MEMORANDUM

To: Holly Piza, P.E., CFM, Brik Zivkovich, P.E, CFM
Mile High Flood District

Via email: hpiza@mhfd.org, bzivkovich@mhfd.org,

From: Wright Water Engineers, Inc.
Andrew Earles, Ph.D., P.E., P.H., D.WRE, Chris Olson, Ph.D., P.E., and Matthew Howard, EIT

Date: October 13, 2023

Re: Determination of Solar Panel Field Runoff Coefficients

This memorandum documents the methods and results of hydrologic modeling analysis to estimate runoff coefficients and imperviousness values for solar panel fields under two different situations. The first scenario addresses solar installations that involve minimal land disturbances in areas that are or will be vegetated using native grasses. This approach assumes that soils are not significantly compacted during construction and that where disturbance (cut and fill) is required, proper measures are taken to manage topsoil (see the Topsoil Management Guide) and all land disturbed is revegetated to an approximate uniform density of at least 80%. The second scenario addresses solar installations that use gravel for the areas between and beneath the panels.

1.0 Methodology

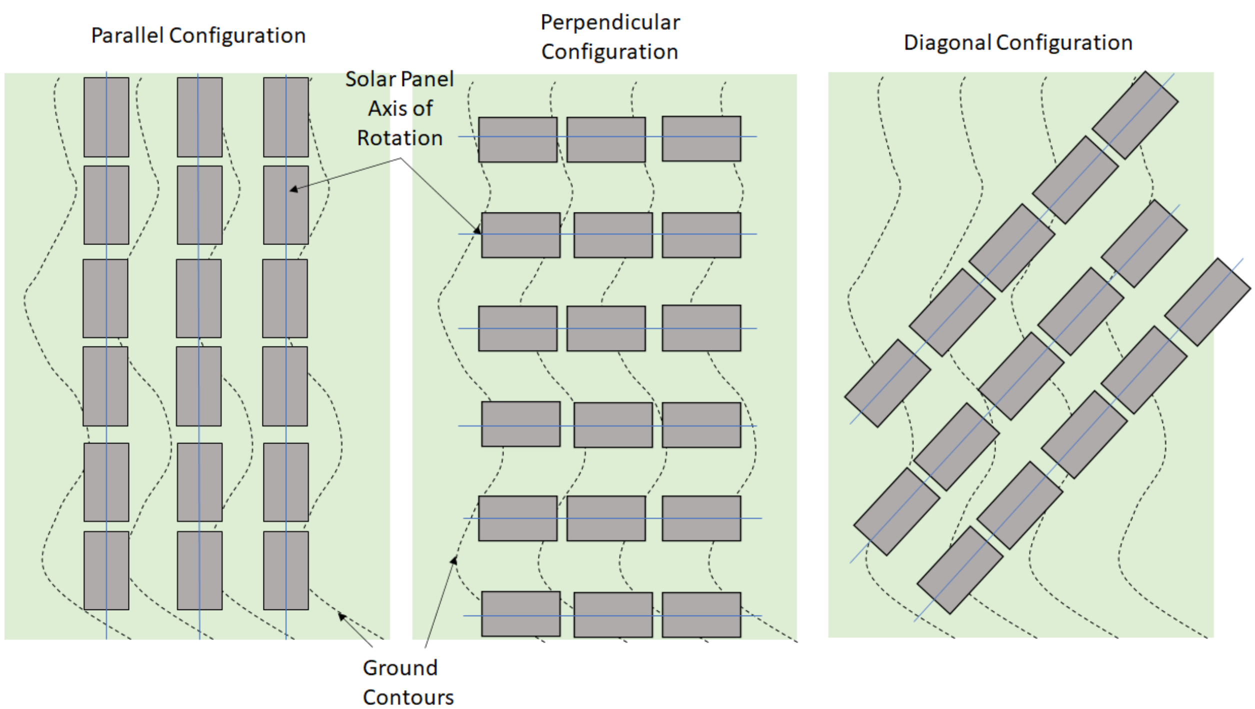
The EPA Stormwater Management Model (SWMM) was used to simulate runoff from typical solar panel field installations. The SWMM model was used because it has the computational and workflow capabilities of being able to “cascade” runoff from one type of surface (e.g., solar panel) onto another type of surface (e.g., ground), with each surface having different runoff-generating characteristics.

For this analysis, we simulated three different surfaces under three different configurations of solar panel alignments. The surfaces were:

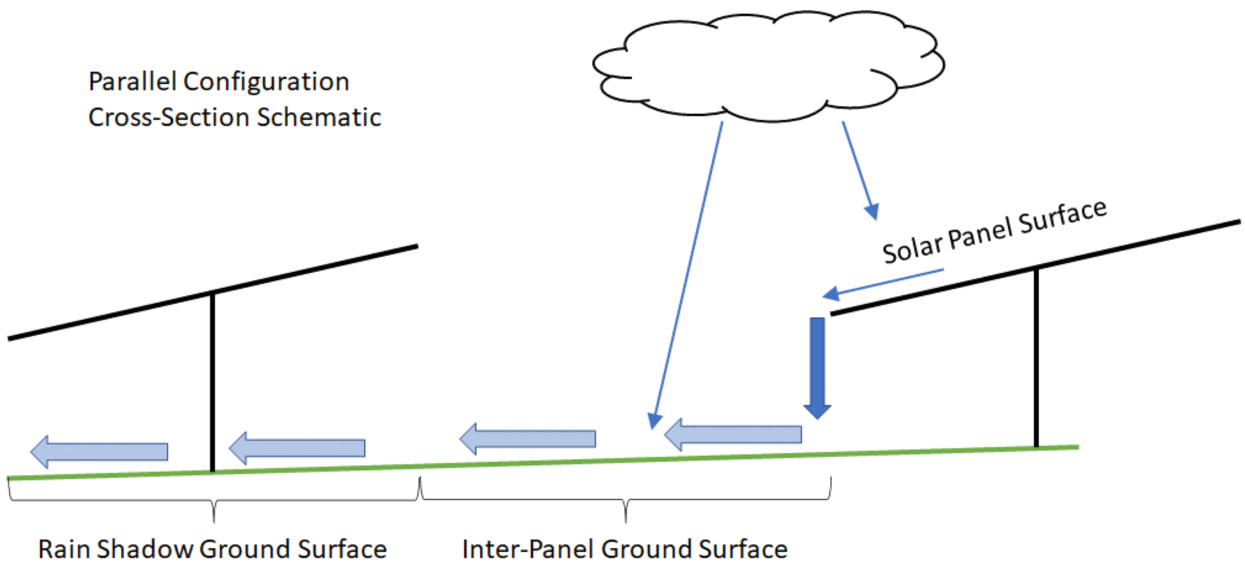
- The Solar Panel surface is impervious, receives direct rainfall and directs runoff onto the Inter-Panel surface.
- The Inter-Panel ground surface represents the ground surface between the solar panels. It receives both direct rainfall and runoff from the Solar Panel surface and directs runoff to either the Rain Shadow surface or adjacent Inter-Panel surfaces depending on configuration. The perviousness of the Inter-Panel is dependent upon the surface type.
- The Rain Shadow ground surface represents the ground surface underneath the solar panels. It does not receive any direct rainfall and only receives direct runoff from the Inter-Panel surface under certain configurations. The perviousness of the Rain Shadow is dependent upon the surface type.

This analysis only addressed the areas of the site where panels are installed. Typically, a solar field will also include additional impervious area such as access roads and pads for electrical appurtenances. These areas must be included in the overall imperviousness by area-weighting appropriate imperviousness values for the solar panel areas and the other impervious surfaces on the project site. An example is provided at the end of this memorandum that illustrates this process.

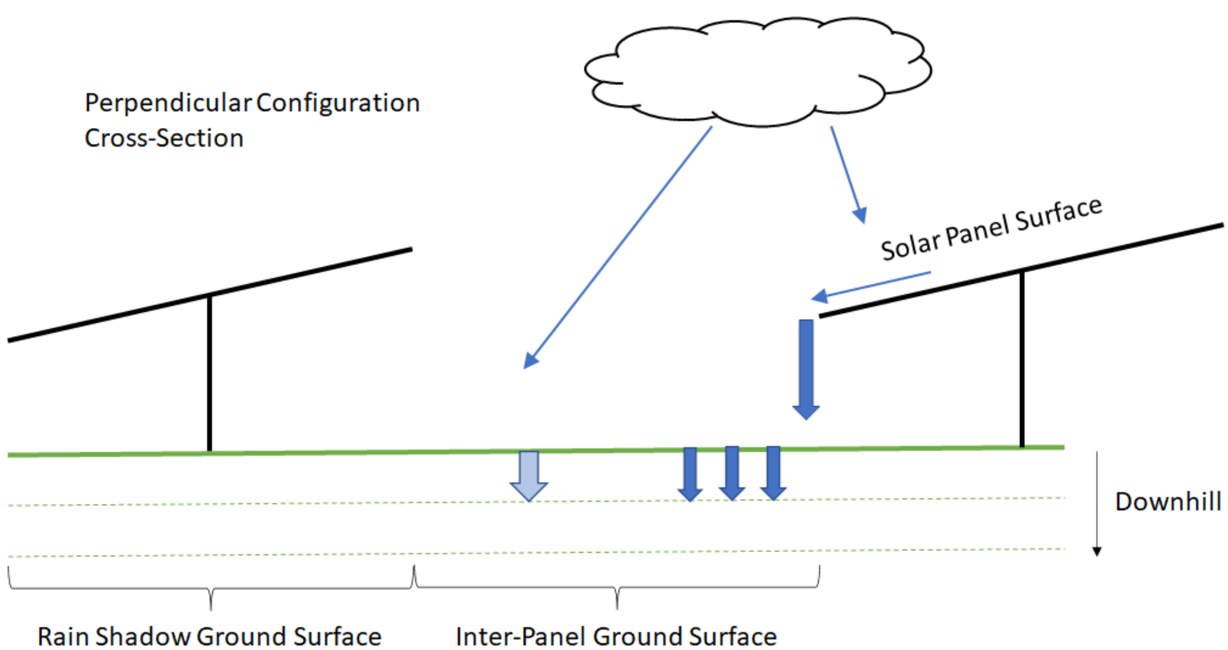
The three different configurations (parallel, perpendicular, and diagonal) represent different alignments of the solar panels with the contours of the ground surface. These alignments affect how runoff from the solar panels cascades across the ground surface in the downhill direction. These three configurations were evaluated for native grass cover and for gravel cover.



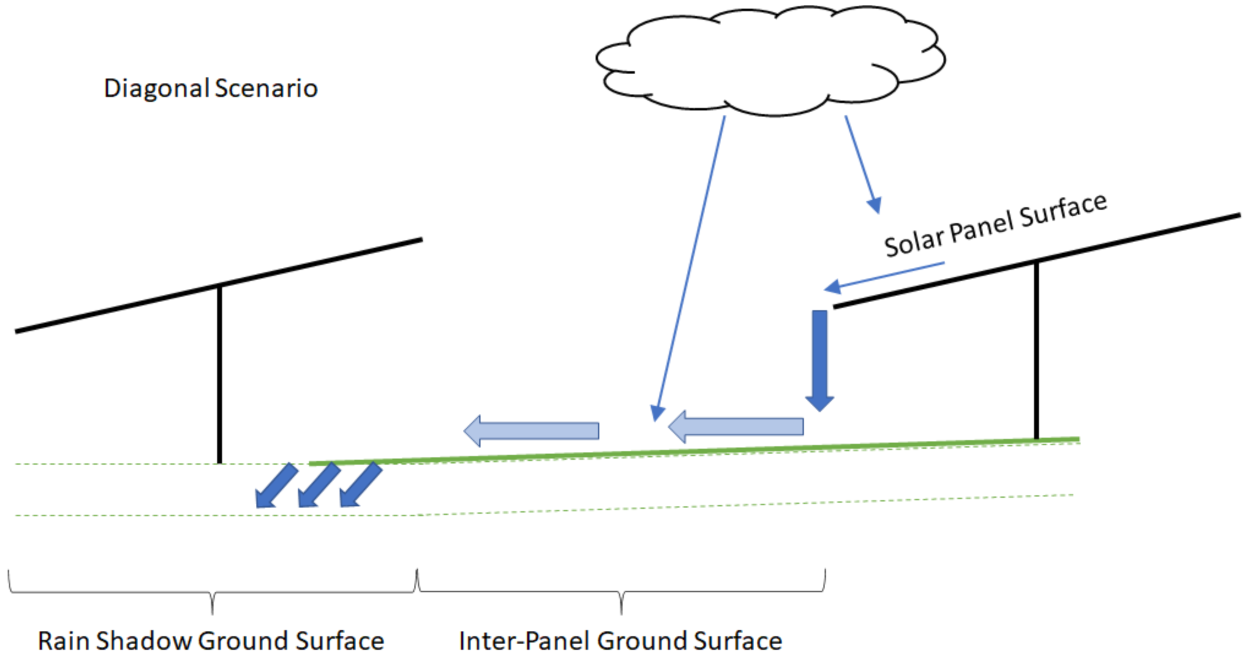
Parallel Configuration - Due to the solar panels being aligned parallel to the ground contours, runoff from the Solar Panel surface is distributed evenly across both the Inter-Panel and Rain Shadow surfaces. This configuration maximizes runoff reduction potential because runoff from the solar panels has the opportunity to attenuate and infiltrate across all available pervious area.



Perpendicular Configuration - Due to the solar panels being aligned perpendicular to the ground contours, runoff from the solar panels becomes channelized quickly after reaching the Inter-Panel surface and does not continue to runoff into the Rain Shadow surface. The Inter-Panel surface is only partially effective for runoff reduction and the Rain Shadow surface is not effective at all for runoff reduction. This configuration represents the minimum runoff reduction opportunity.



Diagonal Configuration - Runoff from the solar panels is distributed evenly across the Inter-Panel surface but becomes mostly channelized by the time it reaches the Rain Shadow surface.



In addition to analysis using SWMM, WWE performed comparisons with results from the University of Minnesota's PV-SMaRT Solar Runoff Calculator Version 3.0[1] (referred to as "Solar Runoff Calculator"). This is a spreadsheet calculator that implements Natural Resource Conservation Service (NRCS) Curve Number (CN) volumetric runoff calculations. The solar calculator is based on a 24-hour storm instead of the 2-hour storm that is used in the Mile High Flood District (MHFD) region. WWE corresponded with the author of the Solar Runoff Calculator, Dr. David Mulla, to confirm that 2-hour storms, with greater intensity, would be expected to have fewer losses (e.g., less infiltration) than represented by a CN for a 24-hour storm. Dr. Mulla provided WWE with a reference that he recommended for adjustment of results for a 2-hour storm duration[2]. Although the CN method, even with adjustments, was expected to generate different results than SWMM due to fundamental differences in infiltration methods, WWE performed calculations using the Solar Runoff Calculator, adjusted for a 2-hour storm duration as a point of comparison with SWMM results.

2.0 SWMM Model Parameterization

The surfaces described above were represented as a series of individual subcatchments. Runoff from each subcatchment was either "cascaded" to downhill subcatchments or directed to the model "outlet," depending on the solar panel configuration. Table 1 summarizes the names, areas and description of the subcatchments used for each configuration.

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[1] Mulla, D. 2023. *PV-SMaRT Solar Runoff Calculator Version 3.0.* University of Minnesota, Technology No. 2023-053, https://license.umn.edu/product/pv-smart-solar-runoff-calculator-version-30.

[2] Meadows, M. 2016. Adjusting NRCS Curve Number for Rainfall Durations Less Than 24 Hours. Journal of South Carolina Water Resources, Volume 3, Issue 1, Pages 43-47.

Table 1. Summary of SWMM Subcatchments Used to Represent each Solar Panel Farm Configuration

Configuration	Subcatchment Name and Area	Description
Parallel	Solar Panel: 1 acre Inter-Panel: 1 acre Rain Shadow: 1 acre	Runoff from the Solar Panel is directed to the Inter-Panel. Inter-Panel runoff is directed to the Rain Shadow. The ratio of Receiving Pervious Area to Unconnected Impervious area is 2:1
Perpendicular	Solar Panel: 1 acre Inter-Panel_1: 0.5 acres Inter-Panel_2: 0.5 acres Rain Shadow: 1 acre	Runoff from the Solar Panel is directed to Inter-Panel_1. Inter-Panel_1 and Inter-Panel_2 runoff is directed to the outlet (downhill). The ratio of Receiving Pervious Area to Unconnected Impervious area is 0.5:1
Diagonal	Solar Panel: 1 acre Inter-Panel: 1 acre Rain Shadow_1: 0.5 acre Rain Shadow_2: 0.5 acre	Runoff from the Solar Panel is directed to the Inter-Panel. Inter-Panel runoff is directed to the Rain Shadow_1 surface. The ratio of Receiving Pervious Area to Unconnected Impervious area is 1.5:1

Rainfall for the 2-, 5-, and 100-year design storms was applied only to the Solar Panel and Inter-Panel surfaces. The 2-hour design storms were generated using CUHP and NOAA Atlas 14 60-minute rainfall depths for Aurora, Colorado.

All simulations used Horton's infiltration parameters for Type C/D soils and slopes of 5%. Typical Manning's N and depression storage values for impervious and pervious surfaces were applied based on the MHFD's Urban Storm Drainage Criteria Manual.

For the Solar Runoff Calculator, WWE used the same geometric parameters and soil types represented in SWMM. WWE implemented an adjustment procedure for CN values based on Meadows' work in 2016 to reflect CN losses for a 2-hour storm duration.

3.0 Results and Discussion

3.1 Solar Fields with Native Vegetation

3.1.1 SWMM Analysis

The results of the SWMM simulations were used to calculate volumetric runoff coefficients. Volumetric runoff coefficients were computed by dividing the total runoff volume by the total precipitation volume. Table 2 and Figure 1 present the runoff coefficient results from SWMM. As expected, the parallel configuration has the lowest runoff coefficients, the perpendicular configuration has the largest and the diagonal configuration is in between the others. Imperviousness percentages were assigned based on Table 6-5 in the MHFD's Urban Storm Drainage Criteria Manual (MHFD Manual) which is provided in Appendix A. WWE calculated imperviousness from SWMM results for the 2-, 5-, and 100-year events. WWE presents results of the SWMM simulations in Table 2 and Figure 1.

Table 2. Volumetric Coefficients and Percent Imperviousness from SWMM Modeling – Solar Fields with Native Vegetation

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.01	2%	0.01	2%	0.37	48%
5-year	0.02	<2%	0.16	15%	0.45	52%
100-year	0.47	<2%	0.58	23%	0.72	58%
Average	----	2%	----	13%	----	52%

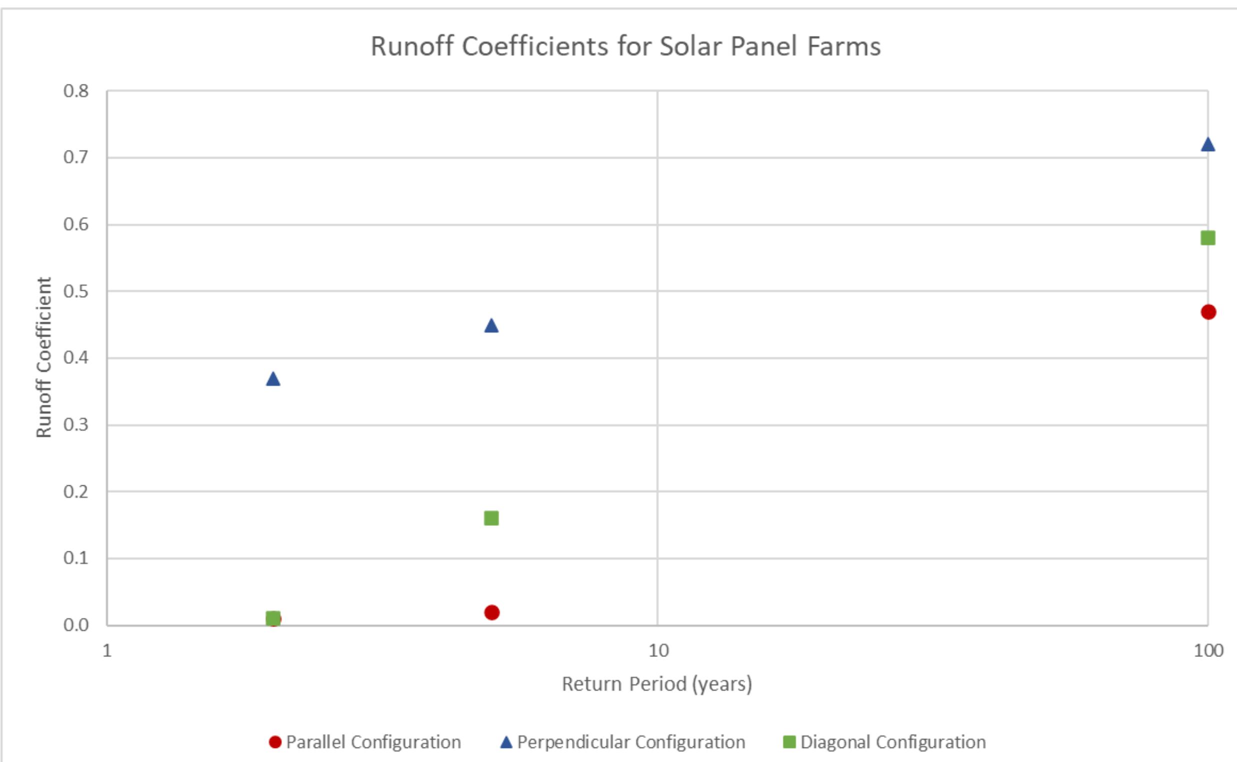


Figure 1. Volumetric Runoff Coefficients from SWMM Modeling – Solar Fields with Native Vegetation

Percentage imperviousness values back-calculated from Table 6-5 varied only slightly for parallel solar orientations, despite the volumetric runoff coefficient increasing from 0.01 to 0.47 from the 2- to the 100-year event. This is due to the low infiltration rate of hydrologic soil group (HSG) C soils once saturated, which is modeled by SWMM and accounted for in the intercepts of the relationships summarized by Table 6-5. For the simulated 2- and 5-year events with solar panels oriented parallel to surface contours, the pervious native vegetation surface type in the Rain Shadow and Inter-Panel infiltrated most of the runoff from the Solar Panel without saturating the HSG C soils. However, during the simulated 100-year event the underlying soils were fully saturated and runoff was produced which was less than but similar to values expected for low-imperviousness watersheds with HSG C soils. The relationship between calculated volumetric runoff coefficients and event return periods varied according to an approximately log-linear relationship for each panel configuration which is expected for watersheds with HSG C soils.

3.1.2 Solar Runoff Calculator

Using similar input parameters and the adjustments from a 24-hour to 2-hour storm recommended by the developer of the Solar Runoff Calculator, the Solar Runoff Calculator produced the results shown in Table 3. As noted above, imperviousness values that were back-calculated from SWMM using Table 6-5 in the MHFD Manual are averaged in Table 3 due to variability in calculated imperviousness values.

Table 3. Volumetric Coefficients and Percent Imperviousness from Solar Runoff Calculator Adjusted for 2-hour Storm – Solar Fields with Native Vegetation

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.01	2%	0.07	12%	0.14	20%
5-year	0.24	25%	0.29	31%	0.33	37%
100-year	0.63	35%	0.65	40%	0.67	45%
Average	----	21%	----	28%	----	34%

While there are differences between the Solar Runoff Calculator and SWMM results (as expected), the Solar Runoff Calculator results clearly show that solar fields have the potential to increase runoff relative to undeveloped conditions. The Solar Runoff Calculator results show higher estimated percent imperviousness for the parallel and diagonal installations relative to SWMM, while the results for perpendicular conditions are slightly lower than the SWMM results, but of a similar magnitude. Table 4 presents averaged and rounded percent imperviousness results from SWMM and the Solar Runoff Calculator with the range of results. This averaging was performed since there is uncertainty associated with both methods, and the two methods yield generally similar results, with some differences. Since SWMM is commonly used for hydrology in the MHFD region and because the Solar Runoff Calculator has been widely applied by the solar industry elsewhere, WWE averaged values from the two methods and then rounded results to the nearest 5% for the recommended values.

Table 4. Averages and Ranges of Percent Imperviousness Values from SWMM and Solar Runoff Calculator for Solar Fields with Native Vegetation

Parameter	Parallel Percent Impervious	Diagonal Percent Impervious	Perpendicular Percent Impervious
Avg of SWMM and Solar Runoff Calculator	10%	20%	45%
Low Range	<2%	2%	20%
High Range	35%	40%	58%

3.2 Solar Fields with Gravel Cover

3.2.1 SWMM Analysis

SWMM simulations were repeated with input parameters appropriate to reflect increased roughness and imperviousness in the rain shadow and inter-panel areas when gravel is selected for solar field installations. Table 5 and Figure 2 present the runoff coefficient results from SWMM modeling of solar fields with gravel ground cover. The runoff coefficients calculated from SWMM modeling results for solar fields with gravel ground cover followed the same trend as the simulations performed for solar fields with native vegetation, but the increased magnitude of calculated runoff coefficients reflects the impact of the increased imperviousness of gravel ground cover. As expected, the parallel configuration has the lowest runoff coefficients, the perpendicular configuration has the largest, and the diagonal configuration is in between the others. Imperviousness percentages were assigned based on Table 6-5 in the MHFD Manual. WWE calculated imperviousness from SWMM results for the 2-, 5-, and 100-year events. WWE presents averages in Table 5 since there is some variability in the imperviousness values when they are back-calculated from SWMM runoff results using Table 6-5 in the MHFD Manual.

Table 5. Volumetric Coefficients and Percent Imperviousness from SWMM Modeling – Solar Fields with Gravel Ground Cover

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.28	37%	0.39	51%	0.65	80%
5-year	0.38	43%	0.51	59%	0.70	81%
100-year	0.69	50%	0.76	68%	0.85	90%
Average	-	43%	-	59%	-	84%

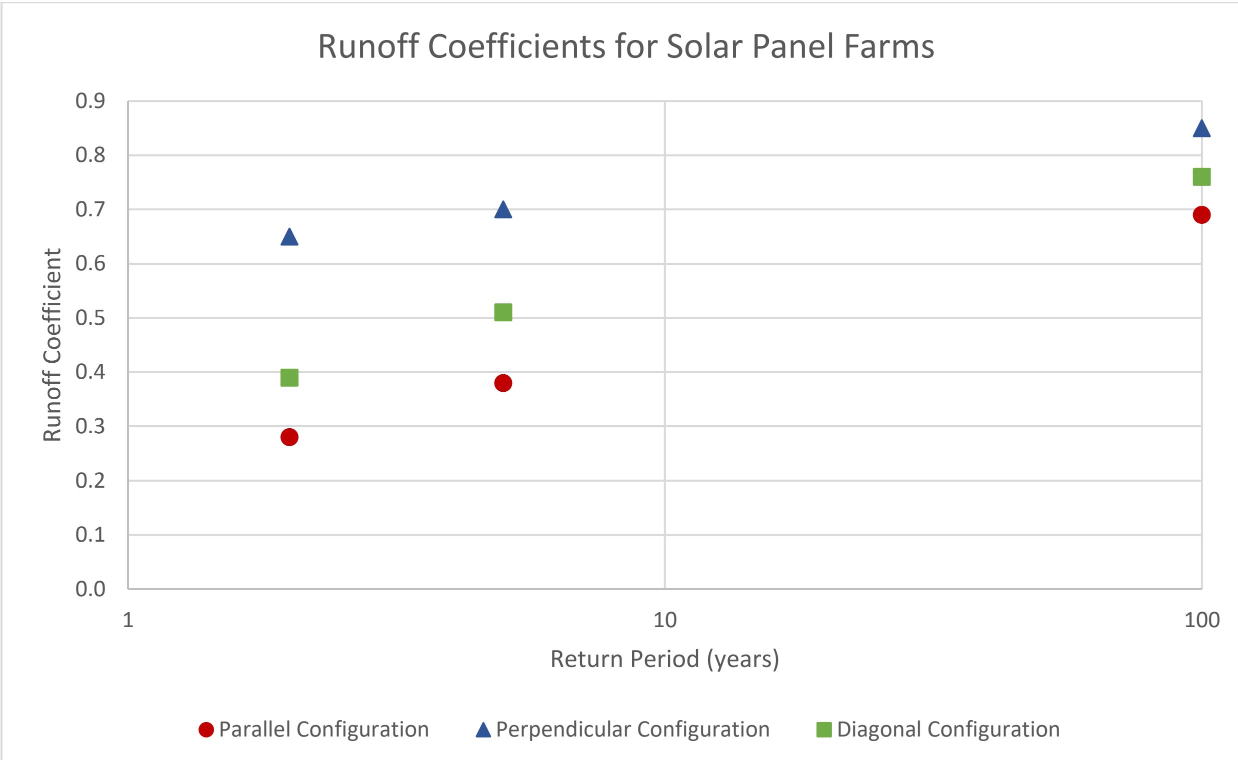


Figure 2. Volumetric Runoff Coefficients from SWMM Modeling – Solar Fields with Gravel Ground Cover

3.2.2 Solar Runoff Calculator

Solar Runoff Calculator analyses repeated for solar fields with gravel ground cover produce the results shown in Table 6. As described above, imperviousness values that were back-calculated from the Solar Runoff Calculator using Table 6-5 in the MHFD Manual are averaged in Table 6 due to variability in calculated imperviousness values. due to variability in calculated imperviousness values.

Table 6. Volumetric Coefficients and Percent Imperviousness from Solar Runoff Calculator Adjusted for 2-hour Storm – Solar Fields with Gravel Ground Cover

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.32	43%	0.38	50%	0.43	55%
5-year	0.47	54%	0.52	60%	0.56	65%
100-year	0.74	63%	0.76	68%	0.78	73%
Average	----	53%	----	59%	----	64%

The differences between runoff coefficients calculated with the Solar Runoff Calculator and SWMM results show the same relationship observed when analyses were performed for solar panel fields with native vegetation. The Solar Runoff Calculator results show higher estimated percent imperviousness for the parallel and diagonal installations relative to SWMM, while the results for perpendicular conditions are similar to, but slightly lower than, the SWMM results. Table 7 presents averages of percent imperviousness from SWMM and the Solar Runoff Calculator with the range of results. As previously noted, we have averaged and rounded results from the SWMM and Solar Runoff Calculator analysis in Table 7. Averaging was performed because there is uncertainty associated with both methods, and the two methods yield generally similar results, with some differences. WWE averaged values from the two methods and then rounded results to the nearest 5% for the recommended values.

Table 7. Averages and Ranges of Percent Imperviousness Values from SWMM and Solar Runoff Calculator for Solar Fields with Gravel Ground Cover

Parameter	Parallel Percent Impervious	Diagonal Percent Impervious	Perpendicular Percent Impervious
Avg of SWMM and Solar Runoff Calculator	50%	60%	75%
Low Range	37%	50%	55%
High Range	63%	68%	90%

3.3 Adjustments for Variable Panel and Aisle Widths

WWE performed SWMM modeling and Solar Runoff Calculator analyses assuming equal widths for solar panels and inter-panel areas. To apply these analyses to solar fields with variable panel spacing, Equation 1 through Equation 4 were developed. Equation 1 accounts for the relative impact of panel and aisle width on runoff coefficients calculated for solar fields, while

Equation 2 through Equation 4 are evaluated to solve Equation 1. Because our analyses indicate that solar arrays parallel to ground contours provide minimal increases in site imperviousness, standard recommended impervious values remain constant for all combinations of solar panel and inter-panel aisle widths.

$$I^* = \frac{2I + I_a C_a + I_p C_p}{2 + C_a + C_p}$$

Equation 1. I^*= The calculated impervious proportion of solar fields with variable aisle/panel widths, I = Standard imperviousness for solar panel orientation/ground cover type, I_a = Aisle ground cover imperviousness, I_p = Solar panel orientation imperviousness, C_a = Aisle width adjustment factor, C_p = Panel width adjustment factor

$$I_p = 2I - I_a;\ I_a = \begin{cases} 0.10 \ if\ native\ grass \\ 0.50 \ if\ gravel \end{cases}$$

Equation 2. NOTE: For solar array configurations oriented parallel to surface contours, $I_a = I_p = I = I^*$

$$C_a = \frac{w_{a,proj}}{10} - 1$$

Equation 3. $w_{a,proj}$ = Width of aisles from project site plans

$$C_p = \frac{w_{p,proj}}{10} - 1$$

Equation 4. $w_{p,proj}$ = Width of solar panels from project site plans

Equation 1 through Equation 4 have been solved for each solar array orientation and ground cover type with a variety of panel and aisle width combinations in Table 8 through Table 11 presented below.

Table 8. Runoff Coefficients Calculated for Variable Widths for Solar Fields Oriented Diagonal to Ground Surface Contours with Native Grass Ground Cover

Width of Panels, $w_{p,proj}$ (feet) \ Width of Aisle, $w_{a,proj}$ (feet)	10	15	20	25	30	35	40	45	50
10	0.20	0.18	0.17	0.16	0.15	0.14	0.14	0.14	0.13
15	0.22	0.20	0.19	0.18	0.17	0.16	0.15	0.15	0.15
20	0.23	0.21	0.20	0.19	0.18	0.17	0.17	0.16	0.16
25	0.24	0.23	0.21	0.20	0.19	0.18	0.18	0.17	0.17
30	0.25	0.23	0.22	0.21	0.20	0.19	0.19	0.18	0.18

Table 9. Runoff Coefficients Calculated for Variable Widths for Solar Fields Oriented Perpendicular to Ground Surface Contours with Native Grass Ground Cover

Width of Panels, $w_{p,proj}$ (feet) \ Width of Aisle, $w_{a,proj}$ (feet)	10	15	20	25	30	35	40	45	50
10	0.45	0.38	0.33	0.30	0.28	0.26	0.24	0.23	0.22
15	0.52	0.45	0.40	0.36	0.33	0.31	0.29	0.28	0.26
20	0.57	0.50	0.45	0.41	0.38	0.35	0.33	0.32	0.30
25	0.60	0.54	0.49	0.45	0.42	0.39	0.37	0.35	0.33
30	0.63	0.57	0.52	0.48	0.45	0.42	0.40	0.38	0.36

Table 10. Runoff Coefficients Calculated for Variable Widths for Solar Fields Oriented Diagonal to Ground Surface Contours with Gravel Ground Cover

Width of Panels, $w_{p,proj}$ (feet)	Width of Aisle, $w_{a,proj}$ (feet): 10	15	20	25	30	35	40	45	50
10	0.60	0.58	0.57	0.56	0.55	0.54	0.54	0.54	0.53
15	0.62	0.60	0.59	0.58	0.57	0.56	0.55	0.55	0.55
20	0.63	0.61	0.60	0.59	0.58	0.57	0.57	0.56	0.56
25	0.64	0.63	0.61	0.60	0.59	0.58	0.58	0.57	0.57
30	0.65	0.63	0.62	0.61	0.60	0.59	0.59	0.58	0.58

Table 11. Runoff Coefficients Calculated for Variable Widths for Solar Fields Oriented Perpendicular to Ground Surface Contours with Gravel Ground Cover

Width of Panels, $w_{p,proj}$ (feet)	Width of Aisle, $w_{a,proj}$ (feet): 10	15	20	25	30	35	40	45	50
10	0.75	0.70	0.67	0.64	0.63	0.61	0.60	0.59	0.58
15	0.80	0.75	0.71	0.69	0.67	0.65	0.64	0.63	0.62
20	0.83	0.79	0.75	0.72	0.70	0.68	0.67	0.65	0.64
25	0.86	0.81	0.78	0.75	0.73	0.71	0.69	0.68	0.67
30	0.88	0.83	0.80	0.77	0.75	0.73	0.71	0.70	0.69

4.0 Recommendations

In Table 12 and Table 13, WWE presents recommended values for runoff coefficients and percent imperviousness based on rounding of average values calculated from SWMM and the Solar Runoff Calculator.

Table 12. Recommended Runoff Coefficients and Imperviousness to Use for Evaluation of Solar Installations with Native Grass Cover*

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.06	10%	0.14	20%	0.34	45%
5-year	0.12	10%	0.20	20%	0.40	45%
100-year	0.52	10%	0.57	20%	0.67	45%

* These values of runoff coefficients and imperviousness percentages are based on assumptions of HSG C soils and equal widths of Panels and Inter-Panel aisles. If site conditions differ from these assumptions, the engineer can follow the SWMM procedures described in the memorandum to perform site-specific analysis.

Table 13. Recommended Runoff Coefficients and Imperviousness to Use for Evaluation of Solar Installations with Gravel Cover*

Return Period	Parallel		Diagonal		Perpendicular	
	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious	Volumetric Runoff Coefficient	Percent Impervious
2-year	0.38	50%	0.47	60%	0.60	75%
5-year	0.44	50%	0.52	60%	0.65	75%
100-year	0.69	50%	0.73	60%	0.79	75%

* These values of runoff coefficients and imperviousness percentages are based on assumptions of HSG C soils and equal widths of Panels and Inter-Panel aisles. If site conditions differ from these assumptions, the engineer can follow the SWMM procedures described in the memorandum to perform site-specific analysis.

WWE recommends basing imperviousness values for determining runoff coefficients on the imperviousness values and runoff coefficients presented in Table 12 and Table 13. At the master planning level, before the layout of a solar site is known, the imperviousness values and runoff coefficients for perpendicular installations should be used. Once the layout is known, the engineer can conduct site-specific analysis to assign runoff coefficients based on the alignment of panels relative to contours, interpolating between values in Table 12 and Table 13, as illustrated in the following example.

5.0 Example

The following example illustrates how to determine runoff coefficients and imperviousness percentages for a project site. There are many ways to perform this analysis and achieve the same results, but a simple and effective method for obtaining runoff coefficients can be performed using the Spatial Analyst extension in ArcGIS Pro.

Step 1. Delineate drainage sub-basins based on best available survey data.

The example solar field is approximately 1 square mile in area and is located in Aurora, Colorado. A gravel access road, gravel parking areas, and concrete pads for energy transmission equipment are included in the example site plan. Due to the extent of the project, it is assumed that grading will be limited to the access road, parking areas, and concrete pads. A total of 8 sub-basins and 7 direct run-off areas were delineated for the site. For brevity of this example, only Sub-basin 5 (highlighted in the figures below) will be analyzed here. Refer to the site map provided in Appendix B for locations of all design points, sub-basins, and non-site-specific drainage basins.

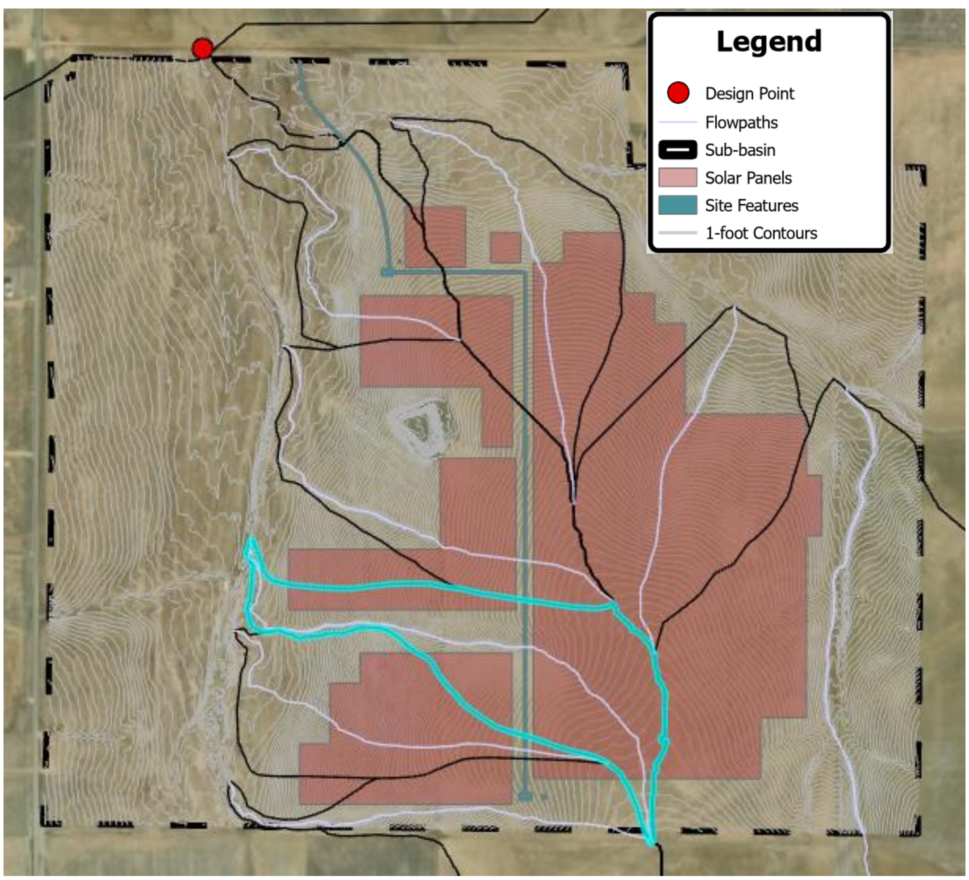


Figure EX-1. Hypothetical Solar Field Site with Sub-basins Delineated: Sub-basin 5 (Used in this Example) is Highlighted in Teal

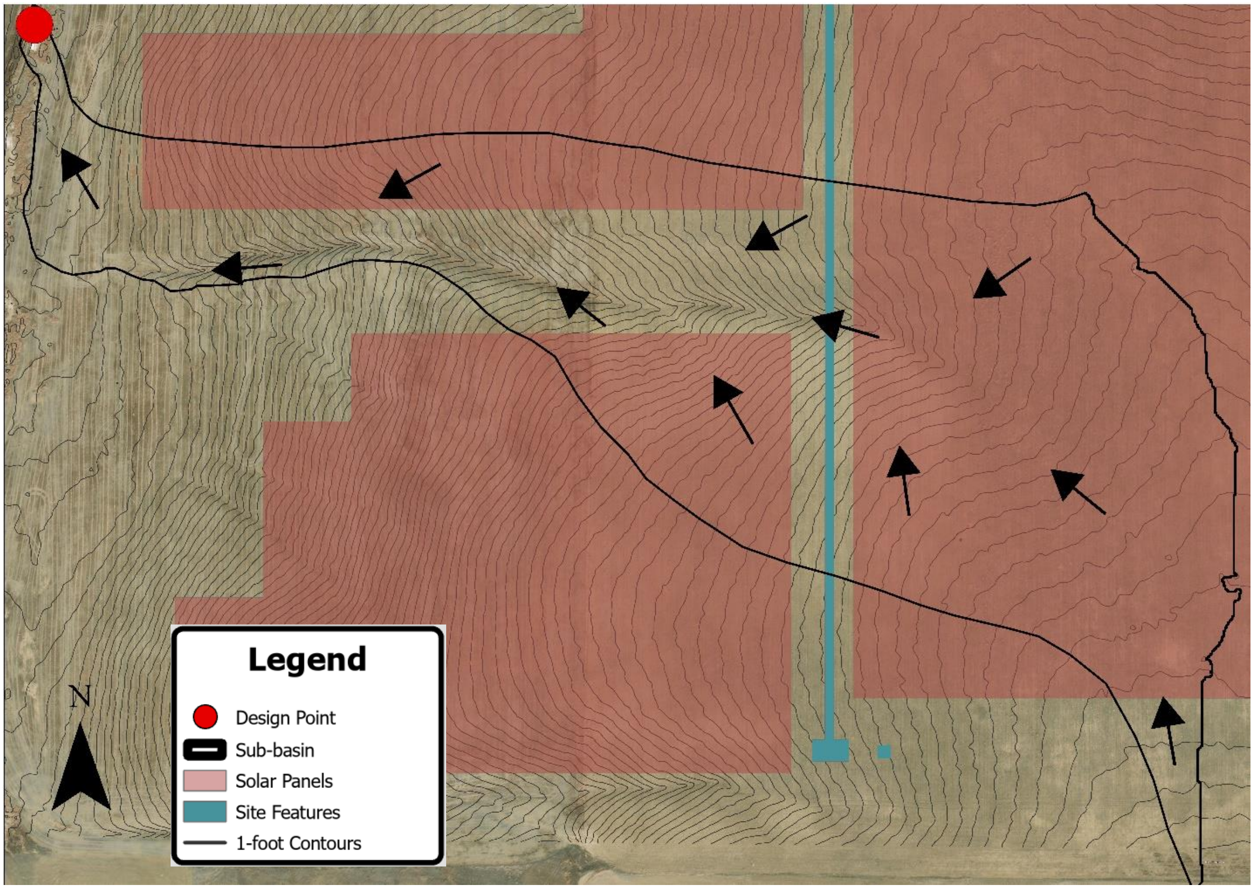


Figure EX-2. Sub-basin 5

Step 2. Determine the percent of each relevant land use within each sub-basin including open space, solar panels, gravel road, gravel pads, and other pervious and impervious land uses.

Land cover in Sub-basin 5 includes a portion of the gravel access road, undeveloped open space, and solar panels in various orientations relative to the natural ground contours. Create sub-basin-specific shapefiles to represent the geometry of each land use within the sub-basin.

Figure EX-3. Land Cover Categories in Sub-basin 5 Include Open-space (Green), Solar Panels (Orange), and Gravel (Yellow)

Once the shapefiles are created, calculate the area of each land use in the sub-basin by adding a field to the shapefile attribute table and using the **Calculate Geometry** function. Once calculated, areas for each component of the shapefile are either be summed manually or calculated using the **Summary Statistics** function. Access the **Summary Statistics** function by right clicking on the attribute table and selecting **Summarize.**

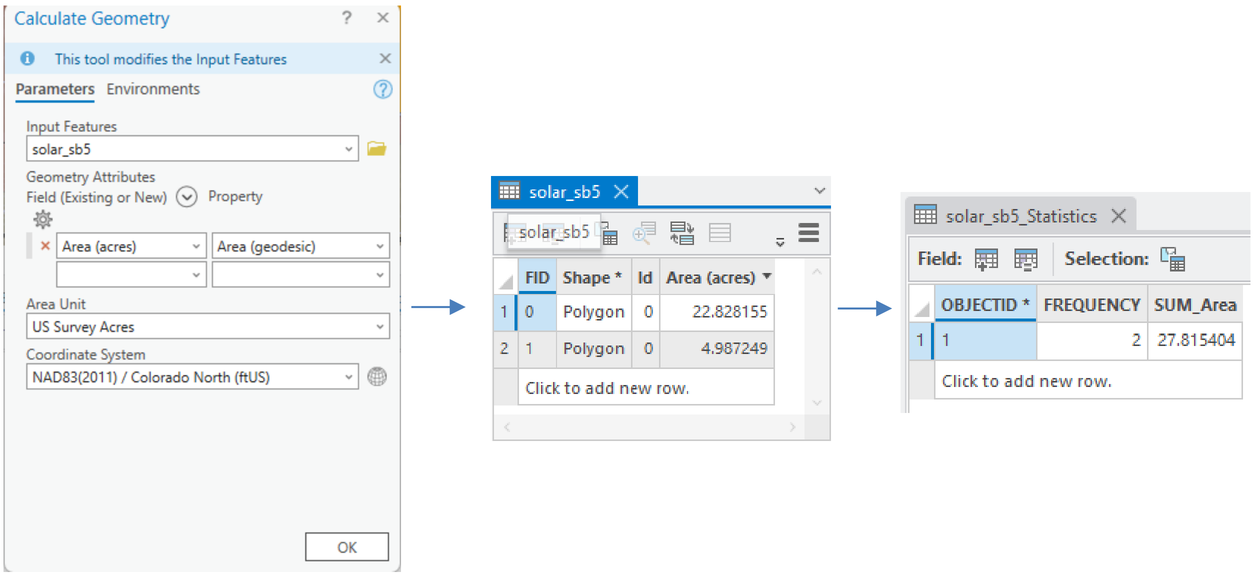


Figure EX-4. Example Area Calculation Workflow in ArcGIS Pro: Figure Shows Calculation of Solar Panel Area within Sub-basin 5 (Orange Area in Figure EX-3)

After calculating the area of all land cover in the sub-basin, tabulate results to determine composite areal percentages for each category.

Table EX-1. Sub-basin 5 Land Cover Summary

Land Cover	Area (acres)	Area (% of Total)
Solar Field	27.82	68%
Gravel	0.41	1%
Open Space	12.95	31%
Total	41.17	100%

Step 3. Determine representative angle of panels relative to ground contours for each sub-basin and calculate the composite imperviousness of the solar fields on site.

Use the **Surface Parameters** tool to calculate the aspect of the natural surface where solar fields are proposed. Aspect is essentially the flow direction of the natural surface measured in degrees clockwise from north. The output cell size is specified by the user and cannot be smaller than the cell size of the input raster. The selected cell size is used to calculated area later in this example.

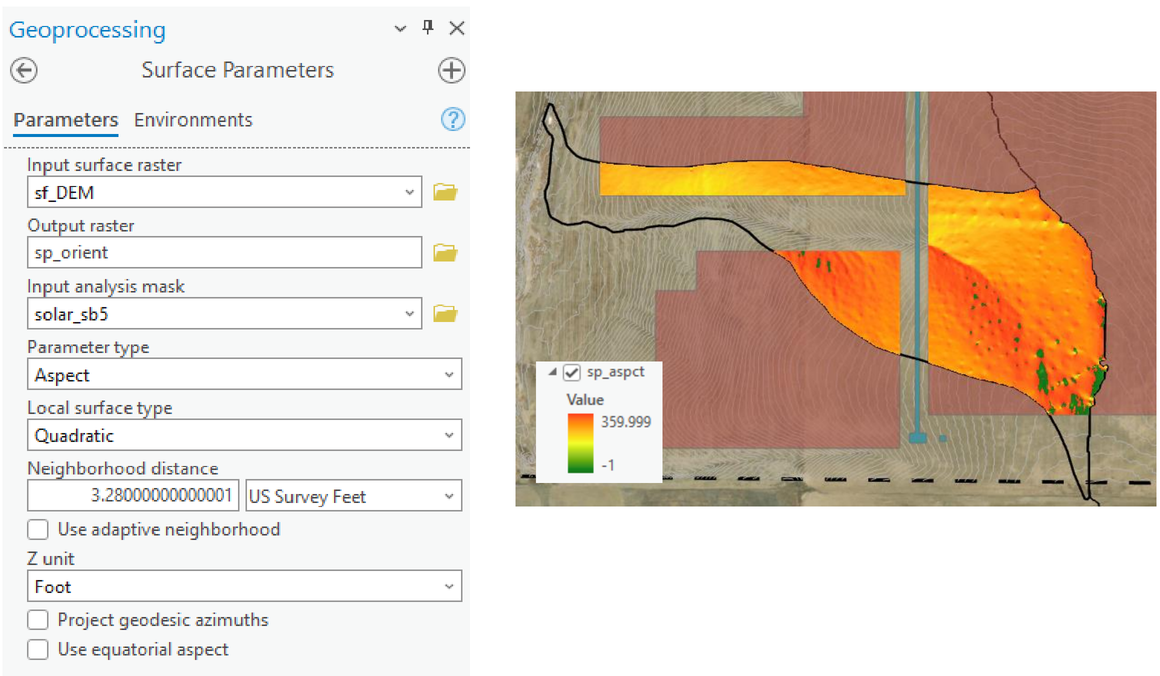


Figure EX-5. Surface Parameters Tool Input and Output Example

NOTE: 1.) A digital elevation model (DEM) must be specified for the "Input surface raster" parameter. 2.) A polygon shapefile can be specified for the "Input analysis mask" option to restrict the tool to only analyze the area within the mask. In this case, the analysis mask is the polygon representing the portions of the solar field within the sub-basin of interest.

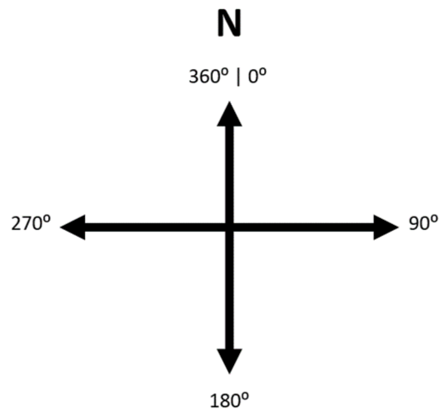


Figure EX-6. Surface Aspect Definition

Once the aspect raster is developed, use the **Reclassify** tool to count the number of cells in the aspect raster within user-specified bins. The start and end values chosen should be selected to define cells in the aspect raster as parallel, perpendicular, or diagonal.

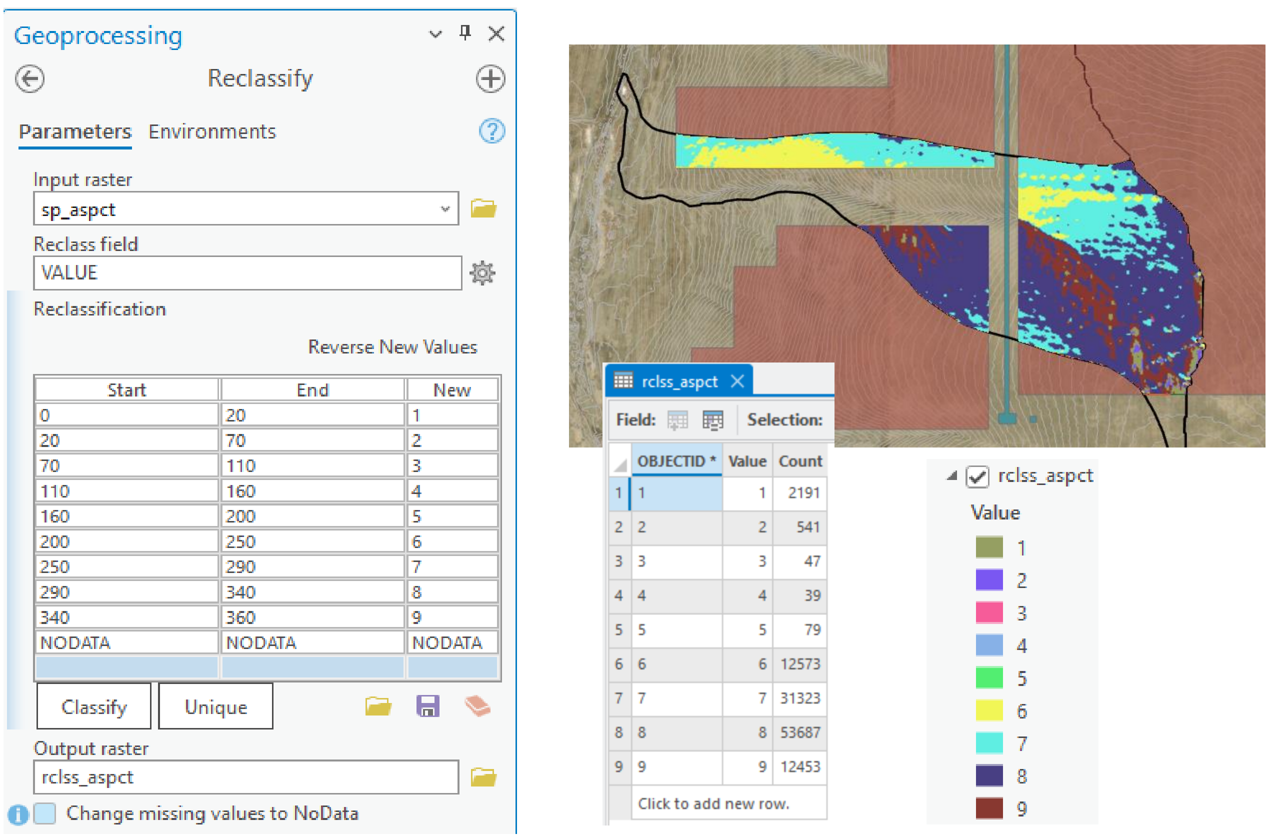


Figure EX-7. Reclassify Tool Input and Output Example

NOTE: For this example, solar panels were considered parallel to contours if the aspect was within 20 degrees of north or south and perpendicular if the aspect was within 20 degrees of east or west. Reference aspect definition in Figure EX-6 above.

The output shapefile from the Reclassify tool will contain an attribute table with the total number of raster cells which meet each bin definition. Once tabulated, sum the counts for each Solar Field Orientation and multiply by the aspect raster cell size to obtain the total area of each panel orientation. Then, calculate composite imperviousness percentages for each sub-basin using total area for each solar field orientation. Analysis results for Sub-basin 5 are presented in Tables EX-2 and EX-3 below.

Value	Representative Aspect (degrees)	Category	Count
1	0 - 20	Parallel	2191
2	20 - 70	Diagonal	541
3	70 - 110	Perpendicular	47
4	110 - 160	Diagonal	39
5	160 - 200	Parallel	79
6	200 - 250	Diagonal	12573
7	250 - 290	Perpendicular	31323
8	290 - 340	Diagonal	53687
9	340 - 360	Parallel	12453

Table EX-3. Composite Imperviousness Calculation for Solar Field within Sub-basin 5 with Native Grass or Gravel Ground Cover

Category	Count	Area (ac)	Imperviousness (%)		Impervious Area (ac)	
			Grass	Gravel	Grass	Gravel
Parallel	14723	3.64	10%	50%	0.36	1.82
Diagonal	66840	16.5	20%	60%	3.30	9.90
Perpendicular	31370	7.75	45%	75%	3.49	5.81
				Total IA:	7.15	17.53
				Composite IA (%):	26%	63%

Step 4. Calculate composite imperviousness percentages for each sub-basin.

Once the imperviousness of the solar field portion of the basin is known, calculate sub-basin composite imperviousness using the land cover areas evaluated in step 3 and imperviousness percentages for surface types in the MHFD Manual. Composite areas were calculated for solar fields with native vegetation and gravel ground cover. Results of analysis for Sub-basin 5 are presented in Table EX-4 and Table EX-5 below.

Table EX-4. Composite Imperviousness Calculation for Sub-basin 5 with Native Grass Ground Cover in Solar Field

Land Cover	Imperviousness (%)	Area (acres)	Impervious Area (acres)
Solar Field	26%	27.82	7.15
Gravel (access roads and parking lots)	80%	0.41	0.33
Open Space	5%	12.95	0.65
	Total	**41.18**	**8.13**
		Composite IA (%):	**20%**

Table EX-5. Composite Imperviousness Calculation for Sub-basin 5 with Gravel Ground Cover in Solar Field

Land Cover	Imperviousness (%)	Area (acres)	Impervious Area (acres)
Solar Field	63%	27.82	17.53
Gravel (access roads and parking lots)	80%	0.41	0.33
Open Space	5%	12.95	0.65
	Total	**41.18**	**18.51**
		Composite IA (%):	**45%**

Step 5. Evaluate runoff coefficients.

Evaluate runoff coefficients using the calculated composite imperviousness values and Table 6-5 in the MHFD Manual. Runoff coefficients for the 2-year, 5-year, and 100-year storms are presented for Sub-basin 5 in Table EX-6 below.

Table EX-6. Runoff Coefficients Evaluated from Composite Imperviousness Values

Recurrence Interval	Solar Field Runoff Coefficient	
	Native Grass	Gravel
2-year	0.14	0.34
5-year	0.20	0.40
100-year	0.57	0.67

6.0 Attachments

- Appendix A. MHFD Urban Storm Drainage Criteria Manual Volume Chapter 6: Runoff– Table 6-5
- Appendix B. Example Solar Field Site Map

Appendix A.

MHFD Urban Storm Drainage Criteria Manual Volume
Chapter 6: Runoff – Table 6-5

Table 6-5. Runoff coefficients, *c*

Total or Effective % Impervious	NRCS Hydrologic Soil Group A						
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year	500-Year
2%	0.01	0.01	0.01	0.01	0.04	0.13	0.27
5%	0.02	0.02	0.02	0.03	0.07	0.15	0.29
10%	0.04	0.05	0.05	0.07	0.11	0.19	0.32
15%	0.07	0.08	0.08	0.1	0.15	0.23	0.35
20%	0.1	0.11	0.12	0.14	0.2	0.27	0.38
25%	0.14	0.15	0.16	0.19	0.24	0.3	0.42
30%	0.18	0.19	0.2	0.23	0.28	0.34	0.45
35%	0.21	0.23	0.24	0.27	0.32	0.38	0.48
40%	0.25	0.27	0.28	0.32	0.37	0.42	0.51
45%	0.3	0.31	0.33	0.36	0.41	0.46	0.54
50%	0.34	0.36	0.37	0.41	0.45	0.5	0.58
55%	0.39	0.4	0.42	0.45	0.49	0.54	0.61
60%	0.43	0.45	0.47	0.5	0.54	0.58	0.64
65%	0.48	0.5	0.51	0.54	0.58	0.62	0.67
70%	0.53	0.55	0.56	0.59	0.62	0.65	0.71
75%	0.58	0.6	0.61	0.64	0.66	0.69	0.74
80%	0.63	0.65	0.66	0.69	0.71	0.73	0.77
85%	0.68	0.7	0.71	0.74	0.75	0.77	0.8
90%	0.73	0.75	0.77	0.79	0.79	0.81	0.84
95%	0.79	0.81	0.82	0.83	0.84	0.85	0.87
100%	0.84	0.86	0.87	0.88	0.88	0.89	0.9
Total or Effective % Impervious	**NRCS Hydrologic Soil Group B**						
	2-Year	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**	**500-Year**
2%	0.01	0.01	0.07	0.26	0.34	0.44	0.54
5%	0.03	0.03	0.1	0.28	0.36	0.45	0.55
10%	0.06	0.07	0.14	0.31	0.38	0.47	0.57
15%	0.09	0.11	0.18	0.34	0.41	0.5	0.59
20%	0.13	0.15	0.22	0.38	0.44	0.52	0.61
25%	0.17	0.19	0.26	0.41	0.47	0.54	0.63
30%	0.2	0.23	0.3	0.44	0.49	0.57	0.65
35%	0.24	0.27	0.34	0.47	0.52	0.59	0.66
40%	0.29	0.32	0.38	0.5	0.55	0.61	0.68
45%	0.33	0.36	0.42	0.53	0.58	0.64	0.7
50%	0.37	0.4	0.46	0.56	0.61	0.66	0.72
55%	0.42	0.45	0.5	0.6	0.63	0.68	0.74
60%	0.46	0.49	0.54	0.63	0.66	0.71	0.76
65%	0.5	0.54	0.58	0.66	0.69	0.73	0.77
70%	0.55	0.58	0.62	0.69	0.72	0.75	0.79
75%	0.6	0.63	0.66	0.72	0.75	0.78	0.81
80%	0.64	0.67	0.7	0.75	0.77	0.8	0.83
85%	0.69	0.72	0.74	0.78	0.8	0.82	0.85
90%	0.74	0.76	0.78	0.81	0.83	0.84	0.87
95%	0.79	0.81	0.82	0.85	0.86	0.87	0.88
100%	0.84	0.86	0.86	0.88	0.89	0.89	0.9

Table 6-5. Runoff coefficients, *c* (continued)

Total or Effective % Impervious	NRCS Hydrologic Soil Group C						
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year	500-Year
2%	0.01	0.05	0.15	0.33	0.40	0.49	0.59
5%	0.03	0.08	0.17	0.35	0.42	0.5	0.6
10%	0.06	0.12	0.21	0.37	0.44	0.52	0.62
15%	0.1	0.16	0.24	0.4	0.47	0.55	0.64
20%	0.14	0.2	0.28	0.43	0.49	0.57	0.65
25%	0.18	0.24	0.32	0.46	0.52	0.59	0.67
30%	0.22	0.28	0.35	0.49	0.54	0.61	0.68
35%	0.26	0.32	0.39	0.51	0.57	0.63	0.7
40%	0.3	0.36	0.43	0.54	0.59	0.65	0.71
45%	0.34	0.4	0.46	0.57	0.62	0.67	0.73
50%	0.38	0.44	0.5	0.6	0.64	0.69	0.75
55%	0.43	0.48	0.54	0.63	0.66	0.71	0.76
60%	0.47	0.52	0.57	0.65	0.69	0.73	0.78
65%	0.51	0.56	0.61	0.68	0.71	0.75	0.79
70%	0.56	0.61	0.65	0.71	0.74	0.77	0.81
75%	0.6	0.65	0.68	0.74	0.76	0.79	0.82
80%	0.65	0.69	0.72	0.77	0.79	0.81	0.84
85%	0.7	0.73	0.76	0.79	0.81	0.83	0.86
90%	0.74	0.77	0.79	0.82	0.84	0.85	0.87
95%	0.79	0.81	0.83	0.85	0.86	0.87	0.89
100%	0.83	0.85	0.87	0.88	0.89	0.89	0.9

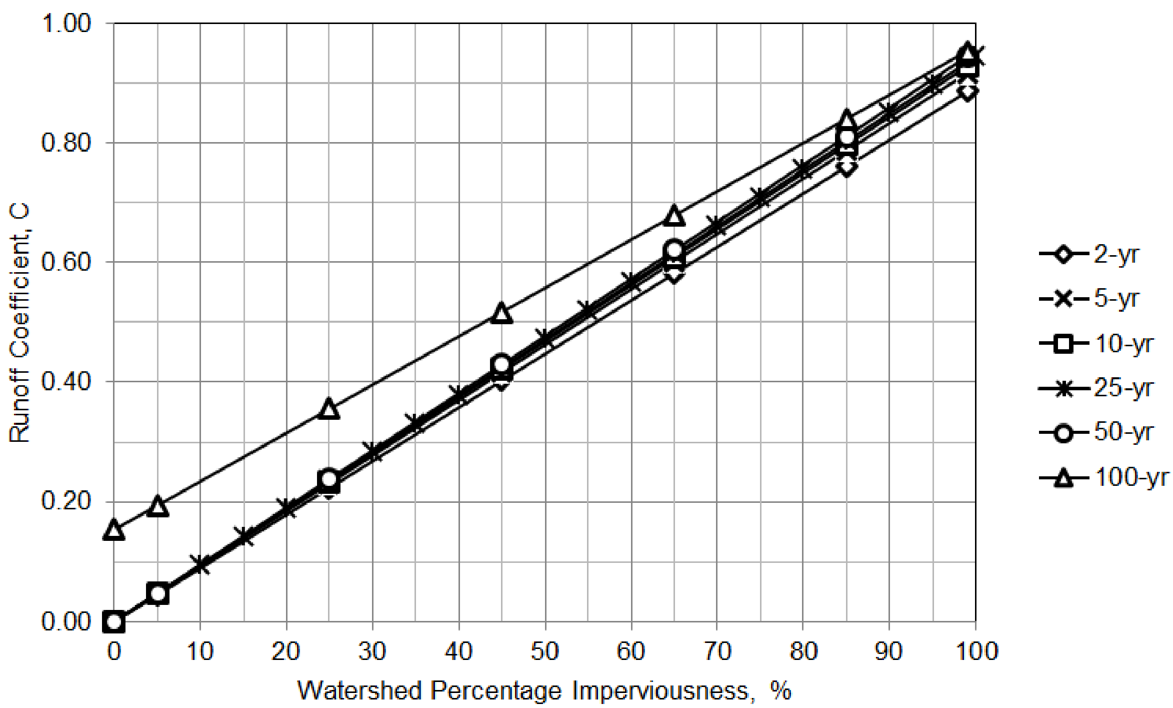
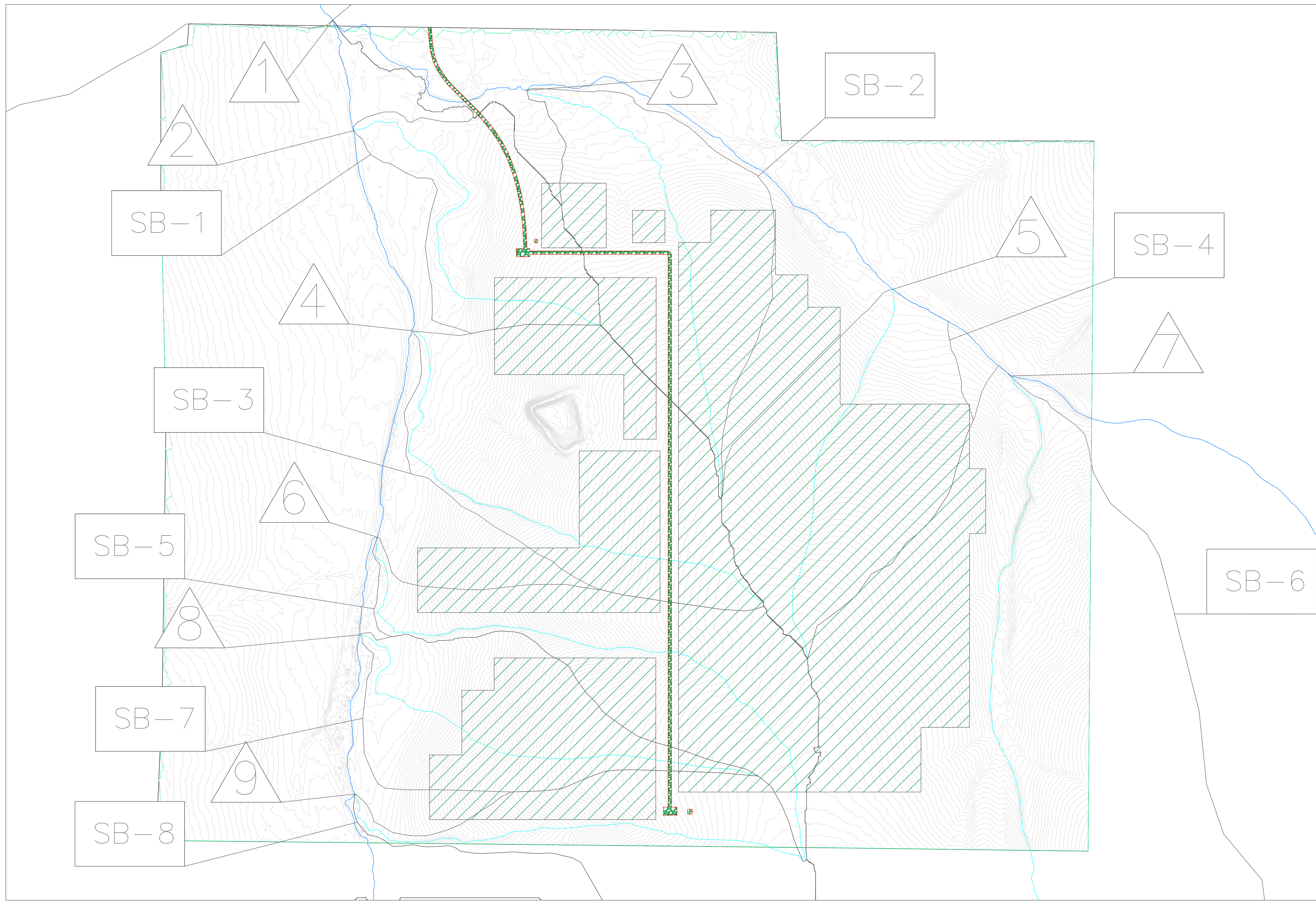


Figure 6-1. Runoff coefficient vs. watershed imperviousness NRCS HSG A

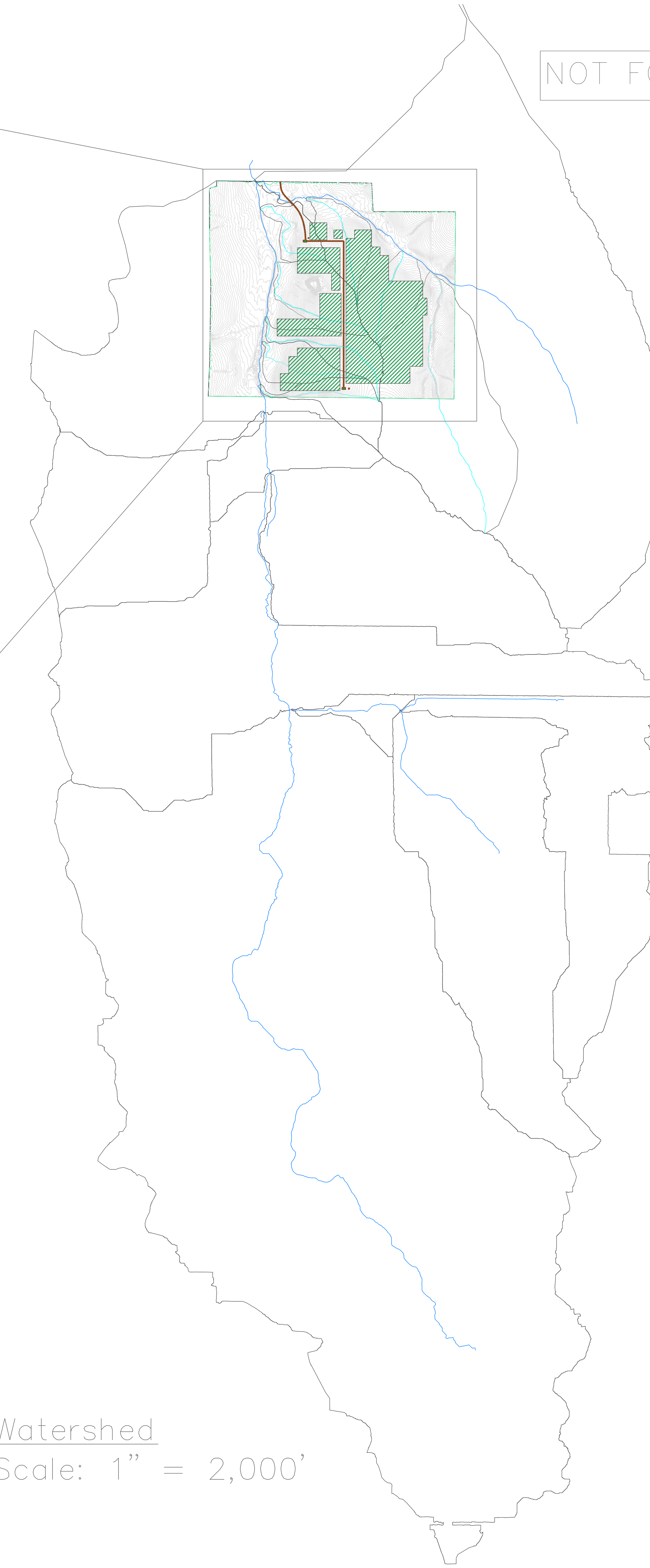
Appendix B.

Example Solar Field Site Map

Solar Field Site
Scale: 1" = 500'



NOT FOR CONSTRUCTION



Watershed
Scale: 1" = 2,000'

LEGEND:

Solar Panels		Drainage Basin	
Road/Parking		Minor Stream	
Concrete Pad		Major Stream	
Design Point	1		

WRIGHT WATER ENGINEERS, INC.
2490 W. 26TH AVE. SUITE 100A
DENVER, CO 80211
(303)480-1700 FAX(303)480-1020

REVISIONS

NO.	BY	DATE	DESCRIPTION	COMMENTS
	-	-	-	-

		DATE
DESIGN	XXX	XX/XX/XX
DETAIL	XXX	XX/XX/XX
CHECK	XXX	XX/XX/XX
APPROVAL		
SCALE		1"=500'
Example_Solar_Farm_Layout.dwg		

SOLAR FIELD RUNOFF COEFFICIENTS

EXAMPLE SOLAR FIELD LAYOUT

JOB NO. —
REVISION NO. —
SHEET NO. —

Plot Date/Time: 07/28/2023, 09:59:48 AM; C:\USERS\MHOWARD\ONEDRIVE\221-009.000\CAD\EXAMPLE_SOLAR_FARM_LAYOUT.DWG-DRAINAGE MAP