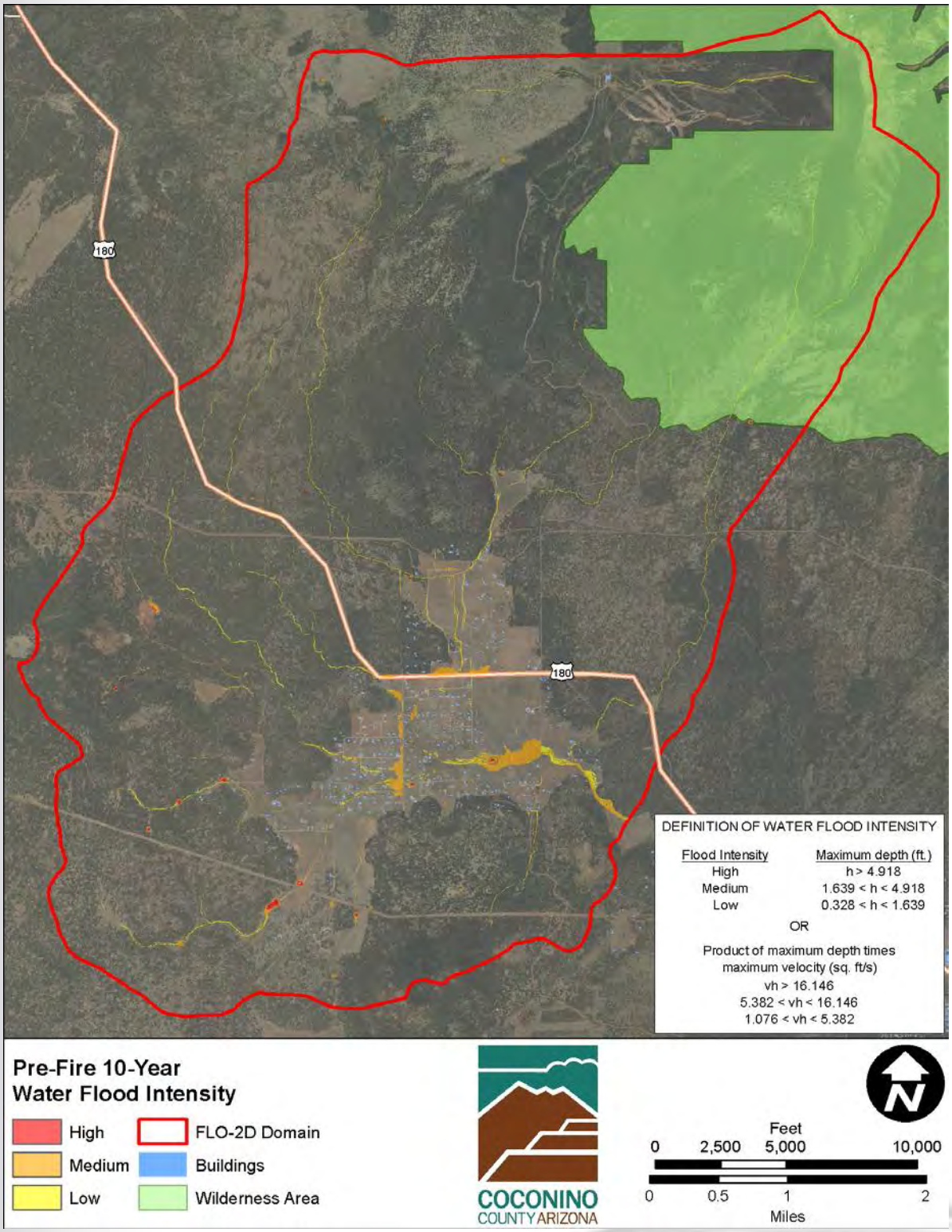

Figure 39. Fort Valley 10-Year Pre-Wildfire Hazard Map

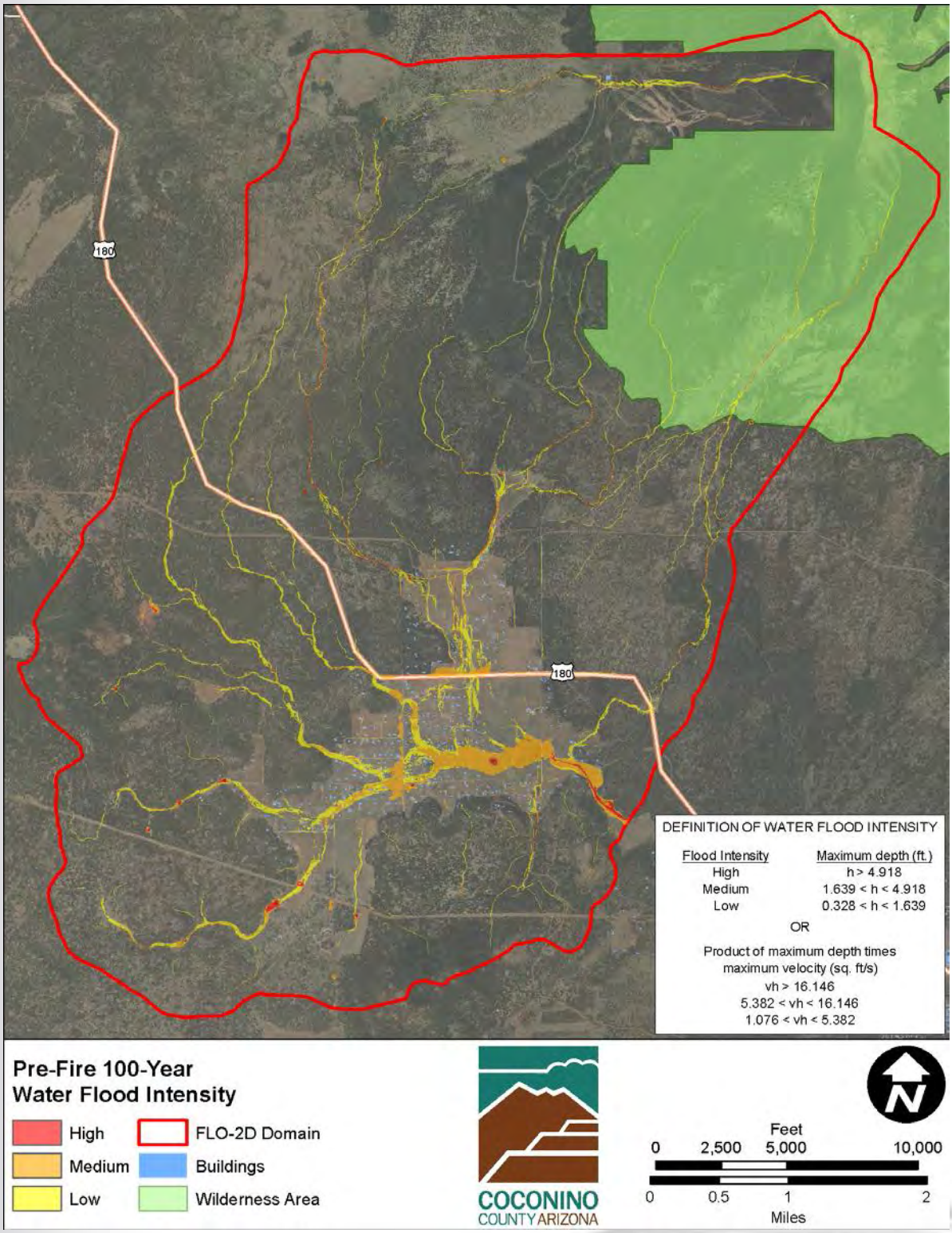

Figure 40. Fort Valley 100-Year Pre-Wildfire Hazard Map

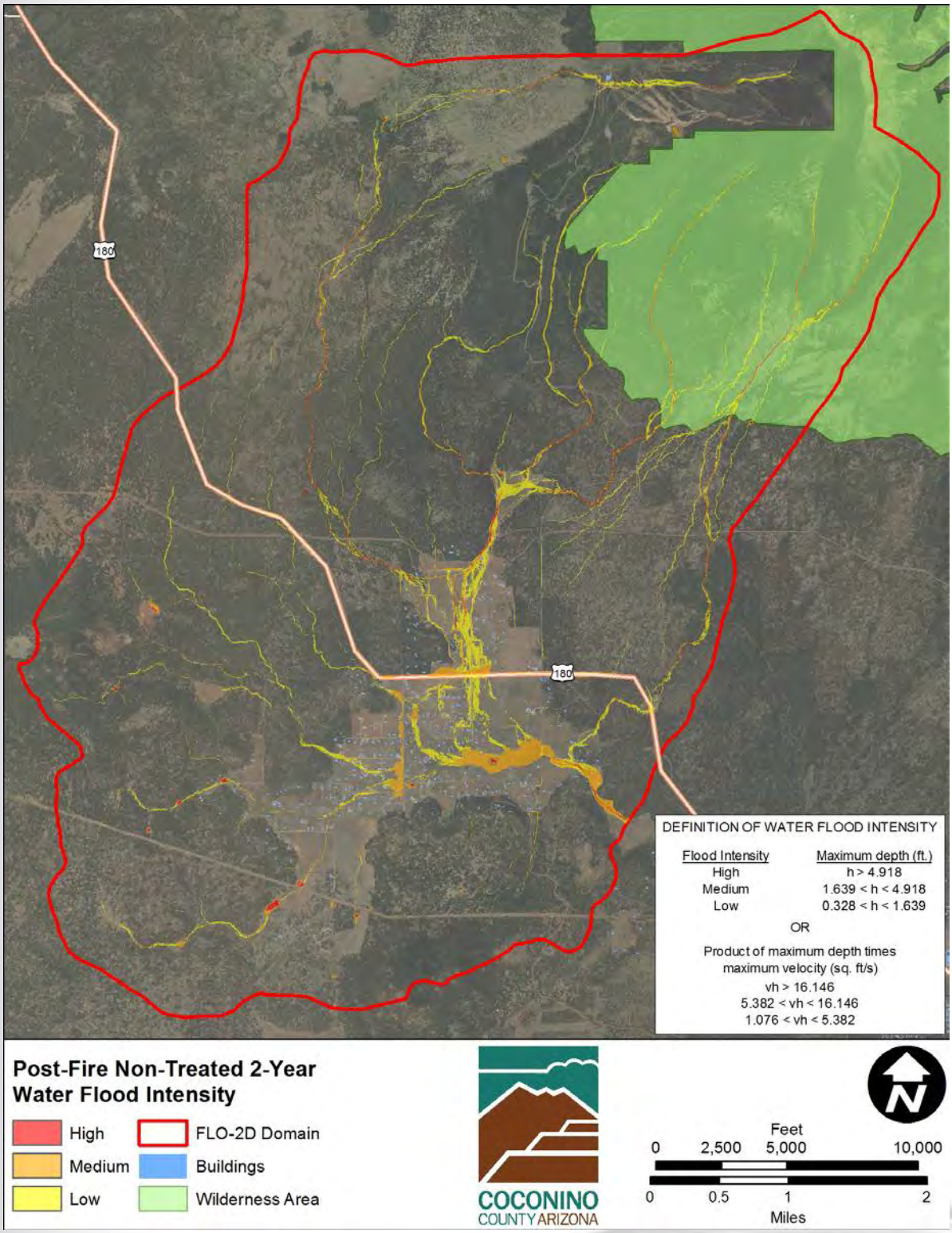

Figure 41. Fort Valley 2-Year Post-Wildfire Non-Treated Hazard Map

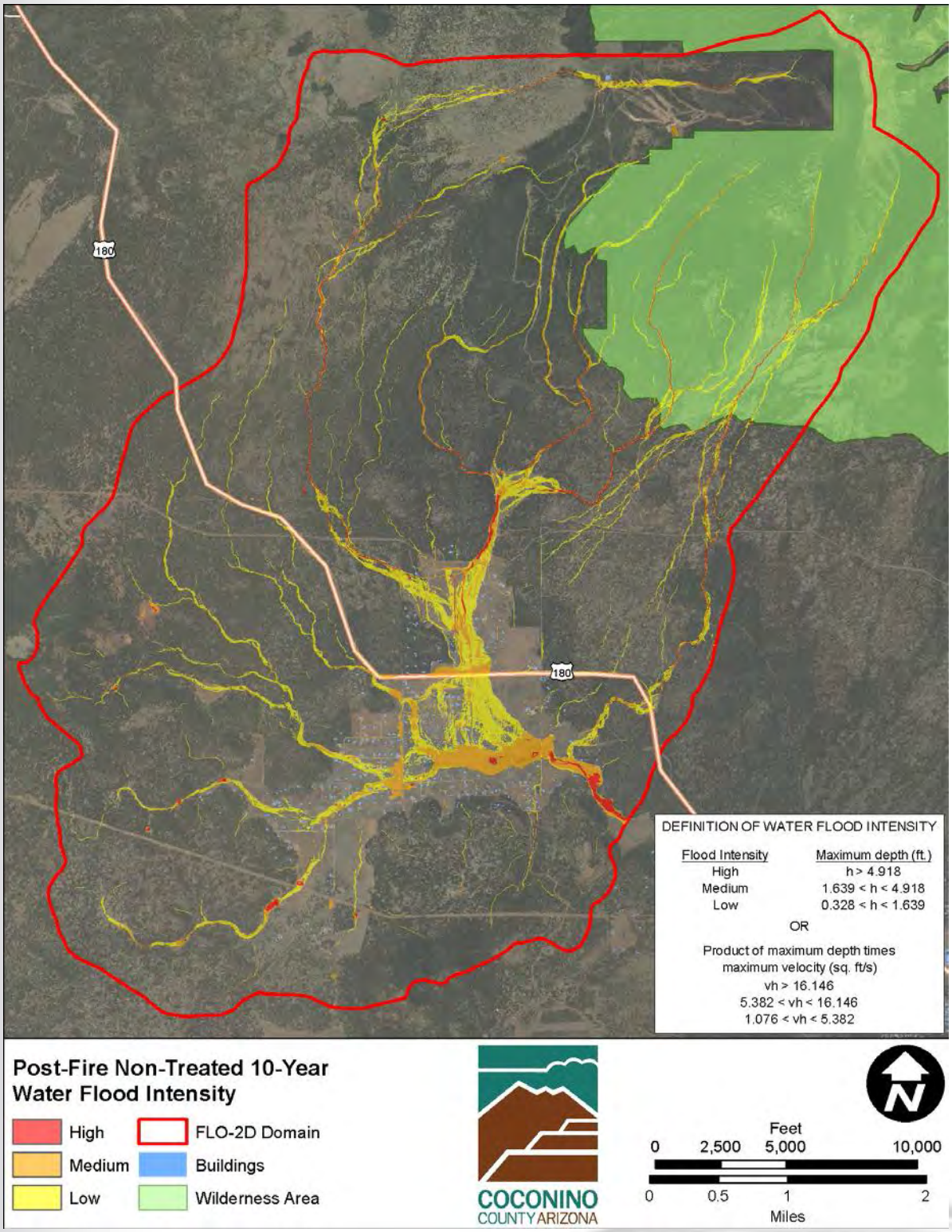

Figure 42. Fort Valley 10-Year Post-Wildfire Non-Treated Hazard Map

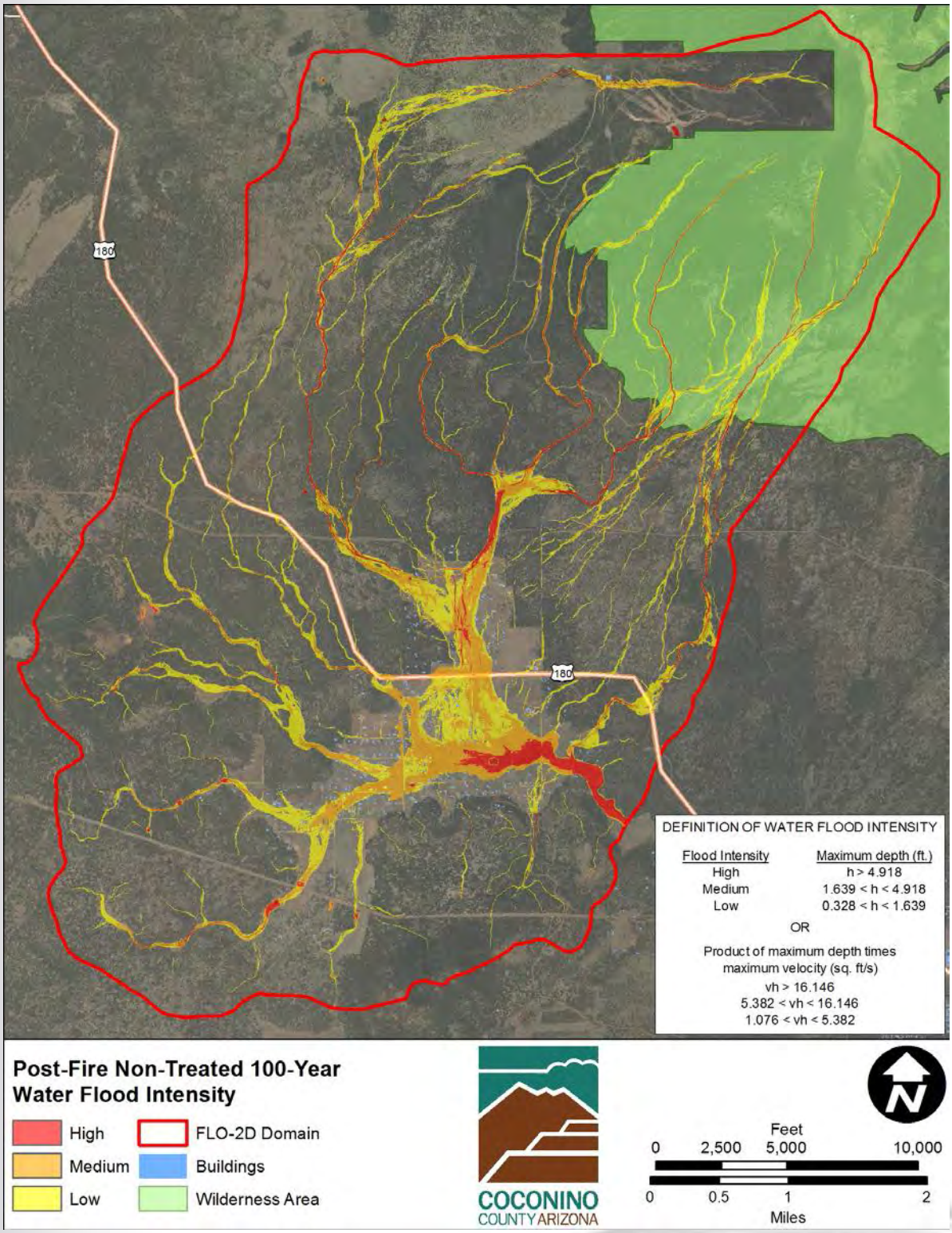

Figure 43. Fort Valley 100-Year Post-Wildfire Non-Treated Hazard Map

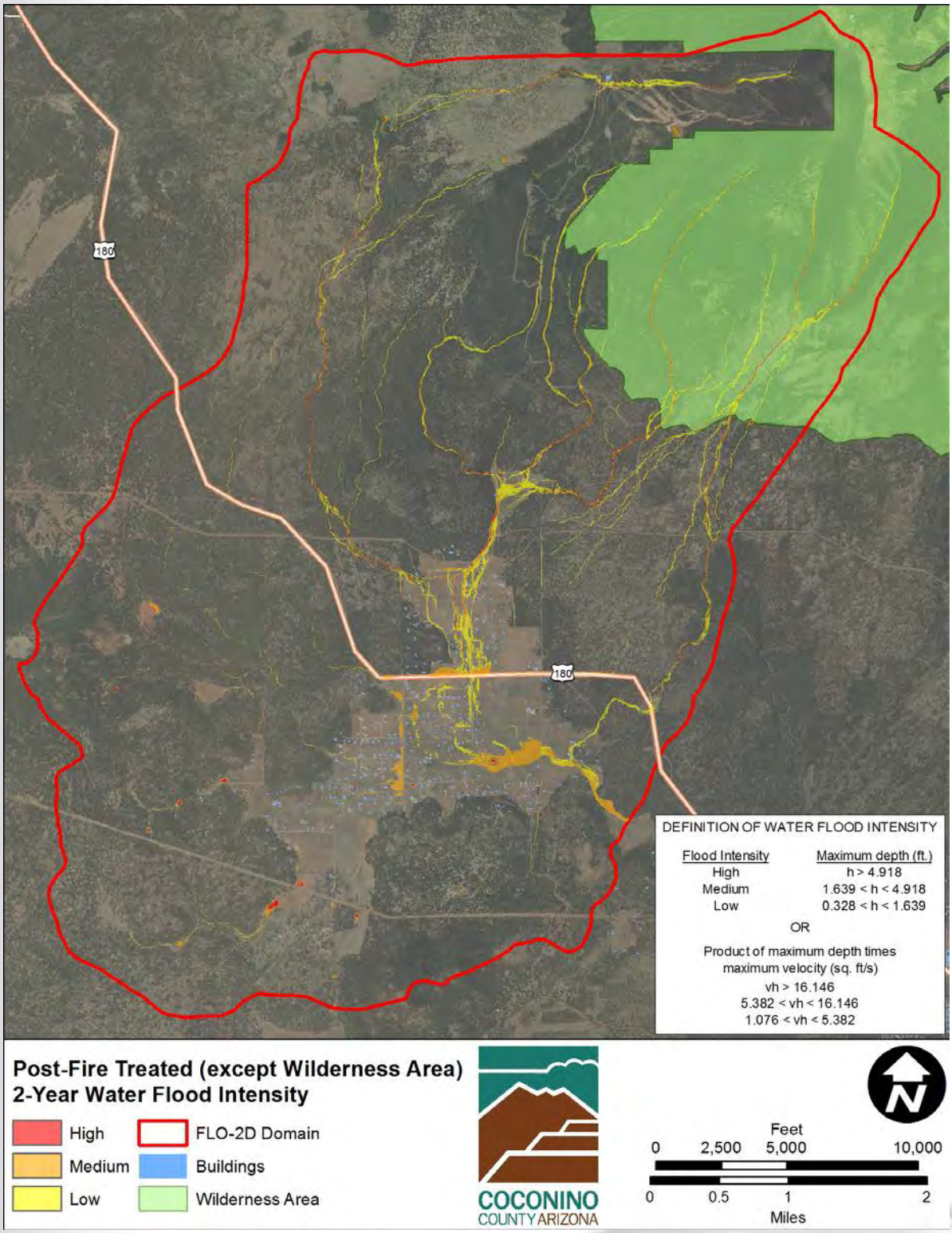

Figure 44. Fort Valley 2-Year Post-Wildfire Treated up to 8200' Hazard Map

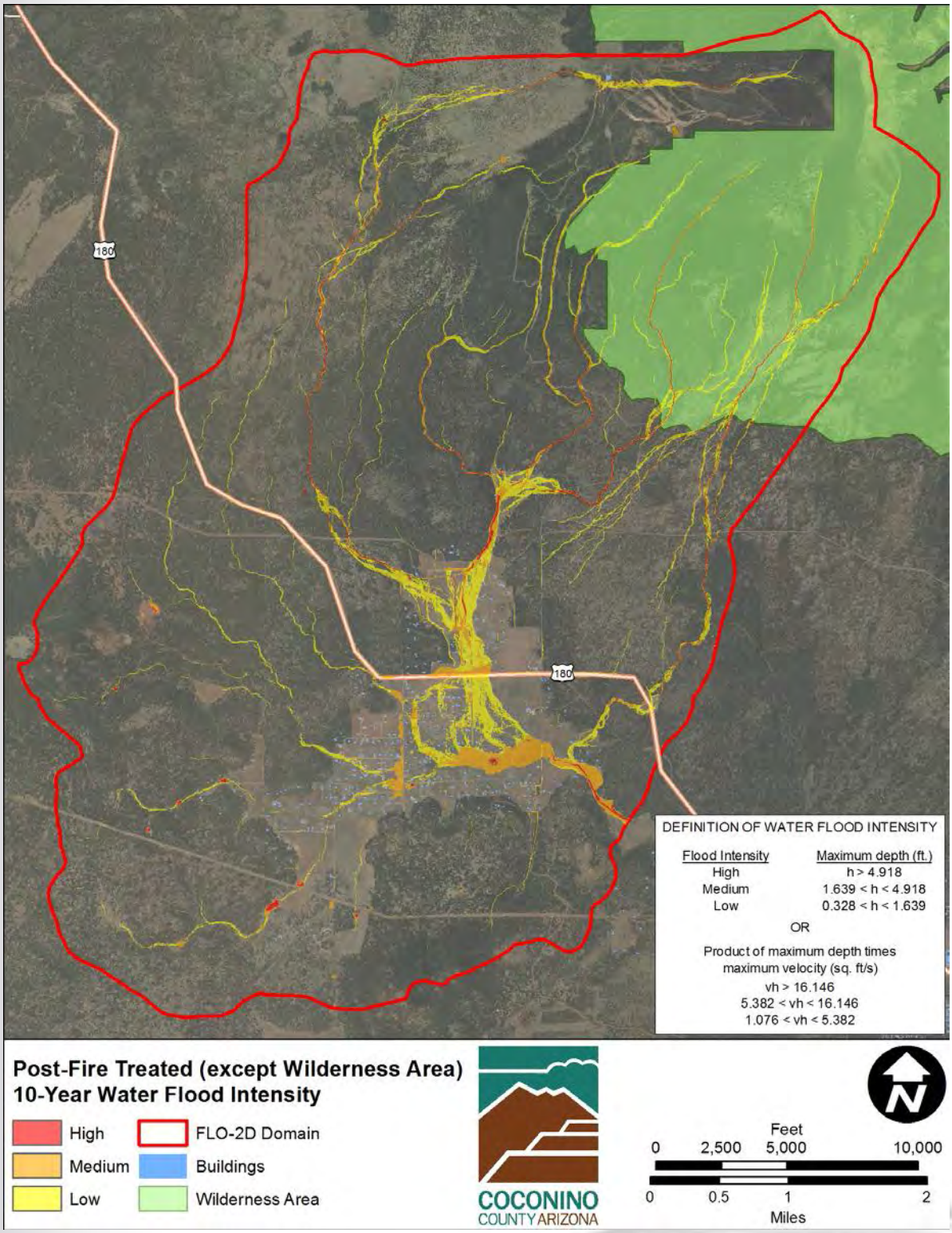

Figure 45. Fort Valley 10-Year Post-Wildfire Treated up to 8200' Hazard Map

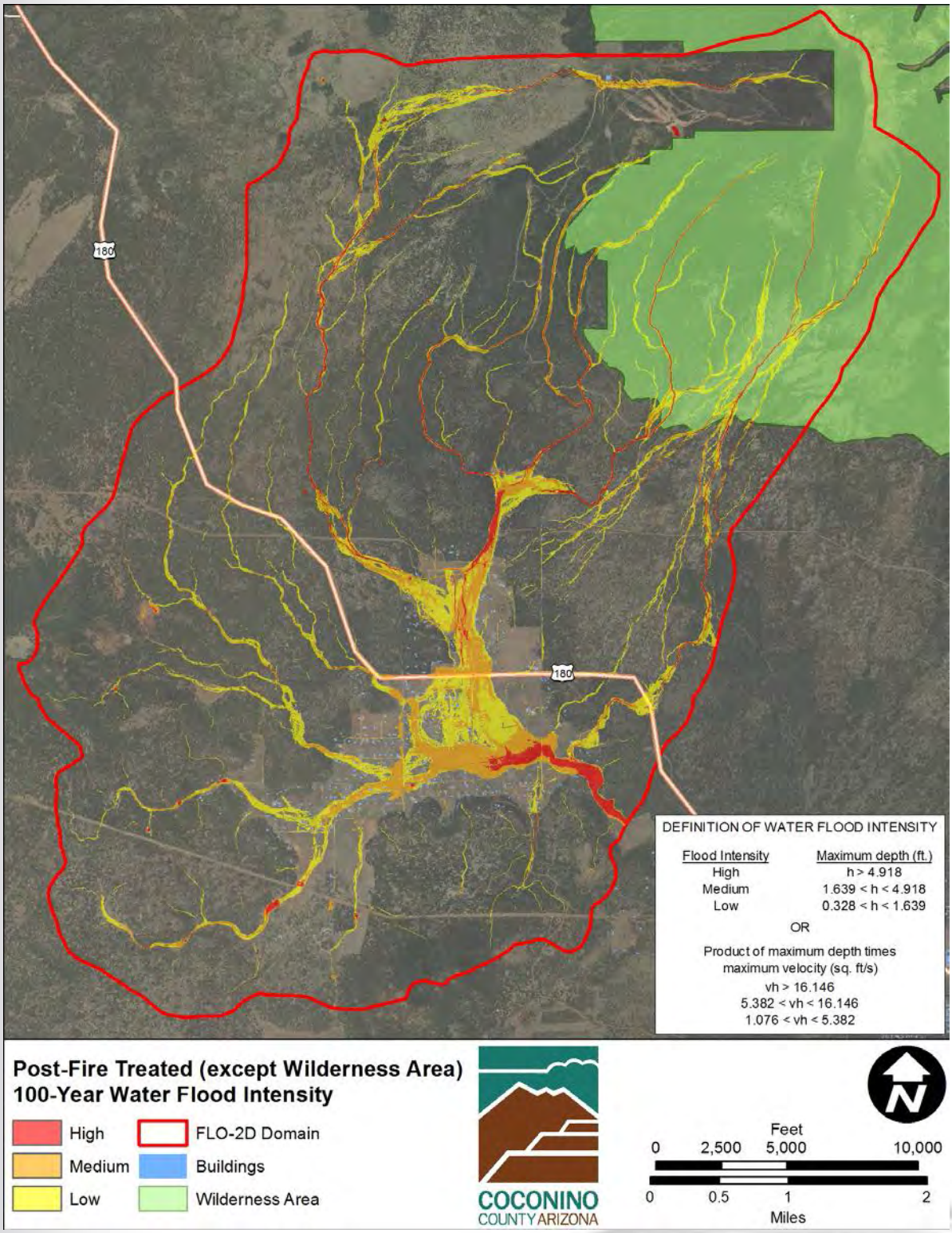

Figure 46. Fort Valley 100-Year Post-Wildfire Treated up to 8200' Hazard Map

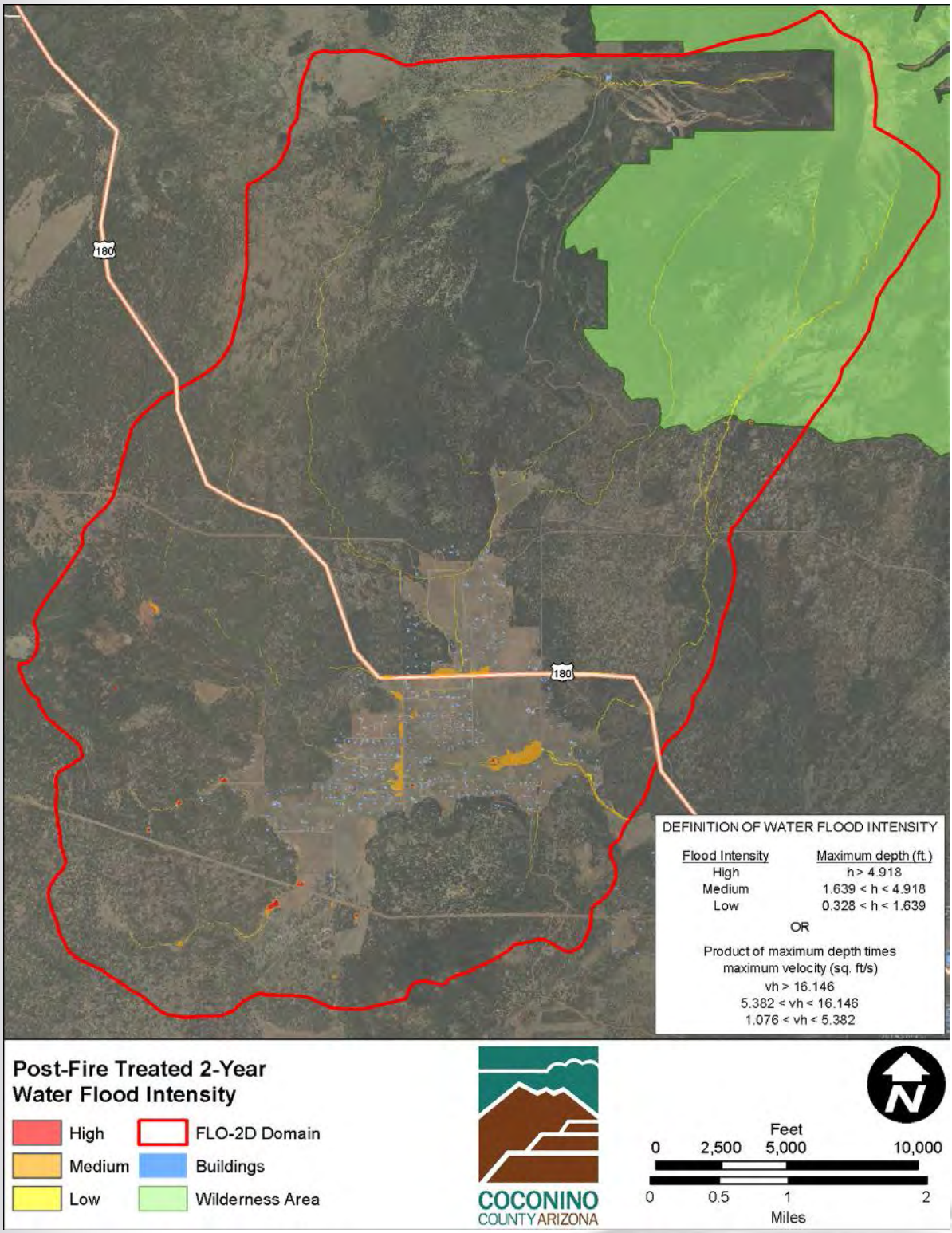

Figure 47. Fort Valley 2-Year Post-Wildfire Treated (all areas) Hazard Map

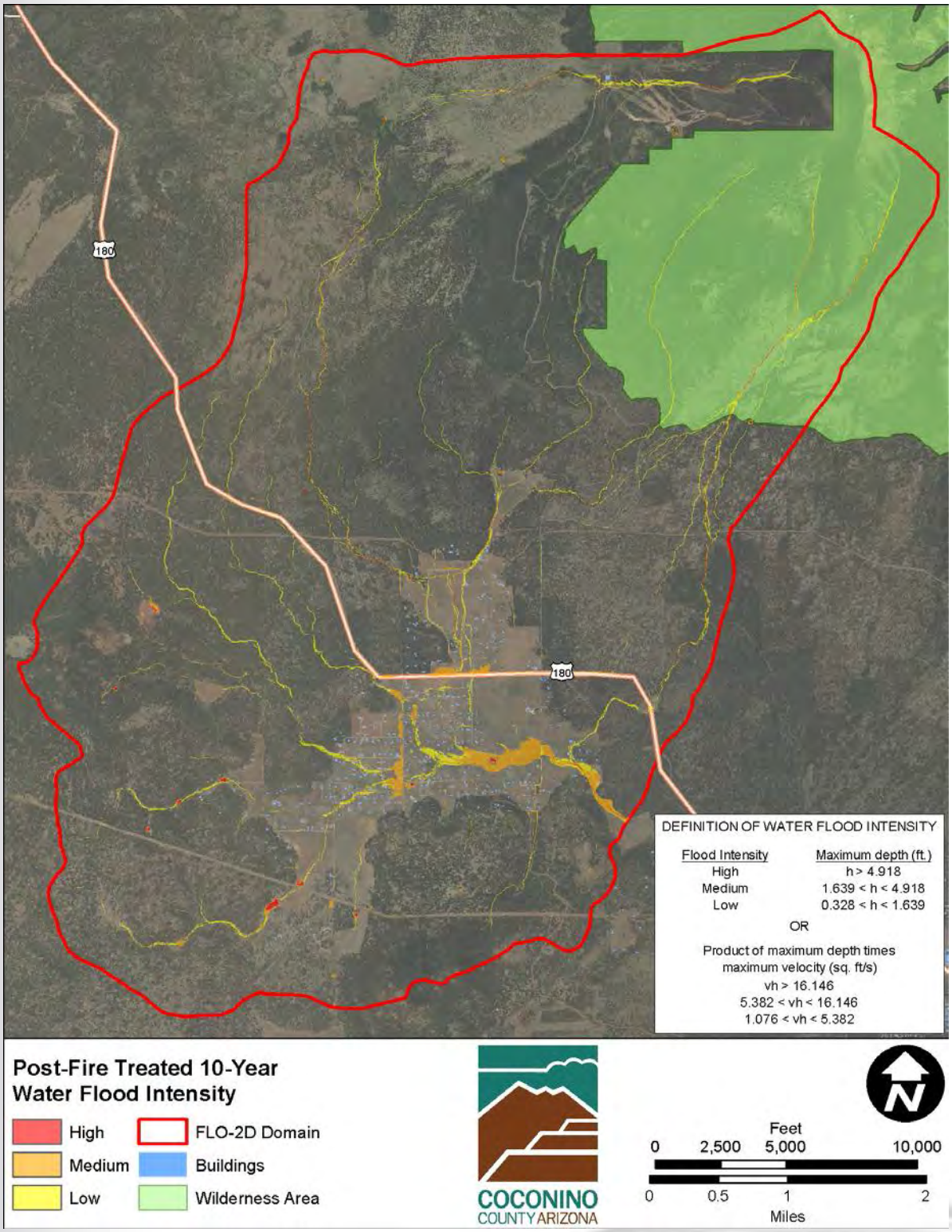

Figure 48. Fort Valley 10-Year Post-Wildfire Treated (all areas) Hazard Map

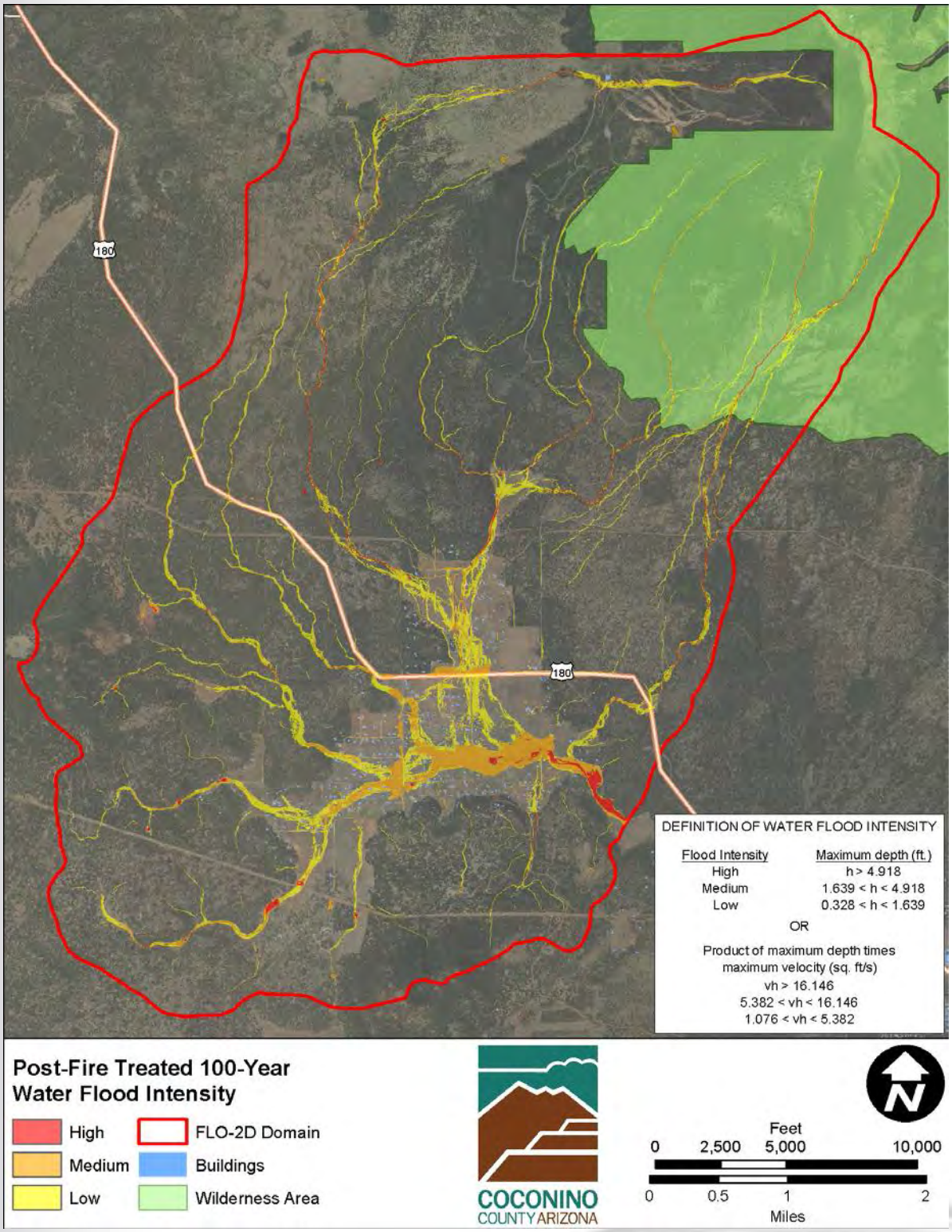

Figure 49. Fort Valley 100-Year Post-Wildfire Treated (all areas) Hazard Map

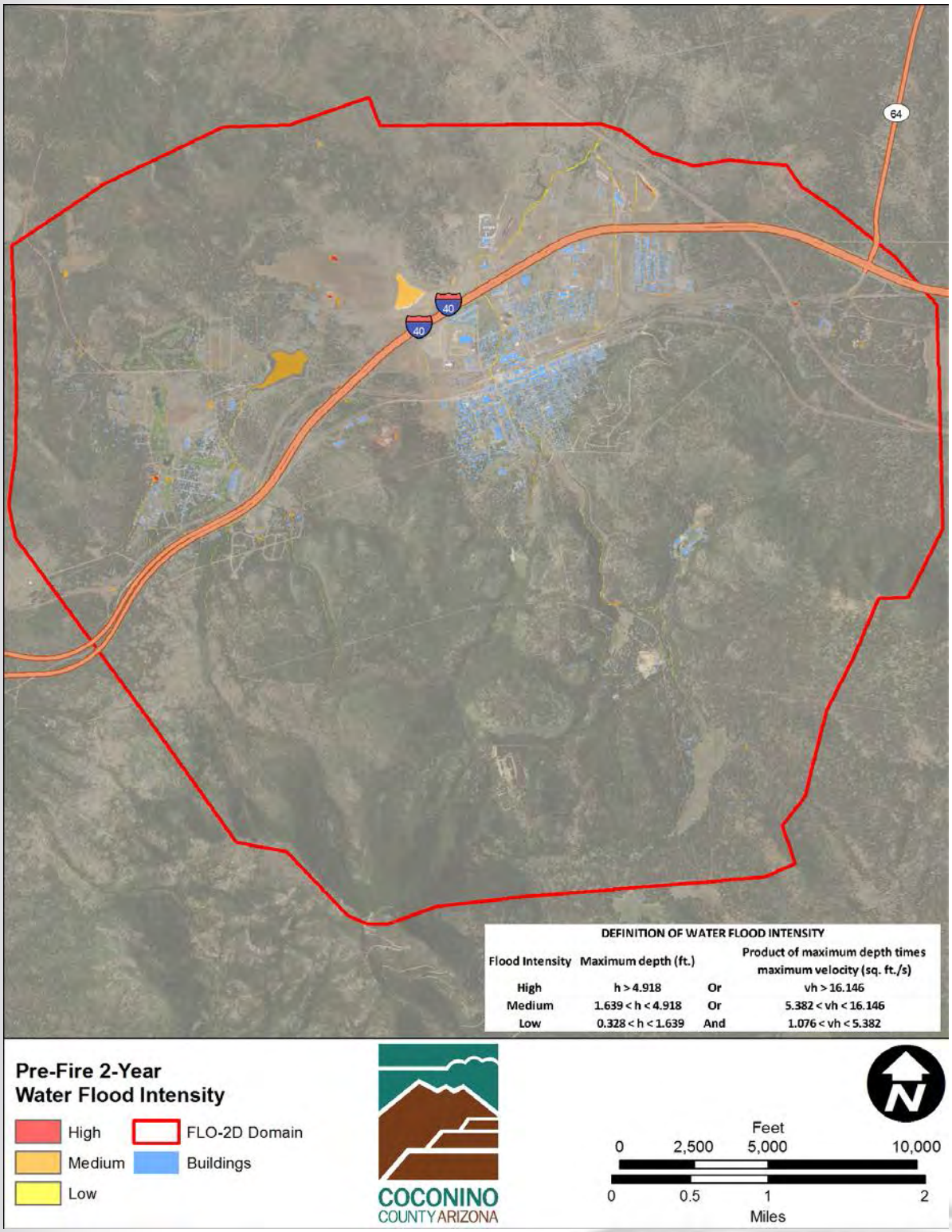

Figure 50. Williams 2-Year Pre-Wildfire Hazard Map

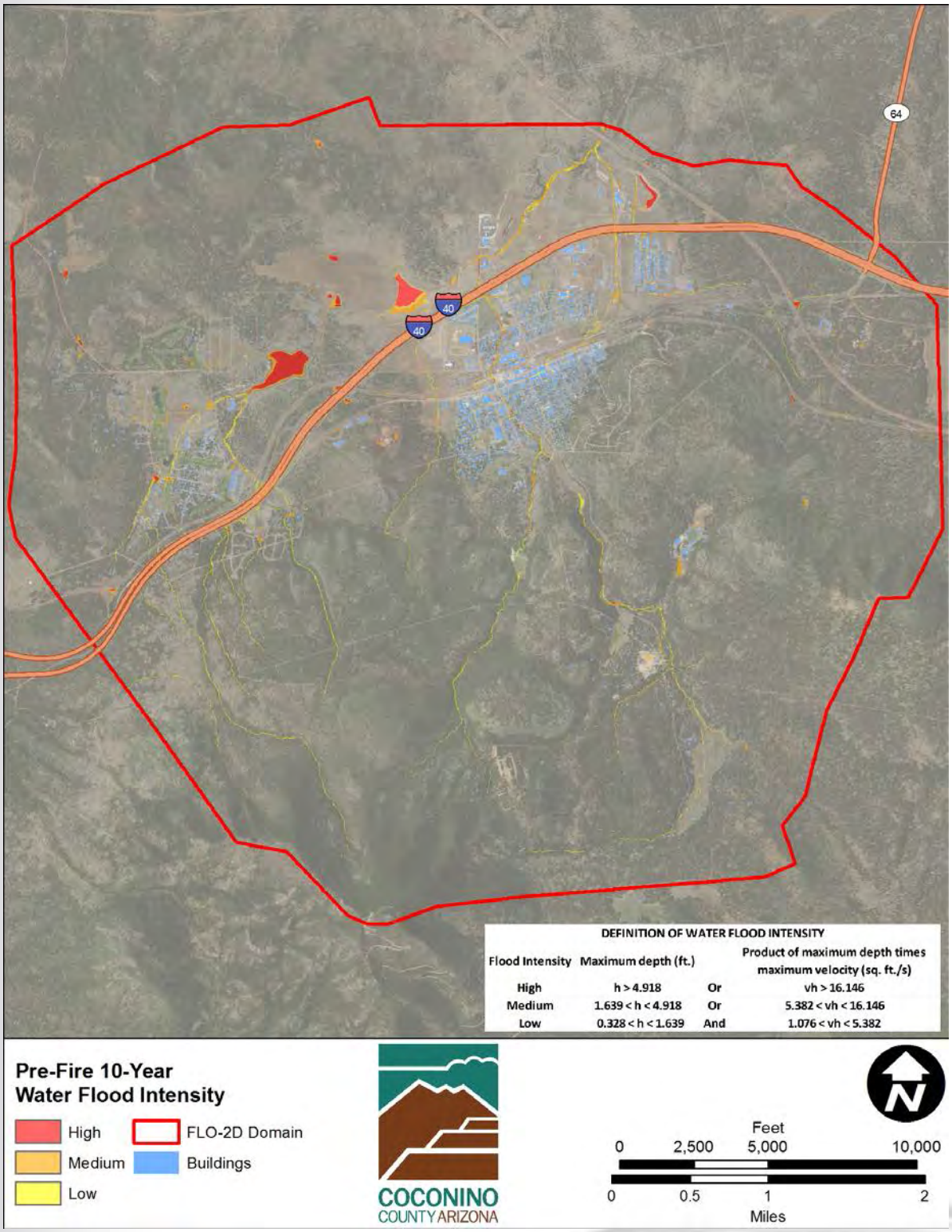

Figure 51. Williams 10-Year Pre-Wildfire Hazard Map

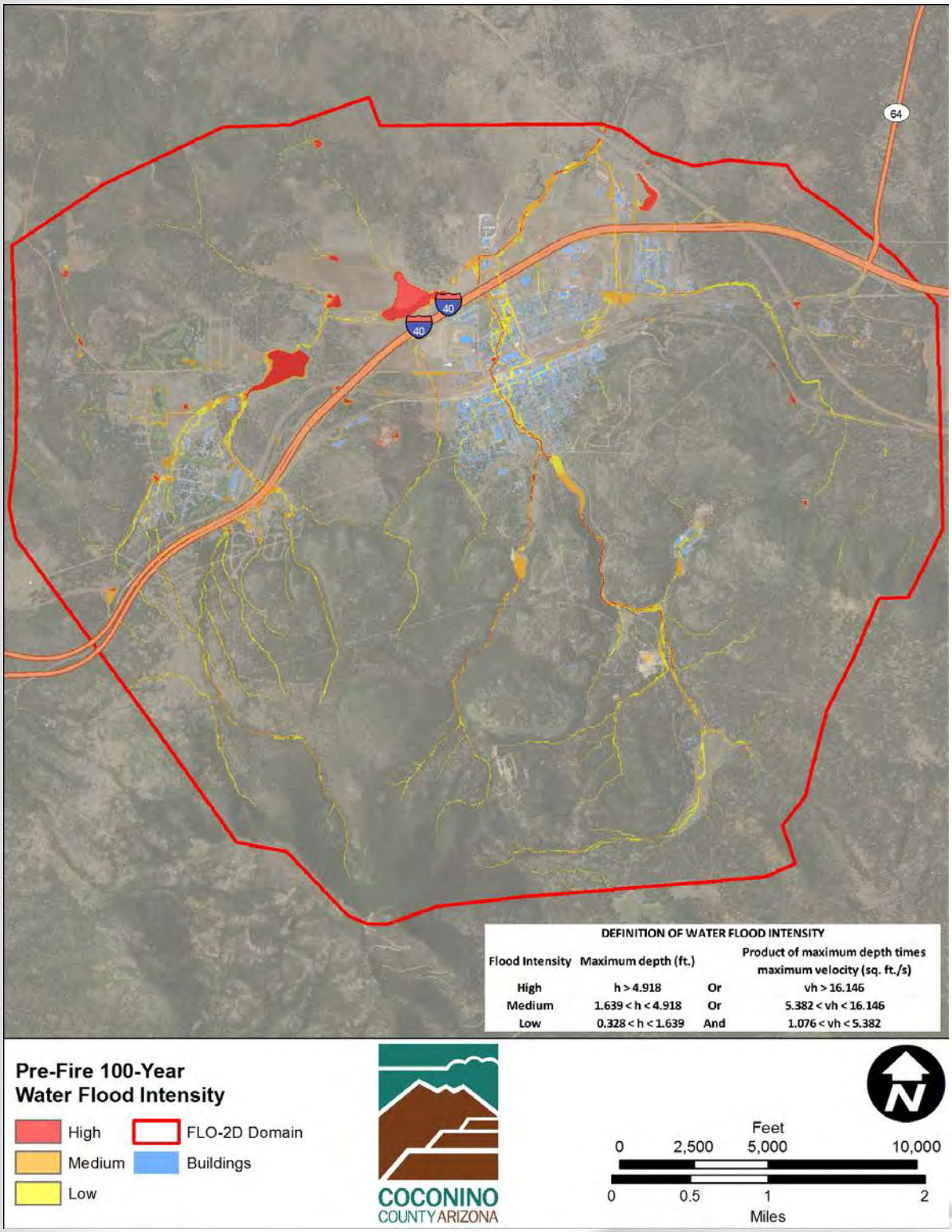

Figure 52. Williams 100-Year Pre-Wildfire Hazard Map

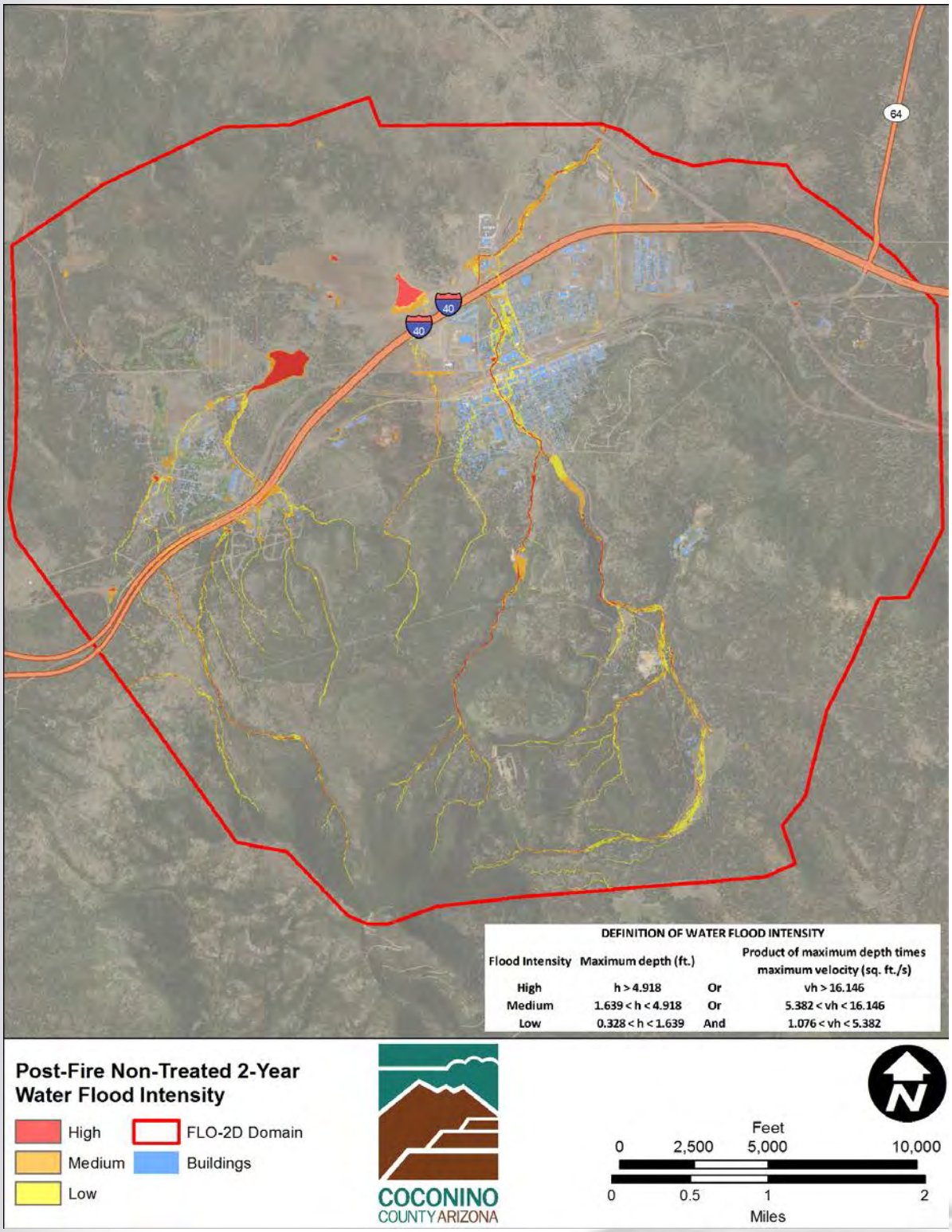

Figure 53. Williams 2-Year Post-Wildfire Non-Treated Hazard Map

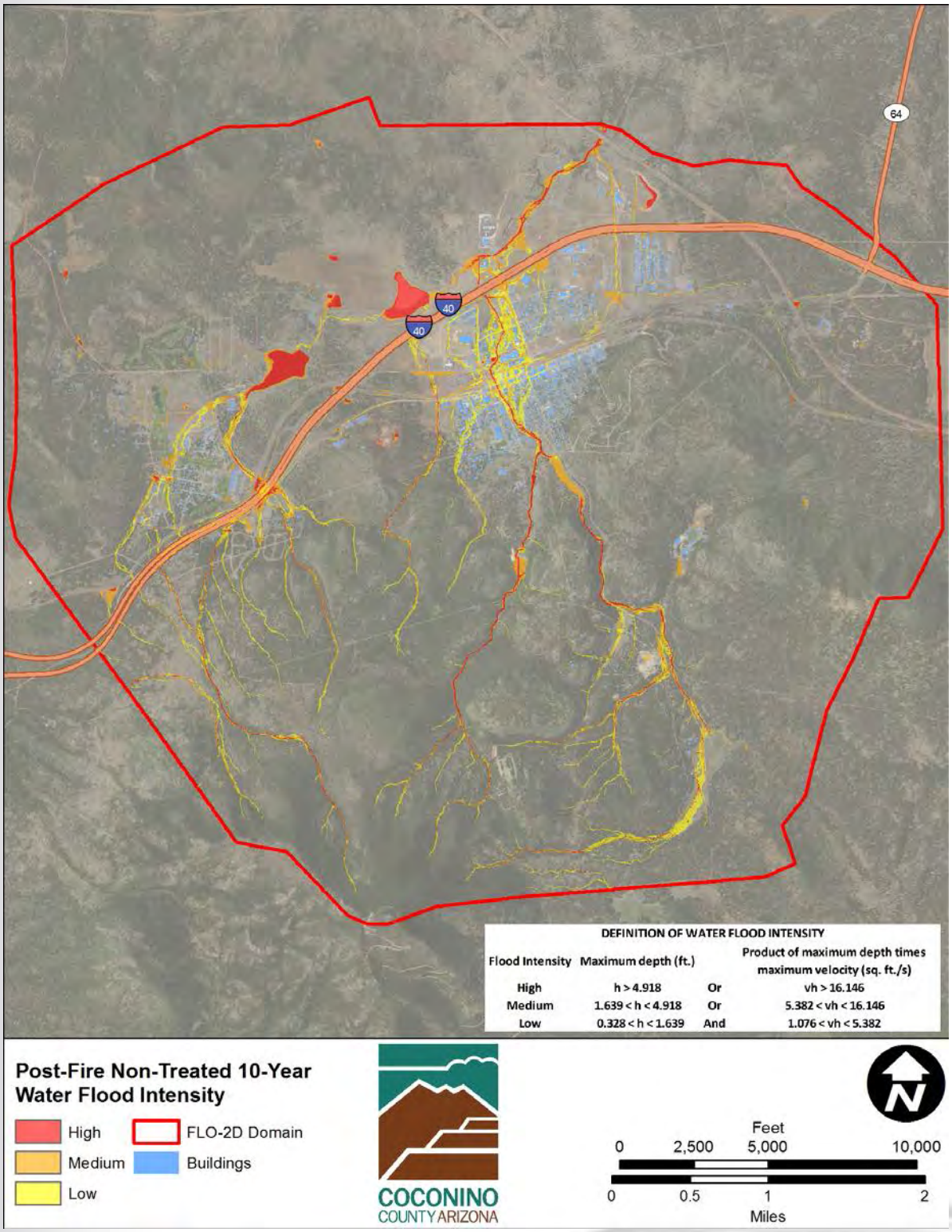

Figure 54. Williams 10-Year Post-Wildfire Non-Treated Hazard Map

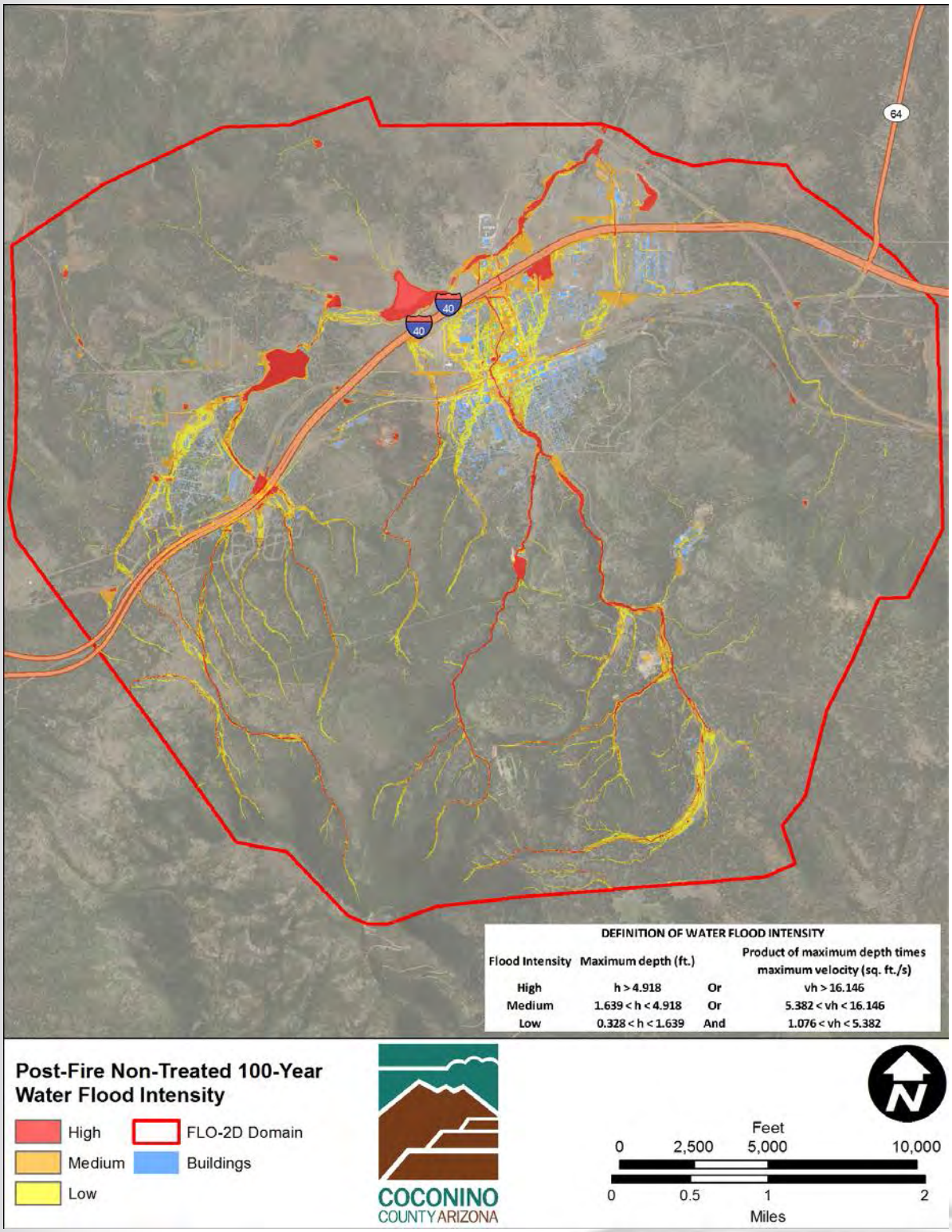

Figure 55. Williams 100-Year Post-Wildfire Non-Treated Hazard Map

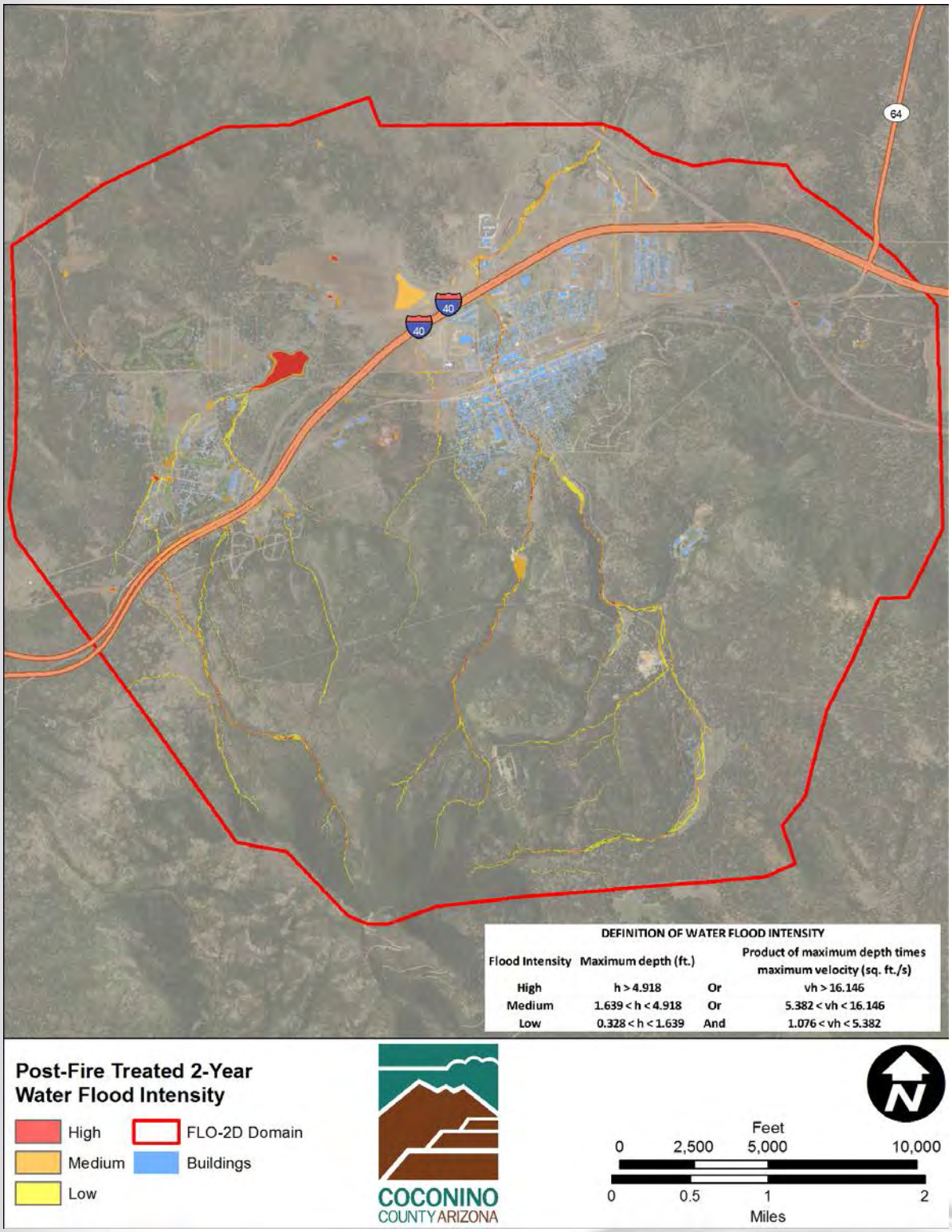

Figure 56. Williams 2-Year Post-Wildfire Treated Hazard Map

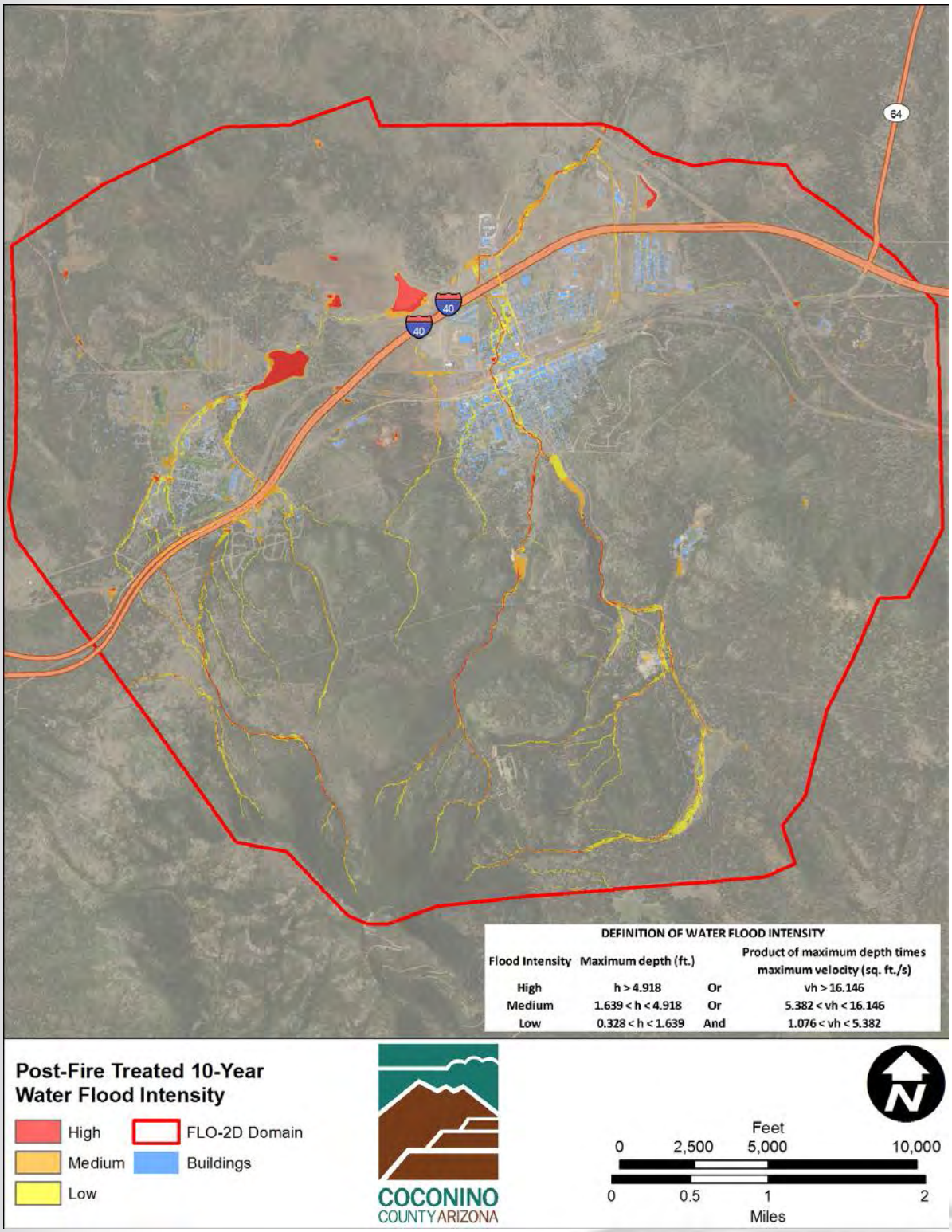

Figure 57. Williams 10-Year Post-Wildfire Treated Hazard Map

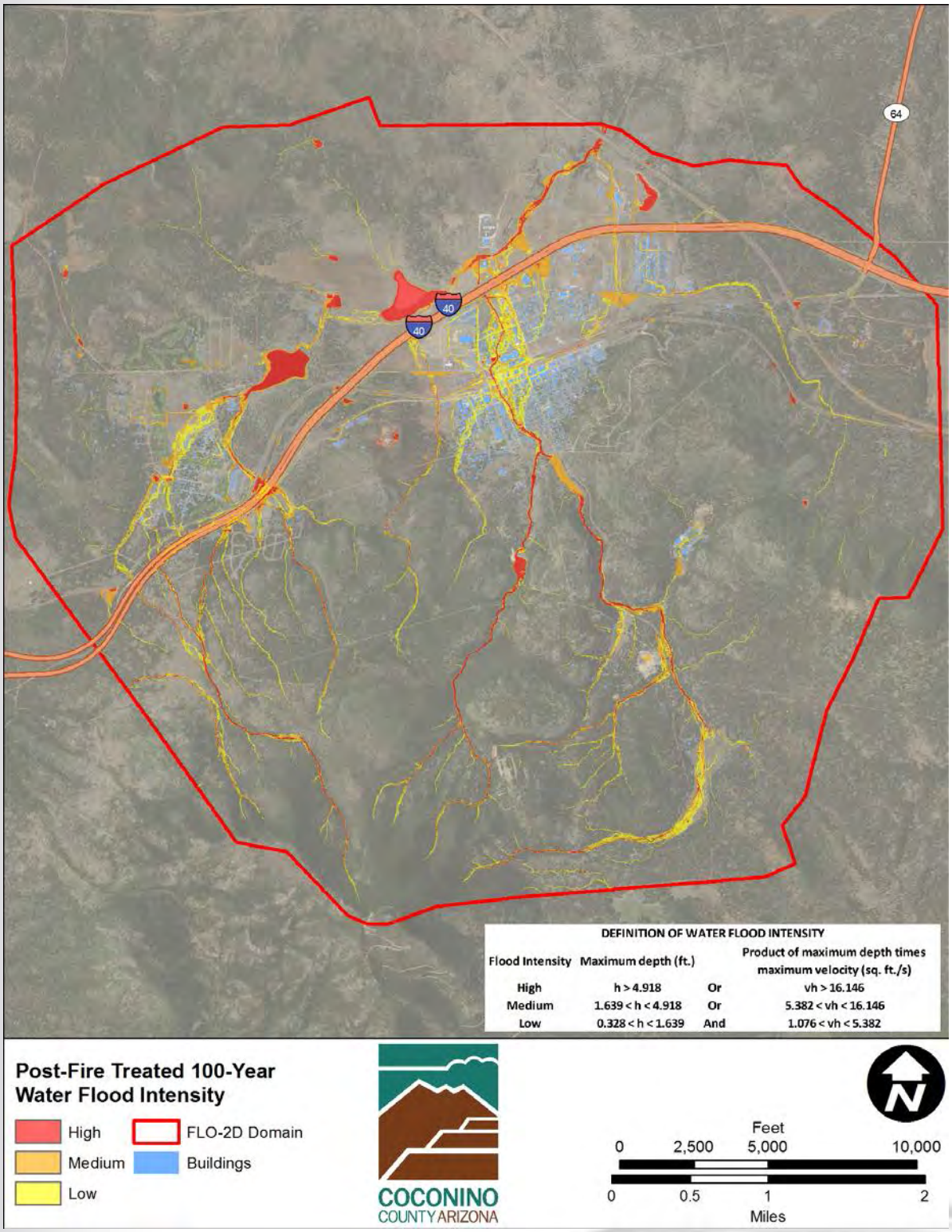

Figure 58. Williams 100-Year Post-Wildfire Treated Hazard Map

A. Flood Hazard Assessment Summary

Table 22 through Table 27 compares the total number of buildings impacted by each hazard level for all the burn scenarios for both Fort Valley and Williams.

Table 22. Fort Valley Impacted Buildings for 2-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire Treatment up to 8200'	Post-Wildfire All Treated
Low	2	57	36	2
Medium	6	25	18	12
High	0	1	1	0

Table 23. Fort Valley Impacted Buildings for 10-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire Treatment up to 8200'	Post-Wildfire All Treated
Low	11	133	81	28
Medium	17	46	33	20
High	0	3	1	0

Table 24. Fort Valley Impacted Buildings for 100-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire Treatment up to 8200'	Post-Wildfire All Treated
Low	86	225	211	135
Medium	36	122	80	50
High	2	11	7	3

Table 25. Williams Impacted Buildings for 2-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire All Treated
Low	8	182	26
Medium	10	42	18
High	1	9	5

Table 26. Williams Impacted Buildings for 10-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire All Treated
Low	18	337	167
Medium	19	111	31
High	4	14	10

Table 27. Williams Impacted Buildings for 100-Year Flood Hazard

Hazard Level	Pre-Wildfire	Post-Wildfire No Treatment	Post-Wildfire All Treated
Low	228	540	399
Medium	39	268	127
High	11	44	20

Table 22 through Table 27 indicate a consistent trend of a reduction in hazard with increased area of forest treatment.

The Fort Valley watershed extends to the top of Agassiz Peak and includes a large portion of wilderness area which has use restrictions that may prohibit certain types of forest treatment. As such, it may be unlikely that future watershed treatments will include thinning within the wilderness area. If that is the case, the most likely future conditions flow scenario would be Post-Wildfire Treatment up to 8,200'. To understand the benefit of forest treatment, even with the constraints posed by the wilderness area, the Post-Wildfire Treatment up to 8,200' was compared to the Post-Wildfire No Treatment scenario. The following reduction in the number of buildings in hazard areas is noted:

Table 28. Fort Valley Hazard Reduction

Recurrence Interval	Low Hazard	Medium Hazard	High Hazard
2-Year	37% reduction	28% reduction	No reduction
10-Year	39% reduction	28% reduction	66% reduction
100-Year	6% reduction	34% reduction	36% reduction

For the Williams watershed, the Post-Wildfire No Treatment vs the Treatment scenario indicates the following reduction of buildings in hazard areas:

Table 29. Williams Hazard Reduction

Recurrence Interval	Low Hazard	Medium Hazard	High Hazard
2-Year	86% reduction	57% reduction	44% reduction
10-Year	50% reduction	72% reduction	28% reduction
100-Year	26% reduction	53% reduction	54% reduction

6. Summary

The modeling results suggest that in a burned condition, the Fort Valley and Williams Pilot Areas produce significantly higher discharges as compared to pre-wildfire conditions. Treatment of the impacted watersheds has the effect of significantly reducing post-wildfire discharges and is critical to reducing the resulting hazards. It is recommended that Coconino County continue to work closely with the Forest Service in managing and treating the forests that contribute runoff to developed areas. The results also suggest that it would benefit the County to include forest treatment in future capital improvement project plans.

7. References

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USCOE, 2000, Rio De Flag, Flagstaff, Arizona Feasibility Report and Final Environmental Impact Statement.

USFS Coconino National Forest Terrestrial Ecosystem Survey, 2001.

APPENDIX A – LIDAR SURVEY REPORTS

November 2, 2016

City of Williams, Arizona LiDAR

Technical Data Report

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PH: 928-214-0887

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Cover Photo: This image was taken by QSI field staff from Bill Williams Mountain looking north over the City of Williams, Arizona.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view from Bill Williams Mountain within the City of Williams site in Arizona.

In August 2016, Quantum Spatial (QSI) was contracted by JE Fuller Hydrology and Geomorphology, Inc. (JE Fuller) to collect Light Detection and Ranging (LiDAR) data in the fall of 2016 for the City of Williams site in Arizona. Data were collected to aid JE Fuller in assessing the topographic and geophysical properties of the study area to support hydrology evaluation and planning.

This report accompanies the delivered LiDAR data, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to JE Fuller is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the City of Williams site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
City of Williams	17,327	18,116	09/15/2016	LiDAR

Deliverable Products

Table 2: Products delivered to JE Fuller for the City of Williams site

City of Williams Products Projection: Arizona State Plane Central Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12b) Units: International Feet	
Points	LAS v 1.2 • All Classified Returns • Ground Classified Returns
Rasters	3.0 foot ESRI Grids • Bare Earth Model • Highest Hit Model 1.5 foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • Survey Control Points • 1 foot Contours

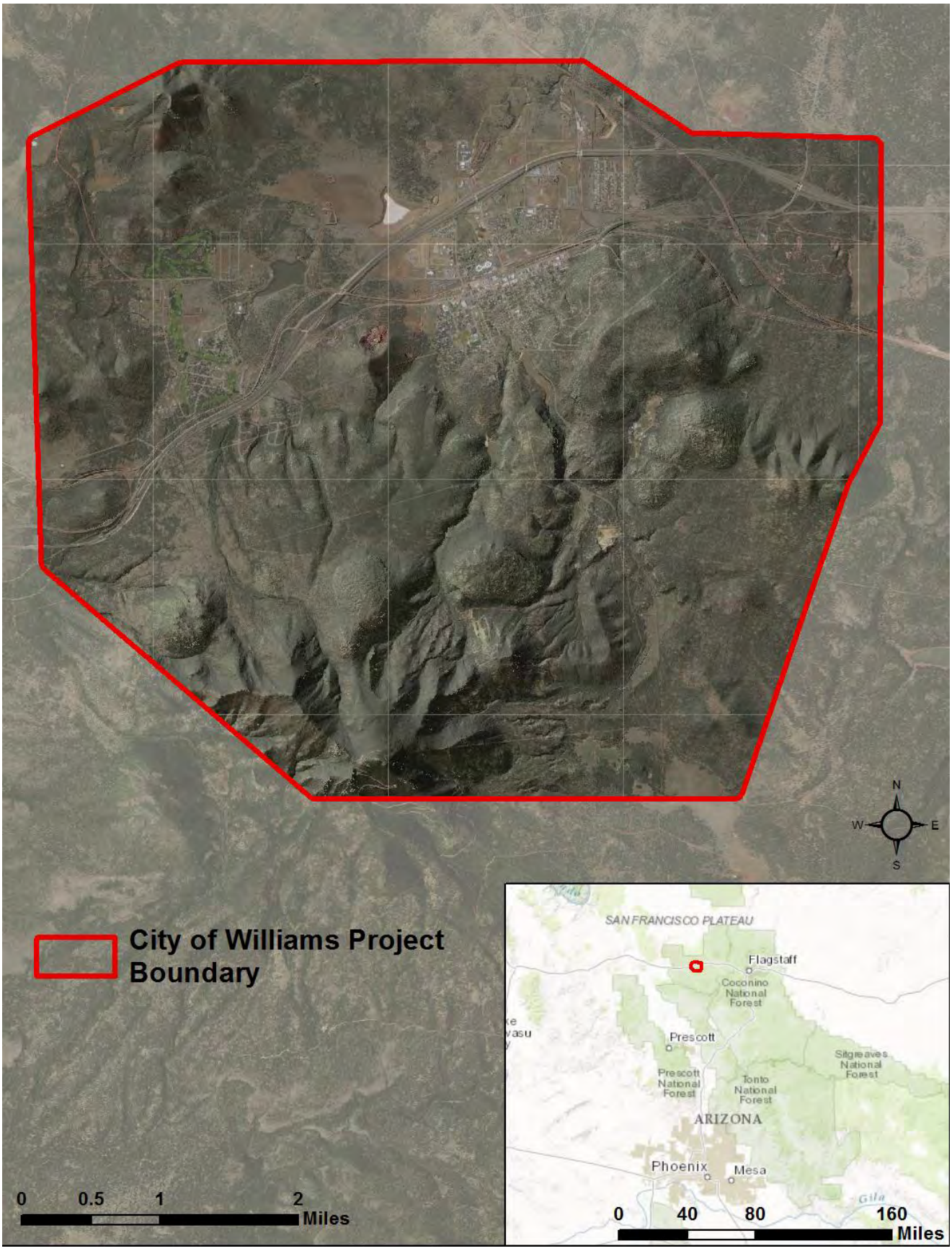


Figure 1: Location map of the City of Williams site in Arizona

ACQUISITION

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the City of Williams LiDAR study area at the target point density of ≥10.0 points/m^2 (0.92 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥10 pulses/m^2 (0.92 points/ft^2) over the City of Williams project area. The Leica ALS80 laser system can record unlimited range measurements (returns) per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	September 15, 2016
Aircraft Used	Cessna Caravan
Sensor	Leica ALS80
Survey Altitude (AGL)	1750 m
Swath Width	938 m
Target Pulse Rate	310 kHz
Pulse Mode	Multi Pulse in Air (MPiA)
Laser Pulse Diameter	38.5 cm
Mirror Scan Rate	58.4 Hz
Field of View	30°
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited
Intensity	8-bit, scaled to 16-bit
Resolution/Density	Average 10 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS80 LiDAR sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Ground Control

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

QSI-Established Monument WILLIAMS_02

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) and fast static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI established two new monuments for the City of Williams LiDAR project (Table 4, Figure 2). New monumentation was set using 5/8" x 30" rebar topped with stamped 2 ½ " aluminum caps. QSI's professional land surveyor, Nick Fusco (AZPLS# 24518) oversaw and certified the establishment of all monuments.

Table 4: Monuments established for the City of Williams acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
WILLIAMS_01	35° 15' 02.66216"	-112° 11' 59.26001"	2037.484
WILLIAMS_02	35° 12' 57.26260"	-112° 10' 10.19926"	2145.655

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.020 m

For the City of Williams LiDAR project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) and fast-static (FS) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R10 GNSS receiver. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK data, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines for post-processing. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 6 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

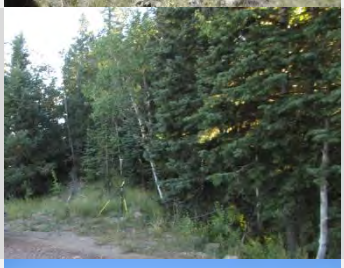
Table 6: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R10	Integrated Antenna R10	TRMR10	Rover

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area. Combined land class cover accuracy was calculated to assess confidence in the LiDAR derived ground models across the land cover class points. Land cover types and descriptions are shown in Table 7.

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description
Bare Earth	BE		Bare rock, sand, packed dirt, and/or clay
Evergreen Forest	EVER_FOR		Forested areas containing evergreen trees
Mixed Forest	MX_FOR		Forested areas containing a mix of deciduous and evergreen trees
Urban	URBAN		Parks, sidewalks, roads, and other recreational areas

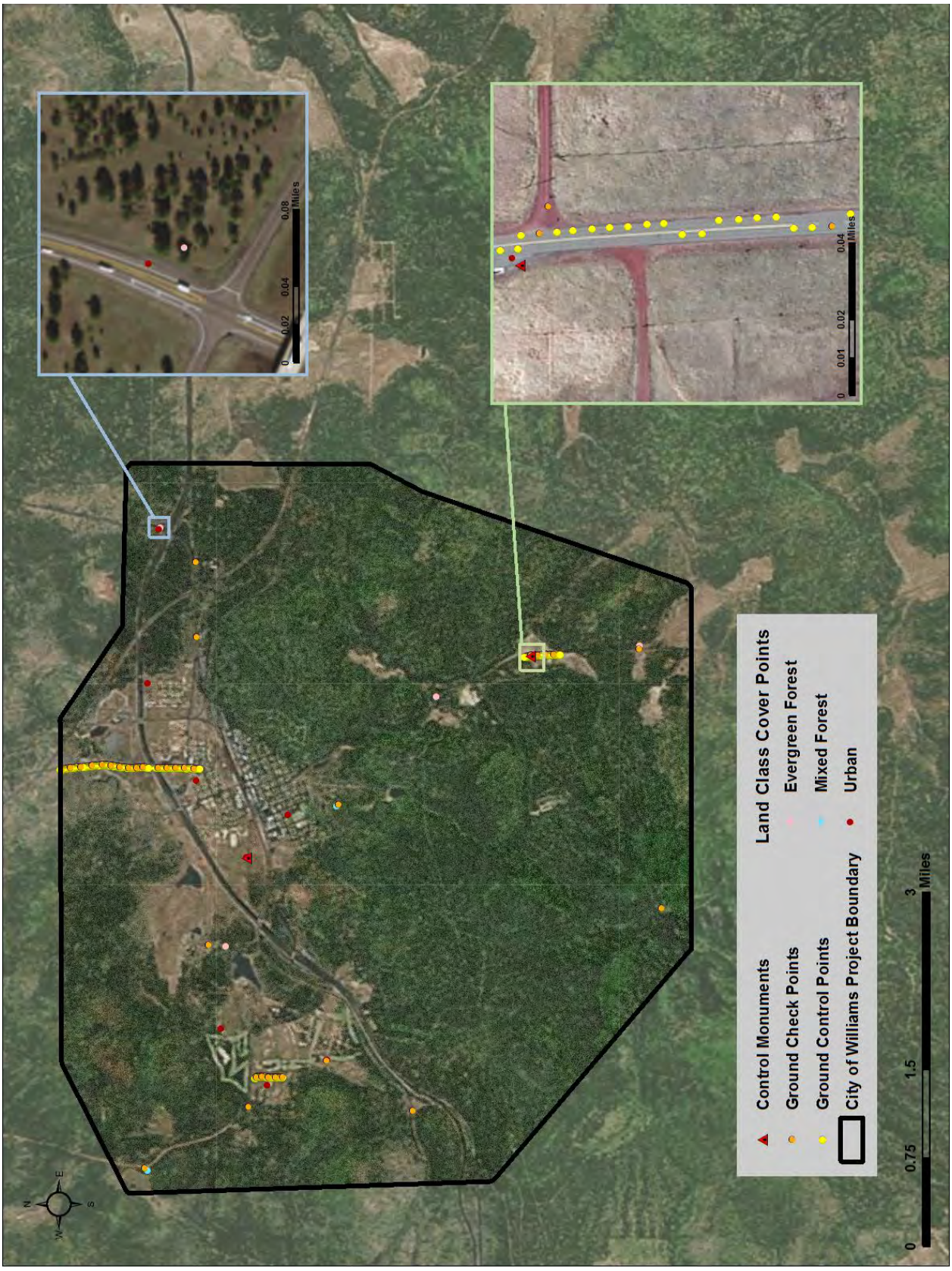
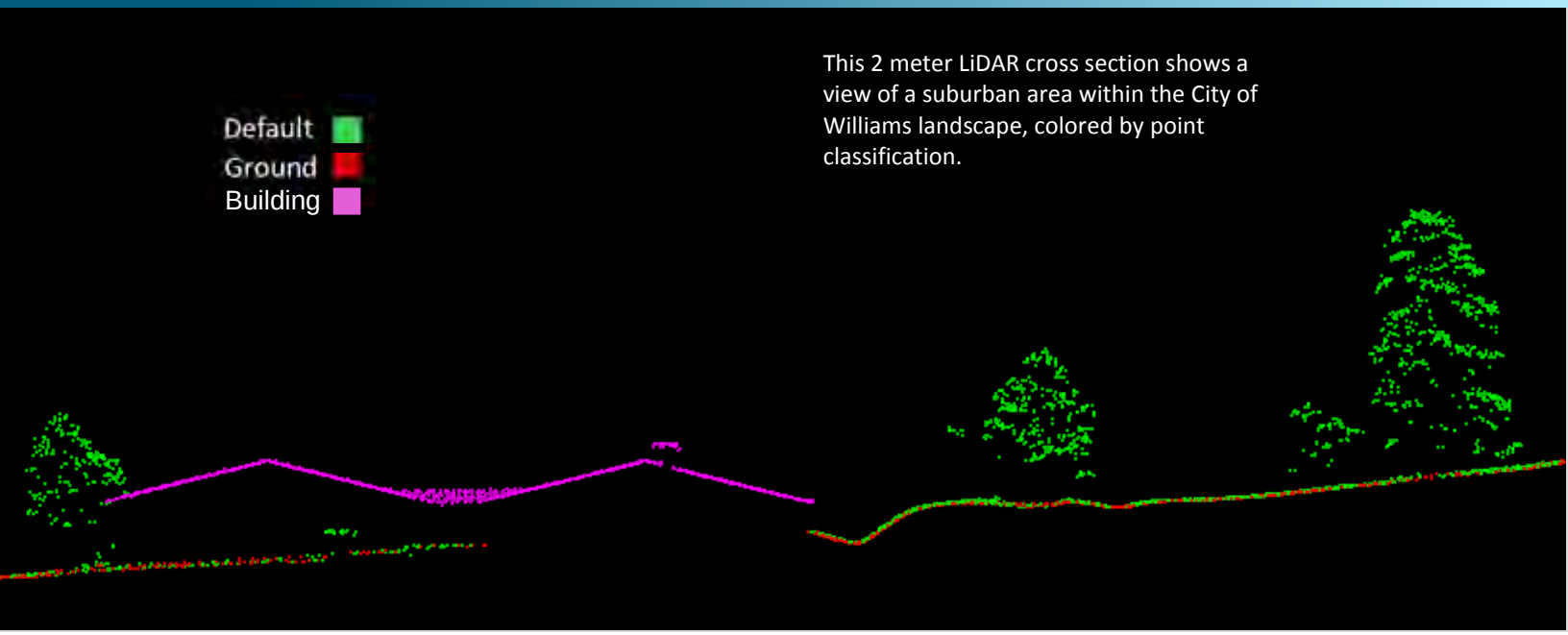


Figure 2: Ground survey location map of the City of Williams project area.



This 2 meter LiDAR cross section shows a view of a suburban area within the City of Williams landscape, colored by point classification.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the City of Williams dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
6	Buildings	Permanent anthropogenic structures

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.6
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.16
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.16
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.16 TerraModeler v.16
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0 foot pixel resolution.	TerraScan v.16 TerraModeler v.156 ArcMap v. 10.2
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey 2.2.1SP2 (QSI proprietary) LAS Product Creator 1.5 (QSI proprietary) TerraScan v.16 TerraModeler v.16 ArcMap v. 10.2

Feature Extraction

Contours

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments.

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 3).

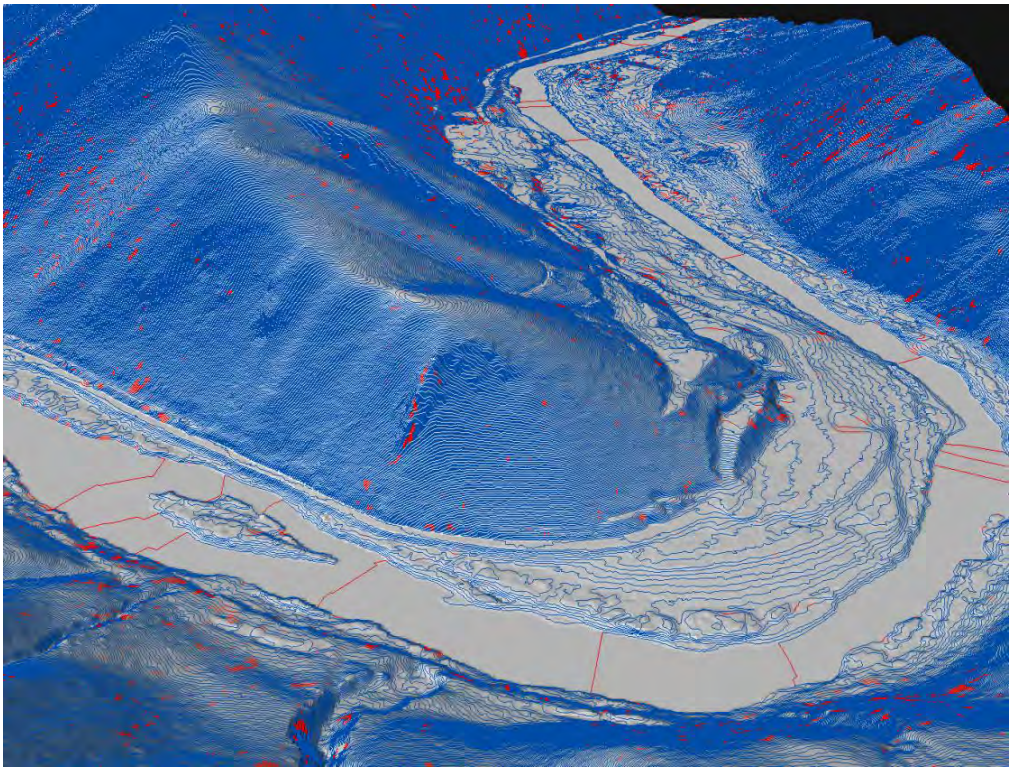
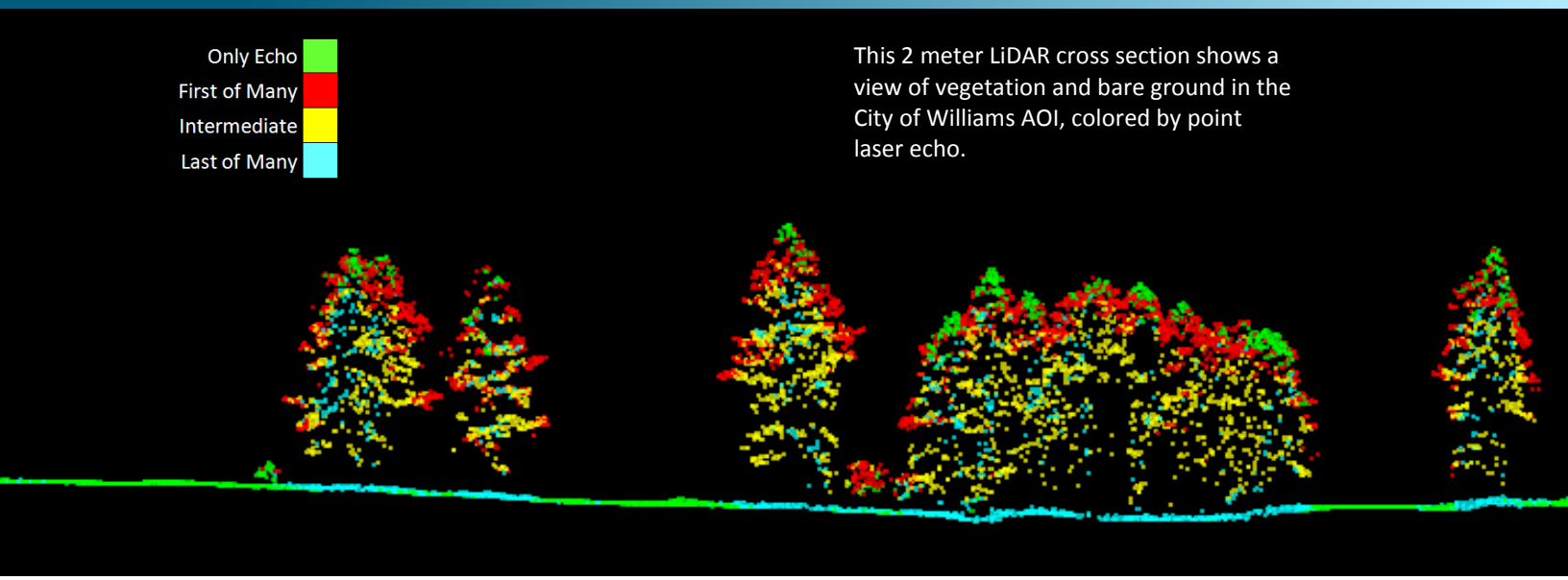


Figure 3: Example image of contours draped over a bare earth elevation model. Blue contours represent high confidence while the red contours represent low confidence.

Buildings

Building classification was performed through a combination of automated algorithms and manual classification. Typically, manual editing of the building classification is necessary where dense canopy is immediately proximate to features. All non-mobile structures such as houses, barns, silos and sheds were classified into the building category. Once classification was complete, automated routines were used generate the polygon shapefile representing building footprints. A total of 1,737 buildings were classed in the data (Figure 4).

Figure 4: This image of building footprints in the City of Williams dataset was created by draping the building shapefile over the bare earth model.



This 2 meter LiDAR cross section shows a view of vegetation and bare ground in the City of Williams AOI, colored by point laser echo.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 10 points/m^2 (0.92 points/ft^2). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of LiDAR data for the City of Williams project was 1.42 points/ft^2 (15.30 points/m^2) while the average ground classified density was 0.35 points/ft^2 (3.74 points/m^2) (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 7.

Table 10: Average LiDAR point densities

Classification	Point Density
First-Return	1.42 points/ft^2 15.30 points/m^2
Ground Classified	0.35 points/ft^2 3.74 points/m^2

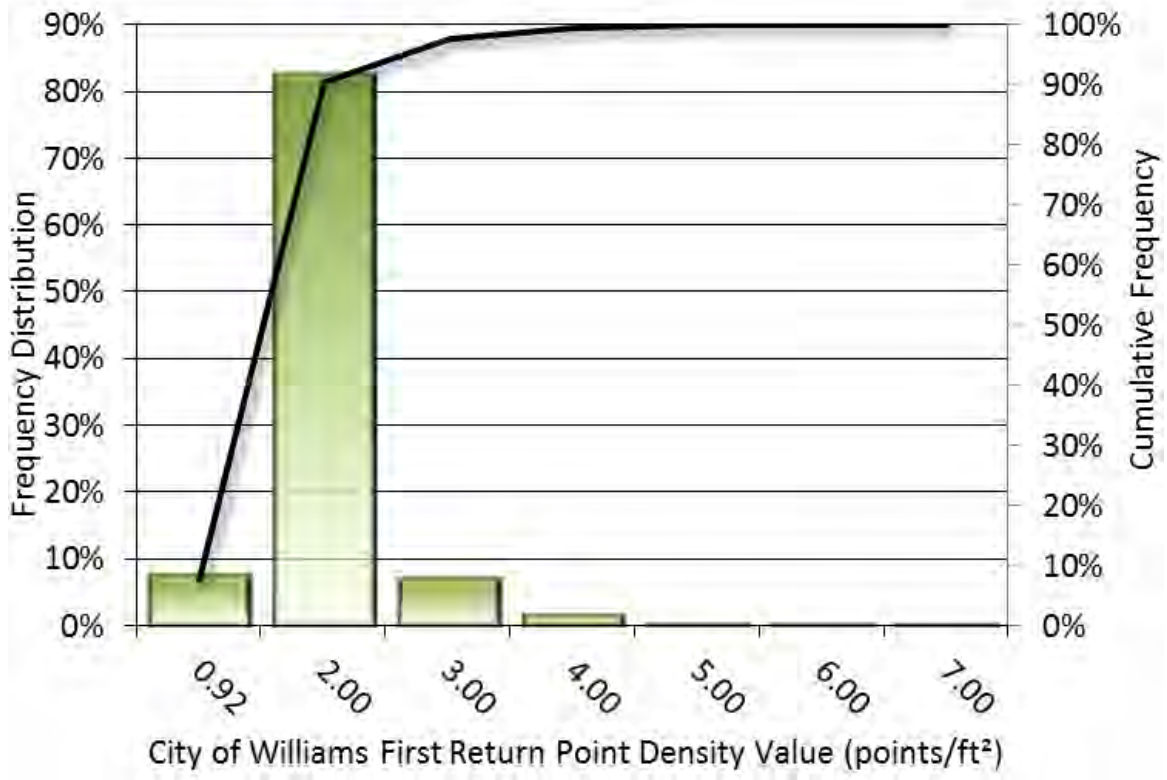


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

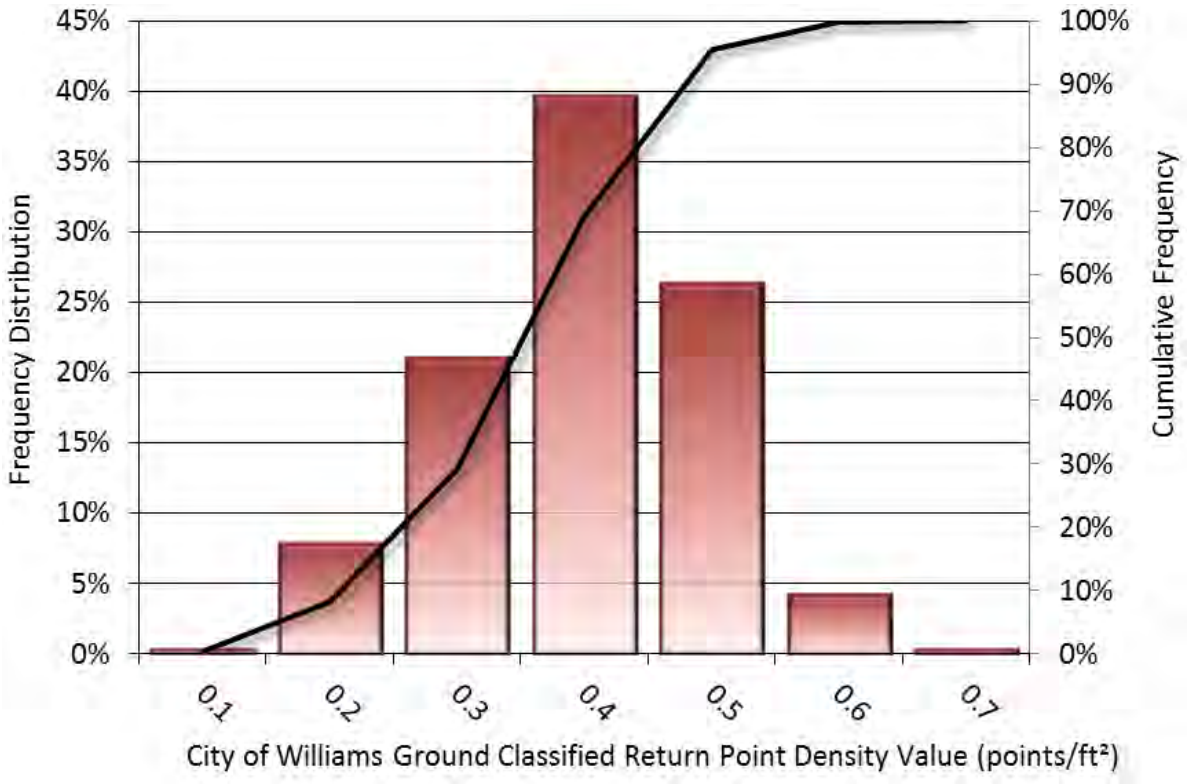


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

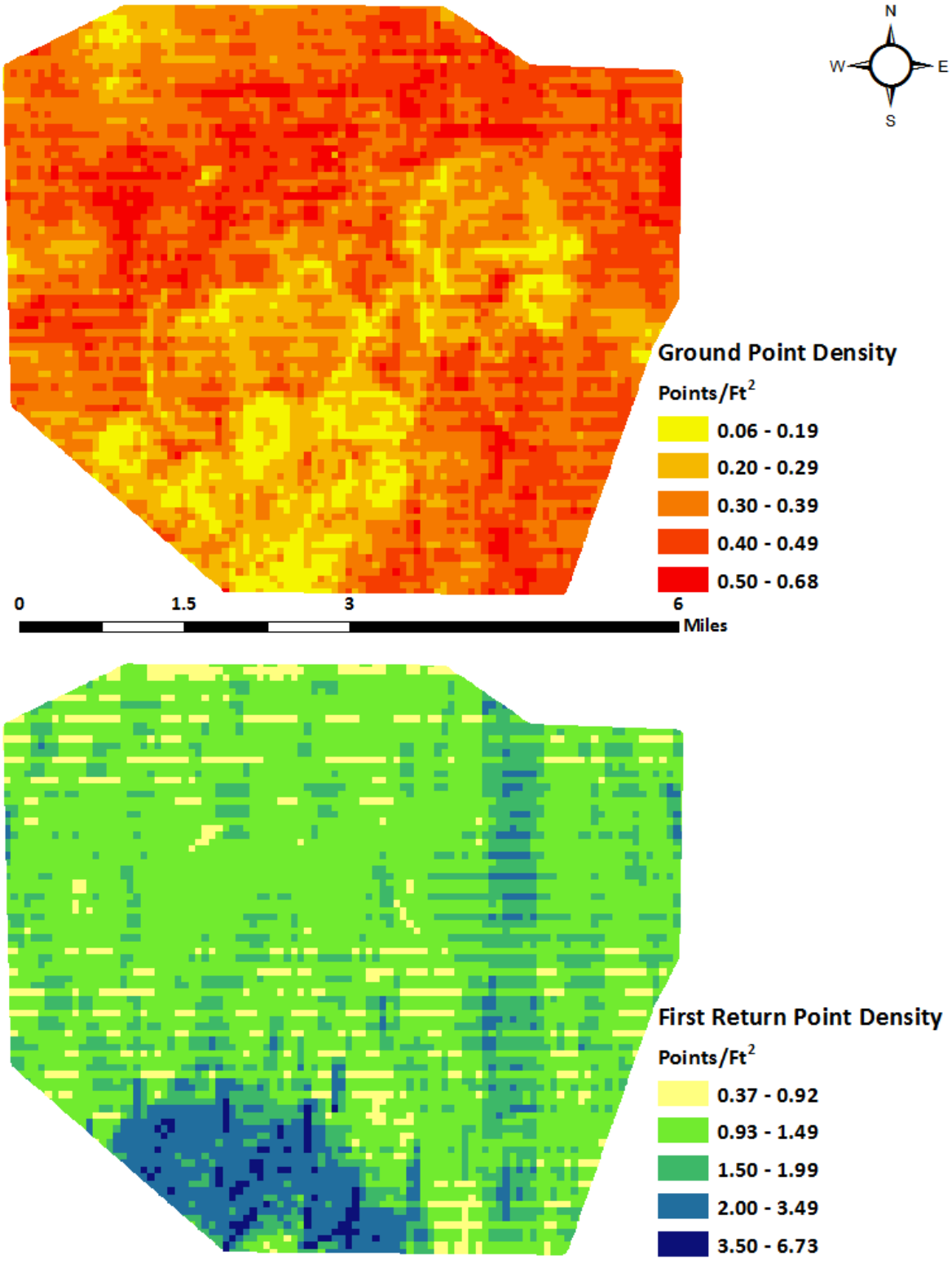


Figure 7: First return and ground-classified point density map for the City of Williams site (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Absolute Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. NVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the City of Williams survey, 36 quality assurance points were withheld in total resulting in a non-vegetated vertical accuracy of -0.026 feet (-0.008 meters) (Figure 8).

QSI also assessed absolute accuracy using 356 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 11 and Figure 9.

Table 11: Absolute accuracy results

Absolute Accuracy		
	Quality Assurance Points (NVA)	**Ground Control Points**
Sample	36 points	356 points
NVA (1.96*RMSE)	0.101 ft 0.031 m	0.085 ft 0.026 m
Average	-0.026 ft -0.008 m	-0.006 ft -0.002 m
Median	-0.023 ft -0.007 m	-0.003 ft -0.001 m
RMSE	0.052 ft 0.016 m	0.043 ft 0.013 m
Standard Deviation (1σ)	0.045 ft 0.014 m	0.043 ft 0.026 m

[3] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

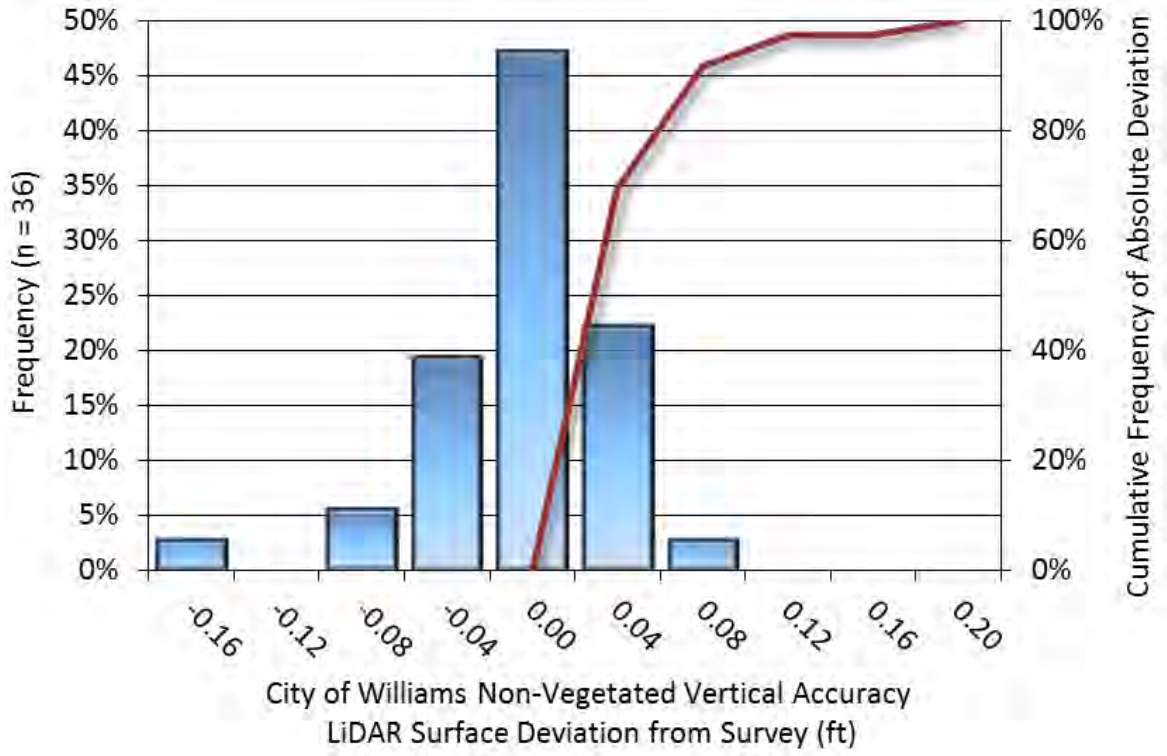


Figure 8: Frequency histogram for LiDAR surface deviation from quality assurance point values

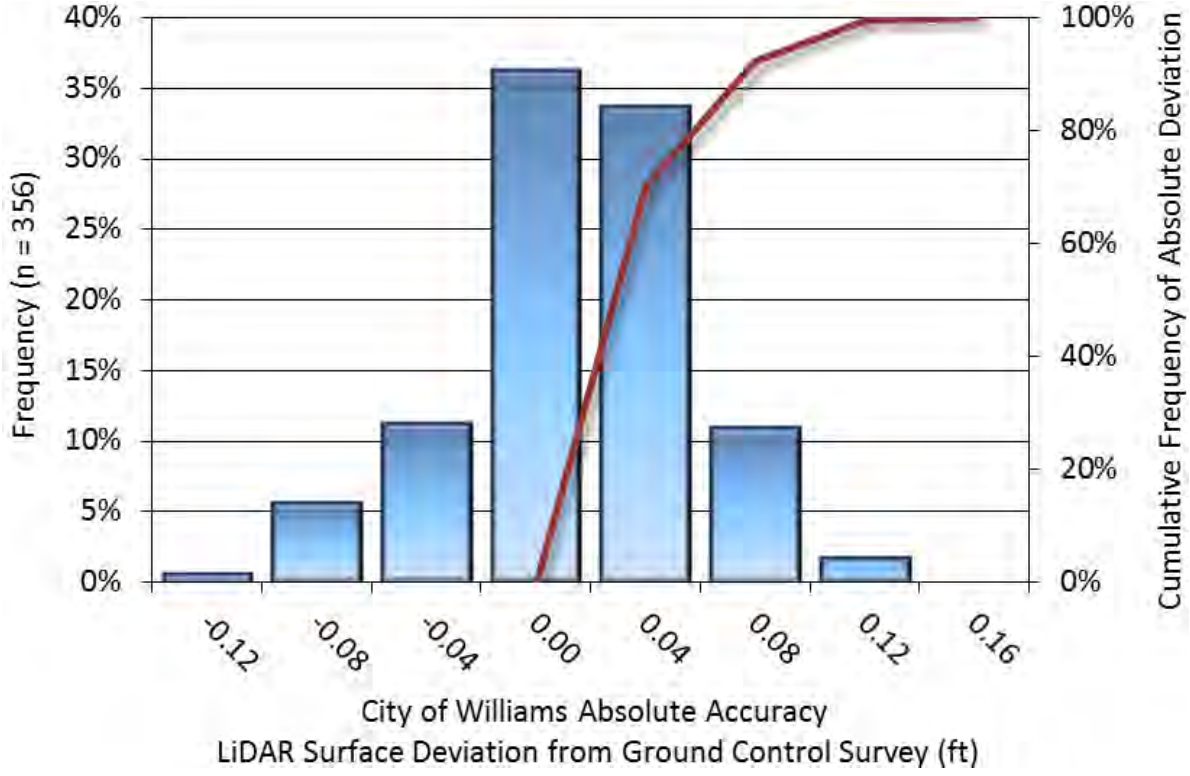


Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground quality assurance point data collected in various landcover types to the triangulated ground surface generated by the ground classified LiDAR points. VVA is evaluated at the 95th percentile (Table 12, Figure 10).

Table 12: Vegetated Vertical Accuracy for the City of Williams Project

Vegetated Vertical Accuracy (VVA)	
Sample	15 points
Average Dz	-0.017 ft -0.005 m
Median	-0.013 ft -0.004 m
RMSE	0.041 ft 0.012 m
Standard Deviation (1σ)	0.038 ft 0.012 m
95th Percentile	0.040 ft 0.012 m

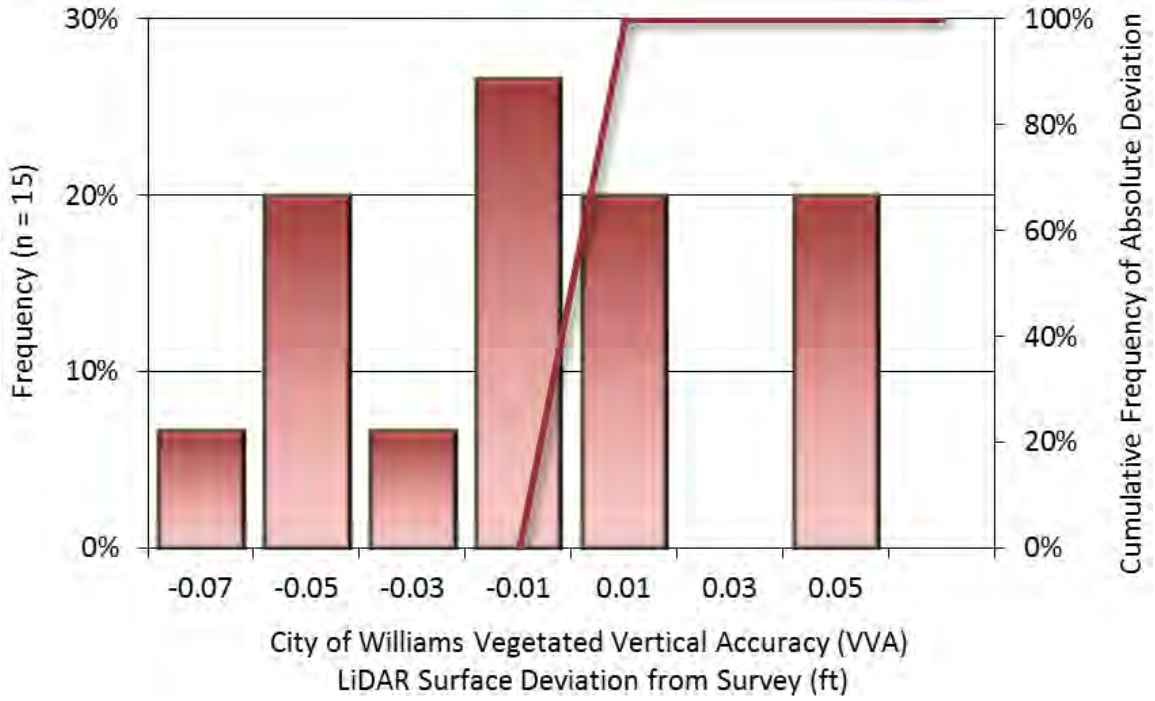


Figure 10: Frequency histogram for LiDAR surface deviation from all vegetated and urban land cover class point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the City of Williams LiDAR project was 0.099 feet (0.030 meters) (Table 13, Figure 11).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	39 surfaces
Average	0.099 ft 0.030 m
Median	0.097 ft 0.030 m
RMSE	0.113 ft 0.034 m
Standard Deviation (1σ)	0.029 ft 0.009 m
1.96σ	0.058 ft 0.018 m

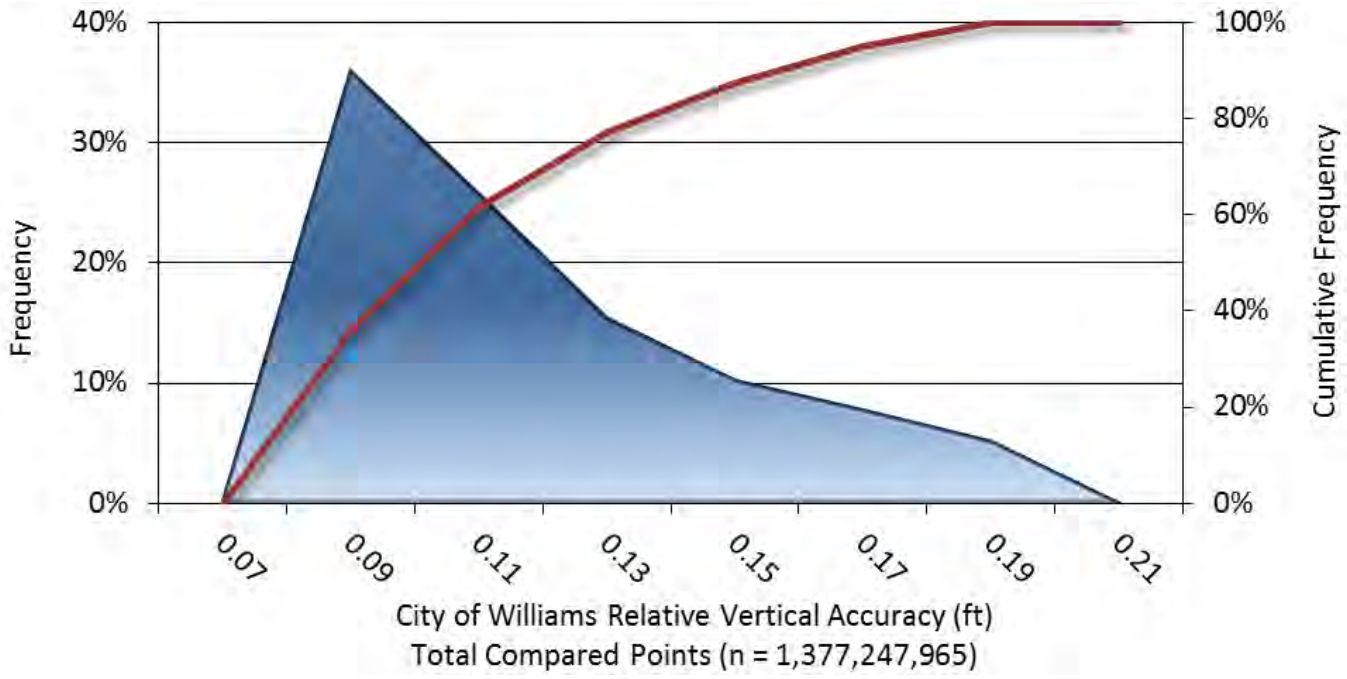


Figure 11: Frequency plot for relative vertical accuracy between flight lines

Surveyor's Certificate

I, Nickolas R. Fusco, being a Professional Land Surveyor in the State of Arizona, hereby certify to the best of my professional knowledge and belief that the survey methodologies and results, outline in the report titled "City of Williams, Arizona LiDAR; Technical Data Report", dated October 31, 2016, were performed and obtained utilizing commonly acceptable survey standards, practices and procedures. The field survey portion of this project was accomplished between September 15, 2016 and September 17, 2016; Aerial LiDAR was collected September 15, 2016.

I have reviewed the accuracy statements as part of my oversight and found them to meet the National Standards for Spatial Accuracy (NSSDA) shown.

Signed October 31, 2016

Nickolas R. Fusco
Professional Land Surveyor Number 24518

Expires 12/31/2017

Figure 12: View looking South of City of Williams toward the Santa Fe Reservoir, Saginaw and Upper Saginaw Reservoirs, and City Reservoir (bottom to top, respectively). This image was created by coloring the bare earth model by elevation.

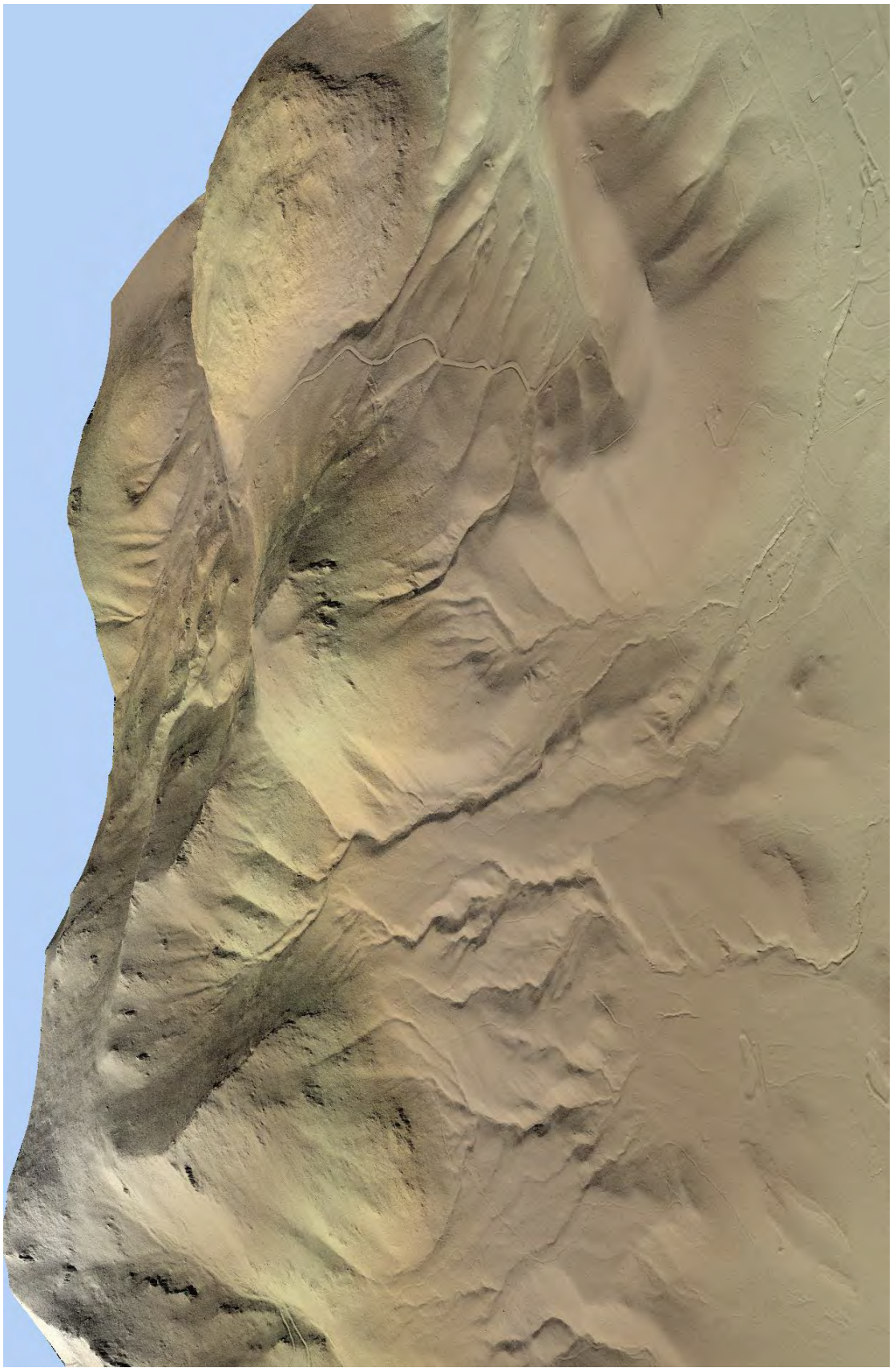


Figure 13: Looking northeast at Bill Williams Mountain, tributaries cut down into the geology creating a drainage basin. This image was created by coloring the bare-earth model by elevation.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-Vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echos) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±15° from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

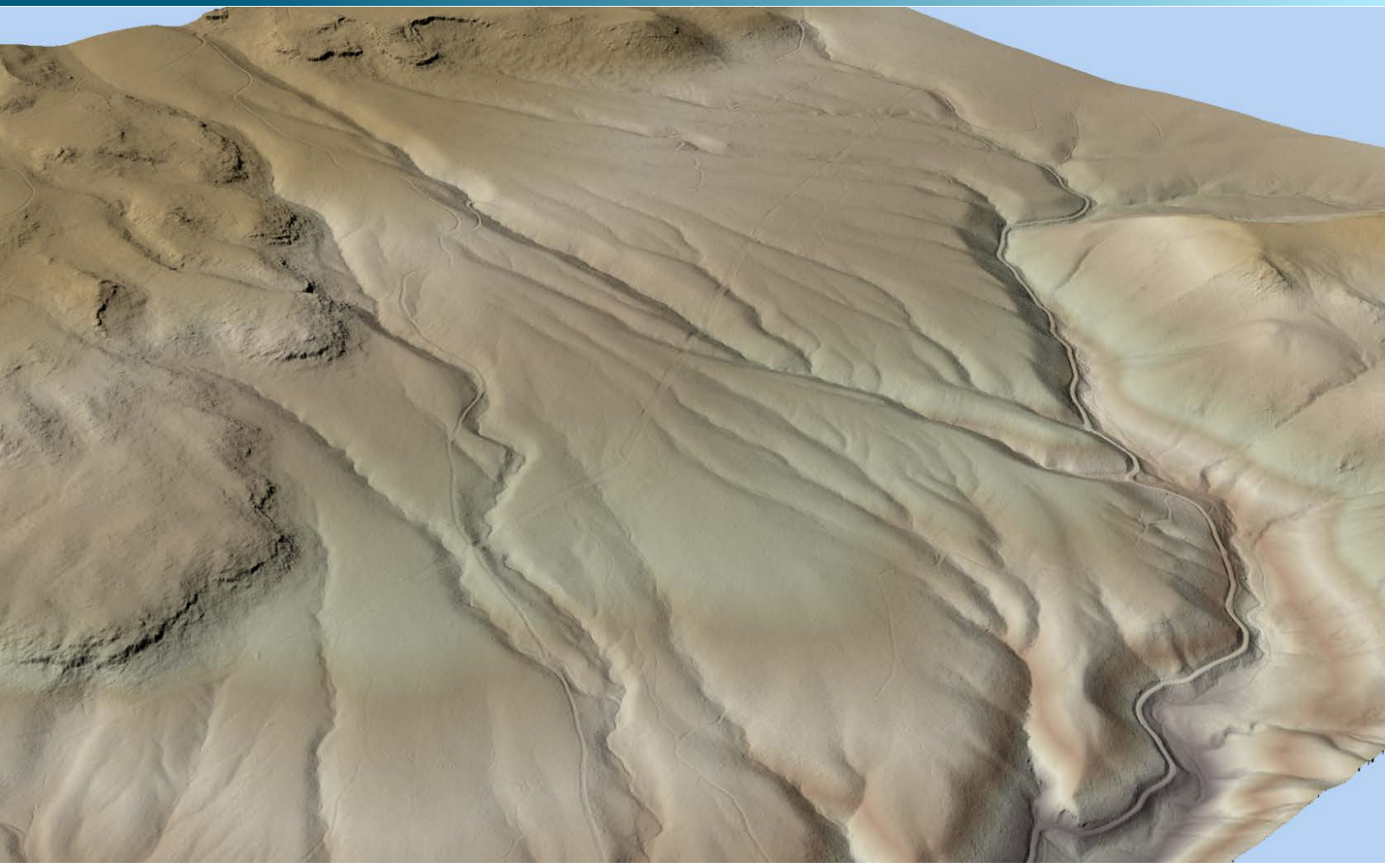
Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

November 3, 2016



Fort Valley, Arizona LiDAR

Technical Data Report

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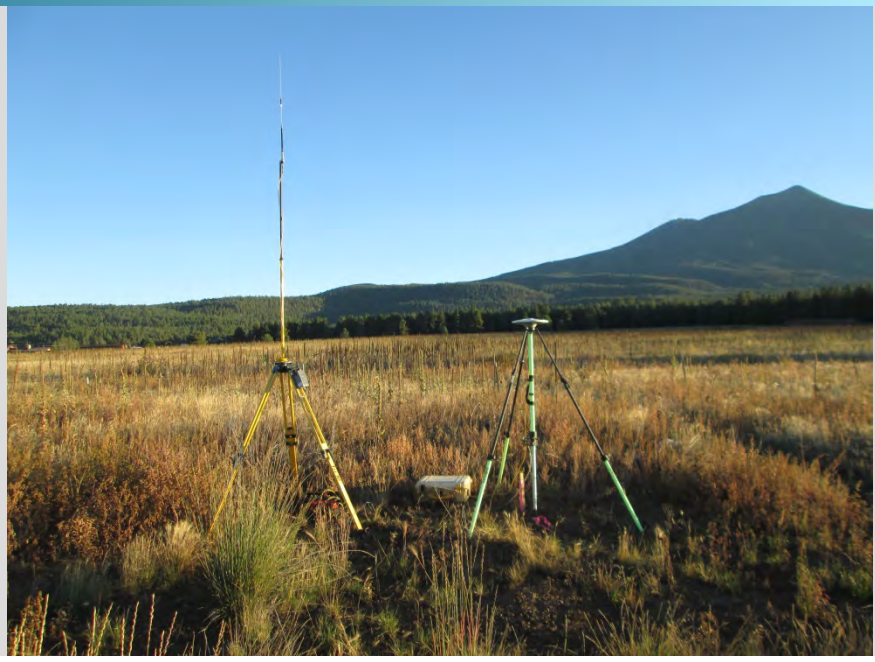
Cover Photo: A view looking northeast within Coconino National Forest at tributaries that flow off of Fremont Peak feeding into Shultz Creek (lower right) in the Fort Valley project area. The image was created from the LiDAR bare earth model colored by elevation.

INTRODUCTION

This photo shows a Trimble R7 receiver and RTK radio antenna within the Fort Valley, Arizona site located northwest of the City of Flagstaff.



In August 2016, Quantum Spatial (QSI) was contracted by The WLB Group, Inc. (WLB Group) to collect Light Detection and Ranging (LiDAR) data in the fall of 2016 for the Fort Valley, Arizona site located northwest of the City of Flagstaff. Data were collected to aid WLB Group in assessing the topographic and geophysical properties of the study area to support hydrology evaluation and planning.

This report accompanies the delivered LiDAR data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to WLB Group is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Fort Valley, Arizona site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Fort Valley, Arizona	35,589	37,321	09/16/2016-09/17/2016	LiDAR

Deliverable Products

Table 2: Products delivered to WLB Group for the Fort Valley, Arizona site

Fort Valley, Arizona Products **Projection: Arizona State Plane Central** **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (GEOID12b)** **Units: International Feet and US Survey Feet***	
Points	LAS v 1.2 • All Classified Returns • Ground Classified Returns
Rasters	3.0 foot ESRI Grids • Bare Earth Model • Highest Hit Model 1.5 foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • 2-foot Contours • Ground Survey Control Points

**Two sets of products were created and delivered to WLB Group: one in International Feet and one in US Survey Feet*

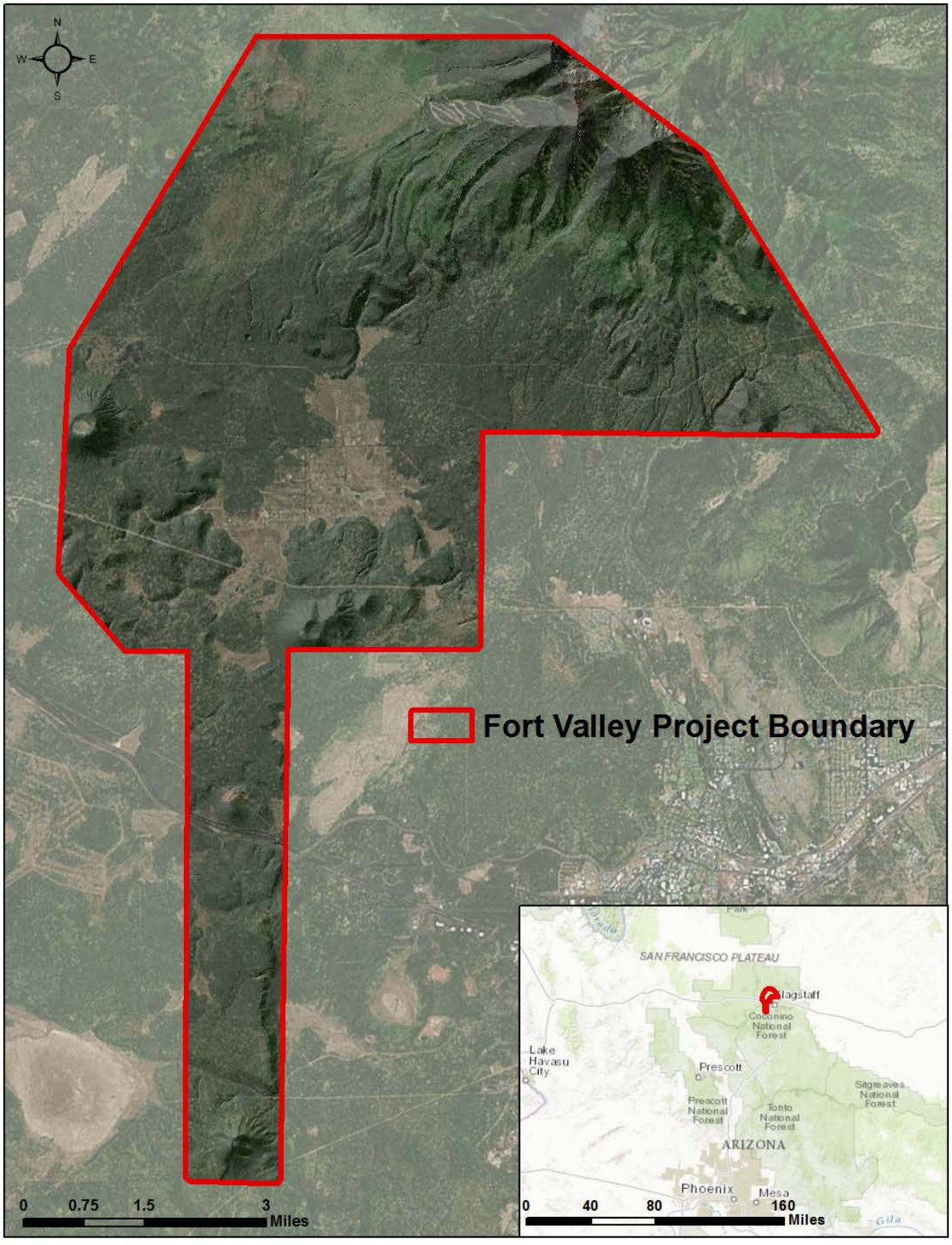


Figure 1: Location map of the Fort Valley, Arizona site located northwest of the City of Flagstaff

ACQUISITION

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Fort Valley, Arizona LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flights were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 (0.74 pulses/ft^2) over the Fort Valley, Arizona project area. The Leica ALS80 laser system can record unlimited range measurements (returns) per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	September 16-17, 2016
Aircraft Used	Cessna Caravan
Sensor	Leica ALS80
Survey Altitude (AGL)	1700 m
Swath Width	911 m
Target Pulse Rate	325 kHz
Pulse Mode	Multi Pulse in Air (MPiA)
Laser Pulse Diameter	37.4 cm
Mirror Scan Rate	56 Hz
Field of View	30°
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited
Intensity	8-bit, scaled to 16-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS80 LiDAR sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Ground Control

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

QSI-Established Monument FT_VALLEY_01

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) and fast static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized one existing monument and established one new monument for the Fort Valley, Arizona LiDAR project (Table 4, Figure 2). New monumentation was set using 5/8" x 30" rebar topped with stamped 2 ½ " aluminum caps. QSI's professional land surveyor, Nick Fusco (AZPLS# 24518) oversaw and certified the establishment of all monuments.

Table 4: Monuments utilized for the Fort Valley, Arizona acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
DN3658	35° 14' 59.65632"	-111° 44' 42.11499"	2214.104
FT_VALLEY_01	35° 16' 06.55112"	-111° 43' 19.84664"	2211.442

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

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[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.020 m

For the Fort Valley, Arizona LiDAR project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) and fast-static (FS) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R10 GNSS receiver. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines for post-processing. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 6 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 6: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R10	Integrated Antenna R10	TRMR10	Rover

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area. Combined land cover class accuracy was calculated to assess confidence in the LiDAR derived ground models across land cover class points. Land cover types and descriptions are shown in Table 7.

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description
Bare Earth	BE		Bare rock, sand, packed dirt, and/or clay
Evergreen Forest	EVER_FOR		Forested areas containing evergreen trees
Mixed Forest	MX_FOR		Forested areas containing a mix of deciduous and evergreen trees
Urban	URBAN		Parks, sidewalks, roads, and other recreational areas

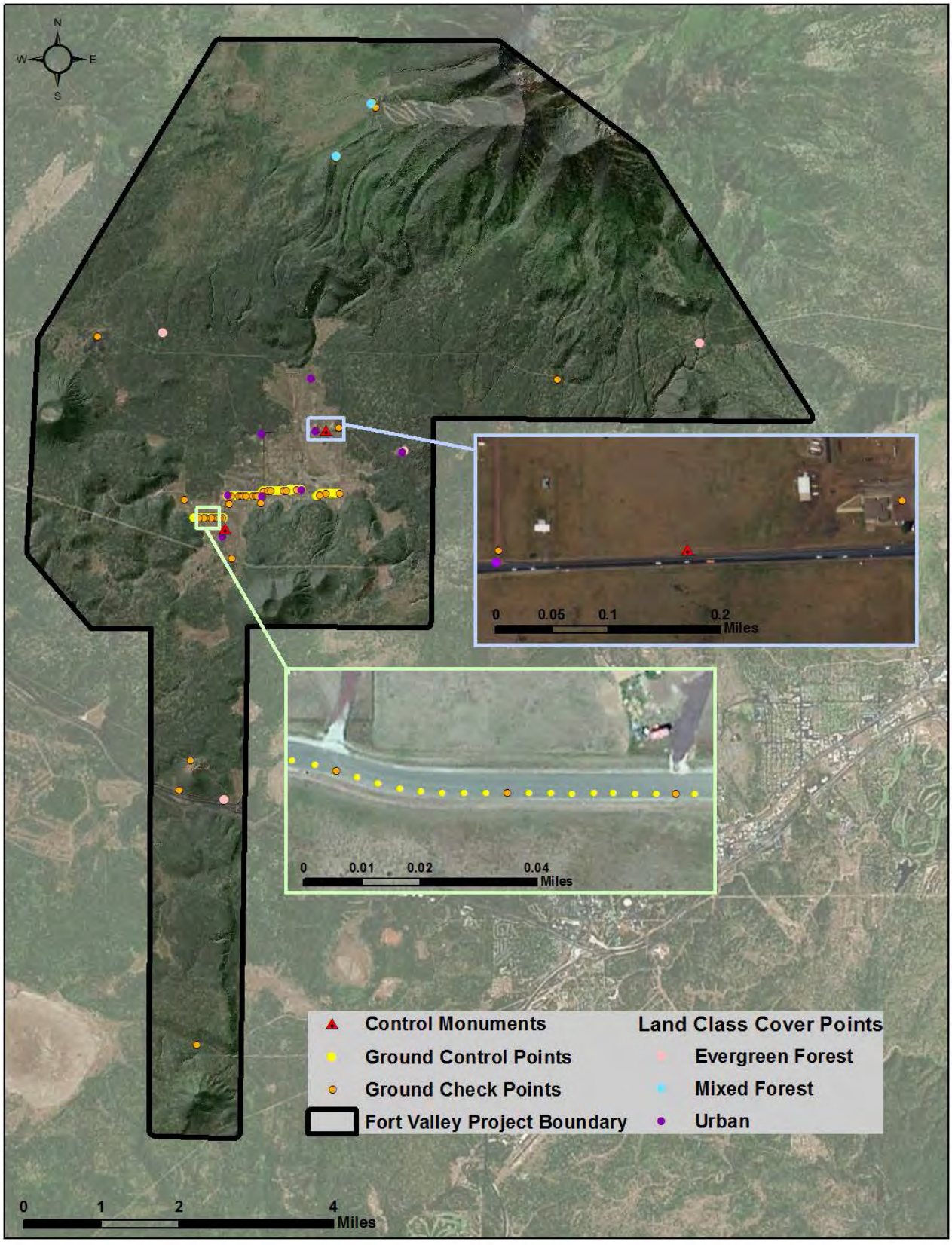
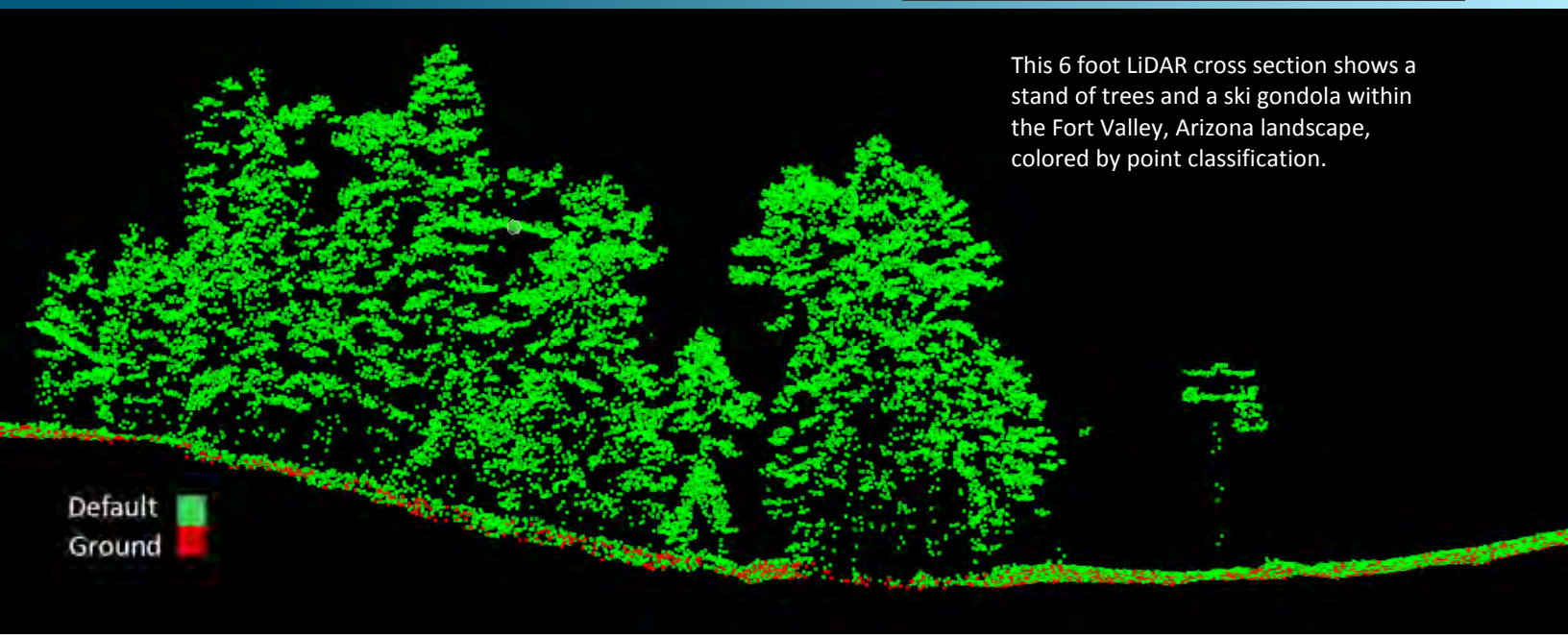


Figure 2: Ground survey location map of the Fort Valley, Arizona project area



This 6 foot LiDAR cross section shows a stand of trees and a ski gondola within the Fort Valley, Arizona landscape, colored by point classification.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Fort Valley, Arizona dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.6
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.16
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.16
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.16 TerraModeler v.16
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0 foot pixel resolution.	TerraScan v.16 TerraModeler v.156 ArcMap v. 10.2
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey 2.2.1SP2 (QSI proprietary) LAS Product Creator 1.5 (QSI proprietary) TerraScan v.16 TerraModeler v.16 ArcMap v. 10.2

Feature Extraction

Contours

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments.

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 3).

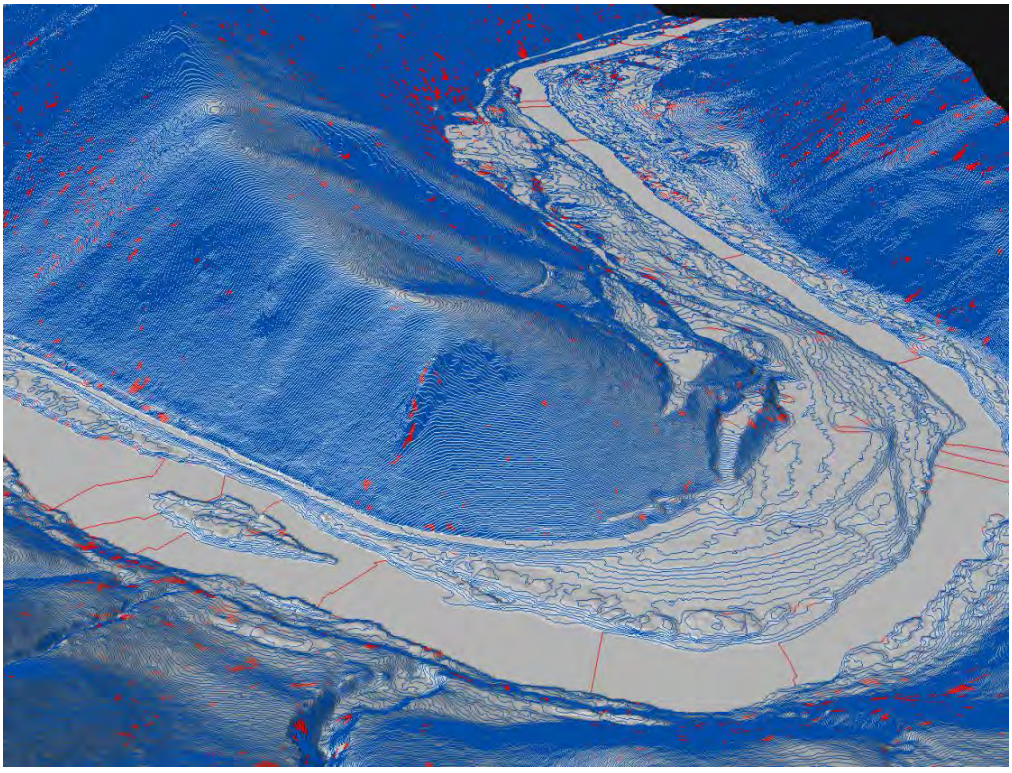
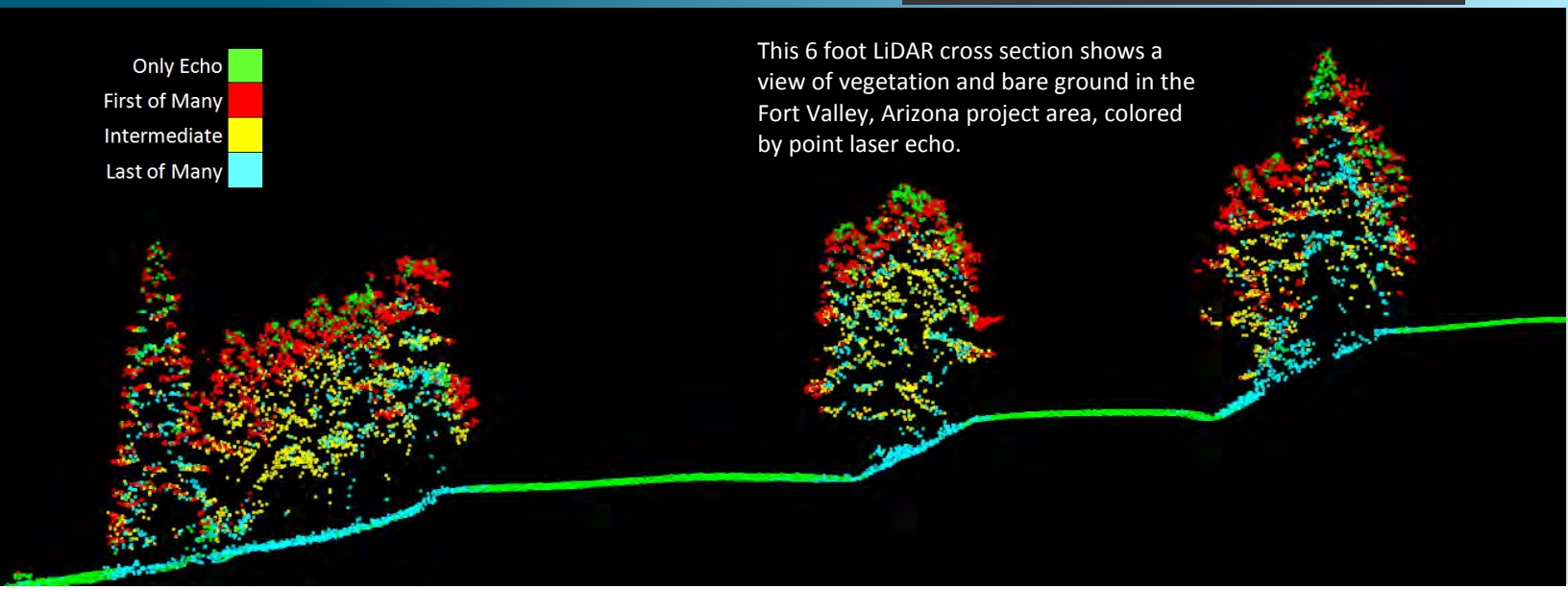


Figure 3: Example image of contours draped over the bare earth elevation model. Blue contours represent high confidence while the red contours represent low confidence.



This 6 foot LiDAR cross section shows a view of vegetation and bare ground in the Fort Valley, Arizona project area, colored by point laser echo.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of LiDAR data for the Fort Valley, Arizona project was 1.38 points/ft^2 (14.85 points/m^2) while the average ground classified density was 0.32 points/ft^2 (3.43 points/m^2) (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 4 through Figure 6.

Table 10: Average LiDAR point densities

Classification	Point Density
First-Return	1.38 points/ft^2 14.85 points/m^2
Ground Classified	0.32 points/ft^2 3.43 points/m^2

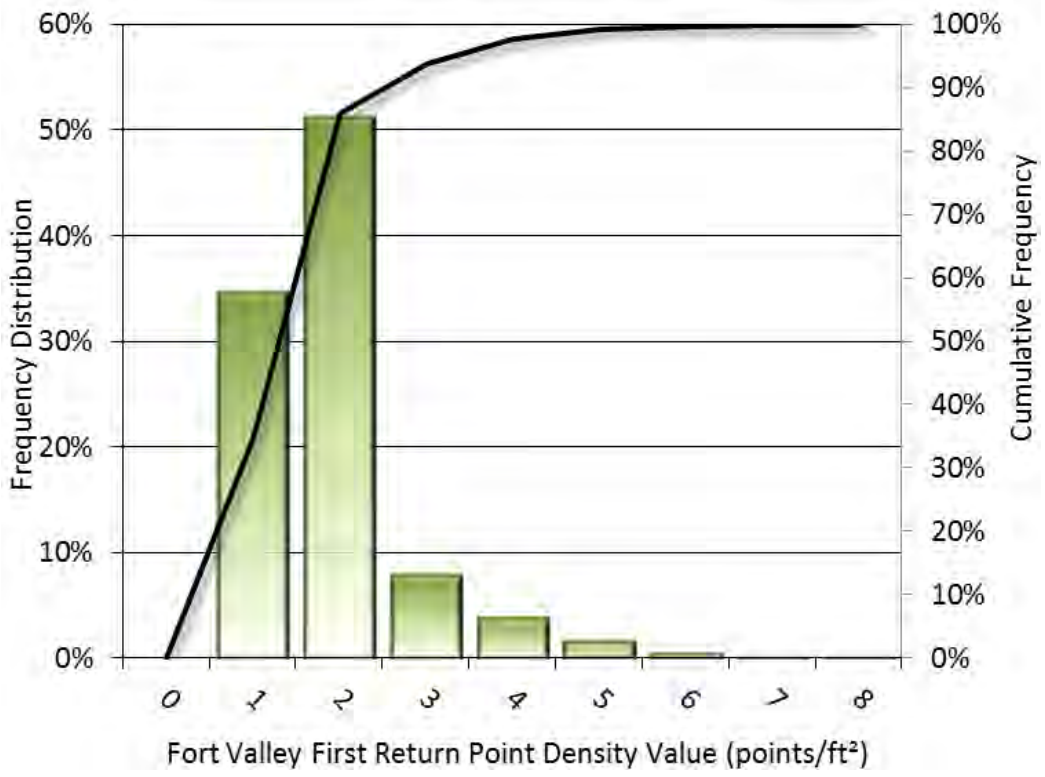


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

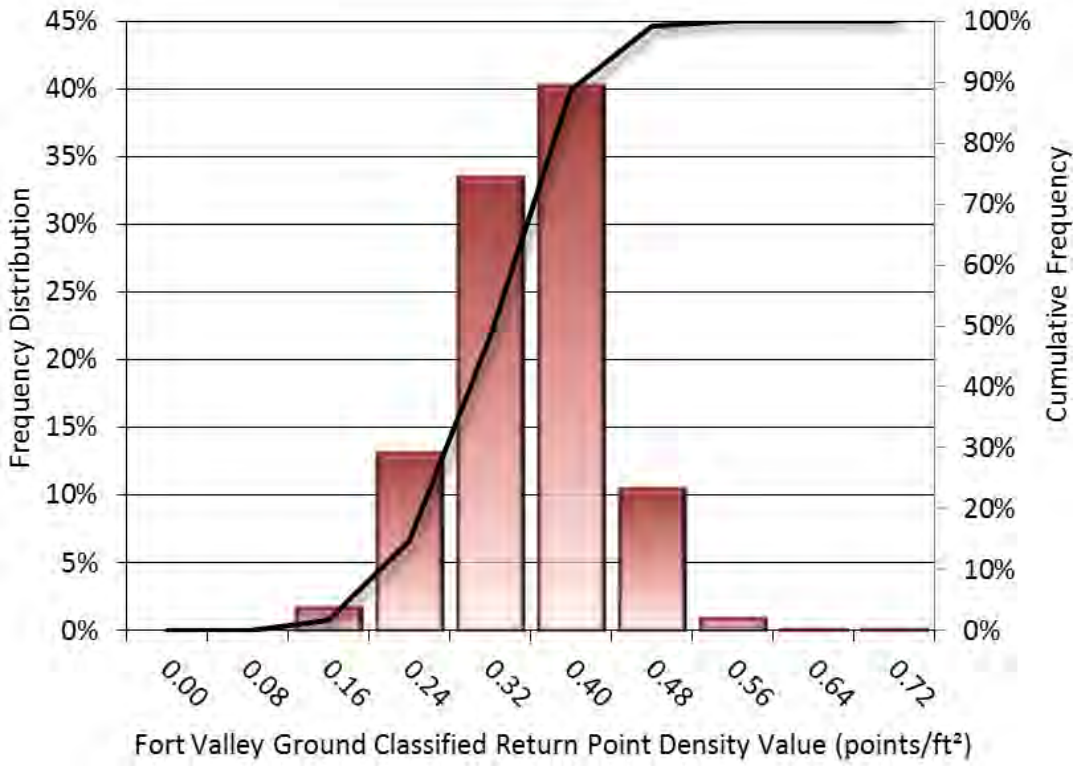


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

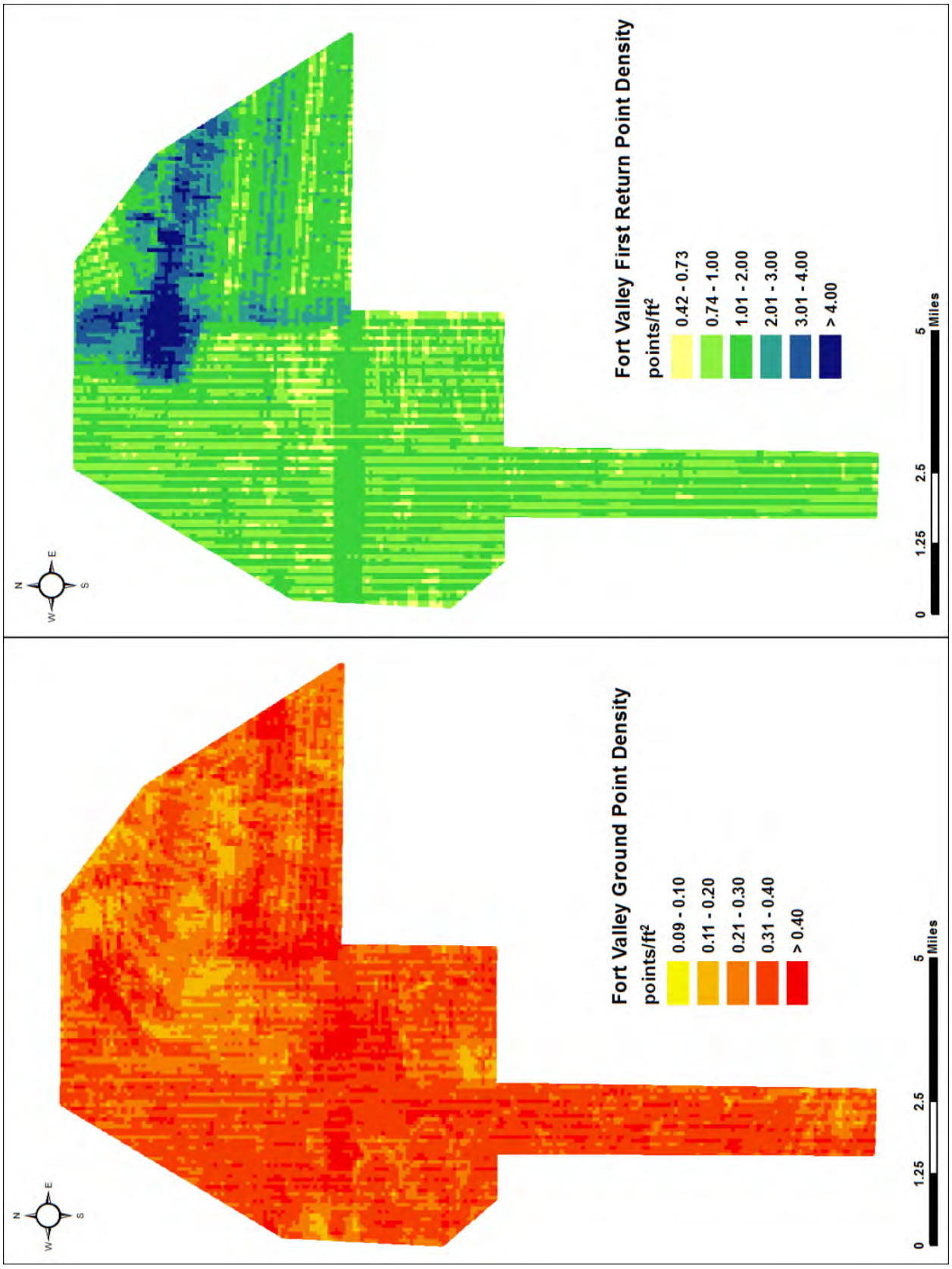


Figure 6: First return and ground-classified point density map for the Fort Valley, Arizona site (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Absolute Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. NVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Fort Valley, Arizona survey, 44 quality assurance points were withheld in total resulting in a non-vegetated vertical accuracy of -0.030 feet (-0.009 meters) (Figure 7).

QSI also assessed absolute accuracy using 388 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they may still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 11 and Figure 8.

Table 11: Absolute accuracy results

Absolute Accuracy		
	Quality Assurance Points (NVA)	**Ground Control Points**
Sample	44 points	388 points
NVA (1.96*RMSE)	0.157 ft 0.048 m	0.111 ft 0.034 m
Average	-0.030 ft -0.009 m	-0.025 ft -0.008 m
Median	-0.026 ft -0.008 m	-0.020 ft -0.006 m
RMSE	0.080 ft 0.024 m	0.056 ft 0.017 m
Standard Deviation (1σ)	0.075 ft 0.023 m	0.051 ft 0.015 m

[3] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

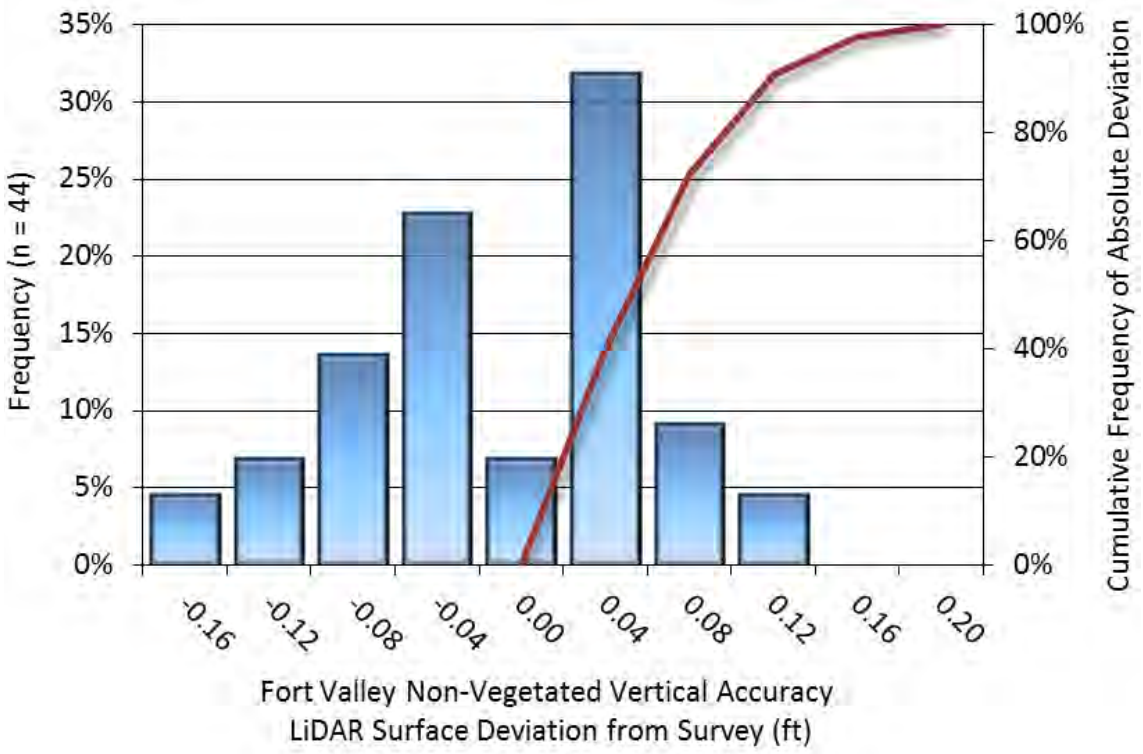


Figure 7: Frequency histogram for LiDAR surface deviation from quality assurance point values

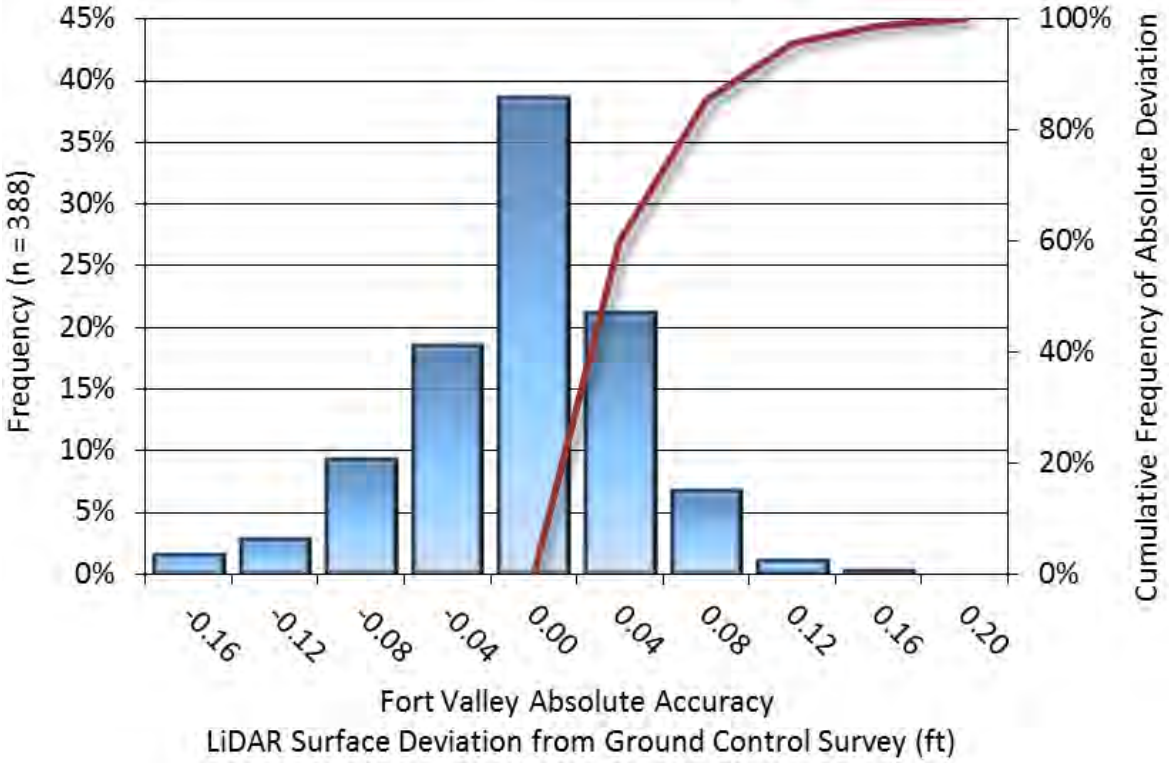


Figure 8: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground quality assurance point data collected in various landcover types to the triangulated ground surface generated by the ground classified LiDAR points. VVA is evaluated at the 95th percentile (Table 12, Figure 9).

Table 12: Vegetated Vertical Accuracy for the Fort Valley, Arizona Project

Vegetated Vertical Accuracy (VVA)	
Sample	14 points
Average Dz	-0.061 ft -0.019 m
Median	-0.080 ft -0.025 m
RMSE	0.133 ft 0.040 m
Standard Deviation (1σ)	0.128 ft 0.039 m
95th Percentile	0.239 ft 0.073 m

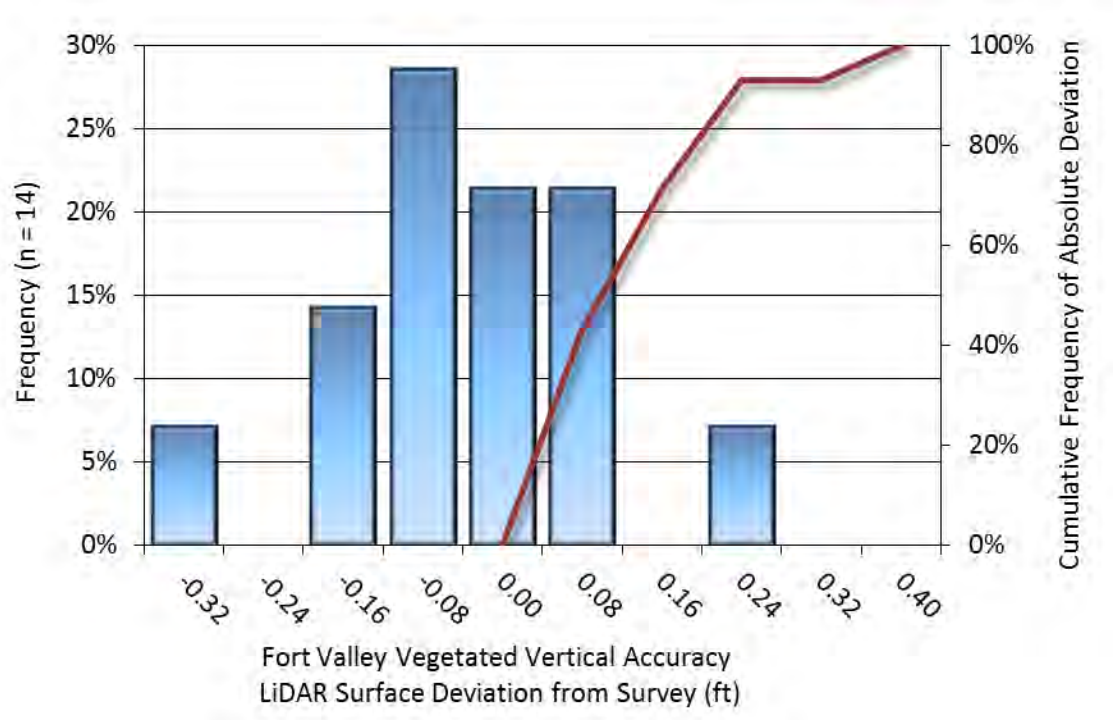


Figure 9: Frequency histogram for LiDAR surface deviation from all vegetated and urban land cover class point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Fort Valley, Arizona LiDAR project was 0.123 feet (0.038 meters) (Table 13, Figure 10).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	87 surfaces
Average	0.123 ft 0.038 m
Median	0.126 ft 0.038 m
RMSE	0.149 ft 0.045 m
Standard Deviation (1σ)	0.045 ft 0.014 m
1.96σ	0.088 ft 0.027 m

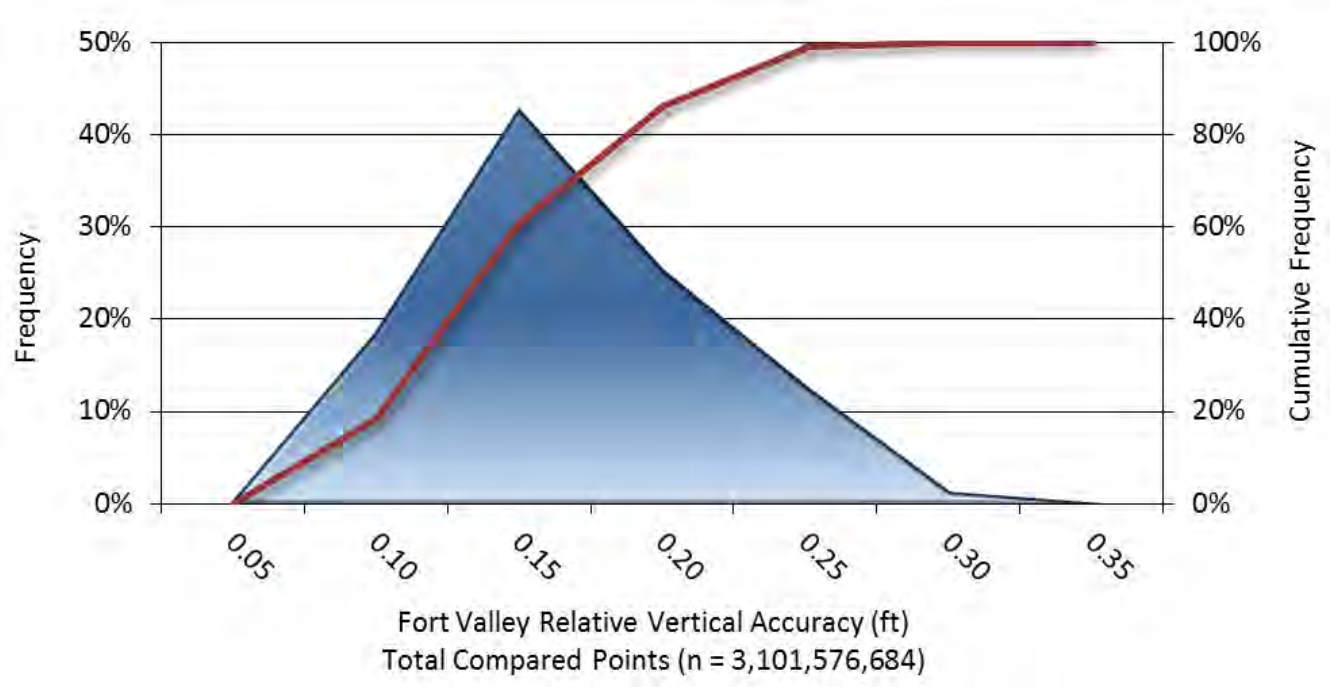


Figure 10: Frequency plot for relative vertical accuracy between flight lines

Surveyor's Certificate

I, Nickolas R. Fusco, being a Professional Land Surveyor in the State of Arizona, hereby certify to the best of my professional knowledge and belief that the survey methodologies and results, outline in the report titled "Fort Valley, Arizona LiDAR; Technical Data Report", dated November 3, 2016, were performed and obtained utilizing commonly acceptable survey standards, practices and procedures. The field survey portion of this project was accomplished between September 16 2016 and September 17, 2016; Aerial LiDAR was collected between September 16, 2016 and September 17, 2016.

I have reviewed the accuracy statements as part of my oversight and found them to meet the National Standards for Spatial Accuracy (NSSDA) shown.

Signed November 3, 2016

Nickolas R. Fusco
Professional Land Surveyor Number 24518

Expires 12/31/2017

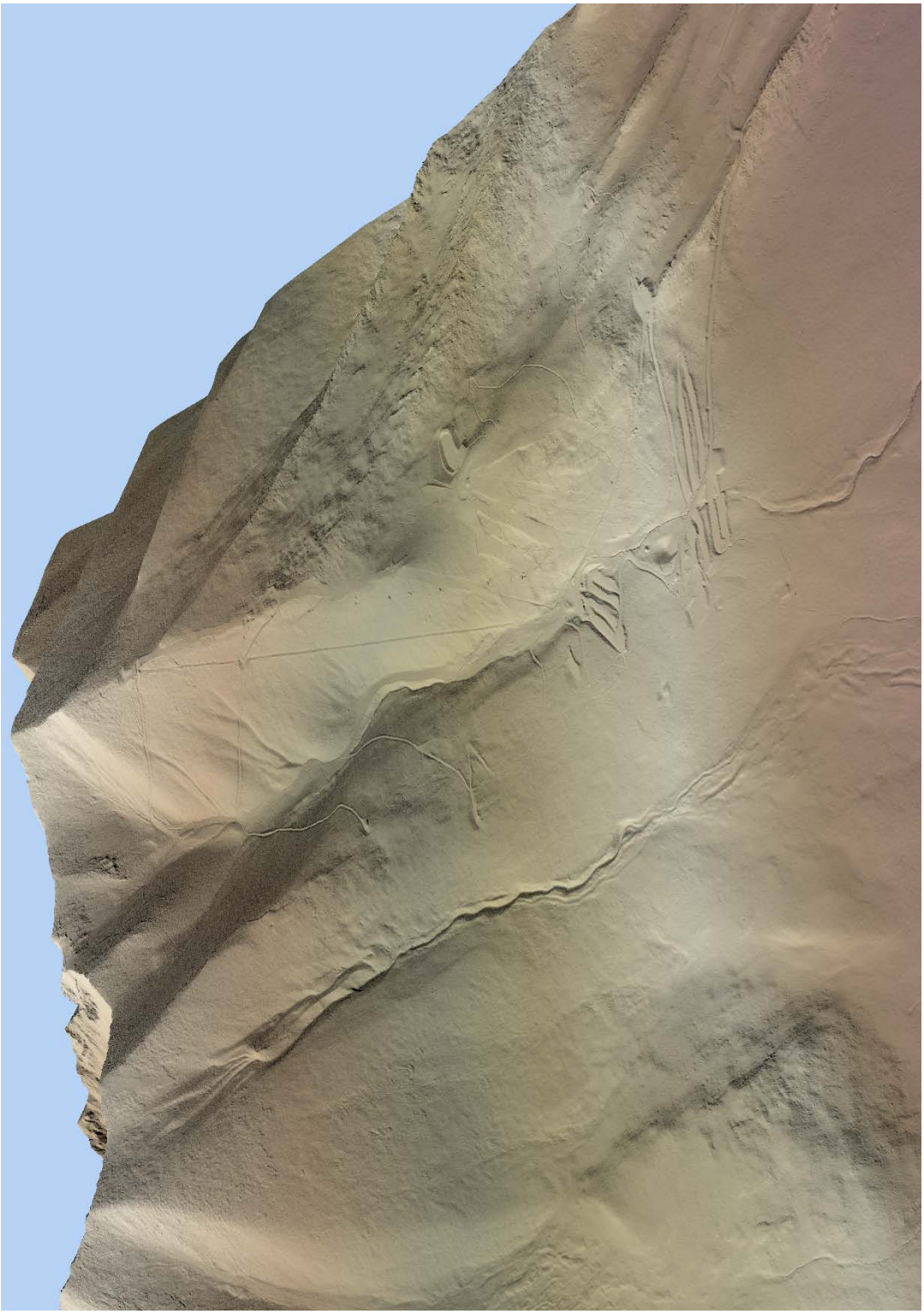


Figure 11: View looking east over the Arizona Snowbowl area on the east side of Agassiz Peak in Fort Valley, Arizona. The image was created from the LiDAR bare earth model overlaid with the above-ground point cloud.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-Vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echos) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±15° from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

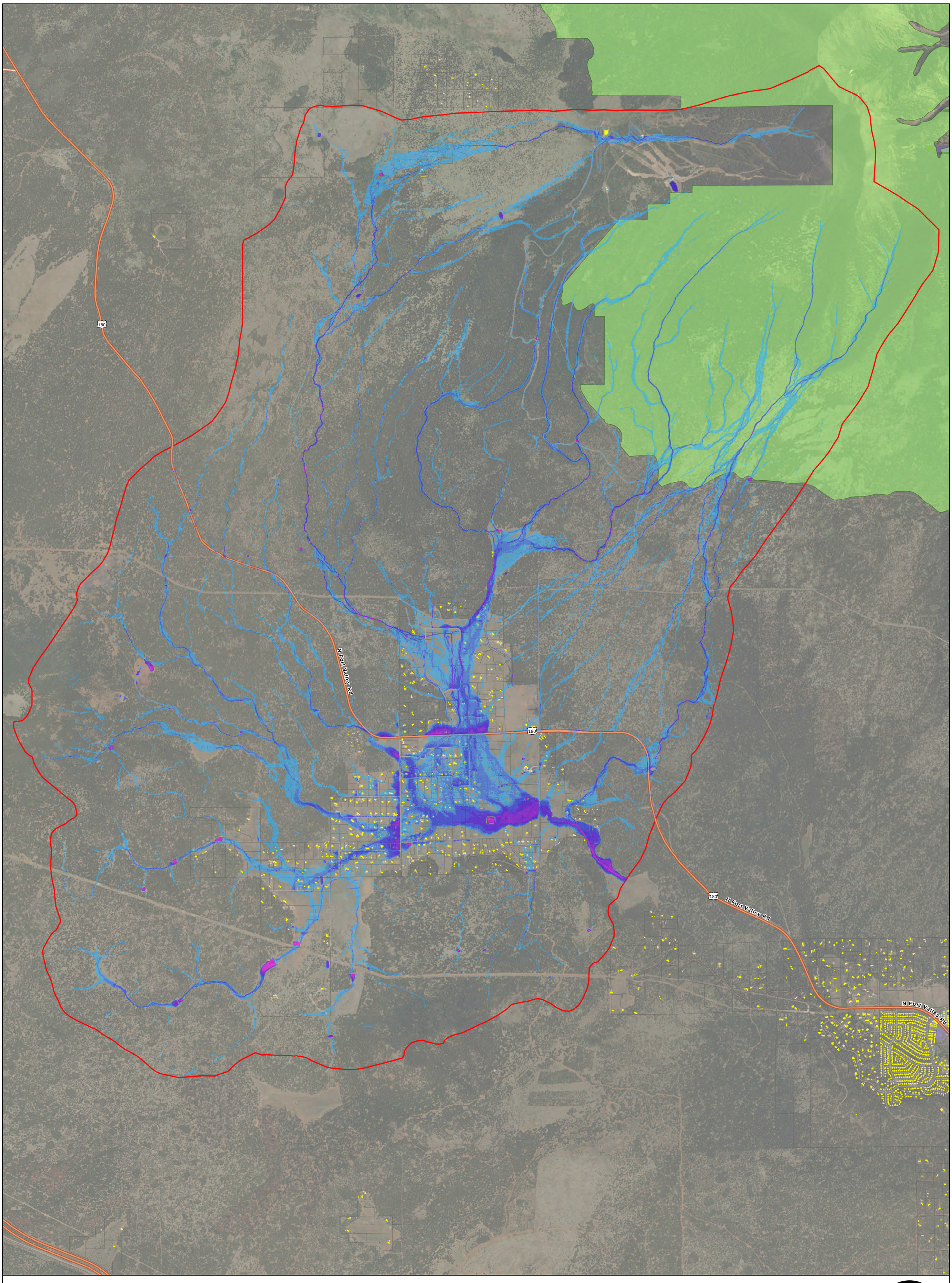
Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

APPENDIX B –FLOOD DEPTH MAPS



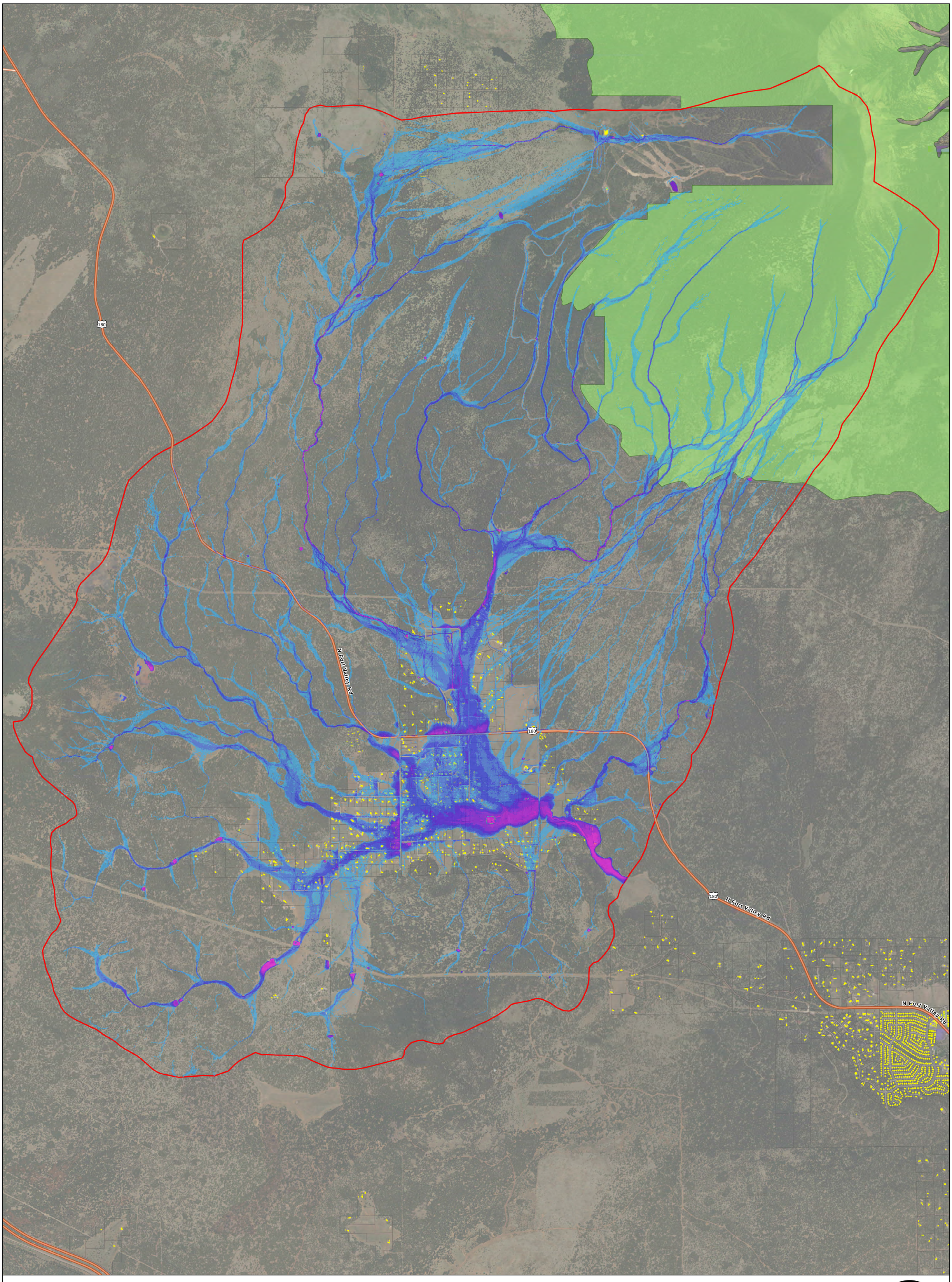
Post-Fire Non-Treated 2-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



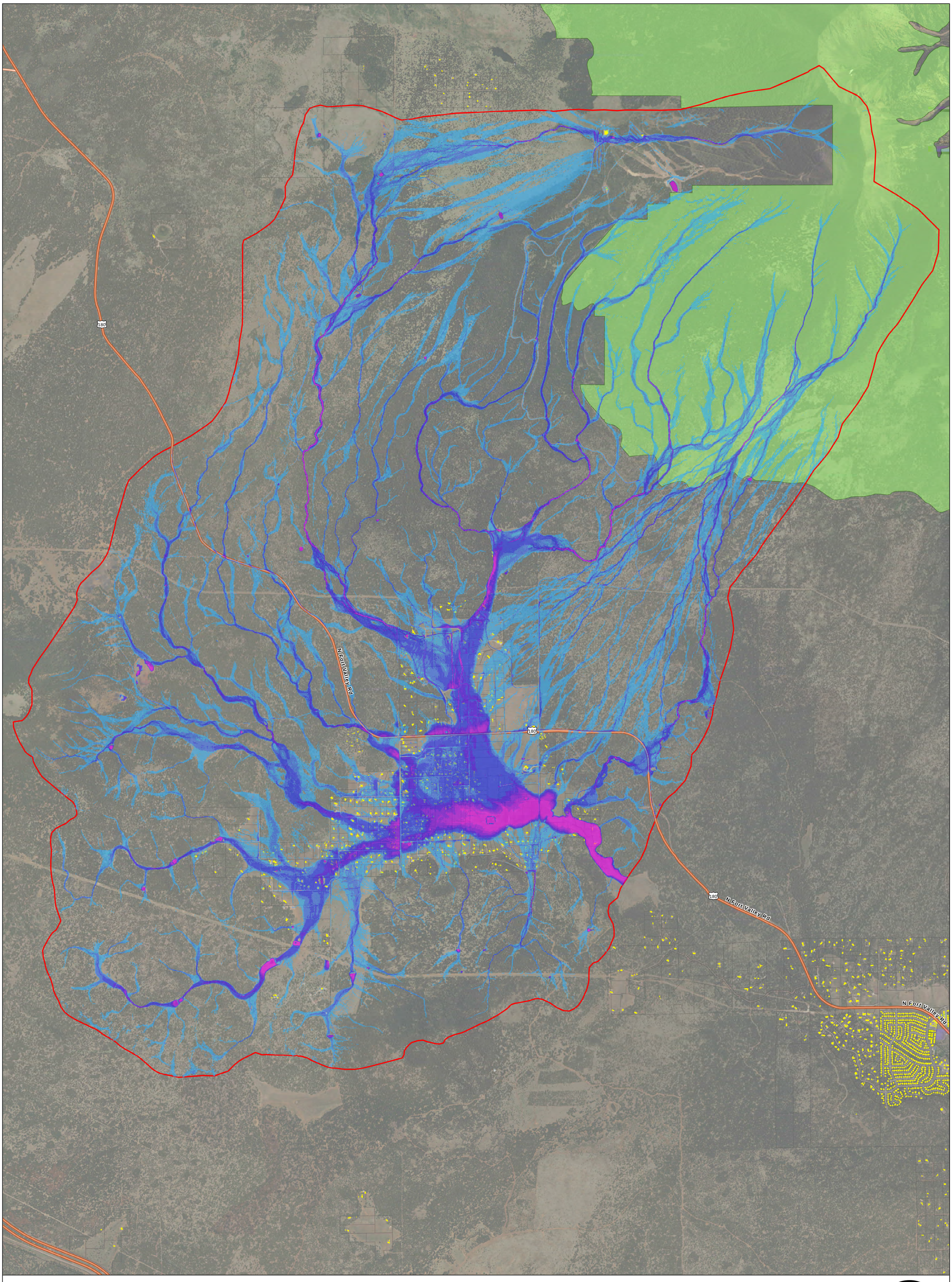
Post-Fire Non-Treated 10-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



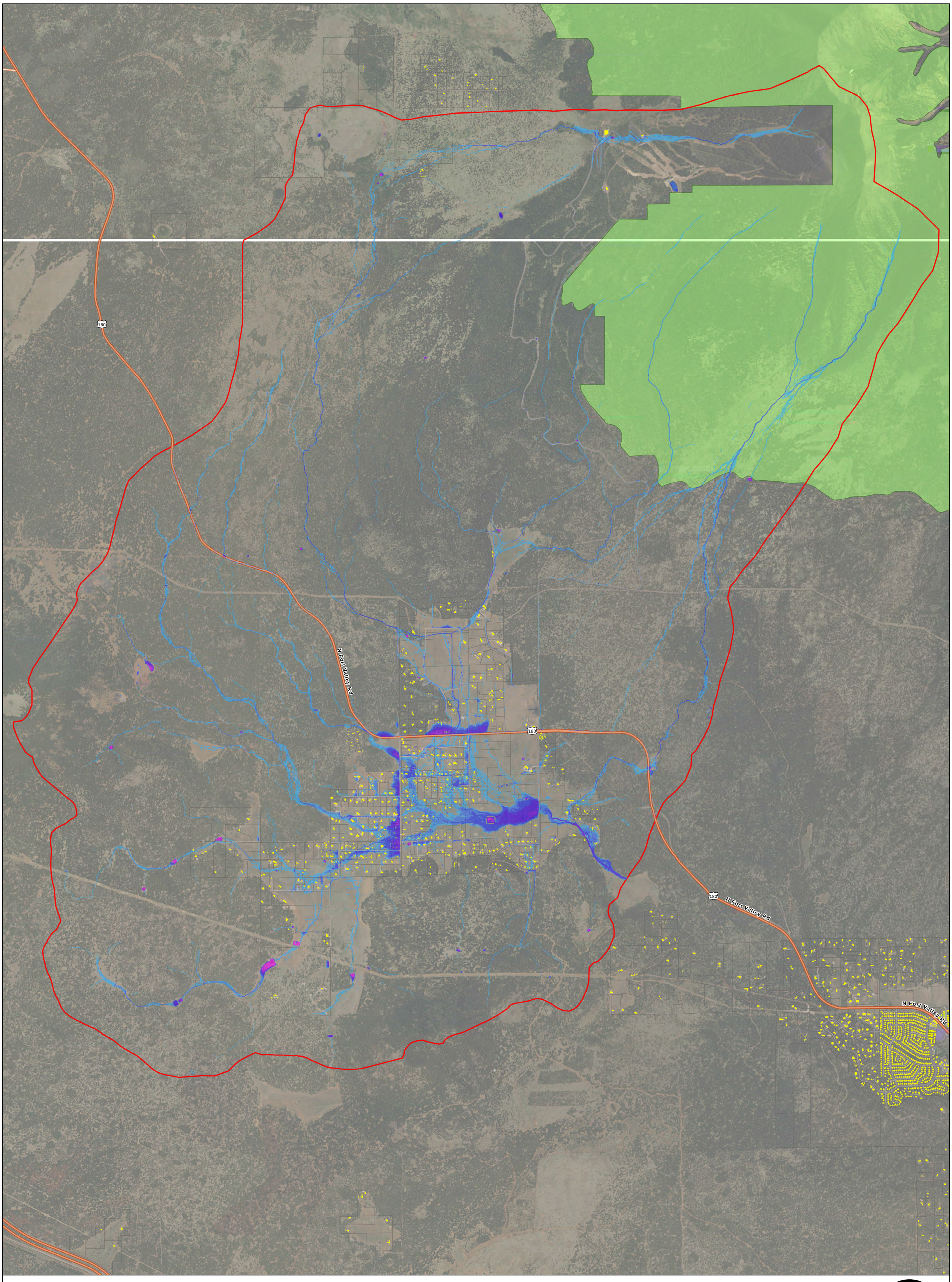
Post-Fire Non-Treated 100-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



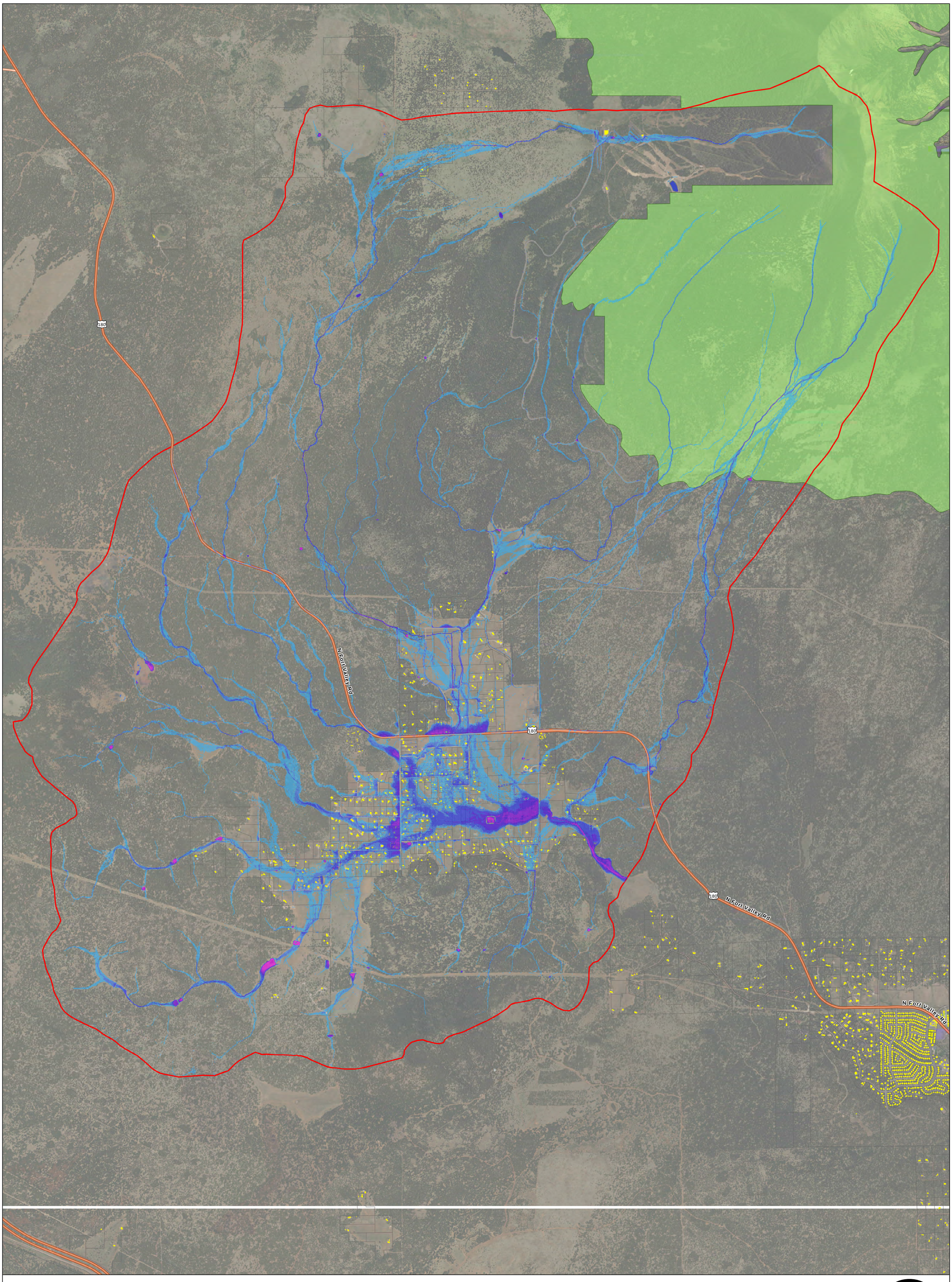
Post-Fire Treated 2-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



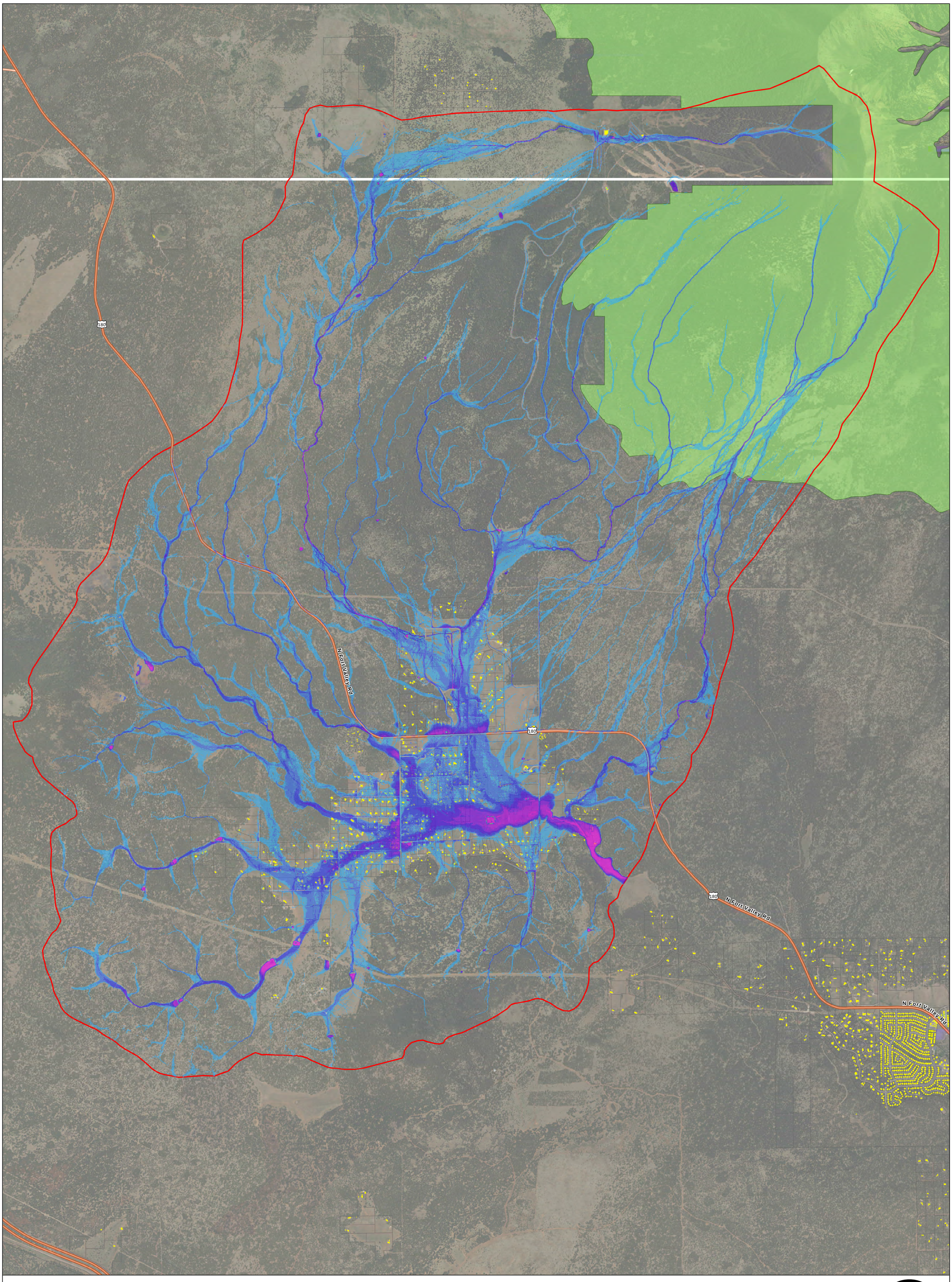
Post-Fire Treated 10-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



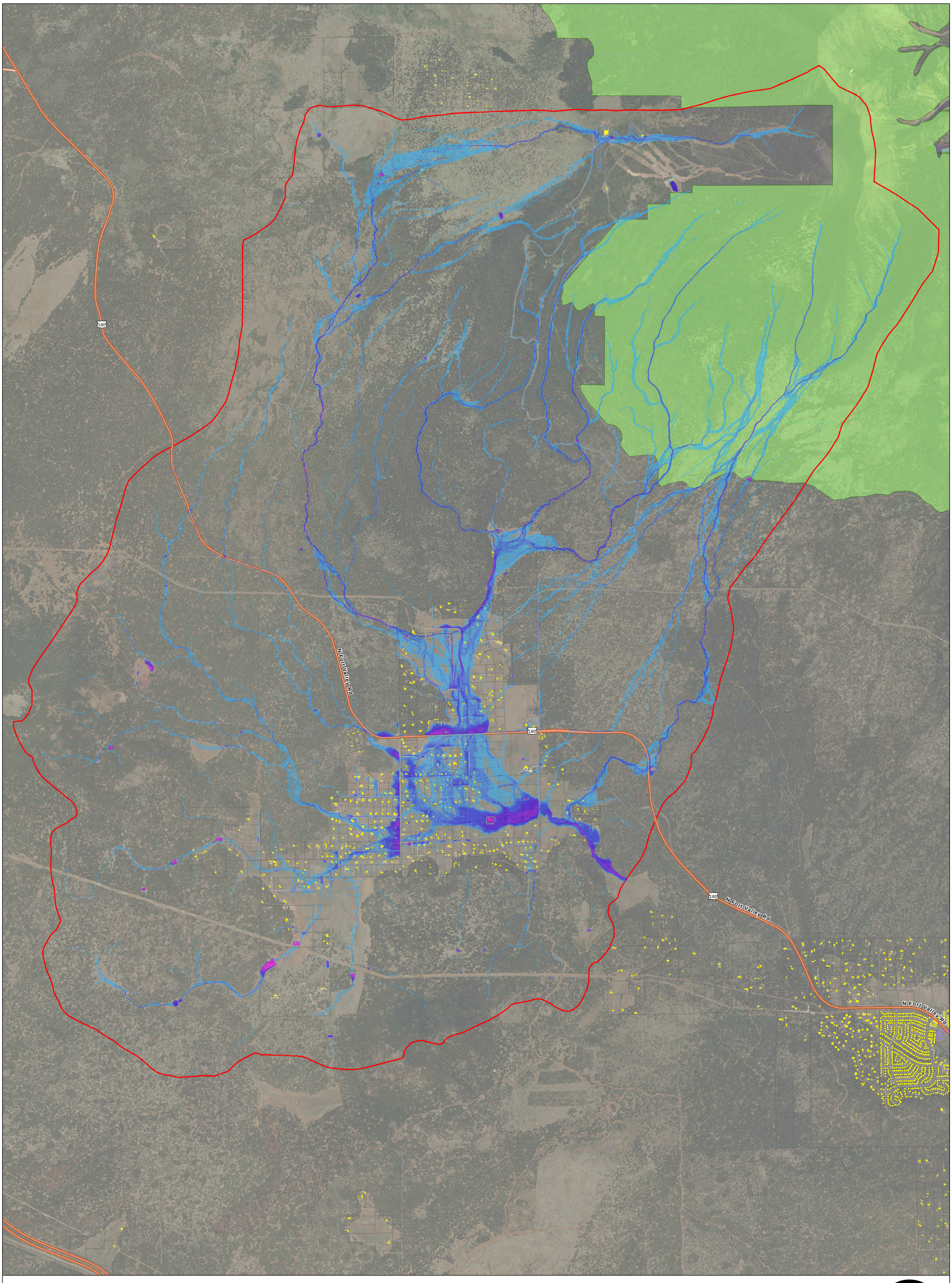
Post-Fire Treated 100-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



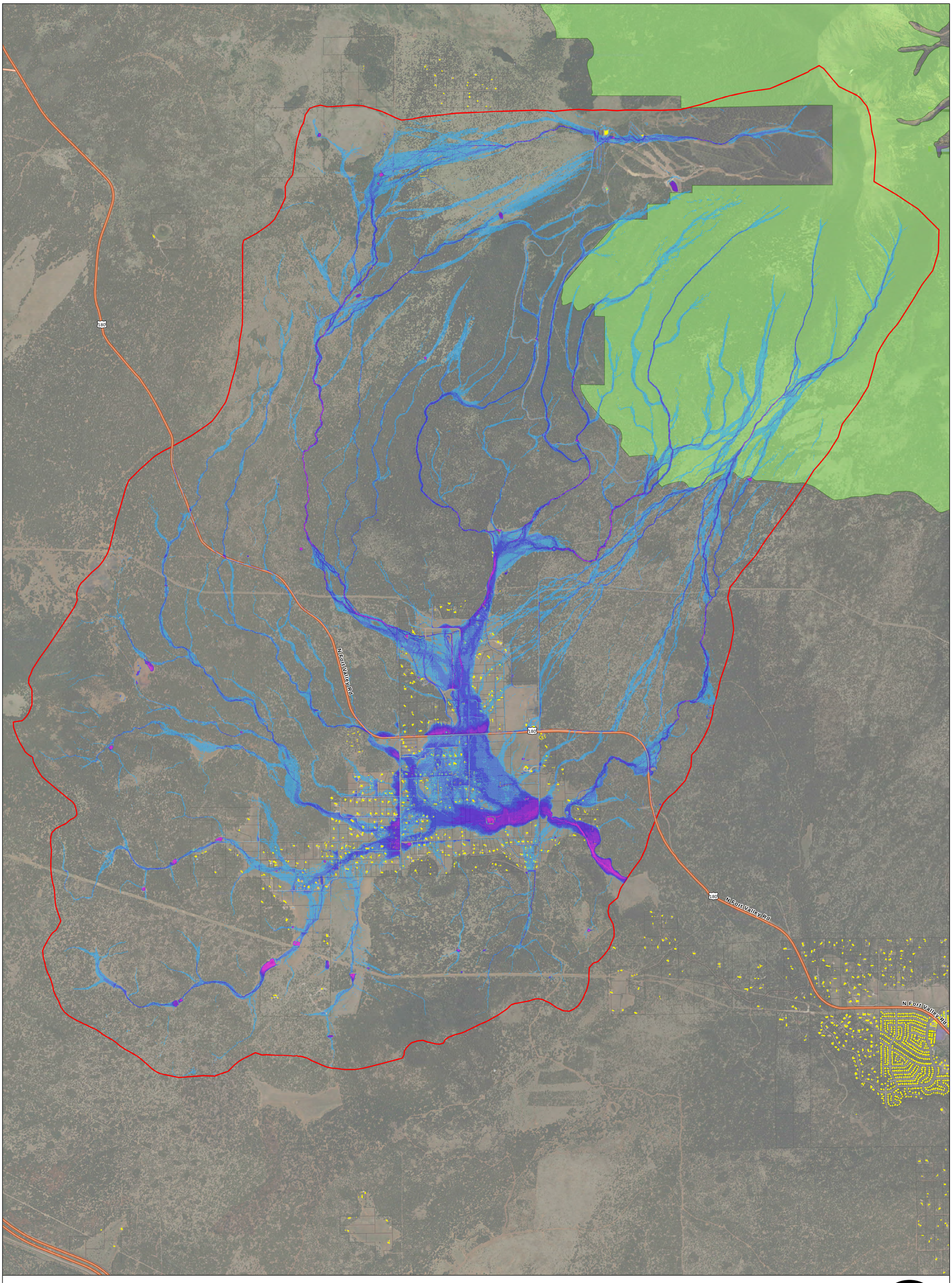
Post-Fire Treated (except Wilderness Area)
2-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



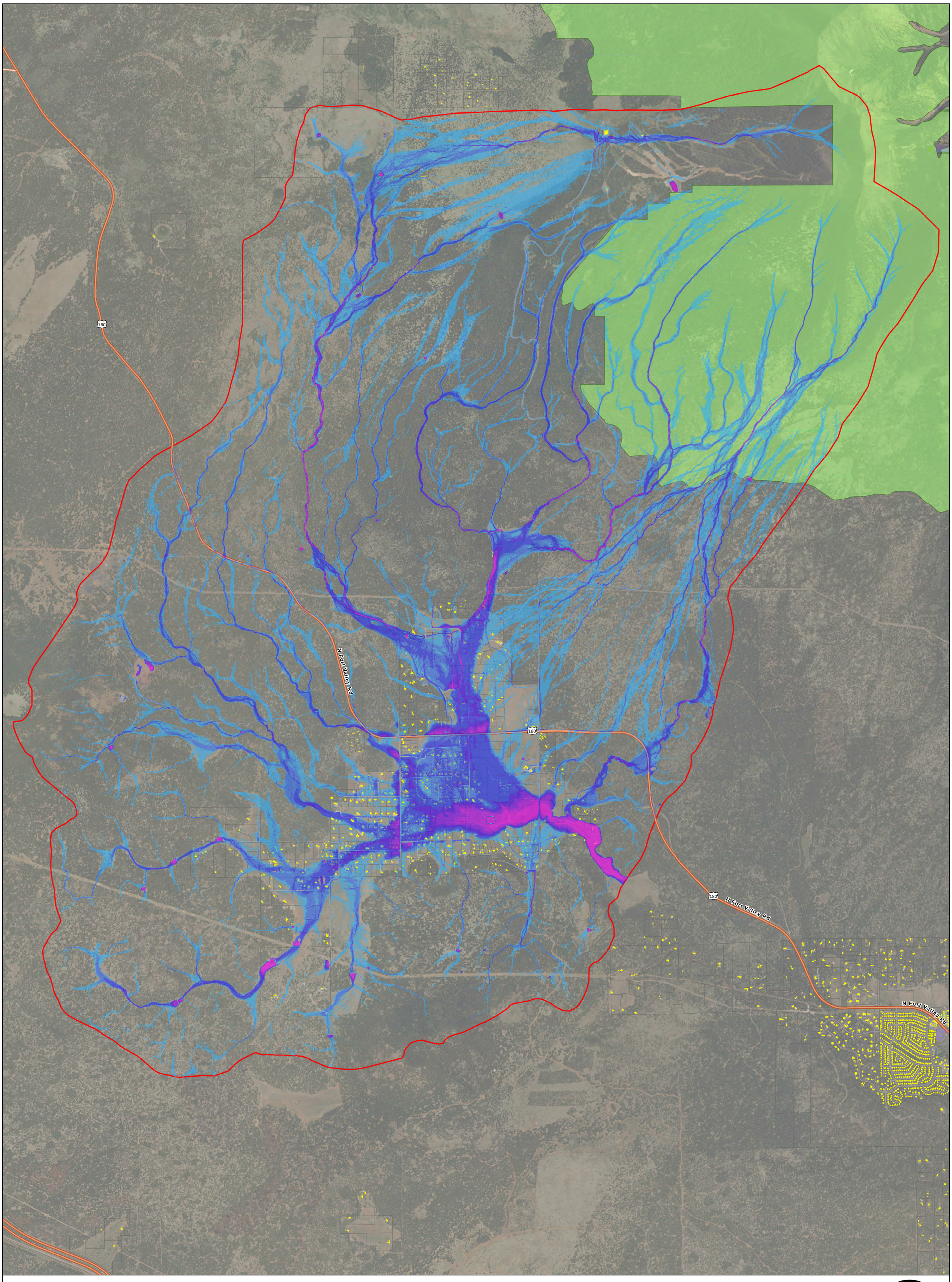
Post-Fire Treated (except Wilderness Area)
10-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



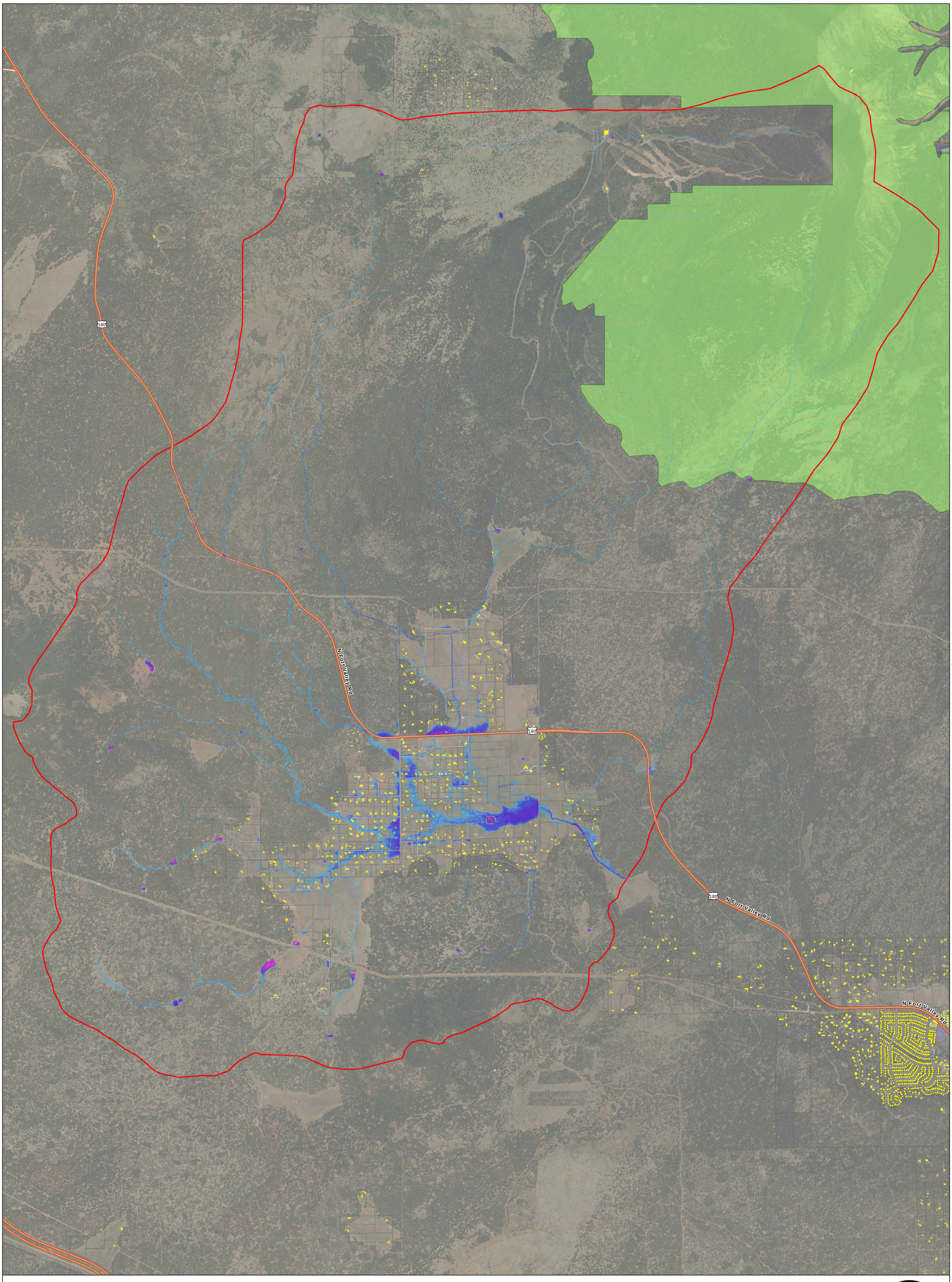
Post-Fire Treated (except Wilderness Area)
100-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



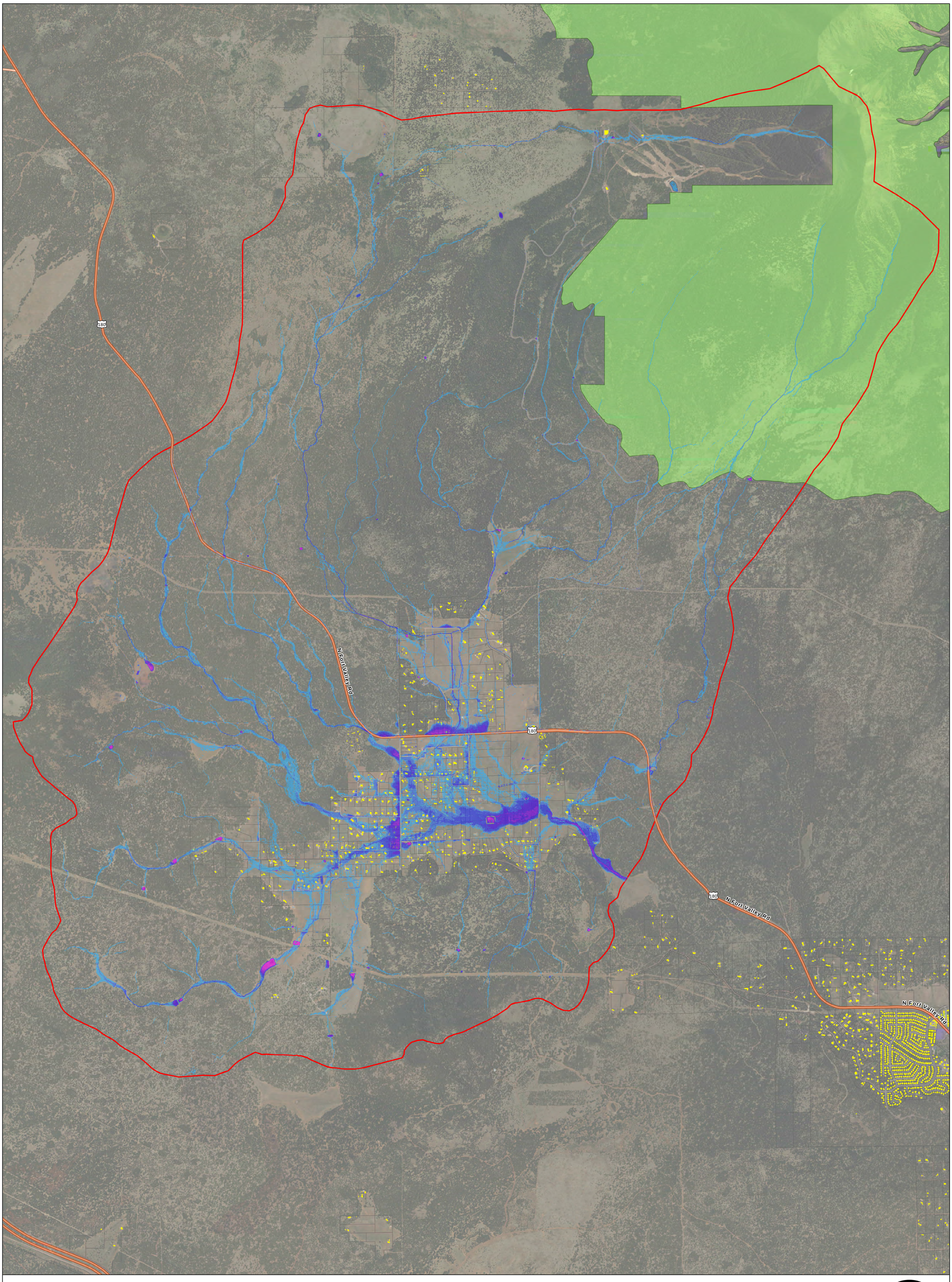
Pre-Fire 2-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



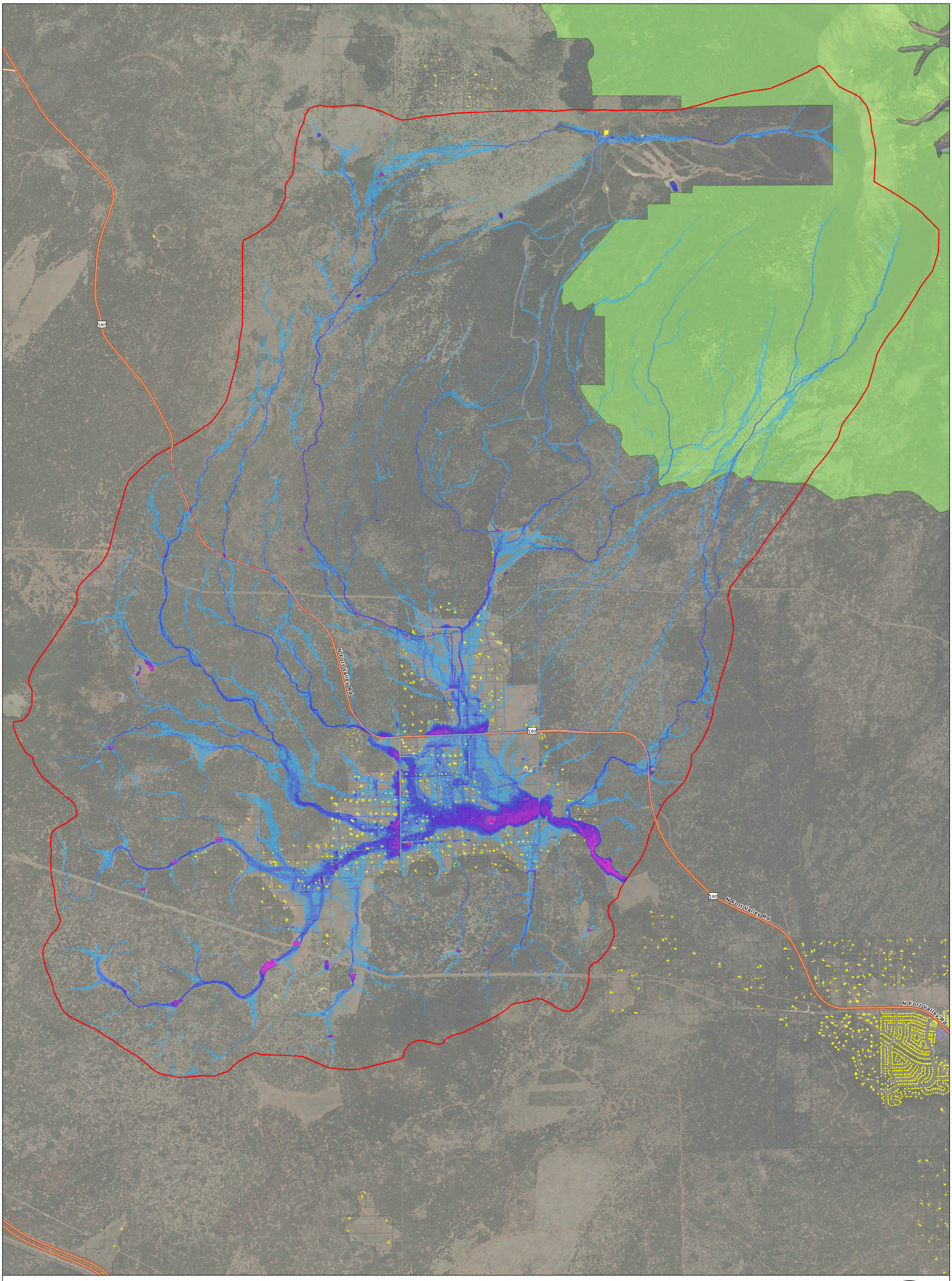
Pre-Fire 10-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



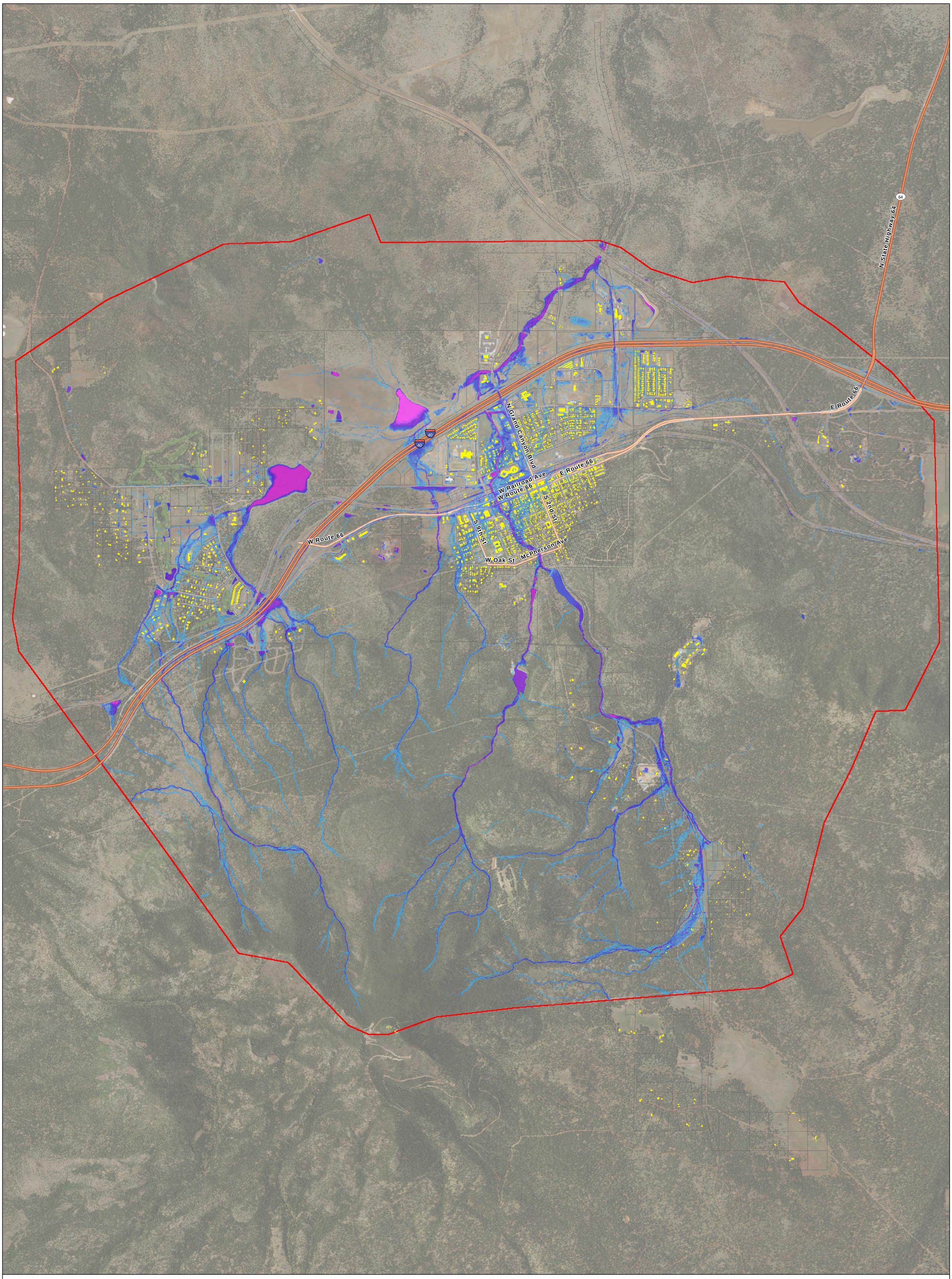
Pre-Fire 100-Year Max Depth (feet)

<0.2	2.0 - 3.0	FLO-2D Domain
0.2 - 0.5	3.0 - 4.0	Buildings
0.5 - 1.0	4.0 - 5.0	Wilderness Area
1.0 - 2.0	>5.0	Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



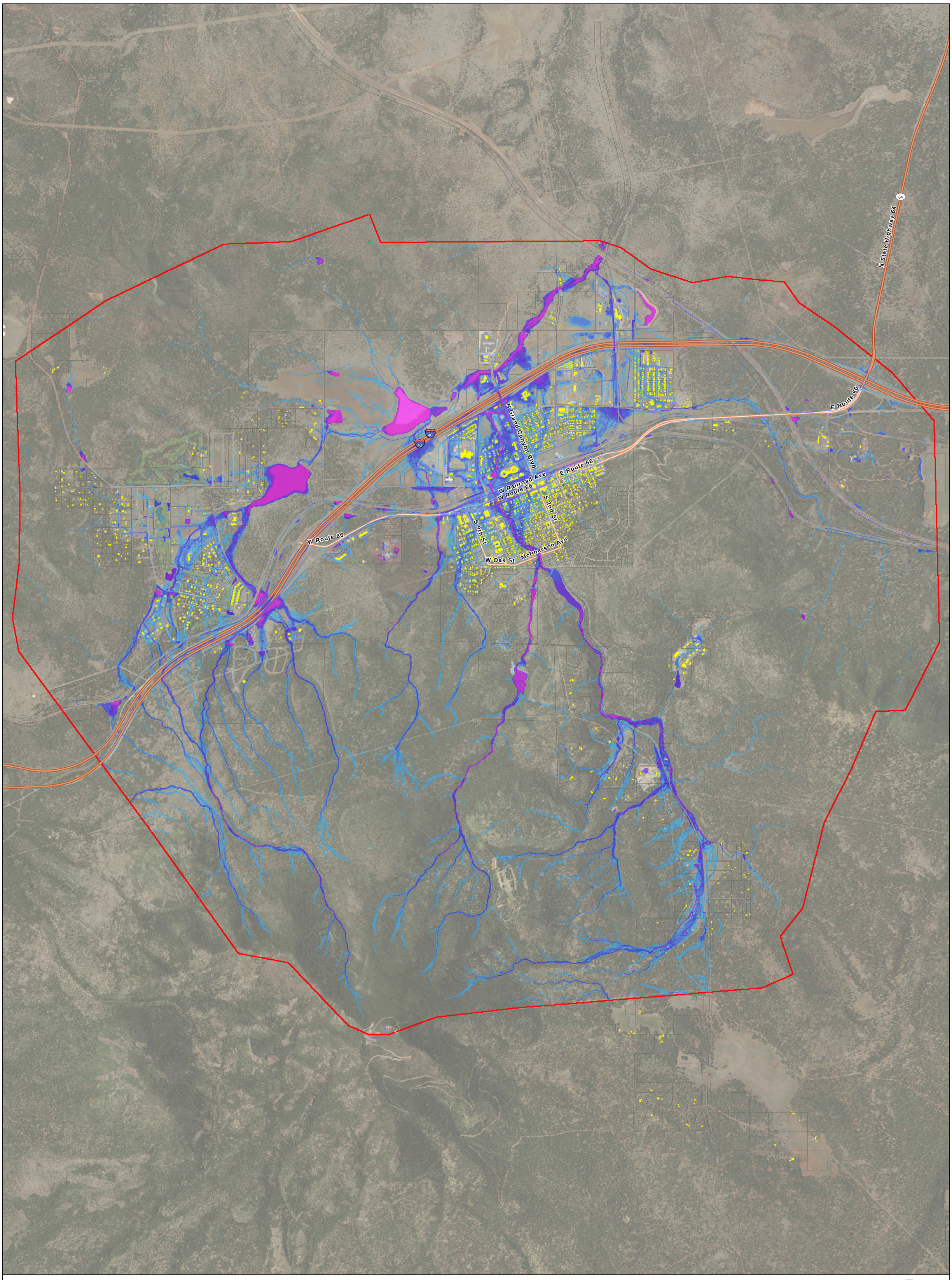
Post-Fire Non-Treated 2-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



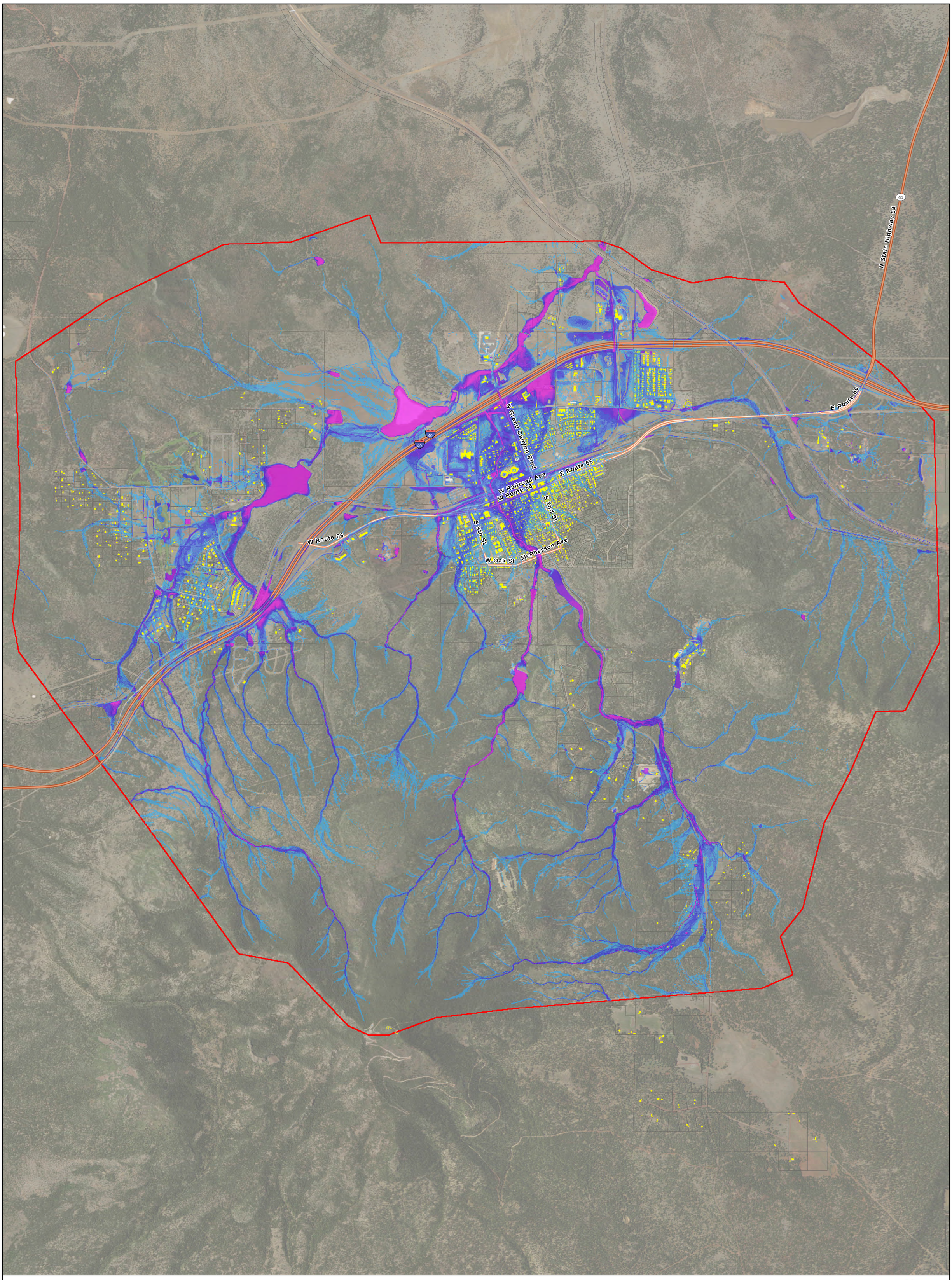
Post-Fire Non-Treated 10-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



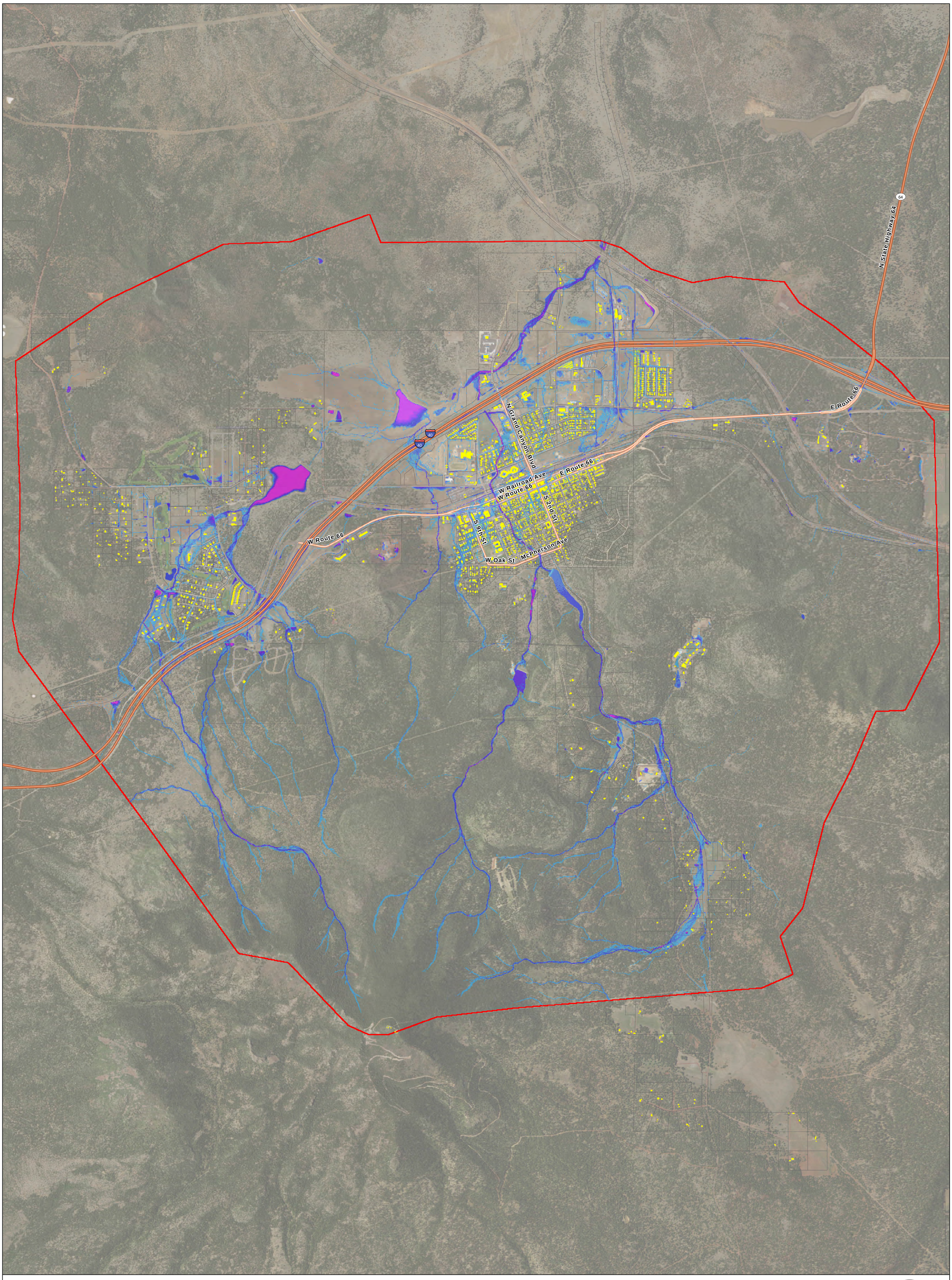
Post-Fire Non-Treated 100-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



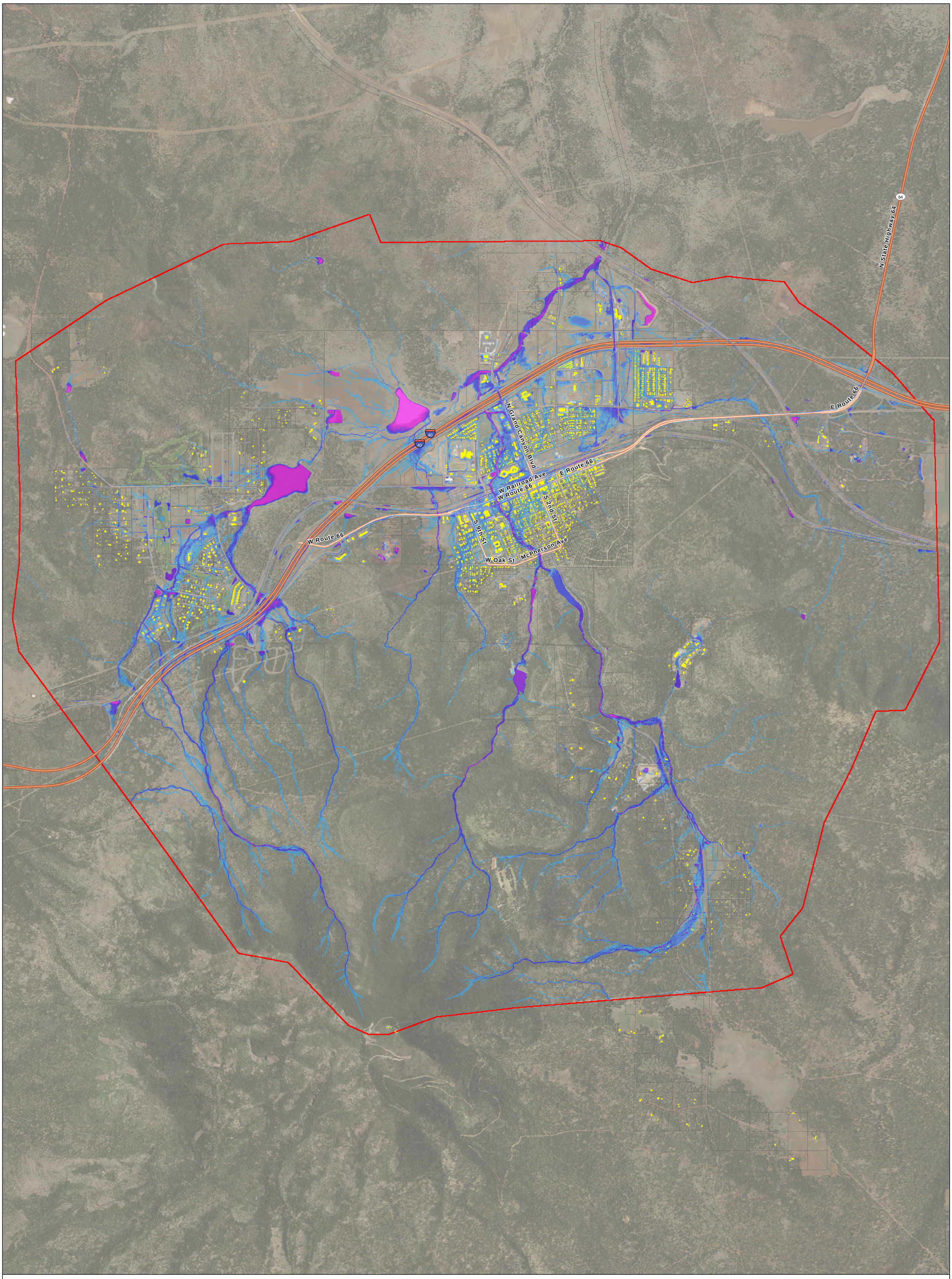
Post-Fire Treated 2-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



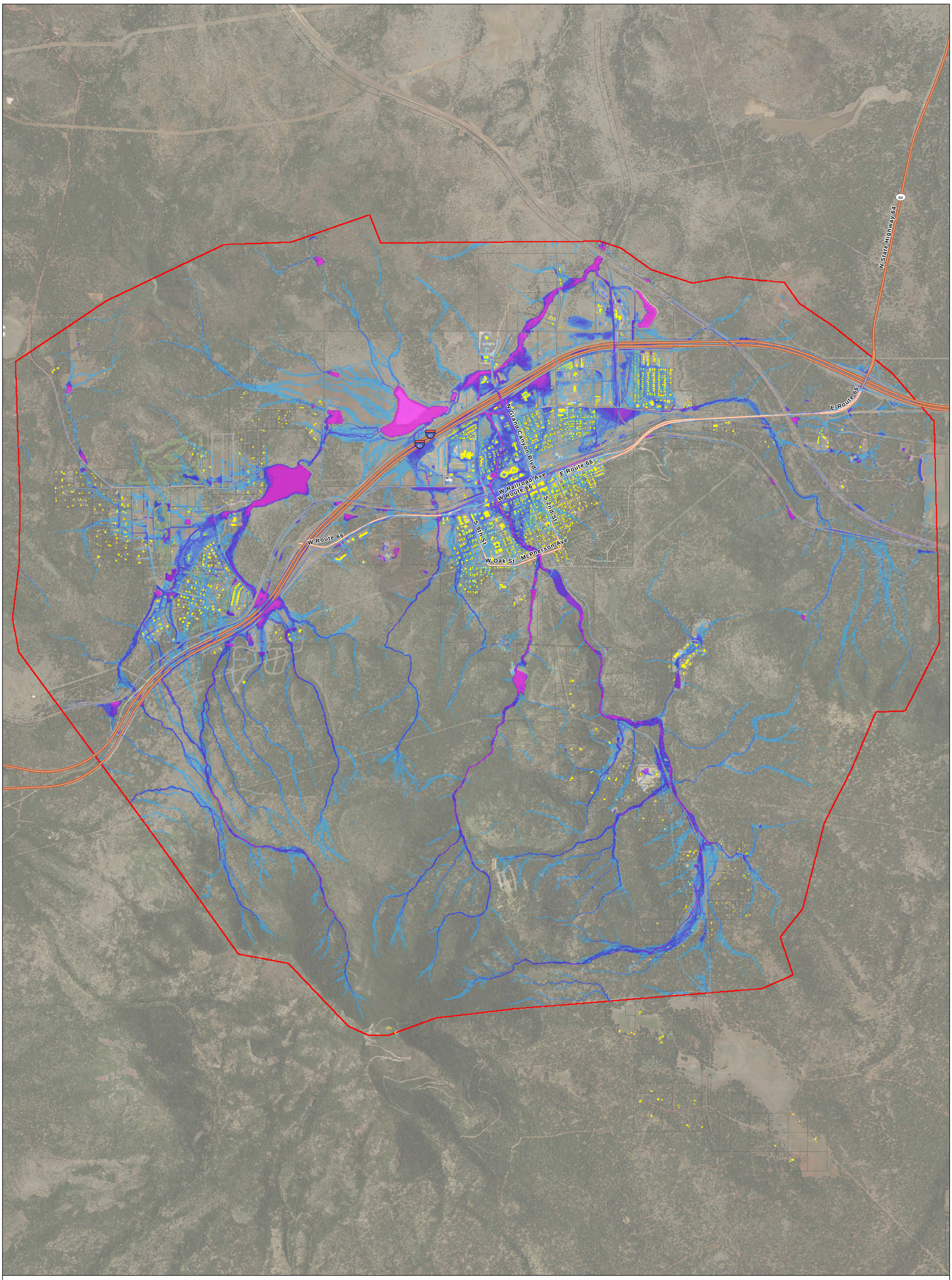
Post-Fire Treaated 10-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



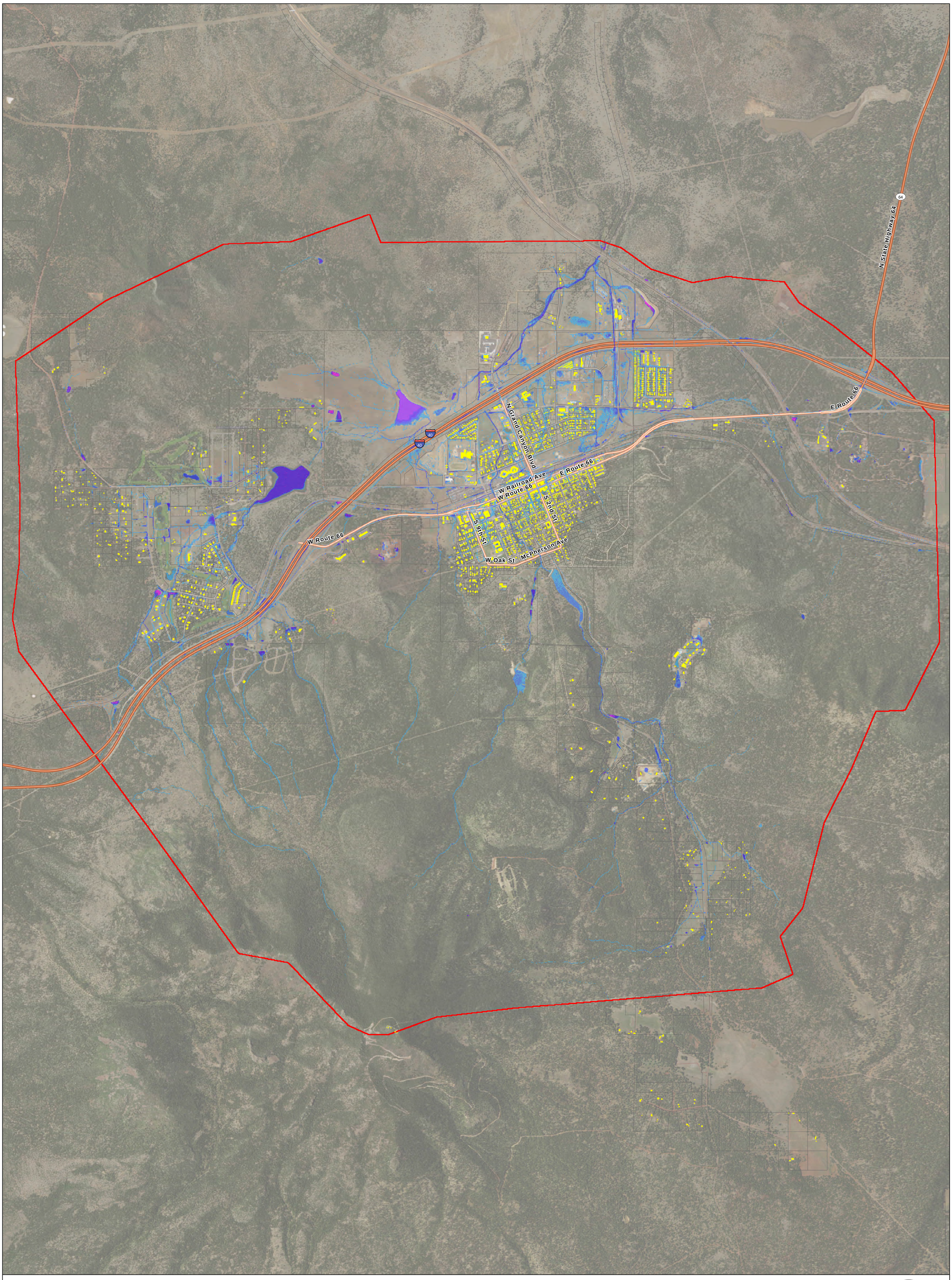
Post-Fire Treated 100-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



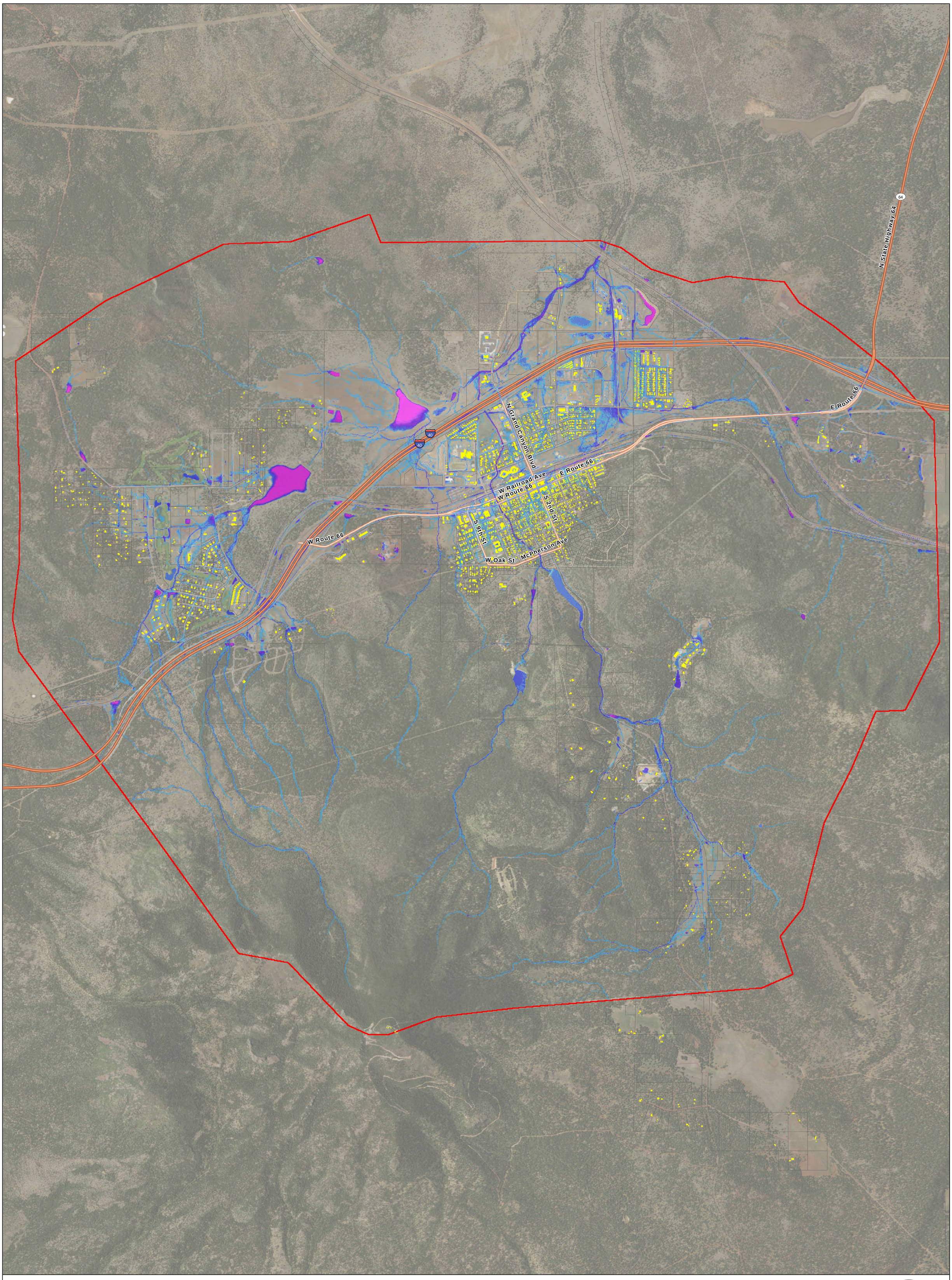
Pre-Fire 2-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



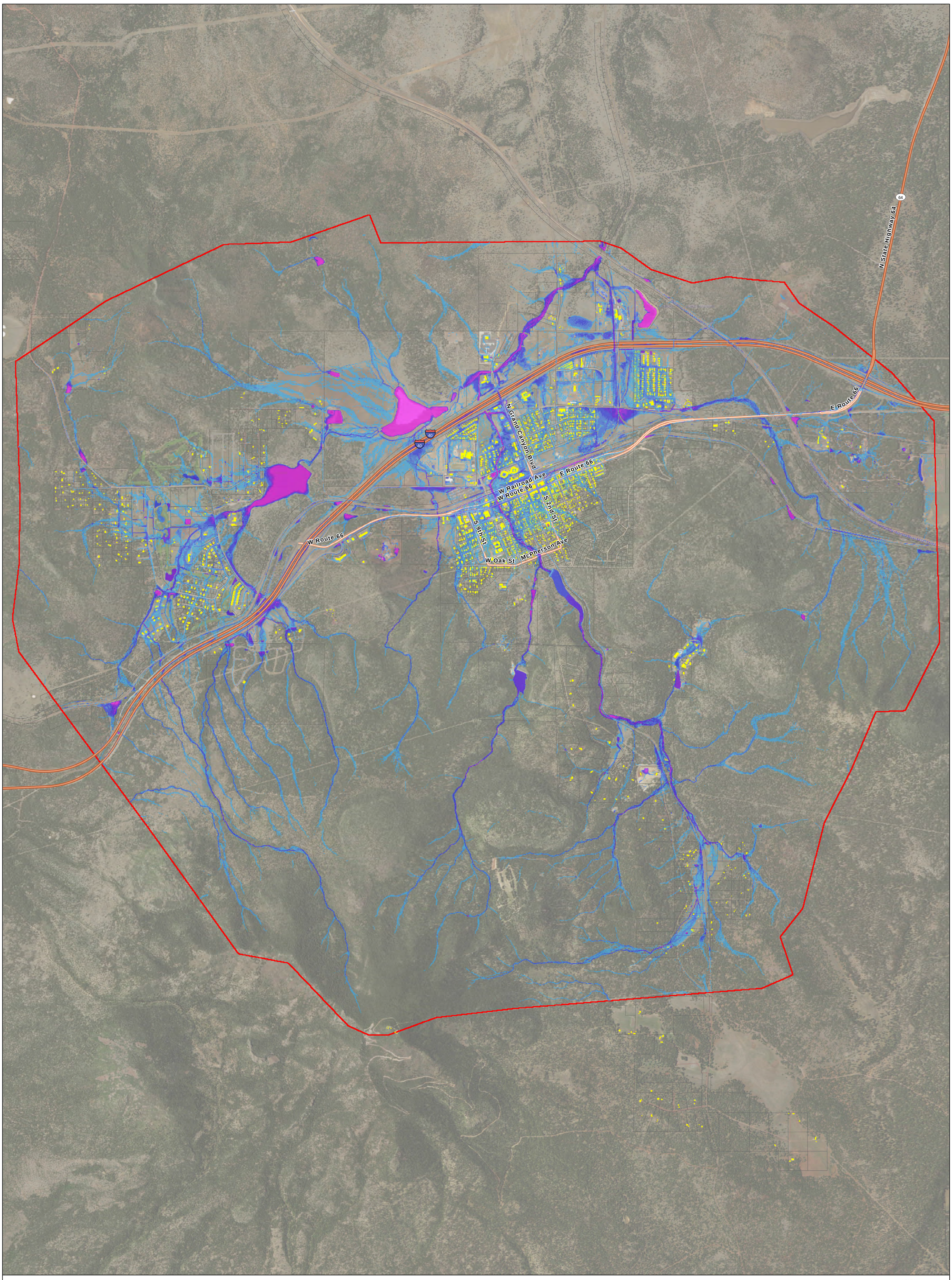
Pre-Fire 10-Year Max Depth (feet)

- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



Pre-Fire 100-Year Max Depth (feet)

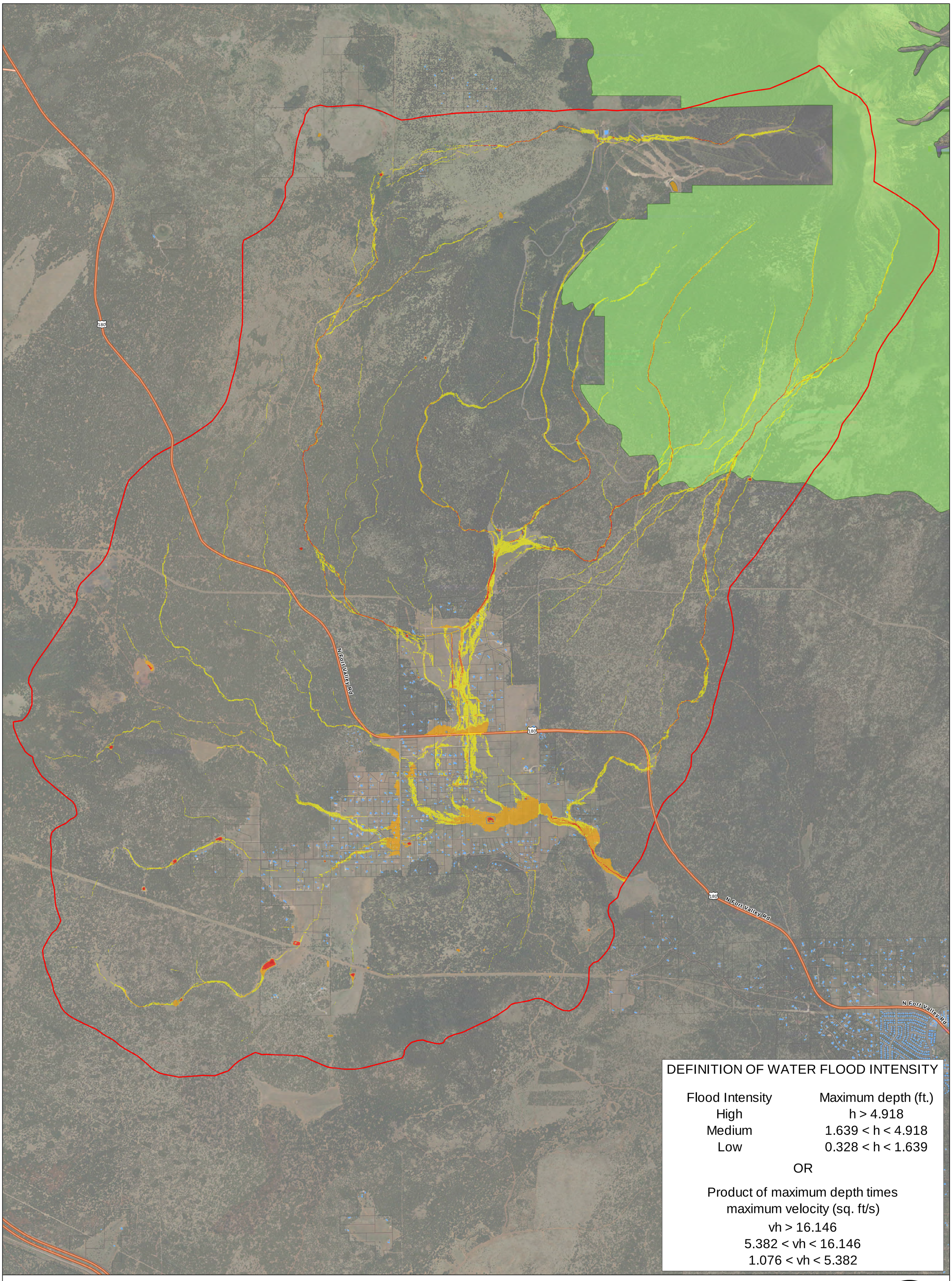
- <0.2
- 0.2 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- >5.0
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles

APPENDIX C – FLOOD HAZARD MAPS



Post-Fire Non-Treated 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

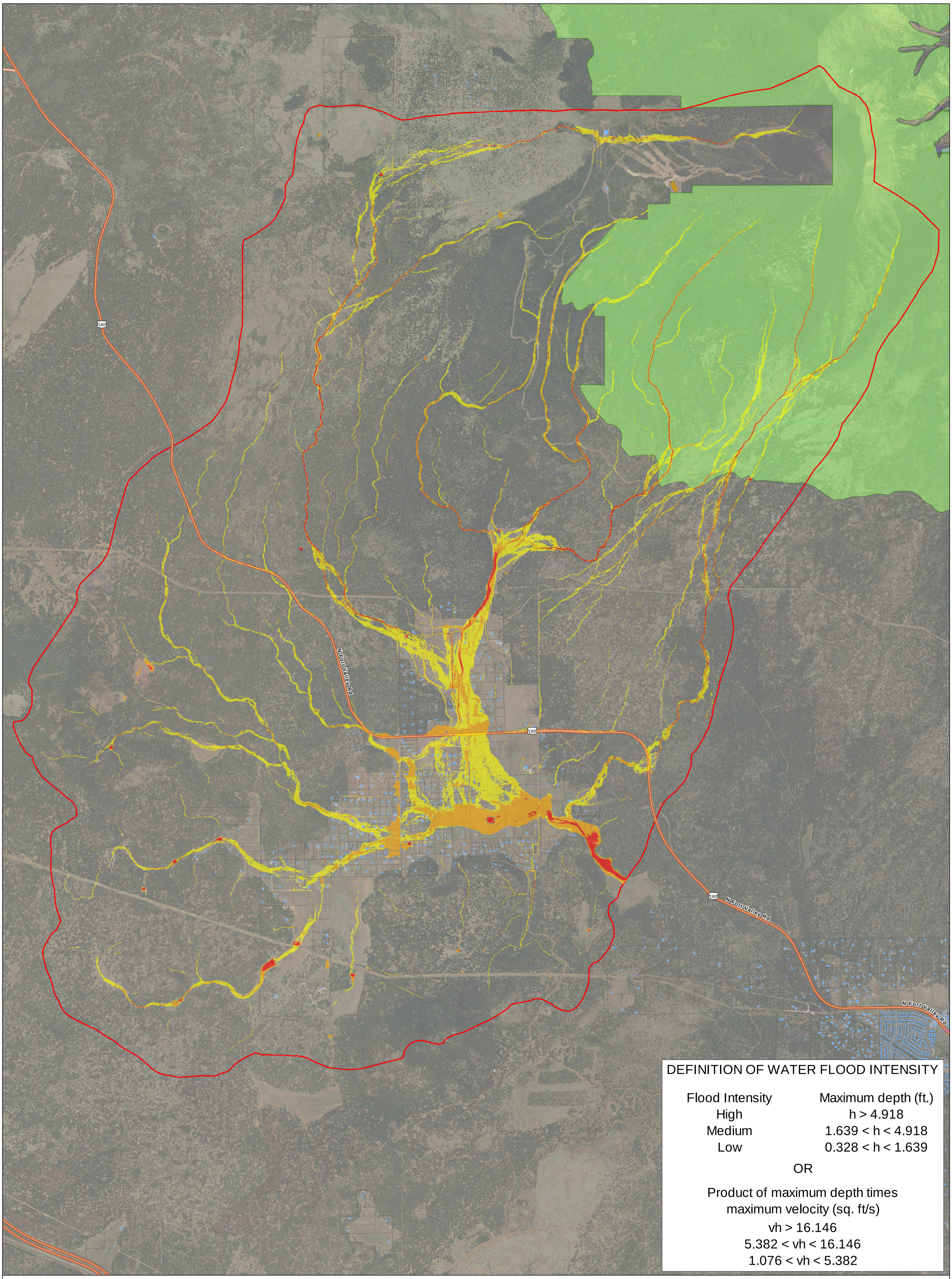
COCONINO COUNTY ARIZONA

Feet

0 2,500 5,000 10,000

0 0.5 1 2

Miles



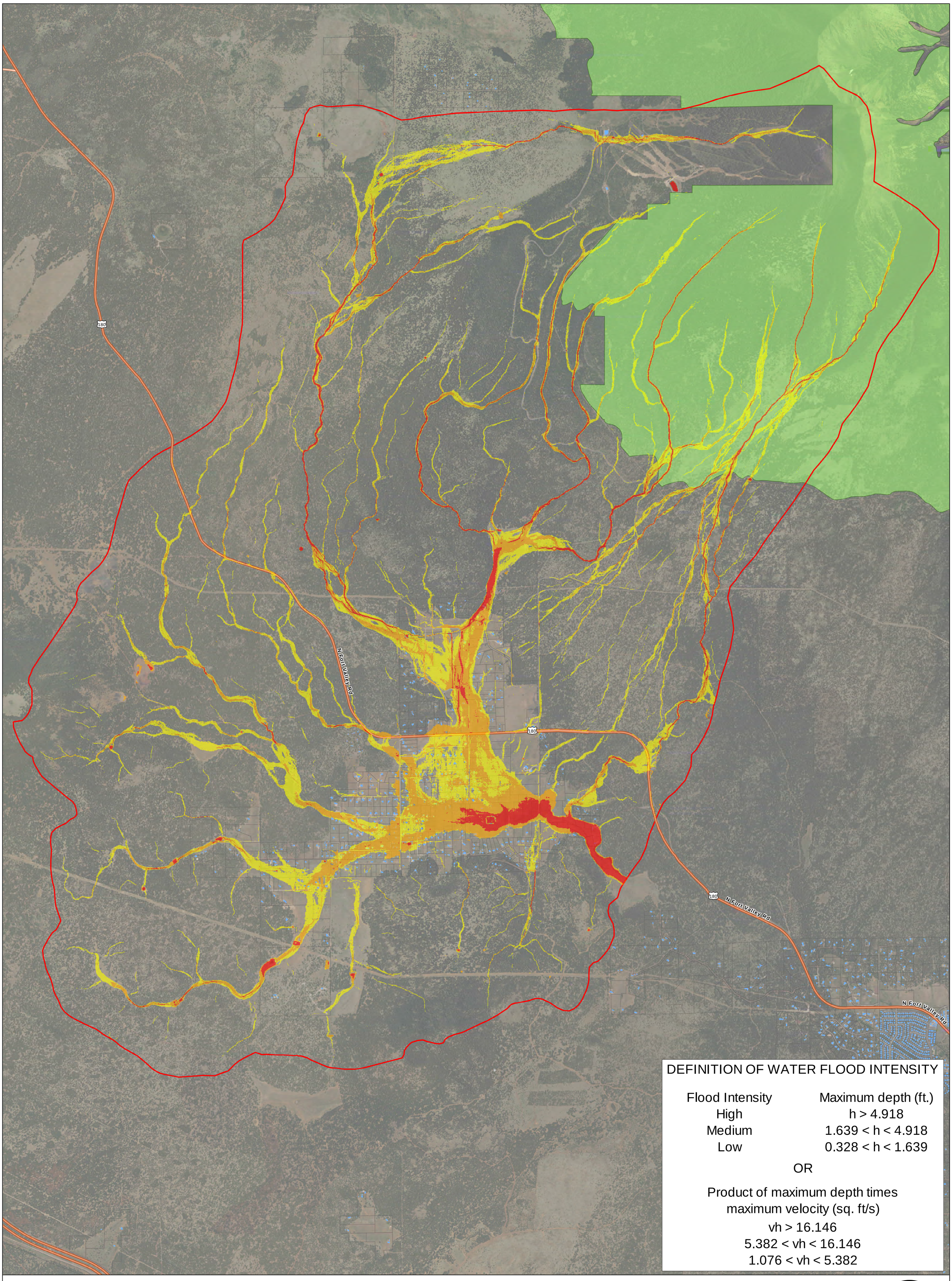
Post-Fire Non-Treated 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet: 0, 2,500, 5,000, 10,000

Miles: 0, 0.5, 1, 2

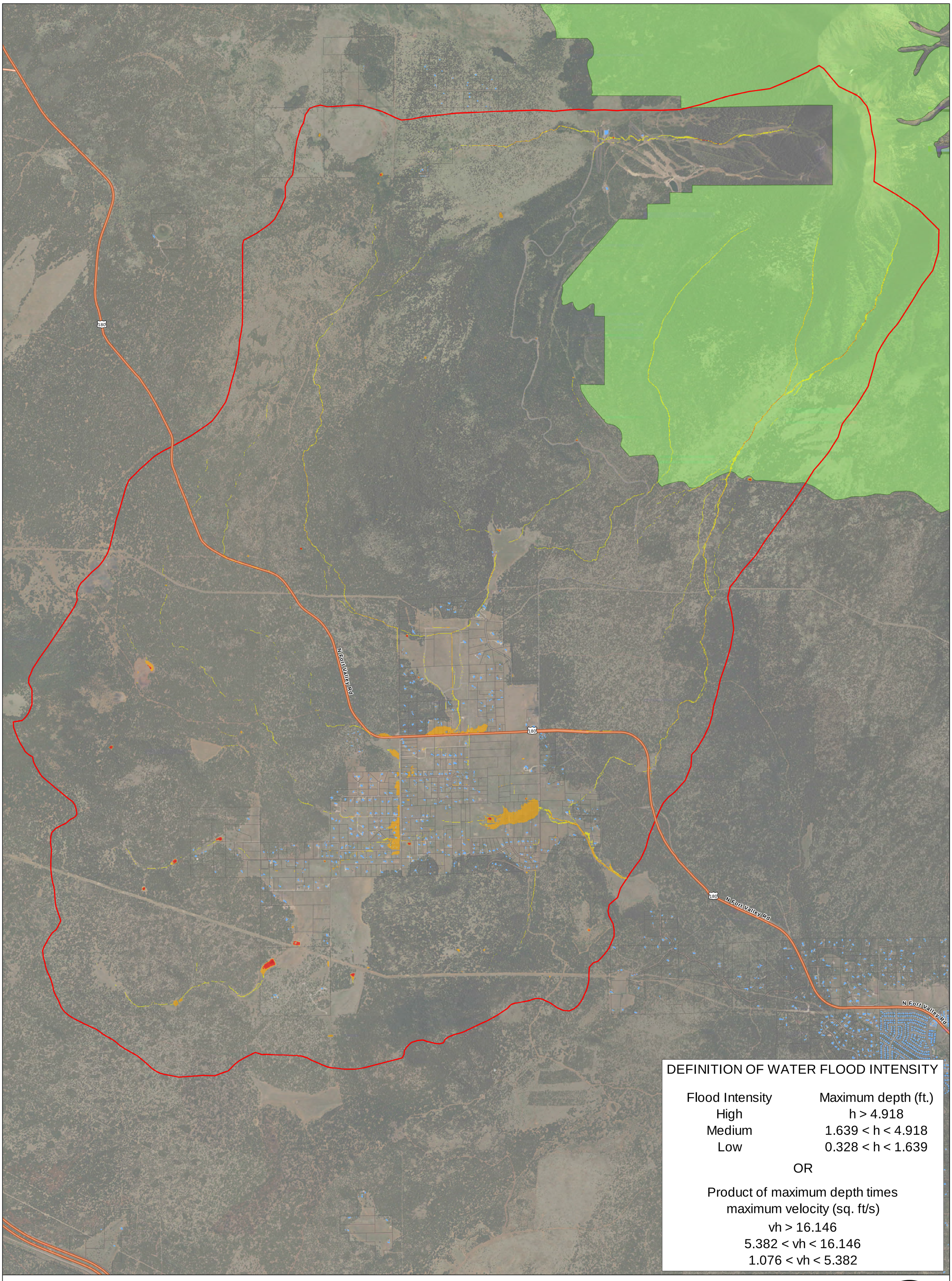


Post-Fire Non-Treated 100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000
0 0.5 1 2
Miles

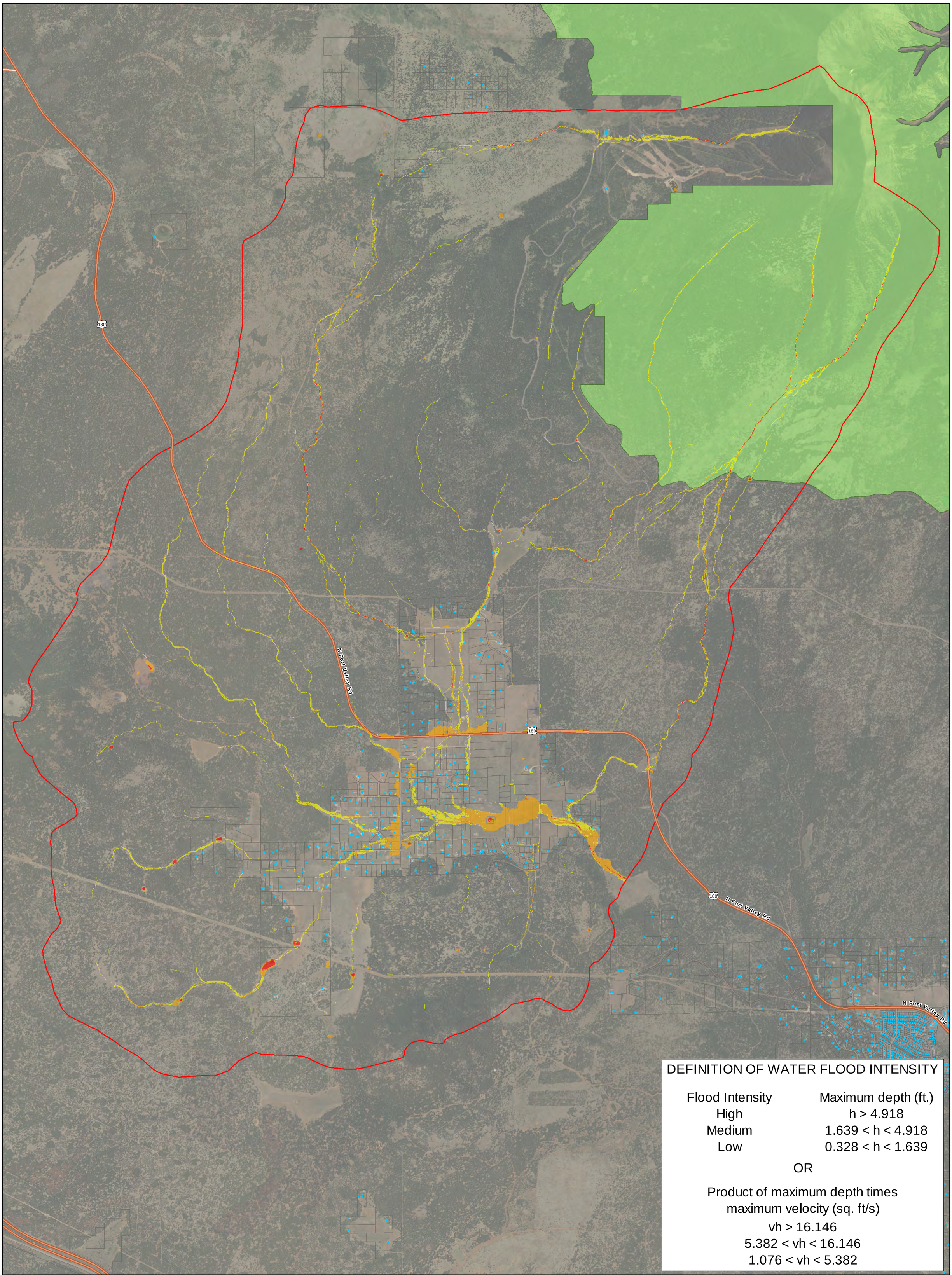


Post-Fire Treated 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000
0 0.5 1 2
Miles



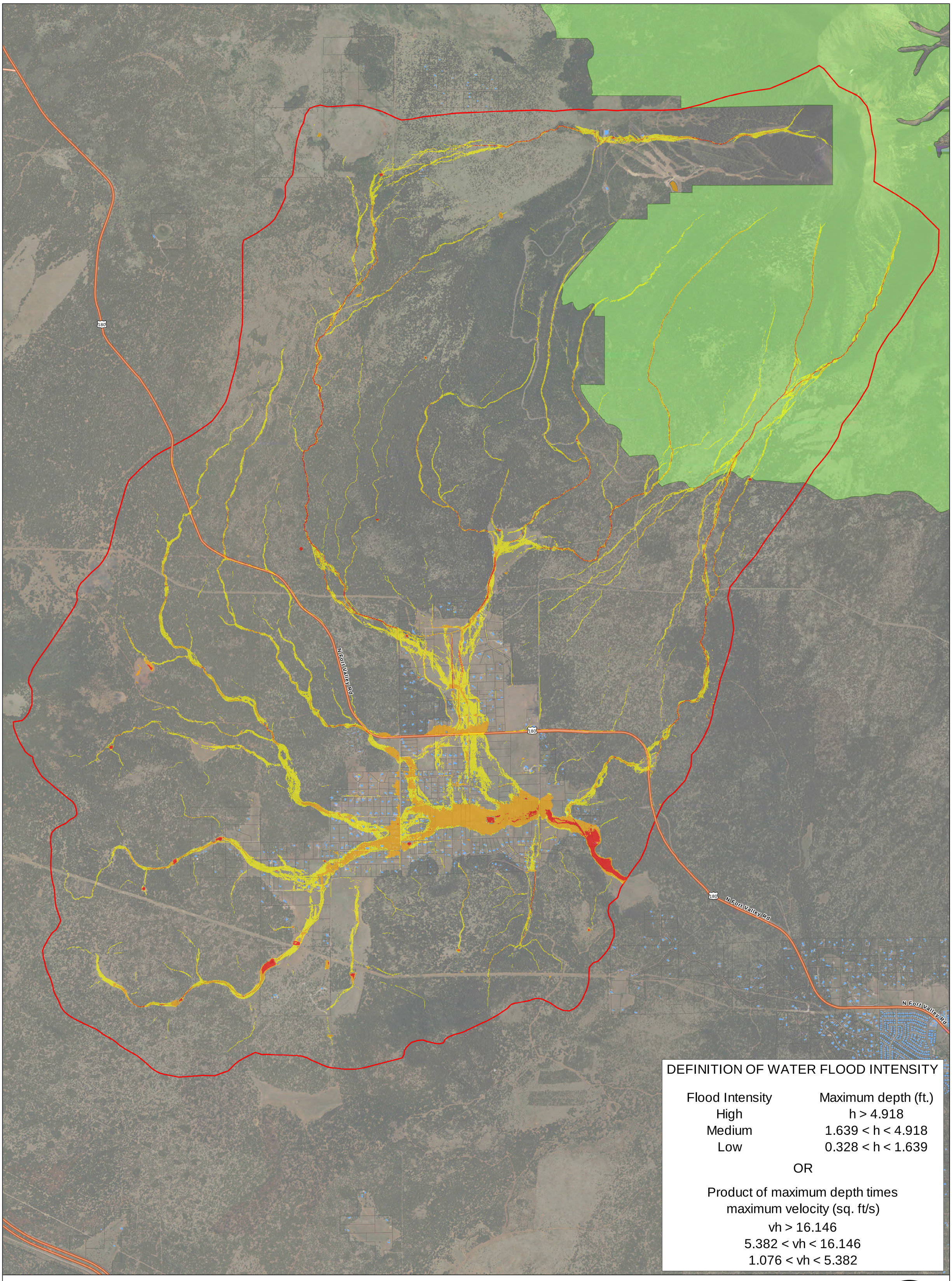
Post-Fire Treated 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



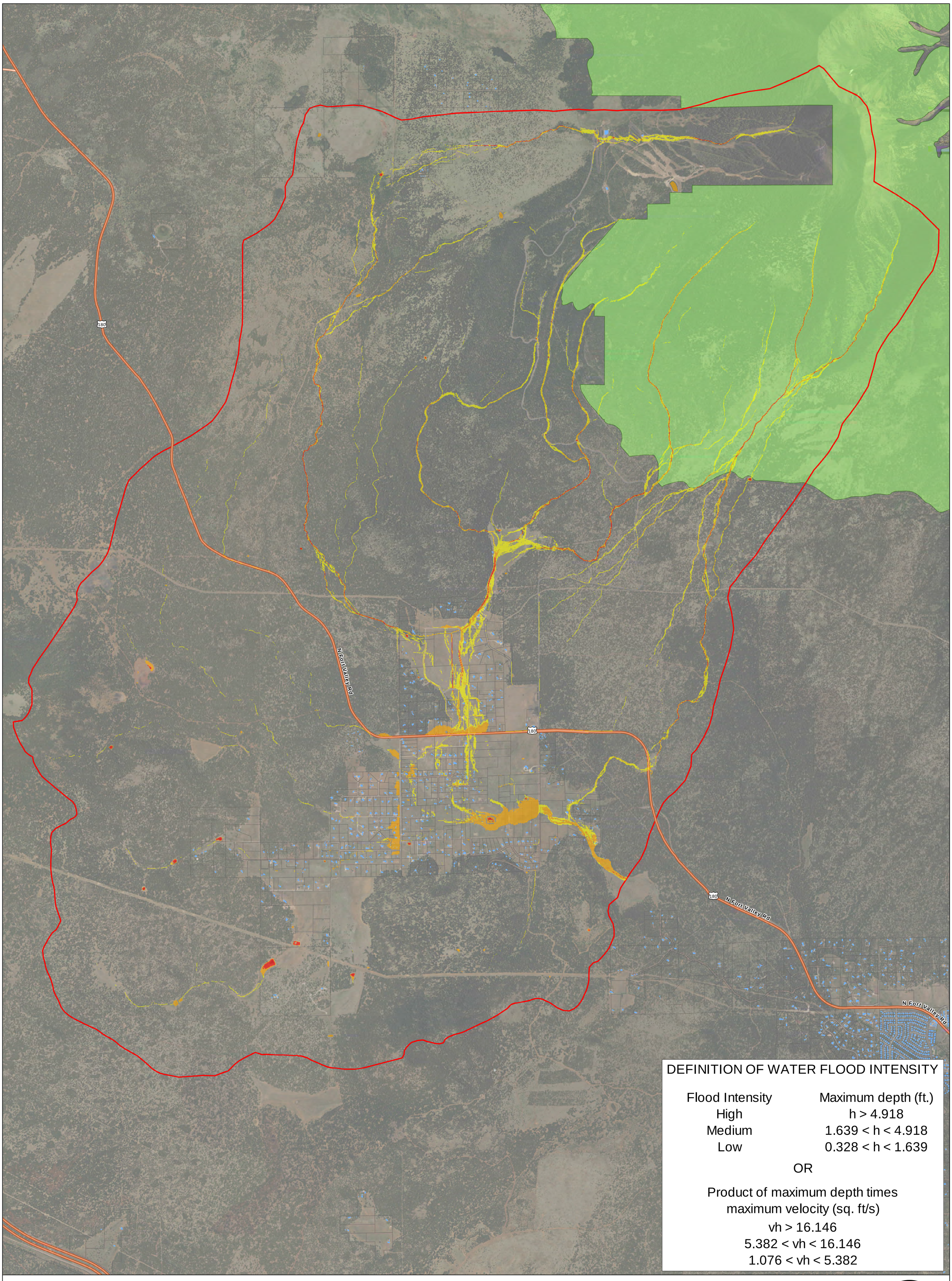
Post-Fire Treated 100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles

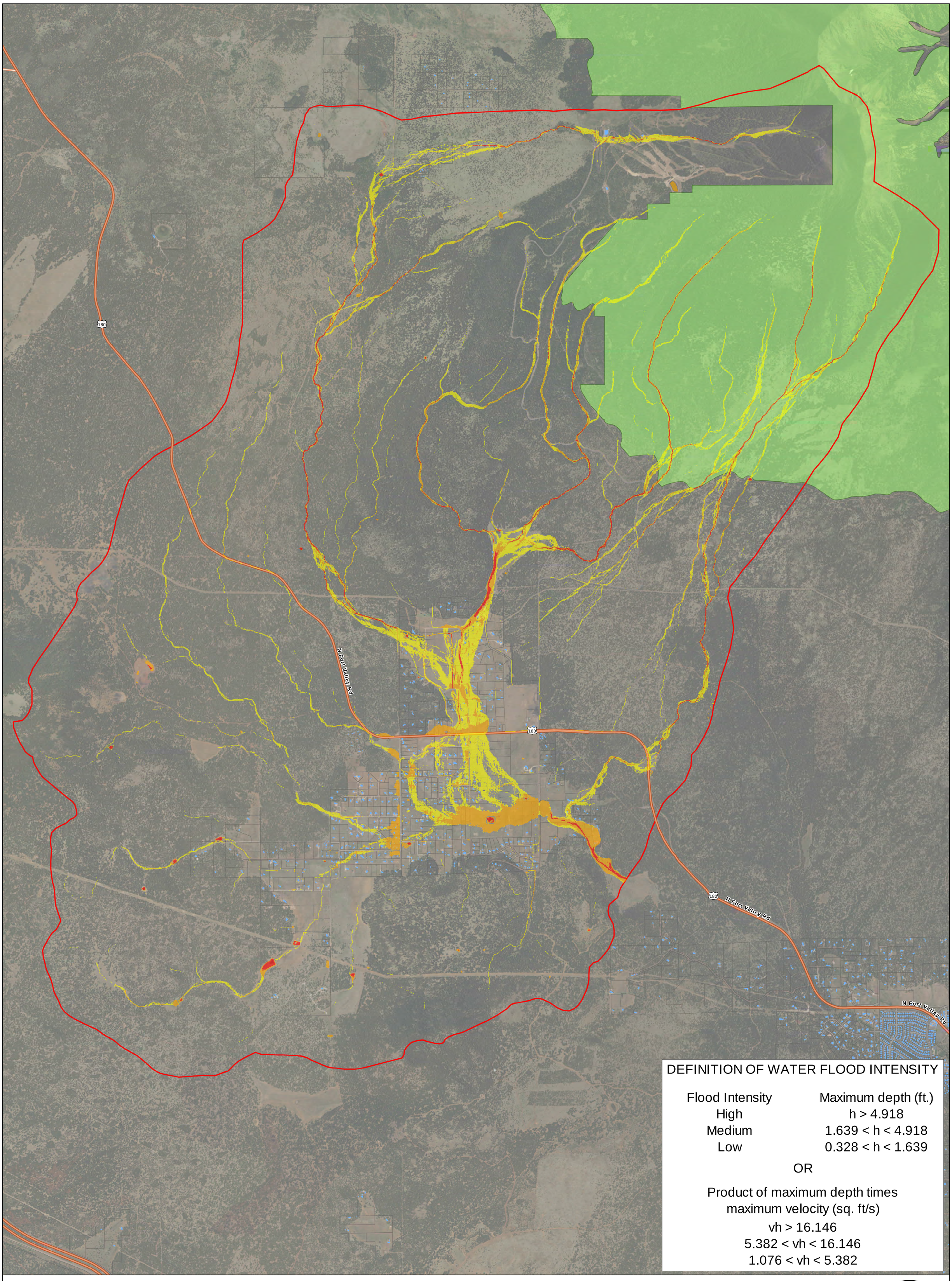


Post-Fire Treated (except Wilderness Area)
2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000
0 0.5 1 2
Miles

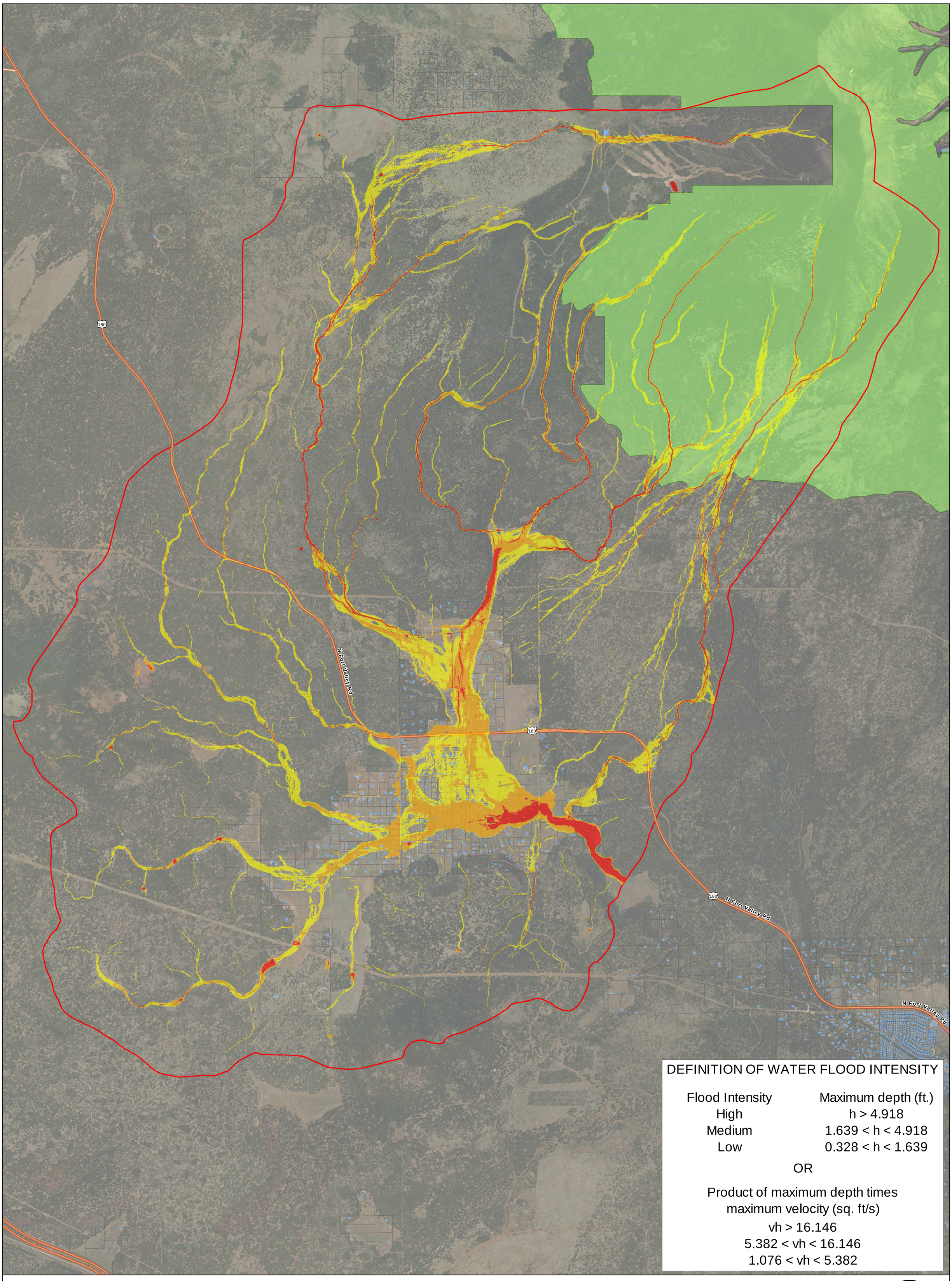


Post-Fire Treated (except Wilderness Area)
10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000
0 0.5 1 2
Miles

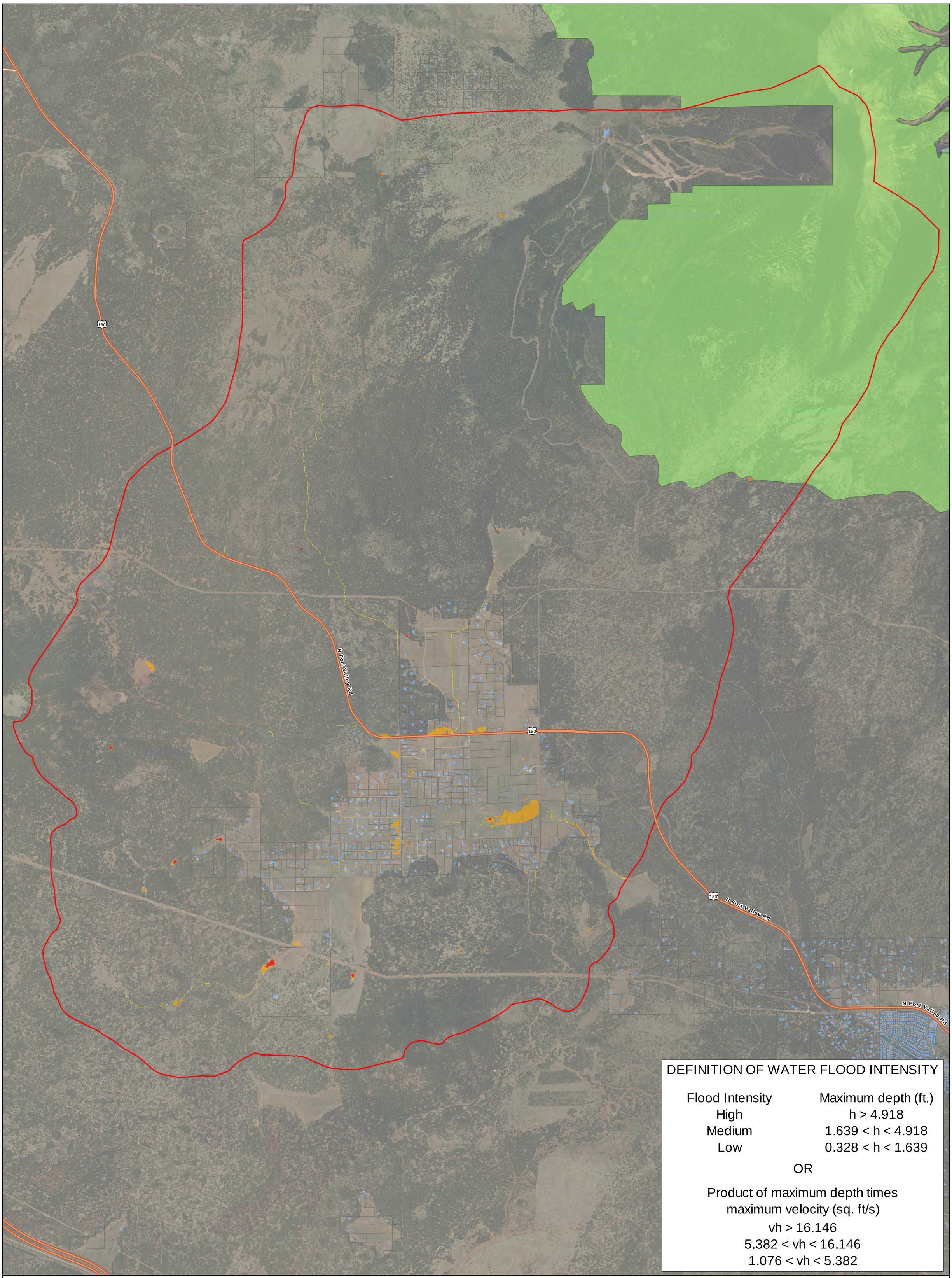


Post-Fire Treated (except Wilderness Area)
100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000
0 0.5 1 2
Miles



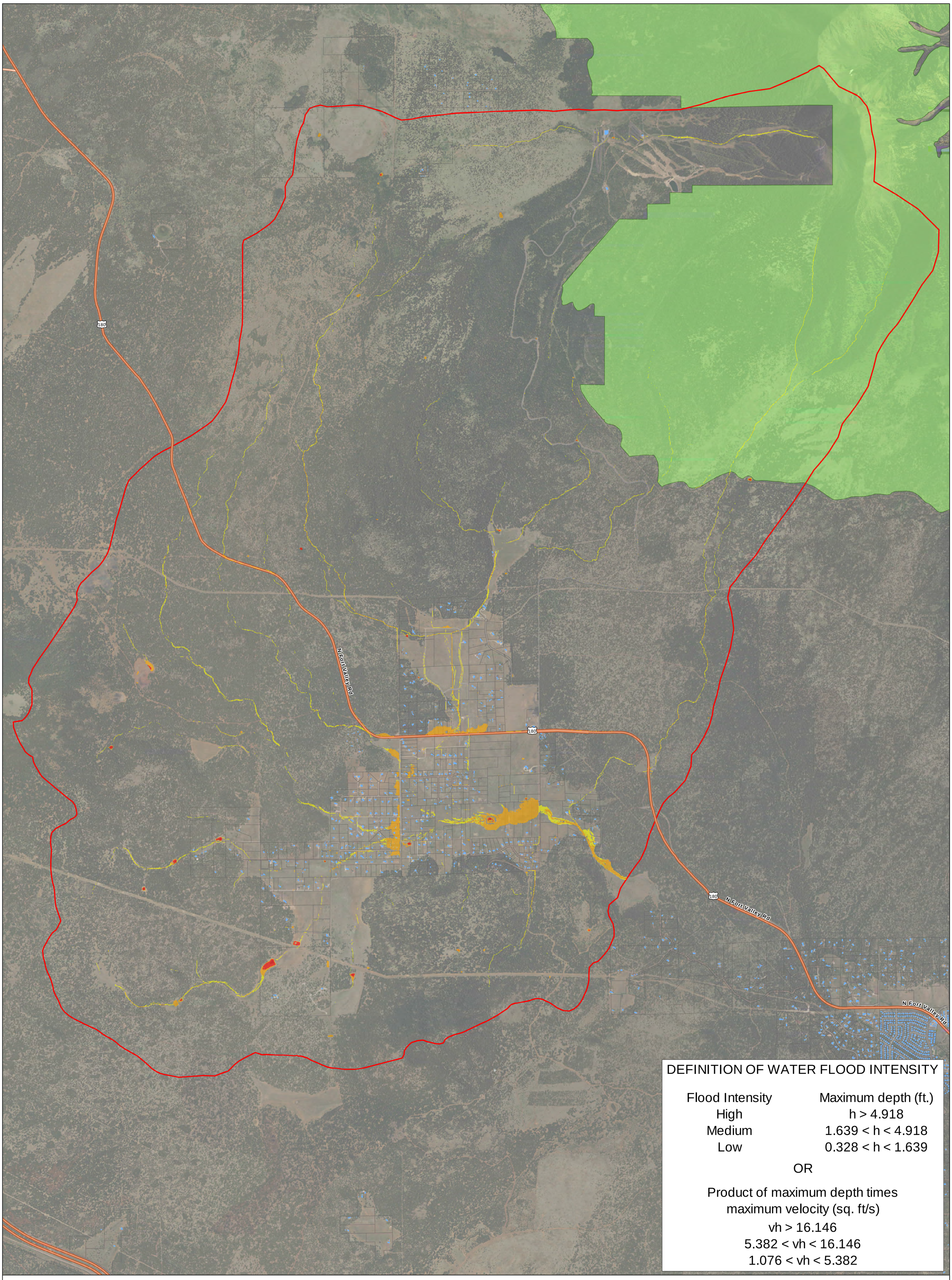
Pre-Fire 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



Pre-Fire 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

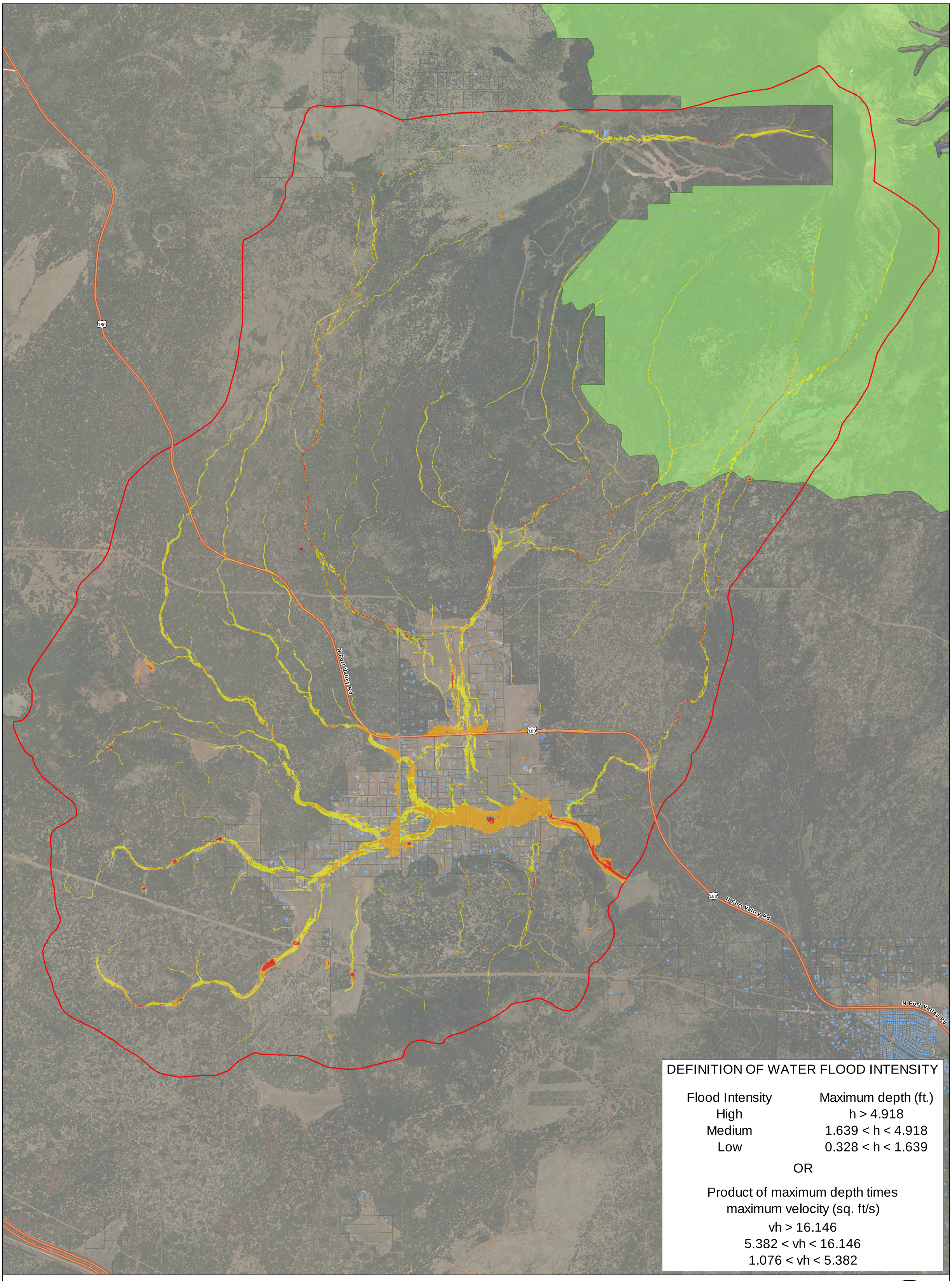
COCONINO COUNTY ARIZONA

Feet

0 2,500 5,000 10,000

0 0.5 1 2

Miles



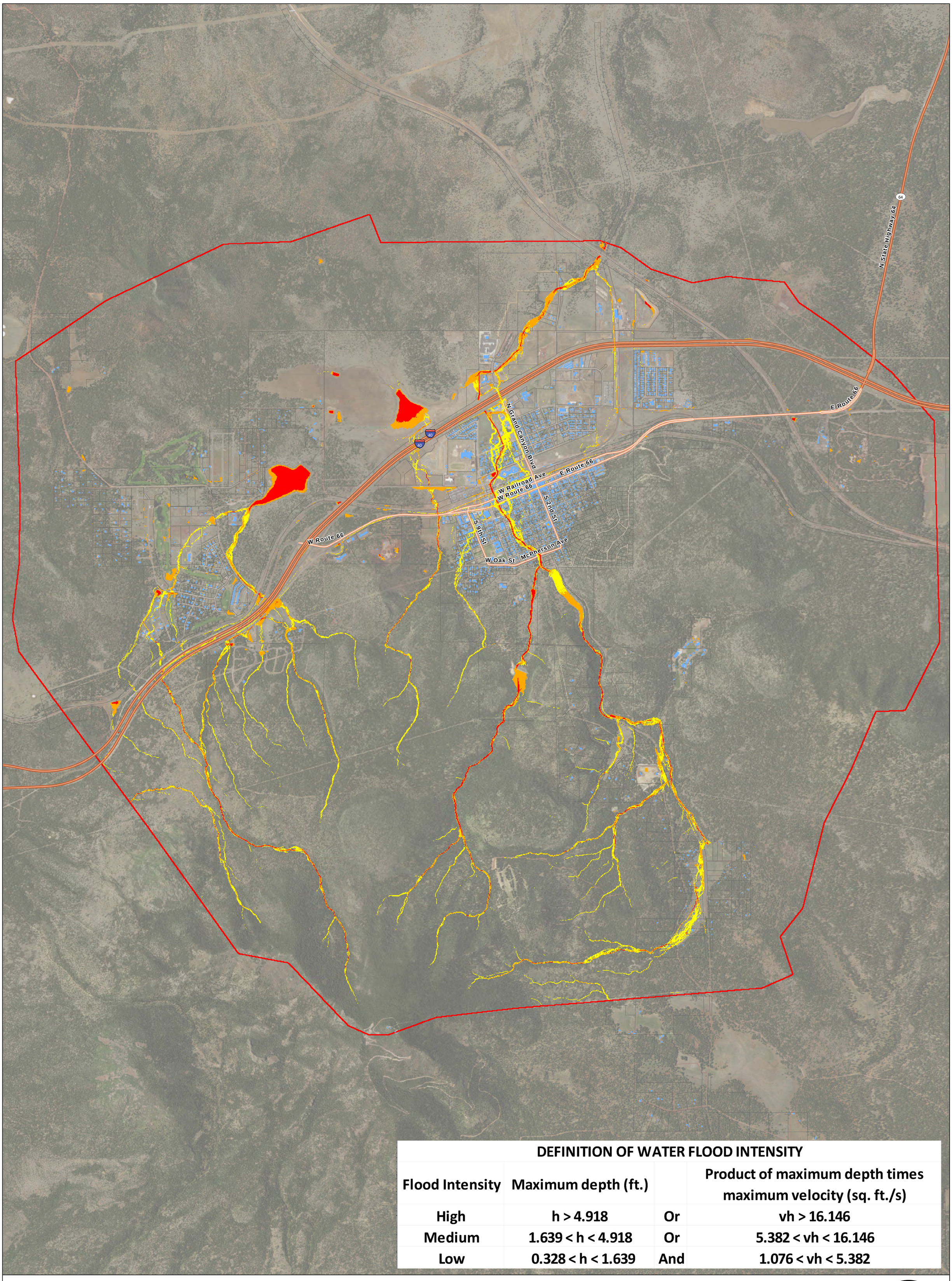
Pre-Fire 100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Wilderness Area
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



DEFINITION OF WATER FLOOD INTENSITY			
Flood Intensity	Maximum depth (ft.)		Product of maximum depth times maximum velocity (sq. ft./s)
High	h > 4.918	Or	vh > 16.146
Medium	1.639 < h < 4.918	Or	5.382 < vh < 16.146
Low	0.328 < h < 1.639	And	1.076 < vh < 5.382

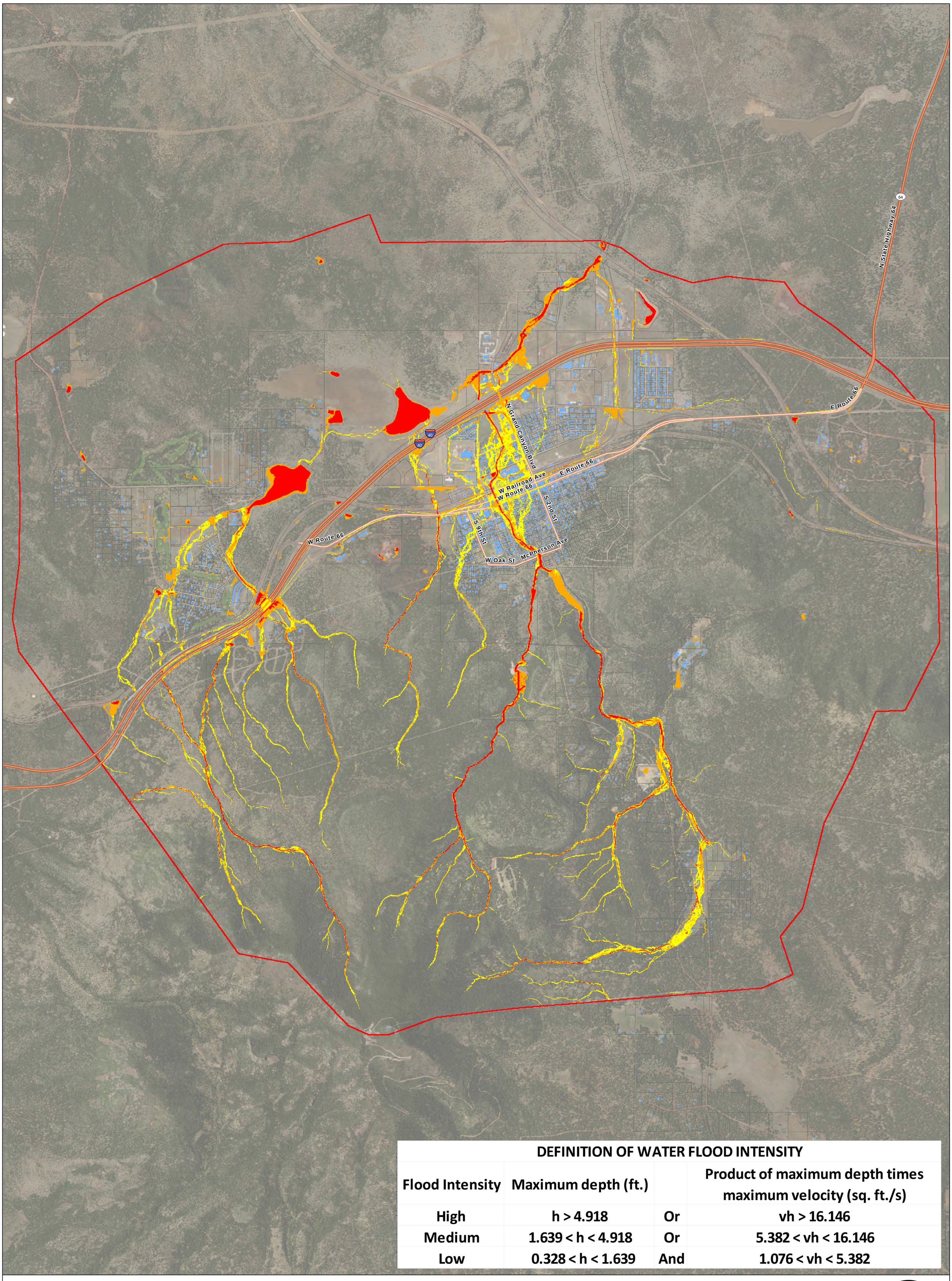
Post-Fire Non-Treated 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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Low	0.328 < h < 1.639	And	1.076 < vh < 5.382

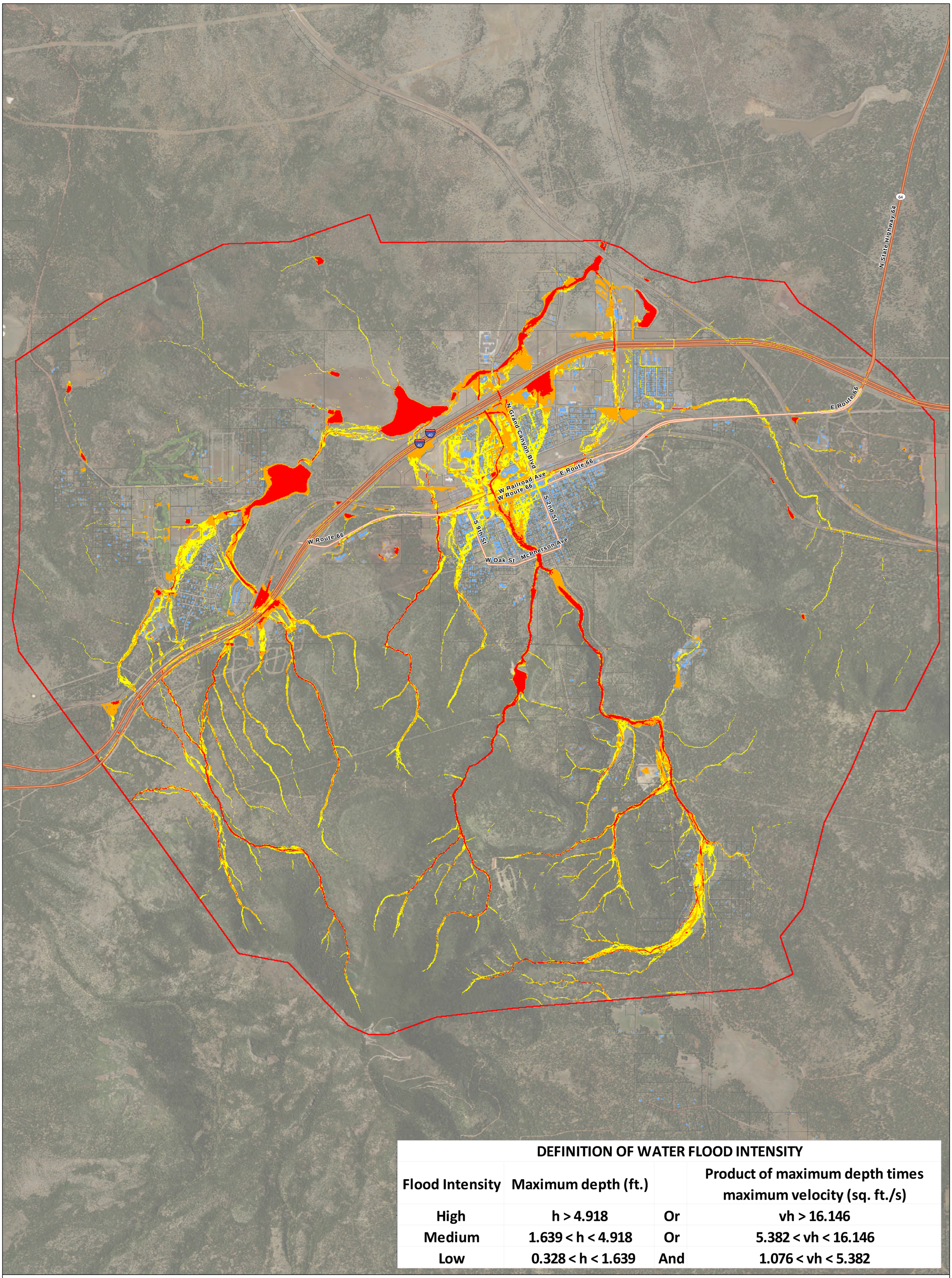
Post-Fire Non-Treated 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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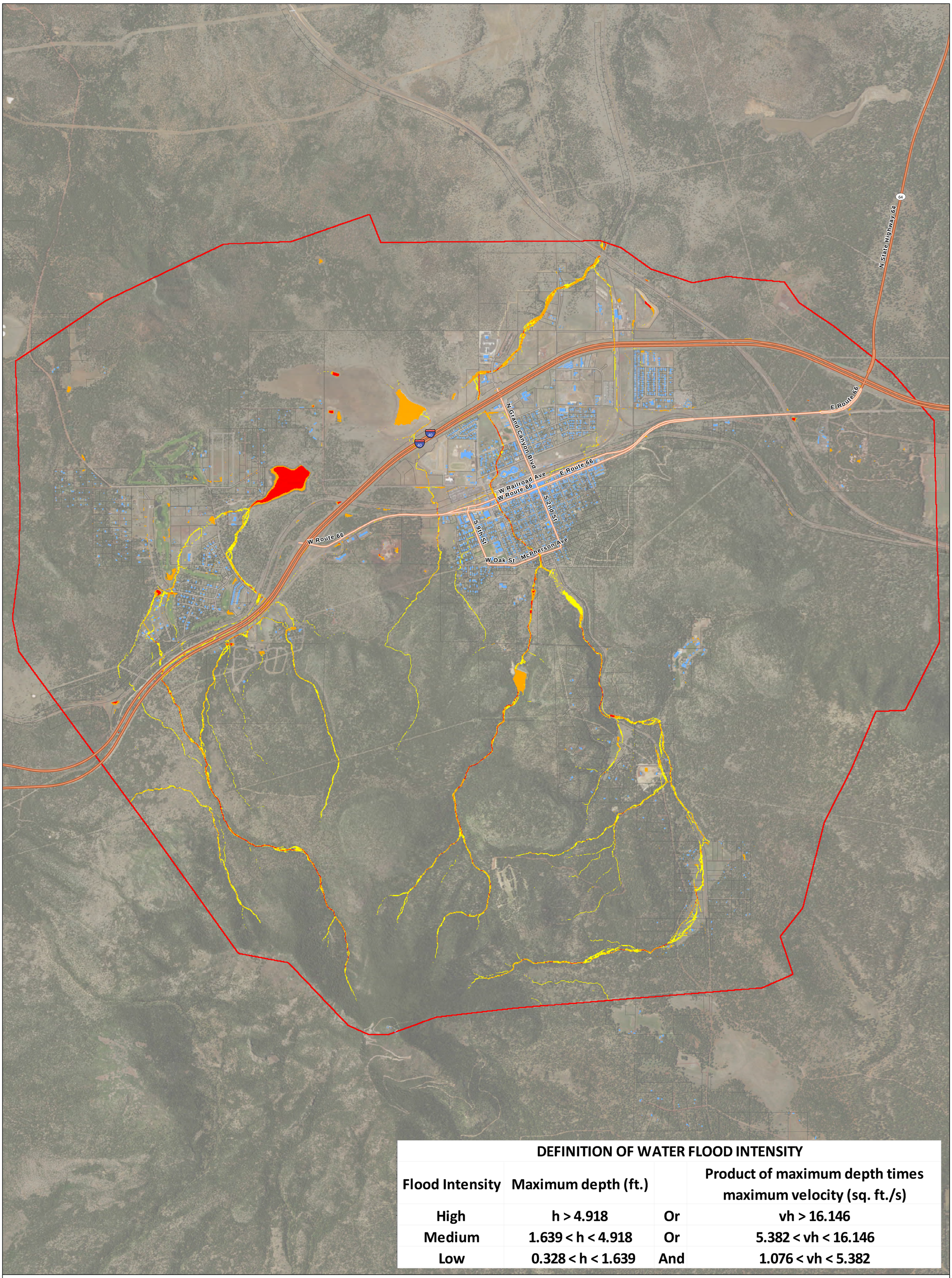
Post-Fire Non-Treated 100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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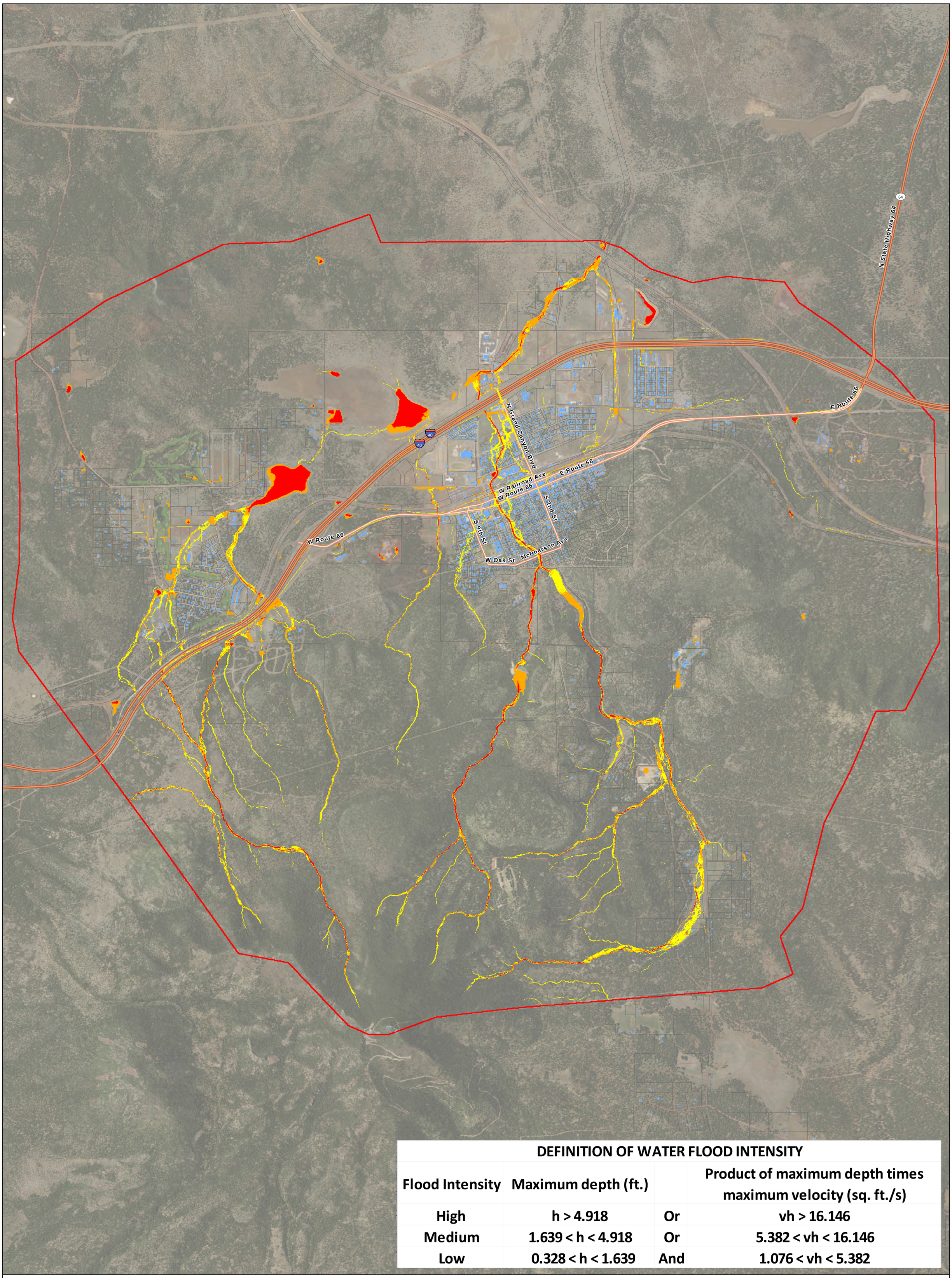
Post-Fire Treated 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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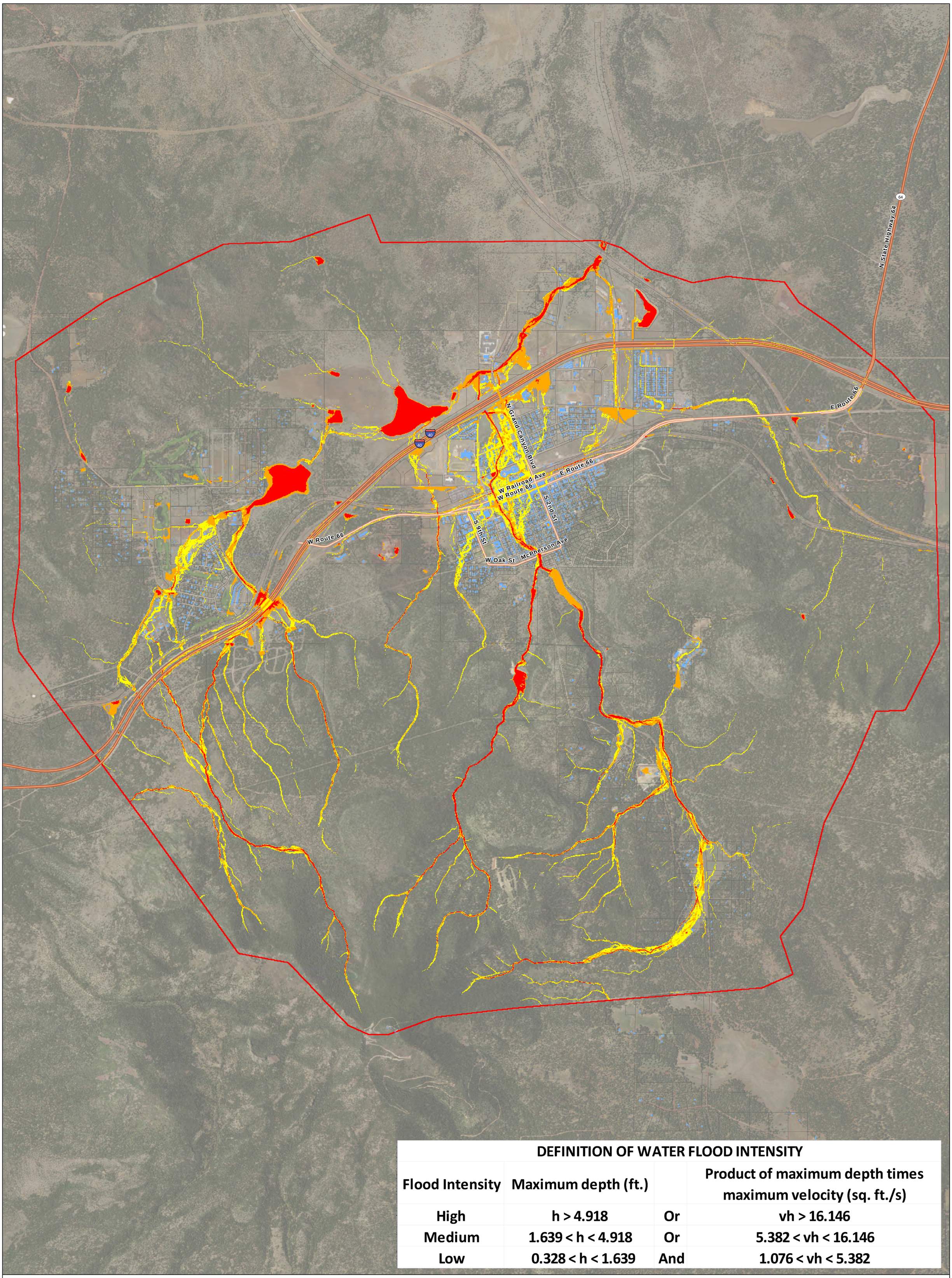
Post-Fire Treated 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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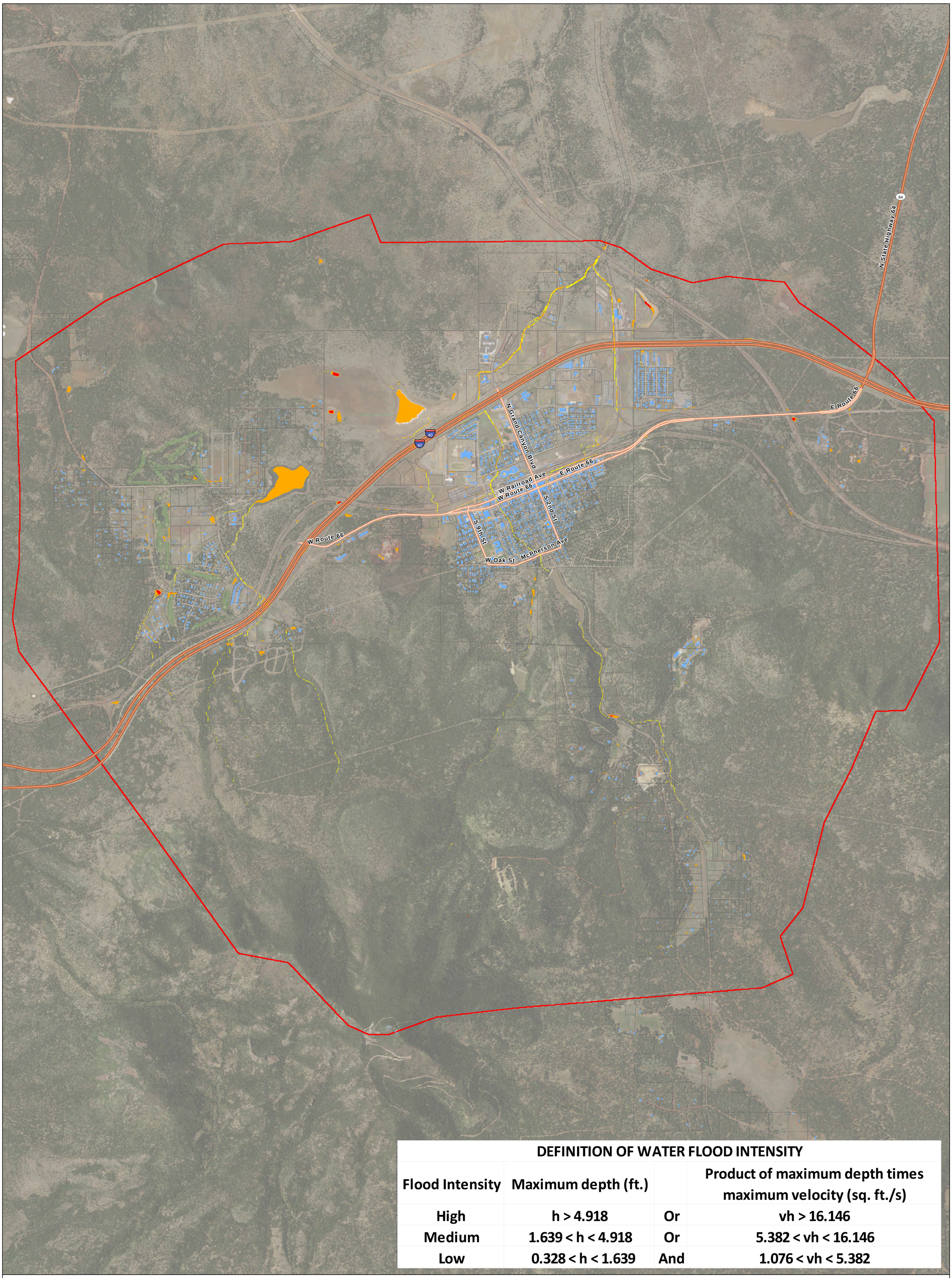
Post-Fire Treated 100-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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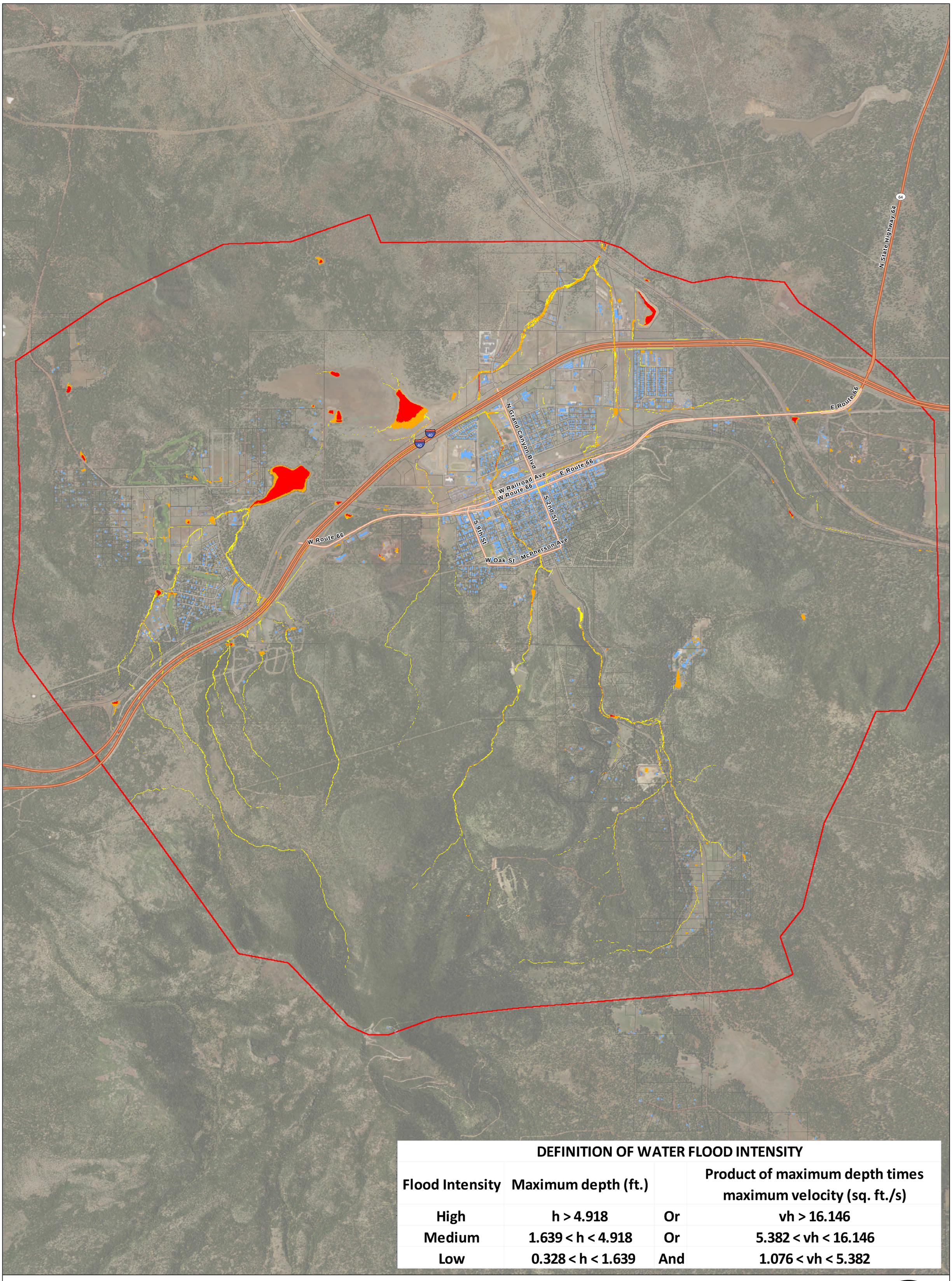
Pre-Fire 2-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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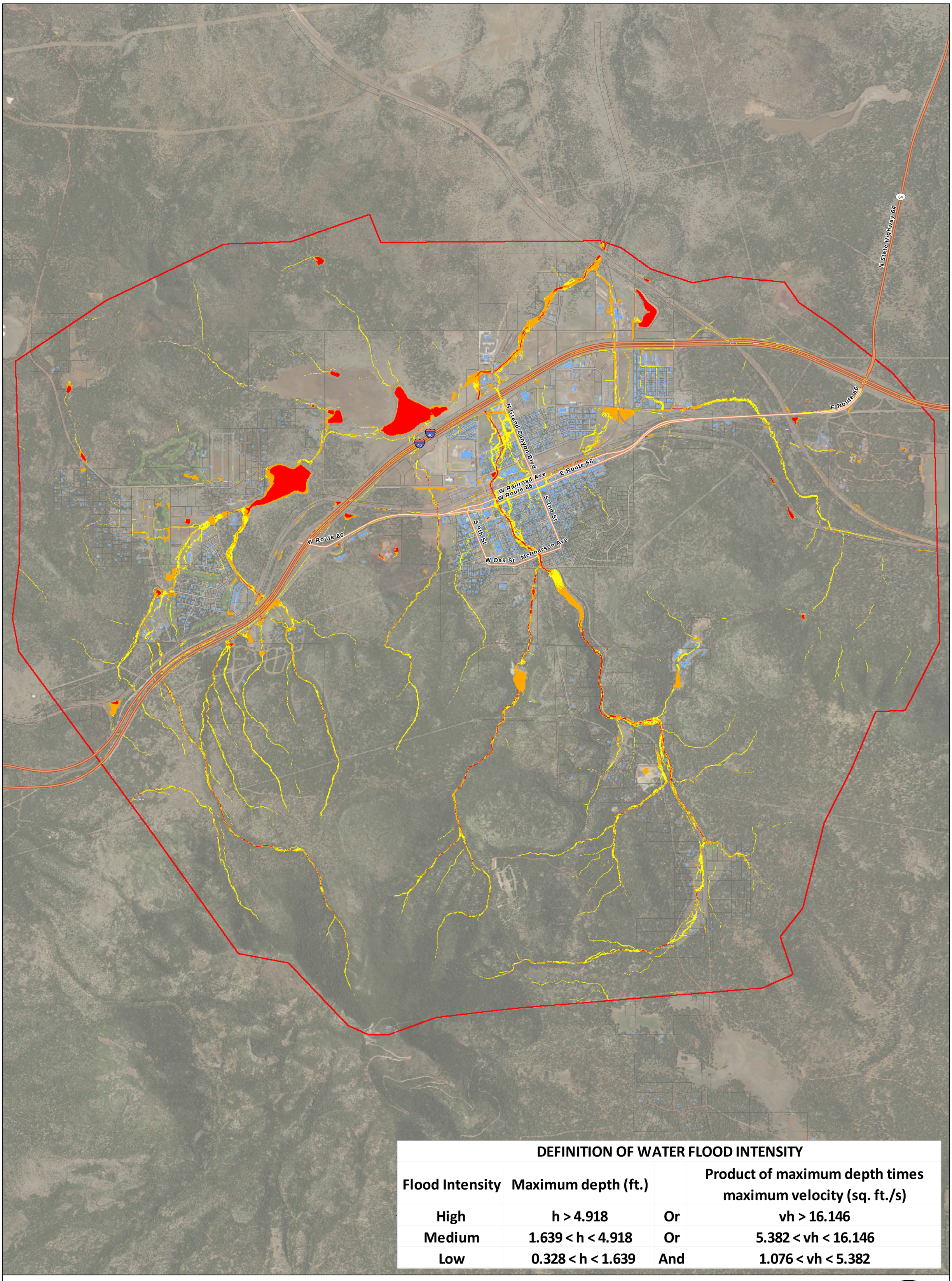
Pre-Fire 10-Year Water Flood Intensity

- High
- Medium
- Low
- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles



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Pre-Fire 100-Year Water Flood Intensity

- High
- Medium
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- FLO-2D Domain
- Buildings
- Parcels

COCONINO COUNTY ARIZONA

Feet
0 2,500 5,000 10,000

0 0.5 1 2
Miles