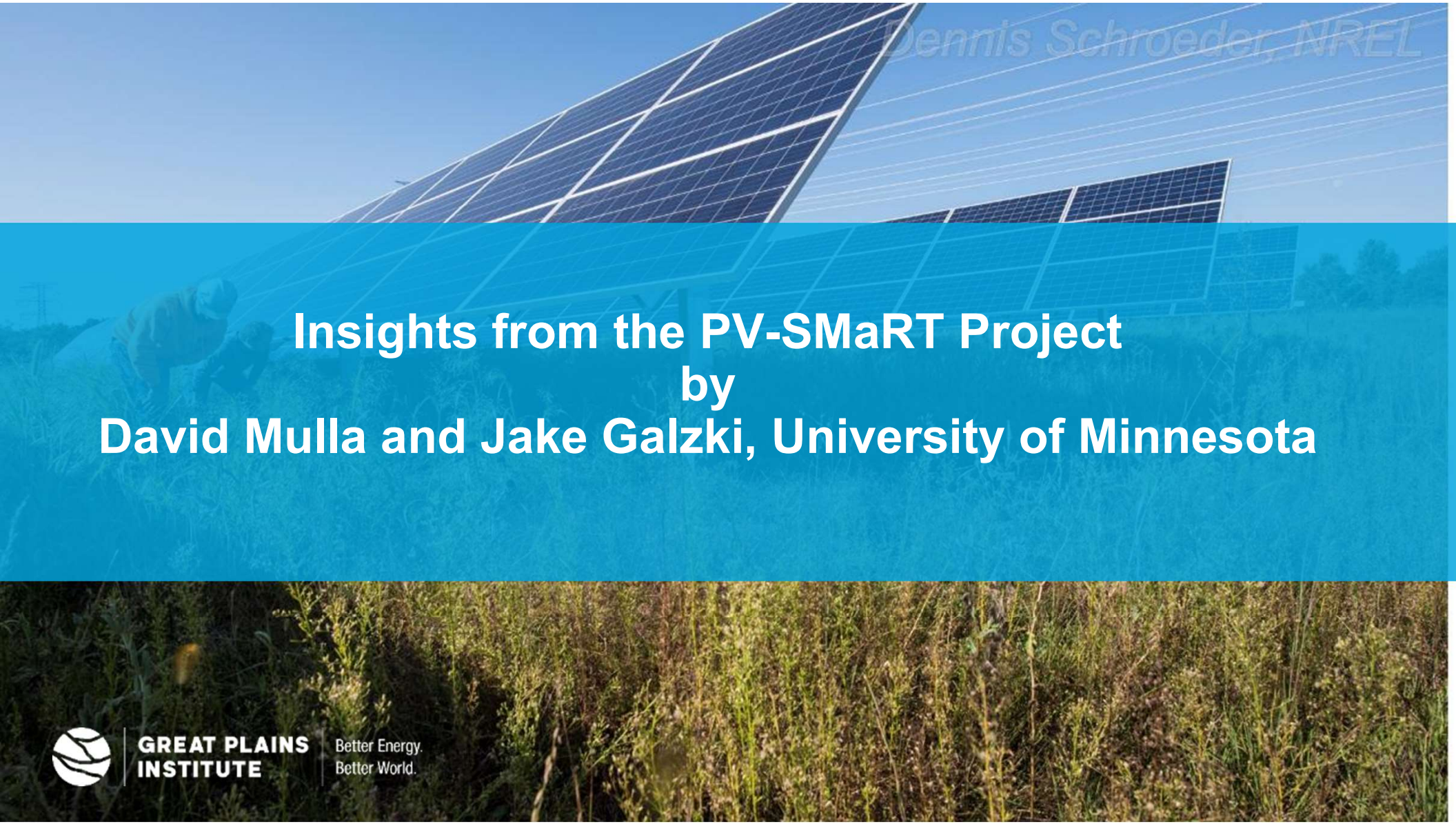

Insights from the PV-SMaRT Project

by

David Mulla and Jake Galzki, University of Minnesota

GREAT PLAINS INSTITUTE

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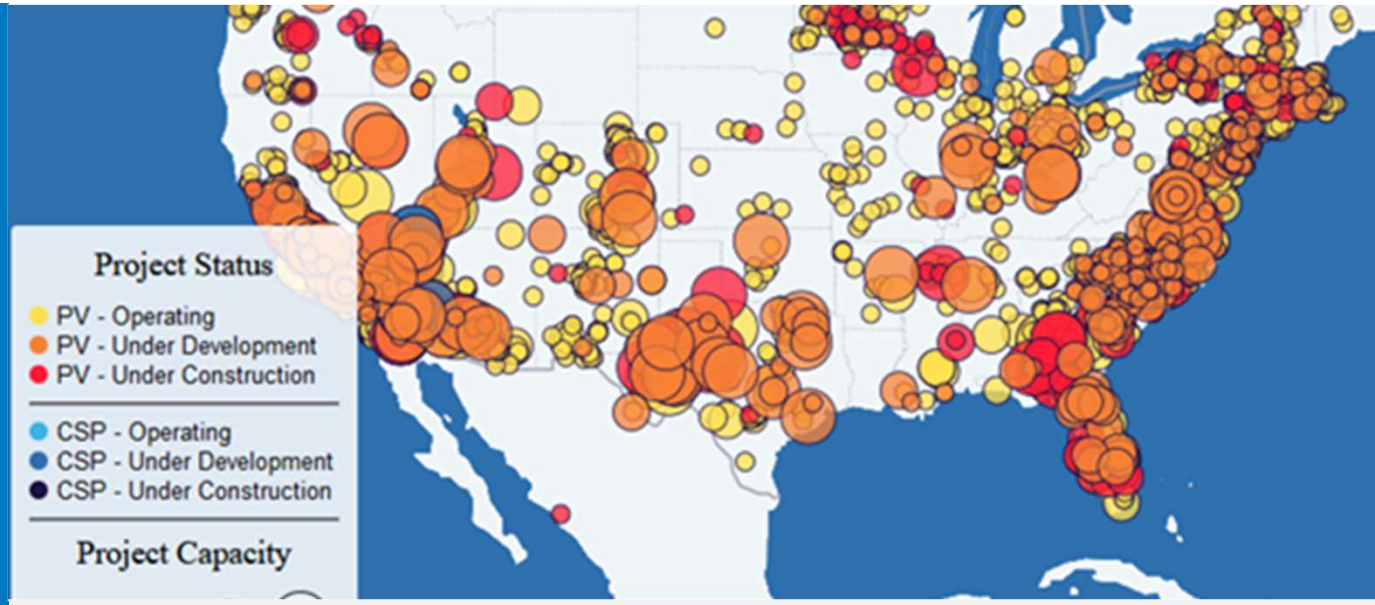
The Problem

At the start of 2021 over 462 GW large-scale solar projects were in the “interconnection queue,” 10 times the total amount of existing large-scale solar (47 GW).

If developed, this would be approximately 3.7 million acres of land, most of it in rural watersheds.

Source: SEIA Major Projects List, https://www.seia.org/research-resources/major-solar-projects-list



- Jurisdictions generally treat ground-mounted PV facilities as predominantly impervious surfaces in local stormwater and water quality permitting
- Most models used by local and state jurisdictions to estimate stormwater runoff, and stormwater best management practices (BMPs) are not tailored to solar development and rely on non-solar research or findings

This leads to inaccurate estimation of stormwater runoff, higher costs and slower deployment of solar projects.

Project Objectives and Study Sites

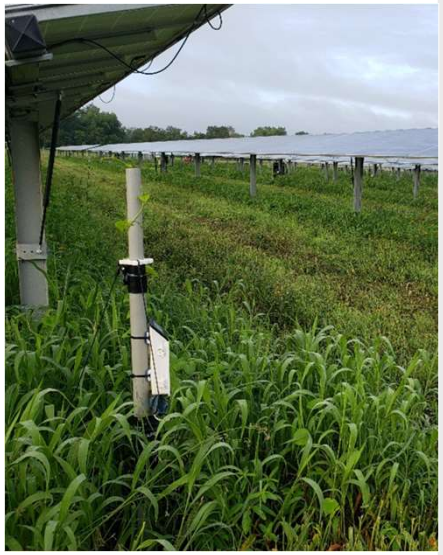
- The objective of this work effort is to develop and disseminate research-based, solar specific best practices for reducing stormwater runoff and improving water quality at ground-mounted PV facilities.
- A runoff calculator has been developed to estimate stormwater runoff at ground solar photovoltaic (PV) sites by accounting for:
  - Soil and topographic characteristics (soil texture, soil depth, soil bulk density, slope)
  - Surface cover (row crop, turf, pollinator habitat, etc)
  - Disconnected impervious surfaces associated with solar panel design (panel spacing)
  - Climatic factors (precipitation)

Study Sites in PV-SMaRT Project

Minnesota

Oregon

New York



Georgia

New York: 18 MW fixed, 2-in-portrait PV array, 108 acres. Silty clay loam soil (D soil) with tall grass and clover mix, ungrazed or grazed by sheep with 49” annual rainfall.

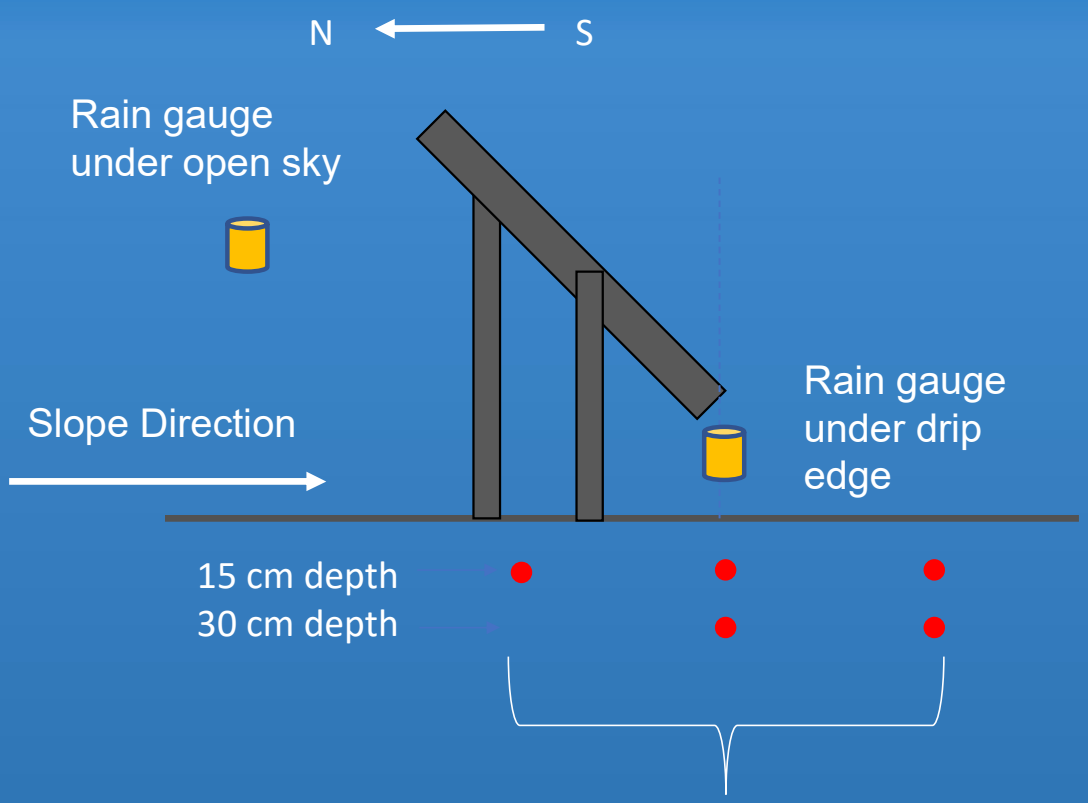
Georgia: 1.3 MW tracking 1-in-portrait PV array, 8 acres. Flat site with sandy clay soil (B soil), mowed cover crops, high diversity pollinator mix, and 49” annual rainfall.

Minnesota: 3.4 MW fixed, 2-in-portrait PV array, 29 acres. Sandy loam soil (A soil) with 5% slope, pollinator mix dominated by black eye Susan daisies, and 37” annual rainfall.

Oregon: 9.9 MW tracking 2-in-portrait PV array, 45.8 acres. Flat site with clay soil (D soil), diverse pollinator seed mix and 16” annual rainfall.

Colorado: 1 MW tracking 1-in-portrait PV array, 6 acres. Clay soil (C soil) with pollinator vegetation, grazed by goats, with 16” annual rainfall.

Sensor Monitoring at E-W Oriented Fixed Angle Solar Arrays (MN)



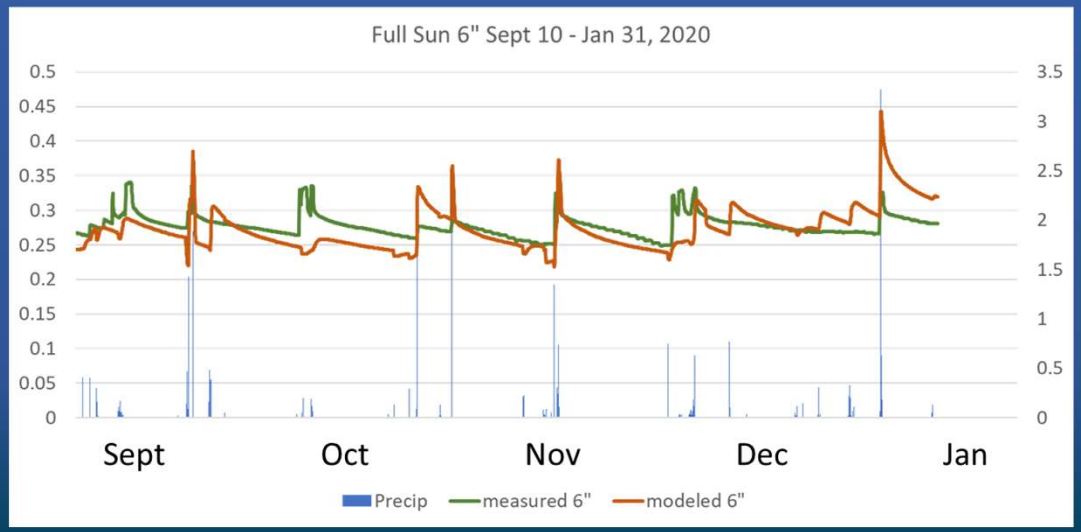
Soil moisture probe locations
Under Panel
Under Drip Edge
Between Arrays

Infiltrometer
to measure
runoff

TDR probe
to measure
soil moisture

Hydrus-3D Model Accuracy

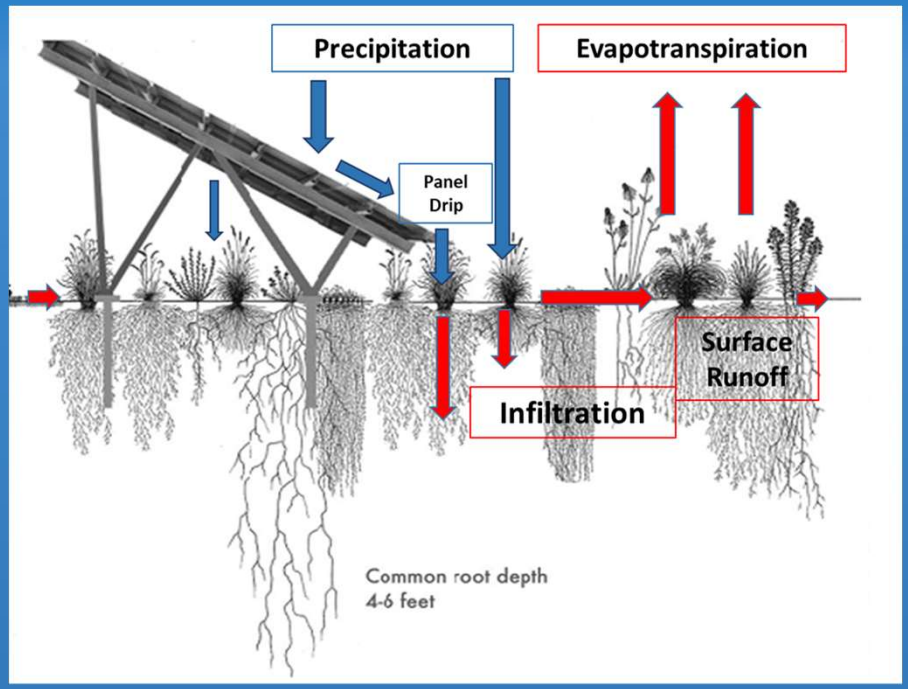
- Simulates two- or three-dimensional variably saturated water flow in vadose zone
- Model inputs include soil depth, soil texture, soil bulk density and saturated moisture content, soil hydraulic conductivity, and slope
- Data from the 5 PV test sites were used to evaluate accuracy of the Hydrus model against measured soil moisture content
- Parameters adjusted included saturated hydraulic conductivity and alpha and n values in the van Genuchten moisture characteristic curve
- An example for sandy clay soil is below

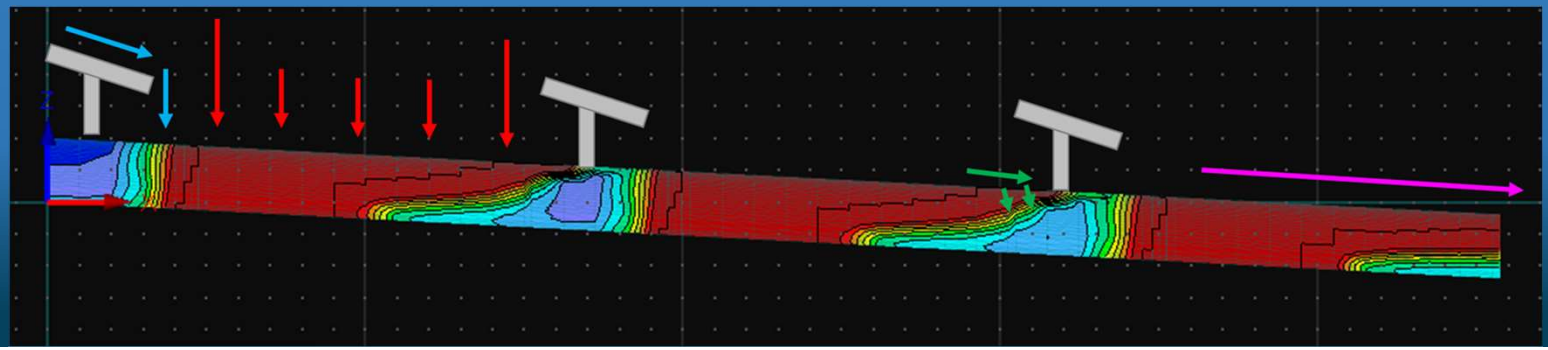


Soil Texture	Calibrated Ks (cm/hr)	RMSE
Sandy Loam	20	0.017
Sandy Clay	1	0.027
Silty Clay Loam	1	0.027
Clay	2	0.046
Clay	0.5	0.021

Solar PV-SMaRT Runoff Calculator Accounts for Complex Hydrology

Model accommodates:
1) concentrated drip-edge runoff
2) incident precipitation
3) routing of surface runoff and infiltration under next panel
4) total accumulated surface runoff of the system





Conclusions From Experimental Studies (CO, GA, MN, NY, OR)

- Hydrus model is able to accurately estimate runoff across a range of ground solar PV sites with perennial vegetation
- Runoff increases on average:
  - at NY and OR by 159% for 100- vs 2-yr design storm
  - by 98% with compacted vs loose soil in full sun area
  - by 78% as soil depth decreases from 150 to 50 cm
  - by 38% for row crop vs mature prairie
  - by 14% with arrays relative to without arrays
  - by 14% as panel spacing decreases from 35’ to 15’

Decreasing influence of factors

- Runoff decreases on average by 38% with Hydrus relative to the NRCS Runoff Curve Number (RCN) method for a 100-yr storm having 25’ array spacings with pollinator plantings

User-Friendly Runoff CN Calculator

- It is not feasible for the average user to run Hydrus on every site
- A user-friendly Excel spreadsheet-based runoff CN calculator was developed based on the nearly 1,000 Hydrus simulations run for different soil textures, soil depths, soil bulk densities and design storms
- Results from the Hydrus runoff CN calculator can be adjusted for different vegetative covers, presence or absence of arrays, array spacings, and slopes building on information developed from detailed modeling at five sites in CO, GA, MN, NY, and OR

Soil Texture	Silty Clay	***BLUE CELLS REQUIRE USER INPUT***	
Soil Depth (inches)	24	***MAROON CELLS REPRESENT TOOL OUTPUTS***	
Bulk Density (g/cm^3)	1.4		
Vegetation Present	Newly Established Pollinator	Runoff Curve Number	76.7
Are Solar Panels Present?	YES	24-Hr Precip Event (inches)	10.00
Panel Width (feet)	10	Expected Runoff (inches)	7.09
Panel Spacing (feet)	25		
Array Orientation	Follows slope contours		
Percent Slope	5		

Soil Texture	Loamy Sand	***BLUE CELLS REQUIRE USER INPUT***	
Soil Depth (inches)	24	***MAROON CELLS REPRESENT TOOL OUTPUTS***	
Bulk Density (g/cm^3)	1.4		
Vegetation Present	Newly Established Pollinator	Runoff Curve Number	38.4
Are Solar Panels Present?	YES	24-Hr Precip Event (inches)	10.00
Panel Width (feet)	10	Expected Runoff (inches)	2.02
Panel Spacing (feet)	25		
Array Orientation	Follows slope contours		
Percent Slope	5		

Assumptions for PV-SMaRT Runoff Calculator

- Runoff estimates were derived assuming panel rows are installed parallel to the slope of the site
- Soils are uniform and initially at field capacity throughout the profile
- The bottom boundary condition is no flux, which increases the risk of surface runoff
- Runoff is routed off the panel and allowed to infiltrate in the area between panels
- Runoff (if any) continues downslope where it can be infiltrated under the subsequent panel
- Panels are at full tilt (downslope) in the simulations, maximizing runoff coming off the drip edge
- Soil is assumed free from snow and frost
- Vegetation present is assumed to have a uniform distribution and density both underneath panels and in the open area between panels

Intended Uses for PV-SMaRT Runoff Calculator

Pre-construction characteristics

- Without arrays
- With pre-construction vegetation
- Can evaluate site-suitability based on soil texture and soil depth (these factors are critically important)

Soil Texture	Loam
Soil Depth (inches)	12
Bulk Density (g/cm^3)	1.4
Vegetation Present	Row Crop (Straight Row, Poor Management)
Are Solar Panels Present?	NO
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	88.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	8.56

Post-construction characteristics that could mitigate runoff without resorting to water retention structures

- Post-construction management
- Soil bulk density (tillage/ripping to lower bulk density or wheel traffic that increases bulk density)
- Vegetation choices (e.g. pollinators)
- Array spacing choices

Soil Texture	Loam
Soil Depth (inches)	12
Bulk Density (g/cm^3)	1.2
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	87.6
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	8.48

Measured data inputs are preferred to ballpark estimates

Effect of Soil Texture

- Choose Soil Texture from drop-down list
- Texture is based on measured % sand, silt and clay data and the NRCS Soil Texture Triangle
- These data are available in the NRCS SSURGO database if site-specific sampling data are unavailable
- Generally, runoff is smaller on coarser soils (e.g. sand) than finer soils (e.g. loam)

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT	
MAROON CELLS REPRESENT TOOL OUTPUTS	
Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

Soil Texture	Sand
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT	
MAROON CELLS REPRESENT TOOL OUTPUTS	
Runoff Curve Number	55.4
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	4.28

Effect of Bulk Density

- Bulk density should normally reflect measured pre-construction baseline values
- An estimate of bulk density is available in the NRCS SSURGO database
- Otherwise use the following:

Loose	Typical loose or recently ripped soil (compaction mitigated)	1 - 1.2
Average	Average soil condition	1.3 - 1.5
Compacted	Typcial compacted soil (post-construction w/no mitigation)	1.6 - 1.8

- In order to evaluate post-construction conditions, enter measured post-construction bulk density values in the tool
- Alternatively, enter projected post-construction bulk density values arising from management activities (e.g. wheel tracks, mowing, ripping,)
- Note: vegetative cover impacts on bulk density are accounted for when vegetation type is selected, so don't adjust bulk density field to represent changes caused by vegetation
- Runoff increases in compacted soil relative to uncompacted soil

Soil Texture	Loam	***BLUE CELLS REQUIRE USER INPUT***	
Soil Depth (inches)	24	***MAROON CELLS REPRESENT TOOL OUTPUTS***	
Bulk Density (g/cm^3)	1.2		
Vegetation Present	Newly Established Pollinator	Runoff Curve Number	72.5
Are Solar Panels Present?	YES	24-Hr Precip Event (inches)	10.00
Panel Width (feet)	10	Expected Runoff (inches)	6.55
Panel Spacing (feet)	25		
Array Orientation	Follows slope contours		
Percent Slope	5		

Soil Texture	Loam	***BLUE CELLS REQUIRE USER INPUT***	
Soil Depth (inches)	24	***MAROON CELLS REPRESENT TOOL OUTPUTS***	
Bulk Density (g/cm^3)	1.6		
Vegetation Present	Newly Established Pollinator	Runoff Curve Number	89.9
Are Solar Panels Present?	YES	24-Hr Precip Event (inches)	10.00
Panel Width (feet)	10	Expected Runoff (inches)	8.77
Panel Spacing (feet)	25		
Array Orientation	Follows slope contours		
Percent Slope	5		

Effect of Soil Depth

- Rooting zone depth represents portion of soil profile where crops can effectively extract water and nutrients for growth
- Rooting zone is assumed equivalent to the depth of a restrictive layer (bedrock, fragipan, impermeable layer, shallow water table, etc.)
- Rooting zone depth is available in the NRCS SSURGO database if site-specific soil borings are not available
- Runoff increases as soil depth decreases

Soil Texture	Loam
Soil Depth (inches)	36
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	69.3
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	6.13

Soil Texture	Loam
Soil Depth (inches)	12
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	91.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	8.92

Effect of Vegetation

- Changing vegetation in the tool affects soil bulk density
- Use drop down menu to select the surface or vegetative cover type that best represents the site for the post-construction period, vegetation choices will internally alter pre-construction baseline bulk density values based on the following options:

Bare Soil	Fallow bare soil condition
Gravel	Gravel ground cover
Row Crop (Straight Row, Poor Management)	Row Crop not planted along contour, lack of year-round cover and crop residue cover <20%
Turf Grass	Represents shallow-rooted, mowed grass coverage
Row Crop (Straight Row, Good Management)	Row crop not planted along contour, year-round cover and crop residue levels >20%
Row Crop (Contoured, Good Management)	Row Crop planted along contour, year-round cover and crop residue levels >20%
Newly Established Pollinator	Includes pasture or grasslands with 50 -75% overall ground cover, not heavily grazed. This is the typical condition of a newly-seeded pollinator mix established at new PV arrays.
Forest	Woods in fair condition, can be grazed, not burned. Some forest litter covers the ground surface.
Mature Prairie	Indicates continuous grassland protected from grazing. A pollinator mix would fit into this category after several years of establishment and root development.

Effect of Vegetation

- If exploring post-construction effects of vegetation, do not simultaneously change both vegetative cover and baseline pre-construction bulk density values, unless there is also a management change that independently alters bulk density during post-construction
- Alternatively, select the vegetative cover type that best represents the site during the pre-construction period to evaluate baseline runoff in the absence of solar arrays

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT	
MAROON CELLS REPRESENT TOOL OUTPUTS	
Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Turf Grass
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT	
MAROON CELLS REPRESENT TOOL OUTPUTS	
Runoff Curve Number	85.0
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	8.15

Effect of Slope Steepness

- Input the average slope of the site in percent
- Runoff increases slightly as slope steepness increases

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	10

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	82.0
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.77

Effect of Arrays, Array Spacing and Orientation

- Answer “no” to represent absence of panels, or “yes” if solar panels are present
- If solar panels are present, input the distance in feet from one panel row to the next row, measured on-center
- Runoff increases as panels are added or their spacing decreases

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	NO
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT
MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	71.7
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	6.44

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT
MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Up and down slope
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT
MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	94.4
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	9.32

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	15
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT
MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	82.4
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.82

Effect of Design Storm

- 24-hr design storm events (inches of rain) can be looked up in NOAA Atlas 14 precipitation frequency tables by location
- Runoff curve numbers are used to calculate expected runoff from a single 24-hour storm entered by user
- Field capacity is the assumed antecedent moisture condition
- Runoff decreases as design storm depth decreases

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	80.2
24-Hr Precip Event (inches)	1.00
Expected Runoff (inches)	0.09

Conclusions: User-Friendly Runoff CN Calculator

- A user-friendly runoff CN calculator was developed based on the nearly 1,000 Hydrus simulations run for different soil textures, soil depths, soil bulk densities and design storms
- User inputs include:
  - Soil texture
  - Soil depth
  - Soil bulk density
  - Vegetative cover
  - Presence or absence of solar array
  - Panel spacing, width and orientation if arrays are present
  - Slope

Soil Texture	Loam
Soil Depth (inches)	24
Bulk Density (g/cm^3)	1.4
Vegetation Present	Newly Established Pollinator
Are Solar Panels Present?	YES
Panel Width (feet)	10
Panel Spacing (feet)	25
Array Orientation	Follows slope contours
Percent Slope	5

BLUE CELLS REQUIRE USER INPUT

MAROON CELLS REPRESENT TOOL OUTPUTS

Runoff Curve Number	80.2
24-Hr Precip Event (inches)	10.00
Expected Runoff (inches)	7.55

- Calculator quickly estimates runoff CN for pre- and post-construction scenarios
- Users can then input the 24-hr design storm depth of interest and Calculator will estimate actual depth of runoff
- Solar farm stormwater depths can range from the amount typical of completely impervious surfaces to no runoff at all, depending on the specific combination of soil texture, soil depth, bulk density, vegetation type, array spacing and orientation
- If user wishes, runoff CN values for different soils or slopes at a given site can be used as area weighted inputs for other models such as TR-55, SWMM or HydroCAD
- PV-SMaRT Runoff Calculator allows for accurate consideration of runoff generated by disconnected pervious surfaces as affected by a wide range in site-specific conditions

Thank You, Questions?

https://www.nrel.gov/solar/market-research-analysis/pv-smart.html

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https://license.umn.edu/product/pv-smart-solar-runoff-calculator

Impacts of Soil Texture on Sat'd Hydraulic Cond.

- Saturated soil hydraulic conductivity is smaller for clay loams than for many other soil textures
- The saturated hydraulic conductivity is larger for a soil with 100% clay than for a clay loam