PV Stormwater Management Research and Testing (PV-SMaRT): Final Technical Report

James McCall,[1] Jennifer Daw,[1] Megan Day,[1] Jake Galzki,[2] Aaron Hanson,[2] David Mulla,[2] and Brian Ross[3]

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3 Great Plains Institute

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Technical Report
NREL/TP-6A20-87555
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Final Technical Report (FTR) – 36472 Photovoltaic Stormwater Management Research and Testing (PV-SMaRT)

James McCall,[1] Jennifer Daw,[1] Megan Day,[1] Jake Galzki,[2] Aaron Hanson,[2] David Mulla,[2] and Brian Ross[3]

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Agency/Office/Program	DOE/EERE/Solar Energy Technologies Office	
Award Number	DE-EE00036472	
Project Title	PV Stormwater Management Research and Testing (PV-SMaRT)	
Principal Investigator	James McCall, Energy and Environment Analyst, james.mccall@nrel.gov, 303-275-3759	
Business Contact	Jeff Cook, BOS Program Lead, jeff.cook@nrel.gov, 303-275-3676	
Submission Date	9/30/23	
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Project Period	**Start:** 1/1/20	**End:** 6/30/23
Project Budget	Total $1,899,000 (DOE: $1,500,000; C/S: $399,000)	
Submitting Official Signature	James McCall	

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Executive Summary

The objective of the Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) project was to develop and disseminate research-based, solar-specific resources for estimating stormwater runoff at ground-mounted PV facilities and detail stormwater management and water quality best practices. These resources and best practices are aimed at reducing the balance of system soft costs associated with stormwater infrastructure requirements and improving water quality outcomes through research-tested best practices.

Assumptions about stormwater impacts vary by jurisdiction, which can lead to regulatory uncertainty and increased compliance costs for managing stormwater runoff at solar sites. To address these concerns, the NREL team and its partners (University of Minnesota, Great Plains Institute, and Fresh Energy) established and engaged an advisory Water Quality Task Force (WQTF); conducted field research on stormwater infiltration and runoff at five ground-mounted PV sites; validated a 3D hydrologic model to predict water runoff and generate stormwater runoff coefficients for a range of site conditions and PV designs; developed a stormwater management and water quality best practices document; and engaged with local jurisdictions and other stakeholders to disseminate best practices, stormwater runoff coefficients, and other tools. Key outputs of this project were a PV-SMaRT runoff calculator developed by the University of Minnesota, a webinar detailing project outcomes and how to use the PV-SMaRT runoff calculator, and a document on best practices for regulators and developers regarding stormwater runoff at PV sites.

Table of Contents

Background

Many state stormwater management regulations were not designed to account for the ways solar development practices differ from more traditional development (e.g., commercial and residential buildings) (Pantella 2022). One way to estimate runoff at solar sites is to utilize runoff curve numbers developed by the United States Department of Agriculture's National Resources Conservation Service. These runoff curve numbers, however, were not created or validated for photovoltaic (PV) sites, which can lead to error in estimating the runoff.

Ground-mounted PV sites are often considered disconnected, impervious surfaces and are essentially treated like a parking lot during local stormwater quality permitting. As such, the simple models currently used in many jurisdictions to assess stormwater runoff are unable to rigorously estimate the impact of solar installations on water quality outcomes. This can lead to regulatory and design uncertainty in the design of PV sites and potentially increase the cost of developing PV projects to comply with stormwater regulations.

The stormwater permitting process can leave unanswered questions for communities and local governments when they attempt to evaluate applications for the construction of PV facilities. Many jurisdictions are currently in the process of evaluating or updating their stormwater regulations and guidelines that can have an impact on solar development. For example, regulators in Virginia have proposed draft ordinances that would treat the area under and around solar modules as impervious surfaces. This could require up to 20% more land for a given amount of solar capacity to mitigate the new estimated runoff, thus increasing project costs or reducing the capacity of solar projects on the same amount of land purchased (McGowan 2022).

The Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) team conducted a review of 12 state stormwater and water quality permitting practices to highlight differences in regulations across the nation. The team also engaged solar development and water quality stakeholders in multiple state and local jurisdictions. The barriers identified below were adapted from Great Plains Institute 2021 and fall into four general categories across the landscape of water quality permitting. The barriers are:

1. *Most existing water quality standards and best practices were not designed or tested for solar installations.* Permit standards and the portfolio of stormwater best management practices (BMPs) were developed for new buildings or infrastructure such as housing and commercial projects, which do not account for the unique disconnected nature of solar development. As a result, these standards can lead to inaccurate assessment of stormwater runoff at PV sites.

2. *Different post-construction and construction stormwater permit goals can lead to suboptimal water quality results.* There can be a potential barrier to market adoption based on conflicting objectives for stormwater permit close out and site establishment.

Solar developers cannot quantify the full range of water quality benefits of green stormwater infrastructure, low-impact development, and perennial and habitat/pollinator-friendly ground cover in the stormwater construction general permit (CGP) process.

3. *Solar projects face varying expectations and standards across jurisdictions, both state and local*. This variation has led to different permitting standards and practices, requiring changes in solar design and consequently stormwater mitigation costs across jurisdictions, even for similar projects. Discussions with state regulators, solar developers, solar engineering, procurement, and construction (EPC) contractors, stormwater professionals, and feedback from Water Quality Task Force (WQTF) members, indicated that disparate approaches to stormwater requirements at ground-mounted PV have led to multiple examples of high-cost stormwater management requirements that lack solar-specific designs. This has been confirmed by discussions with state stormwater permit staff and agency officials.

4. *There is a lack of consistent, data-driven best practices about array design, layout, and site standards that can minimize water quality risks and maximize benefits*. PV system design affects stormwater runoff, and neither regulators nor developers have sufficient data on designing to minimize stormwater runoff or assess the cost-effectiveness of design decisions. Modeling to identify mitigation requirements by authorities having jurisdiction (AHJs) or development teams typically does not account for all design features that affect runoff (Great Plains Institute 2021).

To address these concerns and provide field data to update PV stormwater runoff models, the PV-SMaRT project team proposed a three-year research study. The goals and outcomes of this project are detailed in this report.

Project Objectives

The objective of the PV-SMaRT project is to develop and disseminate research-based, solar-specific resources for estimating stormwater runoff at ground-mounted PV facilities and stormwater management and detail water quality best practices. The project's deliverables include: (1) published stormwater runoff coefficients to estimate PV-specific stormwater runoff for a range of site conditions and PV system types, and (2) published stormwater management and water quality best practices, informed by field research and stakeholder engagement, for ground-mounted PV facilities.

To inform these deliverables, the PV-SMaRT project:

- Engaged an advisory WQTF to provide expert review of project outcomes.
- Conducted field research on stormwater infiltration and runoff at five ground-mounted PV sites to inform scientific models.
- Used collected data to validate a 3D hydrologic model to predict water runoff and generate stormwater runoff coefficients for a range of site conditions and PV designs.
- Developed a stormwater management and water quality best practices guidebook.

- Engaged with local jurisdictions and other stakeholders to disseminate best practices, stormwater runoff coefficients, and other tools, as shown in Figure 1.

Through its research and analysis, PV-SMaRT aims to address the stormwater and water quality challenges facing PV facilities in most jurisdictions.

The audience for this project includes public and private sector entities making stormwater management and design decisions that affect the cost of installing or ability to install PV facilities. These entities include such stakeholders as AHJs for water quality permitting, state and local agencies administering stormwater/water quality programs, solar developers, hydrologic engineers, water quality stakeholder groups, solar energy purchasers (who may be interested in setting standards for facilities from which they purchase energy), and landowners.

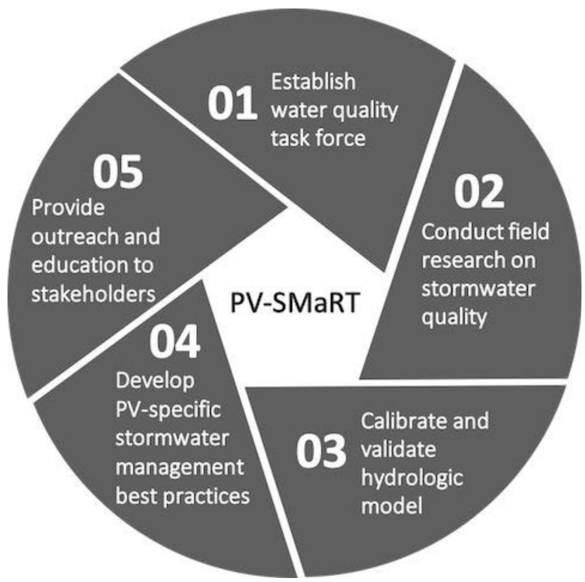

Figure 1: PV-SMaRT task plan (National Renewable Energy Laboratory 2023).

A breakout of the project tasks and their goals is presented below.

Task 1: Recruit at least 10 WQTF members and convene the task force quarterly to provide technical and applied guidance on field research, model development, best practices, and outreach and education.

Goal: The task force will provide technical review of the field-testing approach, model development, and resulting best practices and will provide guidance and support for education and outreach efforts.

Task 2: Conduct field research to measure and document stormwater runoff and water quality at five ground-mounted PV sites with different environmental site conditions and solar design characteristics.

Goal: The goal of this task is to conduct field research to quantify stormwater runoff and water quality impacts at ground-mounted PV sites, and variations that may be influenced by environmental site conditions and solar design characteristics. Site conditions may include storm duration and intensity, soil properties, slope, ground cover (e.g., gravel, turfgrass, pollinator habitat), and seed density and rooting depth of vegetation, when present. Solar design characteristics can include panel dimensions, angle, spacing, and height.

Task 3: Calibrate and validate a 3D hydrologic model using field data and generate stormwater runoff coefficients for different environmental site conditions and solar design characteristics.

Goal: The goal of this task is to use field testing results from Task 2 to calibrate and validate a commercially available 3D hydrologic model (Hydrus 3D), so that it can predict water infiltration and runoff below the drip line of the solar panels, directly beneath the solar panels, and in the regions between solar panels for different site conditions and solar designs. The purpose of the model calibration and validation is to generate modeling capabilities specific to ground-mounted PV projects. These modeling capabilities will add to existing, readily available modeling data and capabilities for development, such as parking lots and buildings. The existing data on other forms of development can be used as a control to compare how PV performs in similar climatic conditions. The one-time license for Hydrus 3D will be purchased from PC-Progress. Once calibrated with the field data collected in this project (Task 2), the 3D hydrologic model will be able to estimate how much runoff is generated at ground-mounted PV sites based on factors such as solar installation design, soil properties, land slope, and ground conditions (bare versus planted).

Based on the estimates of stormwater runoff and water quality from the validated model, the project team will develop tools, including lookup tables and nomographs, that can be used by state and local governments around the country to inform stormwater permitting at individual PV facilities. Lookup tables of coefficients, which are commonly used in water quality permitting, are not currently available for the unique land use case of ground-mounted PV installations. The purchase of Hydrus 3D or another hydrologic model will not be needed to use the lookup tables and other tools produced in this project, increasing access to these design tools.

Task 4: Apply field testing results, hydrologic model outcomes, and stakeholder engagement to develop best practices in stormwater management and water quality at ground-mounted PV facilities.

Goal: The goal of Task 4 is to use the field testing (Task 2), hydrologic model findings (Task 3), and stakeholder engagement (Task 5) to develop data-driven stormwater management and water quality best practices at ground-mounted PV facilities. The project team will review water quality permitting standards for ground-mounted PV facilities in each state in which field test sites are located. The team will conduct interviews with the lead state water quality agency and at least two local AHJs in each state to further understand the current permitting process and expectations for project design, applicant submittal requirements, and standards for approving permits. The emphasis of the review and interviews is to understand when stormwater BMPs are needed to meet permitting standards for sites with different ground cover conditions, site designs, and site characteristics, and how existing permitting processes address these variables. Draft and final deliverables at each stage of the process will be presented to the WQTF.

Task 5: Conduct outreach and education regarding model results and best practices for stormwater management and water quality at ground-mounted PV facilities.

Goal: The goal of was task is to disseminate research findings on model results and best practices to local and state regulators, industry, water quality experts, and other stakeholders. In budget period 1 (BP1), the project team conducted outreach to build stakeholder interest and engagement in the project and obtain stakeholder input in identifying permitting barriers and best practices for ground-mounted PV facilities. In BP2, the project team solicited feedback on initial hydrologic model results and draft water quality best practices for ground-mounted PV facilities. In the final budget period, the project team conducted stakeholder training and dissemination of final best practices and model results. The project team presented results through conference presentations and webinars detailed in Task 5 below. The team coordinated with national associations and professional organizations for water quality regulators and AHJs, as well as the Agriculture and Solar Together: Research Opportunities (ASTRO) committee and WQTF. Project milestones that inform these tasks are shown in Table 1.

Table 1: Project Tasks and Milestone Schedule

Year #	Task #	Milestone #	Milestone Name/Description	Planned End Date
1	1	1	Water Quality Task Force is established, and kickoff meeting is convened.	3/31/2020
1	2	2	Instrumentation is installed at a minimum of two ground-mounted PV facilities in two different states.	6/30/2020
1	2	3	Instrumentation is installed at a total of five ground-mounted PV facilities in five different emerging market states.	9/30/2020
1	3	4	Initial 3D hydrologic model is calibrated and presented to the Water Quality Task Force for review and comment.	12/31/2020
2	4	5	Potential water quality permitting barriers to ground-mounted PV development are documented.	3/31/2021
2	4	6	Draft best practices for stormwater management and water quality benefits at ground-mounted PV sites are presented to Water Quality Task Force for review.	6/30/2021

Year #	Task #	Milestone #	Milestone Name/Description	Planned End Date
2	4	7	Best practices for stormwater management and water quality benefits at ground-mounted PV sites are published.	9/30/2021
2	3	8	The 3D stormwater model is validated and presented to Water Quality Task Force for review.	12/31/2021
3	5	9	Two webinar presentations and two conference presentations on best practices for stormwater management and water quality at ground-mounted PV sites have been completed.	3/31/2022
3	5	10	Excel-based worksheet with PV-specific stormwater runoff coefficients and nomographs is completed.	6/30/2022
3	4	11	At least two stakeholder trainings on application of the Excel-based worksheet with stormwater runoff coefficients and nomographs are completed.	9/30/2022
3	5	12	Research results are submitted for publication in a peer-reviewed publication.	12/31/2022

Project Results and Discussion

The PV-SMaRT project met the objectives laid out above and succeeded in convening a task force to get input throughout the project, collecting data at five solar sites, developing a stormwater runoff calculator and model based on the data collected, publishing a best practices document, and presenting findings and conclusions to different stakeholders. This section will discuss activities for each task and how they met the milestones presented above.

Task 1: Water Quality Task Force

Milestone 1.1 was achieved in the first quarter of the project, and advisory meetings were held every quarter. The project team convened 13 members for the Water Quality Task Force (WQTF) from a variety of backgrounds to represent solar developers, stormwater professionals and designers, state and federal regulators, and researchers. The WQTF members were:

- Jason Bernagros, U.S. Environmental Protection Agency (EPA) Office of Research and Development
- Seth Brown, National Municipal Stormwater Alliance
- Veronica Craw, Georgia Department of Natural Resources

- Dave Gasper, New York Department of Environmental Conservation
- Robert Goo, EPA Office of Wetlands, Oceans, and Watersheds
- Britta Hansen, Emmons and Olivier Resources
- Greg Hoffmann, Center for Watershed Protection
- Jake Janski, Minnesota Native Landscapes
- Gavin Chase Meinschein, ENGIE North America
- David Morley, American Planning Association
- Andrew Nelson, Westwood Professional Services
- Peter Parkinson, AES Distributed Energy
- Sybil Sharvelle, Colorado State InTERFEWS Director.

Over the course of the project, the WQTF met 12 times (quarterly) to discuss research objectives and findings and to project feedback. The WQTF filled a gap in that there was no previously existing stakeholder group focused on water quality and stormwater management at ground-mounted PV sites.

Task 2: Conduct Field Research

Milestones 2.2 and 2.3 were met in the first year of the project to install stormwater monitoring equipment at five solar sites. The project team identified sites in Colorado, Georgia, Minnesota, New York, and Oregon. Monitoring equipment was procured and installed to measure site climatic conditions (rainfall, wind speed, and wind direction) and hydrologic conditions (soil moisture and water infiltration) at each site for three years over the project duration. Instrumentation collected soil moisture data automatically, while water infiltration tests were conducted in-person at least twice a year. A diagram of the monitors is shown in Figure 2. This task filled a gap in that stormwater and water quality measurements at ground-mounted PV facilities did not exist prior to the project to inform PV-specific stormwater management and water quality best practices.

Instrumentation was installed at five solar sites across the country, and data was collected over the three-year life of the project. The site descriptions are in Table 2. These sites represent a wide range of soil characteristics, solar design types, annual mean precipitation, and ground covers. Fresh Energy published case studies for three of the sites to capture differences in the sites and communicate the project outcomes (Kerber 2022a; 2022c; 2022b). Ownership of the monitors at the Minnesota sites was off to another team after the project to continue data collection for other research objectives.

Table 2: Site Parameters for PV-SMaRT Test Sites (Mulla et al. forthcoming)

Site	Capacity (MW)	Area (ha)	Slope (%)	Array Type	Panel # and Arrangement	Array Spacing (m)	Mean Annual Precipitation (cm)	Ground Cover
CO W	1.0	2.4	5%	Tracking	1 portrait	5.6	40.6	Native Mix
GA W	1.3	3.2	1.5%	Tracking	1 portrait	6.2	124.5	Mowed Cover Crops
MN S	4.5	11.7	2.5%	Fixed	2 portrait	7.6	94.0	Prairie Mix
NY C	18.0	43.7	3%	Fixed	2 portrait	7.0	124.5	Tall Grass
OR S	13.0	18.6	3%	Tracking	2 portrait	6.4	40.6	Native Pollinators

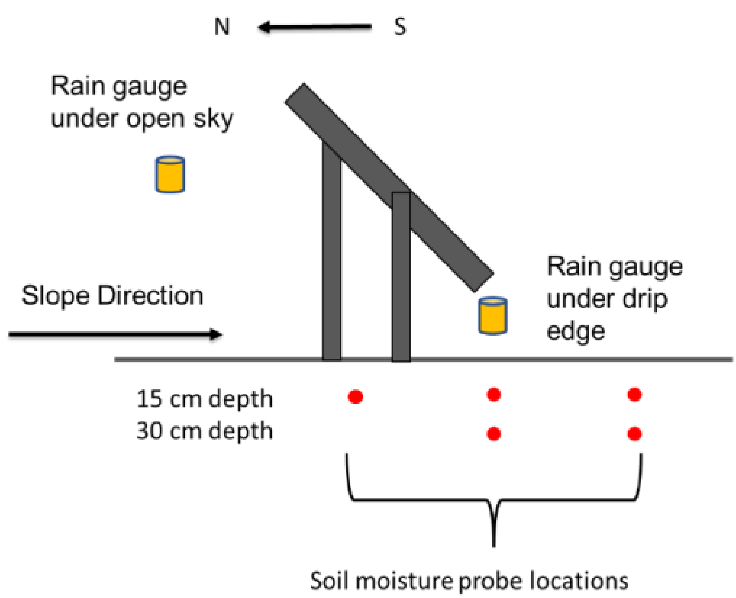

Figure 2: Orientation of monitoring equipment for a fixed tilt system (Mulla et al. forthcoming).

Results of the data collection have been submitted to the *Journal of Applied Energy* and are awaiting editor feedback.

Task 3: Calibrate and Validate Hydrologic Model

Using the data collected in Task 2, the project team (led by the University of Minnesota) developed a Hydrus-2D model representation of stormwater runoff at the solar test sites to meet Milestones 3.4 and 3.8. All information presented below has been submitted to the *Journal of Applied Energy* for publication and is awaiting editor approval. To the team's knowledge, it is the only systematic data collected in real-world conditions to quantify stormwater runoff conditions at solar sites.

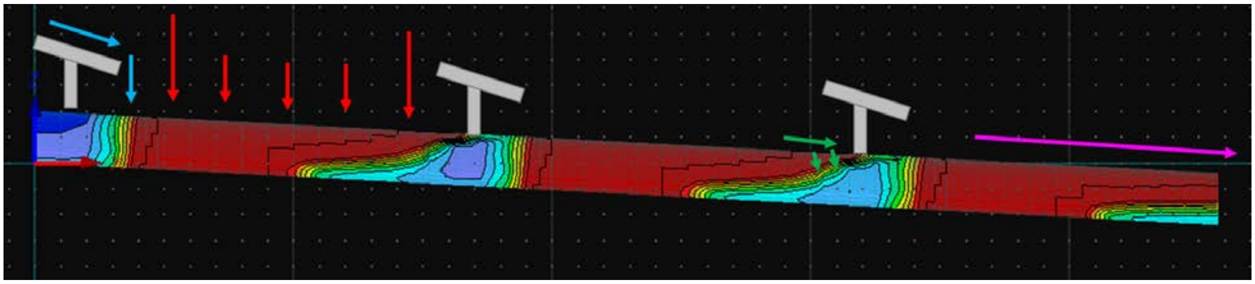

Figure 3: Diagram highlighting 2D Hydrus modeling to represent drip edge runoff, precipitation, water infiltration underneath solar panel, and runoff, adapted from (Mulla et al. under review)

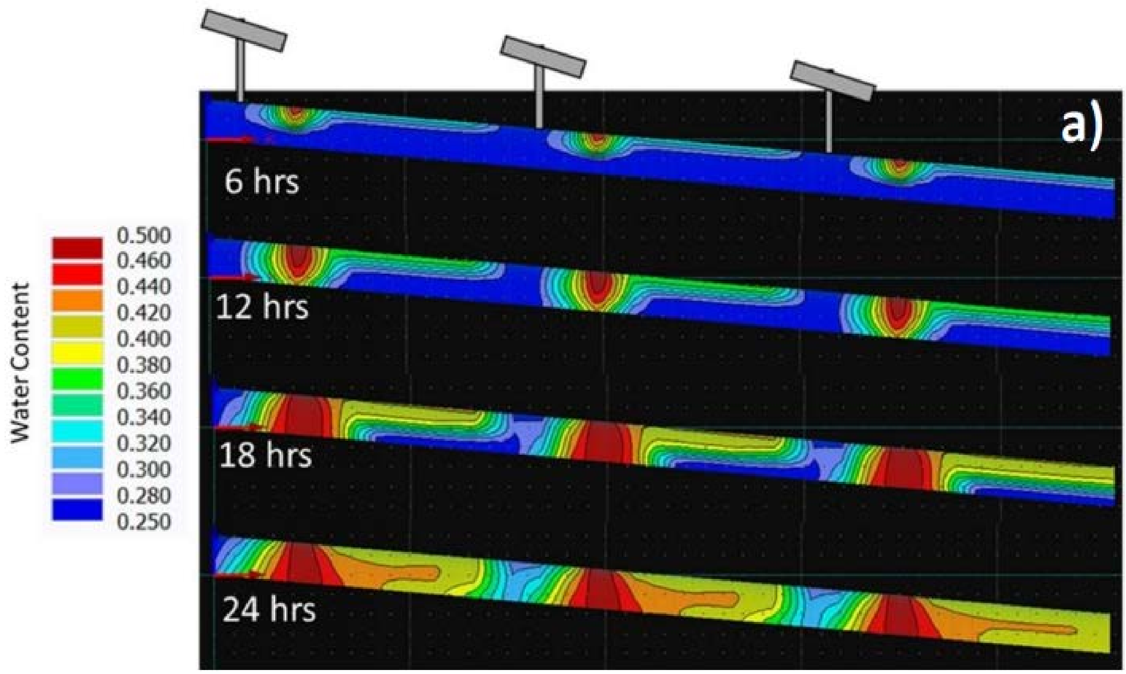

Figure 4: Drip edge infiltration based on different design storm parameters (Mulla et al. under review).

Data collected from Task 2 was used to create 2D and 3D representations of stormwater runoff at the solar sites. The Hydrus 2D model representations are shown in Figure 4 and Figure 5. Both the drip edge and disconnection of the solar panels result in different runoff patterns compared to traditional development practices and show the need for PV-specific models and regulations.

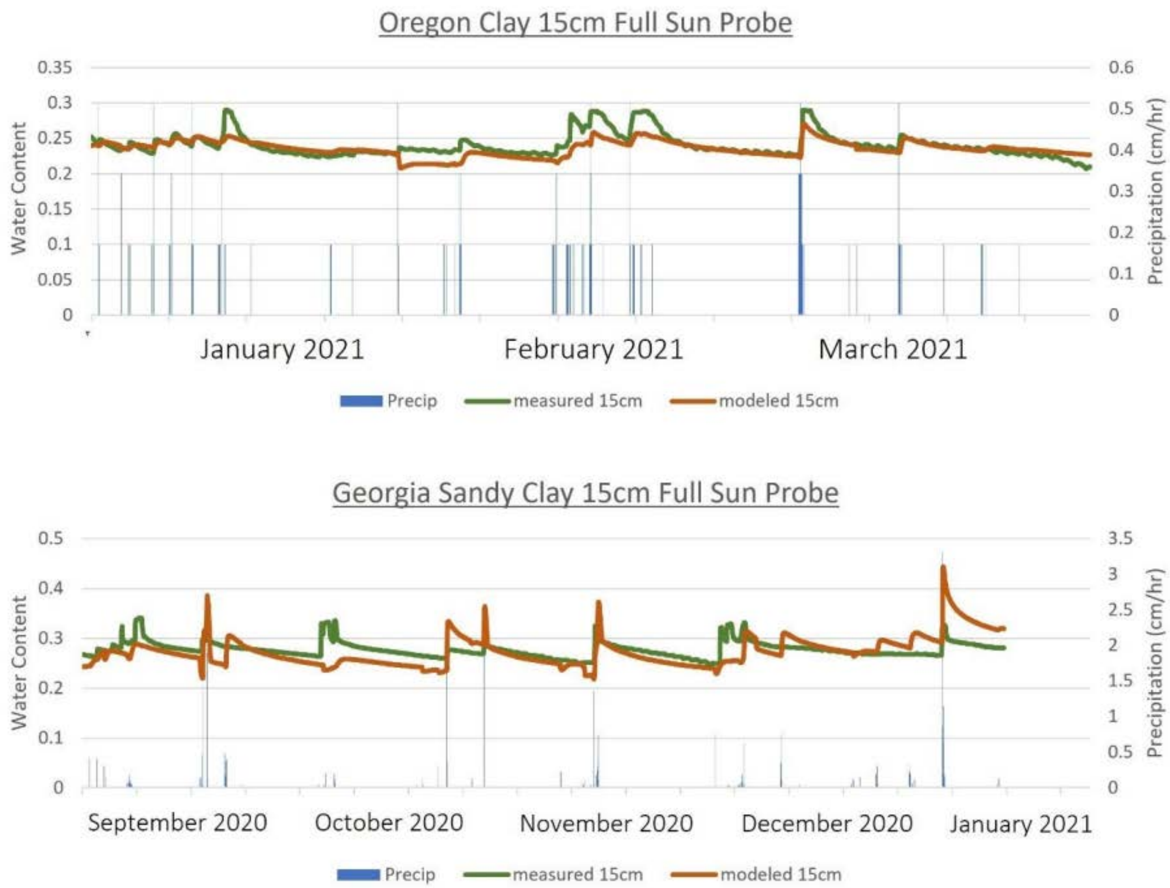

Figure 5: Modeled vs. measured design storms in Hydrus 2D model (Mulla et al. under review).

Once the Hyrdus 2D models were created, the team compared the model with real-world precipitation observations. An example of this comparison for two project sites is shown in Figure 5. There was a high correlation of the Hydrus 2D model to the measured runoff for all sites, with a root square mean error (RSME) that ranged from 0.017–0.041 across the sites.

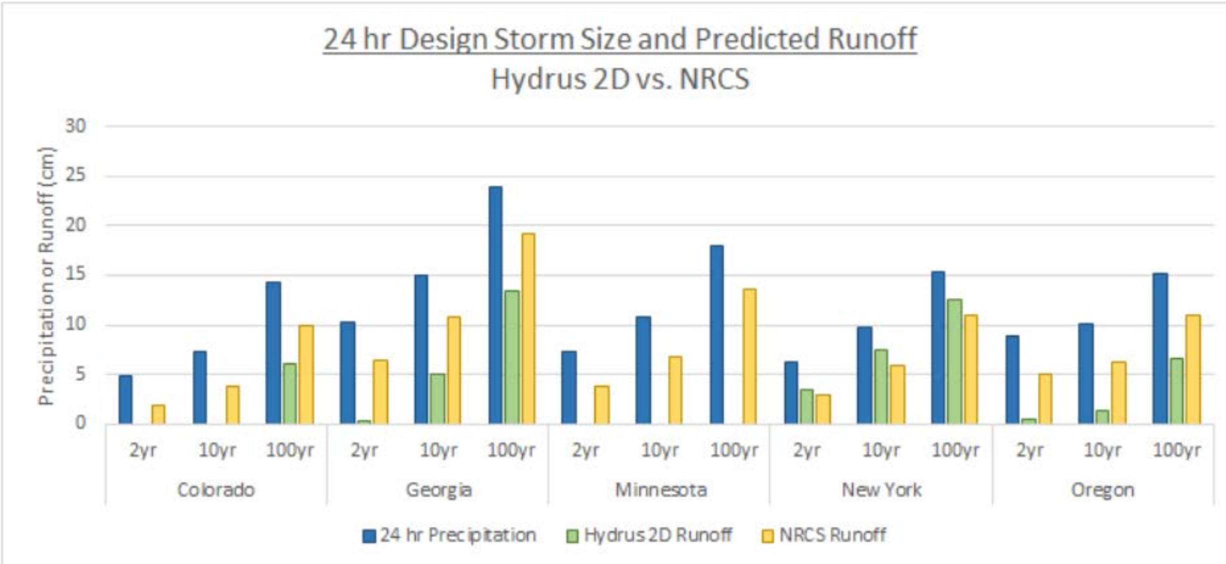

Figure 6: Comparison of 24 design storm runoff values between the project-created Hydrus 2D model and the Natural Resources Conservation Service runoff curve values (Mulla et al. under review).

Runoff across the five experimental sites estimated using Hydrus-2D was, on average, considerably lower than runoff estimated using the standard Natural Resources Conservation Service (NRCS) runoff curve number method. All these values and equations from the models were integrated into a PV-SMaRT runoff calculator that more accurately represents stormwater runoff at solar sites (University of Minnesota 2023). By using outputs from the runoff calculator, runoff calculations decreased by **38%** on average with Hydrus relative to the NRCS runoff curve number (RCN) method for a 100-yr storm having 25-foot array spacings planted with pollinator habitat. This Hydrus 2D model was simplified into an Excel spreadsheet that accounts for the key determinants of runoff to be publicly available and easy to use.

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

Figure 7: Visualization of PV-SMaRT runoff calculator (University of Minnesota 2023).

The PV-SMaRT runoff calculator quickly and easily estimates RCNs for pre- and post-construction scenarios. Users input the 24-hour design storm depth of interest, and the calculator will estimate the 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, and array spacing, and orientation. If the user wishes, RCN values for different soils or slopes at a given site can be used as area weighted inputs for other models, such as Technical Release 55 (TR-55), Storm Water Management Model (SWMM), or HydroCAD. The PV-SMaRT runoff calculator also allows for accurate consideration of runoff generated by disconnected pervious surfaces as affected by a wide range in site-specific conditions. A user manual and the model assumptions are also available for download with the runoff calculator tool (University of Minnesota 2023).

The PV-SMaRT runoff calculator and an associated user manual (v2.0) were licensed for distribution and use by the public through the University of Minnesota in early November 2022. An update to v3.0 was issued April 7, 2023.

Task 4: Best Practices Documentation

Milestone 4.5 was completed through a literature review and systematic review of stormwater permitting barriers and was presented to the WQTF at a quarterly meeting. Based on comments from the WQTF, a draft best practices document was published and made publicly available to get feedback from other stakeholders(Great Plains Institute 2021). This document was then updated to fulfill Milestone 4.6 (Great Plains Institute 2023) and was made available on the project website. Milestone 4.11 was met through presenting at two webinars: one through the WQTF and one through Fresh Energy (Fresh Energy 2022). A recording of this presentation, which details the PV-SMaRT project, runoff calculator, and best practices, can be found at https://www.youtube.com/watch?v=bfwL_2inbpY&ab_channel=FreshEnergy.

Findings from the best practices document are detailed below and adapted from Great Plains Institute 2023. PV-SMaRT's research and modeling highlight four factors that should be considered in stormwater management and water quality permitting for PV arrays (in order of greatest impact):

1. Compaction—managing soil compaction and bulk density across the site. *Runoff increases on average by 98% with compacted vs. loose soil in full sun areas.*

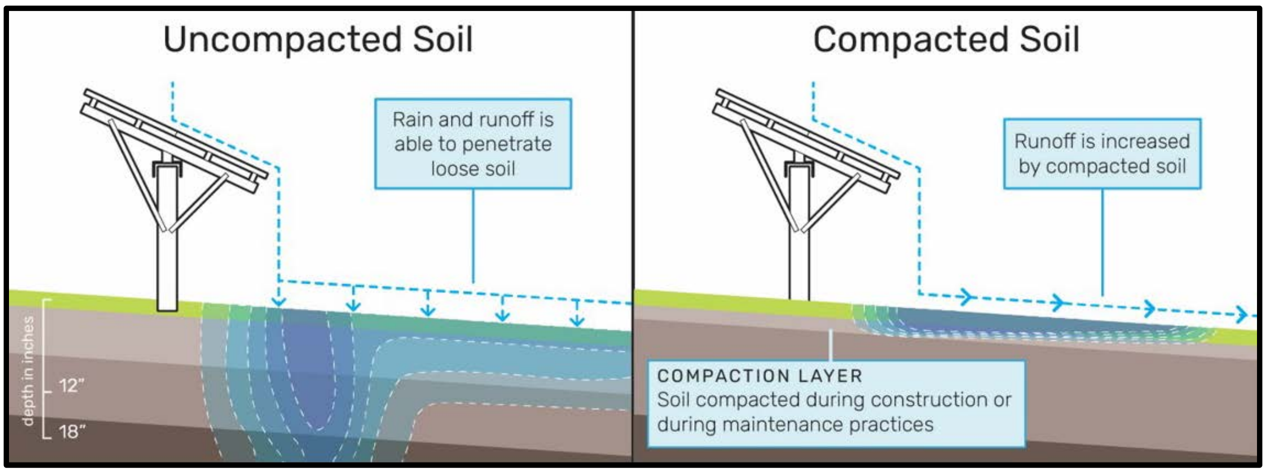

Figure 8: Visualization of compaction impacts on stormwater runoff and infiltration (Great Plains Institute 2023).

2. Soil depth—including soil depth (rooting depth) in stormwater modeling and design. *Runoff increases on average by 78% as soil depth decreases from 150 cm to 50 cm.*

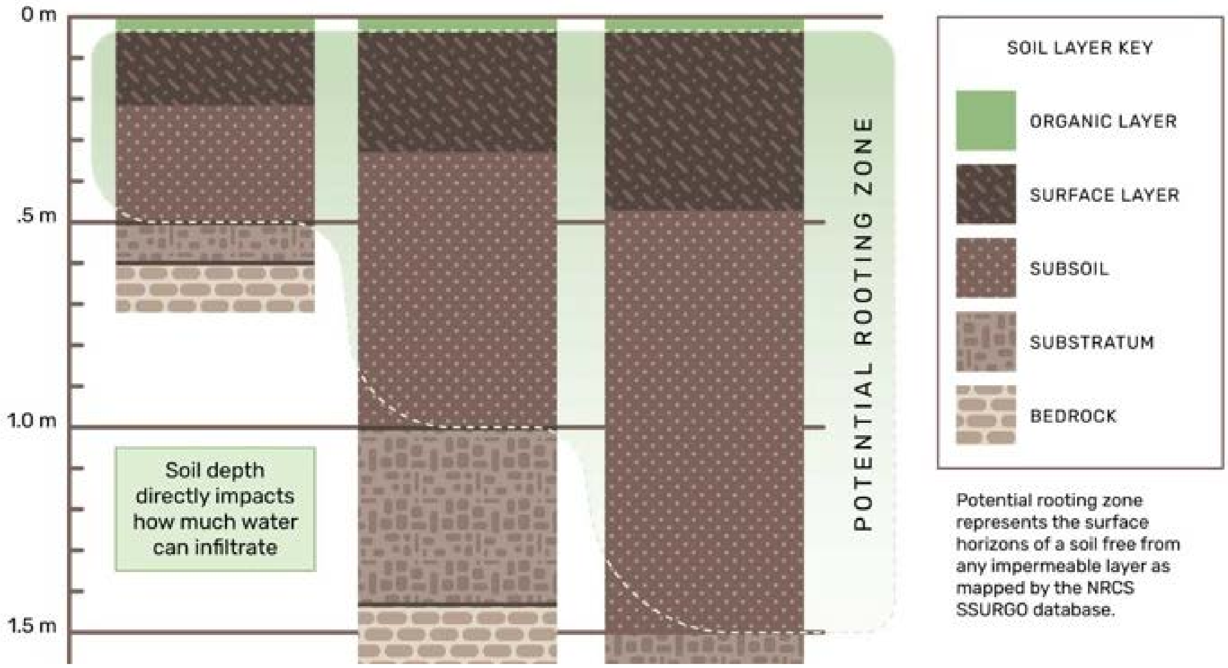

Figure 9: Visualization of soil depth and rooting zone impacts on water infiltration (Great Plains Institute 2023).

3. Ground cover—installing, establishing, and maintaining appropriate vegetated ground cover between and under the arrays to facilitate infiltration. *Runoff increases on average by 38% for row crop vs. mature prairie and 25% for turf grass vs. mature prairie, calculated by the PV-SMaRT runoff calculator.*

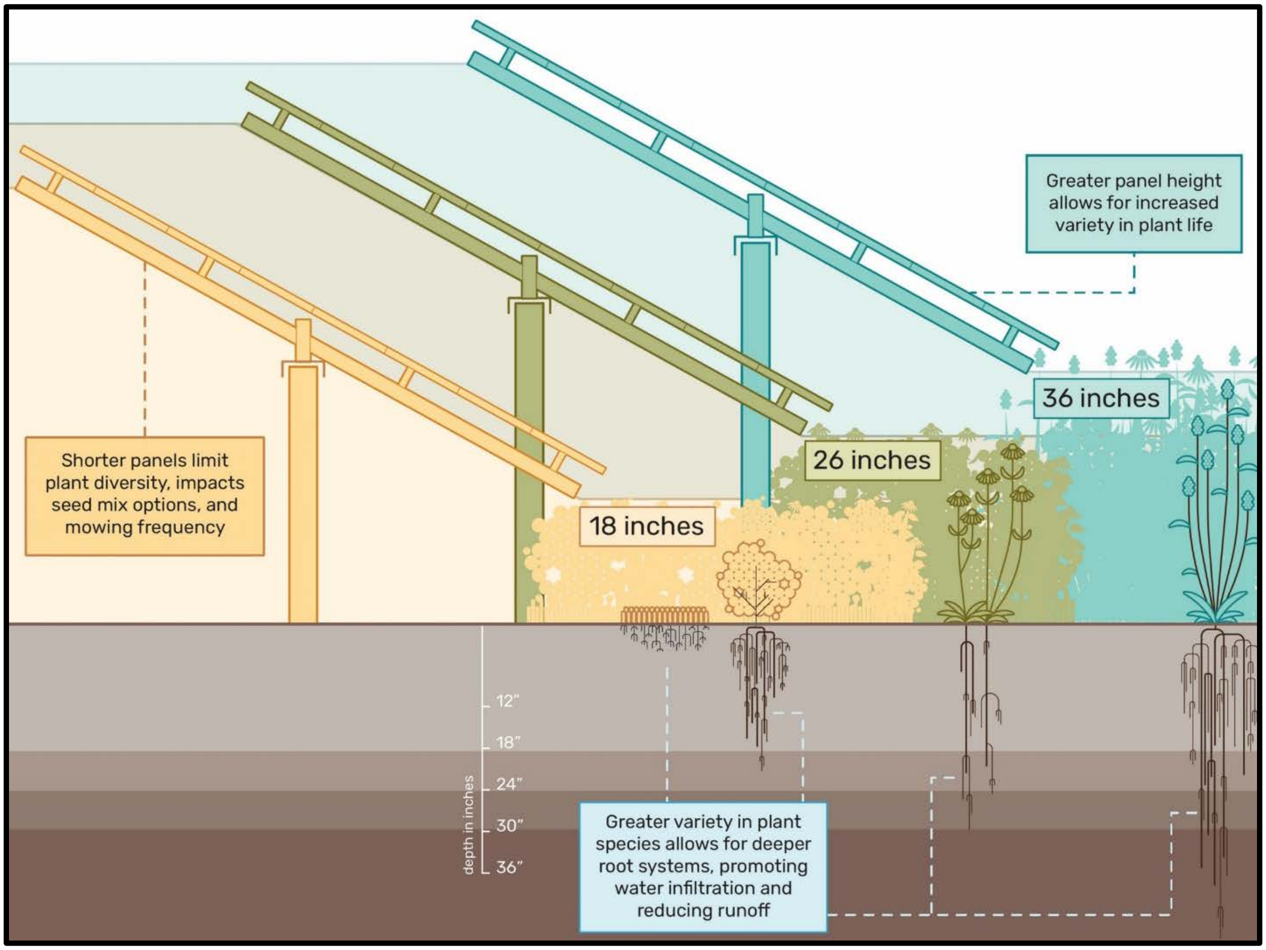

Figure 10: Visualization of vegetation cover on rooting zone and ability for infiltration (Great Plains Institute 2023).

4. Disconnection—ensuring appropriate distance between arrays for infiltration. *Runoff increases on average by 14% as panel spacing decreases from 35-feet to 15-feet.* (Great Plains Institute 2023).

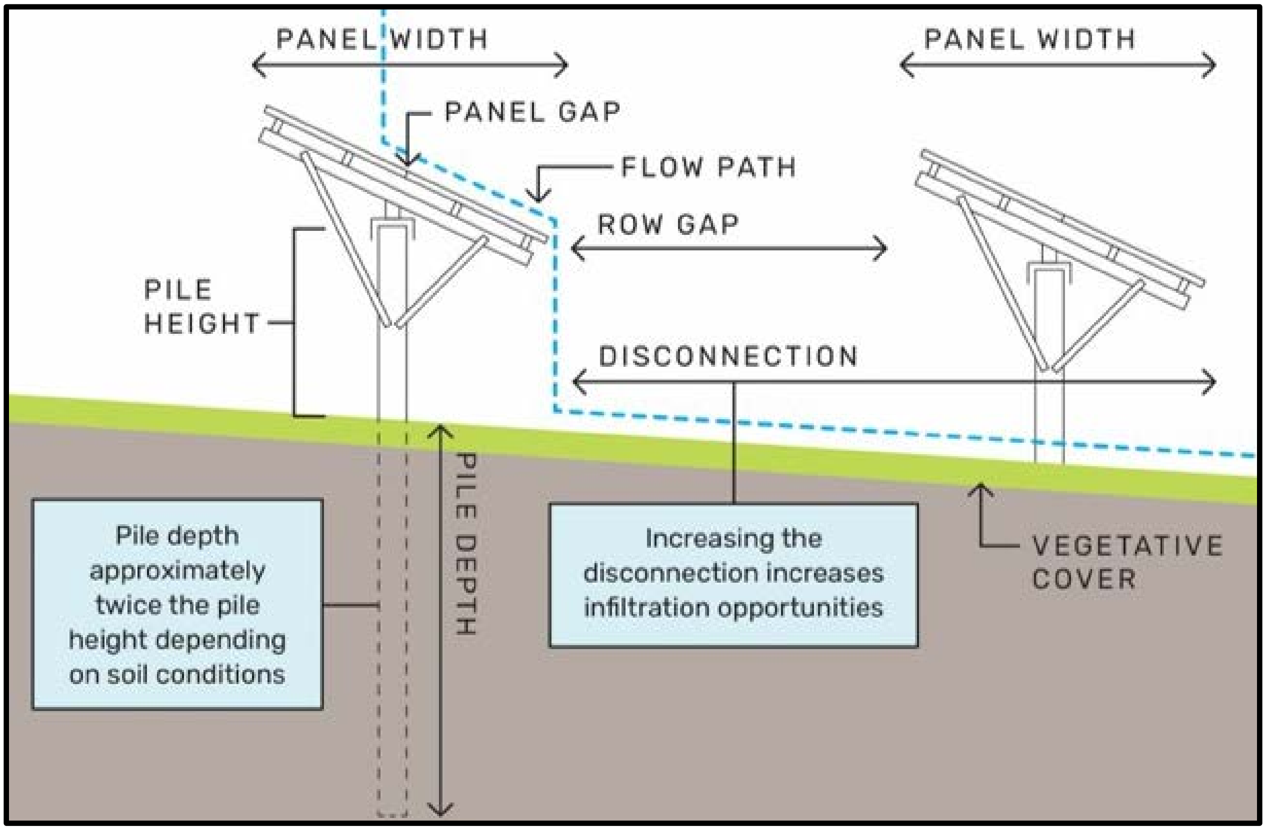

Figure 11: Visualization disconnection differences at solar sites (Great Plains Institute 2023).

Based on these four main factors, the Great Plains Institute developed and published best practices and guidelines for stormwater management (2023). Of the four main factors identified by research, only one of them (disconnection) is currently required or measured in the permitting process for solar sites. Even though disconnection is included in the permitting process, solar sites have a unique opportunity to use it as an advantage to space panels further apart, leading to less stormwater runoff. These findings highlight that there is a potential need for reviewing and updating stormwater guidelines at solar sites.

Task 5: Stakeholder Engagement and Dissemination

Project team members presented findings and results to a variety of stakeholders to meet Milestones 5.9 and 5.10. Below is a list of outreach activities for the project team, in chronological order:

- Q2–Q3 (2020): Outreach to water quality stakeholders, state agencies, local AHJs, and national associations on the project goals, process, and desired outcomes to build interest and stakeholder engagement.
- July 15, 2021: U.S. EPA webinar introducing PV-SMaRT outcomes.
- Q1–Q2 (2021): Presentation at AgriVoltaics 2020, MnSEIA, and RENEW Wisconsin Energy Summit conferences.

- Q1–Q2 (2021): Creation of PV-SMaRT website on nrel.gov domain (National Renewable Energy Laboratory 2023).
- Q1–Q2 (2021) Media outreach efforts successfully secured a feature story, "Scientists tap flowers to protect water quality on solar farms," which was syndicated online, in radio, and in print, reaching a minimum total circulation of 889,000.
- Q1–Q2 (2021): Abstracts on PV-SMaRT were also submitted to the National Association of Environmental Professionals conference, the Soil and Water Conservation Society Symposium (accepted), the Center for Watershed Protection annual conference, the American Solar Energy Society conference (accepted), and the National Watershed and Stormwater conference (accepted).
- Q3–Q4 (2021): Presentations at Soil and Water Conservation Society meeting, National Watershed and Stormwater conference, Kentucky Pollinator conference, and American Solar Energy Society meeting.
- Q3–Q4 (2021): Integrated the PV-SMaRT interim findings into SolSmart's large-scale solar guidance document and the National American Planning Association's Solar@Scale guidebook.
- Q3–Q4 (2021): Multiple local government presentations by the project team also included PV-SMaRT findings, including the Center for Rural Pennsylvania and the 1000 Friends of Iowa solar training.
- Q1–Q2 (2022): Presentations at the American Wind and Wildlife Institute Solar Summit and the keynote speaker at the International Erosion Control Association conference in 2022.
- Q1–Q2 (2022): Continued discussions with state agency stormwater and water quality permit staff (Minnesota, Pennsylvania, New York, and Ohio) on applications for updated 3D Hydrus model.
- Q1–Q2 (2022) participated in two meetings (Minnesota Solar Summit and Minnesota Board of Water and Solar Resources Quarterly Meeting) and one energy training (EUCI Agrivoltaics/Dual Use Solar).
- Q3–Q4 (2022): Stormwater runoff calculator and findings were highlighted in International Erosion Control Association (IECA) online magazine: https://ieca.mynewscenter.org/creating-water-quality-value-in-ground-mounted-solar-photovoltaic-sites/.
- Q3–Q4 (2022): Provided keynote address at IECA Annual Conference.
- Q3–Q4 (2022): Gave webinar with 150+ participants to provide training on PV-SMaRT runoff calculator and updated best practices documents based on findings.
- Q3–Q4 (2022): Wrote and compiled case studies for three project sites (Minnesota, Georgia, and Oregon) shared through Fresh Energy and NREL networks.
- Q3–Q4 (2022): Continued discussions with state agency stormwater and water quality permit staff (Minnesota, Virginia, and Wisconsin) on applications for updated 3D Hydrus model.
- Q1–Q2 (2023): Provided moderation and presentation of solar stormwater impacts at Solar Farm Summit (400+ conference participants).
- Q1–Q2 (2023): Stormwater modeling journal article submitted to *Applied Energy*.

Milestone 5.12 was met through submission of data collected to *Applied Energy*. A more detailed write-up of the PV-SMaRT calculator is currently in development.

Significant Accomplishments and Conclusions

A significant accomplishment of this project has been the adoption and downloading of the PV-SMaRT calculator. As of July 2023, there were over 139 downloads of the PV-SMaRT calculator and over 650 views between the tool webinar and the YouTube recording.

User sectors span universities, engineering/consulting firms, state and local governments, the solar industry, and 18 foreign countries (including Brazil, Canada, Egypt, France, Germany, Israel, Italy, Spain, and Turkey). Users are primarily split between academic (16), engineering (47), government (17), and solar industry (29) sectors. Geographic locations in the United States include 29 states representing nearly all regions, as shown in the figure below.

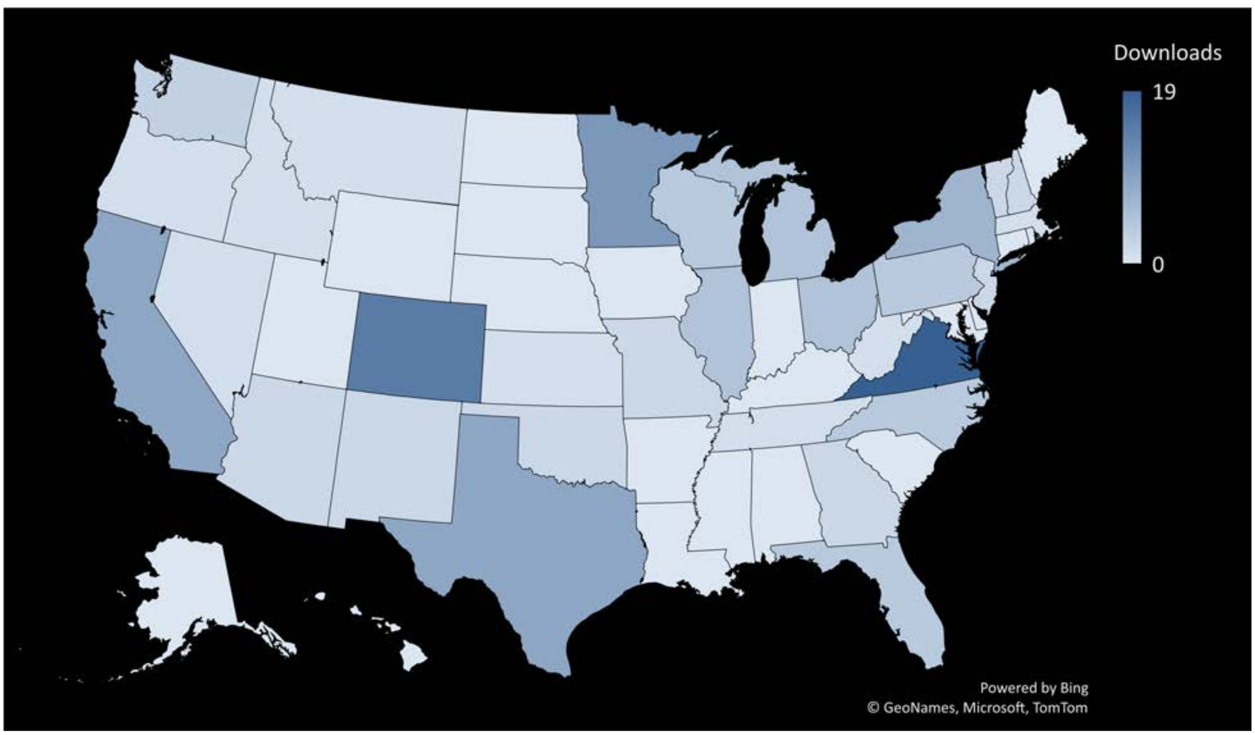

Figure 12: Map of the frequency of PV-SMaRT runoff calculator downloads by state.

Budget and Schedule

The project met the main budget and schedule milestones. The only deviation to the project was a 6-month no-cost time extension for Milestone 5.12 to allow for writing based on staff time constraints. DOE funds on the project were $1,500,000 to meet the project objectives, and there was $399,000 in cost share. Cost share mainly came from time for WQTF members to provide input and access to sites to collect data for the models.

Path Forward

There is the potential for more work to disseminate the project findings and to account for other water quality outcomes, such as impacts to groundwater. The PV-SMaRT runoff calculator will be utilized in an upcoming Great Plains Institute FOA award for the SolWEB FOA to ensure that the calculator remains up to date and reflects more accurate results from future work. Instrumentation at the Minnesota site will continue to collect data for the SolWEB FOA through Great Plains Institute. All information from the project is posted on publicly available websites to allow for adoption of tools and best practices by interested parties in the future.

Intellectual Property

There was only one IP claim on this project for the PV-SMaRT Solar Farm Runoff Calculator Version 3.0 (Technology No. 2023-053) through a nonprofit, academic, or commercial software license. There are no other plans for IP assertion at this time.

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