Attachment L. Hydrologic and Hydraulic Assessment

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Carriger Solar Site Hydrologic & Hydraulic Assessment
-
Completed for: Cypress Creek Renewables

Completed By:

SIERRA OVERHEAD ANALYTICS

Sierra Overhead Analytics, Inc.
PO Box 1716, Twain Harte, CA 95393
Phone: +1.415.413.7558

Introduction

On behalf of Carriger Solar, LLC Sierra Overhead Analytics, Inc (SOA) has prepared this hydrology report (report) for the Carriger Solar Project, located in Klickatat County, Washington. This report summarizes the results of the hydrology study which was performed to assess peak flows and flood risk across the project site. A rainfall-runoff model was developed using HEC-HMS to determine the impacts from a 100-year recurrence interval storm event. A two-dimensional (2D) hydraulic model was developed for the 100-year storm using HEC-RAS rain on grid modeling to assess on-site depth and velocity during a large storm. Publicly available rainfall data, United States Department of Agriculture (USDA) SSURGO database soils data, land use mapping, and United States Geological Survey (USGS) digital elevation mapping (DEM) topographic data was used to delineate the watersheds and to approximate runoff volumes across the project area. The methods used in this report generally follow the guidelines of the National Resource Conservation Service (NRCS), and HEC documentation. Relevant excerpts are contained in Appendix B.

1 Site Description and Existing Conditions

The site is in Klickitat County, approximately four miles northwest of Goldendale, Washington, is bounded to the east by Highway 97, and the south by Highway 142, and surrounded by forests, range land, or agricultural land. The approximate center point of the project is located at: 45.8776°N, -120.8803°W. The project site is primarily agricultural/range land that appears to be well kept and is oriented on a generally south-facing hillside. Multiple small channels are evident in satellite imagery and hydraulic modeling results. None of the man-made structures near the site appear to have a great effect on the hydraulics of the project site. The entirety of the project is located within a FEMA Zone X flood zone.

1.1 Pre-Development Drainage

The existing drainages are characterized by primarily agricultural/range land. Flow within the site generally drains to the south or southwest. Channelized areas of flow are found on site as evidenced by modeled flow patterns and satellite imagery. The site is generally gradually sloping with some moderate to high velocity flow found in the channelized portions of the site. Little ponding of water is shown in the models beyond mapped ponding locations.

The site falls entirely in FEMA Zone X – outside of the 100-year floodplain.

1.2 Site Soils and Land Use

NRCS soils mapping and land use shows on site soils ranging from B to D, representing well-draining to poorly draining soil and low to high runoff potential when saturated. The average curve number for the site is approximately 81, meaning that of the approximate 4.0 inches of water that falls on the site during the 100-year return period storm, 3.22 inches will be excess flow that will impact onsite and downstream structures. Within the site boundaries, erosion potential appears to be low to moderate based on computational modeling. A list of soils types has been included in Table 1. Soil Conservation Service area-weighted curve number for the upstream contributing basin was 68.7, as shown in Appendix B.

Table 1: *Site Soil Types*

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
12D	Lyville bouldery loam, 2 to 20 percent slopes	1.0	0.0%
23	Gunn loam, 2 to 8 percent slopes	102.0	4.9%
23A	Gunn stony loam, 8 to 30 percent slopes	20.7	1.0%
23B	Gunn loam, 8 to 30 percent slopes	5.0	0.2%
25A	Leidl extremely cobbly ashy loam, 2 to 30 percent slopes	125.6	6.1%
30A	Rockly-Lorena complex, 2 to 15 percent slopes	6.4	0.3%
30B	Rockly-Lorena complex, 2 to 15 percent slopes, extremely stony	93.9	4.5%
69	Goldendale silt loam, basalt substratum, 2 to 5 percent slopes	823.7	39.8%
69A	Goldendale silt loam, basalt substratum, 5 to 10 percent slopes	50.6	2.4%
93	Goldendale silt loam, 2 to 5 percent slopes	208.6	10.1%
93A	Goldendale silt loam, 5 to 10 percent slopes	168.0	8.1%
93B	Goldendale silt loam, 10 to 15 percent slopes	71.5	3.5%
93C	Goldendale silt loam, 15 to 30 percent slopes	5.4	0.3%
94	Lorena silt loam, 2 to 5 percent slopes	1.1	0.1%
95A	Konert silt loam, 0 to 2 percent slopes	9.8	0.5%
96	Blockhouse silt loam, 0 to 5 percent slopes	99.8	4.8%
97	Munset stony silt loam, 0 to 5 percent slopes	195.0	9.4%
97A	Setnum silt loam, 0 to 3 percent slopes	81.3	3.9%
Totals for Area of Interest		2,069.4	100.0%

The USGS National Land Cover Database (NLCD) was used to determine land use for the 2D model domain. The site is classified mostly as Cultivated Crop, Shrub/Scrub, and Grassland/Herbaceous.

1.3 Topography

Due to the size of the upstream basins affecting the construction location, SOA utilized National Map Data to create the 1D model domain. 2018 USGS LiDAR data was used for the 2D model domain. The site has general southern exposure, with all basins draining to the south or southwest.

2 Model Setup

2.1 1D Computational Hydrologic Modeling

HEC-1 modeling software was used to calculate the rainfall-runoff hydrographs for the contributing watersheds. Contributing watersheds impacting the 2D model area were delineated using TOPAZ software and National Map Publicly Available Data. One upstream contributing watershed was delineated: 1B. The location and boundary of the contributing watershed is shown in Appendix A, Figure 1. Contributing watershed curve numbers (CN) were determined using SSURGO soils data and USDA land use data. Composite curve numbers were determined from percent areas of each soil type/land use combination, typical values for which are available in TR-55 Appendix B. Basin 1B has an area of 6.061 square miles and a CN of 68.65. Further information about each contributing watershed is provided in Appendix B.

Lag time was calculated using the SCS Unit Hydrograph method, the equation for which is:

$$T_{lag} = \frac{L^{0.8}(S+1)^{0.7}}{1900 \cdot (\%Slope)^{0.5}} \tag{1}$$

L is the longest drainage path in feet, S = (1000/CN)-10, CN is SCS curve number, and %Slope is the average slope of the watershed, determined through topographic analysis. Time of Concentration is determined by dividing Lag Time by 0.6. Antecedent Moisture condition (AMC) is defined by the USDA as the preceding relative moisture of the pervious surfaces prior to the rainfall event. The "Average" AMC-II condition was used for the site. This resulted in no modification to the curve numbers.

2.2 2D Hydraulic Modeling

HEC-RAS was used to develop a 2D hydraulic model for the 100-year 24-hour storm event to model maximum depths and velocities across the site. Grid cells of approximately 50 feet by 50 feet were used for the 2D model area. Topography was interpolated to the grid cells based on the topographic data described above. A land use layer and soil layer were developed using the data described above, and combined to form an infiltration layer. Each land use was associated with a Manning's n value as shown in Table 2.

Table 2: *Land Cover Types and Associated Manning's n Values*

Land Cover	Manning's n
Evergreen Forest	0.15
Developed, Low Intensity	0.08
Shrub-Scrub	0.07
Mixed Forest	0.12
Developed, Open Space	0.035
Grassland-Herbaceous	0.04
Developed, High Intensity	0.15
Emergent Herbaceous Wetlands	0.05
Woody Wetlands	0.07
Developed, Medium Intensity	0.12
Deciduous Forest	0.1
Open Water	0.03
Barren Land Rock-Sand-Clay	0.03
Cultivated Crops	0.05
Pasture-Hay	0.045

Hydrologic soil group data was combined with land use data to assign a CN to each land use/hydrologic soil group combination, as shown in Table 3. These CN values were used in the infiltration layer. The average CN for the 2D model domain under existing conditions was 78.9. In the post-construction scenario, the site area was also assigned an imperviousness of 5%. All other areas were assigned an imperviousness of 0%. All cells were assigned an initial abstraction value of 0.2.

The hydrograph produced by the 1D model at the outlet of Basin 1B was used as an external flow boundary condition to the northeast edge of the 2D model. The 100-year 24-hour precipitation event was simulated as spatially constant across the 2D model domain using an internal precipitation boundary condition. Infiltration was modeled using the SCS Curve Number method. The edges of the model domain were used as external boundary conditions of normal depth where friction slope = 0.01.

Two-dimensional unsteady flow routing was performed in HEC-RAS using the Diffusion Wave Equa-

Table 3: *Curve Numbers*

Land Use	Curve Number			
	Soil Type B	Soil Type C	Soil Type D	Soil Type C/D
Open Water	100	100	100	100
Developed, Open Space	69	79	84	81.5
Developed, Low Intensity	86	91	94	92.5
Developed, Medium Intensity	92	94	95	94.5
Developed, High Intensity	98	98	98	98
Barren Land Rock-Sand-Clay	86	91	94	92.5
Deciduous Forest	48	57	63	60
Evergreen Forest	58	73	80	76.5
Mixed Forest	60	68	74	71
Shrub-Scrub	68	79	84	81.5
Grassland-Herbaceous	71	81	89	85
Pasture-Hay	69	79	84	81.5
Cultivated Crops	80	87	90	88.5
Woody Wetlands	89	90	91	90.5
Emergent Herbaceous Wetlands	90	91	92	91.5

tions, as described in the HEC-RAS Hydraulic Reference Manual. Model stability was maintained through variable timestepping dictated by maximal and minimal Courant numbers where the Courant number (C) =

$$C = \frac{V \cdot \Delta T}{\Delta X} \tag{2}$$

V is the flood wave velocity, ΔT is the computational time step, ΔX is the average computational grid cell size. The maximum Courant number was set to 0.95 and the minimum was set to 0.25. The small cell size of the computational grid dictated a small timestep, on average around 1 second.

3 Results

3.1 1D Hydrologic Model Results

The results of the contributing watershed modeling are shown below in Figure 1. Peak flowrate for the 100-year 24-hour flow event was about 1,040 CFS at the outlet of Basin 1B.

3.2 2D Hydraulic Model Results

Of the total 100-year storm precipitation depth of 4 inches, on average 1.99 inches was infiltrated and 2.01 inches was runoff. Modeled infiltration depths ranged from 0 to 3.34 inches across the 2D model domain. HEC-RAS output for maximum depth, velocity, and scour is shown on Appendix A Figures 2 through 4.

Scour depth was calculated using the methods of Chapter 7 of the HEC 18 Scour Manual. K1, K2, and K3 were calculated to be 1.1, 1.3, and 1.1 respectively, and a box pile of dimensions a=1/3' and

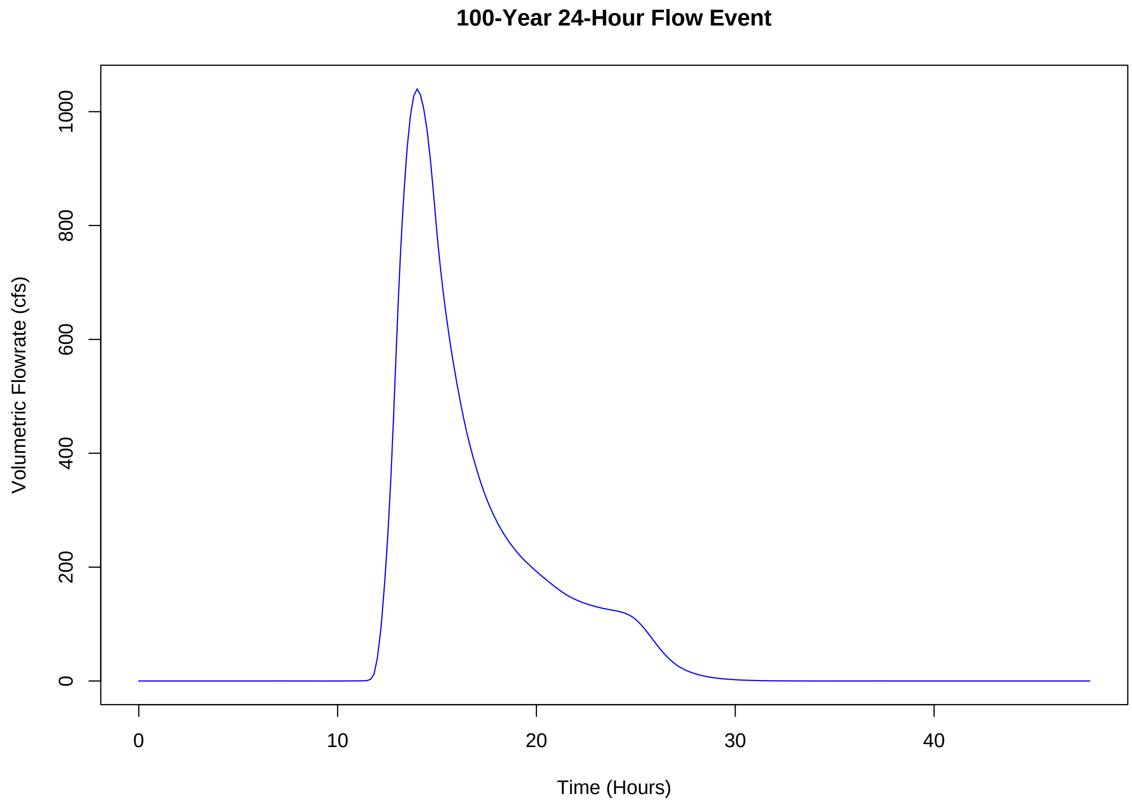


Figure 1: Hydrograph for the contributing watershed

L=1/2' were used. For simplicity, the angle of attack was assumed to be zero for all piles. The proper excerpt pages are included in Appendix B.

Channelized flow is apparent on site in natural flow concentration areas. Flow depths within these areas appear to reach approximately 6 feet in the deepest part of the channels. Overland flow is negligible as enough channels exist on site to adequately drain most overland flow before it can pool. No ponding areas are visible within the site, nor is evidence of ponding found in the publicly available aerial images. Tiff surfaces are available upon request Site flow velocities follow a similar pattern to flow depth onsite. Channelized flow sees velocities as high as 15 feet per second, while overland flow is generally very low velocity. Scour depth does not exceed 4.0 and is limited to the naturally occurring channels. Generally, the soil matrix on site appears to be stable given the aerial images and model results, but further investigation in the form of a Geotechnical Site Investigation would be required before final determinations could be made. Overall, brushing, grading, and slope stabilization within the site may promote increased drainage, while minimizing site soil erosion. Offsite channels should be protected from scour if imperviousness is increased. SOA can run further 2D site models as grading plans are developed. Within the buildable area, flow velocity and erosion potential are not critical items of concern for this site. The site should remain stable under normal flow characteristics. Increased impervious areas can lead to further concentrated flow areas, and therefore a post-construction study should be undertaken before construction begins. Stabilization should be added to the pre-existing drainage structures in order to preserve their integrity.

3.2.1 Post-Construction

Post-construction conditions caused minimal changes to site flow depth, velocity and scour. Peak runoff from the site increased slightly in the post-construction simulation due to an increase in impervious surface. Appendix A, Figure 5 shows locations of flow profile lines where runoff flow profiles were calculated in HEC-RAS along the downstream boundaries of the site areas. Table 4 shows the anticipated increase in runoff due to PV installation. Results of the model run show an increase to affected basins, totaling approximately 1.16-acre feet, based on additional impervious area estimates. The methods used to determine this additional runoff volume rely on HEC-RAS modeling of an increased 5% impervious area over the entire site area. Once final grading plans are developed, individual onsite basins should be investigated for additional runoff volume due to additional impervious area. The developer and engineer of the project should account for this additional storage volume in their design.

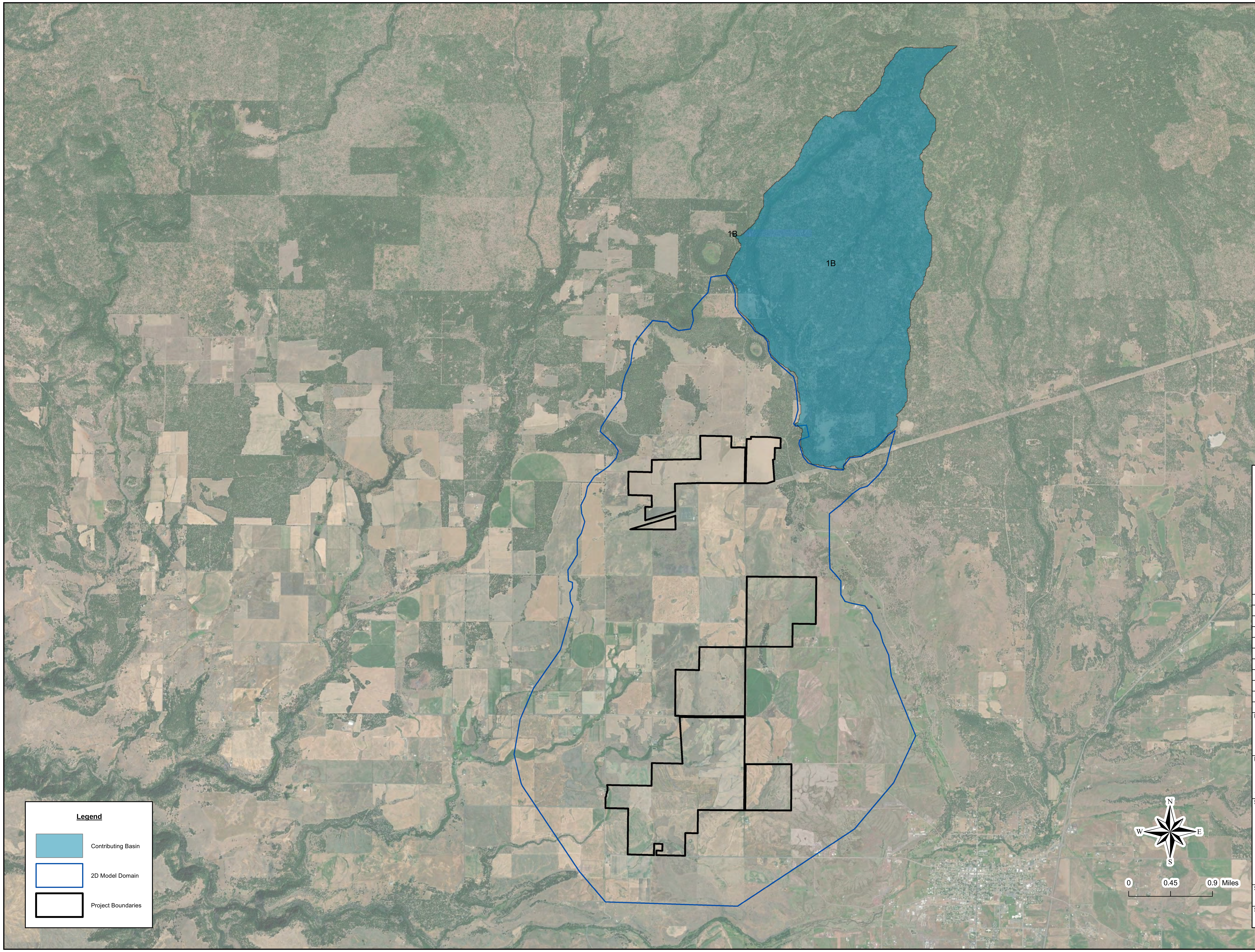
Table 4: *Post-Construction Excess Peak Runoff Volume*

Profile Line	Pre-construction Peak Q (cfs)	Post-construction Peak Q (cfs)	Percent Increase	Runoff Volume Difference (Acre-ft)
Profile 1	3335.0	3384.3	1.5	0.76
Profile 2	240.1	240.7	0.3	0.02
Profile 3	130.5	133.9	2.6	0.05
Profile 4	882.2	906.7	2.8	0.34

Assumptions

1. National Map data is adequate for 1D modeling purposes
2. The elevation data has been deemed appropriate for use in pre-construction 2D hydraulic modeling (HEC-RAS)
3. To the greatest extent practical this model represents ponding and flow conditions for excess rainfall occurring on the model surface. This model is an approximation of real-life flow conditions but is limited in its accuracy by the type and accuracy of its inputs. If future calibration data is gathered, the model can be rerun using the calibration data as inputs to check the viability and accuracy of the model.

APPENDIX A - Figures



SIERRA OVERHEAD ANALYTICS

Sierra Overhead Analytics, Inc.
P.O. Box 1716
Twain Harte, CA 95383
(T) 209-677-3041
(F) 209-215-2799
info@sierraoverhead.com

REV #	DESCRIPTION	DATE

PROJECT NAME:
Carriger Solar, WA

PROJECT ADDRESS:
45.875˚ lat, -120.877˚ long.

SEAL:

DATE: 2023-02-01
PROJECT #: 2020-CCR-7
DRAWN BY: JCT
CHECKED BY: OR

SHEET NAME:
Contributing Watershed Areas

SHEET NUMBER: Figure 1
REV #:

Coordinate System: NAD 1983 2011 StatePlane Washington South FIPS 4602 Ft US   Basemap Source: ESRI   Land Ownership and PLSS Source: BLM   SEZ Source: Argonne National Laboratory

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PROJECT #: 2020-CCR-7

DRAWN BY: JCT

CHECKED BY: OR

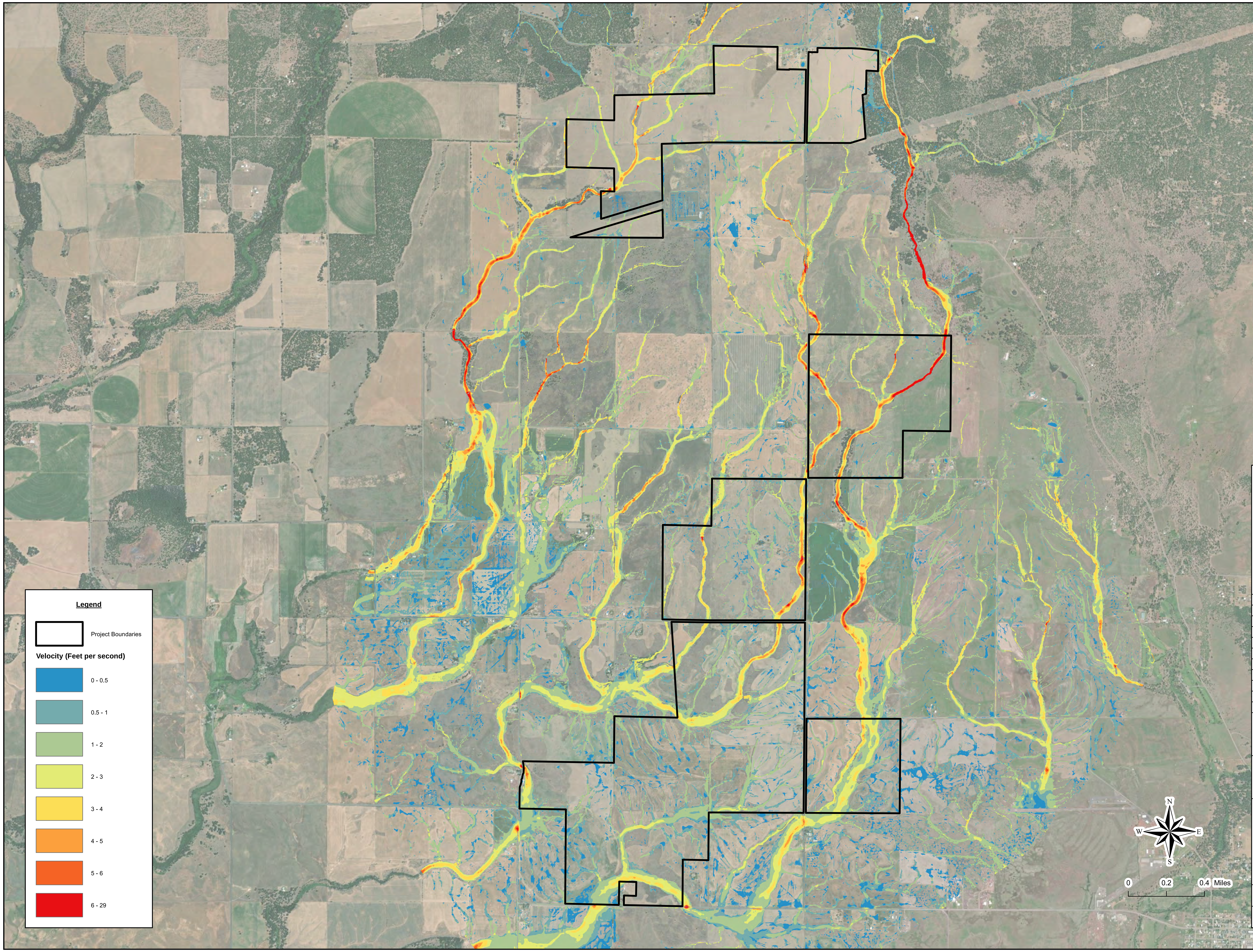
SHEET NAME: 100-Year 24-Hour Flow Event Depth Existing Conditions

SHEET NUMBER: Figure 2

REV #:

Coordinate System: NAD 1983 2011 StatePlane Washington South FIPS 4602 Ft US Basemap Source: ESRI Land Ownership and PLSS Source: BLM SEZ Source: Argonne National Laboratory

A B C D E F G H I J



SOA
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DATE: 2023-02-01

PROJECT #: 2020-CCR-7

DRAWN BY: JCT

CHECKED BY: OR

SHEET NAME: 100-Year 24-Hour Flow Event Velocity Existing Conditions

SHEET NUMBER: Figure 3

REV #:

Coordinate System: NAD 1983 2011 StatePlane Washington South FIPS 4602 Ft US   Basemap Source: ESRI   Land Ownership and PLSS Source: BLM   SEZ Source: Argonne National Laboratory

A B C D E F G H I J

soa
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SEAL:

DATE: 2023-02-01

PROJECT #: 2020-CCR-7

DRAWN BY: JCT

CHECKED BY: OR

SHEET NAME: 100-Year 24-Hour Flow Event Scour Existing Conditions

SHEET NUMBER: Figure 4

REV #:

Coordinate System: NAD 1983 2011 StatePlane Washington South FIPS 4602 Ft US   Basemap Source: ESRI   Land Ownership and PLSS Source: BLM   SEZ Source: Argonne National Laboratory

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SEAL:

DATE:
2023-02-01

PROJECT #:
2020-CCR-7

DRAWN BY:
JCT

CHECKED BY:
OR

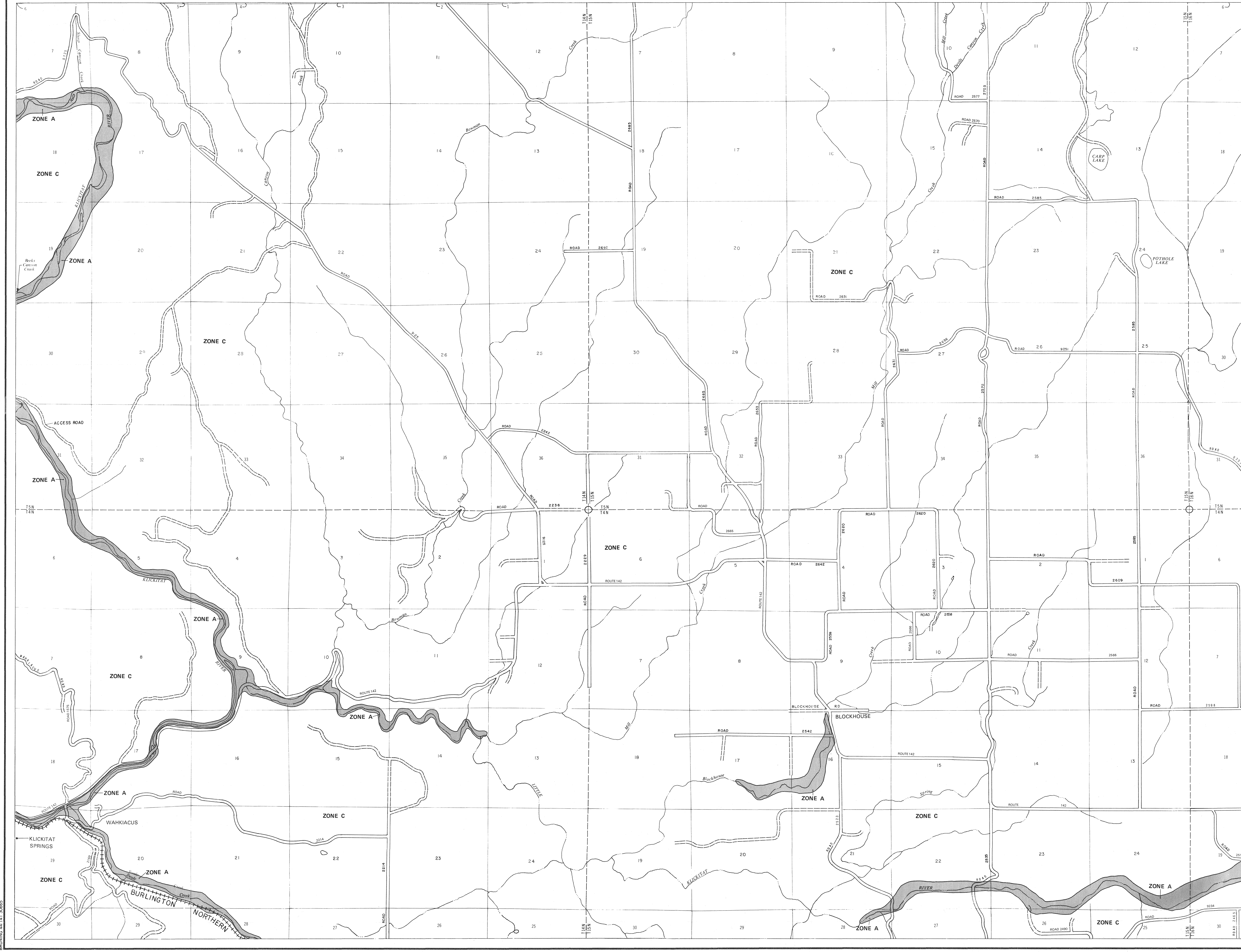
SHEET NAME:
Flow Profile Lines

SHEET NUMBER:
Figure 5

REV #:

Coordinate System: NAD 1983 2011 StatePlane Washington South FIPS 4602 Ft US Basemap Source: ESRI Land Ownership and PLSS Source: BLM SEZ Source: Argonne National Laboratory

APPENDIX B - Supporting Documentation



KEY TO MAP

500-Year Flood Boundary	ZONE B
100-Year Flood Boundary	
Zone Designations* With Date of Identification e.g., 12/2/74	ZONE A1 DATE / ZONE A5 DATE
100-Year Flood Boundary	ZONE B
500-Year Flood Boundary	
Base Flood Elevation Line With Elevation In Feet**	513
Base Flood Elevation in Feet Where Uniform Within Zone**	(EL 987)
Elevation Reference Mark	RM7×
River Mile	• M1.5

**Referenced to the National Geodetic Vertical Datum of 1929

*EXPLANATION OF ZONE DESIGNATIONS

ZONE	EXPLANATION
A	Areas of 100-year flood; base flood elevations and flood hazard factors not determined.
A0	Areas of 100-year shallow flooding where depths are between one (1) and three (3) feet; average depths of inundation are shown, but no flood hazard factors are determined.
AH	Areas of 100-year shallow flooding where depths are between one (1) and three (3) feet; base flood elevations are shown, but no flood hazard factors are determined.
A1-A30	Areas of 100-year flood; base flood elevations and flood hazard factors determined.
A99	Areas of 100-year flood to be protected by flood protection system under construction; base flood elevations and flood hazard factors not determined.
B	Areas between limits of the 100-year flood and 500-year flood; or certain areas subject to 100-year flooding with average depths less than one (1) foot or where the contributing drainage area is less than one square mile; or areas protected by levees from the base flood. (Medium shading)
C	Areas of minimal flooding. (No shading)
D	Areas of undetermined, but possible, flood hazards.
V	Areas of 100-year coastal flood with velocity (wave action); base flood elevations and flood hazard factors not determined.
V1-V30	Areas of 100-year coastal flood with velocity (wave action); base flood elevations and flood hazard factors determined.

NOTES TO USER

Certain areas not in the special flood hazard areas (zones A and V) may be protected by flood control structures.

This map is for flood insurance purposes only; it does not necessarily show all areas subject to flooding in the community or all planimetric features outside special flood hazard areas.

For adjoining map panels, see separately printed Index To Map Panels.

INITIAL IDENTIFICATION:
SEPTEMBER 6, 1974

FLOOD HAZARD BOUNDARY MAP REVISIONS:
OCTOBER 25, 1977

FLOOD INSURANCE RATE MAP EFFECTIVE:
JULY 2, 1981

FLOOD INSURANCE RATE MAP REVISIONS:

Refer to the FLOOD INSURANCE RATE MAP EFFECTIVE date shown on this map to determine when actuarial rates apply to structures in the zones where elevations or depths have been established.

To determine if flood insurance is available in this community, contact your insurance agent, or call the National Flood Insurance Program at (800) 638-6620, or (800) 424-8872.

APPROXIMATE SCALE

2000 0 2000 FEET

NATIONAL FLOOD INSURANCE PROGRAM

FIRM
FLOOD INSURANCE RATE MAP

KLICKITAT COUNTY, WASHINGTON
(UNINCORPORATED AREAS)

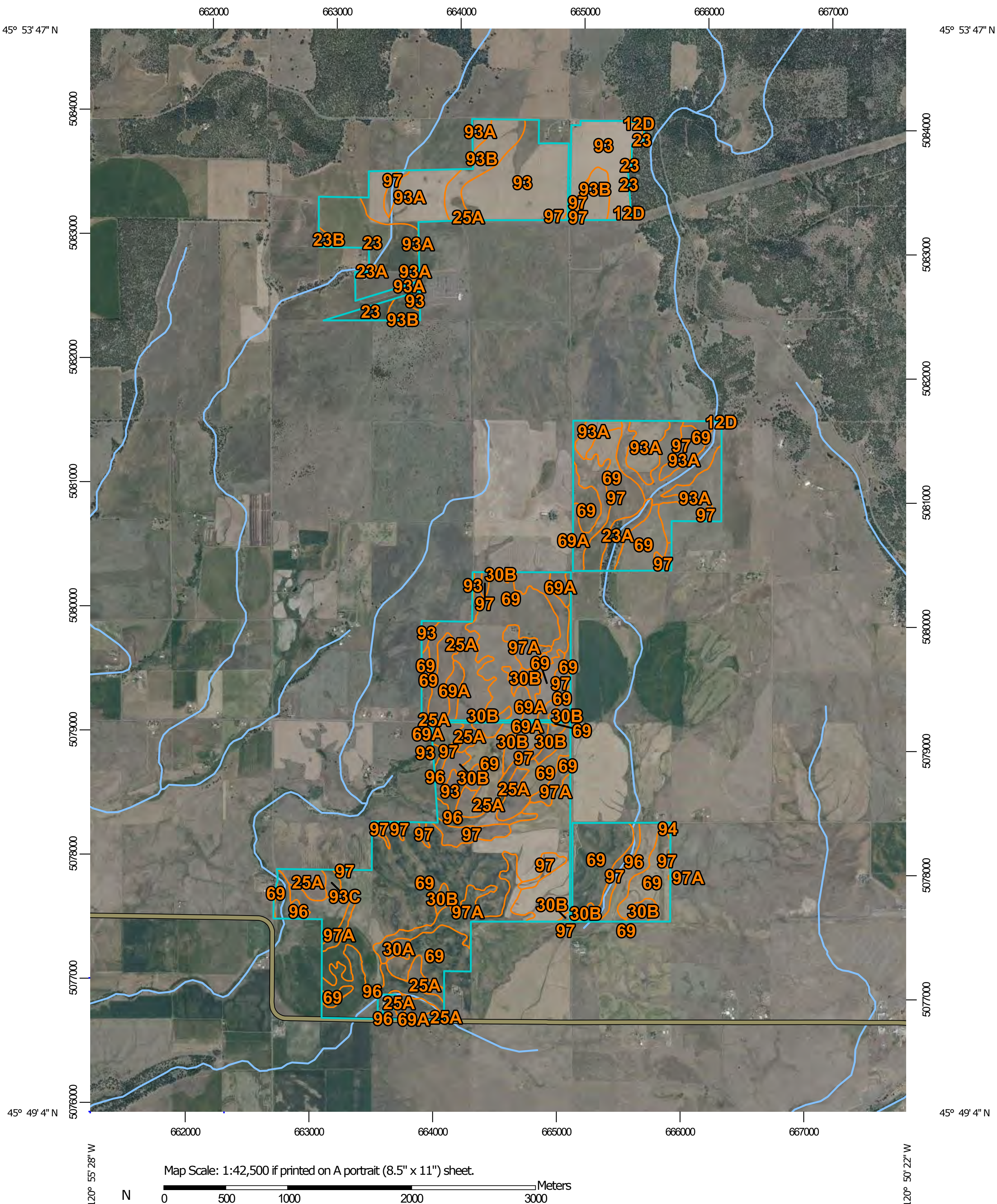
PANEL 250 OF 550
(SEE MAP INDEX FOR PANELS NOT PRINTED)

COMMUNITY-PANEL NUMBER
530099 0250 B

EFFECTIVE DATE:
JULY 2, 1981

federal emergency management agency
federal insurance administration

Soil Map



Map Scale: 1:42,500 if printed on A portrait (8.5" x 11") sheet.

Meters: 0, 500, 1000, 2000, 3000

Feet: 0, 2000, 4000, 8000, 12000

Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 10N WGS84

MAP LEGEND

Area of Interest (AOI)
- Area of Interest (AOI)

Soils
- Soil Map Unit Polygons
- Soil Map Unit Lines
- Soil Map Unit Points

Special Point Features
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh or swamp
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other
- Special Line Features

Water Features
- Streams and Canals

Transportation
- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

Background
- Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL:
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Klickitat County Area, Washington
Survey Area Data: Version 17, Sep 8, 2022

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Jun 1, 2020—Jun 2, 2020

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

Map Unit Legend

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
12D	Lyville bouldery loam, 2 to 20 percent slopes	1.0	0.0%
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25A	Leidl extremely cobbly ashy loam, 2 to 30 percent slopes	125.6	6.1%
30A	Rockly-Lorena complex, 2 to 15 percent slopes	6.4	0.3%
30B	Rockly-Lorena complex, 2 to 15 percent slopes, extremely stony	93.9	4.5%
69	Goldendale silt loam, basalt substratum, 2 to 5 percent slopes	823.7	39.8%
69A	Goldendale silt loam, basalt substratum, 5 to 10 percent slopes	50.6	2.4%
93	Goldendale silt loam, 2 to 5 percent slopes	208.6	10.1%
93A	Goldendale silt loam, 5 to 10 percent slopes	168.0	8.1%
93B	Goldendale silt loam, 10 to 15 percent slopes	71.5	3.5%
93C	Goldendale silt loam, 15 to 30 percent slopes	5.4	0.3%
94	Lorena silt loam, 2 to 5 percent slopes	1.1	0.1%
95A	Konert silt loam, 0 to 2 percent slopes	9.8	0.5%
96	Blockhouse silt loam, 0 to 5 percent slopes	99.8	4.8%
97	Munset stony silt loam, 0 to 5 percent slopes	195.0	9.4%
97A	Setnum silt loam, 0 to 3 percent slopes	81.3	3.9%
Totals for Area of Interest		**2,069.4**	**100.0%**

==
Runoff Curve Number Report
(Generated by WMS)
==

Wed Oct 07 11:35:10 2020

Runoff Curve Number Report for Basin 1B

HSG	Land Use Description	CN	Area mi^2	Product CN x A
B	Evergreen Forest Land	60	2.036	122.155
C	Evergreen Forest Land	73	3.963	289.269
A	Evergreen Forest Land	36	0.006	0.215
D	Evergreen Forest Land	79	0.056	4.394

CN (Weighted) = Total Product \ Total Area
==
68.6513

Table 2-2a Runoff curve numbers for urban areas [1/]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2/]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3/]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4/]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5/]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

1 Average runoff condition, and $I_a = 0.2S$.
2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table 2-2b Runoff curve numbers for cultivated agricultural lands [1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

1 Average runoff condition, and I_a=0.2S
2 Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.
3 Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2-2c Runoff curve numbers for other agricultural lands 1/

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. 2/	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. 3/	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 4/	48	65	73
Woods—grass combination (orchard or tree farm). 5/	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. 6/	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 4/	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.
2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.
3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.
4 Actual curve number is less than 30; use CN = 30 for runoff computations.
5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 2-2d Runoff curve numbers for arid and semiarid rangelands [1/]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition [2/]	A [3/]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

1 Average runoff condition, and I_a, = 0.2S. For range in humid regions, use table 2-2c.
2 Poor: <30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.
3 Curve numbers for group A have been developed only for desert shrub.

Figure 2-3 Composite CN with connected impervious area.

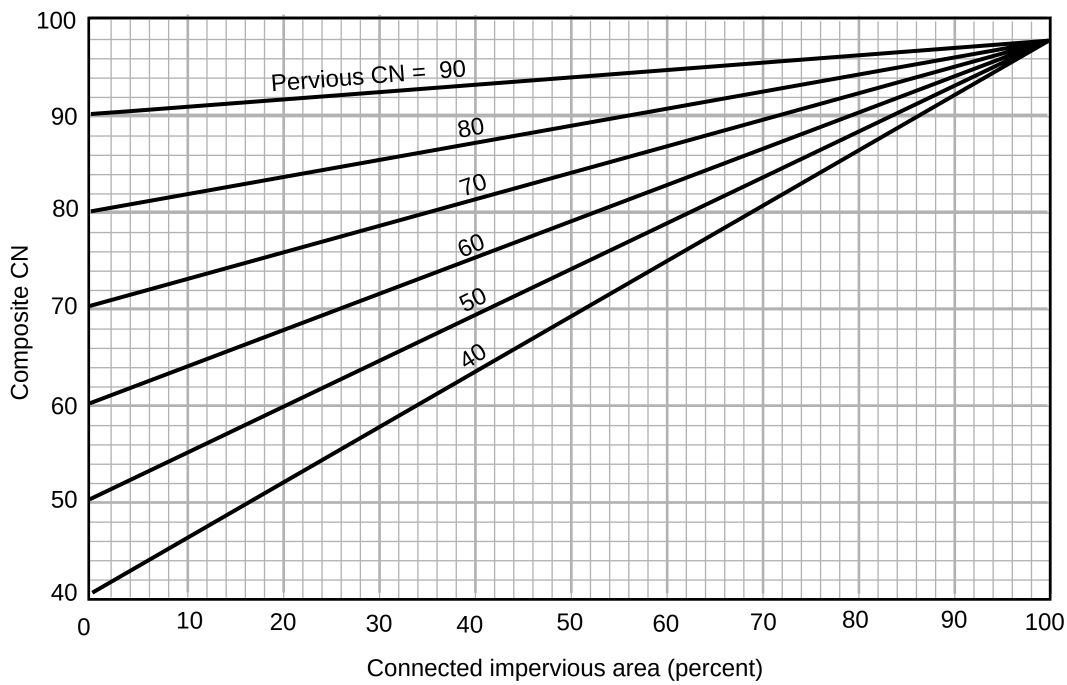
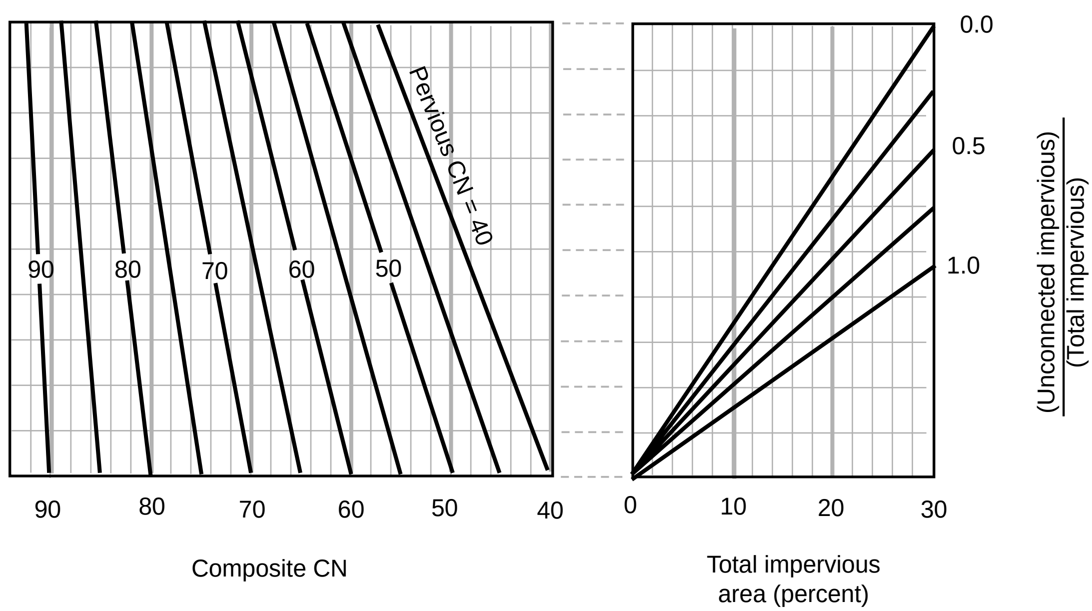


Figure 2-4 Composite CN with unconnected impervious areas and total impervious area less than 30%



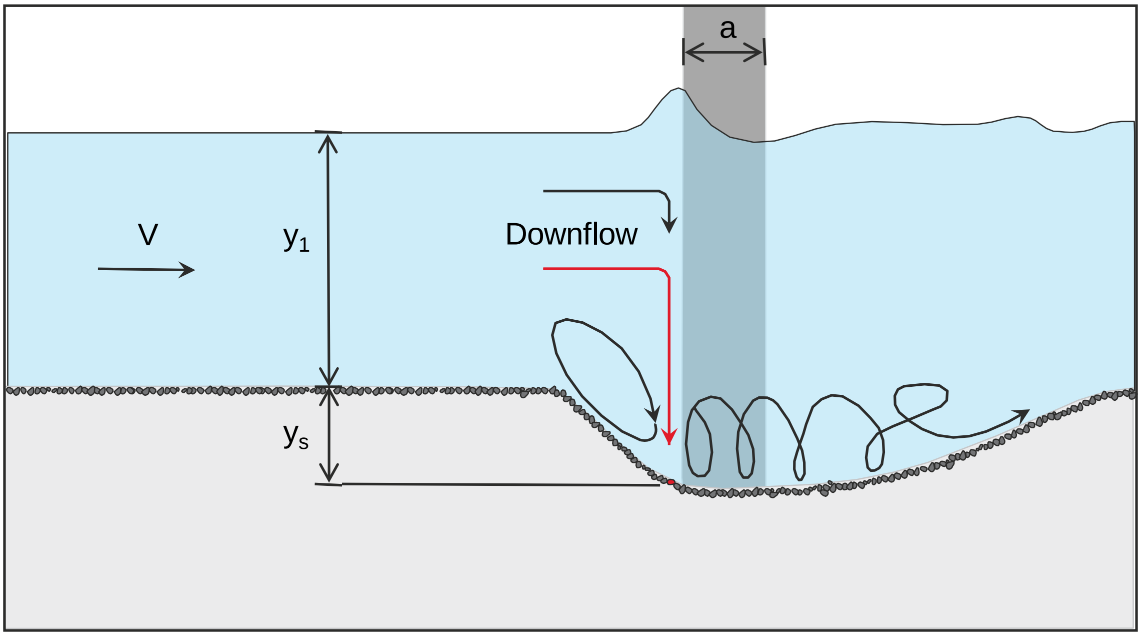


Figure 7.2. Definition sketch for pier scour.

The HEC-18 equation is:

$$\frac{y_s}{y_1} = 2.0\ K_1\ K_2\ K_3 \left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43} \tag{7.1}$$

As a Rule of Thumb, the maximum scour depth for round nose piers aligned with the flow is:

$y_s \leq 2.4$ times the pier width (a) for $Fr \leq 0.8$ (7.2)
$y_s \leq 3.0$ times the pier width (a) for $Fr > 0.8$

In terms of y_s/a, Equation 7.1 is:

$$\frac{y_s}{a} = 2.0\ K_1\ K_2\ K_3 \left(\frac{y_1}{a}\right)^{0.35} Fr_1^{0.43} \tag{7.3}$$

where:

y_s	=	Scour depth, ft (m)
y_1	=	Flow depth directly upstream of the pier, ft (m)
K_1	=	Correction factor for pier nose shape from Figure 7.3 and Table 7.1
K_2	=	Correction factor for angle of attack of flow from Table 7.2 or Equation 7.4
K_3	=	Correction factor for bed condition from Table 7.3
a	=	Pier width, ft (m)
L	=	Length of pier, ft (m)
Fr_1	=	Froude Number directly upstream of the pier = $V_1/(gy_1)^{1/2}$
V_1	=	Mean velocity of flow directly upstream of the pier, ft/s (m/s)
g	=	Acceleration of gravity (32.2 ft/s^2) (9.81 m/s^2)

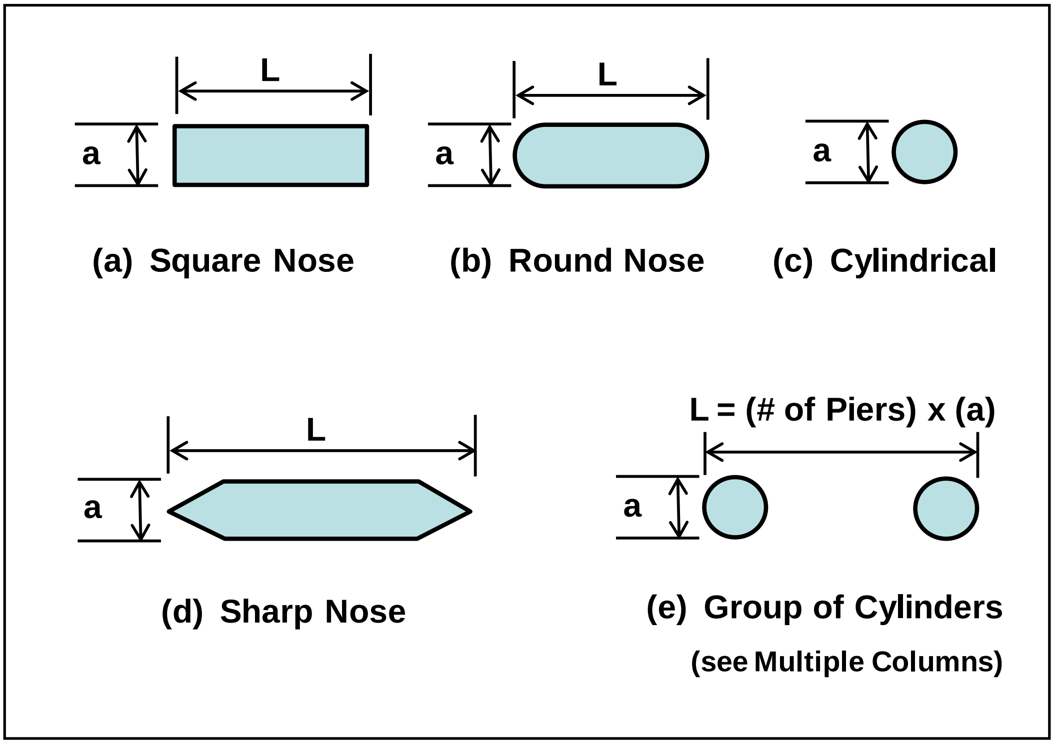


Figure 7.3. Common pier shapes.

The correction factor, K_2, for angle of attack of the flow, 2, is calculated using the following equation:

$$K_2 = (\text{Cos}\ \theta + \frac{L}{a}\ \text{Sin}\ \theta)^{0.65} \qquad (7.4)$$

If L/a is larger than 12, use L/a = 12 as a maximum in Equation 7.4 and Table 7.2. Table 7.2 illustrates the magnitude of the effect of the angle of attack on local pier scour.

Table 7.1. Correction Factor, K_1, for Pier Nose Shape.

Shape of Pier Nose	K_1
(a) Square nose	1.1
(b) Round nose	1.0
(c) Circular cylinder	1.0
(d) Group of cylinders	1.0
(e) Sharp nose	0.9

Table 7.2. Correction Factor, K_2, for Angle of Attack, 2, of the Flow.

Angle	L/a=4	L/a=8	L/a=12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Angle = skew angle of flow
L = length of pier

Table 7.3. Increase in Equilibrium Pier Scour Depths, K_3, for Bed Condition.		
Bed Condition	Dune Height ft	K_3
Clear-Water Scour	N/A	1.1
Plane bed and Antidune flow	N/A	1.1
Small Dunes	$10 > H \geq 2$	1.1
Medium Dunes	$30 > H \geq 10$	1.2 to 1.1
Large Dunes	$H \geq 30$	1.3

Notes:

1. The correction factor K_1 for pier nose shape should be determined using Table 7.1 for angles of attack up to 5 degrees. **For greater angles, K_2 dominates and K_1 should be considered as 1.0**. If L/a is larger than 12, use the values for L/a = 12 as a maximum in Table 7.2 and Equation 7.4.

2. The values of the correction factor K_2 should be applied only when the field conditions are such that the entire length of the pier is subjected to the angle of attack of the flow. Use of this factor will result in a significant over-prediction of scour if (1) a portion of the pier is shielded from the direct impingement of the flow by an abutment or another pier; or (2) an abutment or another pier redirects the flow in a direction parallel to the pier. For such cases, judgment must be exercised to reduce the value of the K_2 factor by selecting the effective length of the pier actually subjected to the angle of attack of the flow. **Equation 7.4 should be used for evaluation and design**. Table 7.2 is intended to illustrate the importance of angle of attack in pier scour computations and to establish a cutoff point for K_2 (i.e., a maximum value of 5.0).

3. The correction factor K_3 results from the fact that for plane-bed conditions, which is typical of most bridge sites for the flood frequencies employed in scour design, the maximum scour may be 10 percent greater than computed with Equation 7.1. In the **unusual** situation where a dune bed configuration **with large dunes** exists at a site during flood flow, the maximum pier scour may be 30 percent greater than the predicted equation value. This may occur on very large rivers, such as the Mississippi. For smaller streams that have a dune bed configuration at flood flow, the dunes will be smaller and the maximum scour may be only 10 to 20 percent larger than equilibrium scour. For antidune bed configuration the maximum scour depth may be 10 percent greater than the computed equilibrium pier scour depth.

4. Piers set close to abutments (for example at the toe of a spill through abutment) must be carefully evaluated for the angle of attack and velocity of the flow coming around the abutment.

7.3 FLORIDA DOT PIER SCOUR METHODOLOGY

Equation 7.1 has been included in all previous versions of HEC-18 and has been used for bridge scour evaluations and bridge design for countless bridges in the U.S. and worldwide. This equation, which was developed and modified over several decades, could be improved by including bed material size and a more detailed consideration of the bridge pier flow field (see Section 3.6.2). An NCHRP study (NCHRP 2011a) evaluated 22 pier scour equations and found that although the HEC-18 equation did well in comparison to the other equations, the Sheppard and Miller (2006) equation generally performed better for both laboratory and